On-line Workshop

Dark and Quiet Skies for Science and Society

Report and recommendations

UNITED NATIONS
Office for Outer Space Affairs

IAU

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

NOIRLab

Cover picture: *Jupiter and Saturn photographed over the "Tre Cime di Lavaredo" (The three peaks of Lavaredo), a famous dolomitic group. The picture symbolically joins two UNESCO World Heritage items, the terrestrial Dolomites and the celestial starry sky.*

Courtesy of Giorgia Hofer, Photographer

«Zwei Dinge erfüllen das Gemüt mit immer neuer und zunehmender Bewunderung und Ehrfurcht, je öfter und anhaltender sich das Nachdenken damit beschäftigt: Der bestirnte Himmel über mir, und das moralische Gesetz in mir.»

I. Kant - Kritik der praktischen Vernunft

«Two things fill the mind with ever new and increasing admiration and awe, the more often and longer the reflection occupies itself with it: the starry sky above me, and the moral law within me.»

I. Kant - Critique of Practical Reason

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ABOUT THE AUTHORS[1]

This Report is the result of the dedicated effort of more than 85 people who worked in five Working Groups under the coordination of their respective Chairs and co-Chairs. Guidelines were provided by the Scientific Organizing Committee (SOC) that had also the responsibility for the final editing of the document. The composition of the SOC and of the five Working Groups is listed here.

1. SCIENTIFIC ORGANIZING COMMITTEE

Chair:

Connie Walker, NSF's NOIRLab, International Astronomical Union, USA

Co-Chair:

Simona Di Pippo, United Nations Office for Outer Space Affairs, Austria

Members:

Martin Aubé, Cégep de Sherbrooke, Canada
John Barentine, International Dark-Sky Association, USA
Zouhair Benkhaldoun, Oukaimeden Observatory/Cadi Ayyad University, Morocco
Piero Benvenuti, University of Padova, International Astronomical Union, Italy
Costis Bouroussis, National Technical University of Athens, Lighting Laboratory, International Commission on Illumination, Greece
Richard Green, University of Arizona, USA
John Hearnshaw, University of Canterbury and Aoraki Mackenzie International Dark Sky Reserve Board, New Zealand
Harvey Liszt, National Radio Astronomy Observatory, IUCAF Chair (USA)
James D. Lowenthal, Smith College, USA
Casiana Muñoz-Tuñón, Instituto de Astrofísica de Canarias, Spain
Kathryn Nield, International Commission on Illumination , Austria
Nathalie Ricard, United Nations Office for Outer Space Affairs, Austria
Jose Miguel Rodriguez Espinosa, Instituto de Astrofísica de Canarias, Spain
Pedro Sanhueza, Oficina de Protección de la Calidad del Cielo del Norte de Chile
Antonia M. Varela Pérez, Fundacion Starlight, Spain
Andrew Williams, European Southern Observatory, Germany

2. DARK SKY OASES WORKING GROUP

Co-chairs:

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[1] The drafting of this report has been coordinated by the United Nations Office for Outer Space Affairs; the opinions expressed in this report are those of the authors and do not necessarily reflect those of the United Nations or its Member States.

John Hearnshaw, University of Canterbury, New Zealand and Aoraki Mackenzie International Dark Sky Reserve Board, New Zealand

Antonia M. Varela Perez, Starlight Foundation/Instituto de Astrofísica de Canarias/International Astronomical Union, Spain

Members:

John Barentine, International Dark-Sky Association and University of Utah Consortium for Dark Skies, USA

Zouhair Benkhaldoun, Oukaimeden Observatory/Cadi Ayyad University, Morocco

Costis Bouroussis, National Technical University of Athens, Lighting Laboratory, International Commission on Illumination, Greece

Steve Lau, Hangzhou Yongdian Illumination Co., Ltd/International Commission on Illumination, People's Republic of China

Casiana Muñoz Tuñón, Instituto de Astrofísica de Canarias, Spain

Kathryn Nield, International Commission on Illumination, Austria

José M. Rodríguez Espinosa, Instituto de Astrofísica de Canarias/International Astronomical Union, Spain

Pedro Sanhueza, Oficina de Protección de la Calidad del Cielo del Norte de Chile, Chile

Connie Walker, NSF's NOIRLab, International Astronomical Union, USA

◆

3. OPTICAL ASTRONOMY WORKING GROUP

Co-Chairs:

Richard Green, University of Arizona, USA

Casiana Muñoz-Tuñon, Instituto de Astrofísica de Canarias, Spain

Members:

Juan Pablo Armas, Andescan SpA, Chile

Martin Aubé, Cégep de Sherbrooke, Canada

John Barentine, International Dark-Sky Association and University of Utah Consortium for Dark Skies, USA

Zouhair Benkhaldoun, Oukaimeden Observatory/Cadi Ayyad University, Morocco

Chris Benn, Instituto de Astrofísica de Canarias, Spain

Peter Blattner, Federal Institute of Metrology METAS, Switzerland; International Commission on Illumination

Costis Bouroussis, National Technical University of Athens, Lighting Laboratory, International Commission on Illumination, Greece

Javier Diaz-Castro, Instituto de Astrofísica de Canarias, Spain

Maurice Donners, Signify Research, Netherlands; International Commission on Illumination

Bryan Douglas, Global Lighting Association, Australia

Dionýz Gašparovský, Slovenská technická univerzita v Bratislave, Slovakia; International Commission on Illumination

Jeffrey Hall, Lowell Observatory, USA

John Hearnshaw, University of Canterbury, New Zealand and Aoraki Mackenzie International Dark Sky Reserve Board, New Zealand

Zoltán Kolláth, Eszterházy Károly University, Hungary

Steve Lau, Institute of Intelligent Lighting YD Illumination, Hangzhou China; International Commission on Illumination

Kathryn Nield, International Commission on Illumination, Austria

Tomas Novak, VŠB-Technical University of Ostrava, Czech Republic; International Commission on Illumination

Sergio Ortolani, University of Padua, Italy

José Miguel Rodríguez Espinosa, Instituto de Astrofísica de Canarias, Spain

Pedro Sanhueza, Oficina de Protección de la Calidad del Cielo del Norte de Chile

Antonia M. Varela Pérez, Fundacion Starlight, Spain

Constance Walker, NSF's NOIRLab, USA

* * *

4. BIOENVIRONMENT WORKING GROUP

Co-Chairs:

Costis Bouroussis, National Technical University of Athens, Lighting Laboratory, International Commission on Illumination, Greece

James Lowenthal, Smith College, USA

Members:

Salvador Bara, Universidade de Santiago de Compostela, Galicia, Spain

Annika Jägerbrand, Halmstad University, Sweden and Chair of the International Commission on Illumination TC4-61

Andreas Jechow, Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Germany

Travis Longcore, University of California Los Angeles/The Urban Wildlands Group, USA

Mario Motta, North Shore Medical Center/Tufts Medical School, USA

Pedro Sanhueza, Oficina de Protección de la Calidad del Cielo, Chile

Luc Schlangen, Eindhoven University of Technology, The Netherlands

Sibylle Schroer, Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Germany

* * *

5. SATELLITE CONSTELLATION WORKING GROUP

Co-Chairs:

Andrew Williams, European Southern Observatory, Germany

Sara Lucatello, European Astronomical Society / INAF Padova, Italy

David Galadí-Enríquez, IAU Commission B7 / Spanish Astronomical Society SEA, Spain

Genoveva Micheva, Leibniz-Institute for Astrophysics, Germany
Angel Otarola, European Southern Observatory, Chile

Members:

Lori Allen, NOIRLab, United States
Michelle Bannister, University of Canterbury, New Zealand
Martin Barstow, University of Leicester, United Kingdom
Cees Bassa, ASTRON, Netherlands
Piero Benvenuti, University of Padova, International Astronomical Union, Italy
Roger Davies, European Astronomical Society / Oxford University, United Kingdom
Daniel Devost, Canada-France-Hawaii Telescope, United States
Richard Green, Steward Observatory, University of Arizona, United States
Olivier Hainaut, European Southern Observatory, Germany
Jeffrey Hall, Lowell Observatory, United States
Moriba Jah, University of Texas at Austin, United States
Kelsie Krafton, American Astronomical Society, United States
Harry Krantz, Steward Observatory, University of Arizona, United States
Daniel Kucharski, University of Texas at Austin, United States
James Lowenthal, Smith College / IAU Commission B7, United States
Timothy Maclay, Celestial Insight, United States
Robert Massey, Royal Astronomical Society, United Kingdom
Charles Mudd Jr, Mudd Law, United States
Jonathan McDowell, Center for Astrophysics, Harvard & Smithsonian, United States
Joel Parriott, American Astronomical Society, United States
Eric Pearce, Steward Observatory, University of Arizona, United States
Meredith Rawls, University of Washington / Vera C. Rubin Observatory, United States
Giuliana Rotola, European Southern Observatory, Germany
Rob Seaman, Catalina Sky Survey, United States
Patrick Seitzer, University of Michigan, United States
Jan Siminski, ESA Space Debris Office, Germany
Lisa Storrie-Lombardi, Las Cumbres Observatory, United States
Rachel Street, Las Cumbres Observatory, United States
Jeremy Tregloan-Reed, Universidad de Antofagasta, Chile
J. Anthony Tyson, Vera C. Rubin Observatory / University of California, Davis, United States
Eduardo Unda-Sanzana, Universidad de Antofagasta, Chile
Richard Wainscoat, University of Hawai'i, United States
Connie Walker, NOIRLab / IAU Commission B7, United States
Olga Zamora, Instituto de Astrofísica de Canarias, Spain

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work with these and other satellite operators.C

6. Radio Astronomy Working Group

Chair:

Harvey Liszt, National Radio Astronomy Observatory, IUCAF Chair, USA

Members:

Federico DiVruno, SKA Telescope, UK
Michael Lindqvist, Chalmers, Onsala Space Observatory, Sweden
Masatoshi Ohishi, National Astronomical Observatory of Japan
Adrian Tiplady, South African Radio Astronomy Observatory
Tasso Tzioumis, CSIRO, Australia
Bevin Ashley Zauderer, National Science Foundation, USA
Liese van Zee, Indiana University, USA

1. INTRODUCTION

Upon request from the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), the UN Office of Outer Space Affairs, the International Astronomical Union and Spain are organising a Conference on "Dark and Quiet Skies for Science and Society", postponed to April 2021 due to the Covid-19 pandemic. An online Workshop took place from 5 to 9 October 2020 to discuss initial findings and draft recommendations. The present report is the outcome from this Workshop; the recommendations it contains will be reviewed during the forthcoming Conference with the aim to be presented to the COPUOS Meeting in June 2021

The purpose and scope of the Conference and Workshop is to propose to COPUOS a set of recommendations, to be acted upon either by local governments or agreed to at an international level, aimed at protecting the science of astronomy[1].

Astronomy is one of humanity's oldest sciences and underpins our exploration and use of outer space. Fantastic progress in the knowledge of our Universe has been made with the development of sophisticated observatories in space and on Earth, operating in synergy and across the entire electromagnetic spectrum. Astronomical knowledge is also essential to enable deep space navigation and exploration, probe the conditions on Solar System bodies, defend the Earth from threatening asteroids, search for life on other worlds, and reveal the origins of our Earth. Cutting edge astronomical discoveries can only continue on the basis of an unobscured and undisturbed access to the cosmic electromagnetic signals: the protection of the dark and quiet skies of major professional observatories from anthropogenic interference is directly aligned with the mission of COPUOS.

The information that we are acquiring from the study of celestial phenomena provides not only a deeper understanding of our place in the universe, but has also led to technological progress. It is therefore in the interest of many sectors of society to enable astronomy and cosmology to benefit from access to the sky, free of manmade interference. Moreover, beyond science and technology, the pristine spectacle of the starry night sky has been inspirational to humankind since prehistoric times and this world cultural heritage should be zealously protected.

In preparing the on-line Workshop "Dark and Quiet Skies for Science and Society", all sources of electromagnetic interference that currently affect or endanger the visibility of the pristine night sky have been considered (including the recent threat represented by satellites constellations), and the present report identifies measures that avoid or mitigate their negative impacts. Care has been taken to propose recommendations that are both technically and economically feasible and do not affect the main purpose behind the source of interference (e.g., safety driven urban illumination, space-based network connectivity).

The on-line Workshop has been very successful, with more than 950 registered participants, while each of the daily sessions was followed by between 250 to 380 on-line attendees. The draft report, prepared during the preceding months by 5 Working Groups of internationally recognized experts, was made available to the registered participants prior to the event. All participants were then invited to submit written comments and suggestions within a week of the Workshop conclusion. The Working Groups then used them to finalize the Report.

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[1] It is not intended to include these recommendations into wider Space Treaties, their scope being solely confined to the protection of the science of astronomy.

The Final Report represents the most up-to-date and authoritative analysis of the impact on astronomy by three classes of interferences: Artificial Light At Night (ALAN), radio wavelength emission, and the large number of LEO (Low Earth Orbit) satellites trails. In accordance with the above-mentioned purpose and scope of the Workshop, the Report contains a number of recommendations aimed at mitigating the impact of the different classes of interference.

The current report has been composed by merging the individual reports of the 5 Working Groups and has been organized in the following sections

- Executive summaries: a general summary followed by the executive summaries of the 5 Working Groups
- Report and recommendations: the 5 full reports by the Working Groups
- Appendices: detailed data have been moved to appendixes in order to make the readings of the reports more fluent.
- References and bibliography

Disclaimer: The International Astronomical Union, in line with its mission[2] , wishes to stress that the sole aim of this Report is to protect the science of Astronomy and the visibility of the night sky from the impact that may be caused by other human activities. It is not intended to express opinions on the intrinsic merit or demerit of any of the latter.

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[2] The International Astronomical Union (IAU) was founded in 1919. Its mission is to promote and safeguard the science of astronomy in all its aspects, including research, communication, education and development, through international cooperation.

2. EXECUTIVE SUMMARY

2.1. GENERAL EXECUTIVE SUMMARY

This report analyses all artificial interference that can have a negative impact on the visibility of the night sky. These interferences can be logically grouped into three categories according to type. The first category refers to the effect caused by the artificial emission of visible light during the night, also known as ALAN (Artificial Light At Night). The second category refers to the impact that the very large number of communication satellites in Low Earth Orbit will have on astronomical observations. The third category refers to the interference that radio broadcasting, both by terrestrial and satellite sources, have on observations by radio telescopes.

The possibility of illuminating our houses and cities during the night time represents great technological progress and is currently an indefeasible asset to our society. However, excessive, ubiquitous and improperly directed illumination has very negative impact on three main aspects:

1. the ability of our citizens to view a pristine, starry sky,
2. the efficiency of scientific observations of cosmic phenomena by amateur and professional astronomers,
3. the bio-environment including human health.

These three aspects have been analysed in detail by three ad hoc Working Groups. Their findings and recommendations are summarized here.

In the case of the preservation of the pristine night sky, it is evident that it would be unrealistic to restore completely its visibility within the boundaries of a modern city, where the street illumination is mandatory for safety reasons. However, in order to safeguard the right of any citizen to enjoy the vision of the starred sky, we recommend that national and local governments establish a suitable number of "Dark Sky Oases" and protect them from excessive ALAN. When these are located nearby densely populated regions, urban illumination has to comply with a number of prescriptions that can mitigate the diffusion of light, including reducing the level of illumination to the minimum necessary and by directing the sources only where needed. Urban illumination that is not strictly needed for safety reasons should be discouraged. It is worthwhile noting that such measures result in substantial energy saving and serve to help promote societal conservation of natural resources.

In the case of the protection of existing or planned astronomical observatory sites, the mitigating measures are more stringent than those recommended for the Dark Sky Oases, not only because the level of light pollution from ALAN has to be kept considerably lower, but also because the control of the spectral distribution is an important factor. Modern astronomical optical observatories usually represent large financial investments by the relevant government institutions, therefore, it is in the interest of the same governmental authorities to protect a suitable area surrounding the observato- ries by adopting and enforcing specific regulations. However, in several cases, astronomical observatories that are financially supported by a given Government are located in a foreign country that offers better geographic and climate conditions for astronomical observations. In these cases, it is essential that clear assurance for enforced protection from ALAN is included in the international hosting agreement. This is one of the reasons why this matter is brought to the attention of the UN COPUOS, which offers the best international forum for proposing a uniform approach to the matter.

By analysing the impact of ALAN on astronomical observations, it was noted that the same polluting sources affect not only the sky, but also the environment in general and in particular biological life and human health. A specific Working Group on bio-environment has analysed these effects and is recommending a number of measures, some of which are germane to those recommended by the previous two cases. In addition, the Working Group is encouraging further study of the effect of ALAN on the bio-environment, in particular those produced by novel light sources, such as various types of outdoor LED lights.

One of the reasons why it is logical to present and discuss the three above cases as belonging to the same category, is the fact that the Working Groups recommendations, even if agreed internationally, can only be adopted and enforced by individual national and local governmental authorities, i.e., by the same authorities that regulate and finance, directly or indirectly, urban illumination.

Nonetheless, if a substantial number of UN Delegations would endorse the recommendations, their strength and value would greatly enhance the chances of their local implementation. It should be stressed, however, that the approach to regulate the ALAN effects differs substantially from those being considered for the remaining two interference sources that impact astronomy: stray light from satellite constellations and unregulated or wayward radio emissions.

The deployment of large numbers (tens of thousands) of communication satellites in LEO (Low Earth Orbit) is a very recent technological feat. Their main purpose is to provide earth-space-earth, low latency communication networking to any inhabited region of the globe. While this endeavor may be an advantage to society, the effect of the fully deployed constellations on the visibility of the night sky and on the professional astronomical observations has not been adequately considered. It turns out that, because of their low orbit, a considerable number of satellites will be visible to the naked eye, especially at low elevation above the horizon and at twilight and dawn.

More seriously, a much larger number of satellites will be detected during their flight paths by the highly sensitive astronomical detectors of modern telescopes during significant parts of the night. The impact is particular dramatic for wide-field telescopes and automated surveys aiming at the detection of moving objects, e.g., the COPUOS supported International Asteroid Warning Network (IAWN). It is estimated that up to 30-40% of the images taken by a wide field telescope, like Vera C. Rubin Observatory, could be made unusable. Differently from the previous category, the mitigation of the effects caused by satellite constellations calls for an internationally agreed regulation; i.e., it falls within the core business of the UN COPUOS. The situation is certainly complex, both from the technical point of view and from the possible regulatory aspects. Therefore, a larger section of the report has been devoted to the matter.

Radio astronomy has a long tradition of coping with interference caused by radio broadcasting and other artificial emissions. Indeed, a number of international agreements have been signed at the level of the International Telecommunication Union aiming at protecting wavelength bands that are of particular astronomical interest. However, the situation is continually evolving and the specific technology used to detect radio emission, substantially different from that used in the visual domain, makes the protection of radio astronomy a very complex matter. In addition, the recent increase of space-borne high-power radio emitters poses serious problems that must be addressed at the international level. In particular, non-GSO (GeoSynchronous Orbit) satellites should be required to avoid direct illumination of radio telescopes and radio quiet zones, especially when using radar and other high-power applications that are capable of burning out radio astronomy's receivers. Moreover, non-GSO satellites should be required to have sidelobe levels that are low enough that their indirect illuminations of radio telescopes and radio quiet zones do not interfere.

The following 5 sections (from 2.2 to 2.6) are the thematic Executive Summaries prepared by the 5 Working Groups: Dark Sky Oases, Optical Astronomy, Bio-environment, Satellite Constellations and Radio Astronomy. The Summaries, as well as the corresponding full thematic reports, have been written independently by the 5 Working Groups and, although an effort has been made to homogenize their style and content, some repetitions were unavoidable.

2.2. DARK SKY OASES EXECUTIVE SUMMARY

The International Union on Conservation of Nature (IUCN) has classified Dark Sky Oases into six classes, based on the type of use to which they are put (such as astronomical research, astro-tourism, heritage values, wilderness areas used for public education and outreach etc.). The IUCN classification scheme has been adopted here. In May 2020 there were 223 Dark Sky Oases across the world. This chapter discusses the nature and causes of a bright night sky resulting from light pollution. This has adverse effect on professional astronomers, amateur astronomers, astro-tourists and on those who want to admire the beauty of a pristine and dark night sky.

Light pollution also has a number of additional adverse effects which are briefly discussed; they include reduced safety at night, wasted electric power, environmental harm and a probable adverse effect on human health. Sections 2.4 and 5. in this report cover some of these topics in more detail.

This Summary focuses on mitigating the effects of ALAN in “Dark Sky Oases,” also known as “dark sky places.” These are areas where the night sky has some form of policy protection from the effects of ALAN, through the means of lighting ordinances, local or national protocols or bye-laws, or the internal policies of land-management entities. Such protected areas have been granted accreditation by one of several internationally recognized accreditation organizations, notably the International Dark- Sky Association (based in Arizona) and the Starlight Foundation (based in the Canary Islands).

The work of the International Dark-Sky Association and of the Starlight Foundation is outlined, and the Dark Sky Oases they have accredited (or certified) are summarized in Section 3.7 and 3.8. The Aoraki Mackenzie International Dark Sky Reserve in New Zealand, with IDA accreditation, and the La Palma Starlight Reserve in the Canary Islands, with Starlight Foundation certification, are presented as typical case studies.

Light pollution has increased dramatically in many countries since the end of the Second World War as a result of the proliferation of outdoor street lighting and the use of lighting for commercial locations such as factory yards, ports and sports facilities and the floodlighting of buildings of heritage value.

Light pollution and bright night skies are a significant problem in eastern North America, Western Europe, India, Japan, and eastern China. Many people in these places are unable to see the Milky Way at all. In the most populated places only a few stars may be visible to the naked eye at night, compared to several thousand in Dark Sky Oases.

The effects of light pollution depend very much on the type of lamp and light source used. A short survey of different lamp types is given. The dominant rise of white light-emitting diode (LED) lamps in the last decade is noted. Many white LEDs have significant blue emission which is largely absent from sodium arc lamps. Here blue light is defined as emission with a wavelength less than 500 nm.

The harmful effects of ALAN in brightening the night sky are considerably greater for blue light, as a result of the wavelength dependence of light scattering in the atmosphere. In this respect, LED light sources present an increased hazard for light pollution and enhanced sky brightness, unless the most recent types of low colour-temperature amber LEDs are used, which have much reduced blue light emission. In addition, smart lighting management systems can control the brightness of LEDs at off-peak hours, which may help reduce their harmful impact.

The need to mitigate the effects of ALAN have been recognized by a number of countries and localities over the last fifty years, and this has resulted in lighting ordinances or lighting bye-laws to be enacted. These regulations often require exterior lights to shine below the horizontal, and they may place limits on the blue-light emission and require lights only to shine where and when they are required for safety or other essential reasons.

The value of Dark Sky Oases for the economy, for science, for promoting culture, for environmental protection, for human wellbeing and for promoting astro-tourism is discussed.

For the six classes of dark sky oasis recognized by IUCN, values of the maximum desirable night sky brightness are proposed. These are aspirational values, and in particular locations may not be attainable or in others, they may be exceeded with yet darker skies. The values range from 10 per cent more sky brightness than the naturally occurring airglow (applicable in the vicinity of astronomical research observatories) to four times the natural airglow for protected dark sky sites near more urban areas.

Finally, a number of technical lighting recommendations are made which will assist dark sky locations to realize the sky brightness limits advocated here. These recommendations are based on the principles that exterior lighting should only be used where and when it is absolutely necessary; that exterior lighting should shine down and not above the horizontal; and that the emission of blue light should be strongly curtailed. Central management systems that actively control LED light output are recommended.

2.2.1. Recommendations to COPUOS

We recommend to COPUOS the levels of sky brightness considered to be appropriate for different dark sky place classes, as defined by the IUCN Dark Skies Advisory Group (DSAG) – see Section 3.4.1 and Appendix A. The International Astronomical Union and the International Commission on Illumination (Cayrel et al. 1980) recommend that for astronomical observatories it should be no more than 10% additional brightness beyond the natural background airglow at a zenith angle of 45°, airglow being typically 174 to 250 μcd m^{-2} (micro candle per square meter, Falchi et al 2016). We have adopted 240 μcd m^{-2} here as a nominal value. Rounding this value and extending it to the DSAG classes of dark sky places, we recommend the following values as a basis for seeking support for abatement of light pollution. Limiting values in μcd m^{-2} are also quoted in visual magnitudes per square arc second and are consistent with those also recommended by IUCN (Welch, 2021).

DS_Oas 1. **Dark Sky Astronomy Site, DSAG class 1: <260 μcd m^{-2}; >21.7 mag arcsec^{-2}. 10 % more than airglow**

DS_Oas 2. **Dark Sky Park, DSAG class 2: no more than 50 % more than the natural airglow, or <360 μcd m^{-2} (>21.4 mag arcsec^{-2})**

DS_Oas 3. **Dark Sky Heritage Site, DSAG class 3: No more than 2.75 times the natural airglow, or <660 μcd m^{-2} (>20.7 mag arcsec^{-2}).**

DS_Oas 4. **Dark Sky Outreach Site, DSAG class 4: given that astro-tourism and amateur**

astronomy often happen at these places, the recommended limit is 2.0 times the airglow, or <480 μcd m^{-2} (>21.0 mag arcsec^{-2}).

DS_Oas 5. Dark Sky Reserves, DSAG class 5: similar to outreach sites, <480 μcd m^{-2} (>21.0 mag arcsec^{-2}).

DS_Oas 6. Dark Sky Community, urban, DSAG class 6a: The recommended limit is 4 times the airglow for protected sites in more urban areas, giving sky brightness <1000 μcd m^{-2} (>20.3 mag arcsec^{-2}).

DS_Oas 7. Dark Sky Community, rural, DSAG class 6b: The recommended limit is 3 times the airglow for protected sites in more rural areas, giving sky brightness <750 μcd m^{-2} (>20.6 mag arcsec^{-2}).

It is recognised that these recommendations may not be realizable in all protected areas and that each area will have its own challenges and circumstances. Values of sky brightness may be more or less than these recommendations in individual locations.

In addition, we make the following practical recommendations for exterior lighting in protected Dark Sky Oases:

DS_Oas 8. In all protected Dark Sky Oases the default condition should be no artificial light. Specific uses justifying light should then be additive once other non-lighting interventions are exhausted.

DS_Oas 9. In ecological reserves and similarly sensitive sites with little or no human presence at night, generally speaking, artificial light should not be used. If it is used, it should be a narrowband amber LED or equivalent emitting no light at $\lambda < 500$ nm. Lighting should be strictly controlled and switched on only when it is needed.

DS_Oas 10. If phosphor-converted amber LED lights are used, the amount of blue light ($\lambda < 500$ nm) should be below 5 per cent of the total spectral power. Generally this requires using LED luminaires with a corresponding colour temperature of 2200 K or less.

DS_Oas 11. All exterior lights should only distribute light below the horizontal, and the upward light output ratio (ULOR) should be no more than 0.5 per cent. This requires luminaires to be mounted horizontally and have flat optics below the light source.

DS_Oas 12. LED lights should have a central management system (CMS) to reduce or extinguish light output in off-peak hours.

DS_Oas 13. No commercial development in or near highly ecologically sensitive sites should be permitted.

DS_Oas 14. Monitoring of nighttime conditions in/near Dark Sky Oases is encouraged through a combination of ground-based and remote sensing methods.

DS_Oas 15. Active management of natural nighttime darkness as a pristine resource is encouraged through recognised conservation best practices.

DS_Oas 16. Restoration plans should be implemented when sky brightness thresholds are routinely exceeded.

2.3. OPTICAL ASTRONOMY EXECUTIVE SUMMARY

2.3.1. NEED AND MEANS FOR PROTECTION OF GROUND-BASED OPTICAL OBSERVATORY SITES

Ground-based astronomical observations continue to be the drivers of major, high-impact discoveries in astrophysics and fundamental physics. They are often essential to interpret observations from space-based telescopes. Major ground-based optical telescopes can be built at a substantially larger scale and some two orders of magnitude lower cost per unit collecting area than those launched into orbit. And they provide the critical data for planetary defence and key aspects of space situational awareness.

Astronomical research and planetary defence are critically dependent on having a clear view of the heavens, but there is currently great concern about the increasing impact of human activities, particularly Artificial Light at Night. In the past decade alone, the globally averaged rate of increase in artificial sky brightness was 2% per year in terms of both lit area and total radiance, dou- ble the rate of world population growth during the same period.

More recently, a new factor impacting the natural night sky integrity has emerged. This impact is from the introduction of energy efficient, white Light-Emitting Diode technology on large scales. As for Dark Sky Oases, that lighting technology may represent a threat to astronomical observations because of the higher blue content of white LEDs, which scatters more efficiently in the atmosphere, compared to earlier lighting technologies. In addition, there is evidence that the high energy efficiency and relatively low cost of operation of LEDs are fueling elastic demand for the consumption of light, leading to higher overall light emissions.

As noted above, the International Astronomical Union has defined the upper limit of artificial light contribution for a professional site to be considered adequate for true dark-sky observing to be <10 % above the natural background at an elevation of 45° in any azimuthal direction. The modern professional observatories have been located at remote high mountain sites that are significantly below this limit of artificial light contamination.

The goal of the model regulatory framework proposed in this document is to slow, stop, and reverse the rate of increasing artificial skyglow at major professional observatories in no more than a decade and on shorter timescales wherever possible.

Each observatory site has its own circumstances, so achieving the goal will require a regional lighting plan with a specific approach, based on detailed modeling. Protection of the site may entail zoning that restricts development and ultimate tightening of regulations with time to reduce light pollution. The Working Group strongly advocates an approach of quality lighting design to match the illumination level to need, limiting unnecessary spectral content, and taking more advantage of precise optical control to reduce spill light. A key aspect of site protection is defining near zones with more stringent limits on outdoor lighting levels. Major observatories are now typically international consortia, but they are situated in individual countries whose own laws apply to light pollution control. The regulatory framework proposed for COPUOS endorsement provides a model for those national, regional and local governments committed to protecting the invaluable assets of professional observatories within their regions.

Many professional observatories see measurable impact of light domes, the dome-shaped glowing sky area over conurbations, at distances even in excess of 300 km. The International Commission on Illumination (CIE) provides evidence-based recommendations for illumination levels by usage and environmental zone. Adherence to the strictest prescribed levels by locality and other best practices will greatly reduce urban skyglow. Adaptive lighting technology, allowing lighting levels to be set based on activity level, is the path to control of nighttime lighting and reduction in energy costs.

The principles of protection of the near zones around professional observatories are based on best practices of lighting engineering and design adapted to the need for very low artificial skyglow. The near zone is an area within a radius of approximately 30 km, depending on local conditions. The recommended regulatory framework has the following provisions:

- Exclusive use of luminaires with no light emitted above horizontal;
- Limiting lamp spectral content in the blue and near-ultraviolet region (below 500nm);
- Limiting the maintained average illuminance;
- Implementation of curfews and light-level controls;
- Defining minimum utilance[1] ratio;
- Designing and mounting luminaires to minimise direct and reflected light in the direction of observatories.
- Placing zonal lumens caps on the full area from which ALAN measurably contributes above 30° elevation from the observatory, in the context of a regional lighting master plan.

Observatories on the most remote mountaintops encounter lighting for special use cases in surrounding areas such as open-pit mines, military and border security operations, prisons, and wind farms. These enterprises can have especially high impact because of their short distances. Best practice design and associated regulation can limit up-lighting, manage spectral output, and limit total luminous output.

There are strong corollary benefits that incentivise the adoption of good lighting practices by host regions that protect internationally significant professional observatories, including sustainability, energy conservation, cost savings, synergy with protection of natural areas, enhancement of nighttime safety, and possible benefits to human health.

2.3.2. RECOMMENDED PRACTICES AND REGULATORY FRAMEWORK

For all specific recommendations for protection of observatory sites that follow, if current applicable regulations or regionally referenced professional lighting authorities place tighter limits, the latter take precedence in all cases. It may be necessary to tighten certain limits with time to reduce current levels of ALAN. Reference to specific CIE documentation and standards is intended to promote regulations based on the most current version of such documents (see Appendix B). Whenever standards or recommendations offer a range, the guidance is to stay within 20% of the low end of that range. The prospect of major reductions in illumination is predicated on the ability to exercise adaptive lighting control, particularly with motion-activated sensors for nighttime traffic and activity.

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[1] utilance: ratio of the luminous flux received by the surface to be illuminated to the sum of the fluxes of all the luminaires of the installation

2.3.2.1. For observatories and their extended protected zones

Opt_Ast 1. Each professional observatory with programmes requiring limiting dark-sky data for which regulation of artificial skyglow is critical should obtain a current baseline and well-sampled time series of night-sky brightness measurements.

Opt_Ast 2. International astronomical organisations are advised to form and support a data repository with consistent formatting to aggregate and make publicly available the sky-monitoring data.

Opt_Ast 3. Such sky-monitoring data should be collected under uniform protocols with standard calibration traceable to the SI system of dark sky units.

Opt_Ast 4. Each major professional observatory and controlling governmental body should undertake a modelling exercise to determine the total amount of fully shielded outdoor lighting allowable, as well as the extent of the area of protection.

Opt_Ast 5. The zone in the immediate vicinity of the observatory in which all outdoor lighting is prohibited should be made as large as possible.

Opt_Ast 6. All luminaires must provide no direct illumination above horizontal.

Opt_Ast 7. No architectural lighting, or electronic message displays with light emitted above horizontal be permitted in Zones E0, E1, or E2 within the extended protected area (see Table B.3 in Appendix B for the definition of Zones).

Opt_Ast 8. The Blue Light Content (percentage of light emitted below 500nm over the total light emitted) should be zero. The lighting devices should be quasi monochromatic sources with maximum radiant flux (in watts per nm) lying within the 585-605 nm spectral range and having Full Width Half Maximum (FWHM) smaller than 18 nm. If modest color rendition is approved as a necessity, spectra with broader FWHM of ~100 nm can be used in those exceptional cases.

Opt_Ast 9. The maintained average illuminance for periods of active use should not be higher than 20% above the minimum maintained average illuminance suggested in technical norms/recommendations published by CIE or IES (i.e. 1.2 times the minimum maintained illuminance prescribed by the norm/recommendation) and this high-side deviation must be kept at the lowest possible level by proper lighting design and employing suitable lighting controls.

Opt_Ast 10. Avoid exceeding luminance or illuminance limits by more than 20% in design, and plan on active control and maintenance to achieve nearly constant light output.

Opt_Ast 11. A maximum possible reduction of the total light levels, with a target of at least 66%, should be applied after curfew (or before that time whenever possible). Any lighting installation that is not needed for public safety reasons should be switched off at curfew. For isolated areas or hours of low traffic, sensors should be used to increase the light level as needed when any activity is detected. Without detection, the light level should be set down to 10% or less of the maintained average luminance or illuminance.

Opt_Ast 12. The utilance ratio should be at least 75%.

Opt_Ast 13. Luminaires should be designed and mounted to minimise direct and reflected light propagating in the direction of observatories.

Opt_Ast 14. Special use cases in remote areas, such as open-pit mines, should employ fixtures consistent with the near-zone regulations to the maximum degree possible, consistent with safety and national and local regulations.

Opt_Ast 15. Civilian regulators and military flight planners should keep approved flight paths as far from observatories as practicable.

2.3.2.2 For more distant urban areas impacting observatories

Opt_Ast 16. Follow (and minimize high-side deviation to no more than 20% from) the lowest luminance and illuminance levels for road lighting of the appropriate lighting class according to CIE 115, but whenever possible, dynamically reduce the levels under low traffic conditions to the appropriate lower lighting class, and down to M6 or even below if the lighting is not immediately needed by any user.

Opt_Ast 17. Follow (and minimize high-side deviation to no more than 20% from) CIE guidance for illumination levels and colour rendition of pedestrian areas and actively adjust by usage class with time of night or by motion sensing.

Opt_Ast 18. Observe (and minimize high-side deviation to no more than 20% from) CIE International Standard S 015/E:2005 for illumination of outdoor workplaces, carefully limiting the illuminated area to avoid spill light.

Opt_Ast 19. Adhere to the zone-appropriate limits by CIE environmental zone for lighting levels, with a minimum Upward Flux Ratio (UFR) and a null Upward Light Ratio (ULR = 0), with application of curfew-time reductions in lighting levels.

Opt_Ast 20. For Zones E2 and E3 impacting observatories, do not exceed ANSI/IES recommendations for maximum luminances for illuminated signs. Take all recommended measures to reduce sky glow from internally illuminated signs and electronic message displays. For E3 Zones, do not exceed the CIE maximum standard permitted luminance levels for building façades; in E0, E1, and E2 Zones in the extended area impacting observatories, façade lighting is not permitted.

Opt_Ast 21. Employ adaptive lighting technology in new installations and major renovations to minimise illumination when there is minimal demand.

Opt_Ast 22. Develop and follow lighting master plans that govern the planning, installation and maintenance of outdoor lighting, especially for urban and suburban areas.

Opt_Ast 23. Use fully shielded lighting and/or other techniques to assure that no light is directly projected above horizontal. Minimise the impact of unshielded lighting like electronic message displays and older sports lighting by imposition of curfews and limitations by usage zone.

Opt_Ast 24. Sharply limit any blue and near-ultraviolet (UV) (<500 nm) spectral content of luminaires. Employ sources with the narrowest possible bandpasses, based on the actual need for colour rendition, and use light sources with the lowest blue-UV content available (colour index G > 2) when colour rendition is necessary.

* * *

2.4. BIO-ENVIRONMENT EXECUTIVE SUMMARY

The introduction and rapid growth of outdoor artificial light at night (ALAN) worldwide over the last century has provided many benefits to humanity but brings new challenges and threats to the health of many organisms in both the natural and the built environments. Research shows that outdoor ALAN can be a pollutant and should be treated as such. Humans, flora, and fauna are profoundly influenced by the daily 24-hour cycle of light and dark.

In humans (and many other vertebrates), ALAN suppresses production of the hormone melatonin, which plays a crucial role in regulating circadian rhythms, and which has been shown to be an aid to the immune system that helps suppress malignant tumour growth. Melatonin is most strongly suppressed by blue light, and excessively bright blue light can also cause retinal damage.

Epidemiological studies show strong correlation between ALAN and elevated rates of some hormonal cancers, obesity, diabetes, depression, and disruption of sleep. There is wide variation in sensitivity to ALAN among individuals, and safe dosage thresholds are not yet clearly established. While both indoor and outdoor lighting at night affects humans and wildlife, in this report we restrict our recommendations and discussion to the effects of outdoor light only.

Glare from poorly shielded or improperly installed outdoor lighting also poses a direct hazard to drivers, bicyclists, pedestrians, and other road users by temporarily impairing their vision, especially for the elderly.

Many species of flora and fauna are negatively affected by ALAN. Approximately 30% of all vertebrates, including more than 60% of all known mammals, and over 60% of all invertebrates known today are nocturnal. A naturally dark night is an essential feature of their natural ecosystem.

ALAN can have significant effects on organisms and reduce the resilience of populations. Some organisms will avoid lit areas, while a few might benefit from the presence of ALAN, which has consequences on food-webs and habitat use. The impact of ALAN on the nocturnal organism level can cascade into ecosystems and can also affect day-active organisms and their ecological functions. ALAN impacts migration and habitat use, ecological functions, the timing and quantity of reproduction, and the immune system in various taxa. The impact of ALAN is a major risk factor for biodiversity and consequently global food supply. The impact threatens many endangered nocturnal taxon groups such as bats and amphibians, but it also threatens the habitat and ecological functions for non-endangered organisms.

The impacts of ALAN are correlated with geographical features such as cities, highways and industrial sites, but the impact of ALAN as a pollutant is not limited by national borders. Skyglow, the brightening of the night sky caused by ALAN scattered within the atmosphere, results in elevated skyglow levels hundreds of kilometers away from cities and towns, where it can negatively impact ecosystems in otherwise remote and unlit natural areas.

The WorkingGroup on the BioEnvironment compiled 13 recommendations to mitigate the impacts of ALAN on humans, flora, and fauna:

2.4.1. AREAS TO BE ILLUMINATED:

Governing bodies (e.g. countries, states, counties, etc.) should define the decision criteria for whether an area must or is allowed to be illuminated. To minimize environmental impact, unnecessary illumination should be prevented and enforced by the governing bodies, while new outdoor lighting installations should be adequately justified.

2.4.2. GEOGRAPHICAL FRAMEWORK TO MITIGATE LIGHT POLLUTION:

Maximum admissible values of the indicators of deterioration of the nighttime environment must be explicitly specified for each zone of the relevant territory (including urban, suburban, rural, and intrinsically dark). Corresponding quantitative caps on the maximum allowable emissions compliant with these deterioration limits should be determined and allocated amongst the relevant territorial and administrative units.

2.4.3. DEFINITION OF ALAN-FREE AREAS AND ECOSYSTEMS:

Environmentally sensitive areas, intrinsically dark areas, nature reserves, ecosystems and other relevant areas can be characterized as ALAN-free zones, with the strictest limits on the spectrum, shielding, and total amount of illumination. The goal for intrinsically dark or pre-defined ALAN-free zones, or other areas where natural darkness is a priority, should be to retain or restore the night sky brightness to natural levels.

2.4.4. ILLUMINATION LEVELS FOR OUTDOOR AREAS:

For areas that are determined to need outdoor lighting, the lighting levels should not exceed by more than 20% the minimum requirement of the usage class as specified in relevant scientifically-supported documents or standards.

2.4.5. LIGHTING CONTROL AND ADAPTIVE LIGHTING:

All new and renovated outdoor lighting installations should incorporate means of control of the luminous flux. Lighting control systems should be added to existing installations when feasible. Lighting levels should be reduced to the absolute minimum level, ideally zero, where and when no or few users are present.

2.4.6. LIGHT DISTRIBUTION AND ORIENTATION:

Light should be distributed only to the area targeted for illumination. Spill light and in general waste of luminous flux delivered to the surroundings should be avoided. Luminaires should be chosen and designed efficiently to avoid spill light and waste of luminous flux through optics, lenses and suitable accessories.

2.4.7. INTRUSIVE LIGHT:

Light entering indoor living areas during nighttime should be minimized and ideally eliminated.

2.4.8. GLARE CONTROL IN ROADS AND OUTDOOR WORKING PLACES:

Glare levels should be controlled and reduced below the recommended maximum levels.

2.4.9. SPECTRAL CONTENT OF THE EMITTED LIGHT:

The spectral content of the emitted light, especially the content in the region of blue, should be carefully selected for the intended application to minimize negative impacts on the surrounding environment. Melanopsin-activating blue content within the radiant/luminous flux should be minimized. This approach is useful for humans and vertebrates where the circadian timing system has a similar spectral sensitivity as humans. However, there is a large variability in photoreceptors, photobiological processes and light-related behavioural responses across the bio-environment. Although reducing blue content is expected to be useful in most cases, individual species/ecosystems may require different, dedicated spectral approaches.

2.4.10. Directionality of light, light modulation, flood lighting, illuminated and colourful façades, and illuminated signs:

The illumination of architectural structures and signs should be avoided during curfew and the luminance levels should be kept as low as possible. Dynamically modulated color façades such as LED billboards are strongly discouraged.

2.4.11. ALAN monitoring measurements:

ALAN that affects humans and the environment should be carefully assessed and monitored, via field measurements and monitoring. ALAN measurements and sky glow monitoring should be implemented in international, national or local regulations. Mitigation and possibly restoration measures should be applied when scientifically justified thresholds are exceeded.

2.4.12. Urgent research topics:

Interdisciplinary research among lighting, medical, and environmental research communities is urgently needed and should be encouraged in numerous fields related to the effects of ALAN on human health, flora and fauna, visibility levels and public safety. Studies should use the correct and appropriate light quantities, metrics, and lighting research methods, which are highly interdisciplinary and deserve careful discussion.

2.4.13. Strategic recommendations:

We propose 10 long-range strategic goals for mitigation of harmful effects of ALAN on humans, flora and fauna:

Bio_Env 1. Establish specific regulations for outdoor lighting within each country

Bio_Env 2. Establish an accreditation system for outdoor lighting installations

Bio_Env 3. Ensure that new installations and renovations follow the relevant regulations

Bio_Env 4. Review and revise the requirements for illuminating roads and highways and the lighting legislation to consider environmental effects of ALAN

Bio_Env 5. Minimize the negative effect of outdoor lighting on vision, human health and natural species

Bio_Env 6. Restore and protect affected existing ecosystems by implementing environmentally conscious lighting technology, and establishing definite and verifiable transition plans to reduce the light emissions where required

Bio_Env 7. Promote education about lighting and the effects of ALAN on human health and the environment among research communities, decision makers, and society at large.

Bio_Env 8. Develop a scale of ecological classes of dark skies to show the differential impact of light over ecosystems and species across the territory.

Bio_Env 9. Establish evidence-based thresholds for lighting levels that should not be exceeded in various environmental zones where there are negative effects of lighting on human health and on species and habitats

Bio_Env 10. Develop standardized methods for measuring ALAN and skyglow and establish them in the relevant national or international standards

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2.5. SATELLITE CONSTELLATIONS EXECUTIVE SUMMARY

2.5.1. INTRODUCTION

Recent technological advances in ground stations, antennas, satellites and space launch capabilities, coupled with new telecommunications business models and high demand for low latency high bandwidth internet, have driven rapid growth in the space-based internet industry (Daehnick et al., 2020). A variety of companies are planning and now implementing communications constellations numbering in hundreds to tens of thousands of satellites, particularly in nongeosynchronous Low Earth Orbit (LEO). While these may provide technological and societal benefits, satellite constellations will fundamentally change the view of the night sky for almost everyone on the planet, in addition to introducing new challenges in space sustainability,. This change to the pristine night sky has impacts on dark sky reserves, astrophotography, religious and cultural practices, animal and insect life, and scientific inquiry. The focus of this report chapter concerns primarily the latter. Astronomers have raised concerns about the impacts on scientific observations from the increasing probability of a sun-illuminated satellite passing through the field of view of a telescope, and also the growing numbers of space-based radio transmitting satellites within view of radio and mm-wave observatories. Many of these concerns have now been empirically validated with observations and simulations.

International Telecommunication Union (ITU) and national regulatory filings indicate that in the order of 100,000 satellites could be launched into LEO in the coming decade. Several companies have already begun construction and launch. Initial studies indicate a variety of possible impacts from severe to minor, depending on the nature of the telescope and satellite system (Walker et al., 2020; Hainaut & Williams, 2020; Ragazzoni, 2020; McDowell, 2020). Observations conducted on wide field of view telescopes and radio telescopes will likely be severely impacted in the absence of substantial mitigations. While narrow field of view telescopes are less impacted as a result of a lower probability of satellites crossing the field of view, observations with long exposure times and particularly in the hours close to twilight and low on the horizon can be affected.

In the context of the UN-IAU Dark and Quiet Skies Conference, a Satellite Constellation Working Group was formed to continue analysis of impacts on astronomical observations and explore possible technical and policy measures that observatories, governments and industry could adopt to minimise impacts on astronomy while supporting a space economy. The Working Group was made up of astronomers from institutes and observatories around the world, industry representatives from some of the major companies, astrodynamicists, policy and government relations experts and space lawyers. The Working Group was divided into four sub-groups, dealing respectively with: simulations,observations, mitigations, and policy recommendations.

2.5.2. METHODS

2.5.2.1. Simulations

At the time of this conference, only two operators – SpaceX and OneWeb – have started launching operational satellites as part of their planned constellations. These satellites currently in orbit represent only a small fraction of the planned constellations and observational data are still fairly limited. Computer simulations offer the only way to assess the impact of large constellations on the observation of the night sky at optical wavelengths on a sound scientific basis. To this end, we use the tools of orbital dynamics, optics and observational astronomy. We set up a realistic constellation profile that fits publicly available information about the final shape of OneWeb's and SpaceX's Starlink constellations, totaling almost 78,000 spacecraft. By applying basic physics and geometry principles, we computed spacecraft visibility from any location on Earth, in terms of apparent position on the sky, direction of the motion and apparent angular speed, and conditions of illumination by sunlight. This can produce statistics for the whole sky (bulk number of artificial objects detectable from a specific location) or for the restricted conditions constrained by realistic observational circumstances: for specific directions of observation, fields of view and integration times.

The Simulations group has collected information from the results of NSF's NOIRLab's SATCON1 Workshop (Walker et al., 2020), recent scientific literature, and from additional simulations elaborated for this workshop by the contributors to this report. Simulations were performed by separate teams using completely independent software, and the results are coincident within the statistical noise level.

2.5.2.2. Observations

The purpose of the Observations group is to observationally support the assessment of the impact from satellites to future astronomy by characterizing their brightness at relevant wavelengths over the entire hemisphere and range of orbital geometries. The findings can support satellite operators with measurements to assess the efficacy of their brightness-reduction mitigation strategies.

Unlike typical astronomical targets, satellites move and their brightness is highly dynamic. Even small changes in the satellite's position or orientation relative to the observer can yield a large change in apparent brightness. Characterizing a satellite's apparent brightness requires many observations to capture the changes in brightness over the full range of parameters. Furthermore to assess the impact to astronomy research we must consider more than just the satellites' brightness but also their apparent velocity, position in the sky, and frequency of sightings.

This report expands upon the previous work of the SATCON1 Satellite Observations Working Group (Walker et al., 2020). The teams observing Starlink and OneWeb satellites have developed and refined new techniques and made additional measurements. Especially relevant are the most recent measurements to quantify the efficacy of Starlink's brightness-reduction mitigations which include operational changes, surface treatments ("DarkSat"), and visors ("VisorSat"). We also add new measurements of OneWeb satellites.

The Observations WG consists of various members of our community that contribute observations of LEO satellites on a voluntary basis. Observations were conducted using a range of astronomical facilities in Chile, Spain and Arizona and Hawaii in the US, and were planned during twilight hours, when the satellites are illuminated by sunlight and are above the local horizon of the given telescope facility.

2.5.2.3. Mitigations

The Mitigations group developed concrete instructions on how to lessen the impact of satellite constellations on astronomy. We review the findings from the NSF SATCON1 report (Walker et al., 2020) and from the other working groups assembled for the Dark and Quiet Skies Conference. We consider further mitigations strategies for both industry and the astronomy community and observatories, with the approach in mind that the problem has to be tackled simultaneously by all involved parties. We also aim to provide mitigations applicable on relatively short time scales, as well as mitigations which may require decades to implement. The mitigations include a broad range of possible effects on astronomy and highlight some important effects for which no mitigation could be suggested.

2.5.2.4. Recommendations review

A fourth "recommendations" group was charged with reviewing the findings and recommendations from the observations, simulations and mitigations groups, and additional relevant recommendations from the other main Working Groups, particularly the Optical Astronomy and Radio Astronomy groups. The recommendations group also incorporated findings and recommendations from the recent SATCON1 workshop (Walker et al., 2020).

In addition to collating and structuring recommendations from the other working groups, the recommendations working group considered how various recommendations could be implemented and supported by a range of stakeholders including policymakers. The recommendations are organised by the main category of stakeholder: observatories, industry, astronomy community, science funding agencies, national and international policymakers.

2.5.3. KEY FINDINGS FROM SIMULATIONS AND OBSERVATIONS

Simulations show that the number of satellites on the sky shows a smooth dependency with observatory latitude, driven by the spatial structure of orbital shells. Only a small fraction of a total constellation is above the local horizon from any given location (about 5 %). Of this amount, only a fraction of satellites are illuminated by the Sun. Both the number of satellites above the horizon and the number of them that are illuminated increase with orbital altitude.

The number of satellites detectable with telescopes strongly varies with solar illumination conditions: thus, the count changes both with local time and with the season of the year. Normally, in winter there are several hours around midnight with zero satellites detectable, but the situation changes in summer nights, in which very often there are detectable satellites all the night long.

Satellites show a very strong concentration towards the local horizon (typically, 50 % of the spacecraft above the horizon are below 20 degrees elevation). This concentration is stronger for lower orbits (i.e., lower orbits leave a cleaner sky at high elevations). Satellites closer to the horizon appear much fainter and display a slower apparent motion.

Current estimates indicate that there will be satellites visible to the naked eye under dark skies, unless darkening measures are implemented. This conclusion is sound well beyond the level of uncertainty of the current photometric models. Absolutely all sunlit satellites are detectable by research telescopes, sometimes inducing even saturation effects.

Observations of pre-mitigation Starlink satellites show typical apparent brightness in the 4-5th magnitude range, making them visible to the unaided human eye. Observations of OneWeb satellites show typical brightness fainter than 6-7th magnitude. This, as observed, is dimmer than the pre-mitigation Starlink satellites. Yet, it is necessary to keep in mind that OneWeb satellites are being deployed at a much higher orbital height, of 1200 km. A relative assessment of brightness apparent magnitude of satellites of different constellations, can only be done when the observations are standardized to a common orbital height or range.

Limited observations of DarkSat and VisorSat indicate that the brightness-reduction mitigation measures implemented in the modified designs are effective but do not achieve the recommendation brightness goals stated in this report in all operational phases and geometries. More observations are needed to characterize the brightness of these satellites in all geometries. Observations of Starlink satellites in multiple spectral bands show the satellites are brighter at longer wavelengths, and the efficacy of the modified-design strategy implemented in DarkSat decreases in the near-infrared.

For a typical observatory latitude, simulations predict an average of two satellite trails passing through each one-square-degree telescope image taken for one minute near the beginning and end of the night. Most of these trails are caused by simulated satellites at higher orbital altitudes.

The distribution of satellites on the local celestial sphere displays a huge amount of spatial fine structure, related to the interplay of the boundaries of orbital shells and illumination conditions. This, in turn, induces strong changes in the density of trails in different pointing directions, that may reach even a factor larger than ten: more than 20 trails inside one square degree during 60 seconds are predicted in some cases.

Specular reflections on flat surfaces of the spacecraft will induce flares and glares that are a real issue only for extremely wide fields of view. A posteriori or a fortiori computation of flare circumstances should be possible, if accurate ephemerides are available.

The existence of satellites in transient orbital phases (before and after their operational lifetime) poses specific threats, because this increases the size of the population in a potentially significant manner, and the spacecraft often show different photometric behaviours in these phases (normally towards a more harmful situation).

2.5.4. RECOMMENDATIONS[2]

The following summary recommendations are drawn from the satellite constellation working groups and the radio astronomy working group, and are intended as guidelines to support various stakeholders in implementing technical and policy mitigations. The recommendations are organised by observatories, industry, astronomy community, science funding agencies, policymakers and regulatory agencies and international law.

Observatories will be faced with implementing many of the technical software and hardware measures, and often facilitate planning for new instruments and telescopes. These mitigation measures will nevertheless require funding, and support from industry in provision of data. **Industry** includes the constellation operators but also manufacturer and industry associations. Ultimately, the industry mitigation measures will need codification in national regulation in terms of setting standards and also in finding ways to overcome the barriers of sharing proprietary data. While observatories and industry can implement technical-focused mitigations, further actions are needed from the **astronomy community**, which includes the wider community of scientists, institutions, societies and governments that support and enable astronomical science. A broad set of recommendations cover actions needed from **policymakers and national regulators**, which includes standards organisations and economic development agencies, and the range of international policy and coordination bodies such as the Committee on Radio Astronomy Frequencies (CRAF) set up with national policymaker representation. The recommendations tables (in section 5.1.) contain the full set of technical and policy recommendations.

2.5.4.1. Recommendations for Observatories

Sat_Con	1.	**Support the development of software applications to conduct long term planning and simulations of observations, scheduling, and to identify and remove satellite-induced artifacts from data. This requires a range of data**

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[2] Please note that some of the Sat_Con recommendations, as they numbered in the Executive Summary of the full Report, have been abridged in the Conference Room Paper to be presented to the COPUOS STSC. For the sake of clarity, the numbering has been maintained consistent between the two documents.

from industry on satellite reflectance, antenna parameters, and predicted and real-time ephemerides. Observatories will also require additional funding for development and to assess overall impacts on science programmes.

Sat_Con 2. Plan for more stringent requirements on future designs of observing facilities to account for the additional losses from satellite constellations, including additional telescopes, increased apertures, additional tools for image processing, higher robustness receivers, and enhanced detector technologies. These measures require additional funding.

2.5.4.2. Recommendations for Industry

Sat_Con 3. Raise awareness of the impacts on astronomy amongst designers, investors, regulators, manufacturers and operators, and include impact mitigations as a core component of corporate social responsibility and sustainability strategies.

Sat_Con 4. Design missions to minimize negative impacts on astronomical observations by: a) minimising operational altitudes — satellites in constellations with higher orbital shells are illuminated by the sun for longer during the night and appear more 'in focus' to telescopes; in general, the impact on astronomy increases with constellation altitude. Scientific analysis shows that orbits on the order of 600km or below offer a compromise between brightness and the length of time satellites are illuminated during the night; b) minimizing the number of satellite units as second priority to altitude while maintaining safe operational practices; c) minimising the time spent in orbit when not in service.

Sat_Con 5. Design satellites to minimize negative impacts on astronomical observations by: a) guaranteeing that all satellites appear fainter than $7.0\ Vmag + 2.5 \times \log(SatAltitude\ /\ 550\ km)$ with a minimum value - corresponding to maximum brightness - of visual magnitude ($Vmag$) 7 during all flight phases, which makes them undetectable to the unaided eye; b) minimizing antenna sidelobe emissions such that their indirect illumination of radio observatories and radio quiet zones do not interfere, individually or in the aggregate; c) preventing direct illumination of radio observatories and radio quiet zones with a satellite's main antenna beam.

Sat_Con 6. Provide timely, transparent and reliable data to the astronomy community and observatories to allow sufficient planning to avoid impacts and post-hoc analysis of incurred impacts. Data required include: spacecraft design, brightness data, mission designs and orbital profiles, attitude control, and predicted and real-time orbital elements.

2.5.4.3. Recommendations for the Astronomy Community

Sat_Con 7. Raise awareness of the impacts of satellite constellations and possible mitigation strategies and their costs and requirements amongst key astronomy stakeholders. Develop mechanisms to coordinate approaches across communities and countries and share information on industry interactions, mitigation solutions and observational data.

Sat_Con 8. Conduct outreach and advocacy campaigns with policymakers, regulators, funders and industry, and represent astronomy interests in satellite industry and professional working groups.

Sat_Con 9. Develop the skill base to operate in the satellite constellation era by: supporting the development of educational material on how to conduct astronomy in the context of high numbers of satellite interferences; organising professional development opportunities, workshops and symposia.

Sat_Con 10. Include considerations of satellite constellations in strategic planning for future observatories and understand impacts on science cases of existing observatories. Improve simulations of the impact of satellite constellations, providing more accurate estimates of apparent brightness, a more detailed consideration of trails due to not point-like sources (spatially resolved and/or out of focus), a better assessment of transitory orbital phases and a quantitative study of the impact on astrophotography.

Sat_Con 11. Support the collection and coordination of multispectral observational data, in partnership with industry and observatories, and citizen-scientists and amateur astronomers.

2.5.4.4. Recommendations for Science Funders

Sat_Con 12. Provide support for understanding impacts on astronomy and the increased overheads in terms of additional observing time or science losses. This includes provision of specific funding instruments for development of software, hardware and facility mitigations, technology developments in detectors and receivers, and taking steps to evaluate, formalise and report to governments the overall impacts on science research and capital investments.

2.5.4.5. Recommendations for National Policymakers and Regulatory Agencies

Sat_Con 13. Formulate satellite licensing requirements and guidelines that take into account the impact on stakeholders, including astronomical activities, and that coordinate with existing efforts in relation to radio astronomy and space debris mitigation.

Sat_Con 14. Develop inquiries and recommendations that encourage flexible technology that can better share spectral resources while ensuring protection of sensitive radio astronomy operations.

Sat_Con 15. Develop spacecraft systems and operational standards that take into account the impacts on astronomical science. Areas include reflectivity of surface materials, brightness of space objects, telemetry data, and spurious antenna emissions.

Sat_Con 16. Support the development of space domain decision intelligence collecting data of proposed satellite constellations and existing orbiting space objects, modelling satellites, their operations in the space environment, and estimate uncertainties to assess the impact of satellite constellations on ground-based astronomical observations.

Sat_Con 17. Investigate policy instruments that account for negative externalities of space industrial activities, including on astronomical activities, and develop incentives and inducements for industry and investors.

2.5.4.6. Recommendations for International Policymakers

Sat_Con 18. Policymakers are encouraged to contemporaneously develop international agreements, on the one hand, and national laws within their respective legal frameworks, on the other hand, relating to reflected or emitted electromagnetic radiation from satellites, its impacts on science (particularly, but not exclusively, astronomical science), and efforts to mitigate (if not eliminate) the deleterious aspects of such impacts.

Sat_Con 19. At both international and national levels, efforts can build upon frameworks in radio astronomy and space debris, informed by this report and by capacity-building and outreach efforts that bring stakeholders together for purposes of discussion and moving policy development forward, such as this international workshop.

2.6. RADIO ASTRONOMY EXECUTIVE SUMMARY

The Report of the Radio Astronomy Working Group has five Sections: 1) Radio astronomy as a discipline; 2) Regulation of use of radio spectrum; 3) Spectrum protection for radio astronomy; 4) Risks to radio astronomy; 5) The way forward and two recommendations regarding non-GSO satellites

2.6.1 DISCOVERY

Section 1 describes the early history of radio astronomy from Karl Jansky's serendipitous 1932 discovery of cosmic radio emission from the core of the Milky Way, while studying the sources of noise in communication systems at Bell Telephone Laboratories. Delayed by depression and upheaval, the radio sky was explored after WWII by radio engineers who came to realize that the bright localized sources of radio waves in the sky were actually in other galaxies, while the visible stars in the Milky Way are radio quiet. In 1953 the simultaneous announcement of emission from Galactic neutral atomic hydrogen gas at a wavelength of 21cm by scientists in Australia, the Netherlands and the United States allowed astronomers to see across the Milky Way for the first time, to trace its rotation and map its spiral arms, and to weigh it. In 1965, Arno Penzias and Robert Wilson, radio astronomers hired by Bell Labs to study noise in a satellite system, realized that one source of noise was cosmic and uniformly distributed over the sky, and this turned out to be the relic radiation from the Big Bang, proving the origin of the Universe in an initial grand explosion.

Radio astronomy has a strong record of scientific discovery with four Nobel prizes since 1974, including one for the discovery of the Big Bang in 1978 and a second in 2006 for the discovery of miniscule fluctuations in its radiation. Those fluctuations eventually grew into all the things we now see in the heavens, the galaxies and all the stars in them, but also the things we see around us, each other. Closer to home, hundreds of molecules have been discovered at radio wavelengths and used to chart the formation of new stars and planetary systems around them, and the pre-biotic chemistry there. There are no other sources of such knowledge.

2.6.2 TECHNOLOGY AND INVENTION

As explained in Section 1, the relatively long wavelengths of radio waves require the use of big individual radio antennas and the construction of array telescopes composed of separate antennas, electrically connected across a few 10's-100's of km, or disconnected and globally crossing continents for Very Long Baseline Interferometry (VLBI). VLBI was used in 2017 to image the shadow of the supermassive black hole at the center of a distant galaxy using antennas in Chile, the US, Mexico, Spain and the South Pole. Radio astronomy benefits when nations jointly fund instruments in a host country, but also when they share their telescopes in joint experiments needing global baselines.

Radio astronomy has always been technology-driven, and learning to observe under the quietest conditions or learning to make coherent observations with disconnected antennas required technique and technology with appreciable spin-off. Compact maser time standards developed to facilitate VLBI are now used in GPS systems, and the imaging technique rewarded with the first Nobel Prize to radio astronomy in 1974 underpins the operation of orbiting Earth-mapping radars that track sea vessels such as those trafficking in illegal arms, but are also capable of burning out a radio astronomy receiver.

Radio astronomy technology and international cooperation combine when the International VLBI Service for Geodesy and Astrometry monitors the sky positions of a grid of quasars – supermassive black holes in the centers of distant galaxies – to determine the coordinate reference frame needed for satellite and space debris tracking, while simultaneously sensing continental plate tectonics and local deformation around an antenna at the level of mm. This effort is a direct response to UN Resolution 69/266 calling on member states to contribute to a global geodetic reference frame for sustainable development and the need for access to spectrum to operate its successor is a key driver in the recommendations here.

2.6.3 HOW THE LAWS OF PHYSICS RENDER RADIO ANTENNAS VULNERABLE TO INTERFERENCE

Much of Section 1 is a broad technical discussion that tries to give a feel for how radio astronomy differs from the more familiar study of visible light. Section 1 explains that radio astronomy relies on the use of low-noise receivers accessing broad swaths of clear spectrum under stable conditions. It explains that cosmic radio waves have no carrier to lock onto and that they are hundreds of millions of times weaker than radiocommunication signals.

One very important idea concerns the unavoidable presence of sidelobes in radio antennas, meaning a susceptibility to sense radiation arising away from where the antenna is pointed. The antenna is a large reflector that gathers as many photons as possible in its so-called “main beam” in the pointing direction. But because the reflector is a passive device with no net gain when averaged over the whole sky, its high gain in the forward direction is electro-magnetically compensated by sensitivities in other directions, sidelobes. An antenna designer can spread them out but their presence is unavoidable. A radio telescope should avoid pointing within 20° of a transmitter to be sure not to boost its signal.

The other side of this coin is that transmitting antennas also do not concentrate all of their emission in the forward direction. All interfering combinations of main beams and sidelobes must be considered, and interfering emissions can accumulate from different sources.

2.6.4 Regulation of the radio spectrum

Use of a common radio frequency to transmit and receive a message requires a degree of cooperation and sharing of that frequency, and that is only worthwhile if there is assurance that use of the frequency will be possible when needed. Use, sharing and protection of the radio spectrum are coupled and the long reach of low-frequency radio waves made such considerations global in scope as soon as radio use became widespread.

Section 2 describes the mechanisms and institutions that support compatible use of the radio spectrum by multiple stakeholders, known as “spectrum management”. This involves classing kinds of radio operations into services; making frequency allocations to services sharing the use of discrete slices (bands) of the spectrum; allowing the services to define “protection criteria” giving the level at which interference would disrupt their operations. Interference can arise from other operators in a shared band or when operators in other bands fail to control the frequency profile of their emissions, which leak into bands where they are not allocated.

Radio astronomers discussed the need for spectrum management soon after the HI line was discovered in 1953. IAU, URSI and COSPAR formed the Inter-Union Committee for the Allocation of Frequencies (IUCAF) under the aegis of ICSU (now ISC) and radio astronomy was given a sole allocation of the band 1400 – 1427 MHz at a Geneva meeting in 1959-1960. Section 2 describes the current activities of IUCAF and other radio astronomy spectrum management bodies working in Europe, Africa, the Asia-Pacific region and the Americas.

2.6.5 SPECTRUM MANAGEMENT HAS MADE ACCOMMODATIONS FOR RADIO ASTRONOMY AND VICE

VERSA

The radio astronomy service is characterized by its detection of extremely weak cosmic radio waves, requiring access to broad swaths of quiet radio spectrum over long observation periods. Radio astronomy use of spectrum is so unusual that the rules regarding the radio astronomy service are still evolving at the ITU-R.

Section 3 describes the particular accommodations that spectrum management has made for radio astronomy and vice versa. Of particular importance are the so-called "passive" frequency bands allocated exclusively for scientific observation and forbidden to transmitters. They can be considered as another form of spin-off from radio astronomy: first created to protect radio astronomy's HI line at 1420 MHz they now form the basis of remote sensing by satellites for weather and climate studies.

As shown in Figure 7.3.1 of the Report, only 1-2% of the spectrum is set aside for science below 50 GHz where almost all commercial radio communication occurs, rising to 10-15% above 100 GHz where scientific observation has long occurred and commercial activity is generally absent. The higher frequency passive bands are now under pressure from spectrum regulators seeking to allow transmissions over the broadest possible contiguous frequency ranges. **The fraction of spectrum that is dedicated to science cannot sustain radio astronomy and is a serious impediment to other scientific users.**

Whenever possible, radio astronomy observatories, especially the largest, are situated in remote locations and surrounded by radio quiet and coordination zones where national spectrum regulators restrict the use of radio transmitters as described in ITU-R Report RA. 2259. These zones are uniformly national in scope and do not usually regulate mobile, unlicensed, airborne or satellite transmitters. They implicitly rely on geographic separation and a de facto segregation between frequencies that are used by transmitters appearing overhead, which cannot be avoided when looking at the cosmos, and frequencies that are avoided near the main beam when pointing upward. **International recognition of radio quiet zones, however informal, is necessary to sustain radio astronomy.**

2.6.6 RISKS TO RADIO ASTRONOMY

Chapter 4 of the Report is the most detailed and comprehensive, and it assesses a wide variety of risks to radio astronomy operations. They range from spillover of unwanted emissions into passive bands, to airborne use of frequencies now used only on the ground, to the use of transmitters in passive bands now dedicated to passive science, to the effects of cars, planes and satellites, including burnout of the radio astronomy receiver from X-band radar satellites whose numbers are increasing from a handful to several hundred. This knowledge is essential to planning.

The risks from satellites stand out for many reasons. Satellites operate beyond national control and appear overhead during observing, from within national radio quiet zones. Radar satellites regularly illuminate radio astronomy sites at power levels sufficient to burn out a radio astronomy receiver. **The numbers of radar and radiocommunication satellites in low Earth orbit are growing by two-three orders of magnitude and the measures that are currently used to protect radio astronomy operations are ill-suited to this future.**

Radio astronomy has a long history of interaction with radiocommunication satellites. The story was told how Wilson and Penzias discovered the cosmic microwave background radiation from the Big Bang while studying the sources of noise in a Bell Labs satellite communication system. In Chapter 4 of the Report it is described how the first GPS and GLONASS global positioning satellites used unfiltered transmitters that interfered over wide portions of the radio spectrum. Also described was the continued interference in a radio astronomy band from a second generation of Iridium mobile phone satellites operating in nearby, not shared spectrum. This interference has not been remedied despite complaints to the highest authorities.

Some 5%-10% of the satellites in a constellation in low Earth orbit are above the horizon at one time. The Iridium constellation with 66 operational and 3-4 instantaneously visible satellites has been causing the loss of a radio astronomy band since 1998. SpaceX and OneWeb are currently in the process of launching some 5300 satellites, and they and other operators have filed with spectrum regulators for permission to launch ten times more.

With 5300 satellites in orbit and 300 above the horizon at any moment over the 20,626 square degrees of the visible sky, the mean angular distance between satellites will be $(20626/300)^{1/2} \sim 8.3^{\circ}$ and on average it will be impossible for a radio telescope to point on the sky without having a satellite within about 4°. With 50,000 satellites in orbit one will be within 1.3°. This is in addition to the aggregate interference from the sidelobes of the other satellites. **These satellites must be rendered invisible to radio telescopes.**

2.6.7 THE WAY FORWARD AND TWO RECOMMENDATIONS REGARDING NON-GSO SATELLITES

Section 5.1 of the Report describes some of the technological innovation that radio astronomy will implement to sustain its operations, taking advantage of modern high speed signal processing to build systems with high dynamic range and high time resolution to resist saturation and contamination from strong transient radio communication signals. With sufficiently flexible control on both sides it might be possible to implement some form of dynamic temporal-frequency coordination, in contrast to the current, rather static model of radio quiet zones.

Nevertheless, no amount of preparation by radio astronomy will suffice to allow it to operate in the presence of many thousands or tens of thousands of satellites in low Earth orbit. **The narrow scope of protection from spectrum management cannot be relied upon for two reasons:** the small amount of scientific spectrum that receives protection and the poor historical record of the national and international spectrum management regime in remediating problems of satellite interference to radio astronomy.

In Section 5.2 the Radio Astronomy Working Group has formulated two recommendations to COPUOS for steps that it regards as necessary to allow continued radio astronomy observations, for measures that are practicable and not so onerous to satellite operators that their ordinary operations would be disrupted. They are an attempt to render the radio sky dark and quiet, to preserve its heritage as a record of the Universe.

Rad_Ast 1. Non-GSO satellites should be required to be able to avoid direct illumination of radio telescopes and radio quiet zones, especially the radar and other high-power satellite applications that are capable of burning out radio astronomy's receivers;

Rad_Ast 2. Non-GSO satellites should be required to have sidelobe levels that are low enough that their indirect illuminations of radio telescopes and radio quiet zones do not interfere, individually or on aggregate.

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Simonetta di Pippo
Director of the UN Office for Outer Space Affairs, Austria

“Since the 1950s, countries have come together through the United Nations in seeking common grounds on governing space activities in outer space with considerable success. As the only UN entity dedicated to space, the Office for Outer Space Affairs is working across the legal, policy, scientific and technical aspects of making successful international cooperation in space a reality. The Dark and Quiet Skies initiative is a joint activity of the United Nations, Spain and the International Astronomical Union proposing recommendations which can eventually be acted upon either by local governments or agreed to at the international level. The recent adoption of the Long-Term Sustainability guidelines, considerable growth of the UN Committee on the Peaceful Uses of Outer Space, and the global attendance at UNOOSA’s events underline the continued appetite for multilateral diplomacy and friendly relations in this frontier environment. We must engineer a step-change in discussions at the international level among all relevant actors, upholding the highest standards of responsibility in space activities, so that we can protect not only safety, security and sustainability in space, but also space science on Earth. It is precisely through this medium of structured engagement with the global space community that we can make a real difference in the world and the skies above.”

Simonetta di Pippo
Excerpt from the welcome speech to the workshop participants

3. DARK SKY OASES REPORT

3.1. WHAT IS LIGHT POLLUTION?

Light pollution is a sum of all adverse effects of artificial light at night, more accurately known as obtrusive light - spill light emitted by a lighting installation which falls outside the boundaries of the property for which the lighting installation is designed and because of quantitative or directional attributes, gives rise to annoyance, discomfort, distraction, or a reduction in ability to see essential information.

Light pollution of the night sky occurs when photons from artificial light at night (ALAN) travel up into the atmosphere and are then scattered back down by air molecules or aerosol particles in the Earth's atmosphere. The result is a brightening of the night sky, increasing its brightness over the naturally occurring value. The bright background of the sky makes stars less visible, given that stars are masked by the sky brightness as a background illumination. The fainter stars disappear first from naked eye vision as a result of reduced contrast against the bright sky, and an increasingly greater number become undetectable the brighter the night sky from ALAN. Light pollution which brightens the night sky is generally referred to as skyglow. Various methods exist to measure and monitor the brightness of the night sky, including both natural and artificial light contributions; these are detailed in Appendix 2 of Chapter 3.

Scattering is an essential process for the sky to brighten. The effect is much exacerbated if light sources are shining upwards, but even for lights only directing photons below the horizontal, reflection off the ground can still contribute to sky brightness. Photons emitted almost horizontally, even if just below the horizontal, can contribute more to skyglow than those emitted straight up, as these latter may escape into space.

Scattering also renders stars fainter than they would be if observed from the ground instead of from space. At the zenith they are typically about 16 per cent fainter, a phenomenon known as atmospheric extinction. The strength of light scattering in the atmosphere depends on the colour, or wavelength, of light. Short-wavelength ('blue') light is scattered most during its transit through the atmosphere, and tends to contribute the most to night sky brightness as seen at large distances from light sources. (Luginbuhl, Boley and Davis 2014)

The sky brightness from ALAN is termed skyglow, which distinguishes the sky brightness from natural sources of light, which include airglow, zodiacal light, auroral light, moonlight, gegenschein and the light from the Sun near dawn or dusk. Scattered starlight can also contribute. The night sky has a certain natural brightness known as airglow, as a result of emissions from the air molecules in the upper atmosphere, generally the recombination of photo-dissociated nitrogen and oxygen molecules to form nitric oxide (NO) and reactions involving the hydroxyl radical (OH). The brightest emission is green 558 nm light from oxygen atoms in a layer 90-100 km high. Vibrationally and rotationally excited OH radicals emit red and infrared photons in a narrow layer centred at about 86-87 km. Another airglow component is the familiar yellow light from sodium atoms in a layer at 92 km. There are also weak blue emissions from excited molecular oxygen at about 95 km. (Roach and Gordon 1973).

In urban environments, the intensity of skyglow at night usually far exceeds any natural sources of sky brightness, and the result is that stars progressively disappear from view. In the most polluted cities no stars at all may be visible, a common situation in most of the mega-cities (10 million or more inhabitants) in the northern hemisphere. The light pollution is partly the result of poorly installed and oriented streetlights that may put as much as 30 per cent of their light output above the horizontal. This represents wasted electrical power to generate that light, much of which goes on upwards into space. In the United States, it has been estimated that poorly installed lights luminaires which brighten the night sky waste $US3.5 billion in electrical power annually (IDA energy waste, 2020). The global figures must be at least an order of magnitude higher. The situation could be greatly improved by suitable shielding of streetlights and ensuring they are mounted horizontally. Full-cutoff luminaires are those where light only shines below the horizontal. They must have flat screens under the light source and no diffusing lens to spread the light. However, such streetlights tend to be the exception rather than the rule.

3.2. Six reasons for good lighting

There are multiple reasons for wanting to protect dark skies and keep them dark. The benefits fall into four main categories, and within each category there are several related benefits. Here we discuss the adverse impact of ALAN and the converse benefits of its absence, which results in dark night skies.

The four main categories are as follows:

- ALAN may have an adverse impact on human health.
- ALAN can be damaging to the bio-environment and to biodiversity
- Poorly installed or oriented outdoor lighting, especially installations that allow light to be projected upwards, wastes electricity and hence there is an adverse economic impact.
- ALAN brightens the night sky and this makes it more difficult to see the stars.

In addition to these four main reasons for wanting to maintain dark skies, there are additional benefits believed to arise from good outdoor lighting that is carefully designed. These are:

- Good outdoor lighting installations promote greater public safety (Schreuder, 1998).
- Dark skies can be a resource of a sustainable economy through astro-tourism.

Here, ‘good lighting’ often implies less light and especially the absence of glare, which is the result of direct illumination from a light source into our eyes. Safer lighting is therefore also lighting which often promotes darker skies; however, we note that the evidence basis for specific lighting recommendations is often unclear (Fotios and Gibbons 2018).

All five of these reasons are central to the theme of the Dark and Quiet Skies conference. Hence, the remainder of this chapter is an analysis of some of these factors in more detail, especially in relation to dark sky oases.

3.3. Measuring the brightness of the night sky

3.3.1 Subjective metrics of night sky quality and the Bortle Scale of light pollution

The Bortle scale of night sky brightness was introduced by the American amateur astronomy John E Bortle in an article published in *Sky and Telescope* in 2001 (Bortle 2001). It uses a nine-point scale to subjectively characterise the quality of the night sky at a given location, Bortle class 1 being for the very darkest sites and Bortle class 9 for the most light-polluted.

Bortle recognised the limitations of the limiting magnitude method of categorizing sky brightness.

However, he ascribed approximate limiting magnitudes to each class on his scale; they ranged from m_V = 7.6 to 8.0 for class 1 to 4.0 for the most light-polluted inner-city skies (Bortle class 9)[1] . For many observers these faint magnitude limits are unrealistically faint, and few people have the visual acuity to detect eighth magnitude (or even seventh) even in the darkest of locations. Certainly such faint stars would require exceptional eyesight, a fully dark adapted eye of a younger person, and experience in using averted scotopic vision, in which the more sensitive peripheral regions of the retina are used, where a greater density of rods (retinal scotopic cells) are located.

In one sense, the Bortle scale does not make estimating sky quality and darkness any easier, as it only ascribes an arbitrary class number to a given site and set of observing conditions. Determination of the Bortle class relies partly on the limiting magnitude of stars, though it also is based partly on the visibility of faint natural sources of light such as the zodiacal light, gegenschein and airglow and on diffuse celestial objects. In the final analysis, Bortle class is the subjective qualitative estimate of a given observer and location, and is not a quantitative objective measurement.

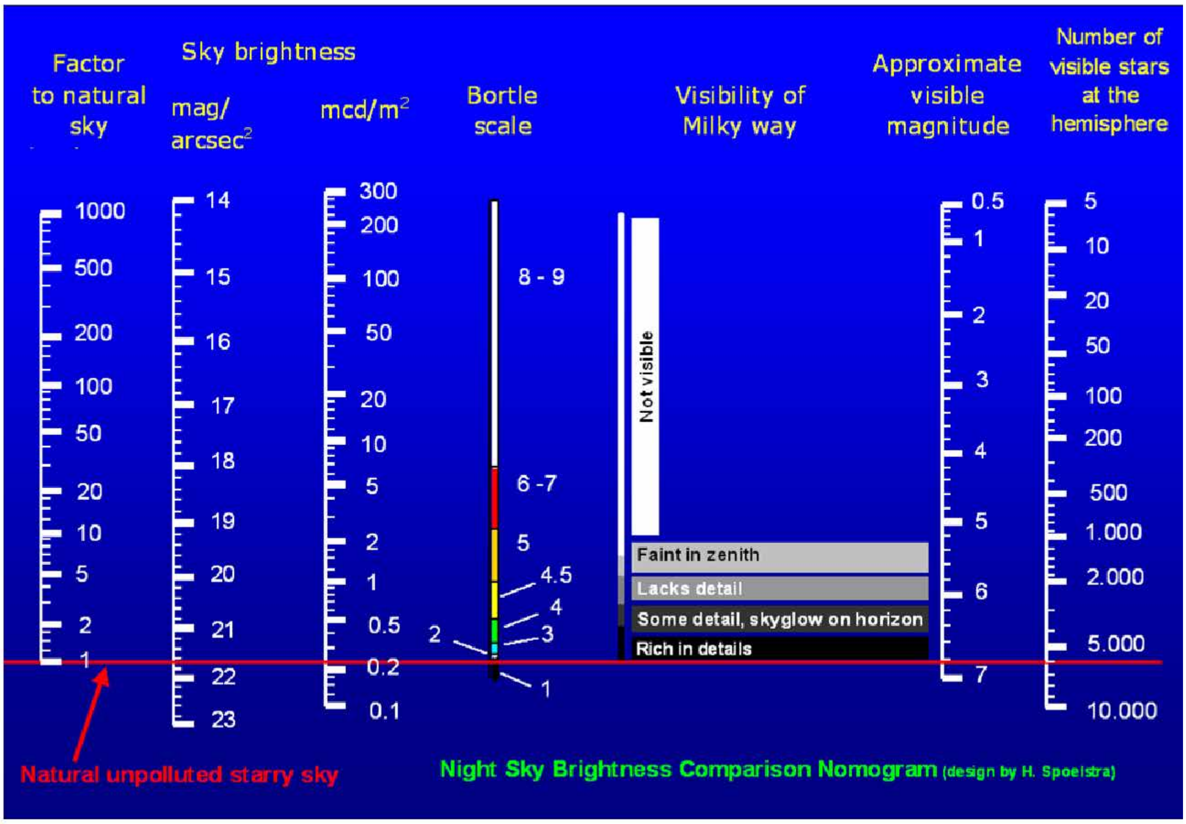

Figure 3.1. Spoelstra's sky brightness nomogram (courtesy of H. Spoelstra)

Henk Spoelstra (2002) in the Netherlands has produced a well-known nomogram that illustrates the Bortle scale (column 4) and relates it to the visibility of the Milky Way (column 5), limiting visual magnitude (column 6) and the number of stars visible above the horizon (column 7). A horizontal line across the diagram indicates the characteristics of a given observing location (such as the dashed line shown as an example).

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[1] Stellar magnitude corresponds to the apparent visual brightness of stars. The brightest stars in the sky are typically magnitude 1 and the faintest discernible by a naked-eye observer are about magnitude 6. The magnitude scale is an inverse logarithmic scale, with each increment of one magnitude corresponding to stars 2.512 times fainter. Larger positive magnitude values correspond to progressively fainter stars, which can be seen with a telescope.

3.3.2 MAGNITUDES PER SQUARE ARC SECOND AND S_{10} UNITS

A more quantitative way of expressing night sky brightness is to use physical units for surface brightness, given that the night sky can be considered as a hemispherical surface with the observer at the centre.

One popular unit of night sky brightness is magnitudes per square arc second (mag arcsec^{-2}). First consider a star of magnitude $m_V = 21$, which is exactly a million times fainter than a naked eye star of magnitude 6. Although stars are essentially point sources of light, we can imagine that light being spread over a tiny square in the sky, whose side in angular measure is 1 arc second (there are 3600 arc seconds in a degree). A hemisphere comprises 2.7×10^{11} square arc sec, so 1 square arc second is a very tiny area of the sky. If the whole sky had the same surface brightness as this tiny area, then the sky brightness would be written 21 mag arcsec^{-2}. This corresponds to a fairly dark sky, about 4 on the Bortle scale. This is shown in the second column of the Spoelstra nomogram (Fig. 1).

The darkest possible skies are at about 21.7 mag arcsec^{-2}, and this figure represents a typical value of the natural airglow which is always present, though somewhat variable in direction and in time. A sky which is 20 times brighter than this natural airglow background would be at about 18.5 mag arcsec^{-2} and this would be a typical value in many urban environments. If the sky is 100 times brighter than the natural airglow background, then the brightness would be 16.7 mag arcsec^{-2}, a value found in the central areas of the world's large cities with Bortle class 8.

Of course the unit of mag arcsec^{-2} are an inverse logarithmic scale, and not therefore very intuitive for those not used to dealing in stellar magnitudes. Sometimes it is more convenient to use a linear scale in which larger numbers represent brighter skies. One such unit sometimes used is S_{10}, the number of tenth magnitude stars per square arc minute, assuming their light were spread uniformly over this small area. One S_{10} unit corresponds to 27.78 mag arcsec^{-2}, which is darker than any night sky. Typically unpolluted airglow will be at about 145 S_{10}, while zodiacal light would be 60 S_{10} and scattered starlight would contribute just 15 S_{10}. A very polluted sky at 16.7 mag arcsec^{-2} would correspond to about 27,000 S_{10}.

3.3.3 PHOTOMETRIC SI UNITS FOR NIGHT SKY BRIGHTNESS

Light sources often radiate in all directions and the luminous intensity determines the lumens radiated into unit solid angle, and is measured in candela (cd), which is a lumen per steradian. For some light sources, such as a laser, the distribution of intensity is highly directional, so the intensity has a high value in that direction, but low or zero elsewhere.

The surface brightness or luminance of a light-emitting surface is measured in candelas per square metre (cd m^{-2}), sometimes referred to as a nit (nt). For the night sky, the millicandela per square metre is a more useful unit (mcd m^{-2}). The natural airglow is at about 0.25 mcd m^{-2}. This is sometimes referred to as one night sky unit (1 NSU). Any sky brightness above 1 mcd m^{-2} is significantly light-polluted. The Spoelstra nomogram (Fig. 1) column 2 shows the typical sky brightness values in mcd m^{-2}. The mean surface brightness of the Sun's disk is about 1.6×10^9 cd m^{-2} (though it varies over the solar disk, being higher in the centre). One property of the surface brightness of any radiating surface is that its value is an intrinsic property of the radiating surface and is independent of distance. The surface brightness of the Sun would have the same value for an observer on Mars or any other planet in the solar system. For that reason, specifying the surface brightness of the night sky does not require specifying the distance to the light scattering hemispherical surface of the sky.

The surface brightness of the night sky (S) in mcd m^{-2} can be calculated from a given value in visual magnitudes per square arc second. The equation relating these two parameters is[2] :

$$S\ (\text{mcd m}^{-2}) = 1.08 \times 108 \times 10^{\ (-0.4\ \text{mag arcsec}^{-2})}$$

Note that one S_{10} unit is close to 1 µcd m^{-2}.

3.4. What is a Dark Sky Oasis?

A dark sky oasis (also often referred to as a 'dark sky place') is a location where the night sky is protected by an outdoor lighting policy, or in legal terms, a *lighting ordinance* which limits the amount and the wavelengths of light that shine upwards into the sky. Most dark sky oases will have controls in the relevant lighting ordinance on street lighting, and where required, on the lighting of sports facilities at night, on outdoor lighting of commercial facilities such as ports and factory yards, and limits on flood lighting of buildings for decorative purposes. However, such facilities will often be absent from a dark sky oasis.

A number of bodies are currently giving accreditation for dark sky oases based on the submitted evidence that the sky is protected and that outdoor lighting complies with these basic criteria. The largest organisation offering such accreditation is the International Dark-sky Association (IDA), based in Tucson, U.S. (IDA, 2018). They offer accreditation in five different categories, namely International Dark Sky Reserves, Sanctuaries, Parks and Communities, and Urban Night Sky Places. These all have slightly different criteria.

Another international organisation with an accreditation programme is the Starlight Foundation, based in Tenerife, Canary Islands (Starlight Foundation, 2020). The Starlight Foundation recognises starlight reserves, starlight tourist destinations and they also have a category of starlight rural hotels and houses. These last are individual establishments with good lighting practices and offering information to their customers on the night sky. The criteria to be met are a little different in each case, being a bit less stringent for the Starlight Tourist Destinations than the Starlight Reserves, as shown in Section 7.2.

The Starlight Foundation has criteria based not only on night sky brightness, but also the requirement for clear skies, good transparency and excellent seeing (a measure of image diameter, and hence of the lack of turbulence in the Earth's atmosphere) (Varela et al. 2012). These criteria are generally more stringent than those from the IDA, where dark skies are the main criterion.

Some national bodies also offer dark-sky place certification, most notably the Royal Astronomical Society of Canada (RASC, 2020).

The International Commission on Illumination (CIE) has defined five environmental zones from E0 to E4 (Pollard et al, 2017). Here E0 are zones which are intrinsically dark and these include Starlight Foundation Starlight Reserves, IDA Dark Sky Places and any sites near major astronomical observatories. Essentially in E0 zones there is no street lighting, and the upward light ratio (ULR), being the percentage of light allowed to shine above the horizontal from any luminaire, is zero.

Zone E1 are dark and relatively uninhabited rural areas. These could also be in a dark sky oasis. For zone E1, the vertical illuminance on properties is recommended to be less than 2 lux before curfew, but less than 0.1 lux post-curfew. The ULR is still recommended to be zero, and the surface luminance on the ground should be less than 100 mcd m^{-2}.

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[2] The constant of 1.08×10^8 is approximate, and depends on the night sky spectrum (Bará et al, 2020).

It is noted that the CIE environmental zones do not make recommendations concerning night sky brightness. Such recommendations are made in this document (see Section 11) and by the IUCN (see Section 4.1 and Welch (2021)).

3.4.1 THE IUCN DARK SKIES CLASSIFICATION SCHEME

The International Union for the Conservation of Nature operates the Dark Skies Advisory Group (IUCN-DSAG). The aims of this group are to:

- Preserve the ecological integrity of natural environments;
- Ensure the full enjoyment of a wilderness experience;
- Appreciate the integrity, character and beauty of rural landscapes;
- Protect and present the authenticity of cultural sites (tangible heritage);
- Help preserve cultural practices and ceremonies related to the night sky;
- Help preserve the intangible heritage that relates to mythology, traditional navigation and cultural heritage related to the night sky;
- Protect human health, both medical and psychological;
- Contribute to energy efficiency;
- Benefit scientific and amateur astronomy (starlight tourism) and the right for all people to enjoy a clear, unpolluted night sky; and
- Improve personal security through non-glare lighting in urban areas.

The DSAG was established in 2009 and has 18 members, including the current and founding chair, Dr David Welch in Ottawa. The DSAG website (DSAG, 2020) gives more information about the IUCN-DSAG.

Part of the work of the Dark Skies Advisory Group is to maintain a world list of dark sky places. This list is to be found at the site DSP (2020) and is regularly up-dated.

At the present time (31 May 2020) there are 223 dark sky oases (or places) in 27 different countries with accreditation in most cases from IDA, the Starlight Foundation or the Royal Astronomical Society of Canada. These dark sky oases have been classified into six main categories as well as several subcategories according to the scheme proposed by the International Union for the Conservation of Nature (IUCN) Dark Skies Advisory Group (DSAG) (Welch 2013). These in turn refer to the IUCN categories of protected natural areas (Dudley 2008; Stolton, Shadie, and Dudley 2013).

The definitions of the IUCN DSAG Dark Sky Places Class system follow both from the IUCN categories of protected natural areas and a set of additional criteria identified by the DSAG. To be classified within this system, a place should:

- be an officially protected area in the sense understood by the IUCN;
- have management policies and practices in place to protect or restore natural darkness; and
- be recognised either by an authoritative body at arm's length from the protected area agency itself, or by legislation, regulation or policy of the appropriate national, territorial, state or provincial jurisdiction.

An additional class recognizing the built environment is added to enable inclusion of the IDA International Dark Sky Community designation category. The IUCN DSAG Dark Sky Places Classes are:

1. Dark sky astronomy site: protected areas that include an astronomical research observatory.
2. Dark Sky Park: protected natural area
   - a Park, reserve, habitat, natural area or other ecological protection;
   - b Unpopulated area set aside for traditional or sacred practices related to the sky;
   - c Rural area, area of outstanding landscape beauty.
3. Dark Sky Heritage Site: protected heritage physical works of mankind.
4. Dark Sky Outreach Site
   - a Urban or suburban site
   - b Rural site

Class	Class type and subtypes	Class description	**Number worldwide** (in brackets, subtype numbers)
1	Dark Sky Astronomy Site	Sites having a science-quality astronomical observatory	**15**
2	Dark Sky Park	Sites which are protected natural areas	**114**
2a	Park, reserve, habitat, natural area or other ecological or geological protection		(85)
2b	Unpopulated area set aside for traditional or sacred practices related to the sky		(4)
2c	Rural area, area of outstanding landscape beauty		(25)
3	Dark Sky Heritage Site	Sites which are protected heritage, physical works of mankind	**9**
4	Dark Sky Outreach Site	Sites where astronomical outreach is carried out, often in or on outskirts of a city or conurbation.	**25**
4a	Urban or suburban site		(6)
4b	Rural site		(19)
5	Dark Sky Reserve	Sites with a core protected area and a sustainable development buffer ma of cooperating community, rural and natural area jurisdictions	**21**
6	Dark Sky Community	A rural area, village, town or city	**39**
6a	City, town or village		(33)
6b	Populated rural area without a formal protected area		(6)
	Global total		**223**

Table 3.1. IUCN dark sky place classes

5. Dark Sky Reserve: mix of cooperating community, rural and natural area jurisdictions.
6. Dark Sky Community: an entire village, town or city
    a Urban
    b Rural

The classifications are summarised below along with the total number of places in each category recognised to date by IUCN-DSAG.

These 223 dark sky oases, which have received accreditation and therefore enjoy some level of protection for the night sky, constitute a total land area of just over 20 million hectares (in fact, 20,395,000 ha), or an average of about 900 sq km each in land area. This is just 0.14 per cent of the total land area present on the Earth's surface, excluding oceans. They comprise, therefore, a tiny fraction of the global land area that is under any kind of protection for the night sky above.

3.4.2 The World Atlas of Artificial Night Sky Brightness

In 2001 an important publication by Pierantonio Cinzano at the Italian Light Pollution Science and Technology Institute and his colleagues mapped for the first time the effect of light pollution on night sky brightness on a global scale (Cinzano et al. 2001). This was the first 'World Atlas of Artificial Night Sky Brightness.' It was produced by measuring from space the upwards-travelling light from the whole Earth in the years 1996-97. Modelling was then done to calculate the resulting night sky brightness at the zenith for an observer at sea level, based on the expected scattering in the Earth's atmosphere by air molecules and aerosols. The United States Defense Meteorological Satellite Program (DMSP) made observations of light going into space on cloudless nights in the wavelength range 440-940 nm, which covers the emissions from most common street-lights (Elvidge et al. 2009; Huang et al. 2014). The map's ground resolution was 0.93 km.

In the World Atlas, the natural sky brightness background was taken to be b_n = 21.6 visual magnitudes per square arc second[1] and the skyglow from light pollution was plotted using six colour-coded levels from 0.11-0.33 b_n (dark and almost unpolluted sky) to more than 27 b_n for the most polluted cases.

Sky brightness was also tabulated for every country in the world to show what fraction of the population of each nation is living under skies for each level of pollution. The most polluted regions of the world were found to be the eastern half of North America, Western Europe and Japan. Countries in the southern hemisphere were much less severely affected.

The data for the first World Atlas were taken in the late 20th century, and today the situation has considerably worsened as anticipated by Cinzano and his colleagues. This was shown in the New World Atlas of Artificial Night Sky Brightness (Falchi et al. 2016) produced using Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS-DNB) data from the Suomi National Polar-orbiting Partnership satellite (Lee et al. 2006). The data were from 2013 and 2014 and with the results calibrated with photometric data of sky brightness from the ground. High resolution maps with 14 levels of light pollution were plotted.

The new world atlas showed that 80 per cent of the world and more than 99 per cent of the U.S. and European populations live under light-polluted skies. The Milky Way is hidden from more than one third of humanity, including 60 per cent of Europeans and nearly 80 per cent of North

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[1] This corresponds to a background airglow natural sky brightness of 8.61×10^7 visual photons cm^{-2} s^{-1} sr^{-1}, or 252 µcd m^{-2}. This was revised to 174 µcd m^{-2} in the new world atlas of Falchi et al (2016).

Americans. These figures are based on a night sky brightness of greater than 14 µcd m-2, or eight per cent of the natural airglow. The plotted maps showed dramatic increases in skyglow in many countries, especially so in eastern China, India and South Korea.

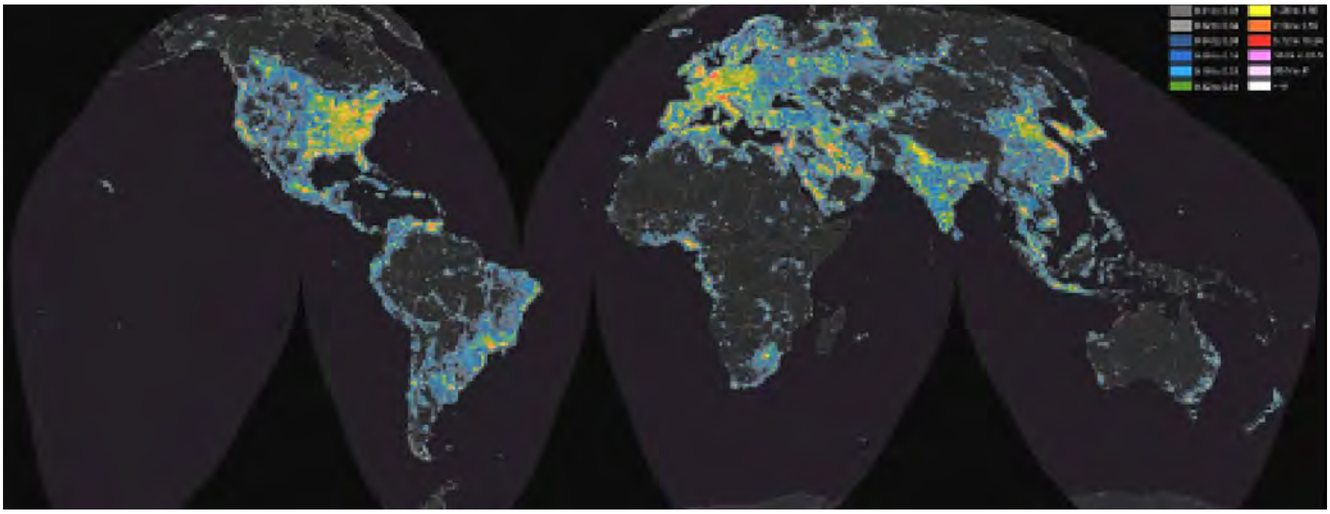

Figure 3.2 - Artificial night sky brightness at ground level from the New World Atlas of Artificial Night Sky Brightness by Falchi et al (2016). Image courtesy of Fabio Falchi

If we limit our attention to the most heavily light-polluted skies with the artificial night sky brightness of 87 µcd m^{-2} or greater (50% of the natural airglow), then 83.2 per cent of the world's population live under these heavily polluted skies, and 8.6 per cent of the world's land area is affected. The polluted land area is vastly greater than the tiny area in protected areas as dark sky oases. What is more, the polluted land area is growing at two per cent annually, or doubling in about 35 years (Kyba et al. 2017).

Unfortunately the New World Atlas was based on satellite data which recorded light pollution on the ground in the wavelength region 500-900 nm. It therefore omitted the blue peak emission ($\lambda \sim 450$ nm) from the numerous LED street-lights that had been installed in the early 21st century, and it is this blue light that scatters most in the atmosphere. The night sky brightness calculated from the satellite data will therefore be an underestimate of the true situation for those localities with a substantial LED component to street-lighting.

3.5. The value of Dark Sky Oases

The value of a resource like natural nighttime darkness stems in part from the perception of its comparative (and increasing) rarity as an everyday experience among humans. The converse begs the question of whether people who have never had access to a particular resource, such as natural nighttime darkness, can value it highly enough to actively support its conservation. As the world's human population becomes increasingly urban, it may be progressively more difficult to build and sustain coalitions aimed at reducing light pollution.

Some scholars have critically evaluated the value of natural darkness beyond what it represents in terms of potential material benefit and the extent to which it is impacted by light pollution, which perhaps devalues the resource. In particular, Stone (2017) asked "that we reconsider darkness, not as an opponent of lighting, but as an equal consideration in the design of nighttime spaces." The suggested approach is therefore holistic and transcends the simple question of whether or not one can see the stars at night.

Here we examine different dimensions of "value" as regards places where night skies have protected status.

3.5.1 Economic value

It is hypothesised that the conservation of dark night skies generates economic value by encouraging tourism and supporting property values if such dark places are considered desirable locations to visit or live. Because the resource of darkness is fully renewable, this value can be sustained indefinitely with good management practices. Further discussion of this subject may be found in Appendix 3.

The economic value of natural darkness may be indicated by the degree to which residents and property owners in and around protected areas agree that public resources should be spent on conservation programs. Simpson and Hanna (2010) applied the Contingent Valuation Method (CVM) to light pollution in terms of survey respondents' Willingness To Pay (WTP) both to improve night sky visibility and to prevent deterioration in visibility. They found that "a larger improvement in night-sky conditions has a significantly higher average WTP, suggesting that larger expenditures for light pollution projects with greater effects may be economically efficient. Gallaway (2010) argued that nighttime darkness has 'instrumental value' (as a means to an end), rather than intrinsic value (an end unto itself)."The passive enjoyment of beauty is fundamental to the value of dark skies, and prevailing economic doctrines make it difficult to appreciate and articulate the importance of beauty and other passive pleasures."

3.5.2 Scientific value

Human understanding of the nighttime environment, and the ways artificial light at night alters it, are still far from complete. To the extent that researchers look to light-polluted cities as environments to study the deleterious effects of light pollution, they need protected dark places to serve as experimental "controls". This is especially important when biological systems are under study. Protected dark-sky places are themselves natural laboratories for studying the natural light of the nighttime environment; as an example, see the recent work in Grauer et al. (2019) resulting from a collaboration between two IDA International Dark Sky Sanctuaries: the Cosmic Campground (U.S.) and Aotea/Great Barrier Island (New Zealand).

Beyond their advantages for research relating directly to darkness itself, protected dark places enable other kinds of science. In recent decades, ground-based astronomical observatories have been situated progressively further from cities in order to limit the impact of skyglow on science observations. To prolong the useful lifetime of these facilities, some observatories have successfully sought protections for territories surrounding their sites. Examples include Mont-Mégantic Observatory in the Mont-Mégantic International Dark Sky Reserve, Québec; Mt. John Observatory in the Aoraki Mackenzie International Dark Sky Reserve, New Zealand; and the AURA Observatory in the Gabriela Mistral International Dark Sky Sanctuary, Chile, Roque de los Muchachos Observatory (La Palma, Starlight reserve and Starlight Tourist Destination) and Teide Observatory (Tenerife, in National Park of Teide, Starlight Reserve and Starlight Tourist Destination), Parc Astronòmic del Montsec (Catalonia, Starlight Reserve and Starlight Tourist Destination) or Pic du Midi (Starlight certification in progress).

The scientific dimension of a starry night is an essential part of the legacy of the sky as a window to the universe (Marín et al. 2015). The ability of the planet's astronomical sites and observatories to detect and interpret data from outside the world we live in should be considered as a resource of extraordinary value for the progress of knowledge, as it has been throughout history. Dark skies are still the windows to our knowledge of the greater universe. Unfortunately current areas devoted to astronomical observation do not enjoy appropriate recognition and some of them are threatened by light pollution. Present-day technical and scientific requirements restrict suitable areas to very specific and limited locations offering good conditions for the development of astronomy, and for optical and infrared astronomy in particular. There are only a few places on the planet where we find this unique combination of environmental and natural circumstances: well-conserved spaces with very little alteration to natural starlight. These exceptional sites, including their natural components, can be considered as "landscapes of science and knowledge". Having identified the best locations for astronomical observation throughout the planet, it is critically important to try to conserve and protect them. The case of Hawaii, the Canaries, Namibia and northern Chile are an ensemble of discrete sites that, within this context, have outstanding universal significance as a group (Ruggles & Cotte, 2010).

3.5.3 CULTURAL VALUE

The close and perpetual interaction between astronomy and its role within human culture is a vital element of the outstanding universal value of the dark sky.

There is a lengthy human history and prehistory terms of astronomical themes in art and architecture, arising as early as the Paleolithic. (Sweatman and McCoombs, 2019) Deliberate alignment of artificial structures to the rising and setting points of astronomical objects points to human use of the night sky as a calendric device by the Neolithic period.

They are places of mystery and wisdom based on the "knowledge of stars". Teotihuacán, Stonehenge, Giza, Carnac, Chichen Itza, Delos, and Jaipur are only a few examples symbolizing this legacy made up of an infinity of artistic, scientific and ethnographic manifestations conserved at all latitudes. (Marín et al. 2015).

Furthermore, the night sky has inspired numerous great works of art, literature, poetry and music across all human cultures, religions and societies.

Although UNESCO has so far declined to recognise the night sky itself in the context of its World Heritage Programme, it has conferred World Heritage status on many monuments and sites associated with both historical astronomy activity and archaeoastronomy.

The cultural and religious practices of many people, especially those in indigenous societies, rely on access to the night sky. Detailed examples are given by Ruggles and Cotte (2010) and by Ruggles (2017).

3.5.4 ENVIRONMENTAL VALUE

Dark Sky Oases offer the possibility of controlling and minimizing, or even, eliminating the artificial illumination into their territories. Consequently, they are literal refuges for wildlife under the stress of increasing human territorial intervention, including environmental light pollution - ELP.

The loss of the natural darkness because of ELP has become a serious threat for many species, disturbing their habits and habitats, as well as the basic functions of ecosystems. Darkness and natural light are indispensable for the healthy functioning of organisms and ecosystems. Wildlife has been adapted to the natural cycles of the moon and stars during millions of years of evolution. As over half of the creatures living on this planet are nocturnal, any insignificant degradation in the quality of the sky is having a profound effect on the behaviour and on the equilibrium of the biosphere. (Marín et al.(2015). In addition, many diurnal species adjust their vital cycle according to night duration. Light pollution, in particular, has been shown to have a widespread, negative impact on many different species and also covering large portions of territory. Scientific evidence for this impact in migratory birds, wilderness fauna, hatchling sea turtles, oceanic species and insects is striking, because of the large-scale mortality that has occurred as a result of artificial night lighting, a phenomenon which is increasing worldwide, also because of the increased negative impact of the blue rich LED; a technology that has been replacing the traditional electric discharge sources of illumination.

Most natural protected areas and sites of importance for conservation were not originally designed or placed to ensure maintenance of ecological processes without disturbance from artificial light or skyglow from distant cities or industrial zones. Dark Sky Oases offer both concrete and successful examples on how to control the ELP in their territories and surroundings.

3.5.5 POTENTIAL HUMAN WELLBEING VALUE

We know the least about this value. There is no known evidence that people who live in and near dark sky places may benefit in terms of health outcomes, especially if they sleep in darkness without light trespass. One example has to do with ‘medical tourism’. The Yeongyang Firefly Eco-Park International Dark Sky Park in the Republic of Korea cultivates the image of a place where people can recuperate from medical procedures in a naturally dark environment, which is thought in some strains of eastern medicine to be beneficial to healing. (Dalton, del Solar and Barentine 2021b)

Another example has to do with an overall sense of well being among people living in dark places, which could be connected to better mental health. Blair (2018) studied the people of Sark, a royal fief among the Channel Islands off the south coast of the United Kingdom that was named an IDA International Dark Sky Community in 2011. She found that residents of Sark place a high value on observing the night sky with others from their island, and that the shared experience supports and extends family and community connections through the transmission of night sky lore. Blair’s observations also validate a “widespread belief that observing the night sky spontaneously or intentionally results in positive (and sometimes transformative) feelings” that “impact positively on wellbeing.” (Blair 2018)

3.6. IMPACTS OF LIGHT POLLUTION ON THE VISIBILITY OF STARS

Given that light pollution is a factor that can have an adverse effect on the practice of astronomical research, curtail star-gazers’ view of the night sky and limit the effectiveness of astro-tourism, it is important to have means of measuring light pollution at any location. One simple method is to estimate the number of stars visible on a given clear moonless night, or to estimate the limiting magnitude of the faintest stars visible to a naked eye. The two parameters are closely related.

The number of stars visible on a clear moonless night to different magnitude limits is given in the table below. The data are adapted from Haworth (2003).

Magnitude	Range	Number of Stars per Range	Cumulative Stars	Number of stars visible above 10°
-1	-1.50 to -0.51	2	2	1
0	-0.50 to +0.49	6	8	3
1	+0.50 to +1.49	14	22	9
2	+1.50 to +2.49	71	93	38
3	+2.50 to +3.49	190	283	116
4	+3.50 to +4.49	610	893	368
5	+4.50 to +5.49	1,929	2,822	1165
6	+5.50 to +6.49	5,946	8,768	3621
7	+6.50 to +7.49	17,765	26,533	10958
8	+7.50 to +8.49	51,094	77,627	32059

Table 3.2 - Number of visible stars in the sky as a function of magnitude

In practice, in most locations stars are only visible to about 10 degrees from the horizon, so at a given location we can only see about 40 per cent of a full sphere, less than a hemisphere. The last column gives the total number of stars visible above 10° elevation to different limiting magnitudes for a dark-sky location. The numbers are approximate.

In practice few people can see below magnitude 6.5 even in the best conditions, and more likely the practical limit is closer to 6 in the absence of light pollution on a clear moonless night. The numbers are very approximate, but indicate that at any given place and time we are unlikely to see more than three and a half thousand stars.

If there is light pollution, the brighter sky lowers the limiting magnitude to perhaps 3 or 4, typical of many urban environments. The table shows that only a few hundred stars can be detected with a naked eye in such conditions. In the most light-polluted cities the limiting magnitude might be only zero or one. In that case, the number of stars visible could be in single figures.

Instead of counting stars, we can find the faintest stars visible under given conditions, and thereby estimate the sky brightness. For every ten-fold increase in sky brightness, the limiting magnitude will reduce by 2.5 magnitudes (i.e. it will go from 6.5 to 4.0), which corresponds to about ten times fewer stars being visible.

The limiting magnitude depends on many factors in addition to light pollution, including sky transparency, phase and position of the Moon, time since sunset or before sunrise, age of the observer and whether complete eye dark adaptation has occurred. All these factors combined make star counts or estimating the limiting magnitude a very crude indicator of light pollution.

3.7. THE INTERNATIONAL DARK-SKY ASSOCIATION AND DESIGNATION OF INTERNATIONAL DARK SKY PLACES

3.7.1 MISSION AND ORGANISATION

The International Dark-Sky Association is a U.S.-based non-governmental organisation whose mission is to preserve and protect the nighttime environment and our heritage of dark skies through environmentally responsible outdoor lighting. The organisation was established to protect the night sky for astronomers in southern Arizona, U.S., from the light pollution of the nearby city of Tucson, but its mission has expanded enormously to become a world-wide organisation to promote good lighting practices which help protect dark night skies and minimise light pollution everywhere, not just near professional observatories. The recognition that light pollution is not only damaging for astronomers, but potentially also harmful to the environment and to human health, has greatly increased the role of IDA in mitigating all these harmful consequences of artificial light at night.

IDA's goals are to advocate for the protection of the night sky; educate the public and policymakers about night sky conservation; promote environmentally responsible, quality outdoor lighting; and empower the global public with the tools and resources to help bring back the night. It pursues these goals by engaging a distributive network of members, advocates and volunteers around the world to lead efforts to create change from the grassroots.

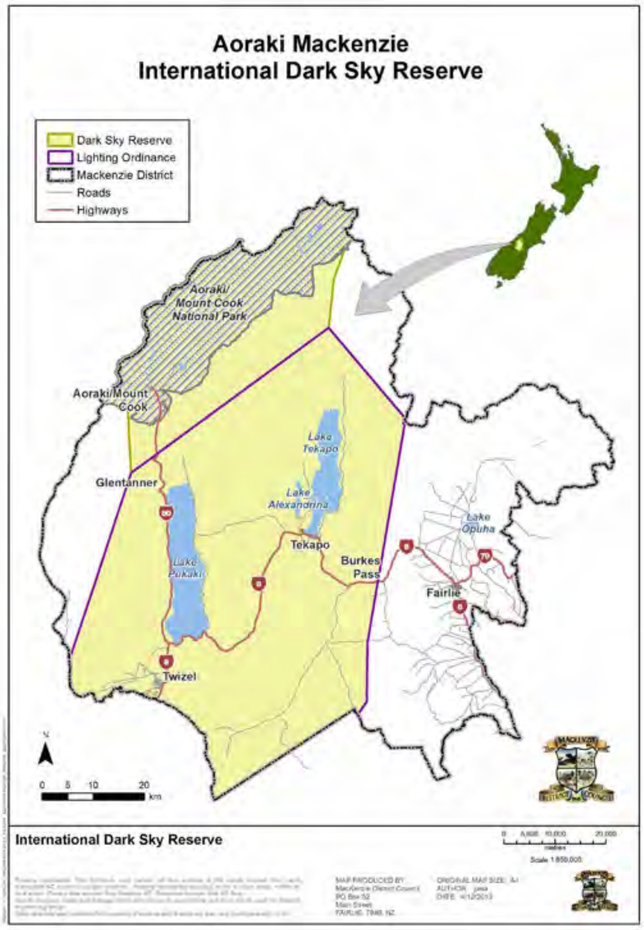

Figure 3.3 - Map of the Aoraki Mackenzie International Dark Sky Reserve. Map courtesy of the Mackenzie District Council.

3.7.2 INTERNATIONAL DARK SKY PLACES PROGRAMME

In 2001, IDA initiated its International Dark Sky Places Programme to encourage communities, parks and protected areas around the world to preserve and protect dark sites through responsible lighting policies and public education. This programme considers two settings for recognition of outstanding efforts to pursue the goal of preserving dark skies: conservation sites and the built environment. Designation is offered to parks and protected areas with credible lighting controls and active public outreach and education programmes in place for protecting dark skies, as well as communities that enact quality outdoor lighting policies, ensure publicly owned lighting complies with those policies, and engage residents toward bringing private lighting into compliance. International Dark Sky Places are recognised in several categories, including International Dark Sky Parks, International Dark Sky Reserves, International Dark Sky Communities, International Dark Sky Sanctuaries and Urban Night Sky Places. (Dalton, del Solar and Barentine 2021a)

At the time of writing, there are 86 International Dark Sky Parks, 16 International Dark Sky Reserves, 29 International Dark Sky Communities and 13 International Dark Sky Sanctuaries. The newest IDA designation category, Urban Night Sky Places (UNSP), consists of municipal parks, open spaces, observing sites, and similar lands in urban or peri-urban settings. One UNSP has been designated since the category was introduced in 2018.

International Dark Sky Reserves are the most complex designation type recognised by IDA. An IDA International Dark Sky Reserve is “a public or private land possessing an exceptional or distinguished quality of starry nights and nocturnal environment that is specifically protected for its scientific, natural, educational, cultural, heritage and/or public enjoyment.” (IDA 2018) Reserves consist of a core area meeting minimum criteria for sky quality and natural darkness, and a peripheral area that supports dark sky preservation in the core.

Figure 3.4: Road sign at Burkes Pass, the entry to AMIDSR (courtesy Maki Yanagimachi)

3.7.3 THE AORAKI MACKENZIE INTERNATIONAL DARK SKY RESERVE AS A CASE STUDY FOR LIGHT POLLUTION MITIGATION

The Aoraki Mackenzie International Dark Sky Reserve (AMIDSR) was created in April 2012 with recognition as a reserve from IDA. The reserve is located in the centre of New Zealand’s South Island and comprises most of the Mackenzie Basin and all of Aoraki/Mt Cook National Park. The Mackenzie Basin lies to the east of the main range, the Southern Alps, and to the west of a lower range called the Two Thumb range. The coordinates of the centre of the reserve are about 44 degrees south and 170.3 degrees east (AMIDSR 2020).

The application document to IDA discussed the geography, topography, population, ecology, climate, fauna, flora, settlement history of the region, the Mackenzie Lighting Ordinance in the

District Plan, Maori astronomy, Mt John Observatory, astro-tourism, land ownership, conservation, local governance and it gave a complete catalogue of all external street lighting in the proposed Reserve.

The decision by IDA to grant the Reserve, just the third to be recognised in the world, the first in the southern hemisphere and the first to be accorded gold tier status (Barentine 2016), was a major step forwards. At 4367 square km, AMIDSR is also the world's second largest dark sky reserve of the 16 reserves currently recognised.

The aims of the reserve are first to protect the exceptionally dark skies we have in the Mackenzie and at Aoraki/Mt Cook National Park. Dark skies free of light pollution help those who come to the Mackenzie for star-gazing, as well as research astronomers at the University of Canterbury's Mt John Observatory. A lighting ordinance was first enacted in 1981 to protect the astronomical research at the observatory.

The reserve is run by a board of a dozen members who operate as a registered charity, and the Board's aim is to educate the public about the dangers of light pollution as well as the benefits of dark skies. Public outreach is a major aspect of the Board's work. Over the last six years there have been three Starlight Festivals, which have entailed public lectures by international visiting speakers, videos on light pollution, star-gazing sessions, exhibitions and cultural activities run over three days. International conferences to promote dark skies were held in the reserve in 2012 and 2019.

The success of the reserve is shown by the rapid rise of astro-tourism in the Mackenzie and at Aoraki/Mt Cook. About 1.5 million tourists[2] come through the Mackenzie District annually and an estimate is that about ten per cent come explicitly to see the beauty of the pristine starlit skies at night or to visit Mt John Observatory by day. Many tourists are from Asian countries with severe light pollution who have never seen the Milky Way from their home towns or cities.

Astro-tourism companies such as the Dark Sky Project at Tekapo and Big Sky Stargazing at Mt Cook have been thriving for the last decade, and tourist numbers with these companies jumped about 20 per cent after the reserve was established. Other companies are now springing up inside the reserve at Tekapo and Twizel to show our visitors the night sky.

In 2019, the New Zealand Transport Agency agreed to replace all the streetlights in Mackenzie District with warm amber-coloured LED lights (with a colour temperature[3] of 2200 K).

3.8. The Starlight Foundation: the commitment to the Declaration in Defence of the Night Sky and the Right to Starlight (La Palma Declaration).

3.8.1 Background to the Starlight Foundation

The Starlight Initiative was born with the 'Declaration in Defence of the Night Sky and the Right to Starlight' (Marín & Jafari, 2007), in which representatives of the Astrophysics Institute of the Canaries (IAC), United Nations Educational Scientific Cultural Organisation (UNESCO), the United Nations World Tourism Organisation (UNWTO), the International Astronomical Union (IAU), United Nations Environmental Programme-Convention on the Conservation of Migratory Species of Wild Animals (UNEP-CMS), Comité Olímpico Español (COE), the Secretariat of the Convention on Biological Diversity (SCBD), the Man and Biosphere Programme (MaB), European Union

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[2] These are pre-covid pandemic figures.

[3] The correlated colour temperature (CCT) of a light source is the temperature of a radiating black body that presents the same apparent colour to the human eye as the light source.

(EU) and Ramsar-Convention launched this international movement in defense of the night sky, promoting the dissemination of astronomy and sustainable, high-quality tourism in those places where the night sky is cared for (Marín & Jafari, 2007). The Starlight sites incorporate the preservation and observation of the night sky as a part of natural, scenic, cultural and scientific heritage; encourage 'Star Tourism'; and promote infrastructure, products, activities and training of specialised guides in sustainable tourism.

The Starlight Foundation (known in Spanish as Fundación Starlight) is a legal non-profit entity created in 2009 by the Institute of Astrophysics of the Canary Islands and the consulting Corporación 5 as the body in charge of the Starlight Initiative, providing human resources and means for its development and promotion.

The XXVIIth IAU General Assembly in August 2009, in Rio de Janeiro (Brazil), unanimously passed Resolution B5 in Defence of the Night Sky and the Right to Starlight, recognizing the principles expressed in the Starlight Declaration. Since then, the IAU has been significantly increasing its work in this line, particularly through the Division C (Education, Outreach and Heritage), or with the creation of commissions and working groups such as the Commission C4 (World Heritage and Astronomy), WG Dark and Quiet Sky Protection, WG Astronomical Heritage in Danger and WG Achieving Sustainable Development within a Quality Lighting Framework.

The Foundation has four main objectives:

1. Protection of the night sky from light pollution
2. Cultural dissemination of astronomy, through outreach
3. Promotion of astro-tourism
4. Adoption of intelligent lighting and innovation, energy saving

3.8.2 The Starlight Certification System

The Starlight Foundation has created an international certification system whereby those areas that have excellent sky quality and represent an example of protection and conservation are accredited.

The Starlight Reserve concept was established in the UNESCO World Heritage Centre, Paris (October 2007), Astronomy and World Heritage. But the criteria were well determined in the International Seminar and World Heritage (London) and at the World Heritage Committee in Quebec, 2008. The final document was adopted during the International Workshop and Expert Meeting on Starlight Reserves and World Heritage held in Fuerteventura in 2009 (Marín, 2009). It is a protected natural area where a commitment to protecting the quality of the night sky and providing access to starlight is established to preserve the quality of the night sky and the different associated values, whether cultural, scientific, astronomical, or the natural landscape. The Starlight Reserve concept is accompanied in each case by a Participatory Action Plan and a set of recommendations. To date they cover the following categories: Heritage Sites, Astronomy Sites (Ruggles & Cotte, 2010), Natural Sites, Landscape, Starlight Oases - human habitats and Mixed Starlight Sites.

Starlight Tourist Destinations are locations with ideal conditions for observing the stars and where light pollution is controlled. This makes them logical destinations for tourism based on the appreciation of the sky as part of the natural world. It must not only prove the quality of its air, and the means to ensure its protection but they must also have appropriate tourism infrastructure and its integration into nocturnal nature. The criteria were established in December 2010, at the UNWTO Centre in Madrid, with representatives of UNESCO, UNESCO-Mab and IAC.

There exist other modalities described in the Starlight Foundation webpage: Stellar Parks and Stellariums; Villages, Wilderness, Rural Hotels and Houses, camps, Inns, monasteries and abbeys, etc. The Starlight Foundation offers its experience and the ability to offer specific advice and consultancy for each destination so as to develop its full potential in this type of tourism. The sky quality parameters and thresholds required for Starlight Reserves and Starlight Tourist Destination are summarised in Table 3.3.

Parameter	Starlight Reserve	Starlight Tourist Destination
Sky brightness (V mag arcsec^{-2})	>21.4	> 21.0
Seeing	<1 arc second	< 3 arc seconds
Transparency/ limiting magnitude for stars	m_{limit} ~ 6	m_{limit} ~ 6
Clear time	> 60 per cent	> 50 per cent

Table 3.3: Starlight Foundation criteria for reserves and tourist destinations

The criteria are based not only on night sky brightness, but also the requirement for clear skies, good transparency and excellent seeing (a measure of image diameter, and hence the lack of turbulence in the Earth's atmosphere). These criteria are generally more stringent than those from the IDA, where dark skies are the main criterion.

At the time of writing (July 2020) there were 14 Starlight Reserves, 30 Starlight Tourist Destinations, seven Starlight Stellar Parks and more than sixty Starlight Hotels and Rural Houses. In 2020 the number of international Starlight certification requests grew by 300 per cent (addressing Costa Rica, Puerto Rico, México, Perú, Argentina, Chile, Rusia, France, Portugal, Maroc, Australia, etc.)

1.8.3 Starlight Training

This new concept of Star Tourism requires specialised training for the professionals in the existing tourism sector in the area, especially those working in the field of nature tourism.

A "Starlight Astronomical Monitor" (60 hours´duration) is a guide who is trained and able to accompany groups complementing their enjoyment of nature with knowledge about the Universe seen either with the naked eye or through simple observation instruments "Starlight Tourist Guides" qualification is awarded to those who complete the Courses in La Palma and Tenerife (of 120 hours' duration) and whose purpose is to train the Guides to accompany groups round the Teide Astrophysical Observatory (Tenerife) and Roque de los Muchachos (La Palma) and their telescopes. The Starlight Guides are the only professionals accredited by the IAC to do the guided tours in their observatories. There are a total of about 600 Starlight trained people of more than 15 nationalities.

3.8.4 Tenth Anniversary of the Starlight Declaration (2017)

In this Congress held in La Palma (18-21 April 2017), it was commemorated the tenth Anniversary of the "Declaration on the Defense of the Night Sky and the Right to the Stars Light", where the institutions signing the same, as well as other institutions invited, adopted resolutions and made a call facing the future. It was acknowledged the full validity of the "Starlight Declaration", signed in the island of La Palma in 2007 and the whole population, the local communities and the governments were encouraged to adopt their principles and guidelines.

Both IDA and the Starlight Foundation have a considerable overlap in their goals of protecting dark sky places through accreditation. They work independently but with some collaborative exchanges. The Starlight Foundation at present is very much focussed on Spain and Latin America, but has the ambition to become more global in its reach in the future. It has links with international organisations such as UNESCO, UNWTO and IAU and a strong emphasis on astro-tourism and on dissemination of astronomy.

3.8.5 IMPACT OF ASTRO-TOURISM IN NUMBERS

- According to data from the Teide National Park, there are some 200,000 visitors/year for stargazing
- Parc Astronòmic del Montsec (PAM) generates an annual income in 2018, of €2.5 million in the territory.
- La Palma …more than 70 business or registered projects, 29 millions €/year (from TIDES, Cabildo de La Palma).
- -AIRBNB DATA: in "some of the main places identified by the Starlight Foundation, in which it is possible to observe the stars, which are becoming trend destinations, the year-on-year growth in arrivals of travelers are": La Palma (Spain), with 90%; Kiruna (Sweden) 134%; Alqueva (Portugal) with 64%; Pic du Midi (France) with 99%; Antofagasta (Chile) with 327% or Acadian Skies & Mik'Maq Lands (Nova Scotia, Canada) with 221%.

Mitchell and Gallaway (2019) recently evaluated the economic impact potential of astro-tourism on the Colorado Plateau in the western United States, finding that non-local tourists who value dark skies will spend in excess of USD 5.8 billion in the next decade, generating USD 2.4 billion in higher wages and creating over 10,000 additional jobs each year in the region.

3.9. LAMP TECHNOLOGIES AND THEIR CONTRIBUTION TO LIGHT POLLUTION

3.9.1 CONVENTIONAL LIGHT SOURCES

Even public outdoor lighting has its origin back in the 15th century, it was only near the 19th century where artificial light sources were widely industrialized. The two major groups of lamp types were based on filament or on arc discharge technologies respectively. A comprehensive analysis on the evolution of light sources can be found in Appendix 2. The most common traditional light sources that can be found either today, are High and Low Pressure Sodium, Metal Halide, Mercury Vapor and Tungsten Incandescent.

The key motivation of developing new light sources was to increase their efficacy while reducing associated manufacturing costs. The evolution of lamp efficiency from few lm/W to more than 100 lm/W in recent years demonstrates the technology advances in the lighting industry. Each lamp technology is associated with specific material and gas types. This association affects one of the most important properties of each type of light source which is the spectral power distribution (SPD). SPD describes the relative emissions of light of different colours (throughout the visible range of spectrum) by a given light source and it has an important bearing on light pollution and night sky brightness.

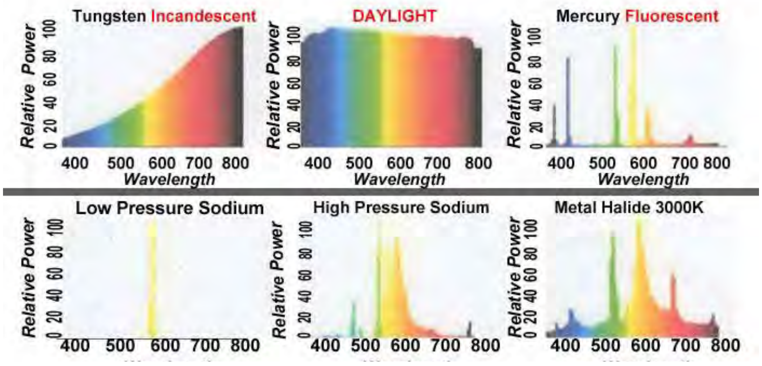

Figure 3.5: Spectral power distributions of some common types of lamp (from Lamptech, 2020, courtesy James Hooker)

Early lighting technologies such as incandescent filament lamps emit a continuous spectrum that includes all colours of light, but are especially strong in red and near-infrared wavelengths. On the other hand, the SPD of carbon arcs has a strong blue-violet peak at a wavelength of about 389 nm and only weak emission in the red. Given that blue light is the main contributor to night-sky brightness, incandescent street-lights would certainly be better for astronomy than carbon arc lamps, although this issue was hardly ever debated in the early 20th century.

To demonstrate the noticeable difference between the conventional light sources used for street and outdoor lighting, their spectral power distributions are shown in Fig. 5 (taken from Lamptech (2020)). They are compared with the continuous spectrum of sunlight. Many of these lamp types are currently phased out in certain countries but can already be found in existing lighting installations all around the world.

3.9.2 The rise of the light-emitting diode (LED) as a light source

The new technology that revolutionized the lighting industry was the Light Emitting Diode (LED). LED is a solid-state, semiconductor chip that emits light under a low voltage (typically about 10 volts). The first LED was developed by Nick Holonyak at General Electric in Michigan in 1962. It was based on gallium arsenide phosphide. The first LEDs emitted red or infrared radiation. Modern LED technology can produce lights of any wavelength from ultraviolet to infrared. In particular blue LEDs using gallium nitride were developed from 1993. In general, LEDs are lightweight, long-lived and highly energy efficient, which are significant advantages for many applications.

Traditional luminaire manufactures adopted LED technology by introducing new products or updating their existing lineup. As a result of their low cost of materials and the fast development process, a lot of new manufacturers appeared in the market, especially from the Asian region. Market penetration by LEDs was so rapid that regulations and standardisation of the technical specifications could not always keep up with the technical developments.

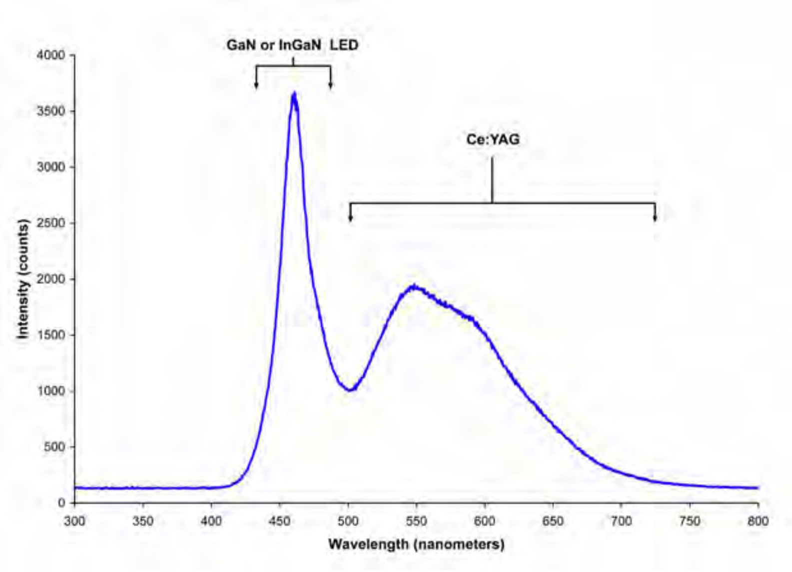

Figure 3.6: Spectral energy distribution of a typical high-correlated colour temperature (CCT) white LED with a strong peak in the blue at wavelength about 465 nm. Wavelength ranges above the SPD indicate the colors for which the LED semiconductor material (GaN and InGaN) or phosphor coating (Ce:YAG) are responsible. (Courtesy of Deglr6328; This image is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license. Original source on Wikipedia https://en.wikipedia.org/wiki/Light-emitting_diode)

Today, large cities all over the world are changing over from legacy lighting technologies such as HPS and LPS to LEDs. For example, Anchorage, Alaska, had installed 4000 LED luminaires by 2008; Los Angeles, California, 140,000 by 2009; and Seattle, Washington, 40,000 by 2010. The low power consumption and maintenance needs represent a huge cost saving for many municipalities. LED technology offers the possibility of easy and efficient control (local or remote), enabling possibilities such as dimming in the early morning hours after midnight. It is also noted that LEDs can give greater uniformity of illumination than older light sources, with the result that fewer lumens may be needed to meet the required lighting technical criteria, such as those for road safety.

The SPD of the first LEDs used for street-lights shows a strong peak at wavelengths between 450 nm and 470 nm in the blue, corresponding to the gallium nitride-based LED to which is added the broad continuous spectrum at longer wavelengths (500 nm - 700 nm) of the Ce:YAG phosphor. The colour temperature of these first white LEDs was often at or above 5000 K, which is usually deemed to be an unattractive harsh white with a high percentage of blue emission. A white LED at 5000 K colour temperature emits about 35 % to 40 % of its energy in the blue region, as represented by the area under the blue peak in Fig. 6.

It is the blue emission which scatters in the atmosphere far more efficiently than longer wavelengths, thereby contributing to excessive skyglow. The blue peak of LED street luminaires has therefore a major influence on the current environmental concerns of light pollution. A useful resource on lamp types, including LED lights giving technical data for each, is to be found in the Lamps Spectral Power Distribution database (LSPDD, 2020). The database gives for each commercially available lamp the percentage of blue light emitted, the colour temperature, the spectral energy distribution , the light output (in lumens) and indices for melatonin suppression, for induced photosynthesis and a starlight index, which measures the amount of light pollution contributing to skyglow for a scotopic dark-adapted eye.

3.10. LOCAL, REGIONAL AND NATIONAL REGULATIONS

To date, a number of countries including Spain, France, Czech Republic, Slovenia, Croatia, Italy and Chile have enacted regional or national legislation for the control of outdoor lighting in order to reduce light pollution (Barentine 2021). Others have attempted some form of rulemaking through executive action. For instance, the environmental impact assessment process in many countries requires applicants for development permits to show that adequate steps to mitigate light pollution impacts have been taken even if no particular statute requires it.

There is little empirical evidence showing that particular policies are more or less effective at reducing or preventing light pollution than others; rather, a sense of emergent lighting policy best practice stems from scientific knowledge about lighting designs and practices that result in varying degrees of night sky impacts, with the goal of codifying into law the elements that seem to be most effective. However, given the global rate of growth of light pollution in recent decades, it is arguable that outdoor lighting policies in many jurisdictions are ineffectual. That is thought to result in part from an overall lack of consistent implementation and enforcement of lighting control laws. With this in mind, policies may be written in ways so as to be more readily enforceable, the ultimate success of this approach relies on broad public support for those policies.

The kinds of policies that are thought to have the greatest potential to make meaningful reduction of light pollution have to do with limiting wasted light, much of which ends up in the night sky. IDA and the Illuminating Engineering Society have identified a series of five principles for responsible outdoor lighting that can be incorporated into legislation and regulations. The principles hold that outdoor lighting should only be used when a clear purpose or need for the light is identified. Once the need for outdoor lighting is firmly established, it should be installed and operated such that its light output is:

5. Directed only where it is needed, illuminating an object or task performance area, avoiding light spill;
6. Used only at times when it is useful, and actively reduced or extinguished during times when users of lighting are not present;
7. No brighter than necessary to perform the intended task, and deployed in such a way as to reduce glare; and
8. Designed to release the least fraction of short-wavelength emissions possible in order to minimise specific impacts to the night sky and biological systems.[4]

These principles are summarised below in Figure 3.7. Their proper implementation results in lighting that is functional and safe, decreases the incidence of glare, preventing conditions of intrusive 'light trespass', and minimises the amount of artificial light released into the nocturnal environment. Regulations following from the principles can be made increasingly prescriptive by adding lighting technical details as needed.

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[4] For general purposes, 'short-wavelength' light is any electromagnetic radiation between 350 and 500 nanometres in wavelength.

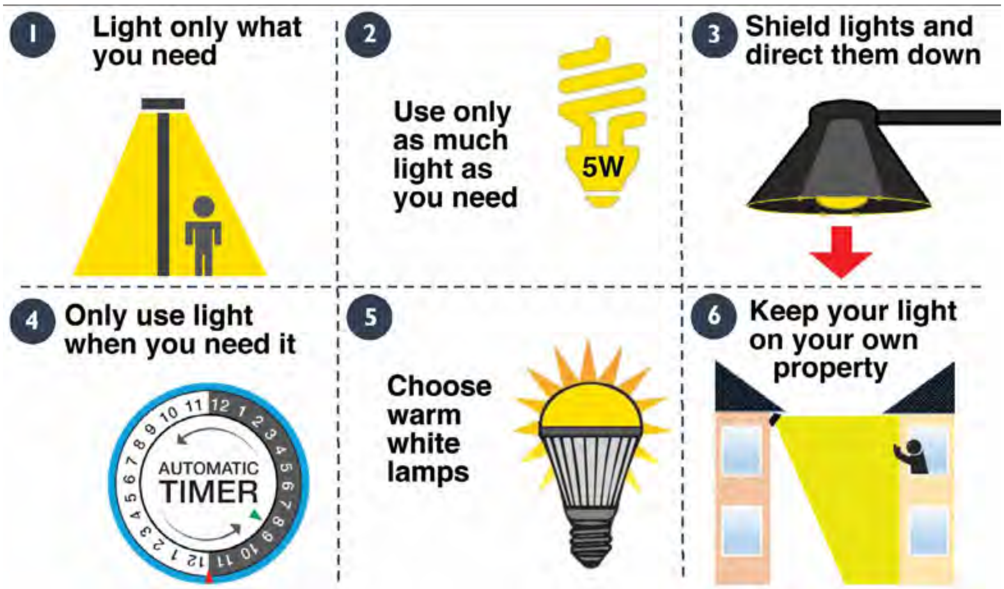

Figure 3.7: Graphical representation of the IDA-IES Principles for Responsible Outdoor Lighting. Graphic by IDA, used with permission.

3.11. RECOMMENDATIONS TO COPUOS

We note that protected area and conservation managers in general have no direct sway over light pollution and the resulting skyglow, because their influence is so often limited, and hence we cannot rely on them to solve the ALAN skyglow problem. Instead we believe that a solution must come from much higher up, and hence our recommendations are being delivered to the member states of the UN through the Committee on the Peaceful Uses of Outer Space, COPUOS.

We recommend to COPUOS the levels of sky brightness considered to be appropriate for different dark sky place classes, as defined by the IUCN Dark Skies Advisory Group (DSAG) – see §4.1 and Appendix 1. The International Astronomical Union and the International Commission on Illumination (Cayrel et al. 1980) recommend that for astronomical observatories it should be no more than 10 % additional brightness beyond the natural background airglow at a zenith angle of 45°, airglow being typically 174 to 250 µcd m^{-2} (Falchi et al 2016). We have adopted 240 µcd m^{-2} here as a nominal value. Rounding this value and extending it to the DSAG classes of dark sky places, we recommend the following values as a basis for seeking support for abatement of light pollution. Recommended limiting values in µcd m^{-2} are also quoted in visual magnitudes per square arc second. These recommended values are consistent with those also recommended by IUCN (Welch, 2021).

- Dark Sky Astronomy Site, DSAG class 1: <260 µcd m^{-2}; >21.7 mag arcsec^{-2}. 10 % more than airglow
- Dark Sky Park, DSAG class 2: no more than 50 % more than the natural airglow, or <360 µcd m^{-2} (>21.4 mag arcsec^{-2})
- Dark Sky Heritage Site, DSAG class 3: No more than 2.75 times the natural airglow, or <660 µcd m^{-2} (>20.7 mag arcsec^{-2}).
- Dark Sky Outreach Site, DSAG class 4: given that astro-tourism and amateur astronomy often happen at these places, the recommended limit is 2.0 times the airglow, or <480 µcd m^{-2}

(>21.0 mag arcsec^{-2}).

- Dark Sky Reserves, DSAG class 5: similar to outreach sites, <480 μcd m^{-2} (>21.0 mag arcsec^{-2}).
- Dark Sky Community, urban, DSAG class 6a: The recommended limit is 4 times the airglow for protected sites in more urban areas, giving sky brightness <1000 μcd m^{-2} (>20.3 mag arcsec^{-2}).
- Dark Sky Community, rural, DSAG class 6b: The recommended limit is 3 times the airglow for protected sites in more rural areas, giving sky brightness <750 μcd m^{-2} (>20.6 mag arcsec^{-2}).

It is recognised that these recommendations may not be realizable in all protected areas and that each area will have its own challenges and circumstances. Values of sky brightness may be more or less than these recommendations in individual locations.

In addition, we make the following practical recommendations for exterior lighting in protected dark sky oases:

1. In all protected dark sky oases the default condition should be no artificial light. Specific uses justifying light should then be additive once other non-lighting interventions are exhausted.
2. In ecological reserves and similarly sensitive sites with little or no human presence at night, generally speaking, artificial light should not be used. If it is used, it should be a narrowband amber LED or equivalent emitting no light at $\lambda < 500$ nm. Lighting should be strictly controlled and switched on only when it is needed.
3. If phosphor-converted amber LED lights are used, the amount of blue light ($\lambda < 500$ nm) should be below 5 per cent of the total spectral power. Generally this requires using LED luminaires with a correlated colour temperature of 2200 K or less.
4. All exterior lights should only distribute light below the horizontal, and the upward light output ratio (ULOR) should be no more than 0.5 per cent. This requires luminaires to be mounted horizontally and have flat optics below the light source.
5. LED lights should have a central management system (CMS) to reduce or extinguish light output in off-peak hours.
6. No development in or near highly ecologically sensitive sites should be permitted.
7. Monitoring of nighttime conditions in/near dark sky oases is encouraged through a combination of ground-based and remote sensing methods.
8. Active management of natural nighttime darkness as a natural resource is encouraged through recognised conservation best practices.
9. Restoration plans should be implemented when sky brightness thresholds are routinely exceeded.

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Patrick McCarthy
Director of NSF National Optical-infrared Astronomy Research Laboratory, USA

> *The night sky belongs to all of us; as scientists and leaders of international laboratories, we have a responsibility for its protection.*

Patrick McCarthy
Excerpt from the welcome speech to the workshop participants

4. OPTICAL ASTRONOMY REPORT

4.1 INTRODUCTION

4.1.1 THE SCIENTIFIC AND STRATEGIC VALUE OF GROUND-BASED OPTICAL OBSERVATORIES

In most sciences, discoveries are made as a result of interacting directly with the things being studied, be they molecules or mountains. In astronomy, the objects being studied are too distant for direct experimental interaction, and astronomers instead make their discoveries about the Universe by observing the behaviour of stars and galaxies from afar. In this section, we focus on major professional ground-based observatories with optical/infrared telescopes, typically with primary mirrors with large collecting areas. There are 40 telescopes in the world with mirrors of diameter 3 metres or larger, sited in the U.S., Chile, Spain, South Africa, Russia, China, Australia, and India, constituting a world-wide investment.

Ground-based astronomical observations continue to be the drivers of major, high-impact discoveries in astrophysics and basic physics. They are often essential to interpret observations from space-based telescopes. And they provide the critical data for planetary defence and key aspects of space situational awareness.

The fundamental constituents of the Universe, dark matter and dark energy, are being delineated by current and planned ground-based surveys. As a paramount example, the Vera Rubin Observatory, an 8.4-meter telescope with a 3-Gigapixel camera now under construction in Chile has as one of its primary goals to perform precision cosmological measurements. The distribution and total amount of dark matter will be measured from the gravitational distortion of the shapes of billions of ultra-faint galaxies. The impact of dark energy on the rate of expansion of the Universe will be determined by the detection of faint and distant supernovae. Any skyglow in the night sky from artificial sources severely compromises the quality of these measurements.

The past four years have seen the revolution that celestial information can be detected by carriers other than electromagnetic radiation (light, radio, or X-rays). Extraordinarily sensitive laser interferometers can detect the distortion of space by the passage of gravitational waves to an accuracy of a fraction of the diameter of a proton. Identifying the source of these waves requires the coordinated deployment of multiple ground-based telescopes, supporting high-energy detections from specialised orbiting telescopes. Gamma rays and an optical flash were found to originate from the merger of two highly dense neutron stars in a relatively nearby galaxy. Many telescopes were needed to search the large area from which the gravitational wave detection arose, and large telescopes were needed for follow-up, as the source faded rapidly over hours and disappeared in a matter of days. It is expected that such objects will often be observed close to the horizon, where the effects of artificial glare are particularly apparent.

Another critical activity of ground-based observatories is planetary defence, the detection and mitigation of the impact of potentially hazardous asteroids. The search for Near-Earth Objects (NEOs) is driven to progressively fainter limits by the need for ample warning of the hazard of these objects, particularly those of 100m diameter and below, a population not currently well characterized. Orbits for these faint objects must often be determined from observations at low elevations, for which the impact of artificial skyglow is most significant. A similar programmatic requirement applies to the monitoring of space debris, where even the smallest detectable particles can damage valuable space assets. The additional noise added by artificial skyglow reduces the detection efficiency

Astronomical research and planetary defence are thus critically dependent on having a clear view of the heavens, but there is currently great concern amongst astronomers about the increasing impact of human activities, particularly light pollution, on observations made with ground-based optical telescopes.

4.1.2 IMPACT OF ARTIFICIAL SKYGLOW AND GOALS FOR ASTRONOMICAL SITE PROTECTION

The expansion of human activity to even the most remote places, the growth in world population and economic development level, and the reduction of the cost to provide outdoor lighting have led to exponentially increasing levels of artificial skyglow on average worldwide. This extra light in the sky veils faint celestial sources that provide key scientific information about the origins of the Universe and the origins of life. Protection of access to the dark night sky requires control of the growth of obtrusive lights in the regions hosting major astronomical research telescopes.

Telescopes are typically built at sites with predominantly good weather, low atmospheric blur and dark skies. Artificial skyglow can severely compromise the darkest skies. The exposure time needed to reach a given signal-to-noise when observing a faint object is typically proportional to the intensity of the sky background. If light pollution increases the total airglow of the night sky, the extra exposure time needed will reduce significantly the total amount of time available for observing. Less science can then be done with the (expensive) telescope time available and the faintest objects cannot be observed at all in a reasonable exposure time. A more detailed technical description is found in Appendix 4.

During the past decades, the level of sky brightness increased significantly worldwide (Falchi et al. 2016). In the past decade, the globally averaged rate of increase was 2% per year in terms of both lit area and total radiance, (Kyba et al. 2017) roughly double the rate of world population growth during the same period. This increase is mainly related to three factors: the increase of the global population, economic growth, and the reduction of illumination costs (Tsao et al. 2010).

More recently, a new factor impacting the natural night sky integrity has emerged: the introduction of energy efficient, white light-emitting diode (LED) technology on large scales. That lighting technology may represent a threat to astronomical observations because of the higher blue content of white LED lighting, which scatters more efficiently in the atmosphere, compared to earlier lighting technologies (Aubé, Roby & Kocifaj 2013; Luginbuhl, Boley & Davis 2014). In addition, there is evidence that the high energy efficiency and relatively low cost of operation of white LEDs is fueling elastic demand for the consumption of light (Kyba et al. 2017), leading to higher overall light emissions. On the other hand, significant benefits are derived from the use of modern high quality LED lighting. LED flux can be easily controlled as a function of the time in accordance with the targeted usage. LED luminaires are also generally better focused on the surfaces that require lighting, with less light spill and in most cases with no upward light emissions.

A major increase in ALAN represents a serious problem for world-class ground-based astronomical observatories operating in the optical region of the spectrum (Luginbuhl, Walker & Wainscoat 2009; Aubé 2015). The International Astronomical Union (IAU) has defined the upper limit of artificial light contribution for a professional site adequate for true dark-sky observing to be <10% at an elevation of 45° in any azimuthal direction. The newest professional observatories have been located at sites that are significantly below this limit of artificial light contamination.

The goal of the model regulatory framework proposed in this document is to slow, stop, and reverse the rate of increasing artificial skyglow at major professional observatories in no more than a decade and on shorter timescales wherever possible.

The goal of the recommended framework covers most of the IAU requirement for site protection, but additional considerations are also needed to reduce the intensity of artificial skyglow as human activity wanes with time during the night, and thus the control of the colour of the artificial light sources. The Working Group recognises that the dominant *sources* of skyglow in cities may change through the night as sports and commercial lighting reduce, along with vehicle traffic. (Bará et al. 2018) The changing spectra of integrated urban light domes are likely to have different impacts on observing programmes involving imaging and spectroscopy.

4.1.3 BASIS OF PROPOSED MODEL REGULATORY FRAMEWORK

Each observatory site has its own circumstances, so achieving the goal will require a regional lighting plan with a specific approach, based on detailed modeling. Protection of the site may entail zoning that restricts development and ultimate tightening of regulations with time to reduce light pollution. The Optical Astronomy Working Group strongly advocates an approach of quality lighting design to match the illumination level to need, limiting unnecessary spectral content, and taking more advantage of precise optical control to reduce spill light. A key aspect of site protection is defining close-in zones with more stringent limits on outdoor lighting levels. The regulatory framework proposed for COPUOS endorsement provides a model for those national, regional and local governments committed to protecting the dark skies of professional observatories within their regions.

Major observatories are now typically funded and operated by international consortia, but they are situated in individual countries whose own laws apply to light pollution control. Some, such as the Observatorio del Roque de los Muchachos (ORM) in La Palma, have been protected by a pioneering law, Ley del Cielo, proposed by the Regional Parliament of the Canary Islands and regulated by law (Law 31/1988, R.D. 243/1992) by the Spanish Government. The government of Chile actively supports such laws in support of the astronomy enterprise (see the Chilean “Norma de Emisión para la Regulación de la Contaminación Lumínica” (1998/2012). International consortia, such as the European Southern Observatory, the Thirty-Meter Telescope International Observatory, the Giant Magellan Telescope Observatory and the South African Large Telescope Observatory, expect that the host countries and regions will commit to keeping the prime natural resource of a dark sky available to the project during its operational lifetime.

A finding at the UN-level that protection of the dark skies at major observatories is necessary to support the mission of the Commission on the Peaceful Uses of Outer Space (COPUOS) will provide a strong impetus for national and local governments to provide such protection. The provision of a model regulatory framework that can be adapted to particular local conditions is the path to implementation.

4.2 DARK OBSERVATORY SITES ON REMOTE MOUNTAIN TOPS

An overview of the development of observatories in the nineteenth and twentieth centuries to take advantage of dark sky conditions is found in Appendix 4. When many of the sites were established over forty years ago, the nearest urban concentrations were small to moderate-size towns with minimal impact on zenith sky brightness and only very modest impact near the horizon. Subsequent population growth and resource development has created measurable artificial light contribution at major professional sites such as those in southern Arizona, California, New Mexico, Texas, north-central Chile, the Canary Islands and southern Spain. Most of those observatories with 4-10-meter-diameter telescopes still fall within the IAU definition of dark sites, and many of them require and have strong cooperation from the surrounding population and regulation and enforcement by government entities to maintain that status.

All the world's largest optical telescopes are now at dark, high-altitude sites. Given that the cost of the European Extremely Large Telescope (E-ELT), with first light planned for 2025 on Cerro Armazones in northern Chile (altitude 2817 m), is substantially over one billion euros, comparable to the Thirty Meter Telescope planned for Mauna Kea in Hawaii and the Giant Magellan Telescope for Las Campanas in Chile, it is understandable that only the very best accessible sites on Earth would be considered. Those sites with nearly untouched dark skies and large-aperture research telescopes are in northern and north central Chile (Cerro Armazones, Cerro Paranal, Cerro Las Campanas, Cerro Pachon, La Silla); in Hawaii (Maunakea and Haleakala observatories), South Africa (SALT, HESS), Australia (Siding Spring) and La Palma island (ORM). Other particularly dark sites with small to moderate-aperture research telescopes and potential for development are in central Asia (Mt Maidanak Observatory, Uzbekistan; Mt Gargash, Iranian National Observatory; Hanle Observatory in the Indian Himalayas; Ali Observatory, western Tibet), in Mexico (San Pedro Martir Observatory), Calar Alto Observatory (Almeria-Spain) and in North Africa (Oukaimeden Observatory in Morocco Atlas Mountains).

In addition, arrays of radio antenna-sized light collecting dishes are deployed in remote locations to capture the faint flashes of blue Cherenkov radiation produced when high-energy gamma rays hit the top of the atmosphere. Such arrays are working in Utah and Arizona in the U.S., in Namibia, in ORM (La Palma) and in central Argentina. They require extremely dark sky conditions.

For these remote areas, growing artificial light impacts come from small villages, major open-pit mining enterprises, wind farms, and other uses of sparsely populated regions. Although yet more remote sites exist, such as Antarctica, the implications for costs, sky coverage, and instrumentation flexibility in these sites make them impractical for the largest-scale astronomical observatories. Major ground-based optical telescopes can be built at a substantially larger scale and some two orders of magnitude lower cost per unit collecting area than those launched into orbit.

4.3 THE EFFECT OF ARTIFICIAL SKYGLOW ON ASTRONOMICAL OBSERVATIONS

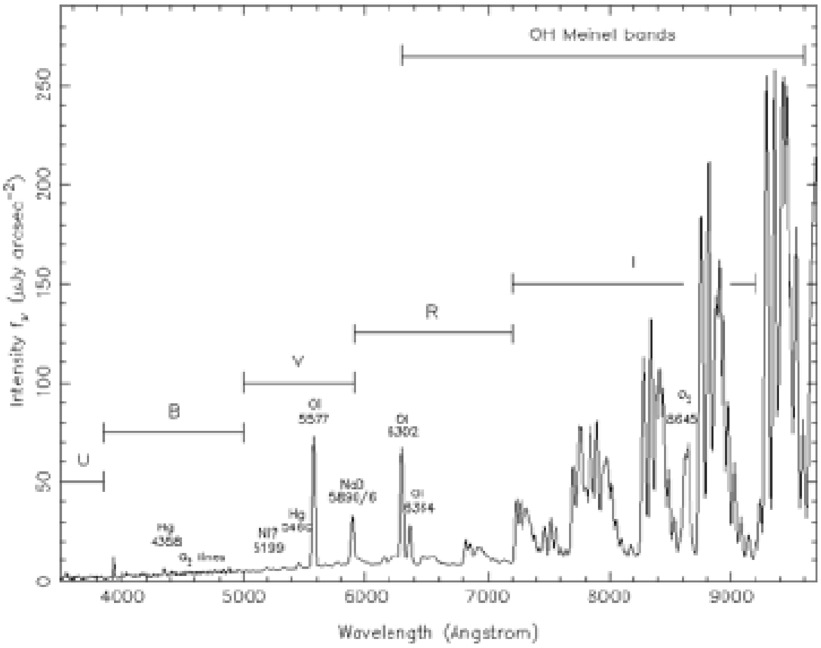
Artificial light at night (ALAN) is a generic term representing the propagation of a variety of sources of artificial light into the outdoor environment. ALAN includes, but is not limited to, road lighting, exterior sports lighting, lighting of outdoor workplaces, area and landscape functional lighting, floodlighting, façade lighting and lighting for monuments and architectural structures. Besides common exterior lighting installations, festive lighting, light from building interiors passing out through windows, light from transportation and other minor sources of light contribute to ALAN as well.

The sum of all the adverse effects of ALAN is colloquially referred to as 'light pollution' and is more accurately known as 'obtrusive light'. Obtrusive light is 'spill light' or 'stray light' emitted by a lighting installation that falls outside the boundaries of the property for which the lighting installation is designed and because of quantitative or directional attributes, gives rise to annoyance, discomfort, distraction, or a reduction in ability to see or record essential information.

Artificial skyglow is the brightening of the night sky that results from ALAN scattered by the constituents of the atmosphere (gas molecules, aerosols and particulate matter) in the direction of observation. It includes radiation that is emitted directly above horizontal and radiation that is reflected upward from the surface of the Earth. Not all photons are scattered; many go on up into space and leave the Earth, as attested by observations from satellites which show major cities pouring light into space. Artificial skyglow adds sky noise to the astronomical measurement of faint objects, essentially veiling them.

Cayrel et al. (1980) noted that the airglow from natural processes in the atmosphere had emission lines, especially those of atomic oxygen at 557.7, 630.0 and 636.4 nm, and those of the atomic sodium D lines at 589.0 and 589.6 nm. The sharp peaks in airglow emission at these wavelengths means that artificial skyglow from lamps that also have emission at or near these same wavelengths can be tolerated. Cayrel et al. recommended that skyglow equal to the airglow intensity would be acceptable at the sodium D lines, and hence (nearly) monochromatic sources in the yellow-orange range of wavelengths are the best near observatories.

Figure 4.1. Night sky spectrum from the William Herschel Telescope on La Palma, Canary Islands in March, 1991. The emission features from Hg and some of the Na are from street lights; the rest of the emission features are natural airglow. (Benn and Ellison 2007)



4.4 INSTRUMENTATION AND TECHNIQUES FOR MEASURING NIGHT-SKY BRIGHTNESS AT ASTRONOMICAL OBSERVATORIES AND TRENDS WITH TIME

4.4.1 SENSING NIGHT SKY BRIGHTNESS

The classical approach to measure and monitor night sky brightness (NSB) is upward from the ground, by direct measurement of the radiance of the night sky. Ground-based measurements are model-independent but typically limited geographically and temporally.

There is also an approach which is becoming more and more used nowadays in which the NSB is assessed by looking down from Earth orbit. The method consists of predicting the night sky radiance seen from the ground by sensing the upward-directed radiance of light escaping the Earth's atmosphere and then applying a model of how light propagates through the atmosphere. (See, e.g., Hänel et al. 2018.)

Direct measurements of NSB from the ground involve sensors that integrate the flux of light

through a known solid angle, within some wavelength range, and over some length of time. These divide into two types: single-channel devices, and multichannel devices. See Appendix 5 for a detailed list of devices and more extensive technical description in a complete version of this abbreviated section.

4.4.1.1 Single-channel devices

Single-channel devices are patterned on photoelectric photometers used by astronomers for almost a century. These devices rely on simple and well-understood physics, require little electric current to operate, and are usually small enough to be easily portable. Their light response is determined in the laboratory, with on-board lookup tables relating measured frequency to light intensity tied to calibrated light sources. Most commercially available devices have their own photometric passbands, which are typically transformed to the Johnson-Cousins *V* filter (547.7nm, FWHM 99.1nm). (Bessell 1990) Researchers have experimented with other filters, but *V* was chosen to match the bulk of existing literature data and the human visual response to light under photopic conditions.

4.4.1.2 Multi-channel devices

Multichannel detectors consist either of arrays of light-sensitive elements whose output is multiplexed through one or more signal amplifiers or panchromatic detectors

behind a filter wheel equipped with filters of various spectral coverage. One commonly encounters cameras capturing two-dimensional images, particularly commercial digital single-lens reflex (DSLR) cameras and mirrorless interchangeable lens cameras (MILC). Some are operated with photometric filters to yield a particular effective passband, while others use Bayer filter mosaics to capture native (pseudo-)true-colour images through the combination of broadband red-, green- and blue-filtered data. Other initiatives using non imaging sensors are also alternatives to DSLR cameras (e.g., the CoSQM project).

One advantage of imaging devices over non-imaging devices is the ability to produce two-dimensional images with some amount of both angular and spectral resolution. They are often paired with very wide-angle lenses to capture views with solid angles as large as 2π steradians (a hemisphere) in a single exposure, while others build up multiple-image mosaics with angular offsets between exposures so that the results can later be “stitched” together in software. As a result, these devices provide significantly more spatial information about the angular distribution of NSB than do non-imaging devices. But the data from imaging devices are more complex to interpret for the non-specialist.

Depending on the pixel scale of the detector, star images may be sufficiently sampled that flux calibration can be performed using spectrophotometric standard stars; other imaging systems make use of lab calibrations from reference light sources and employ integrating spheres for illumination of the camera and lens. Spatial distortion information for particular lens and camera combinations can be used to correct lens aberrations after the fact in software. (Mohar 2015; Kolláth & Dömeny 2017)

4.4.1.3 Standardisation and methodology of Measurements

For matters requiring a decision process and the influence of stray optical radiation on astronomical observations, it is worthwhile to establish protocols compatible with standard definitions, traceable to SI units, and communicable to a broad technical community. The magnitude per square arcsecond is most often used in astronomical measurement. Transformations between, e.g., magnitude per square arcsecond and the SI candela per square meter have been derived so that astronomical brightness in, e.g., *V* magnitudes, can be approximately transformed to photometric values. Noting that the relationship between these quantities depends on the spectral power distribution of the source, Bará et al. (2020) derived the transformation equation and calibrated it using zero-point luminances determined from a variety of skyglow spectra. At the best observatory sites around the world, the darkest moonless skies at solar minimum have a natural (mainly airglow) surface brightness in the astronomical V band of V ~ 21.9 mag/arcsec^2 (2.25 × 10^{-4} cd/m^2).

From a decomposition of the night sky spectrum, Z. Kolláth et al. (2020a) determined that the ‘continuous’ component of the natural sky (zodiacal light, scattered starlight and airglow pseudo-continuum) is nearly constant at all visible wavelengths and has a spectral radiance of ▯2 nW m^{-2} sr^{-1} nm^{-1}, or 2 *dsu* (dark sky units). Because of the relatively limited range of broad-band color variations of natural skyglow under clear, moonless conditions, digital camera-based, three-colour (RGB) radiance measurements in dsu give a usable sky brightness measurement (Z. Kolláth et al. 2020b). The hourly and nightly variations in natural skyglow can be of order 10 %. Therefore, an accuracy of 5 % or better of the natural sky glow level for long-term characterization of an astronomical site is sufficient. High-quality cameras can provide ~2 % accuracy, more than adequate for the task.

Field measurements of NSB are affected by several environmental conditions (weather, air pollution, natural aerosol levels, variation in natural sky brightness, etc.). Thus, it is essential to restrict measurements to nights when conditions are optimal for fieldwork. The necessary conditions to perform a field survey are the following:

- Moon at least ten degrees below the horizon.
- No clouds, fog, high aerosol content, or auroral activity.
- The Sun is at least 18 degrees below the horizon (astronomical twilight).
- Consistent set of spectral bandpasses and altitude-azimuth range.
- No direct light from artificial sources reaching the detector or the camera.
- High Galactic latitude and high ecliptic latitude (if pointed as opposed to all-sky).

These recommendations must be satisfied for long-term surveys to avoid misleading results for trends with time and comparison with other sites.

4.4.1.4 Data modeling

Modeling of observations can assist with their analysis and interpretation. For example, Duriscoe (2013) reported successfully recovering the anthropogenic component of NSB from mosaicked all-sky image data by subtracting 2-D models of natural sources of light. Masana et al. (2020) describe a multi-color model of celestial sources. To the extent that construction and application of such models can be automated, they hold the promise of rapidly disentangling natural sources of light in the night sky from artificial sources for the purposes of modeling the angular and temporal evolution of skyglow. For spectrally resolved measurements, it is possible to model the natural components of NSB in wavelength space to subtract and remove them, leaving only the spectrum of artificial light.

4.4.1.5 Orbital Remote sensing of night sky brightness

The use of orbital remote sensing platforms (namely, Earth-orbiting satellites) to infer NSB from direct measurements of upward radiance offers a number of attractive qualities. Chief among these is the ability to collect information about NSB from essentially anywhere on Earth, which decouples NSB measurement and monitoring from the deployment of ground-based sensors. Falchi et al. (2016) provided such a global data product. They established the radiance-NSB relationship using many thousands of ground-based NSB measurements. Sánchez de Miguel et al. (2020) recently found a strong correlation between the zenith NSB measured on the ground and orbital radiance measurements at both low and high resolution. They suggested that “it should be possible to create maps of regional sky brightness, or even global sky brightness maps” based on radiance measurements from the newest generation of orbital radiometers. However and as in other remote sensing approaches for studying the atmosphere special care has to be taken when comparing numbers at different sites.

Moreover, there are still some problems with existing satellite remote sensing data. For example, the only instrument that currently achieves nightly global coverage, the Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS-DNB; Cao et al. 2014), has no spectral sensitivity shortward of 500 nm. It is then blind to the strong peak in white LED light emissions near 450 nm. This limits what can be reliably inferred concerning short-wavelength light sources within the data set. (Bará, Lima and Zamorano 2019) Other problems with measurements of current facilities include angular resolution, view/screening dependency and effects of varying aerosol concentrations.

4.4.2 MONITORING NIGHT SKY BRIGHTNESS

In the present context, “monitoring” of NSB refers to its repeated measurement to look for trends on timescales ranging from minutes to years. Monitoring entails the concerns of data handling, transmission and storage, as well as reduction and analysis.

4.4.3 RECOMMENDATIONS FOR PROFESSIONAL OBSERVATORIES

It is up to the scientific community to monitor and validate the trends in night sky brightness at professional observatories. This task requires a commitment of resources, potentially in equipment and certainly from the technical workforce. Metrics from full-sky pixel histograms can be very effectively interpreted (e.g., Duriscoe 2016), but require relatively high resolution all-sky cameras. Most observatories operate lower resolution all-sky cameras for weather and extinction monitoring; calibration and interpretation of those data streams is possible with effort. Scientific data archives can be mined after the fact for calibrated sky measurements, again requiring effort. Multispectral radiometers, like the CoSQM, can also be used for observatory sky brightness monitoring.

Each professional observatory with programmes requiring limiting dark-sky data for which regulation of artificial skyglow is critical should obtain a current baseline and well-sampled time series of night sky brightness measurements. That information is critical for objective assessment of the efficacy of regulation and for demonstrating to policy makers and implementers that the astronomers value and need their efforts.

One world standard is preferred, using the SI-traceable system calibration in dsu proposed above, and a self-consistent data set is essential for each site. A standardised approach for the conditions of data collection is recommended, under the uniform protocols of 4.5.1.3. Use of all-sky monitor data may be made most relevant to astronomy by selection of all the pixels above a minimum elevation like 20 degrees.

International astronomical organisations are advised to form and support a data repository with consistent formatting to aggregate and make publicly available the sky monitoring data collected.

4.5 LIMITING THE GROWTH OF URBAN LIGHT DOMES IMPACTING PROFESSIONAL OBSERVATORIES

4.5.1 GENERAL CONSIDERATIONS

Control of urban light domes can be critical to professional observatory operations; for example, island mountain-top sites can be impacted by coastal towns, which are not always shielded by a marine layer. Many older continental sites have seen substantial growth of nearby urban areas since their founding. Adherence to the strictest prescribed minimum required levels by locality and other best practices will greatly reduce urban skyglows that contributes ALAN above 30° from a professional observatory's horizon. That elevation is the practical limit for most limiting observations. Depending on the population, industrial mix, and commitment to quality lighting, the relevant distance can extend even beyond 300 km. Similar impact is seen from growing urban light domes on natural areas (Koen et al. 2018; Garrett, Donald & Gaston 2019).

This section summarises the fundamental outdoor lighting recommendations for the limitation of skyglow and obtrusive light, many as published by the International Commission on Illumination (CIE), the highest scientific authority in the field of light and lighting and a recognised standards body. It contains additional sections relevant specifically to astronomy (4.6.6 and 4.6.7). Adaptive lighting technology, allowing lighting levels to be set based on activity level is the path to control of nighttime lighting and reduction in energy costs. For all specific recommendations for protection of observatory sites, if current applicable regulations or regionally referenced professional lighting authorities place tighter limits, the latter take precedence in all cases. Reference to specific CIE documentation and standards is intended to promote regulations based on the most current version of such documents. The prospect of major reductions in illumination is predicated on the ability to exercise adaptive lighting control, particularly with motion-activated sensors for nighttime traffic and activity.

Figure 4.2. Light domes from Tucson (120 km - 1 million population) and Phoenix (220 km - 4 million population), Arizona, as photographed by M. Pedani in 2008 from the summit of Mt. Graham, site of the world's largest optical telescope.

An overview of the summaries of selected CIE Technical Reports and International Standards can be found in Appendix 6, completed by the Terms of Reference of the newest work items carried out in CIE.

4.5.2 ROAD LIGHTING RECOMMENDATIONS

Road lighting may be the most familiar and visible to the general public. Luminaire manufacturers and lighting designers have paid serious attention for a long time to efficient distribution of the luminous flux and avoiding excess and stray illumination.

CIE Technical Report 115:2010 introduces a classification system according to the type and operational profile of roads for motorized traffic, pedestrians and low-speed traffic areas, conflict areas, and also for some specific situations. Lighting classes for motorized traffic, based on road surface luminance, range from M1 (the highest class) to M6 (the lowest class), recommending average luminance 2.0 cd m^{-2} for M1 to 0.30 cd m^{-2} for M6. Lighting classes M4 and M3 are most commonly associated with major roads with a transport collecting function while M5 and M6 are the most common lighting classes in residential areas. The quality of lighting for each of the lighting classes is defined by two additional parameters.

Recommendation: Follow (and minimize high-side deviation to no more than 20% from) the luminance and illuminance levels for road lighting of the appropriate lighting class according to CIE 115.

An exceptional situation occurs when a particular traffic volume is used as a criterion to provide a lighting system. In those situations – and if no other criterion prevents it – reduction to a lighting level lower than M6 after rush hours may be considered. This is mainly applicable for motorways, which are in general highly predictable and without oncoming traffic, sharp bends or intersections. Systems operating at very low levels cannot be classified as road lighting but as a system of visual guidance. A decision to reduce the lighting level below M6 can be made to satisfy astronomical site protection arguments. In remote areas the lighting can be switched off or decreased to a minimum maintained level. In installations with widely separated luminaires (producing non uniform illumination), care must be taken that the maximum local peak values maintained do not exceed twice the corresponding maximum average level maintained.

Recommendation: Whenever possible, dynamically reduce roadway lighting level under low traffic conditions to the appropriate lower lighting class, and down to M6 or even below if the lighting is not immediately needed by any user.

Lighting classes for pedestrians and low speed traffic areas recommend values of both minimum and average horizontal illuminance. Average horizontal illuminance for the highest lighting class P1 is recommended to be 15 lux (lx), and at the other end, 2.0 lx is recommended for the lowest class P6. Minimum horizontal illuminance requirements can be derived from the average as 1/5 of its value. To provide for uniformity, the actual value of the maintained average illuminance may not exceed 1.5 times the value indicated for the class. A high colour rendering contributes to a better facial recognition.

Recommendation: Follow (and minimize high-side deviation to no more than 20% from) CIE guidance for illumination levels and colour rendition of pedestrian areas and actively adjust by usage class with time of night or by motion sensing.

4.5.3. RECOMMENDATIONS ON LIGHTING OF OUTDOOR WORKPLACES AND AREA LIGHTING

Lighting of outdoor workplaces is covered by the international standard CIE S 015/E:2005. Lighting quality parameters in terms of the maintained illuminance E_m, overall uniformity U_o, Glare Rating G_{RL} and colour rendering index R_a are recommended for typical workplaces, areas, visual tasks, and activities in a wide range of applications. Regarding safety and security, the recommended maintained illuminance ranges from 5 lx for places with very low risks, up to 50 lx for high risks. To provide appropriate visual conditions, however, these values can be considerably higher, in the most visually demanding applications even up to 300 lx. Such values, which are quite normal in interior lighting, are extremely high outdoors where large areas are to be lit; sometimes it is not an easy task to design lighting systems providing such high values, understanding that these can potentially heavily contribute to skyglow. By careful lighting design it is thus very important to focus the lighting onto clearly demarcated target areas consisting of the task area and surrounding area as specified in the standard. Time management is crucially important here too; many industrial sites and other outdoor workplaces are lit all night even with no users present.

Recommendation: Observe (and minimize high-side deviation to no more than 20% from) CIE International Standard S 015/E:2005 for illumination of outdoor workplaces, carefully limiting the illuminated area to avoid spill light.

4.5.4 LIMITING THE OBTRUSIVE LIGHT FROM OUTDOOR LIGHTING INSTALLATIONS

Limitation of the effects of obtrusive light from outdoor lighting installations is guided by the Technical Report CIE 150. This document introduces environmental zones as areas where specific activities take place or are planned and where specific requirements for the restriction of obtrusive light are recommended. These zones are defined in Table A6.1.

It is recommended that the CIE zones E0 and E1 are assigned to all locations within 100 km of a major optical astronomy observatory regardless of the level of urban development. E2 is recommended to designate locations within 30 km of an operating urban optical astronomy observatory and locations between 100 km and 300 km from a major optical astronomy observatory regardless of the level of urban development.

CIE 150 stipulates upward ratios differently for luminaires (ULR) and lighting installations (UFR) consisting of at least from 4 luminaires as shown in Table A6.2, taking into account environmental zoning of an area. It also stipulates that light emitted just above the horizon in a zone between 90° and 110° is extra-critical for sky glow in large areas around observatories.

Upward Light Ratio (ULR) of a luminaire is the proportion of the flux of a luminaire or installation that is emitted, at and above the horizontal, when the luminaire(s) is (are) mounted in its (their) installed position. This is the traditional method to limit skyglow and suitable to compare different single luminaires. ULR however does not take account of the light from the luminaires reflected upwards from the illuminated surfaces.

Upward Flux Ratio (UFR) takes into account both direct and reflected upward components so it is suitable for comparison of whole lighting installations (four or more luminaires) and to assess the lighting design concerning luminaire distribution, geometries of the installation, surfaces reflectance and the area to be lit.

Table A6.2 gives the limits on ULR and UFR by CIE lighting zone. Careful attention needs to be given to the limitation of spill light, including consideration of the type of lighting system to be used, the type of light distribution, their specific location and aiming and the need for fitting of louvres, baffles or shields. The limiting values are based on the use of conventional lighting technology, but with good practice being employed through the selection of appropriate lighting levels, appropriate lighting equipment and aiming practices.

Recommendation: Adhere to the zone-appropriate limits by CIE environmental zone for lighting levels, but minimum UFR and null ULR, with application of curfew-time reductions in lighting levels.

Limitation should be applied also to the effects of over-lit building facades and signs in urban areas outside observatory near zones. In urban lighting it is important to audit and determine appropriately the luminance values that provide visibility. Lighting levels are often increased and can cause negative impacts, such as ratcheting (continuous increase in the lighting levels), glare, rise of energy usage, light pollution and increase in utilisation of lighting. Therefore, some restrictions to the lighting must be made accordingly, ideally following a lighting masterplan (CIE 234).

Recommendation: Local authorities and all legal parties that are involved in planning, implementation and maintenance of lighting installations are encouraged to develop and follow a lighting master plan, especially for urban and suburban areas.

In floodlighting in urban areas outside of the near zones, appropriate lighting techniques might help to significantly reduce light pollution. Wherever possible, light from luminaires should be directed downwards and uplighting should be avoided. If no support for luminaires is available at a higher point than the object of illumination, for example a monument up on a hill, the light beams from luminaires must be narrow enough so that no light is missing the object. If necessary, shields and baffles can be used to fine-restrict the angular beam range. The achieved luminance levels should be aligned with the surroundings to avoid annoyance, glare and significant reflected light. Rigorous adherence to curfew times must take place in this case, too.

CIE 150 recommends maximum permitted values of average surface luminance on building facade L_b and luminance of signage L_s for each of the environmental zones. The Working Group notes that there are other standards for maximum sign luminances that are much more stringent. IES/IDA standards (in the zones corresponding to the CIE zones) call for 0.0 in E0, 20 cd m^{-2} for E1, 40 cd m^{-2} for E2, 80 cd m^{-2} for E3 and 160 cd m^{-2} for E4. (IDA 2019, IES 2019) The recommendation also reduces the lighting allowed that is not directly linked to safety considerations.

Recommendation: For Zones E2 and E3 impacting observatories, do not exceed ANSI/IES recommendations for maximum luminances for illuminated signs. Take all recommended measures to reduce sky glow from internally illuminated signs and electronic message displays. For E3 Zones, do not exceed the CIE maximum standard permitted luminance levels for building façades; in E0, E1, and E2 Zones in the extended area impacting observatories, façade lighting is not permitted.

4.5.5 ADAPTIVE LIGHTING AS A POWERFUL TOOL TO REDUCE LIGHT POLLUTION

The role of adaptive lighting (sometimes called ‘smart lighting’) is to adapt in a holistic way the whole set of lighting parameters to the needs of users depending on current conditions such as availability and quality of daylight, occupancy pattern, user preferences, etc.,changing both temporally and spatially. Adaptive lighting is capable of exploiting dynamic variation of changes and bringing it to a higher level of utilisation.

Adaptive road lighting incorporating a system of sensing devices and smart controllers is promising for considerable reduction of unnecessary illumination, energy consumption and obtrusive light. The lighting level can be adapted to the actual needs of the users with respect to the nature of their visual tasks and the current conditions in traffic, weather, environment, ambient light of the surroundings, etc. Where the pattern of variation in parameter values is well known (e.g., from records of traffic counts on traffic routes) or where it can be reasonably assumed (e.g., in residential areas) a simple time-based (pre-defined) lighting control scheme may be appropriate. In other situations, an interactive control system linked to real-time data may be preferred. This approach will permit the normal lighting class to be activated in the case of road works, serious accidents, bad weather or poor visibility, while it can also compensate for the excess of luminous flux due to the maintenance factor of the lighting installation. The Technical Committee CIE TC4-62 “Adaptive Road Lighting” started in 2020 to prepare relevant guidelines and recommendations.

When there is no user of lighting present, an additional lowest light level can be defined. Both major roads illuminated to higher levels and streets in large residential areas can be dimmed down to a maintained minimum level necessary to safeguard basic visual functions for safety reasons. The lowest lighting class for pedestrians P6 with 2.0 lx minimum illuminance can be appropriate for this purpose. In such cases, the provided lighting, however, cannot be deemed as road lighting as explained in section 4.6.2 above. Adoption of the minimum maintained level approach can lead to huge potential savings. For a case study with standard assumptions, it has been shown that energy saving potential of more than 60% can be achieved for residential areas with M5 and M6 roads only by implementing multi-level lighting control (Gasparovsky et al. 2018). Current lighting technology permits LED luminaires to dim down to 5% of the peak luminous output. In this case, authorities can regulate lighting installations in a way to serve from, e.g., M2 class down to M6 class and even lower when no users are present.

When astronomical observatories are being impacted even in E2 and E3 zones, full switch-off of some lighting installations has to be be considered if the safety level remains unaffected and/or other measures will compensate for loss of lighting (e.g., temporal reduction of speed limit by means of interoperating smart traffic systems), and if lighting is switched on again once sensors detect oncoming vehicles or persons. This special case can be also combined with non-lighting measures such as retro-reflective signage, special road lane painting and so on, ensuring the maintenance of road safety levels.

Adaptive lighting is just beginning to permeate lighting applications, and time is required for adaptive lighting to be applied habitually. There is strong evidence that a combination of appropriate lighting class selection, use of the right luminous distribution and the implementation of adaptive lighting control can significantly decrease the level of obtrusive light beginning from the existing over-illuminated areas and coming to new installations that are required to be designed.

Recommendation: Employ adaptive lighting technology in new installations and major renovations to minimise illumination when there is minimal demand.

4.5.6 FULLY SHIELDED LUMINAIRES

Fully shielded luminaires are important in an urban setting to control the stray light most damaging to nearby observatories emitted above horizontal. Urban nighttime activity, however, draws many exceptions to the general restriction. LED advertising message boards send 15-30% of their luminous output above horizontal. Neon and internally illuminated signs have little directional control. Older “decorative” lighting of tall structures like skyscrapers and bridges can be aimed upward. Low-quality sports lighting often has an upward component, particularly if there is inadequate mast height.

Two mitigations are possible in the case of these de facto exceptions. The immediate one is the imposition of curfews. Sports lighting should be employed only when the field is engaged. This approach may require a change in community attitudes for tighter control of the times of lighting athletic fields in public parks, for example, hence community support. Lighted advertising and decorative structure lighting should be switched off at curfew time, typically midnight. On-site signage should be turned off no later than one hour after close of business if that is later than the curfew.

In the longer term, any replacements of lighting installations should be made consistent with full shielding. Externally illuminated billboards should have fully shielded luminaires, top-mounted. Modern sports lighting, with proper beam formation and full shielding can be implemented to avoid trespass into surrounding areas as well as into the night sky. Sufficient mast height in sports stadia is required to avoid upward tilt; bearing the increase in marginal cost is a consequence of commitment to limiting artificial glare.

Consumer demand and regulatory pressure can combine to reduce the luminance of digital message boards and other lighted signs. Current technology puts limits on the dynamic range of brightness of LED message boards, such that clear visibility during the day at >5000 cd/m² cannot then accommodate appropriate low lighting levels at night. Incentives for running digital message boards at dark sky acceptable 100 cd m^{-2} instead of the currently claimed technological limit of >300 could include a later beginning of curfew.

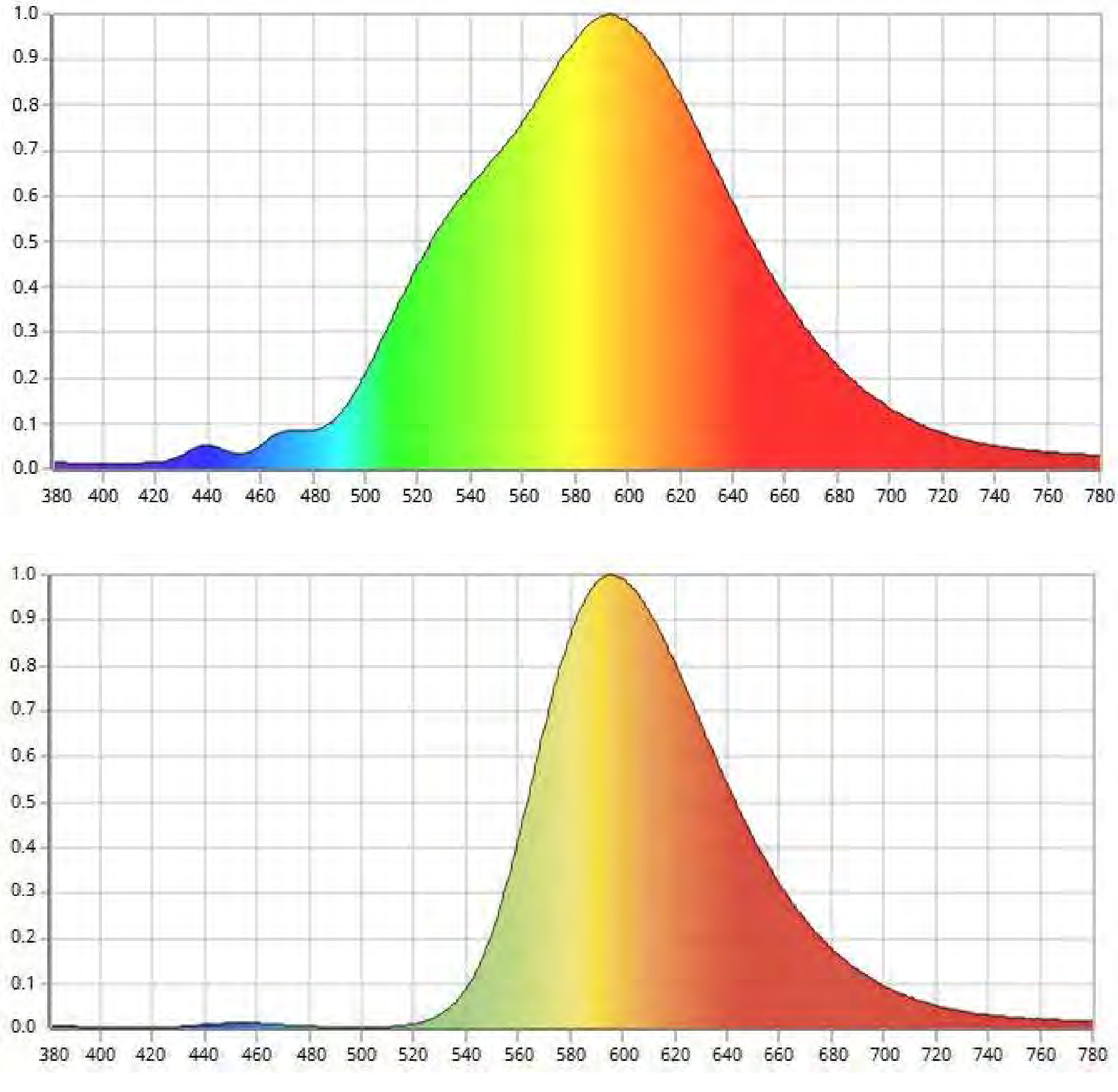


Figure 4.3. Upper - “ultra-warm LED” spectral output; Lower - PC amber LED.

Recommendation: Use fully shielded lighting or other techniques to assure that no light is directly projected above horizontal. Minimise the impact of unshielded lighting like electronic message displays and older sports lighting by imposition of curfews and limitations by usage zone.

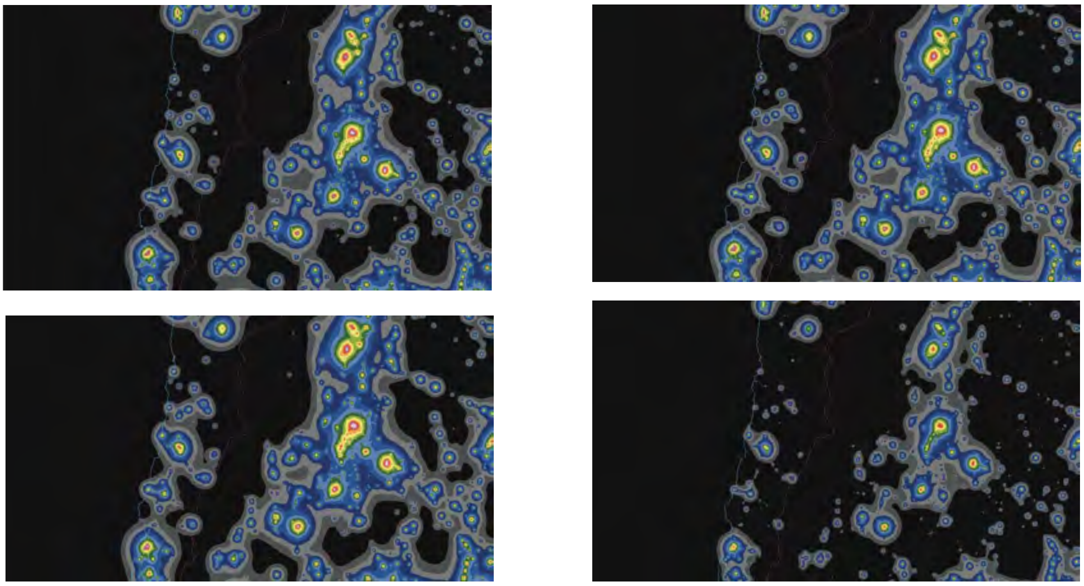


Figure 4.4. Comparatively modelled La Serena - Antofagasta Star Light Index (SLI) from Falchi et al. (2016) algorithm for different colour temperature LEDs. The SLI shows how heavily the night sky will be polluted in the scotopic band (i.e., for a dark-adapted eye) using different lamp types and assuming a constant installed lumen and angular emission function. The step from one colour to the next is a doubling of the sky brightness, starting at a fractional contribution to the natural brightness of 0.01 to 0.02. Upper left: 2200 K; upper right: 2700 K; lower left: 3000 K; lower right: PC Amber.

4.5.7 Limitations on spectral content for illumination, particularly in blue and UV

Although monochromatic sources are the best for astronomy, urban living places greater demand on colour rendition. As discussed in 4.5 above, the artificial sky brightness is inversely proportional to the fourth power of the wavelength of the emitted light. Therefore, it is always recommended to use red or amber (or very warm) light instead of blue (or cool) sources of lights. At far away distances from the observatory, lighting technology requirements can be less restrictive because of the atmospheric extinction that also favors the removal of short wavelengths (blue). Thus, lighting sources with limited emission below 550nm can be used (CIE 150, 2017). Most LEDs with high colour temperatures and Metal Halide (MH) lamps strongly emit in blue, causing severe damage to astronomical observation.

Previous studies (Luginbuhl et al. 2014) have shown that LEDs with high colour temperatures and MH lamps produce a sky brightness 8 times higher than monochromatic Low Pressure Sodium (LPS) vapor lamps and 3 times higher than nearly monochromatic High Pressure Sodium (HPS) vapour lamps. Due to the high content in blue light of such lighting technologies, the artificial sky brightness resulting from these sources is visible at distances greater than 300km (Luginbuhl et al. 2014). LED light sources with colour temperatures (CCT) of 2200K, 2700K and 3000K show low to moderate blue radiant flux (no more than 15% in the latter one, with respect to the integrated radiant flux over the human visible spectrum, 380 – 780nm) but their effects are still significant.

The light pollution effect of these LED sources has been modeled through the software used to calculate the New World Atlas of Light Pollution (Falchi et al. 2016) with spectral weighting (Aubé et al. 2014). Figure 4.4 shows the Star Light Index (SLI) maps (Aubé et al. 2014) which is a comparison at constant lumens based on the scotopic response of human vision. The results can be seen in Figure 4.4 for colour temperatures of 2200K, 2700K and 3000K respectively. The 2200K CCT LEDs, also known as “ultra-warm LEDs” have an integrated radiant flux in the blue (between 380nm and 499nm) of less than 8% of the total emitted radiant flux in the visible range of the human eye (between 380nm and 780nm). Even though this effect is relevant in terms of blue emission reduction, the propagation effect is not that different from the 2700K and 3000K LED lamps. Note that LED sources with CCT 2700K and 3000K comply with many recommendations and even regulations, like the Chilean Norma Lumínica (S.D. N043/2012 Ministry of Environment). The results shown in Figure 4.4 indicate that the reduction in blue light percentage of those LED sources (between a 5% to 15% of the spectral emission at wavelengths between 380nm and 780nm) does not generate a significant reduction in the artificial sky brightness.

On the other hand, Figure 4.4 also shows the effect of using PC amber LED type (phosphor-converted amber LED) in the propagation of light pollution, using the model of Falchi et al. (2016). The difference is clearly seen between the light pollution generated with PC amber LED and with LED sources of 2200K, 2700K and 3000K (Figure 4.4). The spectral response of a PC amber LED does not have emissions below 500nm, significantly reducing the atmospheric scattering. As shown in Figure 4.4, only at the centre of large urban areas would the increase in artificial sky brightness be between 5.12 to 10.2 (colour red), indicating that the Milky Way would not be visible. This result confirms that in the vicinity of optical observatories, the best options are sources with around 1% of emission in the range 380 - 499 nm, with respect to the visible spectrum. It should be noted that these calculations have been performed with PC amber as one of the first available LED technologies with minimum blue light content, a solution that is currently being replaced by more efficient options.

A new, more direct evaluation of the blue light content of LEDs is to define the integrated emissions in the 380-499 nm range per total lumens, as the spectral index “G” does (Galadí-Enriquez 2018). G>2 is sufficient for a colour rendition of 70.

Recommendation: Sharply limit any blue and near-ultraviolet (UV) (<500 nm) spectral content of luminaires. Employ sources with the narrowest possible bandpasses, based on the actual need for colour rendition, and use light sources with the lowest blue-UV content available (colour index G > 2) when colour rendition is necessary.

4.5.8 CONCLUSIONS AND OUTLOOK

Obtrusive light, due to its complexity and novelty, is still separately addressed within different disciplines, e.g. ecology, astronomy, and illuminating engineering. Furthermore, the lighting research community and industry use different methods for the assessment of lighting installations. Lighting technology currently offers technical solutions for efficient, controllable and environmentally friendly lighting. Therefore, knowledge is highly fragmented, and it is sometimes difficult to compare and translate outcomes from and between different fields. Joint effort of CIE, IAU and other interested organisations is recommended to find a common language and to improve the balance between lighting needs and obtrusions.

4.6 MODEL REGULATIONS TO PROTECT DARK SKIES IN THE IMMEDIATE AREAS AROUND PROFESSIONAL OBSERVATORIES

4.6.1 INTRODUCTION

The near zones around professional observatories can be a mix of CIE Zones E0, E1 and potentially E2. The physical radius is approximately 30 km, depending on topology and state of development. Regions that implement protection for such zones meet the criteria for certification as unique Dark

Sky Places, as defined by both *Fundacion Starlight* and the International Dark-Sky Association. Appendix 6 provides details. The Working Group advocates that the need for any artificial light at all must be demonstrated to be approved in the E0 and E1 zones in immediate proximity to the observatory, and the need for colour rendition must also be demonstrated even into adjacent Zones E2; otherwise very narrow bandpass sources are required.

Many regions located nearby major observatories have implemented measures to mitigate the negative impact of ALAN on the astronomical research capabilities. Interventions involving the adoption of modern lighting technologies and design practices are expected to yield the greatest positive environmental consequences (Duriscoe, Luginbuhl & Elvidge 2013). Countries vary on whether the ordinances are applied through the framework of environmental law or land use zoning.

One example is the Observatorio Roque de los Muchachos in Canary Island (Spain), which benefited from an efficient national protection law (*Ley del cielo*) with many successful approaches to limit the threat to the night sky integrity of the Island of La Palma. As for many other cases worldwide, a number of criteria have been defined to protect the night sky as efficiently as possible. The recommended regulatory framework has the following provisions:

1. Exclusive use of luminaires with no light above horizontal;
2. Limiting lamp spectral content in the blue and near ultraviolet region (< 500nm);
3. Limiting the maintained average luminance or illuminance;
4. Implementation of curfews and light-level controls;
5. Defining minimum utilance ratio;
6. Designing and mounting luminaires to minimise direct and reflected light in the direction of observatories.
7. Placing zonal lumens caps on the full area from which ALAN measurably contributes above 30 deg elevation from the observatory, in the context of a regional lighting master plan.

The Working Group discusses each of these criteria in the following sections to establish best practices to protect professional astronomical observatories from the effects of light pollution originating in the immediate surroundings. The focus on areas within a radius of 30 km leads to specific measures when compared to areas located farther. As an example, the blue and UV contents of the light spectra are very important elements to restrict for sources located nearby because of the higher scattering efficiency in the short wavelength, but this factor may be less important for farther sources because of the atmospheric extinction that is higher in the same spectral range. To identify the optimal measures for each criteria, the Working Group takes into account the successful experiments in many regions of the world but more specifically from the Canary Islands case, and also considers the latest advances in light pollution modelling.

4.6.2 EXCLUSIVE USE OF LUMINAIRES WITH NO LIGHT ABOVE HORIZONTAL

It has been demonstrated that full shielding is a very efficient way to reduce the artificial skyglow (Cinzano and Diaz Castro 2000, Luginbuhl et al. 2009, Duriscoe et al. 2013, Schroer and Holker 2014, Aubé 2016). The first element to avoid is any emission of light above the horizontal plane. This is particularly important when the observer is located at a higher altitude than the source and especially when no obstacles can block the light propagation toward the observer. Obstacles are generally associated with buildings, trees and hills. This blocking effect will be treated in Section 4.7.7.

According to Aubé et al. (2018), removing the upward emissions can reduce the sky radiance by a factor of around 2. This is actually a conservative value because that result was obtained assuming a constant luminous flux, but in reality, when the Upward Light Ratio (ULR) is reduced, the flux can also be reduced if one wants to keep the same illuminance on the ground level. This result was obtained without obstacles blocking, because in the case of the studied observatory (Halaekala), light pole heights are higher than houses in the nearby city of Kahului (pop. 26,337). This small city located 30 km away from the observatory is responsible for 96% of the sky brightness when looking toward Honolulu at 20 degrees elevation. This latter result clearly shows why the light emissions from the immediate areas around an observatory are the most important to control.

Recommendation: All luminaires must provide no direct illumination above horizontal.

One implementation is that the luminaires are fully shielded with flat glass and without any tilt angle.

Recommendation: No architectural lighting, or electronic message displays with light emitted above horizontal be permitted in Zones E0 or E1 adjacent to observatories.

4.6.3 Limiting the lamps' spectral content in the blue region

Blue light content (BLC) is defined by the IAU as the percentage of light emitted below 500nm over the total light emitted. Blue light can be more harmful than other wavelengths to the living organism but also to the sky brightness as it impacts astronomical observations. Prior to the introduction of LED lighting, the blue/UV region of the spectrum was naturally dark; now that spectral region is under threat.

Recommendation: The BLC should be null. The lighting devices should be quasi monochromatic sources with maximum radiant flux (in watts per nm) lying within the 585–605 nm spectral range and having Full Width Half Maximum (FWHM) smaller than 18 nm. If modest color rendition is approved as a necessity, spectra with broader FWHM of 110 nm can be used.

As an example, the Spanish *Ley de Cielo* offers more detailed specifications: The maximum radiant flux peak should also lie between 585 and 605 nm. Its spectral content cannot have more than 0.6% of the radiant flux below 440 nm, less than 1.5% below 500 nm, less than 7%, below 550nm, and at least 90% of the radiant flux must lie between 550 and 700 nm. Moreover, any blue light peak should be lower than 2 % of the maximum radiant flux. Most PC amber LEDs comply with these requirements. Those light sources with spectral bandwidth up to 110nm have the advantage of having a colour rendering index higher than 40. When more color rendition (70) is needed (for limited situations), a very warm white LED with a spectral index G 2 could be used.

4.6.4 Limiting the maintained average illuminance

Recommendation: The maintained average illuminance should not be higher than 20% above the minimum maintained average illuminance suggested in technical norms/recommendations published by CIE or IES (i.e. 1.2 times the minimum maintained illuminance prescribed by the norm/recommendation) and this upward deviation must be kept at the lowest possible level by proper lighting design and employing suitable lighting controls.

As an example, in North America, the American National Standard Practice for Design and Maintenance of Roadway and Parking Facility Lighting RP-8 document, the Illuminating Engineering Society (IES) suggests, for a local road and a pavement class R3, a minimum maintained average illuminance of 9 lux. In such a case, the installed maintained average illuminance should not be higher than 10.8 lux (1.2 × 9).

Recommendation: Avoid exceeding luminance or illuminance limits by more than 20% in design in order to accommodate anticipated degradation of performance, and plan on active control and maintenance to achieve nearly constant light output.

If necessary, the frequency of maintenance interventions on the lighting installation can be increased to reach that goal, although the claimed low depreciation of LED luminous output should also contribute. Active control can also dim initial output to desired levels.

4.6.5 Implementing curfews and light level controls

Curfew is time during which stricter requirements (for the control of obtrusive light) will apply. This is often a condition of use of lighting applied by a government controlling authority, usually the local government. A typical curfew start time is midnight and end time at dawn, but varies by locality.

Recommendations: A maximum possible reduction of the light levels, with a target of at least 66%, should be applied after curfew (or before that time whenever possible). Any lighting installation that is not needed for public safety reasons should be switched off at curfew. For isolated areas or hours of low traffic, sensors should be used to increase the light level as needed when any activity is detected. Without detection, the light level should be set down to 10% or less of the maintained average luminance or illuminance.

4.6.6 Defining minimum utilance ratio

Utilance (U) of an installation is the ratio of the luminous flux received by a defined reference surface to the sum of the individual output fluxes of the luminaires of the installation. The reference surface should include surrounding areas as established in norms. The value of the quantity U tells us how much light is projected where it is needed; the rest is useless and therefore contributes unnecessarily to light pollution.

Recommendation: Utilance should be higher than 75% ($U > 0.75$), but any higher value is better.

4.6.7 Luminaires to minimise light propagating toward observatories

Recommendation: Luminaires should be designed and mounted to minimise direct and reflected light propagating in the direction of observatories. Approaches include optical beam forming, directional shielding on the luminaire, and taking advantage of natural shadowing by buildings and topological features wherever possible.

4.6.8 Lumen Caps

The restrictions on individual fixtures are critical, as defined in the sections above. To slow, stop, and reverse the rate of increase of artificial skyglow, a regional lighting master plan is needed as well. While CIE prescriptions for lighting control by installation in near zones E0 and E1 and possibly E2 are likely to be adequate, ALAN impacting the skyglow as seen from the observatory above elevation 30 degrees may originate from towns and cities within a radius of hundreds of km. The practical radius of influence will be set by measurement: if a source of light provides at least 2x the zenith level of artificial sky glow from its direction at 30 deg elevation, that source is to be included in the area of observatory impact. The elevation limit is a practical one above which most limiting observations are conducted.

Control of the total artificial skyglow therefore requires integral limits by zone, based on usage, topography, and pressure for development. Falchi and Bará (2020) make the case for the importance of integral limits as well as per-fixture limits, and describe a linear modeling approach relating key indicators to the integrated limits. A good example of the regional modelling approach is the study by Aubé et al. (2020) for Teide Observatory.

Recommendation: Each major professional observatory and controlling governmental body should undertake a modeling exercise to determine the total amount of fully shielded outdoor light allowable so as to slow, stop and reverse the rate of growth of artificial skyglow and to keep the total contribution substantially below the 10% dark site limit defined by the IAU.

4.7 SPECIAL CASES

Observatories in remote locations can encounter enterprises with outdoor lighting needs and regulations that can be more difficult to adapt to dark sky conformity, e.g.,open-pit mines, military and national border security operations, prisons, wind farms, and airports.

Modern quality lighting design can be applied to 24/7 pit mining operations very effectively to preserve operational safety while significantly reducing stray light. Monochromatic sources can be extensively used; when and where colour rendition is required (e.g., to distinguish oil from blood), an additional bank of broader band lighting can be switched on, then switched off when the operation is complete. Beam-forming can limit the amount of up-light resulting from operations when full shielding is not possible, for example, in the headlamps of large mining vehicles that traverse steeply sloped roads. Matching the illumination level to the task with appropriate contrast to dark night surroundings greatly reduces the total light levels of the operation.

Military bases, prisons, and border security operations often require lighting large areas for night-time operations. These lighting installations can nevertheless be fully shielded and observe the minimum maintained average illuminance + 20% criterion as recommended above for observatory near-zone protection.

Wind farms, transmission line towers, broadcast antennas and any tall structures in aircraft approach paths are typically required to be lit with warning lights. Mitigations near observatory sites can include monochromatic sources (red) and physical shielding for the small solid angle subtended by an observatory with a direct sightline.

Airports have strict requirements for safe operations. Nevertheless, apron work areas can have fully shielded fixtures and illuminance levels appropriate for night-time work without over-lighting. Rotating beacons can be blanked out for the narrow azimuth that contains any direct sightline.

Aircraft wingtip lighting is comparable in apparent brightness to that of the brightest stars. The Working Group recommends that civilian regulators and military flight planners exclude the observatory near zones from approved flight paths, and keep those paths as far from observatories as practicable.

4.8 INCENTIVES FOR COMPLIANCE

Although it is often possible to enact high-quality outdoor lighting policies in various jurisdictions, anecdotally we find many instances in which those policies essentially fail in their intent to bring regulatory solutions to the problem of light pollution. Most often the failures result from inadequate implementation and enforcement of laws and norms relating to outdoor lighting. Governments may enact good outdoor lighting policies for the right reasons, but those policies may not have the intended effect either because they are enforced inconsistently, or because there is inadequate public support for the policies to sustain a strong and effective enforcement regime. Well-intended outdoor lighting policies can therefore fail to obtain improvements to either lighting or night-time conditions. However, rather than simply proscribing bad behaviours through statute or rulemaking, better results with respect to the protection of night sky quality may be obtained through incentivisation of good behaviours. The notion of "incentives" should broadly cover both the path to arrive at enactment and the enforcement side after enactment is achieved. We consider several factors that may incentivize voluntary compliance, especially in cases where the social and/or political will to enforce or to concentrate on the protection of local observatories does not yet exist.

4.8.1 SUSTAINABILITY, VALUING LIMITS ON LIGHT POLLUTION, COST SAVINGS

4.8.1.1 Sustainability

The notion of sustainable living is usually thought of in relation to reducing the consumption of non-renewable resources, increasing renewability, and limiting the generation of waste. As a result, it tends to be targeted toward improving energy efficiency in order to lower dependence on fossil fuels and limit the emission of climate-altering carbon gases to the atmosphere. However, it can be argued that the drive to improve the energy efficiency of outdoor lighting in the name of reducing the carbon footprint of lighting has resulted in significant increases in ALAN emission into the nighttime environment (Kyba et al. 2017), in effect exchanging one environmental harm for another. The reduction of light pollution is therefore an environmental goal of comparable value to actions taken to achieve more environmentally just and sustainable societies. (Hölker et al. 2010) A truly 'sustainable' world would achieve an appropriate balance between legitimate human needs for ALAN and the deleterious effects of outdoor light at night.

4.8.1.2 Valuing limits on light pollution

Light pollution is a manifestation of waste: artificial skyglow is literally light that benefits no one, whether emitted directly into the night sky or reflected from the ground. Eliminating wasted light therefore saves electricity as it reduces light pollution. The benefits of reducing light pollution in this fashion have been offset somewhat by the arrival on the global market of highly energy-efficient solid-state lighting such as LED.

Prior to the introduction of energy-efficient solid-state lighting (SSL), electricity used to power outdoor lighting accounted for about 1.5% of global power consumption. (Brown 2006) Now, an economic 'rebound effect' implied by remote sensing of night lights, attributable to cheap and widely available LED lighting, has the potential to offset most or all of the expected environmental benefit of the transition away from older technologies. It has been argued that the low cost of operating modern lighting calls for a new definition of 'efficiency' that considers primarily the total cost of light including its impact rather than simply its electricity cost of production. (Kyba, Hänel & Hölker 2014) Although the world usage of light is typically quantified in units such as watts of electric power consumption, regulation of light per capita is a better framework to address this problem of consumption of a commodity with environmental consequences. Policies can be formulated in ways that meet development needs, protect public safety, and provide property owners with reasonable use of outdoor ALAN on their own properties while capping the total light emission in a region in a way that is equitable.

Absent regulation of outdoor light use to curb consumption, solid-state lighting threatens the same negative externalities that accompanied earlier technologies in terms of light pollution. When these externalities are considered as part of the total cost of SSL retrofits, their apparent benefits to society appear to fade. For example, one study of a municipal SSL retrofit effort in the United States found a ten-year rate of return of -146.2% compared to +118.2% when the costs associated with avoided carbon emissions and health outcomes related to ALAN exposure are ignored. (Jones 2018)

4.8.1.3 Reduced costs of providing public lighting

In many parts of the world, the provision of lighting in public spaces is taken as a critical infrastructure component to be provided by governments; in certain areas, like the rural U.S, local governments tend to contract the provision of public lighting to private vendors such as electric utilities. Solid-state lighting technology has greatly reduced the cost of providing outdoor lighting. Governments could bank the savings, but available evidence suggests in many cases the difference funds the purchase and installation of new lighting. (Kyba et al. 2017) It is also thought that in many cases, public lighting levels are excessive even in relation to IES/CIE-recommended minima. Lowering lighting levels in the transition from older lighting technologies to SSL can avoid over-lighting while delivering both expected cost savings and expected environmental benefits.

An example of a case where an SSL retrofit resulted in a reduction of light emission is in the city of Tucson, U.S. During the transition from legacy high-pressure sodium technology to 3000K white LED, the city reduced the light emission of the street lighting system by about 60%, resulting in an operational cost savings of USD 2.16 M per year. (Barentine et al. 2018) In addition, the municipality has prolonged the life of its white LED lighting products by routinely operating them below the maximum possible power draw; it realises further electricity savings by actively dimming most of the city's ~19,500 street lights during the night hours.

4.8.2 SYNERGY WITH PROTECTION OF NATURAL AREAS

Protected natural areas sometimes host astronomical observatories. Examples include Observatoire Mont-Mégantic in the Mont-Mégantic International Dark Sky Reserve in Québec, Canada; Mt. John Observatory in the Aoraki Mackenzie International Dark Sky Reserve, New Zealand; and AURA Observatory in the Gabriela Mistral International Dark Sky Sanctuary, Chile. The long-term viability of these sites for conducting ground-based astronomical observations is in part secured by the landscape-level legal protections associated with the sites' international dark-sky designations. Support for these protections, and the land-use restrictions with which they are generally associated, is often related to the economic benefits associated with 'astrotourism', a form of tourism in which visitors come to view and enjoy dark night skies. (Collison & Poe 2013). This form of sustainable tourism can support rural economies, particularly in areas where previous industries based on non-renewable resource extraction have wound down. (Mitchell & Gallaway 2019)

4.8.3 QUALITY LIGHTING ENHANCING NIGHT-TIME SAFETY

Besides its ancillary benefits to the protection of the nocturnal environment, the notion of 'quality' lighting is intended to improve conditions at night for safe transit and use of outdoor spaces by the public. The goal of quality lighting is to improve visibility while minimizing environmental impact and the cost of operation. While there is scant unambiguous scientific evidence to date to support the conjecture, we hypothesize that the same lighting design that is best for minimizing light pollution is also most conducive to public safety by carefully targeting the use of ALAN to the actual needs for light at night, thereby reducing wasted light.

A significant limiting factor in drawing clear and unqualified conclusions about the interaction of outdoor lighting and crime and road safety is that carefully controlled studies involving both are notoriously difficult to design, conduct, and interpret. As a result, many of the claims about outdoor lighting and its impact on public safety -- for better or worse -- may be fundamentally wrong. (Marchant 2017; 2019) The lack of conclusive studies makes developing evidence-based policy and setting minimum illumination levels particularly challenging. More information is found in Appendix 8.

Rafael Rebolo
Director - Instituto de Astrofísica de Canarias, Spain

The National Parlament of Spain approved the law that protect the Canarian Skies above and around the observatories

Rafael Rebolo
Excerpt from the welcome speech to the workshop participants

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5. BIO-ENVIRONMENT REPORT

5.1 INTRODUCTION

For thousands of millennia, nearly all life on Earth has experienced regular daily and nightly rhythms of light and darkness imposed by the rotation of the Earth, and has evolved to depend on those cycles. The DNA in human cells includes multiple “clocks” that operate on roughly 24-hour (circadian) timescales and ultimately regulate many of our most important functions, including hormone secretion, sleep, digestion, and metabolism. While the daily behavior and function of humans was once thought to have evolved beyond sensitivity to light and to be mostly socially regulated, it is now widely recognized that in fact we are physiologically profoundly sensitive to even very low levels of light at night.

Many species of fauna and flora show strong sensitivity to daily light-dark cycles as well and many other impacts of artificial light at night are reported on wildlife and plants. The majority of all animals, a vast majority of invertebrates including crucial pollinators and more than three-quarters of mammal species are nocturnal (Hölker et al. 2010). About 40% of bird species migrate, and an estimated 80% of them do so at night. It has been shown that animals are capable of using the dim lights of the Milky Way and the stars to navigate (Foster et al. 2018).

Thus, the vast majority of life on Earth needs darkness at night to thrive. But humans and wildlife are now increasingly exposed to ever-brighter artificial light at night (ALAN), with a recent dramatic increase driven largely by the advent of new technologies, primarily inexpensive, durable, and energy efficient solid state lighting in the form of light-emitting diodes (LED). The emission of ALAN as detected by satellite imagery is growing by 2% per year, which is twice the rate of population growth (Kyba et al. 2017), and a skyglow model based on such data estimates that more than a third of the world’s population -- and nearly 80% of North Americans -- can’t see the Milky Way (Falchi et al. 2016).

A significant and growing body of scientific research shows that ALAN causes significant negative effects on the health of humans and flora and fauna. The impacts of ALAN are diverse and appear at many different scales. They include, for flora and fauna, changes in habitat use, migration, reproduction, predator-prey relationships, ecosystem functions and services, and fatalities at significant enough levels to pose extinction threats to some species. On humans, the impacts of ALAN include disruption of melatonin production and circadian rhythms and extend to elevated risks of hormonal cancers and other serious diseases.

In this chapter, we summarize the current state of understanding of the impacts of artificial light at night on humans and flora and fauna, and we put forward recommendations for how to mitigate these impacts.

5.2. EFFECTS OF ARTIFICIAL LIGHT AT NIGHT ON HUMAN HEALTH

5.2.1. INTRODUCTION

A century of technological innovation, economic development, and population growth has led to a world where artificial light at night is now one of the most prominent features of the night side of Earth visible to astronauts in orbit. Flame and gas lamps gave way to electric arc lamps, incandescent light bulbs, and gas discharge lights including metal halide lamps and the high-pressure sodium lights that have illuminated streets and highways worldwide for the past 50 years. More recently, the development of high-efficiency, long-lasting white light-emitting diodes (LEDs) has ushered in a new wave of outdoor lighting installation and replacement.

Not all LED light is optimal, however, including when used for exterior applications such as street and parking lot lighting. For example, glare from improperly designed fixtures may create serious road hazards by temporarily blinding road users (Yandan et al 2014, Gibbons and Edwards 2007). In some designs of white LED lighting the emission spectrum is relatively rich in short wavelength, blue light (Fig. 51), and numerous studies have raised significant concerns about the negative human and environmental effects of those blue emissions. Excessive blue light at night can contribute to disability glare, as blue light scatters more in the human eye than longer wavelengths. There are studies showing possible retinal damage from exposure to blue spectrum wavelengths (Shang 2014, Lougheed 2014, EYE 2016).

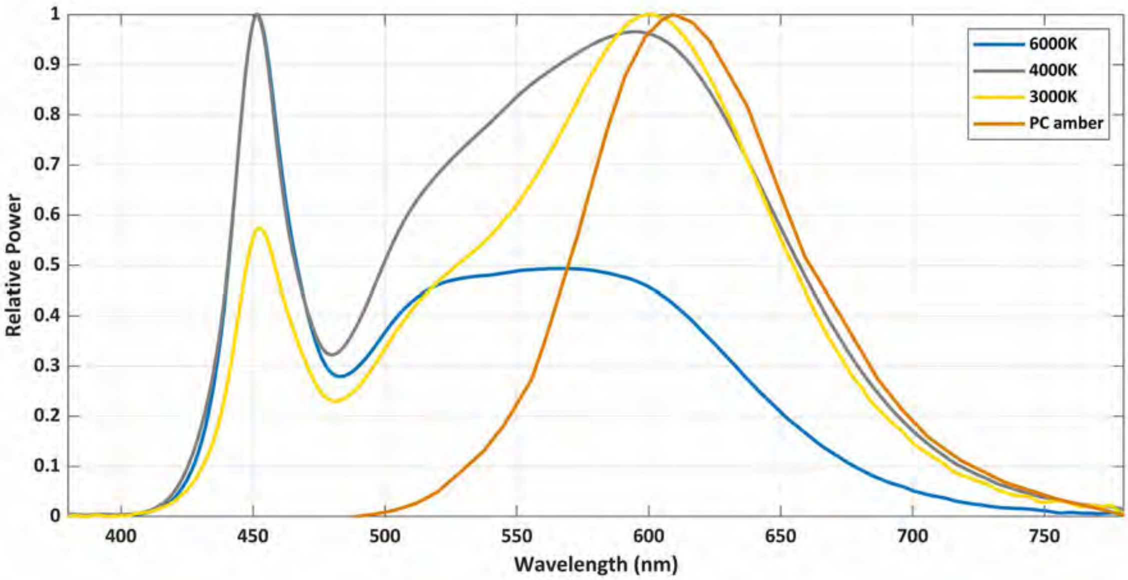

Figure 5.1. Spectral distribution of typical LED light sources.

Light is the most powerful stimulus for regulating human circadian rhythms and is the major environmental time cue for synchronizing the circadian clock (Wright 2013, Cajochen 2011). The discovery that human eyes include not only photosensitive rods and cones that detect the image from the eye's lens, but also photosensitive retinal ganglion cells that play a major role in controlling circadian rhythms, was made only very recently (Hattar et al 2002). In addition to resetting the daily circadian rhythm, light also stimulates additional neuroendocrine and neurobehavioral responses, including suppression of melatonin release from the pineal gland, activating the limbic system improving alertness and performance (Evans 2013). Melatonin is now one of the most studied biomarkers of the human physiological response to light, and this substance is produced only at night, regardless of whether an organism is day-active (diurnal) or night active (nocturnal). The discoverers of the biochemical and genetic mechanism of action of circadian rhythm physiology, Jeffrey C. Hall, Michael Rosbash and Michael W. Young, were awarded the 2017 Nobel prize in medicine (Nobel Prize Medicine website) for that work.

Light exposure at night results in the immediate suppression of melatonin production. Under natural conditions, organisms would never be exposed to light during the night in substantial amounts and would not experience melatonin suppression. Light at night, however, efficiently suppresses melatonin at intensities commonly experienced both in outdoor and indoor typical lighting at night (Blask et al 2012, Grubisic et al. 2019).

5.2.2. GLARE

An internationally accepted definition of glare is in the CIE S 017/E:2011 'International Lighting Vocabulary (ILV) ': "condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts. The disabling effect of the veiling luminance may have serious implications for nighttime driving visibility"

As LED lighting is often more directional than other forms of lighting, it can lead to stronger glare than conventional lighting if insufficient attention is paid to controlling the lighting's spatial and color properties; conversely, proper engineering of fixtures can greatly minimize glare. Some individuals are debilitated by the visual glare from LEDs that are not properly directed and diffused (Ticleanu and Littlefair 2015). LED's are very intense point sources unless shielded or diffused properly that lead to vision discomfort when viewed by the human eye, especially by older drivers. This effect is magnified by higher-color-temperature LED's, i.e. blue-rich white LED lighting, because blue light scatters more in the human eye, leading to increased disability glare (Sweater-Hickcox 2013). In many localities where 4000K and higher lighting have been installed, there have been community complaints of glare and a "prison atmosphere" by the high intensity blue-rich lighting. Many localities in the USA have replaced high CCT lighting with 3000 K or lower CCT because of such public opposition (e.g. Seattle WA; Davis, CA; Queens NY; Scigliano 2013, CBS-13-TV 2014; Chaban 2015). In contrast, lighting with CCT 3000K and lower, while still very "white" compared with legacy HPS, is much better received by citizens in general in side-by-side comparisons with higher-CCT lighting.

There is significant discomfort from glare from unshielded LED lighting. A French government report in 2013 stated that due to the point source nature of LED lighting, their luminance level is inherently higher than 10,000 cd/m^2, causing visual discomfort whenever the lighting unit is within the field of vision. As the emission surfaces of LEDs are highly concentrated nearly point sources, the luminance of each individual source can be 1000 times higher than the discomfort level (Anses 2014). Discomfort and disability glare can decrease safety and are considered a road hazard in cases where they compromise visual performance and acuity (Lighting Res. Tech 2012, Vos 2012). Currently lighting installations are tested by measuring illuminance on the ground, in units of cd/m^2 (or, in the US, foot-candles). This is useful for determining efficiency and evenness of lighting installations; however, this method does not take into account the human biological response to the lighting installation. It is well known that unshielded light sources cause pupillary constriction, leading to worse nighttime vision between lighting fixtures, and cause a "veil of illuminance" beyond the lighting fixture. This leads to worse vision than if the light never existed at all, defeating the purpose of the lighting fixture. Most indoor lighting is equipped with shades to prevent glare, and most theater lighting is designed with shielding to prevent glare for audience members. Ideally, LED street and other exterior lighting should be tested in real-life installations, and visual acuity should be determined to ascertain best designs for optimal public safety. In a study of roadway lighting in 2016, there was no significant difference in roadway detection distance from LED fixtures of CCT 2100 K, 3500 K, or 6000 K (Lewis and Gibbons 2016). Published studies thus far have not shown a decrease in traffic accidents associated with conversion to full-spectrum white LEDs (e.g., CCT >2700 K; Marchant 2020). A prudent approach to balance these human health and safety issues is to use the lowest CCT deemed acceptable; specify high-quality optics to ensure delivery of light only on desired surfaces instead of as glare; and avoid light trespass onto windows of any residential property.

5.2.3. RETINAL DAMAGE FROM SHORT WAVELENGTH BLUE LIGHT

Numerous studies over the past few years have raised concern that excess illumination, especially in the blue part of the spectrum, may affect human vision and promote retinal degeneration or accelerate some genetic diseases. Even low intensity blue light can cause retinal damage over time in animal models, and thus theoretically may accelerate the development of age-related macular degeneration (AMD), retinitis pigmentosa (RP), and certain genetic retinal diseases in humans (Walls 2011, Marquioni-Ramella 2015, Nowak 2014, Paskowitz 2006). Light pollution and especially blue illumination may have detrimental consequences on the retina and its physiology (Kanterman 2009, Pauley 2005). There are two main mechanisms of retinal damage: (a) 'blue-light' and (b) 'visual pigment-mediated process'. Retinal light damage can be produced by low irradiance levels of white light rich in blue over a prolonged time (Behar-Cohen 2011, Wu 2006), or by more intense exposure to high irradiance with an action spectrum peaking at short wavelength of white light (Grimm 2001). Paradoxically, intermittent light exposure may cause greater visual cell damage than continuous light exposure (with the same light source and same total duration) (Organisciak 1989).

Free radical damage can occur when oxygen interacts with certain molecules, a process that can be initiated especially by blue light, and therefore, the retina is sensitive to such damage (Wu 2006). The retina has a system that protects cells and tissue(s) against oxidative stress, but these mechanisms can fail with age and then the pathologic symptoms of retinal degeneration begin (Siu 2008). ALAN from excess blue LED may potentially have negative consequences for retinal health, especially in older individuals where anti-oxidative stress mechanisms are less effective. In many human diseases such as AMD and RP, photoreceptor cells' death is the principal event of retinal degeneration and therefore it is prudent to consider that excessive exposure to natural or unnatural light may accelerate many of these (Grimm 2013).

5.2.4. MELATONIN SUPPRESSION

Melatonin is a hormone that humans naturally produce. It is not detectable during the day (even in dim light) and production peaks at night. With waning ambient light, and in the absence of electric lighting, humans begin the transition to nighttime physiology at about dusk; melatonin blood concentrations rise, body temperature drops, sleepiness grows, and hunger abates, along with several other responses. Melatonin supports night-time behaviour; this means that in humans it facilitates sleep initiation and sleep consolidation. The 24-hour melatonin profile marks the circadian rhythm and the habitual sleep-wake cycle (Czeisler, Shanahan et al. 1995, Dijk, Shanahan et al. 1997). People's usual bedtime is measured to be about 2 hrs after melatonin onset (in dim light; see Duffy and Wright 2005).

These effects are interrupted by exposure to electric light, especially when it is rich in short wavelengths. Light at night can suppress nocturnal melatonin production, disrupt the circadian system and compromise human sleep and health. For some of these responses a large interindividual variability has been reported (see Philips et al 2019). Recently, a new SI-compliant metric was established to quantify light for its stimulation of non-visual responses that are driven by intrinsically photosensitive retinal ganglion cells, ipRGCs: melanopic equivalent daylight illuminance (see international standard CIE S 026:2018). IpRGCs combine melanopsin-based photoreception with rod and cone signals, and the new metric has been demonstrated to be a good predictor for circadian responses to light, such as melatonin suppression and phase shifting (Brown 2020). The spectral sensitivities of the five photoreceptors (as defined in CIE S 026:2018) and the luminous efficiency function for photopic vision, V(λ), , are plotted in Fig 5.2.

In general, the sleep-disruptive effects of evening/nighttime light are stronger when (i) the evening/nighttime light is more bright and more rich in short wavelengths (i.e., higher melanopsin activation), (ii) individuals have been exposed to less light during daytime, and/or (iii) individuals are less sleep deprived, i.e. more well-rested.

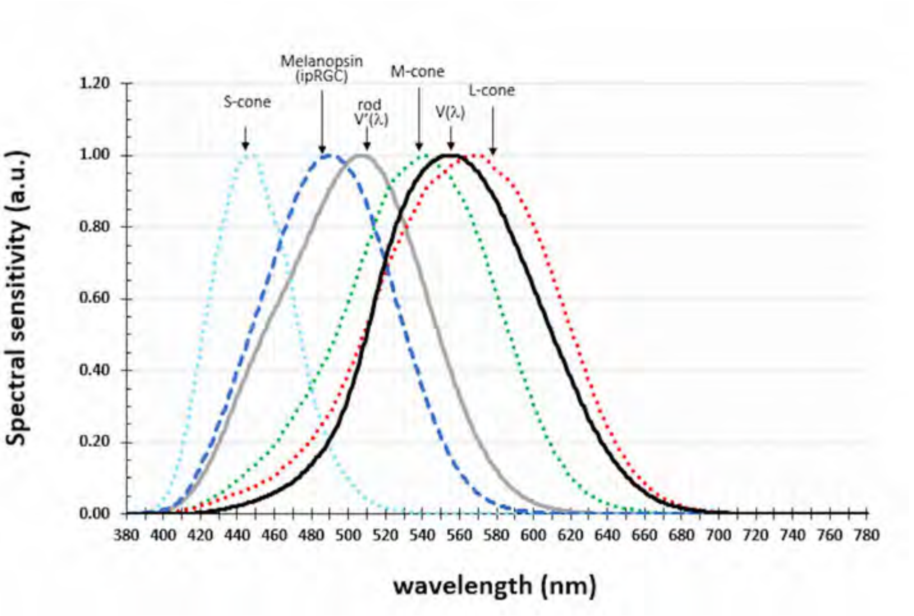

Figure 5.2. The spectral sensitivities of the S-cone, M-cone, L-cone, rod and melanopsin-based (ipRGC) photoreceptor, as defined in CIE S026:2018. For comparison the spectral luminous efficiency function for photopic vision, V(λ), is also shown. The spectral sensitivity function for rods is also known as the spectral luminous efficiency function for scotopic vision, V'(l).

Melatonin is suppressed at very low light intensities, as little as 6 lx in sensitive humans (Grubisic et al. 2019), although a large range in human sensitivity to this effect is observed, including a 50-fold variation between people in melatonin response to light exposure (Phillips et al. 2019). Children are more sensitive to disruption from light at night than adults (Nagare et al. 2019). Office workers exposed only to dim light during the day are more sensitive to disruption from light at night than those who work outside. Men are more sensitive to light at night, including decreased "long sleep" with increased exposure (Xiao et al. 2020).

Melatonin exerts a number of physiological cellular effects, and is suppressed by even low level lighting at night from outdoor lighting sources (Cho et al 2015). In addition, circadian responses that result from melatonin suppression are heavily dependent on the spectrum of light. As light is concentrated closer to the wavelengths of peak sensitivity for melanopsin, the intensity of light (measured in lx) required to suppress melatonin decreases (Grubisic et al. 2019). At 424 nm, the minimum illuminance for melatonin suppression is 0.1 lx (Souman et al. 2018). We note that the lux is a unit based on photopic response of the retina, whereas it is the blue light at about 460 nm to which the ipRGC are sensitive, so quoting the lux level as an indication of blue light intensity can be quite misleading. ipRGC are most sensitive to wavelengths 446 to 477 nm. The relative impact of different lighting sources can be predicted using the melanopic response curve (Aubé et al. 2013, Longcore et al. 2018a). All full-spectrum LED sources have a greater potential circadian impact than HPS, including 2200 K (1.5 times HPS), 3200 K (2.5 times HPS), and 4300 K (3 times HPS).

Outdoor lighting is usually intended to increase the overall safety of people and traffic, but, if poorly designed or improperly installed, can also compromise vision, safety, and public health. The study results on the effects of outdoor nighttime light on sleep find an association with satellite-measured outdoor lighting. For example, subjects in South Korea with higher exposure to light at night as measured by 2.7-km resolution satellite data (Defense Meteorological Satellite Program; DMSP) were 20% more likely to sleep less than 6 hours per night and on average slept 30 minutes less than subjects in areas with lower outdoor lighting levels (Koo et al. 2016). In a study in the United States, higher levels of outdoor lighting as measured by DMSP were significantly associated with reporting < 6 hours of sleep per night, an effect that remained in place even after accounting for noise and population density (Ohayon and Milesi 2016). In that study, people who lived in the brightest areas were more likely to go to bed later, wake up later, and sleep less. They also were more likely to report that they were dissatisfied with sleep quality or quantity and to be sleepy during the day. DMSP-measured light at night was negatively associated with restorative long wave sleep. Importantly, that study validated that brightness in bedrooms correlated positively with satellite-measured outdoor light (Ohayon and Milesi 2016).

Satellite-measured light at night was also associated with the use of more drugs for insomnia in a second South Korean study (Min and Min 2018). Residents living in the lowest two quartiles of light at night as measured by DMSP used significantly less insomnia medication, even after accounting for age, sex, population density, income, body mass index, smoking status, alcohol consumption, exercise, and psychiatric disease. Mean use of insomnia medication increased with each quartile of light exposure from lowest to highest for each of three insomnia medications (Min and Min 2018).

Most recently, a study of the NIH-AARP Diet and Health Study cohort in the United States investigated sleep and exposure to light at night as measured by the DMSP satellite (Xiao et al. 2020). The highest levels of light exposure were associated with 16% (women) and 25% (men) increased probability of reporting short or very short sleep duration. Probability of reporting short or very short sleep increased from lowest to highest quintiles of light at night in models that adjusted for age, race, marital status, state of residency, smoking, alcohol, vigorous physical activity, TV viewing, and median home value, population density and poverty rate at census tract level (Xiao et al. 2020). The authors concluded that, “Taken together, these findings suggest that the prevalence of sleep deficiency is higher in places with higher levels of LAN [Light at Night]” (Xiao et al. 2020). It remains an open question whether indoor exposure to street lighting is of sufficient magnitude to affect circadian rhythms directly, but recent research investigating light spectrum and cancer risk suggests that the color of light outdoors in the vicinity of residences is an important risk factor (Garcia-Saenz et al. 2018).

While studies using remotely sensed data detect associations between sleep disturbance, circadian disruption, and associated diseases and light at night, others question the relationship between outdoor lighting and indoor exposure to light at night. Leaving aside the point that outdoor exposure to lighting can also contribute to circadian disruption, these studies focus on relationships between indoor and outdoor exposure. Recent work confirms the relationship between ground-level irradiance outdoors and satellite-based proxies for light at night. Using a dataset of 515 ground-based measurements of illumination from the upper hemisphere, Simons et al. (2020) showed that ground-based light exposure correlates highly with remotely-sensed light (VIIRS DNB annual composite) and even more with the New World Atlas of Artificial Night Sky Brightness (Falchi et al. 2016). This work conclusively establishes that satellite-measured light at night is a proxy for ambient light in the environment on the ground at night, as one would expect.

With that relationship now established (Simons et al. 2020), ongoing research is now pursuing individual-level studies of correlation between indoor light levels and satellite-measurements of light at night. In a more recent Dutch study, individual-level light exposure for children was measured indoors with a device that had a resolution of 0.1 lx (Huss et al. 2019). They found an influence of outdoor light on indoor light during the darkest time period with a correlation of 0.31. It should be noted, however, that 94% of the children in the study had curtains that controlled light entering the room. In a survey of lighting designers using their own light meters, Miller and Kinzey (2018) reported measurements in a number of different contexts within homes. At windows without drapes a maximum of 20 lx was reported, with a mean of 5 lx and median of 0.5 lx. All of those light levels are dramatically elevated above natural conditions: a full moon would produce 0.1–0.2 lx.

Experiments that involve exposures to light at night document illumination levels that affect health and sleep outcomes. Sleeping under 5 lx of 5779 K light caused more frequent arousals, more shallow sleep, and more REM sleep (at the expense of long wave deep sleep) (Cho et al. 2016). Light greater than 3 lx during the last hour of sleep was associated with weight gain in an elderly population (Obayashi et al. 2016). In another study of an elderly population, increased light at night and especially light at night > 5 lx was associated with 89% increased risk of depression (Obayashi et al. 2013). Further studies indicate that elevated illumination is associated with higher blood pressure as well, with associated excess deaths, at 3, 5, and 10 lx exposures (Obayashi et al. 2014). Metrics of sleep quality (efficiency) were also consistently lower with higher illumination at each category (3, 5, and 10 lx) (Obayashi et al. 2014).

Taken together, this research is consistent with a few different interpretations of the influence of outdoor lighting on human circadian rhythms and health outcomes. It is possible that the correlations between light at night and adverse health outcomes indicate instead variation in another factor, such as air pollution, as suggested by Huss et al. (2019). The robustness of sleep disruption correlations when controlling for population density, however, argues against that interpretation (Ohayon and Milesi 2016). Xiao et al. consider this question and conclude: "[I]t is also possible that the observed associations in our study population represent a true relationship, but primarily driven by individuals whose ALAN exposure was more heavily influenced by outdoor ALAN (e.g. individuals living in rooms facing bright streets and/or with insufficient window treatments to block out light, or individuals with a high amount of nighttime activities outside home)." Such an interpretation, that outdoor light can influence indoor sleeping environments and associated sleep and health outcomes, is consistent with the literature as it currently stands.

5.2.5. Endocrine Cancers (Breast, prostate)

Epidemiological studies are a critical component of the evidence required to assess whether or not light exposure at night (LAN) affects disease risk, including cancer. These studies are necessarily observational and can rarely provide direct causal understanding of the associations observed. Carefully designed and controlled basic laboratory studies in experimental animal models have the potential to provide the empirical support for a causal connection to light exposure at night and biological/health effects and to establish plausible mechanisms. One area of considerable study on the possible effects of nighttime light exposure involves cancer (Stevens et al 2014).

The majority of early studies in experimental models of either spontaneous or chemically-induced mammary carcinogenesis in mice and rats demonstrated an accelerated onset of mammary tumor development accompanied by increased tumor incidence in animals exposed to constant bright light during the night as compared with control animals maintained on a strict 12 hours light/12 hours dark cycle (Blask 1999 & 2003 & 2005, Beniashvili 2001, Travlos 2001, Van den Heiligenberg 1999). Convincing studies have shown the ability of LAN to promote the growth progression and metabolism in human breast cancer xenografts. Nocturnal melatonin suppresses the growth of human breast cancer xenografts; the essential polyunsaturated fatty acid, linoleic acid, is necessary for the growth of such (ER-) tumors, and its metabolism can be used as a biomarker of cellular growth (Anisimov 2004). Exposure of rats with such cancer xenografts to increasing intensities of white light during the 12 hour dark phase of each daily cycle results in a dose-dependent suppression of peak nocturnal serum melatonin levels and a corresponding marked increase in tumor metabolism of linoleic acid and rate of tumor growth. Exposure to even the very dimmest intensity of light during the night (0.2 lx) suppressed the nocturnal peak of circulating melatonin by 65% and was associated with marked stimulation in the rates of tumor growth and linoleic acid metabolic activity (Blask 2003 &2005, Wu 2011).

The ability of light exposure at night to stimulate tumor growth (including dim exposures) has been replicated in rat hepatoma models as well (Dauchy 1997 & 1999, Van den Heiligenberg 1999). The reverse also is true; gradually restoring circulating melatonin by reducing initial exposure to light at night (24.5 lx) is accompanied by a marked reduction in tumor growth and linoleic acid metabolic activity to baseline rates in the breast cancer and hepatoma models (Dauchy 2011). The important role of melatonin as a nocturnal anticancer signal is further supported by the growth responses of human breast cancer xenografts perfused with human whole blood collected from young, healthy premenopausal female subjects exposed to complete darkness at night (i.e., high melatonin), compared with xenografts that were perfused with blood collected from the same subjects during the daytime (i.e., low melatonin; Blask 2005). The growth of xenografts perfused with blood collected during the dark was markedly reduced. Addition of a physiological nocturnal concentration of melatonin to blood collected from light-treated subjects restored the tumor inhibitory activity to a level comparable to that observed in the melatonin-rich blood collected at night during total darkness. Moreover, the addition of a melatonin receptor antagonist to the blood collected during darkness (i.e., high melatonin) eliminated the ability of the blood to inhibit the growth and metabolic activity of perfused tumors. Circadian disruption by chronic phase advancement (i.e., simulating jet lag) also increases cancer growth in laboratory animals (Filipski 2004 & 2005). The preponderance of experimental evidence supports the hypothesis that high circulating levels of melatonin during the night not only provide a potent circadian anticancer signal to established cancer cells but help protect normal cells from the initiation of the carcinogenic process in the first place (Blask 2009 & 2011).

Melatonin exhibits antiproliferative and antioxidant properties, modulates both cellular and humoral responses, and regulates epigenetic responses (Brzezinski 1997, Korkmaz 2009, Reiter 2010). Melatonin also may plays a role in cancer cell apoptosis and in inhibiting tumor angiogenesis (Sainz 2003, Lissoni 2001). While the experimental evidence from rodent cancer models links disruption of circadian rhythms and circulating melatonin concentrations (inversely) with progression of disease, the human evidence is indirect and based on epidemiological studies. Breast cancer has received the most study. The hypothesis that the increasing use of electricity to light the night might be related to the high and increasing breast cancer risk in the industrialized world and to mortality rates in the developing world was first articulated in 1987, and summarized by a comprehensive review by the American Medical Association (Stevens 1987; Stevens 2012; Stevens 2016). Potential pathways include suppression of the normal nocturnal rise in circulating melatonin and circadian gene function. (Hoffman 2010, Stevens 2009). Conceptually, this theory would predict that non-day shift work would raise risk, blind women would be at lower risk, reported sleep duration (as a surrogate for hours of dark) would be inversely associated with risk, and population nighttime light level would co-distribute with breast cancer incidence worldwide. All these effects have been seen and reported (Kloog & Stevens 2010). Based on studies of non-day shift occupation and cancer (mostly breast cancer), the International Agency for Research on Cancer (IARC) concluded that “shift-work that involves circadian disruption is probably carcinogenic to humans” (Recommendation Level 2A; IARC 2010). A detailed review of the individual studies supporting this conclusion is available (Straif 2007). A large case-control study of nurses in Norway found a significantly elevated risk in subjects with a history of regularly working five or more consecutive nights between days off, and another found that as the type of shift (e.g., evening, night, rotating) became more disruptive, the risk increased (Lie 2011, Stevens 2011, Hansen 2011). In the Nurses Health Study cohort, increased urinary excretion of melatonin metabolites also was associated with a lower risk of breast cancer (Schernhammer 2009).

Although shiftwork represents the most extreme example of exposure to light at night and circadian disruption, perturbation of circadian rhythms and the melatonin signal is also experienced by non shift workers with a normal sleep/wake-cycle. Anyone exposing themselves to light after dusk or before dawn is overriding the natural light-dark exposure pattern. After lights are out for bedtime, there is evidence that ambient background light from weak sources in the bedroom or outside light coming through the window could influence the circadian system. In the large and comprehensive study from the Harvard department of population medicine, the Nurses Health study II, which involved 110,000 women followed from 1989-2013, outdoor LAN was directly correlated with higher breast cancer levels (James 2017). The researchers linked data from satellite images of Earth taken at nighttime to residential addresses for each study participant. The study also factored in detailed information on a variety of health and socioeconomic factors among participants. Women exposed to the highest levels of outdoor light at night—those in the top fifth—had an estimated 14% increased risk of breast cancer during the study period, as compared with women in the bottom fifth of exposure. As levels of outdoor light at night increased, so did breast cancer rates. There are now a number of studies that have shown such a link between cancer rates and outdoor lighting levels, including studies from Haim, Kloog, Portnov, and colleagues, who provided correlational data connecting satellite-measured light at night from the DMSP OLS system to breast and prostate cancer, indicating a connection between outdoor lighting levels and rates of these cancers (Li 2010,Rybnikova 2015, Kloog 2008-2011). Similar studies have reinforced these findings in different populations around the world (Bauer2013, Hurley 2014, Garcia-Saenz 2018). In addition, evidence also suggests that once breast cancer occurs, exposure to even dim LAN can accelerate the spread of the cancer (Anbalagan 2019), whereas melatonin has been shown to suppress breast cancer spread by blocking certain gene expression (Lopes 2016, Mao 2016). One negative study from Canada has been published (Ritonja, 2020), possibly explained by higher use of blackout shades for northern summer sleeping.

A number of other case-control studies have now reported an association of outdoor nighttime light level in the bedroom with breast cancer risk (Rybnikova 2015). Despite the difficulty of gathering reliable information on bedroom light level at night, the possibility that even a very low luminance over a long period of time might have an impact is important (Stothard 2017). The lowest level of light intensity that could, over a long time period, affect the circadian system has not been established. In the modern world, though, few people sleep in total darkness, so the potential risks may affect large percentages of the global population.

Light-at-night and circadian disruptions have been suggested to play a role in other cancers. Men who reported the highest level of exposure to indoor LAN were at greater risk of prostate cancer than men who reported no indoor illumination at night. Outdoor LAN in the blue-light spectrum, which is believed to be the most biologically relevant exposure, was also positively associated with prostate cancer (Garcia-Saenz 2018). Other possible associations include ovarian, colorectal, and non-Hodgkins lymphoma, but evidence comparable to that obtained for breast cancer has not yet been developed.

5.2.6. OTHER HEALTH EFFECTS

The modern world is experiencing an epidemic of obesity and diabetes that may be influenced by lack of sleep, lack of dark, and/or circadian disruption, with strong evidence that chronic exposure to light at night increases risk of cancer, diabetes, obesity, and heart disease (Cappuccio 2010, Lunn

2017). Shift workers have a higher incidence of diabetes and obesity (Pietroiust 2010). Epidemiological studies also show associations of reported sleep duration and risk of obesity and diabetes (Gangwisch 2009). Circadian disruption may be a common mechanism for these outcomes and potential links between the circadian rhythm and metabolism (Pietroiusti 2010). In addition, incidence of cardiovascular disease and obesity increases from chronic sleep disruption or shiftwork and is associated with exposure to brighter light sources in the evening or night (Smolensky 2015).

Emerging evidence suggests that other chronic conditions also may be exacerbated by light at night exposure and ongoing disruption of circadian rhythms, including depression and mood disorders, gastrointestinal and digestive problems, cardiovascular effects, and reproductive functions (Obayashi 2018, Koo 2016, Motta 2012). Circadian rhythm and sleep are intimately related but are separate phenomena. Adequate daily sleep is required for maintenance of cognitive function and for a vast array of other capabilities that are only partially understood. Sleep is not required to synchronize the endogenous circadian rhythm, whereas a stable 24-hour light-dark cycle is required, and is adversely affected by outdoor ALAN (Patel 2019, Xiao 2010, Ohayon 2016) and low daytime light exposures (Wright 2013).

A Stanford study of 15,863 people used the Defense Meteorological Satellite Program (DMSP) to measure how much outdoor light those people were exposed to at night. People living in urban areas of 500,000 people or more were exposed to nighttime lights that were three to six times more intense than people living in small towns and rural areas. The study showed that outdoor nighttime light affects sleep duration and was significantly associated with sleep disturbances. People living in more intense light areas were more likely to sleep less than six hours per night than people in less intense light areas, and have higher rates of depression (Keigo 2018). People living in more intense light areas were more likely to be dissatisfied with their sleep quantity or quality than people in less intense light areas, with 29 percent dissatisfied compared to 16 percent. It was recommended that people may want to consider room darkening shades, sleep masks or other options to reduce their exposure, though a better solution would be better engineered lighting taking human physiologic effects into consideration (Am. Academy Neuro, 2016). A large study involving 10,123 adolescents has shown sleep disturbance in highly lit urban areas compared to rural areas, leading to a marked increase in mood and anxiety disorders (JAMA 2020), and low level LAN had adverse effects that persisted later in adolescents (Borniger 2014).

The epidemiological and laboratory research on sleep and health cannot entirely separate effects of sleep duration from duration of exposure to dark, because the sleep-wake cycle partitions light-dark exposure to the suprachiasmatic nucleus (SCN) and pineal gland (Djjk 2004). The distinction is important because a requirement for a daily and lengthy period of dark to maintain optimal circadian health has different implications than a requirement that one must be asleep during this entire period of dark; many individuals normally experience a wakeful episode in the middle of a dark night. Light during the night will disrupt circadian function as well as sleep, and the health consequences of short sleep and of chronic circadian disruption are being intensively investigated (Van Cauter 2008). Media use at night (i.e., televisions, computer monitors, cell phone screens) negatively affects the sleep patterns of children and adolescents and can suppress melatonin concentrations. The American Academy of Pediatrics recommends removing televisions and computers from bedrooms to assist in limiting total "screen time" on a daily basis (Garrison 2011). This action also may help in improving sleep patterns.

Understanding the neuroscience of circadian light perception can help optimize the design of electric lighting to minimize circadian disruption and improve visual effectiveness. White LED streetlights are currently being marketed worldwide in the name of energy efficiency and long-term cost savings, but such lights have a spectrum containing a strong spike at the wavelength that most effectively suppresses melatonin during the night. It is estimated that a blue-rich LED lamp can be 5 times more powerful in influencing circadian physiology than a warmer lamp based on melatonin suppression not seen with dimmer, longer wavelength light (Koo 2016, Falchi 2011, Lucas 2014). Thus, white LED street lighting patterns could contribute to the risk of chronic disease in the populations of cities in which they have been installed.

5.3. EFFECTS OF ARTIFICIAL LIGHT AT NIGHT ON FLORA AND FAUNA

Approximately 30% of all vertebrates and over 60% of all invertebrates known today are nocturnal (Hölker et al. 2010b). Specifically, more than 60% of all known mammals and over 50% of all known insects are adjusted to the ecological niche of the night. Nocturnal animals of all kinds adapted their behaviour and sensory systems to nocturnal low-light conditions and can be directly affected if these conditions are altered by ALAN. ALAN can also affect diurnal animals directly or indirectly (Knop et al. 2017, Kurvers et al. 2018). The duration and intensity of perceived daylight, the course of twilight, and the natural light during night, in particular moonlight, provide signals for orientation and rhythms and thus represent important information for most organisms.

ALAN can have significant effects on organisms and reduce the resilience of populations (Longcore & Rich 2004, Rich & Longcore 2006, Gaston et al. 2012, Gaston et al. 2013, Meyer & Sullivan 2013). Some organisms will avoid lit areas (Beier 1995, 2006, Stone et al. 2009, Stone et al. 2012), while a few might benefit from the presence of ALAN, which has consequences on food-webs and habitat use (Manfrin et al. 2018). The impact of ALAN on the nocturnal organism level can cascade into ecosystems and also affects day-active organisms and their ecological functions (Hölker et al. 2010a, Hölker et al. 2010b, Longcore 2010, Gaston et al. 2013; Bennie et al 2015).

Here we present the impact of ALAN on migration and habitat use, ecological functions, the timing and quantity of reproduction, and the immune system in various taxa. The impact of ALAN is a major risk factor for biodiversity and consequently global food supply. The impact threatens many endangered nocturnal taxon groups such as bats and amphibians (Hölker et al. 2010b), but it also threatens the habitat and ecological functions for non-endangered organisms including many insect species, wildflowers, small mammals, and birds. With noteworthy exceptions, environmental protection regulations in most nations hardly if at all consider ALAN as a detrimental ecological factor and thus mitigation is not widespread, despite guidance that is available to minimize those impacts.

5.3.1. IMPACTS ON MIGRATION AND HABITAT USE

Nocturnal animals have evolved under dark natural night skies and some even navigate and migrate using the stars at night (Foster et al. 2018). Attraction, repulsion and disorientation are possible outcomes of encounters between wildlife and ALAN (Longcore & Rich 2004). The migratory movement of wild animals can be impaired by ALAN in both the horizontal and the vertical. Many migrating species are attracted to light and are held up on their migration routes by ALAN. Other species, however, avoid ALAN and are restricted to non-illuminated areas on their migration routes. The most well-known situation is the attraction and disorientation of sea turtle hatchlings on ocean beaches, which results in the death of the juvenile turtles that do not reach the ocean (McFarlane 1963). Research conclusively shows that ALAN can have an adverse impact on the foraging behavior of bat species, and excludes certain species from foraging routes or areas (Stone et al. 2009, Polak et al. 2011). Cabrera-Cruz et al. (2019) found that the difference in flight altitudes of nocturnally migrating birds between urban and non-urban areas was consistently higher over urban areas, suggesting that the effects of urbanization on wildlife extend into the aerosphere and are complex, stressing the need for understanding the influence of anthropogenic factors on various habitats in air and water, and not only on land.

Aquatic Organisms. The drift of aquatic insect larvae can be impaired in illuminated flowing waters (Henn et al. 2014; Perkin et al. 2014). Zooplankton and smaller fish use the protection of darkness to drift into higher layers of the water column at night time and descend during daylight hours. Direct ALAN or skyglow can suppress this daily vertical migration of zooplankton in urban lakes (Moore et al. 2000). Zooplankton in Arctic waters showed reaction to ALAN down to depths of 200 m (Berge et al. 2020) and was even disturbed by ship lights (Ludvigsen et al. 2018). Cruise tourism with high usage of artificial lighting has been identified as a potential cause of fragmentation and loss of habitats for marine species (Carić and Mackelworth, 2014). Fish predation behavior and the occurrence of small and medium size fish species changed dramatically in coastal waters (Bolton et al. 2017) as well as daytime behavior of fish regarding habitat use in freshwater systems when exposed to ALAN (Kurvers et al. 2018).

Illuminated overpass and crossing structures such as bridges and weirs impose barriers for migratory fish, as demonstrated for salmonid fish and eels that occasionally interrupt their migration at such structures (Cullen & McCarthy 2000; Lowe 1952; Nightingale et al. 2006). Even ALAN on the order of artificial skyglow can disrupt the nightly migrations undertaken by the crustacean amphipod *Talitrus saltator*, which is normally guided by the sky position of the Moon (Torres et al. 2020).

Aquatic predator-prey relationships can also be influenced by ALAN as shown for pacific salmon (Mazur & Beauchamp, 2006), bullheads, juvenile red salmon (Tabor et al., 2004), yellowfin bream, leatherjackets (Bolton et al., 2017) as well as for seals (*Phoca vitulina*) (Yurk & Trites, 2000). The spawning of salmon larvae was observed to be delayed by about three days (Riley et al. 2016), resulting in fishes migrating in smaller groups and thus under higher predation risk.

Birds. Disruption of bird migration and fatalities were already reported more than 100 years ago at lighthouses (Squires and Hanson 1918) and later for floodlights of airport ceilometers (Howell et al. 1958). A study of the *Tribute in Light* installation in New York City documented an increase from 500 birds within 0.5 km of the vertical light beams before they were turned on to 15,700 birds within 0.5 km 15 minutes after illumination (Van Doren et al. 2017). Upwards directed ALAN, measured by satellite, is associated with greater numbers of birds present during the day, especially in the fall when juveniles are migrating south (La Sorte et al. 2017). Birds can be attracted by urban ALAN and then end up disproportionately using urban habitats as compared to rural habitats with higher food availability (McLaren et al. 2018). The major bird migration routes cross highly light-polluted areas. Many migrating birds traverse large expanses of land twice every year at night when ALAN illuminates the sky (Cabrera-Cruz et al. 2018). A helpful tool for future but also past research on nocturnal bird migration is weather radar, which can detect migrating bird species.

Attraction at night is only the first hazard. Urban habitats and especially business districts are dangerous landing grounds for birds, because they are susceptible to collisions with glass, which they do not perceive as a barrier (Klem 1990, Sheppard & Phillips 2015). The combination of ALAN followed by daytime glass exposure is a significant threat to songbirds during the already strenuous migratory period (Cabrera-Cruz et al. 2018). Numerous studies present the risk of coastal birds colliding with natural structures or buildings due to ALAN (Telfer et al. 1987; Rodríguez & Rodriguez 2009; Miles et al. 2010; Rodriguez et al. 2014, 2015) and how warm light spectra and regulated light intensities can reduce fatal collisions (Rodriguez et al. 2017; Rebke et al. 2019). Lighting on communication towers is associated with significant annual bird fatalities correlated with lighting (Longcore et al. 2012, 2013, Gehring et al. 2009)

ALAN also affects habitat use and predator prey-relations in birds. Partridge are documented to roost closer to each other on darker nights and can see predators farther away on lighter nights (Tillmann 2009). An experimental study of the effect of streetlights (20 lx) on breeding bird density shows a negative impact (De Molenaar et al. 2006). The adverse effects of these lights (decreased density of Black-tailed Godwit nests) were experienced up to 300 m (984 ft) from these lights, extending into areas with negligible increased illumination, which means that the adverse impact results from the light being visible, rather than the amount of light incident on the sensitive receptor.

Insects. Many families of insects are attracted to lights, including moths, lacewings, beetles, bugs, caddisflies, crane flies, midges, hoverflies, wasps, and bush crickets (Sustek 1999, Kolligs 2000, Eisenbeis 2006, Frank 2006, Longcore et al. 2015). Female mayflies, performing their upstream compensatory flight, are attracted upward toward bridge lamplight and subsequently to the bridge's road surfaces that appear to them as water surfaces, because the concrete surface causes a light polarization pattern similar to that from water surfaces (Szaz et al. 2015).

ALAN, especially with significant emission at ultraviolet or blue wavelengths, is highly attractive to insects (Eisenbeis 2006, Frank 2006, van Langevelde et al. 2011, Barghini and de Medeiros 2012) and insects attracted to lights are subject to increased predation from a variety of predators, including bats, birds, skunks, toads, and spiders (Blake et al. 1994, Frank 2006). Moths, which have a key role in the ecosystem as pollinators, are particularly attracted to lights (Macgregor et al. 2015, Macgregor et al. 2017, Knop et al 2017) and are often killed in collisions with lights or by becoming trapped in housings (Frank 1988, 2006). Short of death, this attraction lures insects out of their ecological functions (Meyer and Sullivan 2013) in what Eisenbeis (2006) calls the "vacuum cleaner effect".

Bats. The responses of different bat species to lighting are complex (Rydell 2006, Voigt et al. 2018). Some faster-flying and more maneuverable species can be attracted towards ALAN sources in exploiting the high prey abundance. Slower and less maneuverable species will avoid lights, essentially being repulsed by their presence (Stone et al. 2009, Stone et al. 2012, Stone et al. 2015). Light at the entrance of a roost can keep bat species in general from emerging for their nightly foraging (Boldogh et al. 2007). The attraction and avoidance of ALAN is species dependent and associated with their seasonal and daily behaviour such as root emergence, drinking and foraging or resting. For most ecological needs in almost all bat species ALAN is a disturbing factor (Voigt et al. 2018).

ALAN that spills into commuting routes or flyways can significantly reduce the habitat use for many bat species. The behavior of light-sensitive bats can be impaired within the radius of up to 50 m distance to the light source, even if the illuminance level is as low as 1 lx (Azam et al. 2018, Pauwels et al. 2019). Some species of bats avoid artificial lights to reduce predation risk (Stone et al. 2009, Polak et al. 2011). Hale et al. (2015) observed that the success to cross illuminated areas depends on light intensity and width of the non-illuminated gap. The study presents a common urban bat (*Pipistrellus pipistrellus*) selecting dark crossing routes at gaps, e.g. at trees. The avoidance of lit passages can lead especially to disturbed drinking behavior for many bat species (Russo et al. 2017, Voigt et al. 2018). The illumination of roosts or the entrance to it can cause the bats to abandon roosts in the worst case (Stone et al. 2015b). When migrating, some species, e.g., *Pipistrellus* spp., can be attracted especially to white and green lights (Spoelstra et al. 2017) and become distracted by phototaxis from their migration routes (Voigt et al. 2017). Azam et al. (2016) judge the effects of ALAN on bat populations as being more impacting on the occurrence and the activity of bats than increasing imperviousness of the land through development. In Sweden, bat occurrence was observed at illuminated and non-illuminated churches. Bat colonies decreased significantly in frequency from 61% in 1980s to 38% by 2016, especially at sites where churches were lit from all directions, leaving no dark corridor for the bats to leave and return to the roost. In contrast, in churches that were not lit, no colony decrease was observed after 25+ years (Rydell et al. 2017).

Non-flying mammals. The presence of permanent outdoor lighting can erode landscape connectivity for wildlife species (Stone et al. 2009). This phenomenon was illustrated by a radio telemetry study of young mountain lions in Orange County, California (Beier 1995):

> "Overnight monitoring showed that dispersers especially avoided night-lights in conjunction with open terrain. On M12's initial encounter with a well-lit sand factory and adjacent sand pits, he took 2 hours and 4 attempts to select a route that skirted the facility, after which he rested on a ridgetop for 2 hours. During 2 nights in the Arroyo Trabuco, M8 explored several small side canyons lacking woody vegetation. He followed each canyon to the ridgetop, where city lights were visible 300–800 m west. He stopped at each canyon ridgetop for 15–60 minutes before returning to the arroyo, without moving >100 m into the grasslands west of the ridgeline in view of the city lights."

Further data on the use of underpasses and the influence of lighting on landscape connectivity have been reported. An experimental evaluation of underpass use by wildlife found that for mule deer, even nearby lights affected movement compared with a reference period (Bliss-Ketchum et al. 2016). Small mammals respond to illumination in their foraging activities. For example, artificial light of about 0.1 lx reduced the activity, movement, or food consumption of a cross-section of rodent species (Clarke 1983, Brillhart and Kaufman 1991, Vasquez 1994, Falkenberg and Clarke 1998, Kramer and Birney 2001). This phenomenon has been shown in natural (in addition to laboratory) conditions (Kotler 1984, Bliss-Ketchum et al. 2016, Wang and Shier 2017, Wang and Shier 2018, Hoffmann et al. 2019).

The driving force behind patterns of activity and foraging by animals influenced by ALAN is presumably predation. Additional ALAN might increase success of visually foraging predators, thereby increasing risk to their prey, with one critical exception: prey species with a communal predator defence, such as schooling or flocking, have decreased risk of predation with additional light. Evidence for this general pattern continues to accrue. A general review of nocturnal foraging suggests that night is a refuge with decreased overall predation on birds and mammals, and that foraging groups are larger at night, especially for clades that are not strictly nocturnal (Beauchamp 2007). Songbirds that were experimentally relocated moved back to their home ranges at night, a result that is most consistent with predator avoidance (Mukhin et al. 2009). Predator-prey systems are tightly tied into lunar cycles, with many relationships affected by lunar phase (Williams 1936, Sutherland & Predavec 1999, Topping et al. 1999, Riou and Hamer 2008, Upham and Hafner 2013). Even within species, variation in color interacts with the lunar cycle to affect foraging success. White-morph Barn Owls have an advantage foraging during the full moon because the light reflecting off their white feathers triggers their rodent prey to freeze in place, while Barn Owls with darker colored feathers do not have this advantage (San-Jose et al. 2019).

Lit habitats often get lost for the use by nocturnal wildlife and often these areas also are not populated with day-active organisms (Longland 1994; Rotics et al. 2011; LeTallec et al. 2013; Ciach et al. 2019). Illuminated areas thus can become "blind ecological spots", which can become vulnerable to invasive species, better adapted to anthropogenic disturbances. This also includes vegetation, because the avoidance of habitat by frugivores (i.e. frugivore bats) results also in a reduction of seed dispersal into illuminated habitat (Lewanzik and Voigt 2014).

5.3.2 IMPACTS ON ECOLOGICAL FUNCTIONS

Habitat that is not used by organisms due to ALAN avoidance behaviour or the vacuum cleaner effect may be reduced in important ecological functions such as pollination, food supply or clearing functions. *Pollination*. Experimentally lit meadows in the Alps resulted in decreased numbers of visits to a thistle species by nocturnal pollinating insects by 62%. The decreased night-time pollination resulted in reduced fruit developments. The network for both night and day-time pollinators was affected by the night time illumination as food availability was reduced even for day-active pollinators (Knop et al. 2017). The reduced pollination led to reduced numbers of day-active pollinators as well, since the thistle as an important food source was negatively impacted. Thus ALAN has an impact on both pollination and the availability of food. As described earlier, the high attraction of moths to ALAN has a rather high impact on nocturnal pollination activity. Wildflowers are especially affected. Furthermore, nocturnal pollinators were observed to carry pollen from a reduced number of plants when exposed to streetlights, indicating less pollination activity on wildflowers (Macgregor et al. 2017). Their ecological necessity is today not yet fully understood, but studies such as Knop et al. (2017) present a rather high significance function on the stability of biodiversity and functioning of ecosystem networks (Fontaine et al. 2005). *Water quality*. The lack of migration in aquatic zooplankton (Moore et al. 2000) paired with the observation of altered periphyton growth and changed phytoplankton community structures in freshwater bodies (Grubisic et al. 2017, 2018; Poulin et al. 2014) could potentially trigger algae blooms and significantly decrease the water quality in freshwater systems.

Consumption of carcasses. ALAN can significantly impact the food-webs in disrupting predator-prey relations. The oversaturation of insect prey at ALAN sources and beneath them can increase the number of scavengers such as spiders, Harvestmen and snails (Davies et al. 2012; Manfrin et al.2018; van Grunsven et al. 2018).

Food sources and predator prey relations. The massive attraction of insects to ALAN sources leads to reduced food sources for many organisms, an effect that can cascade into higher levels of the food-web. Bats, which in natural conditions prefer to catch beetles, will consume more moths (Cravens et al. 2017), which in turn leads to decreased nocturnal pollination.

5.3.3. IMPACTS ON REPRODUCTION

The rhythm of light and dark is an important Zeitgeber. The timing for pairing and reproduction relies on the circadian, lunar and seasonal rhythms of light. Hormone metabolism is triggered by the signal of light. ALAN can suppress the metabolism of melatonin, which is important for the circadian metabolism and hormones that trigger the circadian and seasonal timing including the signal for reproduction (Grubisic et al. 2019). The lack of the natural light signal can expand the timing of birth in mammals (Le Tallec et al. 2013; Robert et al. 2015), birds (de Young et al; 2016, Dominoni et al. 2013; Ouyang et al. 2017), amphibians (Baker & Richardson 2006), and fish (Brüning et al. 2016a, b).

Mammals. The reproductive state is determined by the trend of the day length and not its absolute length (Gerlach & Aurich 2000). When natural light conditions are polluted by ALAN this signal can become blurred, and thus mammals' seasonal changes can be affected (LeTallec et al. 2013).

Birds. ALAN can affect diurnal species substantially as well. Research on the effects of ambient and artificial lighting on bird reproduction goes back to the 1920s (Rawson 1923, Rowan 1938). Research shows an earlier start to seasonal breeding of birds in urban (lit) environments compared to rural (dark) environments (Havlin 1964, Lack 1965). Light of 0.3 lx can move reproductive seasonality of songbirds by a month and cause irregular molt progression (Dominoni et al. 2013a, Dominoni et al. 2013b). Timing of the dawn song and lay date in a songbird have been shown to be associated with proximity to streetlights, further affecting mate choice, which has implications for fitness (Kempenaers et al. 2010). A songbird (Tree Sparrow *Passer montanus*) exposed at night time to 6 lx in the laboratory secreted luteinizing hormones earlier than controls. This effect was observed also with urban birds exposed to 3–5 lx night lighting (Zhang et al. 2014).

Fish. In perch and roach, two common fish species in inland waters, blood concentration of sex steroids as well as the synthesis of reproduction hormones (luteinizing hormone, follicle stimulating hormone) were reduced (Brüning et al. 2018b).

Plants. ALAN affects the perception of seasonal change by plants and their associated physiological responses. Exposure to ALAN is associated with earlier budburst in plants, in a pattern that cannot be explained by the greater temperatures in cities (Ffrench-Constant et al. 2016). Trees exposed to nearby lights have long been observed to hold on to their leaves later in the fall (Briggs 2006, Škvareninová et al. 2017, Massetti 2018) and prevent seed set in plants cued to shorter day lengths (Palmer et al. 2017). In wildflowers a decline in the quality of pollination was measured (Knop et al. 2017; Macgregor et al. 2017) as well as a negative impact especially of blue-rich white LED street-lights on seed production of wild flowers (Macgregor et al. 2019).

Insects. With an estimated 6-10 million species, insects represent more than half and potentially 90% of known living organisms (Novotny et al 2002; Chapman 2006). About 50% are nocturnal or crepuscular and thus highly adapted to the night niche. Of the order Lepidoptera about 77% are nocturnal and important pollinators (Hölker et al 2010b). Population trends in this order of insects have been observed to decline under long time exposure to ALAN (van Grunsven et al. 2019), and some researchers point to ALAN as a significant driver of the observed overall precipitous population decline of insects worldwide (Owens 2020). The reproduction of insects can be affected by ALAN directly: pheromone production of single female moths exposed to streetlights was observed to be reduced in quality and quantity (van Geffen et al. 2014). Artificial light at night also affects the visual communication required for reproduction of species such as the bioluminescence in fireflies, contributing to the decline of fireflies and other organisms that rely on bioluminescent communication (Lloyd 2006, Hagen and Viviani 2009, Viviani et al. 2010, Bird and Parker 2014, Owens 2018). A Brazilian study documented lower species richness of fireflies in areas of 0.2 lx and greater (even from sodium vapour lamps, which are otherwise considered to be more wildlife friendly), except for those few species that naturally fly at greater illumination (Hagen and Viviani 2009).

5.3.4. IMMUNE RESPONSES

Studies on the physiological effects of ALAN on mammals are numerous, partly because of the implications for understanding human health (e.g., Zubidat et al. 2007, Zubidat et al. 2010). As a whole, they show that ALAN at levels far less intense than previously assumed are able to entrain circadian rhythms and influence physiological functions such as immune response (Bedrosian et al. 2011; Gubisic et al 2019). For example, extremely dim light is sufficient to entrain rhythms in mice, and can be done without phase shifting or reducing production of melatonin (other physiological indicators of light influence) (Butler and Silver 2011). For shorter wavelengths (blue and green) entrainment takes place at 10^{-3} lx. Much greater intensity, 0.4 lx, is needed for red light to entrain rhythms (Butler and Silver 2011). This research is consistent with recently documented differences in mice behaviour for exposure to 20 lx vs. 1 lx at night (Shuboni and Yan 2010). Mice that were exposed to dim (5 lx) light at night consumed the same amount of food as those under dark controls, but gained weight as a result of the shift in time of consumption (Fonken et al. 2010).

Birds (*Parus major*) roosting in white light were much more active at night and present a higher probability of malaria infection (Quyang et al. 2017). Saini et al. (2019) found that chronic ALAN exposure significantly increased bactericidal activity and that this elevation in immune performance manifested at different developmental time points in male and female quails. ALAN intensities of 0.5 to 5 lx significantly increased cell proliferation in the ventricular brain zone and decreased the neuronal densities in two brain regions suggesting neuronal death (Moaraf et al. 2020).

Plants “anticipate” the dawn with a synchronized circadian clock and increase immune defence at the time of day when infection is most likely (Wang et al. 2011). The timing of resistance (R)-gene mediated defences in *Arabidopsis* to downy mildew is tied to the circadian system such that defences are greatest before dawn, when the mildew normally disperses its spores (Wang et al. 2011). The importance of circadian rhythms in plants, for all functions from disease response and flowering time to seed germination, and the potential for disruption by night lighting, has not been explored widely (Resco et al. 2009, Bennie et al. 2016). Adverse effects on ornamental plants and agricultural plant production have been observed in forms of decreased stomatal movements (Kwak et al. 2018), shifted community compositions (Bennie et al. 2016), accumulation of superoxide radicals (Kwak et al. 2017), triggered stress responses (Nitschke et al. 2016; Meravi et al. 2020), soybean maturation delay (Palmer et al. 2017) and changed photo-physiology (Kwak et al. 2018; Meravi et al. 2020).

5.3.5. Impacts on biodiversity and food supply

The impact of direct ALAN and skyglow is thus a major factor in the decline of habitat for nocturnal wildlife, reducing ecological functions and reproduction, and consequently leading to loss of biodiversity as sensitive organisms experience decreasing food sources and habitat. The impact on the hormone systems of many organisms makes the ecosystem vulnerable because many individuals lack sufficient immune response against stress factors such as anthropogenic pollutants and disturbances.

The stress response of trees implies that trees can be weakened by ALAN, which might be critical to climate change as trees are an important factor in balancing CO_2 emissions. ALAN has direct impacts on crops and therefore on food production. The impact of ALAN on primal states of the food webs, as described earlier, such as changes in periphyton communities and insects, are especially important for more detailed study, as the effects will propagate into higher levels of food webs. With both organisms and ecological functions weakened, we face unpredictable changes in ecosystems. Unlike temperature, which has changed dramatically over the history of life on Earth, alterations in the brightness of nightscapes are a very new physical phenomenon, and we lack crucial knowledge about responses and adaptation of organisms to ALAN. Considering the growing stress factors like increasing temperature, changing climate, pollutants such as plastics and heavy metals, and overpopulation, we might want to decrease anthropogenic stressors where possible; light pollution is one anthropogenic factor that could be regulated and reduced easily.

5.3.6. Biodiversity strategy and gaps in protection against adverse effects of ALAN

A global biodiversity strategy and regulations for the protection of nature are important for authorities, decision makers, and other stakeholders in order to protect the quality of life that we are used to. For example the EU biodiversity strategy claims: “Biodiversity is essential for life. Nature provides us with food, health and medicines, materials, recreation, and wellbeing. A healthy ecosystem filters our air and water, helps keep the climate in balance, converts waste back into resources, pollinates and fertilises crops and much more. Nature also provides for businesses: half of the world’s Gross Domestic Product (GDP), €40 trillion, depends on nature. We are losing nature like never before because of unsustainable human activities. The global population of wild species has fallen by 60% over the last 40 years. 1 million species are at risk of extinction” (European Green Deal 2019). However, the strategy hardly considers the effects of ALAN on biodiversity and ecosystem services.

Neither ALAN nor light pollution is considered in the Global Assessment Report on Biodiversity and Ecosystem Services by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IBPES) and the summary for policymakers.

Schroer et al. (2019) discuss protection gaps for adverse effects of ALAN in European environmental protection regulations. While protection is predominantly provided for species with special protection status that reveal avoidance behaviour of artificially lit landscapes and associated habitat loss, adverse effects on species and landscapes without special protection status are often left unaddressed by existing regulations. Legislative shortcomings are caused by difficulties in proving evidence for significant adverse effects on the population level, detecting associations with reduced population resilience and lighting malpractice, and applying the law to ALAN-related situations. Although nature conservation regulations and emission control law provisions apply for example in Europe, substantial shortcomings remain:

a The protection of habitats is spatially limited and even within its application it requires an individual impact assessment. However, assessments for lighting systems are so far not subject to approval procedures, in most European countries and worldwide.

b In order to trigger the protection of listed specially protected species, an adverse effect such as the injury, death, or avoidance behaviour of a specimen generally has to be documented. However, this requirement excludes most of the adverse effects of ALAN, which do not directly harm the specimen but weaken the resilience of populations.

c Most provisions require either a significant increase in killing risks or a significant decline of a local population. Both criteria are in ALAN-related situations difficult to assess.

In the United States, light pollution's impacts on flora and fauna are not well regulated. It is possible to consider them as an impact in the preparation of assessments under the National Environmental Policy Act, but the professional practice of doing so is underdeveloped, leaving concerns to be raised by the public. Direct impacts of ALAN on organisms can also be regulated under the federal Endangered Species Act. At the state level, some states have laws that require environmental review as well, but they too do not have a well-developed practice of considering the ecological impacts of ALAN. The U.S. National Park Service has published a guidance document on management approaches to minimize ecological effects of ALAN on protected lands (Longcore and Rich 2017). The U.S. Bureau of Land Management is developing a set of best management practices for light pollution that will inform decision-making on its vast holdings.

5.4. GEOGRAPHICAL AND TERRITORIAL IMPACTS OF LIGHT POLLUTION

Light pollution is pollution, and should be treated as such. Artificial light at night introduces into the atmosphere a huge number of particles (photons) that should not be there during nighttime, and that give rise to detrimental consequences either by its own direct effects (e.g. by directly activating key physiological processes or distorting predator-prey relationships) or by reducing the spatial and temporal contrast of the natural night light cycles (e.g., erasing the monthly rhythm of natural illumination associated with the Moon).

Light pollution displays the characteristics of any classical form of pollution. It has, like any other kind of pollution, specific spatial and temporal features. Spatially, light pollution is a form of pollution with an intermediate range of spread. Unlike greenhouse gas emissions, which are incorporated into the global circulation of the planetary atmosphere, or unlike very local episodes of contamination such as heavy metal spills, light pollution sources affect wildlife in an area with a typical size of several hundreds of km around the emission points. Photons know no borders (Bará and Lima, 2018), and political and administrative territorial divisions do not prevent their propagation beyond the particular area from where they were emitted. Artificial light can distort natural wildlife by (i) increasing the levels of local illumination (irradiance on ground, due either to the direct radiance of the sources or to the increased skyglow produced by atmospheric scattering), and (ii) by the direct visibility of the source radiance itself, propagated along the line of sight. The direct radiance from the sources is not reduced by geometrical propagation factors (it does not decrease with the square of distance); it is reduced only by intrinsic attenuation processes (scattering plus absorption in the atmosphere). The high transparency of the terrestrial atmosphere allows the direct radiance to propagate with slight attenuation across long distances (~100 km) and in consequence artificial lights on the horizon can act as an extremely powerful distracting factor for those life forms highly dependent on visual processes – especially migratory birds, since at their altitude of flight a wider area of territory is visible.

Temporally, light pollution emissions present an extremely short characteristic time scale. Once the light emitting sources are switched off, in a fraction of a second all photons have been absorbed or have escaped towards outer space, and the light pollution source becomes inactivated. Importantly, though, the environmental effects produced before the switch-off can last for long periods of time, an issue deserving deeper research.

A key feature is that any linear indicator of the level of deterioration of the natural night (artificial sky brightness, horizontal irradiance in any biologically relevant spectral band, direct radiance from sources in the horizon...) depends linearly on the amount of emissions of the neighboring territories, up to several hundreds of km away (e.g. a doubling of emission leads to a doubling of level of deterioration). Non-linear indicators (e.g. the maximum brightness of the night sky) depend on the emissions in a non-linear but monotonically increasing way. Thus, in order to keep the deterioration levels below admissible thresholds for critical effects on biodiversity, it is necessary to keep within definite limits the total emissions from the surrounding territory. Each particular location (city district, village, industrial or agricultural installation) contributes to deterioration of the linear indicators proportional to its total emissions. Overall emissions and the deterioration of the nocturnal environment are inextricably linked and no remediation or control of unwanted light pollution effects can be expected if the overall emissions are not kept at bay (Falchi and Bará, 2020).

The impact of city and industrial light domes covers large portions of the surrounding territory. Even when light sources are correctly installed, adjusted, and shielded, the sky receives a part of their direct emission and another contribution from the reflection on the surfaces they light (Narisadam & Schreuder, 2004). The light is scattered in different directions by the atmosphere, creating a diffuse artificial glow (sky glow). Light emissions set in almost vertical directions run a distance approximately equal to the atmospheric thickness (typically considered as 8 km). Therefore, vertical light emissions do not generate a large contribution to sky glow because they do not suffer much atmospheric scattering. Conversely, lighting emissions in almost horizontal elevations contribute significantly to artificial sky glow because these emissions can run large distances (of more than 100 km), having a much greater probability of being scattered by the atmosphere (Narisadam & Schreuder, 2004). The dominant scattering process is Rayleigh scattering, which has an inverse dependence to the fourth power of wavelength: this means that 450nm (blue) emissions are scattered in the atmosphere three times more than emissions in 589nm (yellow - amber) and six times more than in 700nm (red). Therefore, blue emissions contribute much more intensely to artificial sky glow (Luginbuhl et al., 2009). Such scattering is responsible for the blue color of the day sky. At night, the scattering of artificial blue light by atmospheric molecules is the major cause of the substantial increase of the glow of the night sky. Only a small amount of blue light is needed to have a noticeable effect in the sky.

As discussed above, melatonin is present in an enormous variety of species, adopting multiple biological functions: antioxidant protection (which started in unicellular organisms), environmental tolerance in fungi and plants, immunomodulation and chemical expression of darkness in vertebrates, regulation of seasonal reproduction photoperiodic mammals (Grubisic et al., 2019). The

Melatonin Suppression Index (MSI) shows the potential exposure to different temperature color indices of light. The MSI confirms that the blue part of the spectrum present in LEDs ranging from 2,200 K to higher CCT has the potential to produce enormous impacts on the surrounding territory, for both wildlife and humans. Fig. 5.3 shows models of MSI under two different assumptions of LED streelighting: PC Amber, with zero blue light content, and CCT 5000 K, with 50% blue light content.

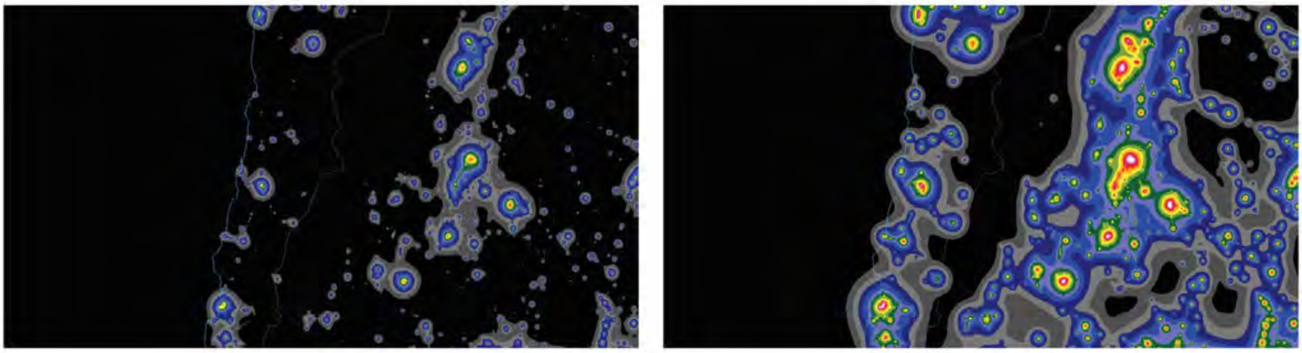

Figure 5.3: Melatonin Suppression Index (MSI) model for region of La Serena / Antofagasta, Chile. Left: Assuming PC Amber LEDs. Right: Assuming 5000K CCT LEDs.

The polarization of light in the atmosphere is relevant for multiple animals and insects, as it generates a pattern in the sky that allows them to orient and navigate. The light reflected by the Moon is also polarized (Kyba et al., 2011), although its contribution is not well understood (Jones et al., 2013). Despite the fact that the brightness of the Moon is >100,000 times less significant than sunlight, it is indeed used by a great variety of nocturnal species to navigate (Kyba el al., 2011). The zodiacal light also presents polarization (Noll et al., 2012). The polarization of Rayleigh scattering does not affect the integrated scattering of light in the atmosphere (Noll et al., 2012), and anthropogenic light pollution is not polarized, so when added to the natural light, it diminishes the total polarization, affecting the orientation capacities of many nocturnal species over the territory (Kyba et al., 2011).

Linear projects, such as highways, can fragment ecosystems, potentially making them non-viable to many species of fauna by their physical obstacles and risk of being killed by motor vehicles. Similarly, light acts as a physical barrier that can fragment ecosystems, limiting the ability of fauna to move freely for foraging, reproduction, and migration.

5.5. RECOMMENDATIONS

The preceding sections demonstrate that the biological environment is affected by ALAN in many ways. ALAN can become a pollutant and should be treated as such: there is a strong need to elaborate emission and immission control for ALAN. Since there is a large variety of affected organisms (i.e. humans and many other species) and ecosystem functions, regulations should be consistently aimed at addressing all adverse effects in a holistic and sustainable approach.

This framework should enable and promote the adoption, adaptation and implementation of environmentally friendly lighting regulations for countries, regions, municipalities, and communities. The strategy can be summarized in the four pillars of the efficient lighting scheme in order to prevent environmental harm: “The right light, at the right place, at the right amount, for the right duration.” In the context of this document, ‘right lighting’ shall be understood as that kind of lighting that verifiably meets the stated goals of environmental and human health protection and improvement, and the remediation of those lighting situations that presently fail to fulfill those goals, while enabling visual performance at the level required upon tasks.

We recommend a strategy to mitigate the adverse effects of ALAN with three main components, in order of priority:

1. Reduce radiant flux (and irradiance). In cases where information needed to specify and meet radiant flux targets is missing, then luminous flux (and illuminance) information and targets can be used. This strategy works for most if not all species and should be started with in all cases.
2. Improve control of directionality of the radiant/luminous flux.
3. Minimize melanopsin-activating blue content within the radiant/luminous flux. This approach is useful for humans and vertebrates where the circadian timing system has a similar spectral sensitivity as humans. However, there is a large variability in photoreceptors, photobiological processes and light-related behavioural responses across the bio-environment. Although reducing blue content is expected to be useful in many cases, individual species or ecosystems may require different, dedicated spectral approaches.

The following more specific recommendations aim to mitigate the adverse effects of outdoor ALAN on humans, flora, and fauna. The order of presentation does not reflect the relative significance of each recommendation.

5.5.1. AREAS TO BE ILLUMINATED

Governing bodies (e.g. countries, states, counties, etc.) should define the decision criteria for whether an area must be or is allowed to be illuminated. To minimize environmental impact, unnecessary illumination should be prevented and enforced by the governing bodies , while new outdoor lighting installations should be adequately justified. Master planning of the outdoor night-time environment shall include strategies for maintaining dark areas dark and for reduction of lighting in currently over-illuminated areas. Planning of outdoor lighting should prevent, restrict, and counteract damages or inconveniences to human health and the natural environment from ALAN.

5.5.2 GEOGRAPHICAL FRAMEWORK TO MITIGATE LIGHT POLLUTION

Maximum admissible values of the indicators of deterioration of the nighttime environment (e.g. maximum irradiance at ground level on sensitive biological bands) must be explicitly specified for each zone of the relevant territory (including urban, suburban, rural, and intrinsically dark). Corresponding quantitative caps on the maximum allowable emissions compliant with these deterioration limits should be determined and allocated amongst the relevant territorial and administrative units.

Lighting zones must be preferentially defined as a combination of the maximum allowable values of the deterioration indicators that must be enforced in each zone, and the technical specifications of the lighting installations per defined environmental zone (e.g as defined in the CIE 150:2017). The maximum allowable values should be applied independently from where the light sources are located within the zone. The technical characteristics of the sources and the absolute amount of emissions of each patch of the territory must be monitored and kept under control in order to warrant compliance with the environmental indicators of all surrounding and even distant zones.

The authorization of new lighting installations should be done (or the reductions thereof must be enforced) in a coordinated way, encompassing all territories that contribute to the deterioration of

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the nighttime environment of any given place, and not only those located in its immediate vicinity.

5.5.3. DEFINITION OF ALAN-FREE AREAS AND ECOSYSTEMS

Environmentally sensitive areas, intrinsically dark areas, nature reserves, and other similar areas can be characterized as ALAN-free zones. A new zoning system should be developed and applied, explicitly aimed at achieving verifiable ALAN-free preservation goals. Initially CIE 2017:150 and Zones E0 -- Intrinsically dark (e.g. UNESCO Starlight Reserves, IDA Dark Sky Parks, major optical astronomical observatories) and E1 -- dark areas, such as relatively uninhabited rural areas, could be adopted provisionally for these areas, although those documents do not provide specific procedures for ensuring that global deterioration limits are not surpassed, and are insufficient for environmental and human health protection goals. These provisions shall be complemented with additional ones ensuring e.g. that no light from other zones (no matter what distance away) contributes significantly to reduce the natural darkness. Further development of outdoor lighting in such areas should be prohibited or restricted by national legislation. Local regulations may also include stronger restrictions, for example on the upper limit of allowed luminance levels or specific restriction on blue light. However, limits of illuminance, luminance and spectral content of the emitted light may require site-specific adaptations if involving protected species since individual species or habitats may require a more specific approach (see section 5.5.9 Spectral content of the emitted light).

5.5.4. ILLUMINATION LEVELS FOR OUTDOOR AREAS

The appropriate lighting classes (which specify e.g. illumination level, contrast ratio, etc.) should be selected for all outdoor illuminated areas according to the established regional, national or international regulations. Lighting classes can be more than one per application area (i.e. lowering the lighting levels according to the functional parameters). The selection criteria should not overestimate the lighting classes, which results in the over-illumination of outdoor areas. Lighting design should always be informed by function-based requirements and scientific evidence-based knowledge. Balancing the goals of human vision, environmental protection, human health and public safety should be pursued via a more integrative approach than traditional lighting practices. The collective social and political decision on the relative weights to be assigned to each of these factors in any particular context should be scientifically-informed and technically-backed. Over-illumination should be avoided. The maintained average illumination levels should not exceed by more than 20% the minimum requirement of the usage class as specified in relevant scientifically-supported documents or standards.

5.5.5. LIGHTING CONTROL AND ADAPTIVE LIGHTING

Lighting control should deliver the right amount of light for the right amount of time, and only as much as necessary. All new and renovated outdoor lighting installations should incorporate means of control of the luminous flux. Lighting control systems should be added to existing installations when feasible. Lighting installations should be controlled through the hours of darkness using a predefined schedule (e.g. according to regulations of curfews) or, preferably, adaptively using sensors and human intervention techniques. Adaptive lighting control is the only mean of application of the multiple lighting classes of an areas as described in 5.5.4.

In certain lighting systems, lighting control can also alter the spectral distribution of emitted light during specific periods of time. Lighting levels should be reduced to the absolute minimum level, ideally zero, where and when no or few users are present in the relevant area. Street lighting should be properly matched to the volume and speed of traffic flow, according to the most recent findings in this field. Dimming or switching off outdoor lighting is highly recommended for rural areas and certain urban areas such as shopping centres, sport centres, and industrial areas that are not active at night.

5.5.6. Light distribution and orientation

Lighting design should be efficient and environmentally conscious. Light should be distributed only to the area targeted for illumination. Spill light and in general waste of luminous flux delivered to the surroundings should be avoided. Appropriate lighting equipment should be used for each application, including outdoor signage. Luminaires should be selected and designed to avoid spill light and waste of luminous flux by means of optics, lenses and suitable accessories such as proper shielding. Temporary lighting installations (for example aesthetic lighting) should ensure there is no negative environmental impact.

Outdoor lighting should be designed in a way to disturb ecosystems as little as possible regardless of the spatial scale, ensuring that species whose orientation and navigation are based on visibility of the stars, moon, Milky Way, and polarization of natural light at night (e.g. migrating birds, sea turtles, etc.) are not negatively affected.

Intrusion of artificial light into areas with rare, protected and/or threatened species or habitats (e.g. Natura 2000) should be avoided to prevent unwanted negative ecological impacts.

5.5.7. Intrusive light

Light entering indoor living areas should be minimized and ideally eliminated. Intrusive light can be mitigated by the following techniques:

- Efficient lighting design of public outdoor lighting near residential buildings, with mounting height of luminaires as low as possible and luminaire shielding to prevent light trespass beyond the intended subject.
- Adaptive control of lighting levels to absolute minimum according to the relevant lighting class during off-peak hours.
- Minimization of façade lighting and switching off during off-peak hours.
- Minimization of colorful and dynamic lighting (colour facades, illuminated signs, advertisements, etc.) near residential buildings and switching off of such lighting during off-peak hours.
- Control of obtrusive light from distant light sources of high intensity (e.g. stadium, park, industrial facility, etc.) by proper lighting design and luminaire shielding.
- Control of signage lighting so it is shielded to prevent light trespass beyond the intended target.

5.5.8. Glare control in roads and outdoor working places

Glare levels should be controlled and kept at their minimum limits Some present recommendations could be used as a guidance for glare control (e.g. CIE 115 for road lighting, CIE S 015 and ISO/CIE 8995-3 for outdoor areas, etc.) or newer developed documents. Rigorous, efficacious, and practicable glare measurement procedures should be developed in revised standards so that lighting projects are assessed for compliance at both the design stage and after installation. Relevant glare control should be applied to all colourful and dynamic outdoor lighting.

5.5.9. Spectral content of the emitted light

The spectral content of the emitted light, especially the content in the region of blue, should be carefully selected for the intended application to minimize negative impacts on the surrounding environment. Melanopsin-activating blue content within the radiant/luminous flux should be minimized. This approach is useful for humans and vertebrates where the circadian timing system has a similar spectral sensitivity as humans. However, there is a large variability in photoreceptors, photobiological processes and light-related behavioural responses across the bio-environment. Although reducing blue content is expected to be useful in most cases, individual species/ecosystems may require different, dedicated spectral approaches.

As a general rule, all areas that must be illuminated should be illuminated with sources having the minimum amount of blue emission possible (e.g. CCT<2200K is preferred over CCT=3000K, which is preferred over 4000K) combined with dimming control. While CCT is in worldwide use, it is a highly imperfect indicator of the detailed spectrum of artificial light sources, and should be replaced with more accurate and nuanced measures such as spectral power distribution (SPD) as they become available and standardized. Emission outside the visible spectrum (e.g. ultraviolet and infrared) should be zero. Tunable white luminaires, with variable CCT (e.g. 2200-3000K) and variable luminous flux, can be used for residential and other urban areas (commercial districts, parks, squares) in cases where there is a demonstrated need for white sources during certain periods.

Unless concerns about particular species dictate otherwise, environmentally sensitive areas should be illuminated only with sources with minimal spectral content in blue (e.g. amber LED, see Fig. 5.1) to avoid disturbance of the surrounding ecosystems. Spectral content should be considered together with luminous flux and luminaire design, e.g. light with more blue content should have lower total luminous flux.

5.5.10. Directionality of light, light modulation, flood lighting, illuminated and colourful façades, and illuminated signs

Illumination into the sky, irrespective of the source, and/or lighting over large geographical areas shall be designed to avoid sky glow and any negative impacts on society, human health, and the environment. Artificial satellites in Earth orbit should not be designed or used to provide illumination of the Earth surface.

The illumination of architectural structures and signs should be avoided during curfew while the luminance levels should be kept as low as possible following efficient lighting design techniques.

Dynamically modulated color façades such as LED billboards are strongly discouraged, especially in residential areas and in environmentally protected areas. Their luminous intensity should be reduced to the minimum level compatible with vision to prevent glare to humans and avoid impact on natural species. All illuminated façades and media advertisements should be switched off during curfew.

Lighting equipment should in general produce flicker-free lighting output. Commonly accepted metrics for the temporal light artefacts (TLA) of temporal modulated light (TML) are the “Short-term flicker index - P_{st}LM”and the “Stroboscopic Visibility Measure -SVM”. The modulation of light should be kept inside the limits defined by relevant regulations (e.g. European Union Commission Regulation (EU) 2019/2020).

5.5.11. Light measurements, ALAN and skyglow monitoring measurements

ALAN and sky glow should be carefully assessed and monitored. Lighting projects should take into account both the visual and non-visual aspects of human photoreceptors and the visual sensitivity and ecology of sensitive wildlife. A holistic assessment for urban, suburban, rural and ecological reserves should be followed. Pre-final verification of lighting installations is recommended to avoid over-illumination or other bad lighting practices. ALAN measurements and sky glow monitoring should be implemented in international, national or local regulations. Mitigation and restoration measures should be applied when scientifically-informed, socially unacceptable thresholds are exceeded. Measurements should be made using luminous quantities in conjunction with radiometric spectral quantities.

Current technical lighting norms, standards and recommendations should be revised to achieve a consistent set of prescriptions coherent with these global goals. Norms should incorporate the interdisciplinary scientific findings made in recent decades in the fields of human vision, traffic safety, effects on the environment and interactions of artificial light with human physiology and behavior.

5.5.12. URGENT RESEARCH TOPICS

Interdisciplinary research among lighting, medical, and environmental research communities is urgently needed in the following fields and should be encouraged.

- Effects of ALAN on human health, flora and fauna, visibility levels and public safety
- Thresholds for impacts of artificial light at night on humans and natural species, especially for protected and threatened species
- Measurement, monitoring and impact assessment of ecological effects of ALAN
- Studies on impact of new technologies including adaptive lighting, and other characteristics of light such as light modulation (flicker) and glare
- Scientific analysis of the need to update or adjust current technical guidelines and standards to prevent unwanted impacts on human health and the environment

Studies should use the correct and appropriate light quantities and metrics, and lighting research methods that are highly interdisciplinary. Examples of multidisciplinary methods can be found in LEUKOS Vol 15, 2019, Special issue 2-3, Lighting research methods. Finding a common language across different scientific, technical and clinical traditions is essential to ensure the results can be communicated between disciplines and implemented.

5.5.13. STRATEGIC RECOMMENDATIONS

- Establish specific regulations for outdoor lighting within each country
- Establish an accreditation system for outdoor lighting installations
- Ensure that new installations and renovations follow the relevant regulations
- Review and revise lighting the requirements for illuminating roads and highways and the lighting legislation to consider environmental effects of ALAN
- Minimize the negative effect of outdoor lighting on vision, human health and natural species
- Restore and protect affected existing ecosystems by implementing environmentally conscious lighting technology, and establishing definite and verifiable transition plans to reduce the light emissions where required
- Promote lighting education in research communities that are studying the influence of light on human and biological systems, on relevant radiometry of environmental and human health issues to lighting planners and designers, engineers, and technicians and education on the politicians, responsible officials, ecologists, and society at large for the effects of ALAN

on the environment.

- Develop a scale of ecological classes of dark skies to show the differential impact of light over ecosystems and species across the territory.
- Establish evidence-based thresholds for lighting levels that should not be exceeded in various environmental zones where there are negative effects of lighting on human health and on species and habitats
- Develop standardized methods for measuring ALAN and skyglow and establish them in the relevant national or international standards

5.6 DISCLAIMER

This report was written by the members of the Dark & Quiet Skies Bio-Environment Working Group. All members of the WG had the opportunity to view, edit, and comment on the document. The views expressed in this report are the opinions, findings, and conclusions or recommendations of the authors and do not necessarily reflect the views of the International Astronomical Union, the Commission International d'Eclairage, the United Nations Committee on the Peaceful Uses of Outer Space, or any other organizations affiliated with the authors. Most of the findings and recommendations expressed in this report reflect a consensus view by the entire Working Group. All WG members were offered the chance to express minority opinions in the following section.

Ewine van Dishoeck
President - International Astronomical Union

The International Astronomical Union (IAU), founded in 1919, consists of more than 12,000 professional astronomers of 107 different nationalities worldwide. Its mission is to promote and safeguard astronomy in all its aspects through international cooperation. Preserving the Dark and Quiet Skies is therefore a key part of its mission, and its Working Group is one of the few groups that reports directly to the IAU Executive Committee. The IAU is fully committed to raise attention to the negative impact that Artificial Light At Night (ALAN) and the deployment of satellite constellations may have on the visibility of the pristine night sky and on scientific observation of cosmic objects at all wavelengths. Its 2009 Resolution B5 on "Defence of the night sky and right to starlight" highlights the fundamental socio-cultural and environmental right of every human to enjoy, contemplate and research the firmament. The IAU activities range from outreach and education of the general public, to working with relevant national and international authorities like UNOOSA to set up policies and guidelines for the protection of astronomical quality.

The IAU hopes that this on-line workshop could lead to the establishment of a permanent forum for openly discussing the evolving interplay between technological progress and maintaining undisturbed access to the exploration of the cosmos to address the most fundamental questions that humans have. Where do we come from? What is our place in the Universe? Are we alone?

Ewine van Dishoeck
Excerpt from the welcome speech to the workshop participants

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6. SATELLITE CONSTELLATION REPORT

6.1 SIMULATION

6.1.1. CONTEXT AND OBJECTIVES

The goal of the simulations group inside the D&QS Satellite Constellations Working Group is to assess the impact of large constellations on the observation of the night sky at optical wavelengths on a sound scientific basis, using the tools of orbital dynamics, optics and observational astronomy. Using the available information about the different large constellation projects, physics and geometry allow us to compute the spacecraft visibility from any location on Earth, in terms of their apparent position in the sky, direction of their motion and apparent angular speed, and conditions of illumination by sunlight. This can produce statistics for the whole sky (bulk number of artificial objects detectable from a specific location) or for the restricted conditions constrained by realistic observational circumstances: direction of the observation, field of view and integration time.

To this end, the group has collected information from the sources available, mainly from the results of NSF's NOIRLab's SATCON1 Workshop (Walker et al., 2020), from the scientific literature and from materials elaborated by the contributors for this report. Additional simulations have been performed when needed.

The results allow formulating proposals of technical standards and mitigation strategies addressed both to the companies that launch and operate the satellites and to the astronomical community. The conclusions lead to recommendations and guidelines to mitigate the impact that may be considered by the United Nations Committee on the Paceful Uses of Outer Space (COPUOS) and other policymakers.

Our tools and conclusions share concepts and results with other subgroups, such as the observations subgroup. The conclusions reached are reliable, but there is still room for improvement in several aspects, mainly related to the fine tuning of the photometric models used to predict the apparent brightness of the satellites.

6.1.2. SIMULATIONS AND RESULTS

Our conclusions are based on simulations of three kinds: all-sky counts, pointing-oriented and spatially resolved. Both discrete and analytic approaches have been used. More technical details on the simulations are included in the Appendix D to this report, and in the technical appendices to NSF's NOIRLab's SATCON 1 report (Walker et al., 2020).

The results we present have been deduced considering a scenario with almost 78 000 satellites. These correspond to the two main projects proposed to the US Federal Communications Commission (FCC): Starlink Generation 2 (SL2) and One Web 2 (OW2). SL2 plans to place 30 000 satellites in several shells with different inclinations and with low altitudes (maximum around 600 km above the Earth surface). OW2 may place up to 48 000 satellites in shells with different inclinations, but a same altitude of 1200 km. The Appendix D provides details on the simulations and includes Table D.1, with a full description of the orbits and the number of satellites they contain.

We now very briefly describe the simulations of the three kinds and the results obtained from them. We underline that the computations have been performed by separate teams, using completely independent software, and that the results are coincident within the statistical noise level. A somewhat more detailed discussion on reliability is presented in the Appendix D.

6.1.2.1. All-sky, bulk satellite counts

All-sky (or A-kind) simulations consider the spacecraft orbits and, given a location on Earth, they predict the number of satellites that are detectable at any given instant in time. This implies computing which satellites are *above the horizon*, or above a certain elevation, and, after that, deciding which of them are truly *detectable* because they are illuminated by direct sunlight. Note that, here, *detectable*, does not necessarily mean “accessible to the naked eye”: only the brightest fraction of detectable satellites will be naked eye objects. Finally, a bulk count of detectable satellites is performed. The results strongly depend on solar illumination conditions that vary during the night (due to the change of the position of the Earth’s shadow as projected onto the sky) and with the season of the year.

The altitude of the orbits foreseen for the main large constellations range from 400 to 1200 km, much lower than the global positioning system satellites (GPS, beyond 20 000 km) or geostationary orbits (more than 35 000 km). This causes an effect seen even in the simplest A-kind simulations: only a small fraction of the satellites is above the horizon from any given location. For the combined SL2+OW2 case, this amounts to only 5 % of the total constellation, with a dependence on latitude that reflects the concentration of satellites towards the northern and southern boundaries of the orbital shells.

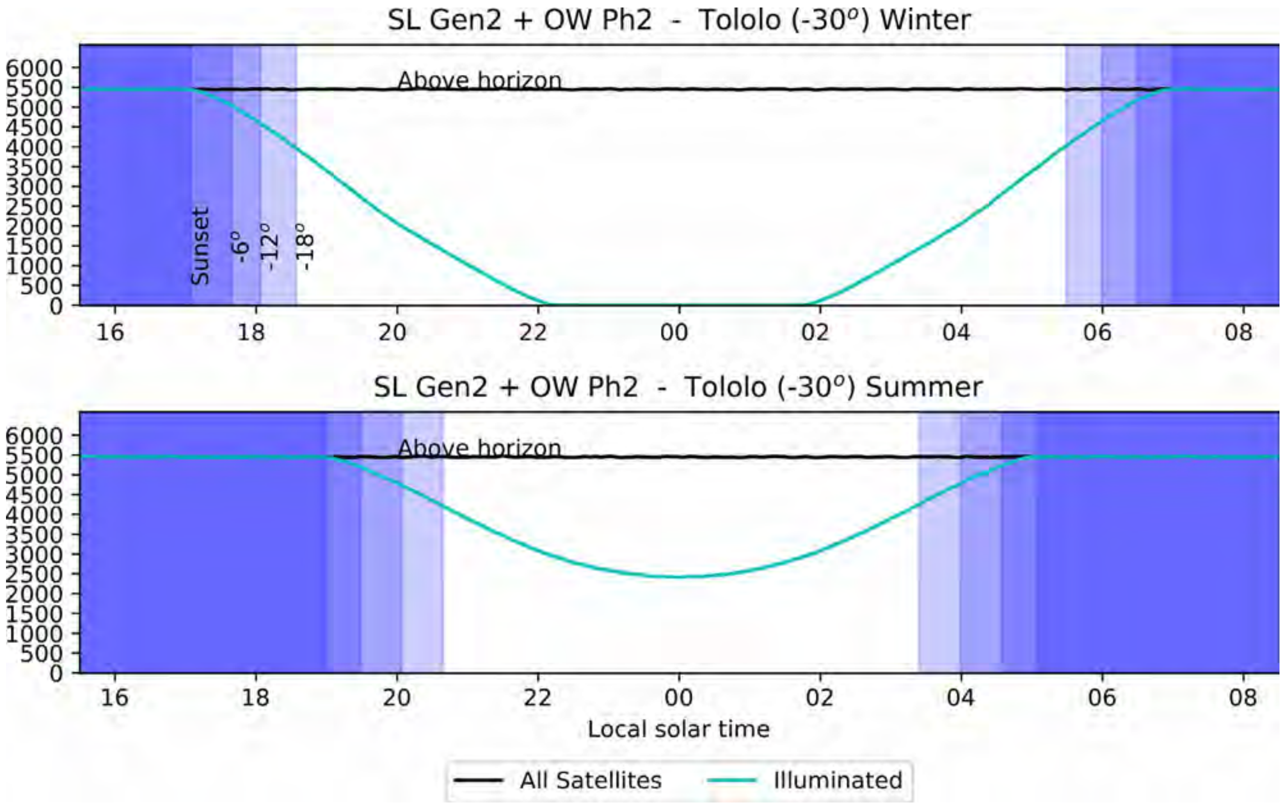


Figure 6.1.1. Evolution over the night of the number of satellites above the horizon at latitude 30° south (representative of Cerro Tololo and Cerro Pachón, for instance) on winter and summer solstices. The black curves show the total number of satellites above the horizon (illuminated or not), while the cyan curve shows only those that are detectable, because they are illuminated by direct sunlight. Sunset, sunrise and the various twilights are indicated with shading: the white area corresponds to astronomical night. While in winter the number of detectable satellites plummets towards the middle of the night, in summer many satellites remain illuminated and above the horizon even at midnight. O. Hainaut.

The fraction of a shell that is above the horizon increases with the altitude of the shell itself. For an altitude of 500 km (SL2), less than 4 % of all satellites in a shell are over the horizon from a latitude intermediate between the equator and the shell inclination, while this number more than doubles (almost reaching 8 %) if the shell altitude is 1200 km (OW2).

Not all satellites above the horizon will be detectable, but only those illuminated by the Sun. A-kind simulations show that, for this reason, the number of detectable satellites decreases as the Sun reaches lower (negative) elevations below the horizon, with a minimum at local solar midnight. The season of the year is linked to the Sun's declination and this, in turn, determines the geometry of the Earth's shadow on the local celestial sphere during the night. In winter, most satellites that are above the horizon remain fully in the Earth's shadow for a certain fraction of the night. In contrast, in summer the Sun still illuminates directly a large fraction of the space above the observer, making some satellites detectable even at midnight. This is especially true for observers at higher latitudes. Simulations separating SL2 and OW2 show the effect that higher orbits (OW2) remain illuminated longer than the low ones. High satellites not only remain detectable at midnight around the summer solstice, but their numbers also decay more slowly as the night sets in, compared to satellites in lower orbits.

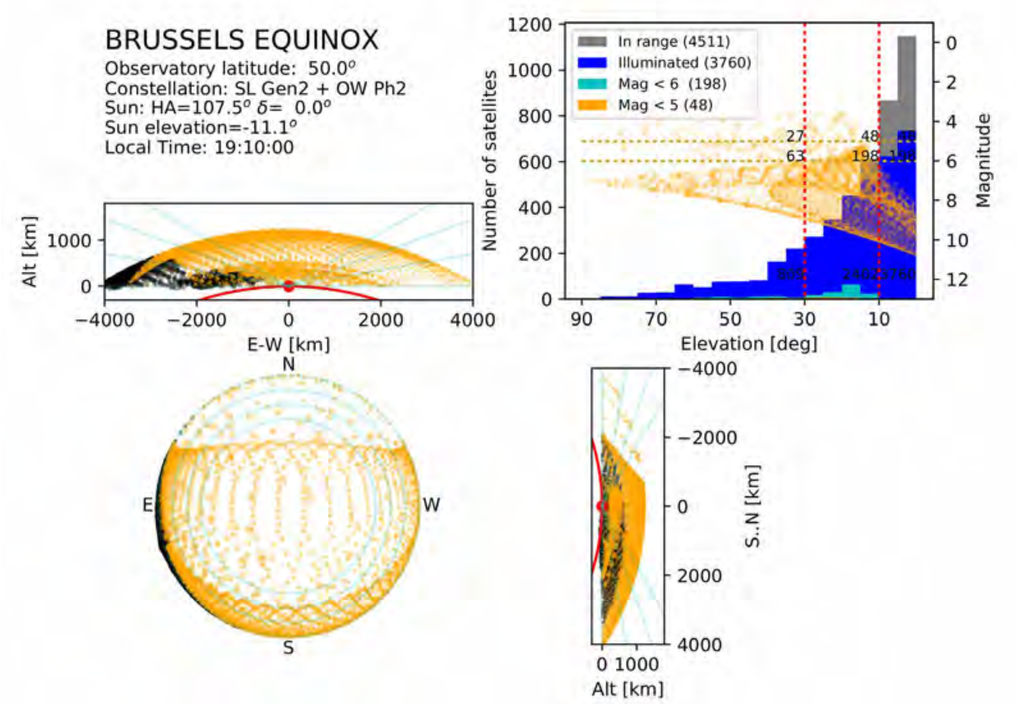


Figure 6.1.2. View during twilight, from Brussels (Belgium, latitude 50° north), of the satellites from the full SL2+OW2 constellation in the sky (bottom left), and side projections (the red arc is the limb of the Earth). Dots mark the positions of the satellites: those in orange are illuminated, while the others are dark. The histogram (top right) shows the number of satellites as a function of elevation above the horizon, and the sky views illustrate that most of the satellites are concentrated along the horizon. The size of the dots represents an estimate of the apparent brightness of the satellite, expressed in magnitudes (higher magnitudes are fainter; the limit for naked-eye visibility is between 6 and 8). Magnitudes are estimated through a simple model (see Sec. D.1.4. in the Appendix D). Figure by O. Hainaut.

Typically, and for the SL2+OW2 study in particular, about half the satellites above the horizon are still illuminated (and thus detectable) at the end of the astronomical twilight. The fraction is greater for higher orbits (85 % at 1200 km), and less for lower orbits.

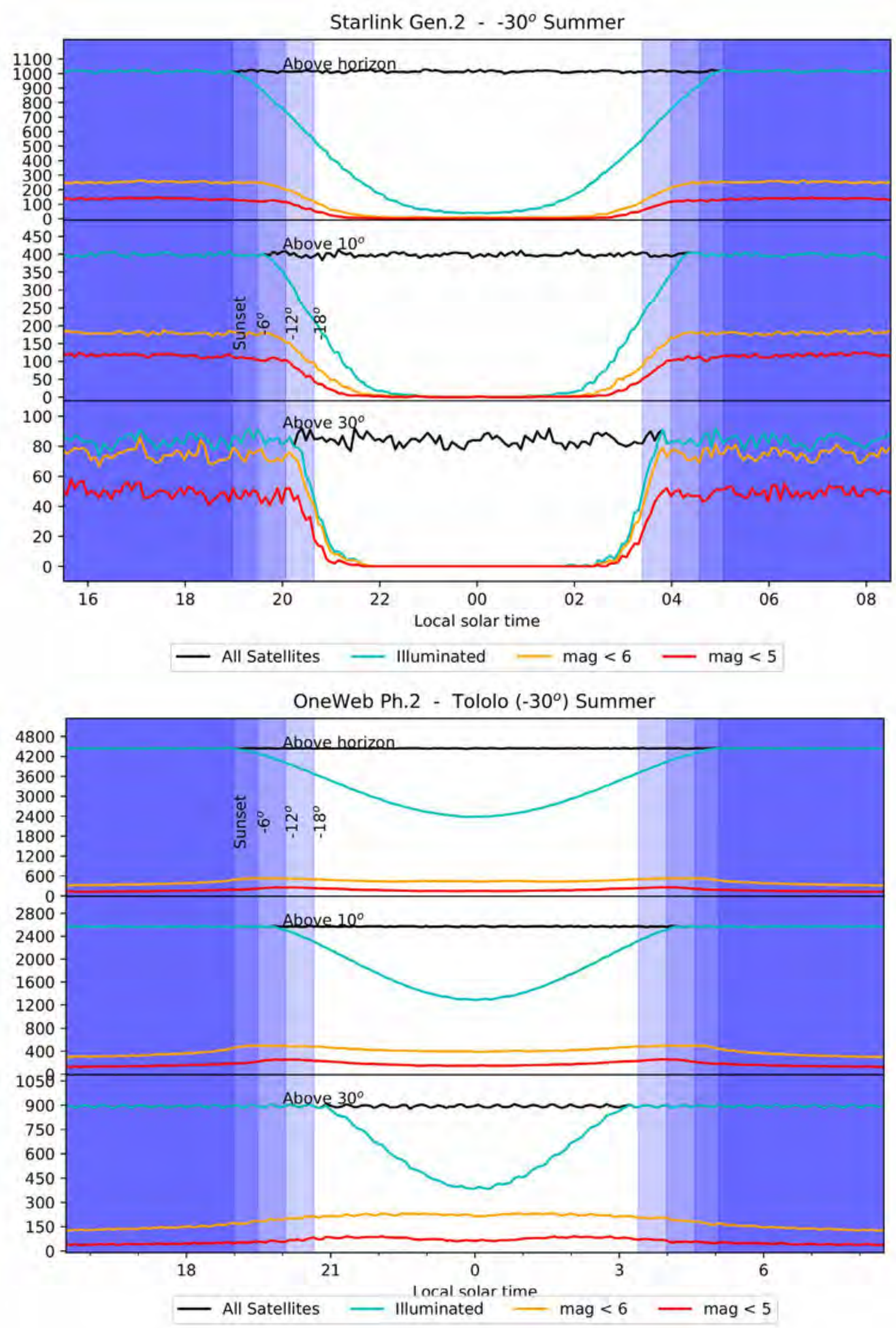


Figure 6.1.3. Influence of orbital altitude on satellite detectability. The upper panel shows the detectability of the 30000 satellites of Starlink 2 constellation (orbits around 350 km altitude), while the lower panel displays the results for the 50 000 satellites of One Web 2 (1200 km altitude). The simulation is for latitude 30° south (Cerro Tololo and Cerro Pachón) and for summer (December) solstice. There are three graphs inside each panel, from top to bottom: satellites above horizon; satellites above 10° elevation; and satellites above 30° elevation. Black lines indicate satellites above the indicated elevation; cyan is for satellites detectable (above reference elevation *and* illuminated by the Sun), and the lower lines indicate satellites that may be visible to the naked eye under good darkness conditions (red for magnitude < 5, orange for magnitude < 6). Magnitudes are estimated through a simple model (see Sec. D.1.4. in the Appendix D). Figure by O. Hainaut.

Bulk counts of detectable satellites can also be done restricting the count to objects appearing above a given elevation over the horizon. This reveals a strong concentration of satellites towards the horizon. This concentration is a simple perspective effect. For the case study SL2+OW2 the concentration implies that, typically, 50 % of the detectable satellites are concentrated below 10 degrees elevation.

While most scientific observations are performed above an elevation at or above 30°, the increasing satellite density towards the horizon indicates a significantly larger impact on research projects that need to point towards these areas of the celestial sphere, such as: cometary studies; and search and follow-up of near-Earth objects (NEOs), including potentially hazardous asteroids. These projects usually point towards elevations as low as 20°. Their search techniques are based on looking for moving sources; any satellite trails in their images may reduce the efficiency of their searches. This may amount to ten or more trails for typical integration times and fields of view.

Also, observation projects devoted to the so-called *targets of opportunity* rely on the observation of astronomical sources that suddenly appear at any position on the sky and whose observation may require pointing to sky areas crowded by satellites. Among these projects we may mention the search for optical counterparts of cataclysmic events: sources of gravitational waves, gamma ray bursts, radio bursts, and supernovae.

Not only the number density, but also the remaining observational parameters of detectable satellites change as a function of elevation above the horizon. The same distance and perspective effects mean that the apparent brightness of a satellite closer to the horizon is much fainter and, at the same time, its apparent angular speed is much slower than when near the zenith. More distant satellites appear fainter, their brightness decreasing as the distance to the observer squared. But their apparent motion is also slower, thus requiring more time to cross one image element and accumulating more light in it. The two effects somewhat compensate for each other (Ragazzoni, 2020) and it can be shown that, in absence of extinction and ignoring phase effects, the light accumulated in one pixel due to a (point-like, not spatially resolved) satellite is inversely proportional to satellite distance or directly proportional to the sine of the angle of elevation above the horizon.

Current estimates indicate that there will be satellites accessible to the unaided, naked eye, under dark night skies, a conclusion that is sound and safe well beyond the level of uncertainty of the current photometric models. Also, absolutely all sunlit satellites in large constellations are detectable by any research telescope, sometimes even inducing saturation effects that may ruin not only the image area affected by the trail, but a much larger region, potentially the whole image in some cases. For the Simonyi Telescope at Vera Rubin Observatory (Cerro Pachón), it is estimated that the limit of severe effects is around apparent visual magnitude 7, although the exact figure depends on observational circumstances such as angular speed and the apparent size of the spacecraft projected on the detector. Angular size of satellite images may be different from the point spread function of distant point-like sources (i.e., stars) for two reasons: defocusing due to their relative closeness and true spatial resolution of their structure, and both factors are distance-dependent.

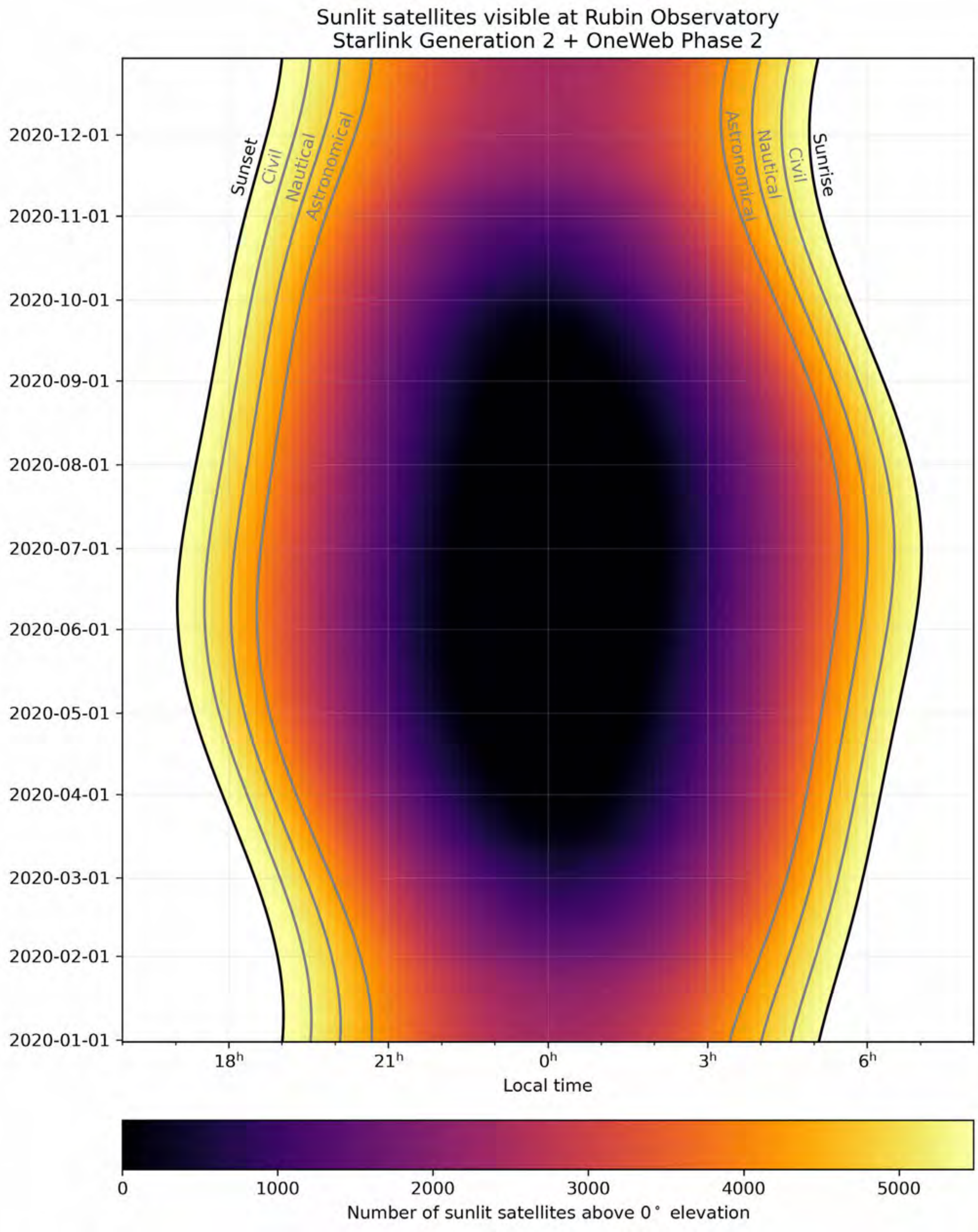


Figure 6.1.4. Bulk number of satellites of the constellation SL2+OW2 that are **above horizon** and illuminated from latitude 30° south (Cerro Pachón, Cerro Tololo) as a function of both local time (horizontal axis) and date of the year (vertical axis). The white area corresponds to daytime (Sun above horizon). Curved lines indicate sunset and sunrise, and the times of the different twilights. Compare to the following figure to check the influence of the elevation above the horizon. Colour code runs from zero (black) to more than 5000 (yellow). Figure by C. Bassa using analytic methods.

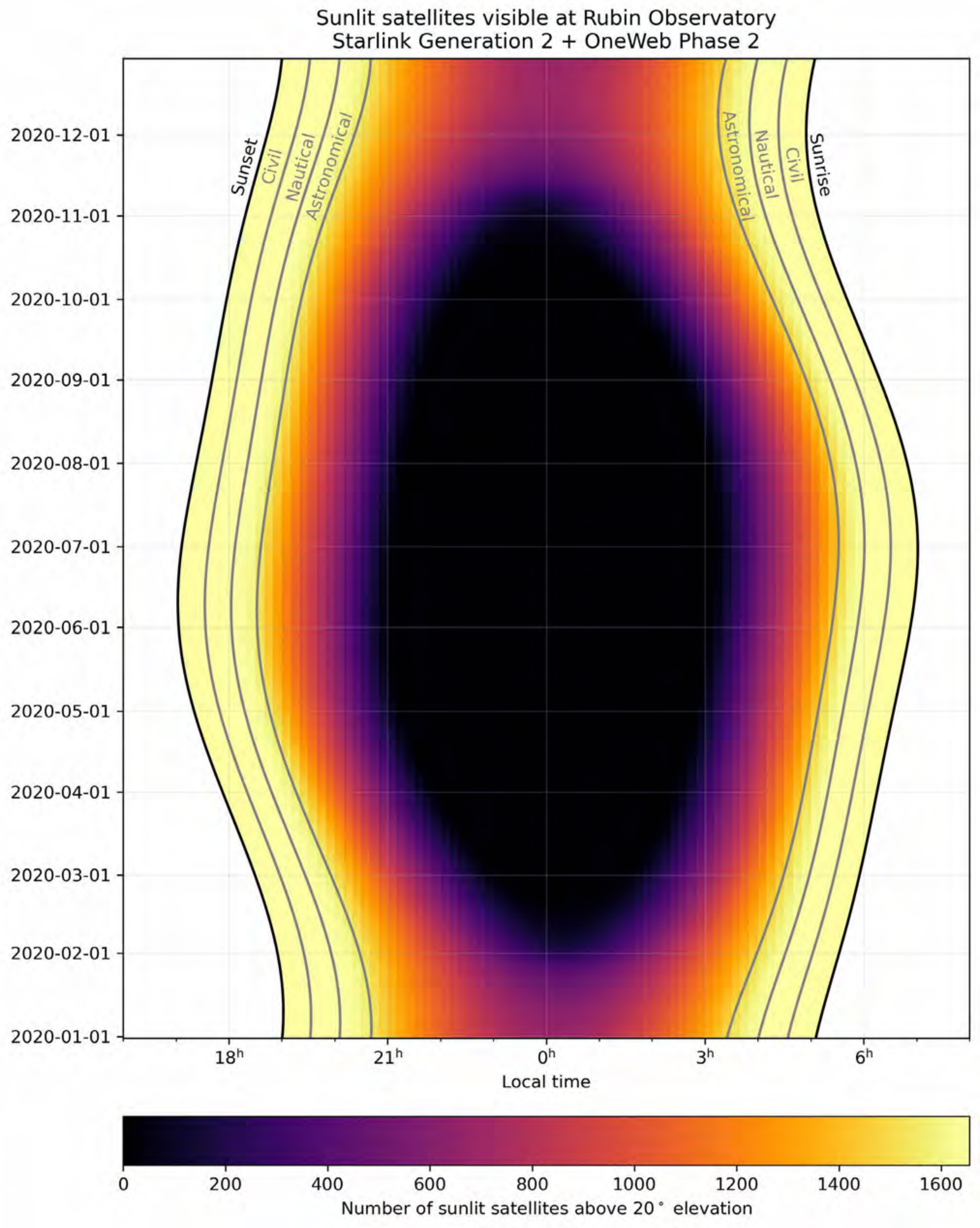


Figure 6.1.5. Bulk number of satellites of the constellation SL2+OW2 that are **above an elevation of 20 degrees** over horizon, and illuminated, from latitude 30º south (Cerro Pachón, Cerro Tololo) as a function of both local time (horizontal axis) and date of the year (vertical axis). The white area corresponds to daytime (Sun above horizon). Curved lines indicate sunset and sunrise, and the times of the different twilights. Compare to the previous figure to check the influence of the elevation above the horizon. Colour code runs from zero (black) to slightly more than 1600 (yellow). Figure by C. Bassa using analytic methods.

6.1.2.2. POINTING-ORIENTED SIMULATIONS

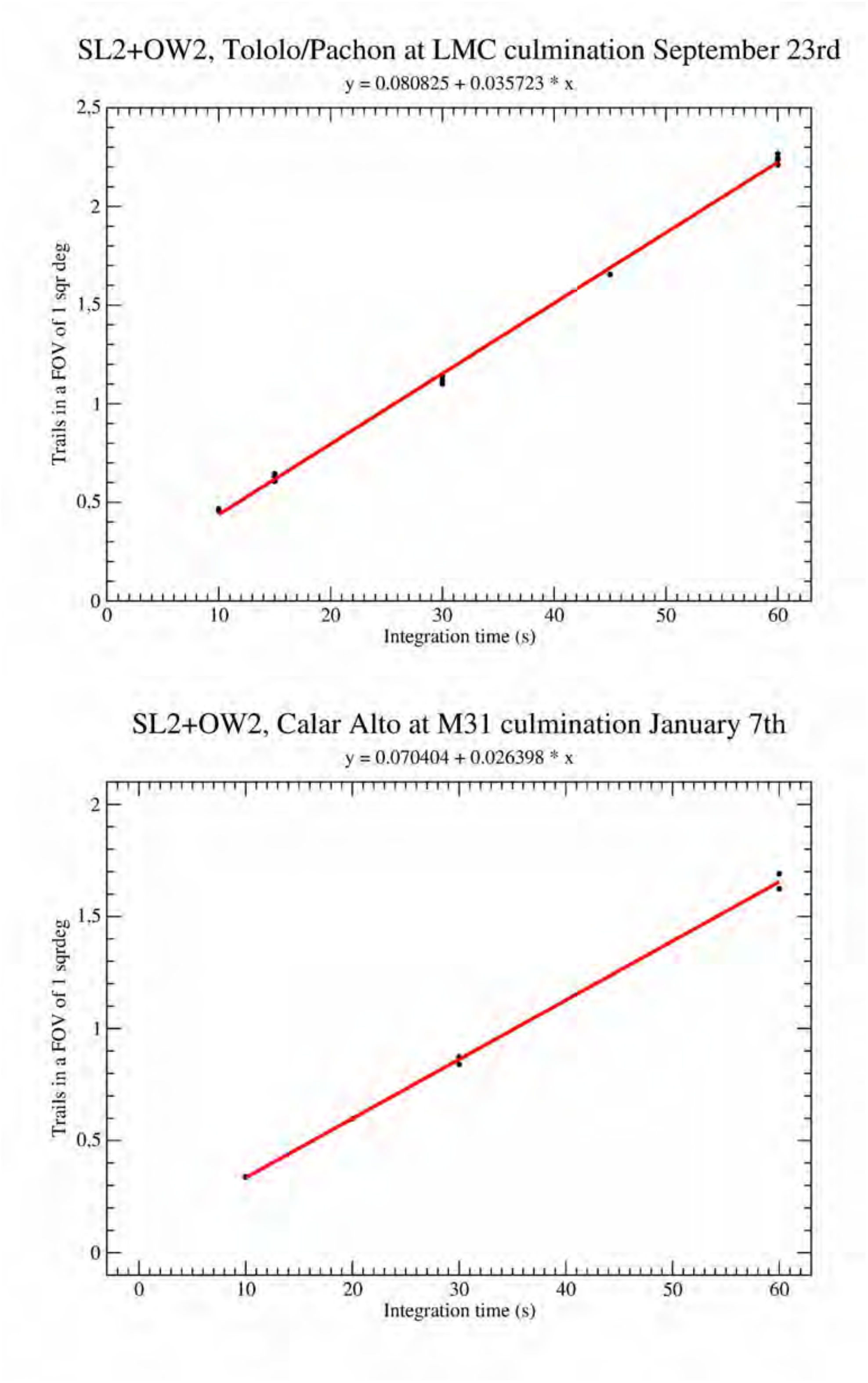
Besides computing the global number of satellites detectable over a specific elevation (as described in the previous section), it is also necessary to investigate the details of their distribution in specific directions on the local celestial sphere, because this is a strong function of time and of the direction of observation.

We may consider the example of the Rubin Observatory in Chile, at 30° south latitude, representative of many other observatories in the same area. From here, and in summer solstice conditions (Sun declination -23°), the southern region of the sky, for satellites above 1000 km altitude, is illuminated during the whole night. One of the sky areas most often observed from southern observatories is the Large Magellanic Cloud (LMC), a galaxy that is a satellite of our own stellar system. This sky area reaches culmination at midnight and, thus, optimum observation conditions, around the beginning of the southern summer and is visible towards the southern circumpolar cap (LMC declination = -69°). The simulations performed demonstrate that, at this time of year and from northern Chile, a field of view (FOV) spanning one square degree in the direction of the LMC will experience two satellite trails per minute all night long. Most of these trails, 88 % to 100 % (depending on the local apparent configuration of the Sun), will be due to spacecraft belonging to the OW2 shells (1200 km altitude). If we take into account that OW2 constellation is larger than SL2 in number of satellites, then the normalised proportion changes a little bit: 82 % to 100 % trails would be due to high-orbit crafts.

The results depend on a combination of the sky position of the object to be observed, the observatory latitude and the Sun's declination, but they are often comparable. For instance, from the latitude of Calar Alto Observatory (latitude 37° north), approximately representative also of observatories in Arizona, U.S. (latitudes 32-35°), a FOV of one square degree pointing in the direction of the Andromeda Galaxy will be hit by similar satellite traffic, with an average only slightly below two trails per minute in certain epochs of the year (in this case, the simulation is performed for Andromeda culmination in July-August, local summer again).

Another example of areas of interest where long exposures are expected to go as faint as possible are the deep fields studied by the Hubble Space Telescope and other space-based observatories (Chandra or XMM-Newton X-ray, for example). Ground-based spectroscopy of objects in these fields is essential to understand the nature of sources. Here the exposure times could be one hour or more. These fields are distributed all over the sky.

In typical conditions for observations around the equinox, at the end of the nautical twilight, looking northwest at 20° elevation over the horizon, from intermediate northern latitudes (Arizona, Calar Alto), the SL2+OW2 scenario leads to two satellite trails in each shot with FOV of one square degree and 60 s integration time, each with apparent magnitudes ranging from 7 to 10 (mean: 9.0) and moving with an apparent mean angular speed of 11 arcminutes per second. This number increases to three traces per shot if the pointing is at 10° elevation, and to five for integrations toward directions grazing the horizon. Although few scientific observations are usually performed at such low elevations, these sky areas are very often the subject of wide-field astronomical and night landscape photography. These astrophotographic techniques will be severely affected, even more so if we take into account that their usual FOVs span hundreds of square degrees grazing the horizon. Tens to hundreds of streaks will potentially appear in every shot, depending on the sensitivity of the systems used.



SL2+OW2, Tololo/Pachon at LMC culmination September 23rd

SL2+OW2, Calar Alto at M31 culmination January 7th

Figure 6.1.6. Number of trails inside a field of view of one square degree as a function of integration time for two celestial objects of special interest in astrophysics. Top: pointing towards the Large Magellanic Cloud (LMC) upon culmination in September from latitude 30º south (Cerro Pachón, Cerro Tololo). Bottom: pointing towards the Andromeda Galaxy upon culmination in January from latitude 37º North (Calar Alto, Arizona). Figure by D. Galadí-Enríquez.

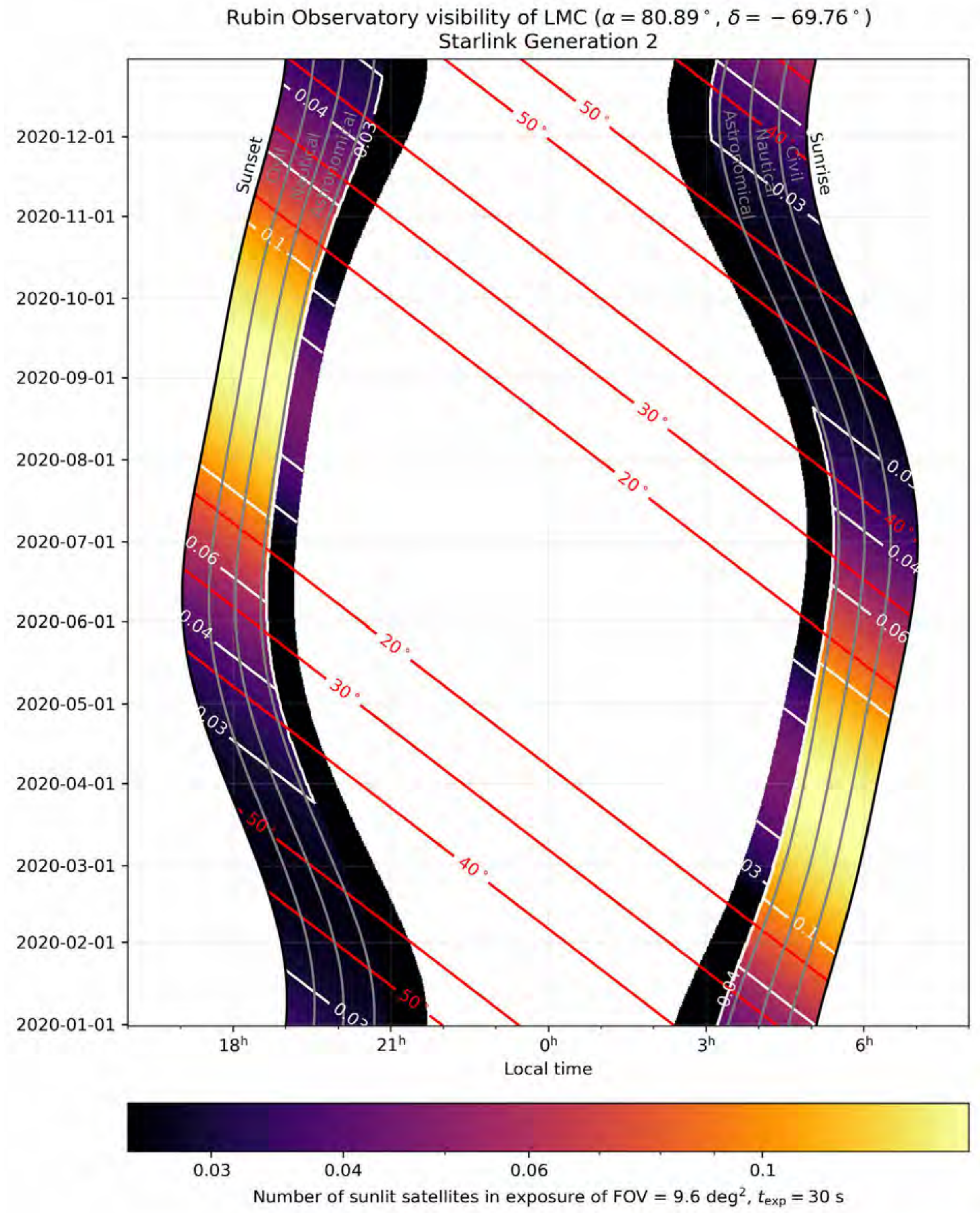


Figure 6.1.7. Number of trails inside the field the 9.6 square degree field of view of the Simony telescope (Cerro Pachón), pointing to the Large Magellanic Cloud (LMC), for integrations of 30 seconds. This graph displays only the contribution of the **Starlink 2 constellation** (orbits around 350 km altitude). The horizontal axis indicates local time and the vertical axis corresponds to the date of the year. The white areas at the left and right of the graph correspond to daytime, while the central white area indicates that no satellites are detectable because any spacecraft in the field of view would be inside the Earth's shadow. Red lines indicate the elevation of the LMC. The colour code runs from zero trails per field (black) to 0.13 (yellow). At most, one out of seven shots would display a trail from

the SL2 constellation; compare with the following figure, showing the equivalent effect of the higher-altitude OneWeb 2 constellation. Figure by C. Bassa, obtained using analytic methods.

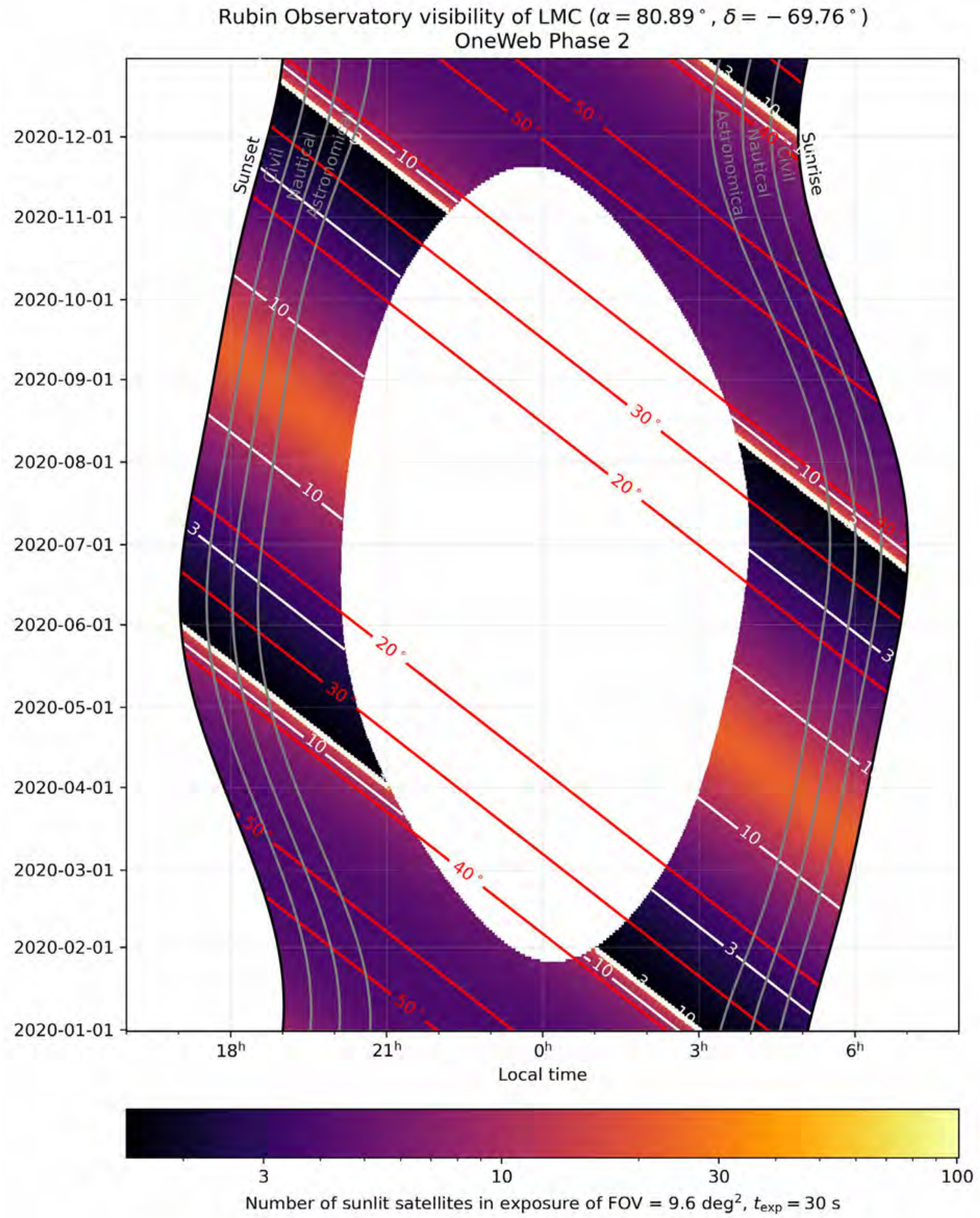


Figure 6.1.8. Number of trails inside the 9.6 square degree field of view of the Simony telescope (Cerro Pachón), pointing to the Large Magellanic Cloud (LMC), for integrations of 30 seconds. This graph displays only the contribution of the **One Web 2 constellation** (orbits at 1200 km altitude). The horizontal axis indicates local time and the vertical axis corresponds to the date of the year. The white areas at the left and right of the graph correspond to daytime, while the central white area indicates that no satellites are detectable because any spacecraft in the field of view would be inside the Earth's shadow. Red lines indicate the elevation of the LMC. The colour code runs from zero trails

per field (black) to 100 (yellow), although the maximum is around 25 trails. The impact of higher satellites is stronger and it extends much deeper into the night, as can be seen compared with the previous figure. Figure by C. Bassa, obtained using analytic methods.

6.1.2.3. Spatially resolved simulations

Bulk satellite counts from all-sky simulations provide relevant information, but we know that they do not convey the full picture because the distribution of satellites detectable on the sky is highly non-uniform. Some hints on this already arise from the strong elevation-dependence shown by all-sky simulations, but there has to be an even stronger spatial dependency related to the position of the Earth's shadow on the local celestial sphere, which changes both during the night and also, for the same local time, with solar declination (seasonal dependency). Two more factors may affect detectable satellite distribution on the sky in a way that has to be assessed: First, the fact that the spatial density of satellites inside each shell is non-uniform, but shows a latitudinal dependence. Second, the existence of shell boundaries linked to the inclination of the orbits (satellites do not reach the zenith, seen from locations with latitudes larger, in absolute value, than their orbital inclination).

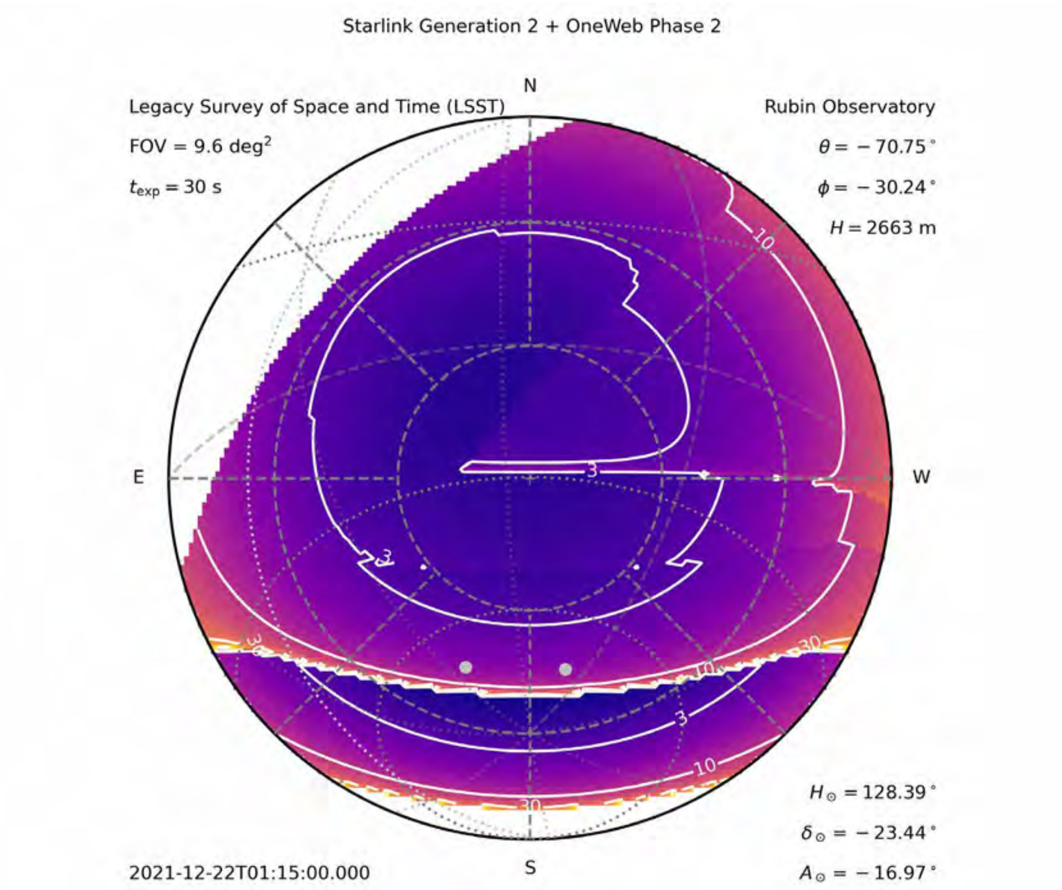


Figure 6.1.9. Spatially resolved simulation of the density of satellites detectable (above horizon and illuminated) from Cerro Pachón (latitude 30º south) in local summer conditions (December solstice) at 20:30 local time (Sun 18 degrees below the horizon, start of local astronomical night). The colour code is set in units of number of detectable satellites inside the field of view of the Simony telescope (9.6 square degrees solid angle) and during 30 seconds integration time: anywhere the telescope points, it would find at least one satellite inside its field of view, but more than 30 trails are possible.

Observe the intricate spatial fine structure induced by the texture of orbital shells. The area devoid of detectable satellites in the North-East (upper left) is due to the Earth's shadow. The dots in the lower part mark the locations of the Large (left) and Small (right) Magellanic Clouds. Constellation: SL2+OW2. Figure produced by analytical methods by C. Bassa.

Conceptually, the easier way to study the true spatial distribution would rely on discrete simulations. Even simple implementations of this spatially resolved, discrete approach show the strong non-uniformity of the satellite distributions and their night-long evolution, dominated by the apparent pass of the Earth's shadow across the celestial sphere.

Analytical approaches to the spatially resolved simulations are best suited to this problem, allowing a complete description of the instantaneous satellite density over the celestial sphere and revealing a good amount of (maybe unexpected) spatial fine structure. Shell boundaries reveal themselves as important features that are able to modify the expected numbers of satellite crossings in the FOV by a factor of 10, in case they are illuminated and accessible from a given location. Observatories placed at latitudes whose absolute value is close to the inclination of some shell will see these boundaries (where the density of satellites increases) crossing through zenith. At other positions, shell boundaries are able to interfere in a geometrically complex way with observation in specific directions, and they are behind the behaviour observed when studying telescope pointings towards specific objects of interest (pointing-oriented kinds simulations; see previous section).

6.1.3. FLARES AND GLARES

Specular (mirror-like) reflections of sunlight off of the flat, fairly polished surface elements of the orbiting satellites are common and often directed towards the Earth. Such reflections can be detected by the ground-based observers, if their location falls within the ground footprint of the reflected rays. The ground location of the reflection footprint changes as the angular configuration between the satellite centred direction towards the Sun and the reflective surface normal vector change due to the spacecraft's orbital motion. Moreover, the intensity profiles of the reflection flares can be predicted by taking into account the satellite shape, surface material properties and the optical characteristics defined by brightness models like the bidirectional reflectance distribution function (DRDF).

On the first generation of Iridium satellites, each of their three door-sized antennas could cause spectacular flares, sometimes reaching magnitude -8 for a few seconds. In the case of three-axis stabilised satellites, the place and time where flares are detectable can be accurately computed (even popular websites and apps listed custom-made predictions for the Iridium flares before the last of the first-generation Iridium objects de-orbited in 2020).

The information available on the objects in upcoming satellite constellations suggests that they won't have large, flat surfaces oriented in an attitude susceptible to produce Iridium-like flares. Nevertheless, even smaller areas can cause flares, albeit fainter ones. Some occurrences of such flares have been reported for early Starlink satellites[1]. Scaling the approximate size of the largest ground-facing, flat polished surface on a Starlink satellite (about 0.3 × 0.3 m) to that of Iridium (about 2 × 1 m) suggests a flare of mag ~ -4 to -5 could be possible (Starlink solar panels are larger, but their spatial orientation in normal operation prevents specular reflections towards the ground). Such bright flash, caught in the field of view of an astronomical instrument, is likely to ruin the observation. In the case of the Starlink satellites this should be mitigated by the sunshades as imple-

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[1] An astrophotographer photographed a flare on a starlink satellite: https://www.cieletespace.fr/actualites/exclusif-en-plus-de-rayer-le-ciel-les-satellites-starlink-diffusent-de-puissants-flashes-lumineux

mented in the recent ‘VisorSat’ Starlink designs.

The well documented occurrences of the Iridium flares can be used as a benchmark to evaluate the number of flares that a future constellation could produce, as done by Hainaut & Williams (2020). Using the same methodologies as those used to evaluate the number of satellite trails affecting an observation, it is estimated that $< 10^{-5}$ of the Simony Telescope (LSST project) exposures during twilight would be affected by a flare (Hainaut, priv. comm.), assuming that each satellite has one large flat flare-producing surface, which is conservatively pessimistic. Intuitively, this result is driven by the very short duration of the flares (10 s in the simulation), and the rare occurrence of the flares.

While flares are short (seconds), the very fast apparent angular velocity of the satellites ensures that the flares will also appear as long trails on the sky. Therefore, they will not appear as point sources (which would be even more difficult to identify and filter out as spurious), but as very bright trails.

Furthermore, in the case of actively stabilized, nadir-pointing satellites, the occurrence of a flare is predictable, as illustrated by the former Iridium flare-related websites and apps. It would therefore be practical to check whether an observation about to start would be affected and to reschedule it in case of need.

Finally, the region of earth affected by a flare is determined by the attitude of the satellite causing it. A very modest change of attitude can therefore re-locate the flare to a different region. Such attitude adjustments are common in satellite operation (e.g., OneWeb’s “progressive pitch” each time a satellite crosses the equator). It is therefore realistic that selected observatories could be protected by ‘no flare zones’.

The non-perfectly specular reflections occurring on non-flat surfaces (for instance, on the corrugated insulating layer that covers some satellites) can cause much more diffuse (hence longer) flashes than the flares - called ‘glares’. As the geometrical conditions are less stringent than for flares, they are likely to be more numerous than flares. However, the fast apparent motion of the satellites ensures that a glare will leave a degrees-long trail on the detector. The resulting spurious transient object detection that may result from a glare will have to be dealt with, just like for the normal satellite trails and natural signatures of the same type, like meteor streaks. At this stage, we have no information on glare-causing features on the satellites, and therefore we cannot determine whether they are relevant.

Overall, because of the frequency of the flares and glares, their duration, the low probability of them affecting observations, their predictability and the fact that they are controllable (the latter two for actively controlled satellites), the effect of specular reflections on astronomical observations is therefore completely secondary compared to the effect of satellite trails.

6.1.4. TRANSIENT ORBITAL PHASES

Artificial satellites are intended to be operational on station; i.e., once they have been placed at their predetermined working orbits. However, they have to reach those positions through a series of manoeuvres that imply a time of stay in lower, preliminary orbits, where their effect on astronomical observations may be very different than on station. Also, it is worth considering the impact of the satellites once they have finished their operational lives.

6.1.4.1. From launch to operations

Most artificial satellites launched until recently were placed on their final, operational orbits following fast procedures that typically involved few thrust episodes and classical, deterministic transient orbits (such as Hohmann trajectories), that take just a few days to complete. However, Starlink satellites are not placed at their final operational orbits in this traditional way. The satellites carry low-thrust ionic engines that are used over weeks or months to make the satellites to slowly drift from the very low provisional trajectory into which they are placed by the launcher, to the final destination orbit. This implies that all satellites in these large constellations will have a significant transient initial phase during which they follow orbits lower than the operational ones. Low orbits reduce the probability of crossing over a given position, but they make the satellites apparently brighter. Apparent brightness, in these phases, is also affected by spacecraft attitude during these manoeuvres, because during these phases the satellites may be oriented in a way different to the final, operational attitude, in order to minimise atmospheric drag. In the case of the early Starlink launches, this caused the very bright 'string of pearls' appearance of the satellite trains. SpaceX now orients the Starlink satellites in a way that reduces both atmospheric drag and apparent brightness.

The sizes of large satellite constellation projects and the information available about the pace at which the satellites will be launched, operated and replaced indicate that there will always be a significant number of spacecraft in the initial transient phases of orbit altitude rise. An informal communication by one of the operators suggests that 3-5 % of the fleet would be on transfer orbits at any time. This means that this population of objects cannot be neglected. While specific simulations should still be done to assess this part of the problem, the simulation of low-altitude constellations gives an estimate on what to expect by scaling the numbers down to 3-5 %. During the very early phases after launch, the grouping of the satellites in 'trains' makes the issue more spectacular, but less problematic, since they affect a restricted part of the sky.

In terms of simulations, the effect of low-altitude satellites should be increased by 3-5 % of the total number of satellites to account for the objects on a transfer orbit.

Overall, the companies should be encouraged to adopt measures to minimize the impact of their spacecraft also during the initial phases after their launch, in particular to minimize their brightness.

6.1.4.2. Orbit decay: active and passive

The observation scenarios modelled so-far assume an operational satellite constellation. In a realistic scenario additional phases must be investigated, i.e. the initial orbit acquisition, the end of operational phase, and possible failures. Lost satellites without active attitude control will not be able to use visors to efficiently reduce the visual brightness. Typically, spacecraft operators perform re-entry maneuvers to reduce the orbital lifetime in order to comply with space debris mitigation guidelines (Inter-Agency Space Debris Coordination Committee, 2007). However, the mitigation compliance in terms of observed successful post-mission disposal (PMD) is well below 90 % (Bastida Virgili et al. 2016), which is often used as an optimistic estimate. The Inter-Agency Space Debris Coordination Committee (IADC) has issued a special statement in this regard (Inter-Agency Space Debris Coordination Committee, 2007), that man-made space debris today poses little risk to ordinary unmanned spacecraft in Earth orbit, but the population of debris is growing, and the probability of collisions that could lead to potential damage will consequently increase. It has, however, now become common practice to consider the collision risk with orbital debris in planning manned missions. So the implementation of some debris mitigation measures today is a prudent and necessary step towards preserving the space environment for future generations. Several national and international organisations of the space faring nations have established Space Debris Mitigation Standards or Handbooks to promote efforts to deal with space debris issues. The contents of these Standards and Handbooks may be slightly different from each other but their fundamental principles are the same. While satellites in lower altitudes will be decelerated by the remaining atmosphere and re-enter in a few years (depending on area-to-mass ratio and solar activity), satellites at 1000 km will remain in orbit for centuries (depending on area-to-mass ratio and solar activity). Assuming an area-to-mass ratio of 0.008 m²/kg a satellite at 350 km altitude will re-enter within 7-9 months, one at 550 will take 12-18 years, and one at 1200 will remain in orbit for more than 1000 years. Bastida Virgili et al. (2016) performed a long-term simulation for large satellite constellations assuming different PMD scenarios and assesses the resulting number of objects in orbit.

The number of detectable objects is dependent on the compliance assumptions used in a high-fidelity simulation of the realistic scenarios and would require a detailed sensitivity analysis. However, it can be assumed that a failed PMD attempt will lead to more detectable satellites and that the simulation results presented in this report provide, at least, a lower bound.

Even those satellites with successful post-mission disposal may remain in a descent orbit for a significant period. The v0.9 group of 60 prototype Starlink satellites launched in May 2019 began to be actively retired in summer 2020. As of 16 Sep 2020, 26 of them had been removed from orbit (McDowell, 2020b). The process for each satellite descending from an initial 550 km orbit took from four to nine months. The orbit is lowered using electric propulsion at about 4.7 km/day, but the process is occasionally interrupted by pauses of a month or so. If this process is typical of future retirements, with an approximate six-month duration compared to five years active life, we may expect 10 percent of the constellation to be in this (lower, brighter) phase at any one time even without failures. The situation would be much worse if active de-orbiting does not aim to re-entry, but simply to parking orbits with expected natural decay time of some 25 years, as currently recommended by international guidelines: in this case, and for an operational lifetime of 5 years, we may end up with up to 5 complete generations of satellites accumulated in parking orbits, waiting for natural decay.6.1.5. Recommendations from the simulation work

6.1.5.1. For the industry

S.1. Information on constellation profiles

Deliver transparent and reliable information about their plans, including the relevant details of spacecraft design and orbit profile, as soon as they are decided, even if they may be subject to later changes for any reasons (commercial, legal, engineering).

While not needed for statistical simulations, observatory mitigation measures which would be derived from simulation work need reliable ephemeris. Predictions of night-to-night visibility of current spacecraft are needed for observation planning (avoidance) or for image analysis (a posteriori trail identification). Share up-to-date (ideally real-time) information on the orbit of each satellite, and keep a record of past orbital elements for retrospective data analysis. Given current uncertainties of orbits calculated with standard and supplemental TLEs,most probably a new standard will have to be defined to allow more accurate position predictions.

S.2. Limit the number of spacecraft

The most obvious conclusion from all tests is that astronomical observations would benefit if the planned satellite constellations are kept as small as possible, in terms of the number of spacecraft, with an optimum number equal to zero.

S.3. Limit orbit altitude

Evaluating the balance among apparent brightness and satellite illumination conditions, the results lead to the recommendation to use satellite shells as low (closer to the Earth surface) as possible. This reduces both the number of satellites above the horizon and the night interval during which some of them are detectable (sunlit). From the tests and simulations performed, we are suggesting an upper bound on the order of 600 km altitude above surface for these projects.

S.4. Information for flare prediction

Provide the data about satellite design and attitude control that may allow predicting flare geometry, at all phases of the orbital evolution of the spacecraft.

S.5. Enforcing effective de-orbiting

Enforce solutions for efficient active de-orbiting. The current international consensus about the time period considered as acceptable for natural orbital decay after the phase of active de-orbiting needs to be re-evaluated and significantly reduced, at least for satellites belonging to large constellations, and it may probably be set as a decreasing function of the size of the constellation. Implement active de-orbiting solutions that are reliable enough to guarantee a very low absolute number of uncontrolled spacecraft. Thus, these reliability requirements should be more restrictive for larger constellations.

S.6. Satellite darkening

Darken satellites in large constellations, through whatever engineering solutions may be feasible and compatible with their functions. Set maximum brightness due to diffuse reflection below the naked-eye limit under all circumstances. Study, test and, if feasible, implement additional engineering and attitude control measures to reduce average brightness due to diffuse reflection below the limit of 7 visual magnitude.

6.1.5.2. For the Astronomy Community:

S.7. Improving photometric models: information, observation

The simulations of apparent brightness will benefit from detailed information on spacecraft design to be provided by the companies, including the best available estimations of the diffuse and specular reflectance distribution functions (that depend on surface materials and satellite geometry). These input data will interact with real observations of spacecraft already in orbit that will benefit, too, from the availability of the best up to date orbital data (provided by the companies) in order to compute individual predictions that will allow observation planning and exploitation of the resulting data.

S.8. Improving simulations

Introduce improvements into the ongoing and forthcoming simulation efforts: better photometric models, more detailed consideration of trails due to not point-like sources (spatially resolved and/or out of focus), assessment of transitory orbital phases before and after the operational life of the spacecraft. A more quantitative study of the impact of satellite constellations on astrophotography is direly needed.

6.2. OBSERVATIONS

6.2.1. SUMMARY, FINDINGS AND RECOMMENDATIONS

The purpose of the Observations group is to observationally support the assessment of the impact to future astronomy of satellites by (a) characterizing the brightness of satellites at relevant wavelengths over the entire hemisphere and range of orbital geometries, and (b) to support the satellite industry with measurements to assess the efficacy of their brightness-reduction mitigation strategies.

Since the launch of Sputnik in 1957, scientists and space surveillance specialists have tracked and studied satellites and space debris with optical telescopes. The first attempts to use optical photometry to characterize satellites were published by the U.S and Russia in the late 1950s and mature techniques and capabilities have been developed for geosynchronous satellites (Moore, 1959 ; Souvari, 1979; Grigorevskij 1959). However, the new LEO-satellite mega-constellations, such as Starlink, OneWeb and others, pose new challenges in optical measurement techniques. Towards that end, we developed survey photometric techniques to measure many satellites over a wide range of geometries (University of Arizona), and adapted traditional astronomical imaging and analysis techniques to produce precision measurements for the evaluation of satellite mitigation techniques (Universidad de Antofagasta/European Southern Observatory collaboration, Vera Rubin Telescope/ LSST project/Cerro Tololo Interamerican Observatory collaboration).

Unlike typical astronomical targets, satellites move and their brightness is highly dynamic. Even small changes in the satellite's position or orientation relative to the Sun and/or observer can yield a large change in apparent brightness. Characterizing a satellite's apparent brightness requires many observations to capture the changes in brightness over the full range of parameters. Furthermore to assess the impact to astronomy research we must consider more than just the satellites' brightness but also their angular velocity through the field of view of astronomical detectors, position in the sky, and frequency of sightings.

This report expands upon the previous work of the SATCON1 Satellite Observations Working Group (Constance Walker et al., 2020). Since the commissioning of our SATCON1 report, the teams contributing observations of Starlink and OneWeb satellites have developed and refined new techniques, and made additional measurements. Especially relevant are the most recent measurements to quantify the efficacy of Starlink's brightness-reduction mitigations which include operational changes, surface treatments ("DarkSat"), and visors ("VisorSat"). We also add new measurements of OneWeb satellites.

6.2.1.1. Findings:

The WG reports the following key findings:

- Observations of pre-mitigation Starlink satellites show typical apparent brightness in the 4-5th magnitude range and are easily visible with telescopes or even the unaided human eye.
- Observations of OneWeb satellites show typical brightness fainter than 6-7th magnitude. This, as observed, is dimmer than the pre-mitigation Starlink satellites. Yet, it is necessary to keep in mind that OneWeb satellites are being deployed at a much higher orbital height, of 1200 km. A relative assessment of brightness apparent magnitude of satellites, of different constellations, can only be done when the observations are standardized to a common orbital height or range.
- Limited observations of DarkSat and VisorSat indicate that the brightness-reduction mitigation measures implemented in the modified designs are effective but do not achieve the brightness goals recommended by the Mitigations Working Group in all operational phases and geometries. More observations are needed to characterize the brightness of these satel-

lites in all geometries.

- Observations of Starlink satellites at multiple spectral bands show the satellites are brighter at longer wavelengths, and the efficacy of the modified-design strategy implemented in DarkSat decreases in the near-infrared.

6.2.2. LEO Satellites Observations Group Goals

The Observations group consists of various members of our community that contribute observations of LEO satellites on a voluntary basis. The main contributors are three groups:

A collaboration of scientists from the astronomy group at the Universidad de Antofagasta (Chile) and the European Southern Observatory. This collaboration is not based on institutional agreements but on the voluntary effort contributed by its members that have provided telescope time, observations of LEO satellites, and processing of the images. This collaboration conducted specific observations of Starlink satellites, including DarkSat and VisorSat.

The Space Situational Awareness research team of the Steward Observatory at the University of Arizona. This team operates the POMENIS telescope and has conducted many hundreds of observations of Starlink satellites, including VisorSat, and OneWeb satellites.

A team of scientists with the Vera Rubin Observatory and LSST Camera project conducted observations with the DECAM camera operated on the Victor Blanco telescope, part of the NSF funded, Cerro-Tololo Interamerican Observatory.

6.2.2.1. Goals

The Observations group's main goals are:

- Conduct observations of LEO satellites over the entire hemisphere and range of orbital geometries, and across a range of spectral bands from visible into the mid-infrared.
- Characterize the brightness of LEO satellites over the entire hemisphere and as a function of the relevant parameters including solar illumination angle and the angular position of the satellite with respect to the observer.
- Assess the efficacy of brightness-reduction mitigation strategies including design and operational changes. The main subjects of this goal are the Starlink satellites including DarkSat and VisorSat.

6.2.3. Summary of Results

6.2.3.1. Telescopes Facilities

The observations in this report were obtained using the following facilities:

- The Ckoirama observatory is located in the Atacama desert in northern Chile. It is owned and operated by the Centro de Astronomía (CITEVA), Universidad de Antofagasta, Chile. The observatory contains the Chakana 0.6 m telescope and is equipped with a FLI ProLine 16801 camera. The filter wheel contains three scientific filters: Sloan g' (475.4 nm), r' (620.4 nm), and i' (769.8 nm). The CCD covers a field of view of 32.4 × 32.4 arcmin with a pixel scale of 0.47 arcsec pixel^{-1} (Char et al. 2016).
- VISTA (Visible and Infrared Survey Telescope for Astronomy, see Sutherland et al., 2015) equipped with the world's largest near-infrared imaging camera, VISTA IR Camera (VIR-

Cam). VISTA is a 4 m class telescope designed for wide-field surveys in the southern hemisphere and is situated at ESO's Cerro Paranal Observatory in Chile. VIRCam has a 1.65 degree diameter field of view with a mean pixel scale of 0.339 arcsec pixel−1. The camera has five broad band filters Z, Y, J, H, and Ks along with three narrow band filters. Once the raw data has been collected, they are processed by the calibration pipeline at Cambridge Astronomy Survey Unit (CASU).

- The POMENIS telescope (Rascon et al., 2018) is a unique system developed specifically to perform synoptic surveys of Earth satellites such as Starlink. The 180 mm Takahashi astrograph provides a 4.2 x 4.2 degree field of view on a 3056 x 3056 CCD imager with a 7-color filter wheel. The system is fully robotic and automated, allowing for remote operation and intelligent automated observing. The telescope is housed in a unique portable trailer-mounted enclosure allowing for relocation for different projects or observing programs. The observations included in this report were conducted from two locations: Mt Lemmon Sky Center and Biosphere 2 (both are near Tucson, AZ).
- The Víctor M. Blanco 4-meter Telescope at Cerro Tololo Interamerican Observatory in Chile, utilizing the Dark Energy Camera (DECam) with a 60-CCD wide-field visible imager. DECAM is one of two main precursor instruments used for verifying and validating the LSST Science Pipelines by Rubin Observatory Data Management (Tyson et al., 2020).
- The "0m4-04" 0.4 m telescope at the LCOGT node, Haleakala (HI), of Las Cumbres Observatory (Brown et al., 2013). LCOGT is constructing a world-wide network of telescopes, including the two 2m Faulkes telescopes, as many as 17 x 1m telescopes, and as many as 23 x 40cm telescopes. The observations were conducted under proposal DDT2020B-003.
- The Zeiss 1.23 m telescope based at the Calar Alto observatory (Barrado et al., 2010), Spain. The Zeiss telescope uses a CCD DLR-MKIII camera with a 21.4 by 21.4 arcmin field of view, with a pixel size of 0.314 arcsec pixel^{-1}.

6.2.4. Methods

For the satellite observations, the observations were planned during the twilight hours, when the satellites are illuminated by sunlight and are above the local horizon of the given telescope facility. The celestial coordinates of the satellites are computed for a given location, date and time, using the orbital ephemeris of the satellites. The observations are conducted such that the telescope is tracking in sideral mode at the time that the satellite is expected to cross the field of view of the imaging device. This way, the stars within the field of view of the camera, are well defined and are used as a reference to compute the apparent magnitude of the integrated flux of the satellite streaks imprinted in the imaging device. The observation procedure includes the standard techniques used in photometry, including the acquisition of dark, bias and flat field frames to calibrate the images of the satellite observations. Ideally the entire satellite streak will be visible within the image frame. This simplifies the photometric analysis and provides unambiguous timing information as we can definitively determine the satellite's position at the beginning and end of the timed exposure. However, in most cases because of the high angular speed of the satellites and small field of view of the imaging device, the satellite streak can't be captured in its entirety. However, the total length of the satellite streak, in the effective exposure time of the images, can be computed from its known angular speed, and consequently the total apparent brightness magnitude of the satellite be computed. Details on the data processing is found for instance in the work of Tregloan-Reed et al. (2020a).

When comparing the brightness of satellites from different observations, the photometry of the satellites was normalized to zenith using the range^{-2} power law, and also calibrated by their corresponding solar illumination, and observer viewing angles at the moment of their observations.

6.2.5. Main Results

6.2.5.1. Pre-Mitigation Starlink Satellites

Figure 6.2.1 shows a histogram of 567 brightness measurements of the pre-mitigation Starlink satellites as observed by the POMENIS telescope[1]. The mean of these measurements is 4.7 mag with a large range of values. What this means is an observed pre-mitigation Starlink satellite may be as bright as 2nd magnitude or as faint as 7th. The observed brightness is dependent on numerous factors related to the Sun-satellite-observer geometry. Observations from the other facilities also fall into this range.

This large dataset will now be used to develop and validate models which characterize the satellites' apparent brightness in various geometries.

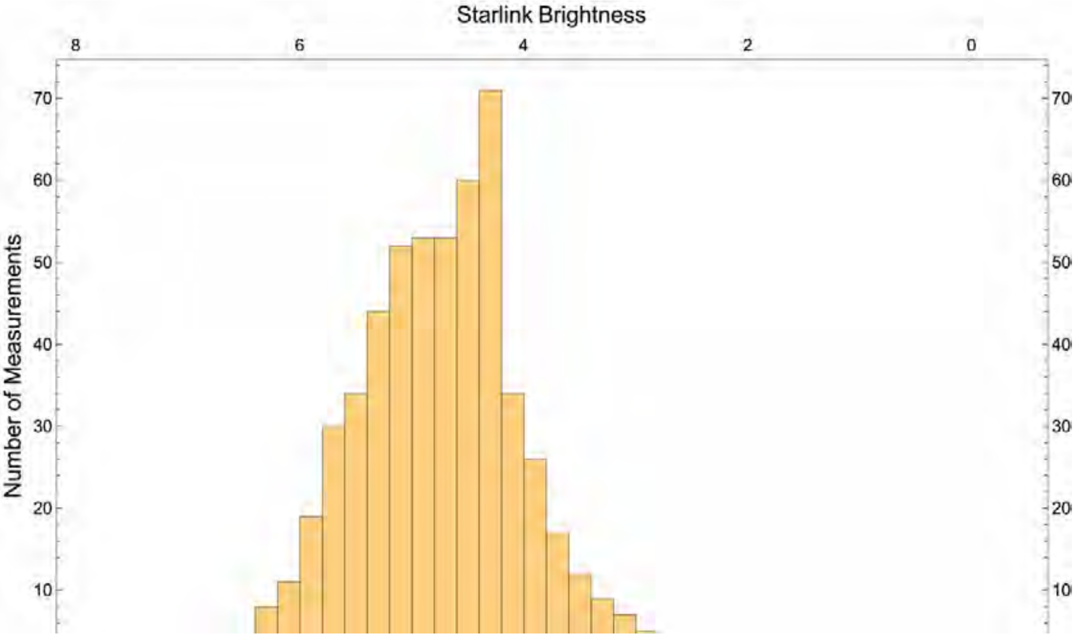

Figure 6.2.1. A histogram of 567 Johnson V magnitude measurements of pre-mitigation Starlink satellites imaged by the Pomenis telescope from May to September 2020. The mean of all the measurements is 4.7 with a standard deviation of 0.85. This broad distribution demonstrates the varied brightness which depends on numerous geometric factors.

Figure 6.2.2, shows the results of 23 observations of Starlink satellites performed with various astronomical facilities and at various spectral bands. The spectral bands wavelength coverage is given by the horizontal bars. All observations, conducted in the same spectral band, where averaged and the standard error computed. The statistical weighted mean and standard error are shown in the center of the corresponding spectral bands. The brightness magnitude of the 23 observations summarized in here are those listed in Table D.2.7 (Appendix D).

The results in Figure 6.2.2 show that the brightness magnitude of pre-mitigation Starlink satellites (i.e. those not given a darkening treatment or visor) have an apparent brightness magnitude brighter than 6 at all spectral bands.

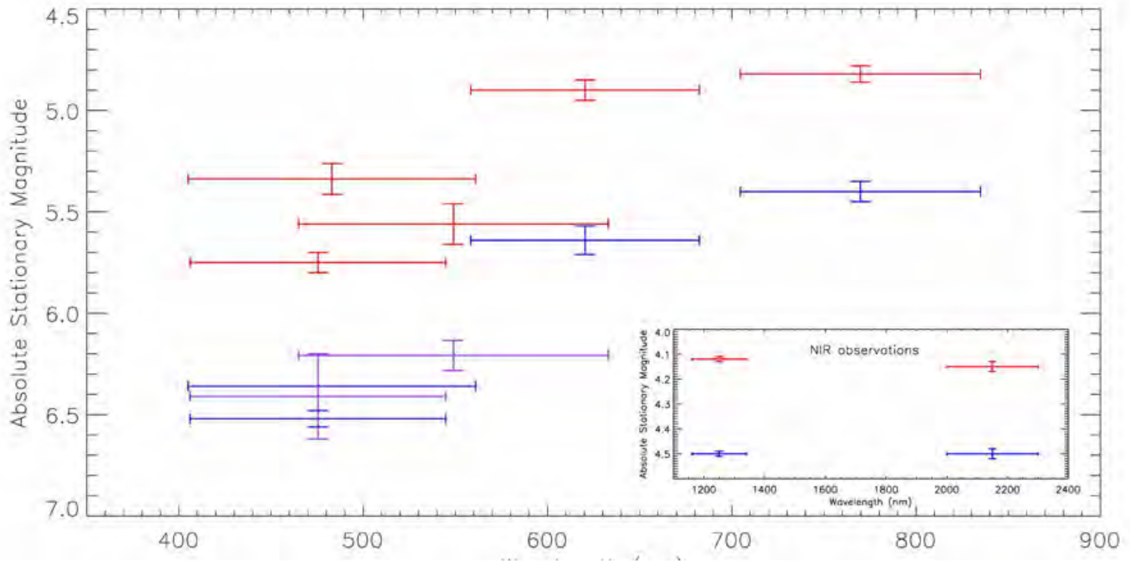

Figure 6.6.2. Summary of the multiwavelength observations to date of Starlink LEO satellites. These include Visorsat (purple), Darksat (blue) and non-darkened Starlinks (red). These results show the statistical weighted means of the observations for each LEO satellite type and wavelength. Insert: Summary of the Near Infrared observations to date of Starlink-1113 (red) and Darksat (blue). The data is from Tregloan-Reed et al. 2020a,b, Tyson et al. (2020), and the POMENIS Telescope team. Note: All these brightness magnitudes correspond to observations that have been normalized to a range of 550 km (equivalent to the nominal orbital height of the Starlink satellites) and also corrected by the solar incidence angle and observer angle. The normalization and corrections are done such that observations done at different epochs and of different relative angles of the satellites with respect to the sun and observer, can be compared.

6.2.5.2. OneWeb Satellites

The Pomenis telescope made over a hundred observations of OneWeb satellites in September 2020. In the majority of images the satellites were too faint to be automatically detected by the current software processing pipeline. This indicates the OneWeb satellites are typically fainter than 6-7th magnitude which is the approximate detection limit of the current software. A small number of

OneWeb satellites were detected by the software and measured as bright as 3rd magnitude, indicating that while the OneWeb satellites are typically faint they may be brighter in certain geometries. A definitive assessment on their flux density (photons/arcsec^2), from observations using telescopes/cameras that allow a high accuracy photometry, is still much needed to assess their brightness magnitude, and their effect on the imaging system of highly-sensitive, large field of view instruments, such as the Vera Rubin Observatory's LSST camera.

For the OneWeb satellites to meet the Recommendation #5 of the SATCON1 Report (C. Walker et al., 2020), the OneWeb when deployed at their nominal orbital height of 1200 km shall consistently exhibit an apparent brightness magnitude at 7.85 or fainter in the visual spectral band.

6.2.5.3. DarkSat

DarkSat is Starlink satellite with a modified design intended to reduce the apparent brightness.

DarkSat features a black coating on the nadir facing antennae where the original-design has white antennae. The intention of this modification is to reduce the satellite's albedo and the amount of light reflected towards observers on Earth. DarkSat was launched in January 2020.

The Observations Working Group has made a small number of observations of DarkSat. With a typical apparent brightness of 6th-7th magnitude (see Figure 6.2.). DarkSat is generally dimmer than the pre-mitigation Starlink satellites. Since the DarkSat mitigation strategy is an albedo reduction we do not expect its efficacy to be highly orientation dependent. However, it is not yet known how much the antennae contribute to the overall brightness of the Starlink satellites and the orientation dependence of such.

Additionally, separated multi-color measurements of DarkSat to assess its efficacy at various wavelengths, have been made. As shown in Figure 6.2.3, the reduction in albedo is less at longer wavelengths. Additional multi-color measurements, preferably simultaneous, are needed to confirm this result in various geometries.

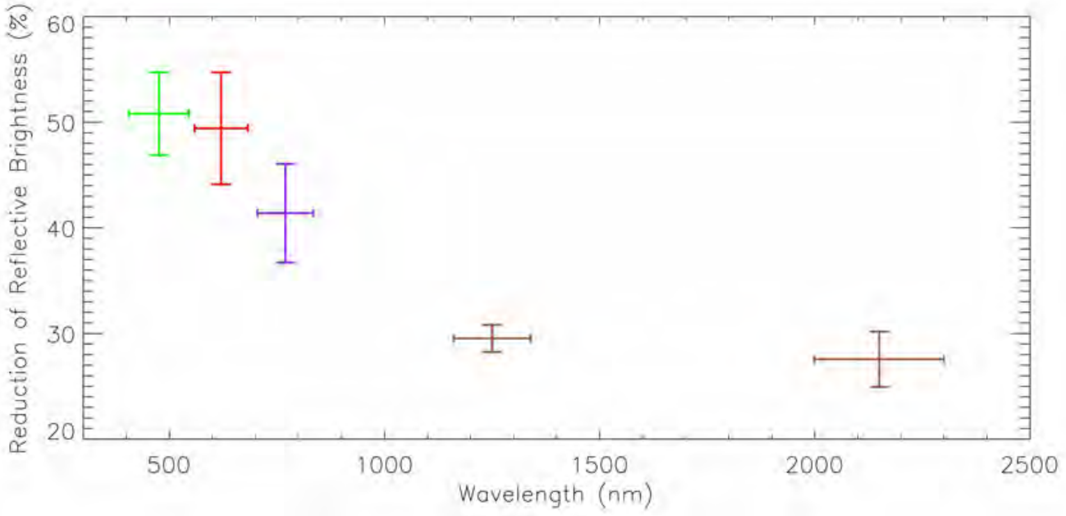

Figure 6.2.3. Reduction of reflective brightness between Darksat and STARLINK-1113 for the Sloan g' (green), Sloan r' (red), Sloan i' (purple), J (brown), and Ks (brown) calibrated results (adapted from Tregloan-Reed et al. (2020a,b)). The horizontal error bars represent the FWHM of the passband filters, while the vertical error bars represent the uncertainty in the reduction.

6.2.5.4. VisorSat

VisorSat is a Starlink satellite with a modified design intended to reduce the apparent brightness. VisorSat features Sun visors attached to the side of the satellite bus which are intended to block sunlight from hitting the nadir facing side of the satellite bus and thus reduce the amount of light reflected towards observers on Earth. VisorSat was launched in June 2020 and after successful operational tests all new Starlink satellites feature the same design starting in August 2020.

The WG has made a small number of VisorSat observations, these show that VisorSat is generally dimmer than the pre-mitigation Starlink satellites and similar to DarkSat, in the optical spectral bands. Visorsat typical apparent brightness is in the range 6th -7th magnitude (see Figure 6.2.2). We expect the VisorSat mitigation strategy is highly orientation dependent because the visors are in a fixed position and only block sunlight in one direction. When the satellite is opposite the Sun relative to the observer the visors may themselves reflect sunlight and result in an increase in apparent brightness. More observations are needed to characterize the apparent brightness of VisorSat and its siblings in various geometries.

[1] There are a small number of additional measurements for which the satellite was too faint to be automatically detected by the current software processing pipeline.

6.3. MITIGATIONS

6.3.1. SUMMARY AND AIMS

The Satellite Constellations 1 (SATCON1) workshop held virtually in June–July 2020 created a set of key recommendations, targeted at mitigating the impact of low-Earth orbit (LEO satellite constellations specifically on optical and infrared astronomy as well as stargazers worldwide. In this report, we recap the SATCON1 findings (Walker et al., 2020), and add additional such recommendations — generated through discussion among a broader group of astronomers, space scientists, and satellite industry engineers. In a potential future with tens of thousands of low Earth orbit satellites (LEOsats), no combination of mitigations can fully avoid the impact on astronomy, despite the deep cultural significance and scientific merit of the night sky. At present, the situation for astronomy is reaching a point of no return from continuous interference with observations and loss of science. With this in mind, we comment on critical impacts.

Note that the specific numbers stated in our report are taken from the work of the simulations group which draw from filings from regulatory agencies and the ITU. They are based on scientific reasoning and represent the current knowledge of impacts.

6.3.2. FINDINGS FROM SATCON1

> “If the 100,000 or more LEOsats proposed by many companies and many governments are deployed, no combination of mitigations can fully avoid the impacts of the satellite trails on the science programs of current and planned ground-based optical-NIR astronomy facilities” (Walker et al. 2020)

The SATCON1 Mitigations Working Group Report, Appendix C (Tyson et al., 2020b), describes several efforts to mitigate the effects of proposed LEOsats on optical astronomy research. There are nine main recommendations, followed by a discussion of how LEOsats impact certain astronomical observatories. The recommendations are limited in scope to technical mitigations for LEOsat operators and/or ground-based optical and IR observatories. They do not consider mitigations for radio-frequency interference (RFI), space-based telescopes, or broader impacts of wider importance, such as cultural significance, ethical concerns, regulations, policy, or funding. We summarize and endorse the recommendations here:

M1. Fewer satellites

No currently apparent combination of known mitigations can completely avoid the impacts of tens of thousands of LEOsats on the science programs of the coming generation of astronomy facilities. If satellite operators can achieve their goals with fewer satellites, this is the simplest mitigation.

M2. Darken satellites in all phases of the orbit

This has to occur during LEOsats’ “lifetime” phases: launch/insertion, orbit raise, parking orbit, final on-station orbit, and deorbit/decay. While the phases outside of final orbit represent a small fraction of the satellite’s lifetime (of order weeks, compared to lifetimes of several years), maintaining a population of thousands of LEOsats at a steady state requires regular additional launches. A substantial fraction of the overall LEOsat population will thus always be in these two, potentially brighter phases on any given night.

M3. Darken satellites to at minimum fainter than 7th visual mag when at 550 km altitude, and preferably > 8th mag

Seventh visual magnitude corresponds to a radiance of < 44 W/sr for a satellite at 550 km, which needs to be incorporated in the satellite design. This threshold is based on the analysis in Tyson et al. (2020a) which measured electronic crosstalk in Vera C. Rubin Observatory's LSSTCam CCDs in a laboratory. Bright satellite trails cause nonlinear electronic crosstalk signals — parallel "ghost" satellite trails which must also be removed before science can be done. The removal process leaves residual systematic errors above the sky noise level when the main satellite trail is brighter than about 7th V mag at 550 km, which may severely impact precision astrophysics and cosmology studies. Even if darkened to 7th mag (at 550 km) the remaining trail itself presents severe data analysis challenges, impacting a wide range of science. This faintness target is a function of satellite altitude, and partially mitigates only one of the impacts on science: the effects on the detectors. A separate and very large impact is that LEOsats at altitudes much higher than 600 km will leave streaks on astronomical images all night long, as discussed in the next section.

M4. LEO satellites on orbits as low as possible

LEOsats have to be low: no satellites at altitudes significantly higher than 600 km; OneWeb satellites at 1200 km are particularly damaging. This is crucial for three reasons. First, LEOsats at 1200 km may be illuminated all night long, rather than just in evening and morning twilight.

Second, a higher-altitude LEOsat is visible above the horizon for longer than a lower-altitude one. Third, higher-altitude LEOsats have slower angular velocities and appear more "in focus" to telescopes on the ground. The result is a brighter satellite trail in the image. The impact of an 8th V mag satellite at 1200 km is roughly equivalent to a 7th V mag satellite at 550 km.

We note that the specific altitudes 550km-600km and 1200km are taken from the work of the simulations group. It is important to understand that any satellite altitudes significantly above ~600km will be highly damaging to astronomy. The 1200km altitude is just an example.

M5. A global public community repository of up-to-date and highly accurate orbital and location data for satellites

The current standard for predicting satellite locations in the sky uses two-line elements (TLEs), which assume projectile motion and account poorly for non-uniform acceleration.

This is particularly problematic during the phase of orbit raising. To enable some astronomy facilities to attempt to avoid a subset of LEOsats, the international community requires accurate LEOsat population ephemerides with a sky location precision of arcseconds and a time precision of a tenth of a second. In addition, limiting satellites to certain orbital planes that are well-defined and understood will permit more robust advance scheduling.

M6. Satellite locations as a public service

We envision a server application to the database described in (5) that can be queried to provide the known distribution of LEOsats on the sky. It would have a user-friendly web interface as well as an Application Programmable Interface to facilitate interfacing with applications used by astronomers for planning and executing their observations, and for the wider community (e.g., smartphone apps).

M7. Advanced algorithms for avoidance of bright satellites

Given a known distribution of LEOsats on the sky, advanced telescope scheduling algorithms may have potential to more effectively avoid them: the development of AI algorithms and scheduling tools should be pursued. Whether this is feasible depends a lot on other constraints of a given observatory (e.g., where the telescope can physically point) and its unique science observing program (e.g., whether a neighboring field of sky must be observed immediately after, integration time, monitoring special sky locations).

M8. A predictive model for satellite brightness versus orbit, relative to geographic locations

This is a significant undertaking that needs to be applied consistently on an industry-wide scale, with three main components. One is analyzing observations of satellite trails for their brightness. Another is using satellite bi-directional reflectance distribution function (BRDF) measurements to characterise how incident light is reflected, diffused, or absorbed by exposed surface elements during the design process. Another is a satellite reflectance simulation analysis. All of these should be done in a coordinated way to create a true predictive model of how a given satellite will appear in astronomical images and data Products.

M9. Ongoing support for “end-to-end” simulations of broad science impact by researchers

Given our best knowledge of satellite locations, numbers, and brightnesses, and ideally with a reliable predictive model as described above, astronomers can use this to simulate how different populations of satellites will affect the many types of astronomical science. Even if LEOsats are sufficiently darkened to avoid systematic errors from crosstalk “ghost” trails, the main trail will still impact astronomy, in both the time domain and the space domain. For example, in the time domain, flux variations or glints may be mistaken for a transient astronomical source, which would pollute the detections and statistics of the wide range of changing physical phenomena that produce transient sources. In the space domain, deciding where a satellite trail ends and true sky background begins is not straightforward; this will affect precise background sky level measurements, which for instance are critical for cosmology studies.

6.3.2.1. Additional Recommended Mitigations

Here we present additional mitigations which are new to this report or were not fully described in the SATCON1 Mitigations Working Group Report, Appendix C (Tyson et al., 2020b).

M10. More telescopes and telescope networks

While large next generation optical astronomy facilities are most heavily impacted by bright LEOsat trails, as outlined in the SATCON1 report, smaller telescopes and networks of telescopes play an important role particularly in following up discoveries of novel transient events.

For such science cases, a useful mitigation would be to deploy additional telescopes (see for example, Rascon et al., 2018). Since multiplexed telescopes can observe in different directions at any given time, if one is impacted by a satellite trail, another may not be. The overall increase in available telescope observing time also compensates somewhat for observations lost due to trails. One example is planetary defense: the community of near-Earth asteroid surveys and telescopes that provide astrometric follow-up of their discoveries. Satellite constellations will impose a several percent up to several tens of percent tax on the observing assets deployed in the search for potentially hazardous asteroids — depending on the altitude, brightness, and number of satellites deployed. The only way to search for Near-Earth Objects (NEOs) that are near the Sun is by observations in twilight, looking low in the east in the morning, or low in the west in the evening. These Critical observations will be immediately affected by the strong twilight streaking of LEOsats.

NEO searches (Catalina Sky Survey, https://catalina.lpl.arizona.edu; Pan-STARRS, https://www.ifa.hawaii.edu/research/Pan-STARRS.shtml) generally make a time series of four observations for each of hundreds of fields each night to detect moving objects. More and more of these fields will be hampered by streaking as satellite constellation deployment proceeds. As an increasing fraction of images are lost to streaking, the efficiency of the surveys will inevitably suffer, field by field. A tipping point will be reached when the NEO surveys will need a series of five observations to overcome these losses, incurring a penalty of 25% in sky covered per night.

More generally, one trend in astronomy, especially in studying time domain phenomena, isto deploy assets in networks of telescopes (Hot-wiring the Transient Universe VI, https://sites.northwestern.edu/hotwired6/) distributed in both longitude and latitude Las Cumbres Observatory, https://lco.global). These Networks are generally composed of 1m-class telescopes, but could benefit from larger and more numerous apertures. Larger telescopes can also benefit from a twin or near-twin in the other hemisphere, or even multiple small, medium, or large telescopes on the same site.

Additional telescopes, distributed in worldwide networks, and in some cases improving detector instrumentation on current telescopes, could partially compensate for the anticipated loss of efficiency due to foreground satellite constellations. This requires not just funding for construction, but also to cover the proportionate additional operational and maintenance costs. For future telescopes that are in the early planning stage, an additional mitigation would be to increase the aperture. A larger aperture would allow shorter exposures that may be less impacted. Increasing the aperture results in cost increases as with additional telescopes and camera upgrades. These fundamental issues of aperture, field-of-view, and diversity of telescopes will continue to apply to future astronomical research assets.

M11. Development of a “digital twin” of the space environment and its satellites

An increasing number of non-State actors are being authorized by States to launch tens of thousands of satellites over the next few years. Assessing the combined impact on ground-based astronomical observations of proposed satellite constellations, along with space debris mitigation standard practices, is important to develop future guidelines and determine which decisions will result in the most effective outcomes.

We recommend developing Space Domain Decision Intelligence to determine the best decisions that can be made, given the quantifiable impact which different satellite operations and the behavior of the greater anthropogenic space object population have on the various fields of astronomy. To reach this point, one must first develop and maintain a space domain “digital twin”. At a minimum, it must model the satellites themselves, the space environment, their relationships and interactions, and include reasonable estimates of uncertainties.

Satellite operators, regulators, and the broader community affected by space activities should perform Monte Carlo analyses incorporating, at a minimum, uncertainties in the size, shape, and material properties of satellites, as well as how accurately and precisely the location and predicted errors might be quantified. The analyses will enable the astronomical community to holistically estimate and statistically quantify the impacts of proposed space operations on observations, and will provide a way to understand which satellite design and operations decisions will best minimize the impact to astronomy. To accomplish this, we strongly recommend satellite operators share the necessary details openly and without requiring non-disclosure agreements.

M12. Mitigations for radio astronomy

As noted in Chapter 7, satellite radiocommunication signals are some ten billion times stronger than cosmic radio sources. Satellite radars are much stronger still. Such satellites therefore pose a particular challenge to radio astronomy because they pass overhead and cannot be shielded. For reasons that are explained in Section 7.1, satellites can interfere even when they are not directly over the observatory or when the telescope is not directly pointed at them.

One mitigation is to dynamically turn off the transmitter or deflect its emission while the satellite passes within sight of an observatory. This is only feasible for satellites with small beams, which is a general feature of LEOsats below 600 km. For constellations planned for 1200 km, the beam sizes are large (serving wide regions) and turning off the radio transmitter is infeasible. A related mitigation is to place satellite ground stations away from radio astronomy sites to prevent interference from the satellite-ground links that most constellations require.

Given the science-driven push to broadband radio astronomy with unprecedented sensitivity and spectral coverage, there is no combination of feasible mitigations that can fully protect radio astronomy science. A complete discussion of the interference problem from the point of view of radio astronomy is given in Section 7, along with appropriate recommendations.

M13. Mechanisms and alerts for temporary dimming of satellites

Characterization of the Solar System populations during twilight times is particularly imperiled by the abundant twilight satellite streaks characteristic of LEOsat constellations. We propose a mechanism to inform LEOsat operators of critical sky regions and times, so that satellites may temporarily be moved or darkened further to enable urgent time-sensitive science.

For example, astronomical and nautical twilight is one important time for key classes of astronomical observations, such as the detection and characterisation of comets, interstellar objects and near-earth objects. This is also the time when the largest number of LEOsats are visible in the sky — especially in the near-Sun direction at moderately low elongations, which is a region of the sky that is crucial for study of these Solar System small-body populations. Another example is transient events such as gravitational waves, which are time-sensitive, but could be located anywhere in the sky.

In the event of a critical observation opportunity for an observatory, in particular where that observation has high scientific value and is rare or transitory, we strongly propose design capabilities for satellites to make an orientation change in order to reduce brightness in the direction of the observatory, making the observation again possible.

Such an orientation change may degrade the satellite's ability to perform its mission for the duration of the adjustment. Also, the change might result in undesirable brightness increase in the direction of a different location on the ground. Detailed understanding of the potential scientific value of these kinds of maneuvers, effects on the constellations, and geographic dependence require further study. For this kind of mitigation to be effective, satellite and constellation design will need to routinely include this capability. The astronomical community will need to augment the existing scientific rapid-alert mechanisms, providing a communications channel for satellite operators to monitor.

M14. Mechanisms for knowing which spectra to throw out

Large spectroscopic facilities need a mechanism for identifying which spectra are affected by satellite contamination. The large collecting area of the telescope's primary mirror combined with long integration times is a prescription for trouble. One might think the small filling factor of the fibers or slits in the focal plane and a 1–3 arcsecond satellite trail width would make the likelihood of a collision with a satellite trail rare. However, this assumes the satellite trail is only a few arcseconds wide. In fact, LEOsats leave a much wider trail, at a surface brightness level which can seriously impact long spectroscopic integrations on faint objects. A typical large spectroscopic facility has a mean separation between fibers or slits of about 0.2–1 degree in the focal plane. This is comparable to LEOsat trail width, which makes the probability of pollution of one or more spectra quite high in the scenario of tens of thousands of LEOsats.

When a satellite crosses a spectrograph fiber or slit, the target's spectrum is contaminated with reflected sunlight. If the satellite is very bright, this contamination may be discovered early in a quality control pipeline. If the satellite has an effective magnitude comparable to the science target, the contamination may be discovered later. For example, if the data analysis shows that a galaxy spectrum unexpectedly shows Sun spectrum features, then clearly the spectrum has been contaminated by a satellite. However, if the science target itself is a Sun-like star, it will be impossible to determine if contamination exists, much less to disentangle which spectral features belong to the science target.

Due to the long exposure times, there is no mitigation beyond identifying which data to throw out. The spectra from all affected fibers must be discarded. Affected fibers can only be reliably identified via knowledge of the exact position of the satellite trail in the field of view. This is currently not possible for most spectroscopic instruments, because spectra do not record spatial information. One workaround could be to attach a smaller secondary telescope with a wide-field imager to the primary telescope. The secondary telescope would point where the primary points, see the same field of view, and take exposures alongside the spectroscopic instrument. Any satellite trails could then be detected during post-processing, and their position and orientation would indicate which fibers or slits are impacted. This technique would not mitigate the fact that all affected spectra must be discarded and observations repeated — which may never be possible for time-sensitive phenomena.

M15. Clump satellites in parking and orbit raise

The spacing of LEOsats is governed by their chosen configuration. To minimize effects on ground-based observations, operators could modify the satellite configurations to clump together as many as possible as close as feasible, rather than spreading them out over the entire orbital plane.

This will help to minimize effects on ground-based observations, making fewer discrete interfering events, during a time when the satellites can be in relatively bright configurations and prior to being widely spaced in their eventual orbits. The lower limit on spacing is driven by space safety and the need to prevent collisions which would have more serious consequences. Soon after launch while the satellites are performing checkout and are not yet fully operational, they may not yet be communicating, have precision navigation data, nor be ready to maneuver with thrust. Consequently, collision avoidance in the earliest flight phases is driven by separation.

M16. Development of smarter instruments

Scientific Complementary Metal Oxide Semiconductor (sCMOS) development is accelerating. In contrast, most astronomical instruments use charge-coupled devices (CCDs), a mature and well-established technology. In sCMOS development, medical imaging applications are driving larger formats, and quantum computing applications are driving high quantum efficiency and rapid read characteristics. There has been recent progress in back-illuminated sCMOS. Whether via mosaicing or larger individual sensors, it is likely that much larger sCMOS will be developed by 2030. Embedded signal processing is becoming more common, and in the future this new class of intelligent imager could emerge as an attractive choice. CMOS focal planes would enable dynamic self-shuttering. Unfortunately, a generic feature of CMOS is that neighboring pixels are correlated. We emphasize this is a far-future mitigation that would only be applicable to some transient detection missions. It cannot address most science from next generation sky surveys such as Rubin Observatory.

M17. Make satellite locations more predictable by maintaining all satellites in a constellation on “Gravity-Only” trajectories

Gravitational accelerations experienced by anthropogenic space objects are not dependent on their physical characteristics: a rocket body and a cubesat with the same kinematic state at a common epoch will both experience the same acceleration due to gravity. This is extremely attractive, because it removes the need for a satellite owner/operator to provide extensive details about the physical characteristics of their satellites, which could be seen as sensitive or proprietary. Define the gravity field you are using and anyone with a computer is able to compute and predict the trajectory. This is ideal for planning purposes as it greatly simplifies this task. Each satellite owner/operator would need to agree to a threshold of control to maintain their specific gravity-only trajectory.

For example, a satellite owner/operator could make it public that they will control their satellites to a EME2000 inertial reference frame trajectory with a designated set of initial conditions, using the EGM96 gravity field up to and including degree and order 20 of a spherical harmonic expansion model. Any non-gravitational accelerations their satellites then experience would need to be removed by the operator, through their own guidance, navigation, and control systems, to keep satellites on this gravity-only trajectory. This significantly provides the community with the ability to predict when and where satellites will be in their field of view since this prediction is only based upon this knowledge of initial conditions and not specific physical characteristics of these satellites.

6.3.3. EFFECTS ON SPACE TELESCOPES

The impact on space telescopes is unclear and should be carefully studied. For instance, in the current case of the Hubble Space Telescope (HST), due to the small field of view of HST, their relative proximity to the HST, and the fact that they will be severely out of focus, decreasing their brightness, one could argue that the impact should be minimal. However, already at present about 5% of HST imagery is affected by satellite trails. Adding tens of thousands of satellites will only make it worse. Additionally, some current and future space telescopes operate in orbits which keep them Sun-synchronous on the Earth’s terminator (e.g. CHEOPS), which means that the satellites orbiting above them are always illuminated, making the overall frequency of trailing higher than that seen by ground-based telescopes.

An additional impact on space telescopes in general is likely to come in a flow-on way: ground-based facilities discover new phenomena and find interesting targets, and then space telescopes perform follow up observations of these targets. Exploratory and open-end investigations are technically challenging and too expensive to do from space, and are therefore predominantly done with ground-based telescopes (atmosphere permitting). If ground-based facilities are impacted, and interesting discoveries and targets are missed, this means there will be a decreased number of follow-up observations with space telescopes. It is difficult to estimate exactly how much science will be lost, but it is clear that the physics of newly discovered phenomena in ground-based surveys cannot be understood without followup using space facilities.

We note the decrease in efficiency of ground-based observatories due to LEOsats cannot be mitigated by increasing the number of space telescopes. Space and ground-based astronomy complement each other and are used in concert to allow for the most comprehensive science. Facilities in space cannot perform the mission of ground-based telescopes, due to a wide variety of prohibitive technical challenges, ranging from size and weight to instrumentation to data processing.

6.3.4 BROADER IMPACTS ON ASTRONOMY THAT ARE WITHOUT MITIGATIONS

Even if all mitigations above were implemented, astronomy will pay dearly. The exact damage is impossible to estimate: one cannot put a price on lost science opportunities. How does one estimate the risk of stymying the utility of ground-based telescopes? How does one calculate how public knowledge and appreciation of the universe will suffer when we miss out on new exciting and unpredictable discoveries?

What we can say is that the presence of tens of thousands of satellites will decrease the time available for uncontaminated, satellite-free observations across the world. All observatories planet-wide will be affected, to varying degrees.

The upcoming contamination will degrade the legacy that each and every observatory leaves to future generations: its data archives. The contamination of ground-based observations (images and spectra) with LEOsats will lead to systematically biased data archives. For example, cosmological simulations have to be calibrated against observations, and if the observations are contaminated on a level that remains undetected, then the simulation calibrations will also be wrong. This can lead to unforeseeable outcomes when testing and interpreting simulations. Contaminated legacy databases like Rubin Observatory's LSST will affect astronomical science for decades to come. Several 30-meter class ground-based telescopes (ELT, GMT, TMT) are under construction, each with a $2 billion price tag including instruments. Their mission is mainly spectroscopy, and because of the large light collecting area and long exposures, they will be impacted (see M14).

Astronomy is its people, never just its telescopes. Professional telescopes have observing time competitively assigned, and are oversubscribed. In state-of-the-art facilities such as VLT, Keck, Gemini, Subaru, GTC, and many others, the competition for observing time is already fierce. Decreasing the available time will mean that more observing proposals will have to be cut from the selection. Astronomers worldwide will have fewer executed observing proposals. Major community telescopes have always been the training ground for observational science. This will disproportionately affect early-career astronomers, and that will certainly hinder efforts to improve diversity and equity in the field. This long-term harm to astronomy will be as globally apparent as the visibility of first-generation LEOsat constellations in the current sky.

6.4. RECOMMENDATIONS

6.4.1. POLICY RECOMMENDATIONS: INTRODUCTION

A large, international and diverse team of astronomers, industry representatives, policy and legal experts was assembled to study the impacts of satellite megaconstellations on astronomy. As part of this overall Satellite Constellation Working Group, three sub-working groups were established to study satellite observations, simulations, and mitigations.

A fourth "recommendations" sub-working group was charged with reviewing the findings and recommendations from the observations, simulations and mitigations groups, and additional relevant recommendations from the other main Working Groups, particularly the Optical Astronomy and Radio Astronomy groups. The recommendations group also incorporated findings and recommendations from the recent SATCON1 workshop.

In addition to collating and structuring recommendations from the other working groups, the recommendations sub working group also considered how various recommendations could be implemented and supported by a range of stakeholders including policymakers. The recommendations are organised by the following tables by the main category of stakeholder: *observatories, industry, astronomy community, science funding agencies, national and international policymakers*. In each case, where applicable, supporting stakeholders are identified in the right-hand column.

6.4.1.1. Recommendations: Observatories

Recommendation	Stakeholder
Observatory Mitigation Measures: Optical, Infrared	
Development of software to manage impacts of satellite constellations	
R1: Support the development of a software application available to the general astronomy community to identify, model, subtract, and mask satellite trails in images on the basis of user-supplied parameters. [Ref: SATCON1 rec.1]	Observatory Leadership Science Funding Agencies
R2: Support simulations of the effects on data analysis systematics and data reduction signal-to noise impacts of masked trails on scientific programs affected by satellite constellations. Aggregation of results should identify any lower thresholds for the brightness or rate of occurrence of satellite trails that would significantly reduce their negative impact on the observations. [Ref: SATCON1 rec.3]	Observatory Leadership Science Funding Agencies Industry (provision of data)
R3: Support development of a software application for observation planning available to the general astronomy community that predicts the time and projection of satellite transits through an image, given celestial position, time of night, exposure length, and field of view, based on the public database of satellite ephemerides. Current simulation work provides a strong basis for the development of such an application. [Ref SATCON1 rec.2]	Observatory Leadership Science Funding Agencies Industry (provision of predicted ephemerides)
R4: Support the development of a predictive model for satellite brightness versus orbit relative to an observatory, to create a predictive model of how a given satellite will appear in astronomical images and data products. This requires analysing observations of satellite trails, collecting satellite bi-directional reflectance distribution function (BRDF) measurements to characterise how incident light is reflected, diffused, or absorbed by exposed surface elements during the design process, and satellite reflectance simulation analysis. [Ref: SATCON1 rec4; Mitigations report M8]	Observatory Leadership Science Funding Agencies Industry (provision of data)
Development of hardware / facilities to manage impacts of satellite constellations	

R5: For future facilities, consider measures to allow shorter time exposures, minimising the effects of satellite trails (e.g. increase telescope aperture). [Ref Mitigations report M10]	Observatory Leadership Technology Development Planners Science Funding Agencies
R6: Support the provision of additional telescopes to cover observing losses for science cases requiring low elevation twilight observations (e.g. Near Earth Objects), and to compliment spectroscopic observations with simultaneous exposures to determine if satellite trails passed through the FoV, and to support identification of noise subtraction or identification of affected fibers. [Ref Mitigations report M10]	Observatory Leadership Science Funding Agencies Industry (provision of positional data)
R7: Support the development of "smarter instruments" designed for rapid and flexible mid-exposure shuttering and invest in new CMOS detector technologies allowing individual pixel shuttering and embedded signal processing. [Ref: Mitigations report M16]	Observatory Leadership Technology Development Planners Science Funding Agencies
Observatory Mitigation Measures: Radio	
Development of software to manage satellite constellation impacts	
R8: Support the development of reliable and accurate simulations that enable calculation of equivalent power flux density at radio observatory locations. [Ref: Recommendation WG discussion]	Observatory Leadership Science Funding Agencies Industry (provision of data)
Development of hardware / facilities to manage impacts of satellite constellations	
R9: Support developments to increase the robustness of receiver electronics and prevent saturation: Increase robustness of radiofrequency system's low noise amplifiers to tolerate higher input radiation power over a wide band. Increase dynamic range of receivers within data processing trade-off limits. Design radiofrequency and digital transport system to the highest possible dynamic range. [Ref: Radio Astronomy WG Report; Mitigations Report M12]	Observatory Leadership Science Funding Agencies Industry (provision of data)

6.4.1.2. Recommendations: Industry

Recommendation	Stakeholder
Industry and Satellite Operators	
Raise awareness amongst key stakeholders	
R10: Participate in astronomy conferences and educational workshops, and likewise, encourage astronomy stakeholders to participate in satellite industry fora. [Ref: Recommendation WG discussion]	Industry Satellite industry associations Astronomy community
R11: Include fundamental science and astronomy as considerations in initiatives to increase corporate social responsibility and in the development of best practices and standards. [Ref: Recommendation WG discussion]	Industry Satellite industry associations National regulators Investors
Design missions to minimize negative impacts on astronomical observations	
R12: Conduct missions from the lowest possible altitudes, in order to minimize the time satellites are illuminated. [Ref: M4 from Mitigations WG report]	Industry National regulators

R13: Minimize the number of satellites required to fulfil their missions. In general, minimizing altitude should take priority over minimizing the number of satellites. [Ref: M1 from Mitigations WG report; Simulations WG report]	Industry National regulators
R14: Minimize the time satellites spend in orbit when not in service. [Ref: Simulations WG report]	Industry National regulators
Design satellites to minimize negative impacts on astronomical observations	
R15: Design satellites to minimize overall brightness at all orbital phases, dynamic variations, and specular flares when observed from the ground. Investigate and implement all commercially reasonable design and operational measures to reduce average brightness from diffuse reflection as much below 7 visual magnitude as possible. Reflected sunlight ideally should be slowly varying with orbital phase to be fainter than 7.0 Vmag +2.5 × log(SatAltitude / 550 km), or equivalently, 44 × (550 km / SatAltitude) watts/steradian, as recorded by high etendue (effective area × field of view), large-aperture ground-based telescopes. [Ref: M2 and M3 from Mitigations WG report; S5 from SATCON1; see also Tyson et al. 2020, Fig 5 & 6 for context to the formula[2].]	Industry National regulators
R16: Conduct reflectance simulation analyses on satellite designs and perform Bi-directional Reflectance Distribution Function (BRDF) measurements on satellites as part of development activities. [Ref: S4 in SATCON1]	Industry
R17: Provide greater detail on antenna power density fluxes, beam patterns and out of band sidelobes across the range of operating frequencies, than provided for ITU and regulator filings. Design satellites to have sidelobe levels that are low enough that their indirect illuminations of radio telescopes and radio quiet zones do not interfere, individually or in the aggregate [Ref: Radio WG report; also discussed as part of general radio recommendations in M12 Mitigations WG report]	Industry, manufacturers National regulators Observatories
Conduct satellite operations in a manner that minimizes negative impacts on astronomical observations	
R18: Provide astronomers with pre-launch predictions and timely post-launch confirmations of the initial deployment orbits for satellites [Ref: M5 and M6 in Mitigations WG report; S9 SATCON1]	Industry National regulators Space traffic management
R19: Maintain and make available to astronomers, satellite ephemeris predictions with a sky location precision of arcseconds and a time precision of a tenth of a second, up to 12 hours in advance. Ephemeris predictions should be accompanied by covariance information and other (to be determined) metadata necessary to support mitigation efforts by observatories. (Note: these positional and timing requirements need further analysis) [Ref: M10 in SATCON1; M5 in Mitigations WG report]	Industry National regulators Space traffic management
R20: Support the development of software applications for astronomical observation planning. [Ref: S6 SATCON1; S7 in Mitigations WG report]]	Industry Astronomy community Space traffic management
R21: Minimize the possibility of specular reflections and flares interfering with observatory activities through operational means (i.e., articulating components, controlling orientation, etc.). If flares cannot be avoided, operators could work with affected observatories to predict such occurrences. [Ref: S6 in SATCON1]	Industry Observatories Astronomy Community
R22: Provide predictive models for satellite brightness versus orbit, relative to geographic locations [Ref: 8 Mitigations WG report]	Industry Observatories Astronomy Community

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[2] The Vera C. Rubin Observatory "correctable crosstalk" level in the LSST detectors is based on simulations is around 7th mag at 550 km but 8th mag at 1200 km (Tyson et al., 2020).

6.4.1.3. Recommendations: Astronomy Community

Recommendation	Stakeholder
ASTRONOMY COMMUNITY MITIGATION MEASURES	
Raise awareness amongst key astronomy stakeholders	
R23: Raise awareness of the increased overheads for conducting astronomy in the future and work with national funding agencies to develop funding instruments to support studying impacts and mitigation measures. [Ref: Recommendations WG discussion]	Astronomy Community Observatories National / Regional Astronomy Societies
R24: Develop mechanisms to coordinate approaches across communities and countries, and share information on industry interactions, mitigation solutions, and observational data concerning satellite constellations.	Astronomy Community Observatories National / Regional Astronomy Societies IAU
R25: Conduct outreach and advocacy campaigns with policymakers, regulators, funders and industry to raise awareness of the value of astronomical science and the impacts of satellite constellations. Engage directly in regulatory and licensing proceedings through providing public comments or writing position papers for regulatory authorities. [Ref: Recommendations WG discussion]	Astronomy Community Observatories National / Regional Astronomy Societies European Committee on Radio Astronomy Frequencies Committee on Radio Frequencies
R25: Represent astronomy interests in satellite industry and professional working groups by participating in satellite conferences and educational workshops. [Ref: Recommendations WG discussion]	Astronomy Community Observatories National / Regional Astronomy Societies
Develop skill base to operate in the satellite constellation era	
R26: Support development of educational materials and courses on how to conduct astronomy in the era of satellite constellations, covering observational strategies, mitigations, scheduling tools, image processing and radio frequency interference management. [Ref: Recommendations WG discussion]	Astronomy Departments University Administrations
R27: Organise professional development opportunities, collaborative research and exchanges of experience, including: Developing proposals for conference sessions; Submitting applications for collaboration networks, workshops and symposia; Identifying possibilities for grant funding to develop competencies and knowledge. [Ref: Recommendations WG discussion]	Astronomy community Universities, Research Institutes Observatories IAU National and Regional Astronomy Societies Science Funding Agencies
Include satellite constellation considerations in strategic planning and understand impacts on science cases of existing observatories	

R27: Take into account the issues of satellite constellations in the process of conducting national strategic plans, decadal surveys and solicitation processes for new instruments and telescopes. [Ref: Recommendation WG discussion]	Astronomy community National / Regional Astronomy Societies IAU Science Funding Agencies
R28: Develop techniques to include satellite constellation considerations in developing science cases for telescopes and instruments. Using a combination of predictive models of location and brightness, support the development of simulations to determine the broad impacts on science cases for existing and future observatories. [Ref: Recommendation WG discussion; Mitigations WG report Simulations WG report]	Astronomers Observatories Project / Instrument Scientists Science Funding Agencies
Support collection of observational data (partnership with Industry and observatories)	
R29: Support an immediate coordinated effort for multiple spectral bands in optical and infrared observations of LEOsat constellation members, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations. Such observations require facilities spread over latitude and longitude to capture Sun-angle-dependent effects. In the longer term, support a comprehensive satellite constellation multispectral observing network with uniform observing and data reduction protocols for feedback to operators and astronomical programs. Mature constellations will have the added complexity of deorbiting of the units and on-orbit aging, requiring ongoing monitoring. [Ref: Satellite Observations WG report]	Astronomy community Observatories Science Funding Agencies Industry (provision of data)
R30: Support "citizen science" campaigns to involve the astrophotography community and amateur astronomy community in supporting data collection understanding of impacts. [Ref: Recommendation WG discussion]	Astronomy community Observatories

6.4.1.4. Recommendations: Science Funding Agencies

Recommendation	Stakeholder
Science Funding Agencies	
Provide support for understanding impacts on astronomy and the increased overheads in terms of additional observing time or science loss [Ref: Recommendations WG discussion]	
R31: Support provision of funding instruments to help astronomy communities and observatories develop software, hardware and facility mitigations. [Ref: Recommendation WG discussion]	Observatory Leadership Science Funding Agencies
R32: Identify necessary technological developments in telescopes, instruments, detectors, receivers, etc, required to mitigate impacts. [Ref: Recommendation WG discussion]	Science Funding Agencies Observatories Astronomy Community
R33: Take steps to evaluate and formalise the impacts on funding instruments (i.e. astronomy grant funding) and capital investments (i.e. telescopes and instruments) and report to political levels of governments. [Ref: Recommendation WG discussion]	Science Funding Agencies Observatories Astronomy Community National / Regional Astronomy Societies

6.4.1.5. Recommendations: National Policymakers and Regulatory Agencies

Recommendation	Stakeholder
National Policymakers and Regulatory Agencies	
Licensing Requirements	
R34: Formulate satellite licensing requirements and guidelines that take into account the impact on stakeholders, including astronomical activities, and that coordinate with existing efforts in relation to radio astronomy and space debris mitigation. [Ref: Recommendation WG discussion]	National space regulators Industry
R35: Develop inquiries and recommendations that encourage flexible technology that can better share spectral resources while ensuring protection of sensitive radio astronomy operations. Consider study of and incentives for new transmitter requirements toward a dynamic approach where coordination could be automated and based on the frequency of the scientific observation being taken and the direction in the sky where the radio telescope is pointed. Coupled with dynamic spectrum hopping and other techniques, these types of dynamic models could enhance spectrum efficiency and replace the current static model of quiet zones that assume fixed transmitter requirements based on a given set of parameters Satellite operators should be encouraged to share the details of their radio systems to a much greater extent than contained currently in public filings with the International Telecommunications Union or radio spectrum regulators that support their authorization or licensing. [Ref: Recommendation WG discussion]	International Telecommunications Union Committee on Radio Astronomy Frequencies National Communications Regulators National radiofrequency managers
R36: Formulate licensing requirements that take into account the location of radio quiet zones and radio telescopes, such that satellites can avoid direct illumination of these areas. [Ref: Recommendation WG discussion and Radio Astronomy WG report S 5.5.2]	National Communications Regulators Committees on Radio Astronomy Frequencies
National Standards Agencies	
R37: Develop spacecraft systems and operational standards that take into account the impacts on astronomical science. Areas include reflectivity of surface materials, brightness of space objects, telemetry data, and spurious antenna emissions. [Ref Recommendation WG discussion]	National Standards Organisations International Standards Organisation National regulatory agencies
National economic and space policymakers	
R38: Support the development of space domain decision intelligence collecting data of proposed satellite constellations and existing orbiting space objects, modelling satellites, their operations in the space environment, and estimate uncertainties to assess the impact of satellite constellations on ground-based astronomical observations. [Ref: Mitigations WG report rec S11]	National space regulators Science funding agencies Industry Space traffic management

R39: Investigate policy instruments that account for negative externalities of space industrial activities, including on astronomical activities, and develop incentives and inducements for industry and investors. [Ref: Recommendation WG discussion]	National economic policy makers National space regulators Industry

6.4.1.6. Recommendations: International Policymakers

Recommendation	Stakeholder
International Policymakers	
Explanatory Note on Existing International Law	
International law applicable to astronomy is scarce, with international law add*ressing light pollution and visual appearance of and access to the night sky nearly non-existent.* *Of the five United Nations space treaties (only four of which have been adopted by most countries), only the Outer Space Treaty ("OST") and the Liability Convention can arguably apply to the impacts of reflected sunlight from satellites. As to the OST, the language relating to freedom of scientific exploration, non-interference, cooperation, and the environment can arguably be interpreted to implicitly include astronomy and dark skies (Articles I and IX). As to the Liability Convention, it only sets a framework for addressing disputes. (Ref: UN Space Treaties, Outer Space Treaty, Liability Convention).* *However, the foregoing arguments remain theoretical because of their implicit aspects and the absence of any judicial cases where such arguments have been applied to astronomy.* *That being said, there do exist international regulations and guidelines (e.g., ITU) and national laws protective of radio astronomy ("RA") in the context of avoiding harmful interference in applicable radio frequencies (Ref https://www.itu.int, ITU Reports on RA, ITU Handbook on RA)* *Additionally, there do exist laws regulating space advertising through, in particular, the use of satellites. (Ref U.S. (51 U.S.C. § 50911)), and international guidelines on and national laws for mitigating space debris, which is a related topic. UNOOSA Compendium. And yet, there exist no known domestic or national laws addressing the impacts of reflected sunlight or reflected or emitted thermal radiation from satellites.*	
Recommendations for Development of International Law	
R40: Policymakers are encouraged to contemporaneously develop international agreements, on the one hand, and national laws within their respective legal frameworks, on the other hand, relating to reflected or emitted electromagnetic radiation from satellites, its impacts on science (particularly, but not exclusively, astronomical science), and efforts to mitigate (if not eliminate) the deleterious aspects of such impacts. At both international and national levels, efforts can build upon frameworks in radio astronomy and space debris, informed by this report and by capacity-building and outreach efforts that bring stakeholders together for purposes of discussion and moving policy development forward, such as this international workshop.	National space regulators National space agencies Astronomy Community Industry National licencing agencies COPUOS

Pedro Duque
Minister for Science, Innovation and Universities, Spain.

The night sky is a precious resource shared by all the humanity. It is our duty to protect and preserve it so that scientists can continue to carry out groundbreaking research and so that society at large can continue to learn more about the Universe we are surrounded by. Spain is strongly committed to preserving the night as we have demonstrated with our protection of the skies of the Canary Islands. The excellent conditions for astronomical observations in these islands merited special protection that the Spanish government implemented by law.

...

In conclusion, I hope this week´s working sessions have been fruitful. The final document that will be presented in Vienna will reflect the various perspectives and opinions expressed ... rest assured of the Government of Spain´s full support in this important work with the conviction that it will also lead to the advancement of Scientific knowledge.

Pedro Duque
Excerpt from the welcome speech to the workshop participants

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7. RADIO ASTRONOMY REPORT

7.1 RADIO ASTRONOMY AS A DISCIPLINE

7.1.1 INTRODUCTION

Radio astronomy has revolutionized our understanding of the Universe in the last century. Quasars, pulsars, the Big Bang and many other phenomena were first revealed by radio astronomy.

Radio waves are emitted by most astronomical objects and observations in the radio region of the electromagnetic spectrum - frequencies up to 3000 GHz or wavelengths longer than 100 microns - are important for research in essentially all disciplines of astrophysics. Radio waves can be generated thermally, from the heat contained by a body, or non-thermally during the interaction of charged particles and magnetic fields. Emitted radiation may be broadly distributed in frequency (continuum radiation), as when electrons spiral at near lightspeed in magnetic fields and when ions recombine in a hot plasma. It is of utmost importance to observe continuum radiation over a wide frequency range because the origin of the radiation is only evident from the overall shape of its spectral distribution.

Radiation may also appear at discrete frequencies corresponding to the internal structure of an atom or molecule and these lines are Doppler-shifted in frequency due to any relative motion with respect to the observer. Observing a sufficient number of such *spectral lines* reveals both the chemical identity of the particles (as with laboratory gas chromatography) and the speed of their motion. Spectral line radiation from the earliest known galaxies appears shifted to frequencies that are ten times smaller than measured in the laboratory.

Hydrogen is the most abundant element and study of the so-called 21 cm or HI ("H-One") line from neutral atomic hydrogen at a rest frequency of 1420.4 MHz is of fundamental importance. A very basic question is how hydrogen was distributed in the early Universe. Due to the expansion of the Universe the HI line is predicted to be redshifted somewhere in the range 50 - 180 MHz. Pinning down the so-called Epoch of Reionization (EoR) when the first stars turned on, ionizing the hydrogen, is a key science driver for current instruments such as LOFAR as well as new flagship instruments like SKA.

The radio spectrum is especially rich in spectral lines and nearly 200 molecular species are known in cosmic sources, mostly discovered at radio wavelengths, and 50 in comets. Increasingly complex organic molecules have been detected in the interstellar gas and in star- and planet- forming nebulae. CO (carbon monoxide) and other small molecules like HCO^+ and HCN are general tracers akin to atomic hydrogen but at much higher frequencies. CO lines appear at 115.3, 230.5, 345.8, … GHz.

7.1.2. A HISTORY OF DISCOVERY

Radio astronomy began when Karl Jansky of Bell Labs serendipitously detected radio waves from the center of the Milky Way in 1932. Radio astronomy's biggest discovery occurred in 1965 when newly-hired Bell Labs radio astronomers Robert Wilson and Arno Penzias identified a faint cosmic microwave signal that was subsequently shown to originate in the Big Bang, demonstrating the origin of the Universe and its expansion in a grand explosion at the beginning of time. Both discoveries occurred during efforts to quantify the noise in telecommunication systems, in Jansky's case it was a terrestrial system, and later it was for a satellite link. In the meantime, radio astronomy had progressed to the point that its methods were used to refine the operation of a satellite telecommunication system.

The first of four Nobel Prizes in physics related to radio astronomy was awarded to Martin Ryle and Antony Hewish in 1974 “for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars”. In 1978, half of the Prize was given to Arno Penzias and Robert Wilson “for their discovery of cosmic microwave background radiation”. Russell Hulse and Joseph Taylor were awarded the Prize “for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation” in 1993. John Mather and George Smoot shared the 2006 Prize for “their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation.” Tiny fluctuations in the background radiation represent the seeds of all subsequent structure in the Universe – galaxies, stars, planets and their inhabitants – and continued study of our cosmological origins is at grave risk from the launch of satellite mega-constellations discussed below.

Examples of discoveries showing the broad range of topics during the last decade include:

- The image of a black hole shadow in the nearby radio galaxy M87 by the Event Horizon Telescope (EHT) Collaboration involving more than 200 scientists and engineers from 19 countries
- Observation of galaxies forming within 250 million years after the Big Bang
- The most precise measurement of the Hubble Constant, challenging predictions of standard cosmological models
- Imaging of fine detail in the planet-forming disc around HL Tau implying the presence undetected of planetesimals
- Detection of complex organic molecules, precursors to life, in protoplanetary gas disks around newly-forming stars
- Discovery and location of Fast Radio Bursts
- Detection of a jet of gas emerging from the gravitational wave event involving two neutron stars, using a global VLBI network of 32 antennas on 5 continents
- Gravitational lensing measurements testing the nature of dark matter.

7.1.3 RADIO ASTRONOMY AS AN ENGINE OF TECHNOLOGY AND INNOVATION

Radio astronomy contributes to developments that are in widespread use for commerce and the benefit of society. Global positioning, satellite tracking and other applications needing accurate positions on a global scale all use a coordinate reference frame established by the International VLBI Service for Geodesy and Astrometry (IVS). This antenna network triangulates on signals from quasars – black holes in the centers of distant galaxies – using radio astronomy Very Long Baseline Interferometry (VLBI) techniques. IVS monitors Earth rotation for time-keeping (UT and leap seconds) and tracks crustal deformation for surveying and earthquake prediction. The mm-level of precision attained by VLBI is required to keep track of sea-level rise, and, so, global climate change. The importance of such measurements was recognized in UN Resolution 69/266 calling on member states to contribute to a global geodetic reference frame for sustainable development that is used in many scientific, societal and industrial applications. In response, the VLBI Global Observing System (VGOS) is now under construction to serve the needs of 21st century technology. Providing access to adequate radio spectrum for services like VGOS is a main driver now.

Global positioning satellites and satellite tracking antennas use compact hydrogen maser time standards originally developed for VLBI, on antennas that perform better with more efficient, lower-noise electronics after application of radio astronomy techniques. The signal reconstruction codes used to map cosmic radio sources underly medical imaging and detection of ships trafficking in illicit arms on the high seas from orbiting miniaturized radio telescopes. Such miniaturized orbiting radio telescopes image the Earth's land and water for weather and climate study in spectrum bands originally allocated to allow radio astronomy to study the far reaches of the Milky Way (See Section 3).

7.1.4 HOW RADIO ASTRONOMY IS DONE

7.1.4.1 Radio contrasted with optical astronomy

The optical spectrum extends roughly over the range 300-1000 nm (1-3 x10^{15} Hz) while the proportionally much wider radio spectrum is defined as 0 – 3x10^{12} Hz. Radio and optical astronomy work according to the same laws of electromagnetism but practical matters cause vast differences in their instruments and operations. Large optical telescopes have about the same size as small radio antennas but observe at wavelengths that are many thousands of times shorter. Optical telescopes attain the diffraction limit with difficulty but readily achieve arcsecond resolution using cameras with millions of detector elements in the focal plane. Relatively few radio astronomy detector elements fit across the focal plane of a radio antenna. Long radio wavelengths make it easy to attain the diffraction limit but require very large telescopes to achieve arcsecond resolution. Radio astronomers compensate by building large antennas and/or operating arrays of physically separated but electrically coherent antennas, in some cases globally using VLBI techniques, but generally using Fourier transform techniques to reconstruct images from imperfectly-sampled data.

7.1.4.2 The sensitivity of radio telescopes

The cosmic signals observed by radio astronomy are no more than differences in the level of noise: more noise in some direction, at some frequency, and perhaps at some instant, in addition to receiver noise and interference. There is no carrier on which to lock or carrier modulation with which to decode an astronomical signal. If cosmic noise cannot be distinguished from other noise it will be missed.

Radio astronomy achieves high sensitivity using some combination of large collecting area, high directivity, low noise, broadband receivers, and accumulation of signals over long periods of observation. It does not function moment-moment like a radio communication system and its sensitivity must be assessed on its own terms.

The most fundamental aspect of sensitivity is the ability to integrate coherently over time under stable conditions. For a receiving system characterized by a noise temperature Tsys (K), observing over a bandwidth B (Hz) for an integration time t (s), the rms sensitivity is

$$\Delta T = Tsys/(B^{*}T)^{1/2}$$

In Kelvins, within factors of order unity. This is the so-called radiometer equation that applies broadly across radio science. On an antenna with diameter D and usable receiving area A (~ $0.7^{*}D^2/4$), this can be related to the rms flux density for an unpolarized signal

$$\Delta S = k_B \, \Delta T/A$$

where k_B is the Boltzmann constant, 1.38x10^{-23} Joule/K, and the units of flux density are energy per unit area or power per unit area per Hz (power flux density). Radio astronomy defined an unofficial unit to capture the brightness of the strong cosmic sources that were found in early radio surveys: 1 Jansky (Jy) = 10^{-26} W/m^2/Hz. **A 1 Jy radio source is now considered to be a bright object. Commercial radiocommunications use signal levels of order 10^{-16} W/m^2/Hz, or billions of Jy.**

Several current telescopes taking rather different forms have A ~ 5x10^3 m^2, corresponding roughly to one 100m antenna. With t = 2000s, B = 1GHz and Tsys = 25K one has

$$\Delta S = 1.0\text{x}10^{-31}\ \text{W/m}^2\text{/Hz} = 10\ \text{microJy}$$

A cosmic radio source with S=50 microJy could be detected with high confidence with these parameters. Alternatively, an isotropic 1 W transmitter with 100MHz bandwidth – a 4G phone – could be confidently detected on the Moon, or could create strong interference on Earth. Threshold sensitivities used to protect radio astronomy observations from interference are given in Recommendation ITU-R RA. 769.

7.1.4.3 Spectral bandwidth and frequency resolution

For study of spectral lines of gas or objects in motion, a velocity with Δv ~ 1 km/s is typical and such motions are resolved at frequency ν using frequency sub-intervals Δν = ν∗(Δv/c) ~ ν∗1/300,000. RAS spectrometers subdivide the spectrum into 10^4–10^6 independent sub-intervals and have 1m/s ultimate resolution.

For continuous radiation that is observed broadly across the spectrum, 50% bandwidths and bandwidths ranging up to ~10 GHz are available. In many cases, even the broadest bandwidths are observed by summing over narrower sub-channels, preserving the possibility to mitigate interference within the band. But some of the most sensitive imaging devices detect radiation bolometrically across an entire band and do not have such ability.

7.1.4.4 Angular resolution

Radio astronomy achieves high angular resolution using some combination of individually large antennas; distributed arrays of widely-separated electrically-phased antennas; and operation of smaller antennas at higher frequencies. The diffraction-limited angular resolution of a single antenna of diameter D at wavelength λ is θ = λ/D and real antennas achieve a resolution that is only slightly poorer. Larger antennas are generally used at longer wavelengths and lower frequencies. Attaining 1” angular resolution requires D = 44 km at λ = 21 cm (1.420 GHz) where atomic hydrogen (HI) is observed, or 700m at λ = 2.6 mm (115.3 GHz) to observe the lowest line of ^{12}CO.

A diffraction-limited antenna has a beam solid angle $\theta^2 = (\lambda/D)^2$ occupying a sky fraction $\theta^2/4\pi = \lambda^2/(4\pi D^2)$, where $\lambda^2/4\pi$ is recognizable as the collecting area of a theoretical isotropic antenna. $\theta^2/4\pi = \lambda^2/(4\pi D^2) = 10^{-6}$ for a 100m antenna operating at 1 GHz (λ = 30 cm) or 10^{-8} at 10 GHz. Thus a 100 m antenna operating at 10 GHz has a forward gain of about 80dB (10^8) relative to the theoretical isotropic antenna, which is defined as 80 dBi (note the *i*).

The need to maintain a shape against gravity has made it impossible to build a fully steerable antenna larger than 100 m. To achieve angular resolution corresponding to larger sizes, radio astronomers most often build arrays of movable dishes that are connected electrically in adjustable configurations extending up to about 35 km. But even larger telescopes spanning the globe are made by networking instruments on different continents.

7.1.4.5 Sidelobes and immunity to interference

Very high gain enhances the sensitivity of an antenna but does not render it immune to radiation received from other directions. To understand this, note that antennas, no matter their size or frequency of operation, have the same overall net gain, which is in fact no gain at all: 0 dBi. This is most easily understood by imagining an antenna used to transmit. It is a passive device and no matter how much of the energy it focuses in the forward direction, nothing is added. If the brightness is high around one direction but must average down over all directions, those other directions must also have a pattern of electromagnetic fields, and sensitivity. Sensitivities in other directions are called sidelobes and they are unavoidable.

Good antennas have high forward gain while spreading out sensitivity to other directions as uniformly as possible, without gross anomalies or peaks in their sidelobes. But all antennas have sidelobes and no antenna can avoid seeing radiation arriving from directions far from where it is pointed. Anyone with eyeglasses knows it is possible to see reflections of objects behind them on the inside surface of an eyeglass lens. Eyeglasses have sidelobes, too.

The sensitivity of radio astronomy antennas is so high that there is no way to prevent interference when a radiocommunication transmitter is seen too close to where the telescope is pointed. On this account, criteria to protect radio astronomy from interference use only the net antenna gain, 0 dBi in static situations. This simplifies calculations but corresponds to a microscopic fraction of the actual antenna area: Even so it is not always easy to achieve compatibility. Moreover, astronomers implicitly agree to avoid pointing within about 19° of transmitters, because the gain is expected to be above 0 dBi at smaller separations. Radio astronomy loses access to a wide swath of sky behind the belt of satellites in geosynchronous orbit on this account.

7.1.4.6 Where are radio astronomy telescopes located? What do they look like?

Any operating site needs service access, but radio observatories also need isolation from Radio Frequency Interference (RFI), good weather, high atmospheric transparency and room for the antennas they may have. Telescopes working above 200 GHz are all at 3-5 km elevation. No matter how remote, radio astronomy sites are vulnerable to interference from air- and spaceborne transmitters and are not isolated by high atmospheric opacity. Sites in Hawaii and Northern Chile host both radio and optical astronomy telescopes. The complexity of operating in remote locations exacts severe costs in monetary and human terms.

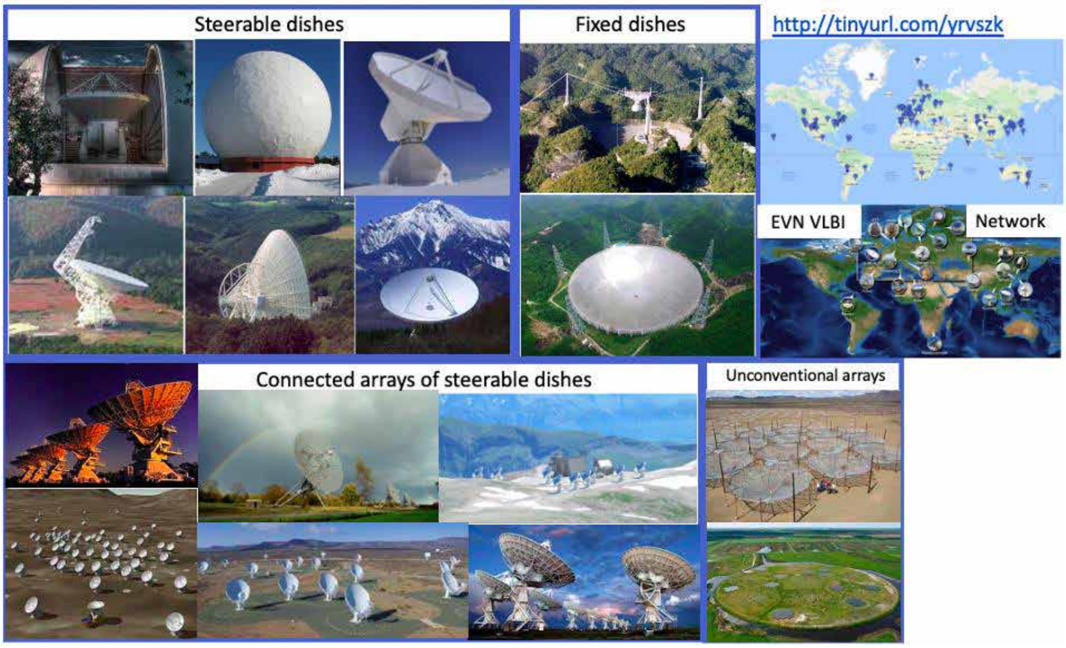


Figure 7.1.1 World radio telescopes. Steerable dishes, clockwise from upper left: ARO 12m telescope, Onsala 20m, IRAM 30m, NRO 45m, MPIfR Effelsberg 100m, GBO Robert C. Byrd 100m Green Bank Telescope . Fixed dishes, top to bottom: Arecibo 300m, Chinese Academy of Sciences 500m (FAST). Connected arrays: CSIRO ATNF Compact Array, ASTRON Westerbork Array, IRAM NOEMA array, NRAO Jansky Very Large Array, SARAO Meerkat telescope, Atacama Large MM-Wave Array (ALMA). Unconventional arrays, Top HERA telescope, bottom LOFAR core.

IUCAF's world map of radio telescopes has 130 sites but does not include all the outlying stations of widely-distributed instruments like LOFAR and LWA. Some sites host more telescopes than are noted or linked to the map.

7.1.4.7 Investment in instruments and operations

Flagship arrays like Meerkat in South Africa and JVLA in the US have current replacement costs of $400,000,000 and $750,000,000, respectively. The ALMA telescope in northern Chile cost $1,300,000,000 in Y2000 currency. The largest planned telescopes, the Next Generation VLA (ngVLA) and Square Kilometer Array (SKA) have cost estimates that are several times larger. As a rule of thumb, annual operating costs are 5–10% of the construction cost, not considering the major upgrades that all telescopes must undergo on one–two decade time scales to take advantage of new technology.

7.2 REGULATION OF USE OF RADIO SPECTRUM

7.2.1 SPECTRUM IS A SHARED RESOURCE FOR EVERYONE

Radio astronomical research is conducted by receiving extremely weak radio signals from cosmic bodies that radiate radio waves following physical laws. Such radiation includes continuous blackbody (thermal) radiation and synchrotron radiation, and discrete transitions between quantum energy levels of atoms or molecules. Distinct physical phenomena occur at all frequencies, and the expansion of the Universe causes the same physical phenomena to be received at different frequencies from different cosmic epochs. As a result enthusiastic radio astronomers say "We need to access ALL frequency, and ALL frequency should be protected for us." While this is a true statement, it leads to a very difficult situation for radio astronomy in a world where the commercial demand for spectrum access is so great.

For example, people now use mobile phones and WiFi hot spots to connect to the Internet. Aircraft are controlled by means of radio communication channels and satellites beam television news broadcasts across the globe Indeed, there are many radio applications that make our life safer and more fruitful. Because most of such radio applications utilize much stronger radio signals compared with those received by radio astronomy antennas, a ban on radio applications would be needed in order to completely protect radio astronomical studies, and this could never be accepted. In other words, every radio user including radio astronomy has to respect the others and find ways to "share" the radio resource.

The process of organizing this common use of the radio spectrum resource for so many varied purposes is known as "**spectrum management.**"

7.2.2 SPECTRUM MANAGEMENT: INSTITUTIONS, MECHANISMS, SERVICES, ALLOCATIONS

It is apparent that radio waves propagate regardless of any geographical border that human beings made. It is also apparent that radio communications are only possible by using the same frequency (or channel) between a sender and a receiver. Therefore, we need to regulate the usage of radio waves internationally, regionally, and nationally.

The international organization for this is the International Telecommunication Union (ITU). One of three Sectors under ITU is the Radiocommunication Sector (ITU-R) that develops and maintains the Radio Regulations (RR): the RR has the status of an international treaty and all member countries joining the ITU-R are bound to the RR. In addition there are several regional bodies for regulating radio resources within individual regions. For example, the European Conference of Postal and Telecommunications Administrations (CEPT) is responsible for regulating radio resources within the CEPT member countries. CEPT's rules are mostly compliant to the RR. Since any nation has its sovereignty inside its borders, it is possible to deviate from the RR within its territory unless a radio use causes harmful interference to neighboring countries.

In the RR, any radio use is categorized into a "service" (Article 1.19 of the RR). There are 39 services, such as the fixed service for microwave data backhaul, the mobile service (including cell phones), the broadcasting service and many others including satellite versions like the fixed-satellite and mobile-satellite services for communication with satellites. The radio astronomy service (RAS) is recognized within the ITU in Articles 1.13 and 1.58 of the RR as a service that receives radio waves of cosmic origin. Because it receives and does not transmit, the RAS is known as a *passive service.* Because it receives radio waves of cosmic origin the RAS is a *radio* service but not a *radiocommunication* service like nearly all others.

The regulatory bodies allocate frequency bands to radio services, not to specific operations or companies. A radio service has either primary or secondary status in a particular band and is known as a primary or secondary service in that band, denoted by capital or lower case letters, respectively, in the Table of Frequency Allocations, in Article 5 of the RR. A secondary service is inferior and (its users) "shall not cause harmful interference to primary services nor claim protection from primary services" (Articles 5.28 through 5.31 of the RR). When a service has primary status within an allocated band, it is said that "the band is allocated on a primary basis". RAS has many bands allocated on a primary basis between 13 MHz and 275 GHz. Within these bands, RAS has the right to claim protection from other radio services. It is noted that not all frequency ranges that are allocated to radio astronomy are allocated on a primary basis: in some bands, other radio services have priority over the RAS. For some bands shared on a co-primary basis between RAS and other services, RAS cooperates to share the same spectrum resource.

It goes without saying that the users of a frequency band should not suffer unduly from interference resulting from transmissions - so-called unwanted emissions -- arising in other bands. Nevertheless, some of the thorniest problems suffered by RAS inside its allocated bands are of just this nature. An important distinction is made between a transmitter's "wanted" emissions that are purposefully created to operate the system within an allocated frequency band, and the "unwanted" emissions that are created outside the allocated band, either as out of band (OOB) emissions relatively nearby, or as spurious emissions at more distant and harmonic frequencies. Control of unwanted emissions is important for efficient spectrum use, but is all too often slighted.

7.2.3 NOTIONS OF SPECTRUM COMPATIBILITY AND PROTECTION

To successfully operate multiple services in the same or adjacent bands it is essential that the characteristics and requirements of each radio service are well defined. This is achieved within the ITU-R via the ITU literature including Recommendations and Reports, developed by the Study Groups (SG) and their Working Parties (WP) that are dedicated to each service: RAS is the subject of WP 7D under SG 7 for the science services, along with the time service (WP 7A) disseminating time signals, space research service (7B) servicing deep space probes, and the Earth-exploration satellite service (7C) for remote sensing, see here and here.

An essential requirement for each service is the definition of threshold levels of unwanted radiation from other services that can be tolerated before harmful interference occurs (Articles 1.166-1.169 of the RR). In addition, a non-zero level of acceptable interference is defined that each service agrees to tolerate to allow the operation of co-allocated or adjacent services. All such requirements comprise the "protection criteria" for each service that need to be taken into account when new or modified services are planned. As the levels of radiation received by radio astronomy are extremely low, radio astronomy stations are very susceptible to interference and the protection criteria for RAS are very stringent. Thresholds for harmful interference to radio astronomy are given in Recommendation ITU-R RA.769 and acceptable levels of data loss arising from interference above RA. 769 levels, roughly 2-5%, are defined in Recommendation ITU-R RA.1513.

The ITU-R Working Parties and Study Groups meet regularly and on a continuing basis to develop and maintain the technical basis for world-wide radio telecommunications. Questions to address arising issues in each service can be raised at any time, often related to new radiocommunication services that are developed and require new or modified spectrum allocations. Any new proposal must be studied carefully to establish the impact on already co-allocated services and develop sharing criteria such as permitted radiation levels or any necessary geographical separation between stations. New services or users proposed to be added to a spectrum band must prove compatibility with existing services not only for in-band sharing but also with unwanted out-of-band radiation in adjacent or harmonically related bands.

7.2.4 The Radio Regulations, modified at the WRC

The technical criteria and rules and regulations necessary for world-wide radiocommunications as defined by the ITU-R are encapsulated in the Radio Regulations, a legally enforceable international treaty. However, technological changes and new services are being developed at an increasing rate with a huge impact on our lives. The ITU-R must regulate any such new service, and hence there is a need to regularly revise the RR. The only legal mechanism for RR modification in ITU-R is the World Radiocommunication Conference (WRC), a month-long international negotiating forum scheduled every 4 years, next in 2023.

Each WRC develops a set of Agenda Items (AI) for issues and changes to be considered at the succeeding WRC. The interval between WRCs is defined as the "study cycle", where changes to the RR proposed by the preceding WRC are evaluated in the responsible Working parties and "methods" involving technical standards, operating rules and allocations are developed to "satisfy" the Agenda Items. Technical studies provide sharing and compatibility analysis for each AI and also develop possible regulatory options for implementation of the RR changes. The results of the studies are encapsulated in the Conference Preparatory Meeting (CPM) Report, which is finalized and published about half a year prior to a WRC and forms the basis of the negotiations by participating governments at the WRC. At the WRC, all decisions are made on a consensus basis, eschewing voting, and implemented after long technical and political negotiations. The concluding sessions at the WRC are a treaty-signing ceremony and the closing ceremony where everyone heaves huge sighs of relief over battles fought and won, licks wounds, and girds for the next cycle.

The Agenda of the succeeding WRC is finalized at a CPM meeting (CPM-1) immediately following the just-concluded WRC. WRC decisions are published in a set of Final Acts that are incorporated and published in new RR about nine months later. With these in hand, administrations can incorporate changes into their own national regulations, with appropriate accommodation for their particular concerns.

7.2.5 HOW RADIO ASTRONOMERS RESPOND

Involvement during the study cycle and at the CPM and WRC is essential for the successful on-going protection for each service: RAS, as a passive service with very sensitive receiver systems is affected by most WRC AIs. Radio astronomy spectrum managers, almost all trained as radio astronomers, devote considerable effort to learn an arcane craft that has few direct rewards for their careers as professional astronomers.

Most radio astronomers participate at ITU-R as national delegates of administrations that operate radio astronomy facilities, while working to see radio astronomy priorities represented inside their administrations. However, these priorities may be lost in consensus national positions that necessarily reflect other interests, so radio astronomy has formed specialized bodies to represent it. The oldest of these, dating from 1960, is IUCAF that is chartered by the ISC and has a global membership drawn from IAU, URSI and COSPAR. CRAF operates in EU and CEPT administrations, and RAFCAP represents the Asia-Pacific region. CORF, in the US, works on behalf of radio astronomy and passive remote sensing. IUCAF and CRAF are Sector Members, privileged to contribute, at ITU-R. The SKA, as one of the largest future radio astronomy observatories in the world, also collaborates on the protection of radio astronomy frequencies as a Sector Member of the ITU-R.

7.3 SPECTRUM PROTECTION FOR RADIO ASTRONOMY

The Radio Regulations (RR; see Section 7.2) provide different levels of protection for radio astronomy observations including frequency and geographic separation and rules for frequency sharing. Most frequency bands are shared among several services, whether active (transmitting) or passive (receive-only), but 21 frequency bands have been allocated exclusively to the passive science services. These “passive bands” provide critical access to clean spectrum that is not corrupted by anthropogenic emissions. However, while access to clean spectrum is preferred, the majority of radio astronomy allocations are shared with active services. In these instances, geographic separation between transmitters and radio astronomy facilities can help mitigate instances of radio frequency interference (RFI). Indeed, designated radio quiet zones around astronomical facilities provide local access to relatively clean radio spectrum. Coordination between radio astronomy observatories and active services enables scientific discoveries that require access to shared resources.

7.3.1 FREQUENCY BANDS ALLOCATED TO RADIO ASTRONOMY

A full list of the frequency allocations to radio astronomy is contained in the comprehensive International Table of Frequency Allocations, Article 5 of the RR. The US has a useful representation. The RR include allocations from 8.3 kHz to 275 GHz, with additional indication of frequency bands relevant to radio astronomy between 275 GHz and 1 THz listed in footnote RR 5.565. The Table is organized by ITU-R Regions (wherein emergency response frequencies are harmonized) having somewhat different allocations.

Region 1 includes Europe, Africa, the Middle East, and countries associated with the former Soviet Union; Region 2 includes North and South America, Greenland, and some of the Pacific Islands; Region 3 includes Australia, New Zealand, India, China, Iran, and large parts of Asia. Each country may have its own table, but in practice most follow the International Table as closely as possible since radio emissions do not recognize international borders. Most RAS allocations are identical among the Regions but there are a few frequency bands that are allocated to RAS in only one or two Regions.

RAS is allocated a very small percentage of the spectrum below 50 GHz where there are numerous commercial applications; 2% or less on a primary basis, mostly in spectrum shared only with other passive services (Figure 3.1). A much larger percentage of the spectrum is allocated to radio astronomy at higher frequencies where there are many molecular spectral lines and little historical commercial development.

Footnote 5.340 of the RR lists 21 frequency bands shared only among the passive services, in which "all emissions are prohibited". Nearly all are allocated to radio astronomy and were chosen to observe a particular spectral line or to provide octave sampling of continuous radio emissions. A narrow RAS allocation at 48.94-49.04 GHz is included in 5.340 specifically to prohibit airborne transmissions. The bands 50.2-50.4 GHz, 52.6-54.25 GHz and 190-191.8 GHz are allocated only to EESS(passive) and SRS(passive) to measure the physical parameters associated with oxygen and water and are in spectral regions with high atmospheric absorption making them less useful for radio astronomy observations.

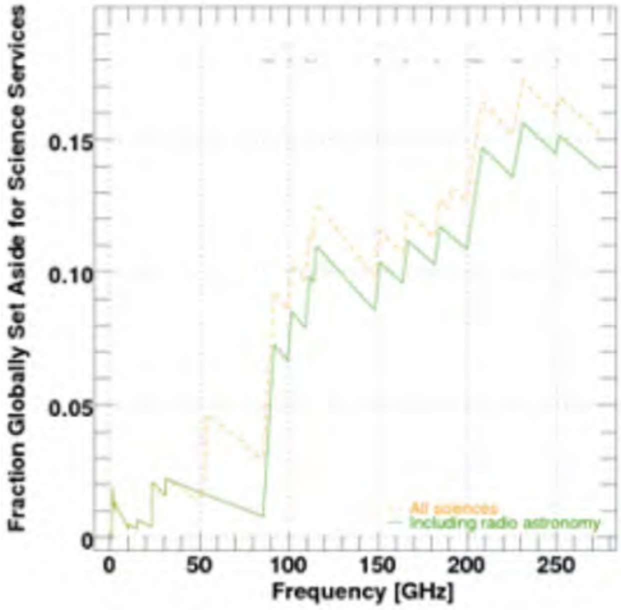


Figure 7.3.1. Spectrum globally set aside for science. The plots show the fraction of spectrum that is allocated to science below each frequency. Some bands are not allocated to radio astronomy, as shown by the separate green and orange lines.

Figure 7.3.1 shows the distribution of the frequency bands that are protected globally under RR 5.340 from all emissions and the fraction of the spectrum that is protected below each frequency. There are clearly three regimes. Below 86 GHz where nearly all commercial applications now operate, 0-2% of the spectrum is protected; this rises to 7-12% at 86 – 200 GHz and to 14-16% above 200 GHz.

Footnote 5.149 of the RR lists 49 frequency bands for which "administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. Emissions from spaceborne or airborne stations can be particularly serious sources of interference to the radio astronomy service." Many of these bands are allocated to RAS on a primary basis and RR 5.149 is a historical relic in this context, but a few narrow frequency bands associated with spectral line observations in our Galaxy are mentioned in RR 5.149 in the absence of an allocation. As there has been some recent resistance to recognizing the importance of frequency bands that are only listed in the

International Footnotes, it may be appropriate to seek allocations to RAS for these frequency bands.

International Footnote 5.565 of the RR lists eight frequency bands between 275 GHz and 1 THz that are identified for use by radio astronomy for which "Administrations ... are urged to take all practicable steps to protect these passive services from harmful interference until the date when the Table of Frequency Allocations is established in the above mentioned 275-1000 GHz frequency range." The specified frequency bands correspond to regions of relatively high atmospheric transparency (often known as atmospheric "windows") that is required for ground-based observations of faint cosmic sources. As noted in Section 7.1, most millimeter-wave radio telescopes are located on high, dry sites to reduce the atmospheric absorption.

7.3.2 IMPORTANCE OF SPECTRUM DEDICATED TO PASSIVE USE

The frequency bands listed in footnote 5.340 of the RR provide a unique resource for scientific observation of the Universe and are essential both for calibration and scientific discovery. These passive bands have the most significant protections available in the RR, which is well justified due to their integral function in scientific measurements. At a very basic level, it is critical to be able to make measurements in regions of the radio spectrum where there are no anthropogenic emissions and all received signal is from natural sources. Without these measurements, it would be impossible to characterize the instruments and receivers used for scientific observations; it would be impossible to detect the faintest spectral lines that reveal the chemistry and physical structures of the interstellar medium; it would be impossible to trust measurements from time-variable (not repeatable) observations; and it would reduce opportunities for new discoveries, where the observed phenomenon is at the limit of the sensitivity of the instrument. The passive bands are a valuable resource for which there is no replacement. Indeed, because of the unique nature of these bands – once anthropogenic transmissions corrupt these bands it likely will be impossible to return to a clean spectral region again – significant effort is required to both protect these bands from direct transmission and from out-of-band, spurious, and unwanted emissions.

Radio astronomy instruments and receivers are designed to detect extremely faint signals from cosmic sources. Indeed, accurate measurements can require flux calibrations to the micro-Jansky level (10^{-32} W/m^2/Hz). Thus, it is necessary to be able to use interference-free regions of the radio spectrum to characterize radio astronomy instruments and receivers, including gain and sensitivity. In addition, on-sky measurements that include both protected and non-protected spectral regions can be calibrated using portions of the radio spectrum that are assumed to be interference-free. For these reasons, it is important to retain regions of the radio spectrum that are not corrupted by anthropogenic emissions in order to provide accurate calibration of astronomical observations.

At the same time, the significance of a detection is indicated by the signal-to-noise ratio, which is a direct function of both the strength of the signal and of the noise. Thus, to improve the signal-to-noise ratio of an observation, one must either increase the signal strength or reduce the noise value. Since, by their very nature, it is not possible to increase the signal strength from naturally occurring radio emissions, the only option to increase the significance of an astronomical detection is to decrease the associated noise. This can be accomplished by increasing the integration time, increasing the bandwidth for continuum observations, or by reducing the noise floor, the latter of which can be accomplished by eliminating anthropogenic emissions in the frequency band. In particular, because the frequency range associated with an emission-line is set by the physical conditions and kinematics of the astronomical source, detection of faint emission lines requires spectral regions in which the only source of noise is the natural emission from the cosmos. Several of the RR 5.340 bands are specifically identified to enable observations of spectral lines, such as the neutral hydrogen spin-flip transition (rest frequency 1420.4058 MHz), the rotational transitions of CO (e.g., rest frequencies of 115.271 GHz and 230.538 GHz), and the inversion transitions of ammonia (e.g., rest frequencies of 23.694, 23.723, and 23.870 GHz). For most of these emission lines, the RR 5.340 spectral region is based on the Doppler shifted frequencies for radial velocities of +/-300 km/s, which is appropriate for emission occurring within our own Milky Way galaxy. However, due to its importance, the protected region for neutral hydrogen extends to lower frequencies to enable observations of nearby galaxies. Furthermore, at higher frequencies, molecular transitions of simple (e.g., CN, CS) to complex (e.g., methanol, formaldehyde) molecules are ubiquitous and thus allocations of broader spectral regions that include multiple spectral lines are constructive. These protected bands are critical to measurement of the spectral line flux and the gas kinematics, as traced by the Doppler shift of the line center and spectral line shape (i.e., velocity dispersion, rotational velocity, and/or evidence of multiple components). Observations of spectral lines reveal the chemistry and kinematics of the interstellar medium and, particularly through observations of the neutral hydrogen line, trace the structures of the universe from small to large scales.

One of the most exciting research areas of the twenty first century is the discovery and detection of time variable phenomena such as gamma-ray bursts and fast radio bursts, as well as solar system objects that are only visible for a limited period of time (e.g., asteroids and comets). In this context, some astronomical observations are unique and cannot be repeated at a later time as the sources fade or become more distant. Therefore, if such observations are corrupted by radio frequency interference, the measurements they would have provided are lost forever. Thus, access to portions of the radio spectrum that are free of anthropogenic interference is a critical requirement to enable observations of time sensitive astronomical phenomena.

Finally, radio astronomy is fundamentally a discovery-based science. Over the past decades, radio astronomy observations have revealed unexpected phenomena that elucidate the need for further measurements throughout the electromagnetic spectrum and require the development of theoretical models and new computational simulations to explain and predict that which is observed. In this context, we cannot know the precise discoveries that will occur in the future, but we can predict that such observations will require access to portions of the radio spectrum that have not been corrupted by anthropogenic transmissions. Indeed, by their very nature, most serendipitous discoveries are unexpected and do not have well established properties by which one can eliminate contaminating source(s) of emissions. In particular, instances of weak radio frequency interference are particularly pernicious since they corrupt the data, but at a level wherein the data may still be included in the analysis. Access to frequency bands in which no anthropogenic transmissions are permitted is a fundamental requirement for our continued exploration of the universe and for the future of radio astronomy.

7.3.3 USE OF SPECTRUM THAT IS NOT ALLOCATED TO RADIO ASTRONOMY

As discussed above, it is critical that a portion of the radio spectrum be reserved exclusively for scientific measurement of naturally-occurring radio emission. However, it is also the case that, as a receive-only service, radio astronomy cannot interfere with other users of the radio spectrum. Thus, when appropriate for the scientific project, radio astronomy observations can occur in portions of the radio spectrum not allocated to RAS under Article 4.4 of the RR without interfering with incumbent users of those bands. There are two main scientific drivers for use of unallocated spectrum: 1) red-shifting of spectral lines due to the expansion of the Universe and 2) broad bandwidth radio continuum observations that can increase the signal-to-noise ratio of weak radio sources according to Section 7.3.2.

For 1) the scientific case for observations of red-shifted spectral lines is straightforward. Due to the finite speed of light, radio astronomers are able to probe conditions earlier in the Universe by observing more distant objects, whose radiation took longer to reach us. However, the Universe is expanding, and the radiation from these more distant objects is shifted to lower frequencies. Thus the neutral hydrogen spin-flip transition at 1420.4058 MHz can be observed inside the 1400 – 1427 MHz spectrum band protected by RR. 5.340 for the Milky Way, but the same kind of radiation is shifted below the protected band for sufficiently distant galaxies. At the extreme, experiments to detect neutral hydrogen at "Cosmic Dawn," during the epoch of formation of the very first stars 180 million years after the Big Bang must observe at 100 – 200 MHz. Thus, measurement of the neutral hydrogen content across cosmic time requires access to the radio spectrum not only in the narrow frequency bands designed for observations of the Milky Way and very nearby galaxies, but also in the broader frequency range 0.1 - 1.4 GHz.

For 2), measurements at a range of frequencies are required to distinguish continuous thermal (heat) radiation from that arising from for example electrons spiraling in magnetic fields. Unlike spectral lines, where high spectral resolution is required to resolve the line shape, radio continuum emission changes slowly as a function of frequency. To improve the signal-to-noise ratio, radio continuum observations are usually designed to make use of broad bandwidths. Indeed, recent improvements in receiver technology now enable observations with multi-GHz bandwidths. By utilizing broad bandwidths to increase the signal-to-noise ratio for these measurements it is possible to measure the spectral energy distribution of very faint objects and infer the source of their radio emission.

7.3.4 RADIO QUIET ZONES: USES AND LIMITATIONS

Radio astronomy has benefited by choosing operational sites that are remote and shielded from terrestrial anthropogenic radio emissions. Figure 7.3.2 compares the radio spectrum in three areas of Australia having greatly different population density.

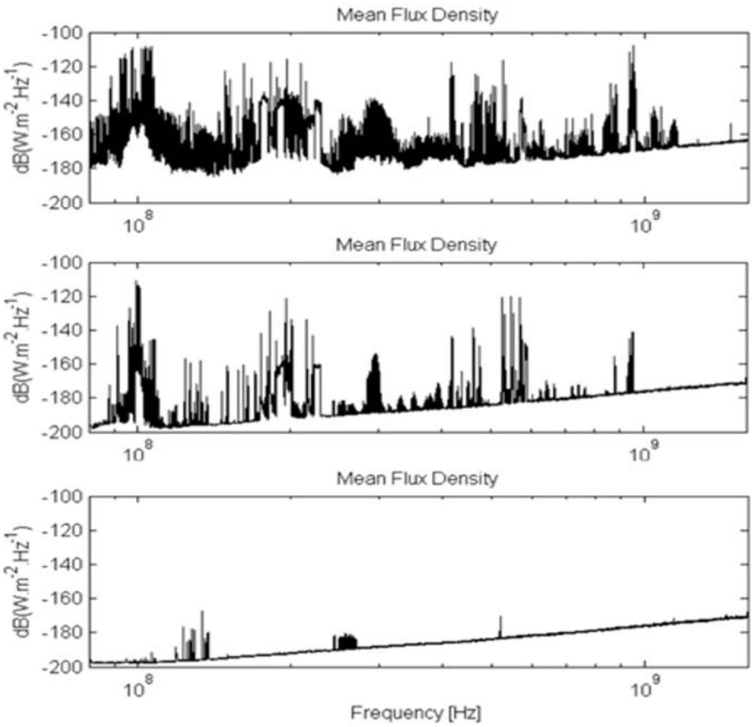


Figure 7.3.2. Radio frequency spectrum use in Australia. From top to bottom Sydney (6 Million people), Narrabri (~6000 people) and Murchison (<10 people).

To preserve the electromagnetic environment in rural areas, electrical and electronic equipment under the immediate control of an observatory is carefully vetted and installed so as to avoid interference. Automobile use and visitors are controlled. But even these measures may not suffice. Indeed, Recommendation ITU-R RA.769 which lays out threshold protection levels for radio astronomy has as its first *recommends* "that radio astronomers should be encouraged to choose sites as free as possible from interference." This is followed by an urging for administrations to "afford all practicable protection to the frequencies and sites used by radio astronomers in their own and neighbouring countries and when planning global systems".

In practice, some administrations have combined these Recommendations by creating radio spectrum regulatory zones known as *radio quiet zones* (RQZ) around radio telescopes, where emissions are controlled and some form of coordination is required, even at frequencies not allocated to radio astronomy. The first of these, the US National Radio Quiet Zone covers 13,100 sq. miles and was created in 1958 before radio astronomers began to attend the ITU-R. It limits the power and placement of fixed transmitters at all frequencies and provides a coordination process with the observatory and the national spectrum regulator to ameliorate potential problem cases, allowing the vast majority of transmitter license requests to proceed.

Report ITU-R RA. 2259, "Characteristics of radio quiet zones" describes these zones worldwide. There are three basic types of zones. First, there are zones where all radio transmissions are prohibited in some frequency bands. This type of zone is typically limited to the immediate area around a telescope. The RQZ around the core of ALMA is of this kind, prohibiting transmitters within 30 km in frequency bands allocated to radio astronomy on a primary basis. This is surrounded by a 120 km-radius coordination zone limiting the power levels of more distant transmitters at other frequencies.

The second type of zone also prohibits transmissions but is broader geographically and may include waivers for transmissions if they are found to meet strict thresholds after coordination. This coordination process involves evaluation of individual systems, including the distance from the telescope, the local topography, the directionality of the proposed transmission, and the power levels. The SKA, for example, has evaluated hundreds of commercial devices in an anechoic chamber to determine and document how compatible they are. This second type of zone leads to very intensive work to carefully coordinate and has been implemented in a variety of zones around the world for decades.

The third type of zone is similar to the second, with the exception that emissions are not prohibited as long as coordination takes place. In cases where transmissions are not necessary at all times, coordination can occur by radio astronomy sites and operators agreeing upon the times when each will be making use of some particular frequencies.

7.3.5 CHALLENGES TO RADIO QUIET ZONES

There are several critical challenges to the quiet/coordination zone model for the protection of radio astronomy. Most of the established quiet zones regulate only fixed terrestrial transmitters, not emissions from mobile, airborne or space-borne transmitters (the radio quiet zone around the widely-distributed SKA is an exception). Mobile transmitters like cell phones that are electronically tethered to fixed base stations are indirectly limited. Automobiles, however, are now WiFi hotspots, and they monitor their environment with 76 – 81 GHz radar in frequency bands shared with radio astronomy, at power levels that are incompatible with interference-free operation within many tens of km. If the internet of things proliferates, "wearables" (devices on the person) may become common.

Coordination is feasible when transmitters are fixed on the ground. However, we are in a new era of airborne and spaceborne use of the radio spectrum, including dozens of systems on a single aircraft; command, control and payload communications of unmanned aerial vehicles (UAV or “drones”) flying in commercial air space; stratospheric high altitude platform stations (HAPS); and so-called mega-constellations of tens of thousands of satellites in low earth orbit (LEO). Consider, for example, satellite transmissions from GPS or satellite phone providers in the 1 - 2 GHz band (“L band”). The footprints of these satellites are thousands of kilometers on the ground, making it impossible for them to avoid radio quiet zones. In these cases, the best that radio astronomy sites could do is coordinate in time, which is not always practical.

At the frequencies above 10 GHz used by new LEO mega-constellations, there is an opportunity to have smaller satellite footprints and more finely-controlled steerable beams. This would all them to avoid illuminating radio astronomy sites and to make more efficient use of the radio spectrum for all services.

The concept of radio quiet/coordination zones for airborne and spaceborne transmitters has not been developed and will require international cooperation.

7.3.6 SUMMARY

The most critical frequency bands for the radio astronomy service are those allocated in the ITU-R Radio Regulations, especially those frequency bands listed in footnote 5.340 of the RR, but also those that are mentioned in footnote 5.149 and not allocated to radio astronomy on a primary basis. However, as noted in Recommendation ITU-R RA.769, radio astronomy has made important discoveries from the ground using frequencies ranging from 2 MHz to more than 1 THz, including the radio spectrum above 275 GHz that is entirely unallocated. Astronomy increasingly relies on using wide bandwidths that cover both allocated and unallocated spectrum, increasing the importance of quiet/coordination zones globally.

Radio quiet zones around radio telescopes are critical for continued radio astronomical exploration of our Solar System, the Milky Way, and the Universe. In the same way that parks are set aside as special preserves for humanity to enjoy nature, quiet zones are a radio “preserve” enabling a window for astronomers to “see” stars, galaxies, and the constituent molecules which make up the Universe.

7.4 RISKS TO RADIO ASTRONOMY

Being a purely passive service that aims to detect extremely faint cosmic signals in very wide frequency ranges makes the radio astronomy service very vulnerable to interference. This vulnerability represents a risk for RAS observations, but only one among many that range from destruction of receivers in the most extreme case to the inability to observe in certain frequency ranges at certain moments in time. In between are other risks such as saturation and non-linear behaviour of the receiver producing misleading results. This risk can have two very different interpretations, depending on whether the frequency range that is suffering the interference is a protected RAS band. As explained in Sections 7.2 and 7.3, if interference is encountered inside one of the RAS allocated bands, there is a regulatory path to address it through national administrations and eventually through the ITU-R. On the other hand, if problems are encountered outside the protected bands, where RAS frequently needs to conduct observations, there is no regulatory protection since these frequencies are allocated to other services. So when considering the risks to RAS observations we can classify them into “unwanted emissions in the protected RAS bands” and “increasing occupation of spectrum outside the RAS bands”.

7.4.1 UNWANTED EMISSIONS IN THE PROTECTED RAS BANDS

Protection of the frequency bands allocated to the RAS is not perfect: the sensitivity of RAS observations depends on the system temperature, bandwidth and integration time and the protection thresholds in Rec. ITU-R RA.769 are a compromise between short and long observations, considering typical bandwidths and using estimates of system temperatures. Furthermore, these protection levels are accompanied by a maximum percentage of data loss that can be accepted by the RAS, defined in Rec. ITU-R RA.1513 as 2% data loss for any single network and 5% for the total aggregation of networks in-band and in adjacent or nearby bands. The interpretation of the 2% data loss criterion is sometimes a subject of discussion with active services, and even more the 5% aggregate because of the need to consider many different systems in one analysis or measurement.

In the worst case, even the existence of a regulatory regime is not enough to protect the RAS operations in an allocated band. A rather tragic example continuing for more than 20 years is radio astronomy's inability to observe the OH molecule in the envelopes of evolved stars using the radio astronomy band at 1610.6-1613.8 MHz, due to interference from a satellite constellation that is authorized to operate only above 1617.8 MHz. In most cases, regulatory protection from unwanted emissions extends only to such relatively nearby bands, and systems using frequency bands that are not adjacent to an RAS band do not consider radio astronomy protection criteria even when it would be appropriate.

7.4.2 INCREASING OCCUPATION OF SPECTRUM OUTSIDE THE RAS BANDS

The advancement of wireless technology keeps increasing the spectrum occupancy especially near populated areas, as is the case with FM and TV broadcasting, mobile communications (5G), mm wave ranging applications used for car radars or industry, and other licensed and license-exempt applications to name a few. Radio telescopes in such locations have to choose very carefully where they can operate, given that in some bands the interference can be strong enough to saturate the receivers. This is particularly important in the case of airborne and spaceborne transmitters.

7.4.3 IMPACT OF SATELLITE CONSTELLATIONS, INCLUDING GSO

As noted in Section 7.3, even radio telescopes protected by RQZs are not completely free from interference. Their main concern now is interference that is generated from air- and space-borne transmitters. The line of sight distance to protect radio astronomy from an airplane at 10 km altitude is approximately 350 km, for a HAPS system at 20 km altitude it will be 500 km and for a LEO satellite system at 1200 km altitude it will be at about 4000 km. National regulations in RQZs are implemented very differently from country to country and some even have a coordinated air-space which provides a certain degree of protection from airplanes and other air-based transmitters, but certainly there is no protection against satellite transmissions.

Satellite transmissions present a very challenging interference situation because a radio telescope must look toward and past the satellites to observe. RFI aside, there is the possibility of a direct beam coupling, where the satellite and telescope point directly at each other and extremely high power levels may be received. Depending on the orbit, interference can be minimized in different ways. Radio telescopes can easily avoid pointing at the small number of visible GSO satellites in geosynchronous orbits (Figure 7.4.1) within a well-defined belt around the sky (the Clarke Belt) and, due to the low count of visible satellites using the same frequencies, post-processing techniques such as de-mixing are possible to subtract them from the astronomical data. In the case of LEO and MEO satellites, their relatively fast movement combined with the narrow beam patterns of most radio telescopes results in a rapidly changing interference pattern.

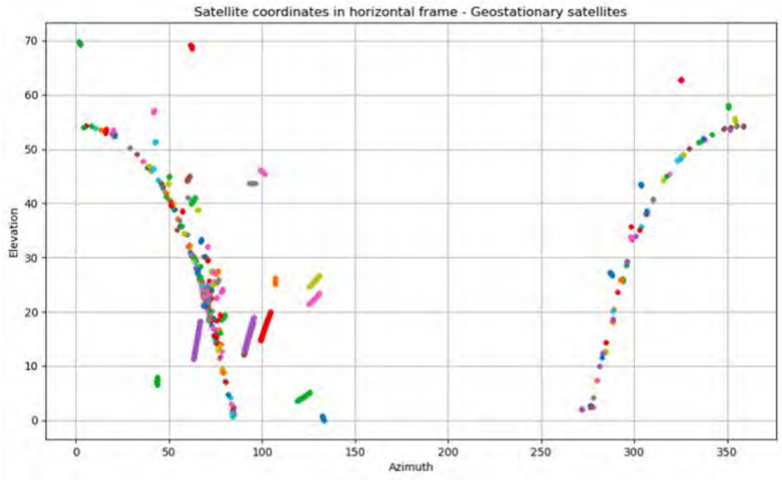


Figure 7.4.1. Position of all active GSO satellites as seen from the SKA-Mid site in the Karoo area in South Africa (longitude: 21.4 deg, latitude: -30.7 deg), over 2000 seconds.

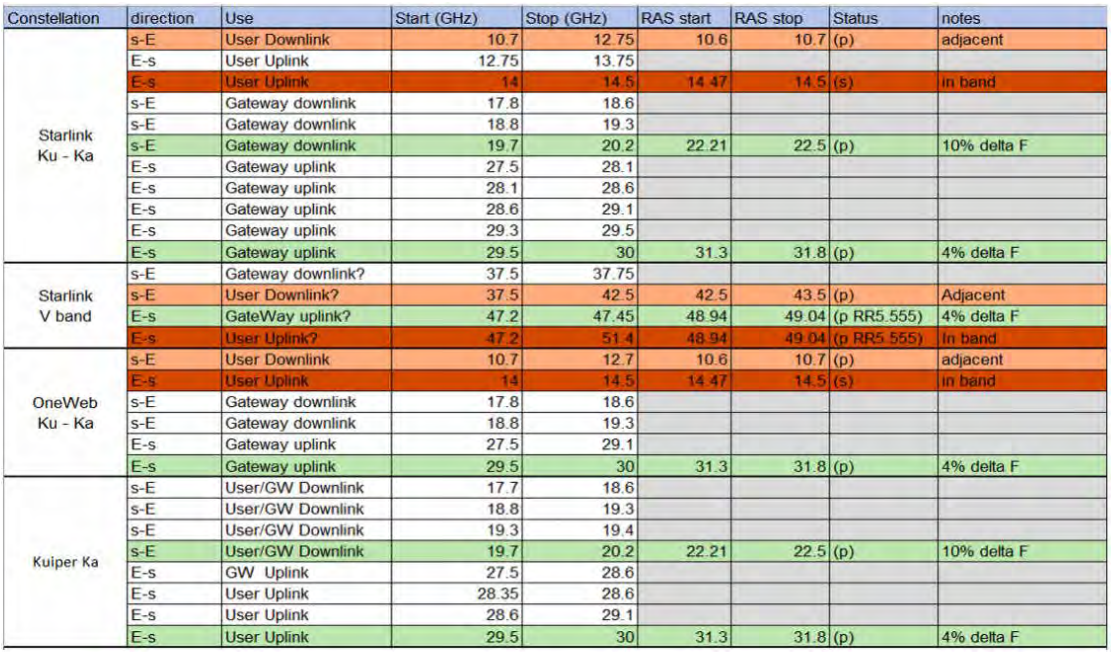
For most of the current MEO or LEO satellite systems, RAS receives interference in the antenna sidelo bes for virtually 100% of the time. But that is not the case for the new NGSO "mega-constellations", with immediate deployment of constellations having 1000–4000 satellites and with prospects to deploy more than 100,000. These extreme numbers will mean that hundreds to thousands of satellites will be above the horizon at all times, contributing to the interference through the sidelobes of the radio telescope but also increasing the probability of strong interference received through main-beam coupling.

7.4.4 IMPACT OF NGSO SATELLITE CONSTELLATIONS

Table 7.1 shows the frequency bands planned for use by three of the currently-deploying NGSO constellations, along with the RAS frequency bands that are adjacent or nearby. The RAS bands that could be affected will be the primary bands at 10.6–10.7 GHz (including 10.68–10.7 GHz protected under RR 5.340), 42.5–43.5 GHz and 48.94–49.04 GHz, along with the secondary band 14.47–14.5 GHz. There are other primary RAS bands located relatively near the satellite bands, at 22.21–22.5 GHz and 31.3–31.8 GHz (partly covered by footnote 5.340 of the RR). The first overtone of transmissions in the band 11.8–12 GHz falls in the frequency band at 23.6–24 GHz that is protected by RR 5.340.

Until recently, radio astronomy observations at such frequencies were possible because they were used mostly by terrestrial point to point links (with very narrow aperture) or from the downlinks of GSO satellites located in the geostationary belt. Knowing the exact location of GSO satellites makes it possible to select a strategy to mitigate their effect on RAS observations as much as possible (see Section 7.4.3).

Now, however, the situation will change dramatically, with more than 400 satellites above the horizon at any moment moving rapidly through the sky, only considering the original filings of about 6400 satellites. Combined with very densely distributed earth stations the RAS will face a real challenge if observations in the bands in Table 7.4.1 are to continue.



Constellation	direction	Use	Start (GHz)	Stop (GHz)	RAS start	RAS stop	Status	notes
Starlink Ku - Ka	s-E	User Downlink	10.7	12.75	10.6	10.7	(p)	adjacent
	E-s	User Uplink	12.75	13.75				
	E-s	User Uplink	14	14.5	14.47	14.5	(s)	in band
	s-E	Gateway downlink	17.8	18.6				
	s-E	Gateway downlink	18.8	19.3				
	s-E	Gateway downlink	19.7	20.2	22.21	22.5	(p)	10% delta F
	E-s	Gateway uplink	27.5	28.1				
	E-s	Gateway uplink	28.1	28.6				
	E-s	Gateway uplink	28.6	29.1				
	E-s	Gateway uplink	29.3	29.5				
	E-s	Gateway uplink	29.5	30	31.3	31.8	(p)	4% delta F
Starlink V band	s-E	Gateway downlink?	37.5	37.75				
	s-E	User Downlink?	37.5	42.5	42.5	43.5	(p)	Adjacent
	E-s	GateWay uplink?	47.2	47.45	48.94	49.04	(p RR5.555)	4% delta F
	E-s	User Uplink?	47.2	51.4	48.94	49.04	(p RR5.555)	In band
OneWeb Ku - Ka	s-E	User Downlink	10.7	12.7	10.6	10.7	(p)	adjacent
	E-s	User Uplink	14	14.5	14.47	14.5	(s)	in band
	s-E	Gateway downlink	17.8	18.6				
	s-E	Gateway downlink	18.8	19.3				
	E-s	Gateway uplink	27.5	29.1				
	E-s	Gateway uplink	29.5	30	31.3	31.8	(p)	4% delta F
Kuiper Ka	s-E	User/GW Downlink	17.7	18.6				
	s-E	User/GW Downlink	18.8	19.3				
	s-E	User/GW Downlink	19.3	19.4				
	s-E	User/GW Downlink	19.7	20.2	22.21	22.5	(p)	10% delta F
	E-s	GW Uplink	27.5	28.6				
	E-s	User Uplink	28.35	28.6				
	E-s	User Uplink	28.6	29.1				
	E-s	User Uplink	29.5	30	31.3	31.8	(p)	4% delta F

Table 7.4.1 Ku, K, Ka, and V-band frequencies used to LEO constellations and nearby RAS frequency allocations.

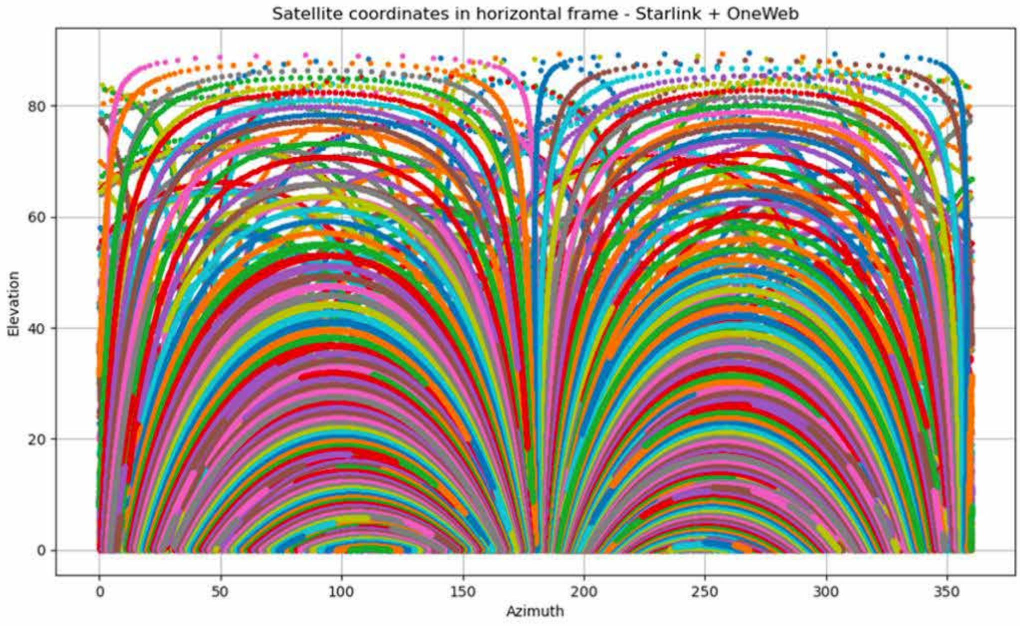


Figure 7.4.2. Position of Starlink and OneWeb satellites with a 2000s persistence for the original filings, with a total of 6400 satellites.

7.4.5 EARTH-TO-SPACE TRANSMISSIONS ASSOCIATED WITH NGSO SYSTEMS

RFI from subscribers and gateways in the Earth-to-space ("E-s", upward) direction are generally controlled on a case-by-case basis, where the administration responsible for the RAS station can establish a minimum separation distance with ground stations or subscriber according to the local terrain. Most RAS stations working at the frequencies in Table 4.1 are in remote areas and use parabolic antennas (See Figure 7.1.1) minimizing their gain near the horizon where interference would originate.

While protection from links in the upward direction may seem a relatively straightforward issue, it was agreed at WRC-19 that maritime and airborne Earth Stations In Motion (ESIM) may be used as ground terminals of NGSO constellations. So the challenge of protecting a RAS station from terrestrial transmissions in the E-s direction now becomes more complicated since the transmitters could be moving on land, sea or at 10km altitude overhead an observatory.

Mobile, airborne and satellite-born use of frequency bands that previously were dedicated to transmission from fixed locations presents enormous challenges for protection of radio astronomy using geographic radio quiet and coordination zones.

7.4.6 Space-to-Earth transmissions associated with NGSO systems

Transmission in the space-to-Earth ("s-E",downward) direction will be much more challenging. Radio astronomy has long experience suffering from interference created by existing satellite constellations that are 2-3 orders of magnitude smaller than those now planned. Earlier generations of radio navigation satellite systems with some twenty satellites interfered over broad swaths of the radio spectrum after 1978 and were not certified compliant with the RR until 2007 at WRC-07. Old and new constellations of a satellite phone (mobile-satellite service; MSS) provider operating only 66 LEO satellites have harmfully interfered with radio astronomy use of its spectrum band at 1610.6-1613.8 MHz since launch in 1998, even though only 3-4 of its satellites are above the horizon at any time. The interference arises in part from overdriving amplifiers over an operating band that is too wide and extends too close to the RAS band for compatible operation. Figure 7.4.3 shows harmonic intermodulation products and other unwanted emissions spilling over into frequency bands outside the band that is allocated to MSS (see also Section 7.4.1).

Formal complaints to the operating administration and the highest level of the ITU-R have not remedied this situation, illustrating the difficulty of curing interference problems once they have been embedded in a satellite system.

When 400 satellites are above the horizon, a random sky position will on average be only 3-4 degrees from at least one satellite. This is much larger than radio astronomy telescope main lobe beamwidths but much smaller than the 19° angular separation that is needed to reduce the gain of a generic radio telescope to the 0 dBi level that is used to define radio astronomy's interference thresholds (See Section 7.1). The gain of a generic antenna model used in ITU-R studies (see below) is **30 dBi** at 3° angular separation.

In the space-to-Earth direction the level of interference will depend on many factors. To address protection in this dynamic scenario the ITU-R developed a procedure (originally for NGSO-GSO compatibility) called "equivalent power flux density (epfd)" (RR Article 22.5C and Recommendation ITU-R M.1583) where the average received power in a representative integration time is calculated using a time-varying numerical simulation and converted to the equivalent brightness of a source observed in the main beam of a telescope.

The epfd is calculated using Monte Carlo computer simulations tracking both the motion of satellites in the constellation and the movement of a radio telescope as it follows a random position on the sky during a typical observing period (2000s as also used in RA. 769). The sky is sub-divided into cells and the average signal level is evaluated in each cell by redoing the simulation enough times to achieve statistical reliability. The epfd in each sky cell is then compared to the harmful interference level defined in Recommendation ITU-R RA.769, and the constellation is judged to be compatible when no more than 2% of the cells (Rec. ITU-R RA.1513) have epfd exceeding the RA. 769 level. The 2% dataloss allowance could be lowered if other networks use part of the 5% aggregate data loss allowed for all networks.

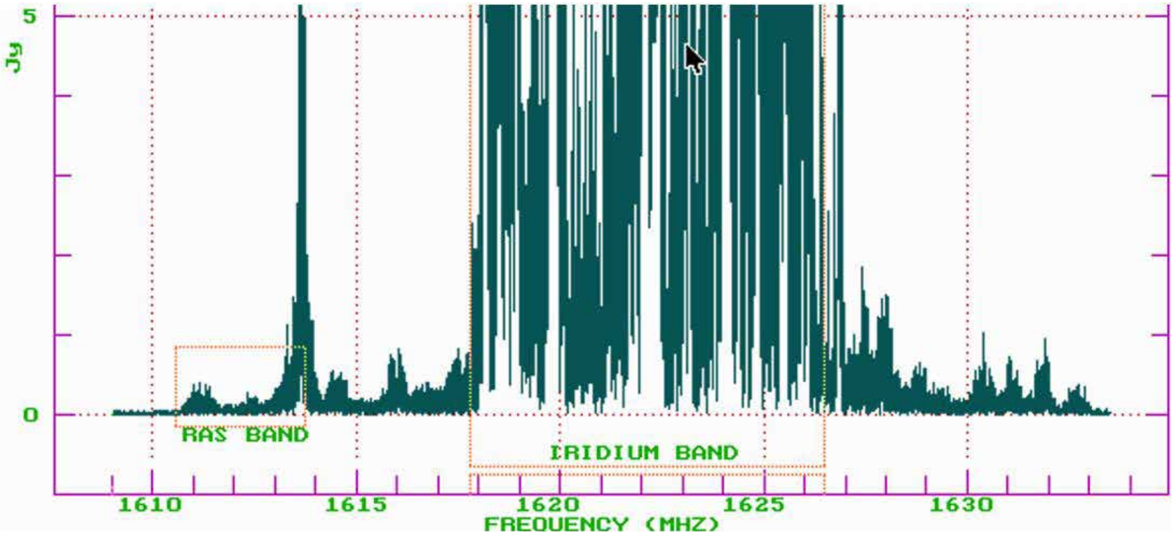


Figure 7.4.3. A GBT spectrum from 2019 May showing unwanted emission in the RAS band at 1610.6 – 1613.8 MHz including intermodulation distortion products.

Using the epfd method means that some regions in the sky can have significantly higher data loss than 2% locally while the constellation complies overall. An example of this can be seen in Figure 7.4.4 where the data loss in some areas of the sky reaches 12% while the total (average) data loss is below 2%. These areas of particularly high data loss are related to the inclination of the orbital planes in the constellation, causing a higher density of satellites at similar latitudes. This effect can aggregate and be amplified for multiple similarly-inclined constellations, rendering significant portions of the sky unusable.

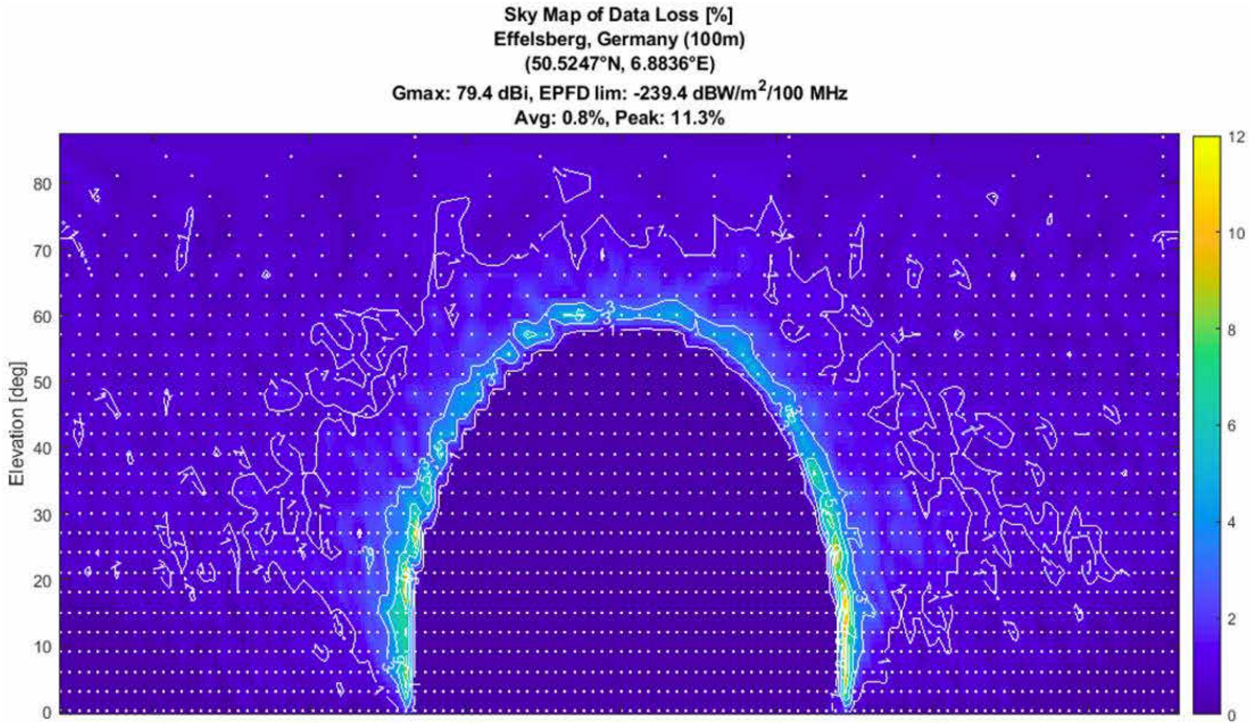


Figure 7.4.4: Sky Map of Data Loss at 10.6-10.7 GHz from ECC report 271

7.4.7 USE OF SPECTRUM IN THE PRESENCE OF STRONG RADIOCOMMUNICATION SIGNALS OVERHEAD

Radiocommunication systems, including satellite downlinks, use power levels that appear on the Earth typically 100 dB, 10^{10} or more times stronger than the radiation radio astronomers study. As noted in Section 7.5, radio astronomy systems are hardened in various ways to accommodate such disparities, but when powerful transmitters are visible overhead, radio astronomy must cope with them even when studying phenomena in its protected bands. Satellite downlink power levels will saturate or cause non-linearity in RAS receivers when a satellite (or other transmitter) and telescope point too directly at each other. This situation becomes increasingly hard to avoid as the number of satellites increases overhead. With even 100, relatively strong encounters are occurring continuously between the beam and beam sidelobes of the RAS telescope and several satellites.

7.4.8 PROLIFERATION OF SPACEBORNE AND MOBILE RADARS THAT CAN DESTROY A RADIO ASTRONOMY RECEIVER

Advancing technology is allowing several companies to launch constellations of a few dozens of satellites to do synthetic aperture radar (SAR) imaging of the Earth, an activity previously limited to a handful of flagship missions launched by national space agencies due to the major monetary investment and very long lead times previously needed to produce such spacecraft. Without naming names, examples may be found here, here and here. They seek to map the surface of the earth *every hour*. SAR systems use kW transmitters to generate signals that are known to be as much as 17 dB (50 times) above the power levels that will burn out a radio astronomy receiver. Radio telescopes must at all costs avoid pointing near such satellites when they are mapping anywhere near the telescope site. Recommendation. ITU-R RS.2066 is a mandatory measure defined in the RR, requiring operators of SAR working around 9.6 GHz to refrain from illuminating a specific set of astronomy sites without advance notice, if their satellites are using the outer portions of the SAR frequency allocation. RAS tries to identify and maintain contact with all SAR operators to encourage them to observe the restrictions in Recommendation ITU-R RS. 2066 even when they are not mandatory.

Comparably powerful and dangerous signals are used by 94.05 GHz nadir-pointing cloud-profiling radars, one of which has operated since 2005, and another of which will come into operation in 2021 or 2022. The earlier radar was not designed to avoid RAS sites and it briefly saturates every RAS receiver over which it passes each 16 days, no matter where the antenna is pointed. The operator of the newer radar has promised RAS to make every effort to avoid directly illuminating RAS sites.

76-81 GHz vehicular radars are also powerful enough to destroy a receiver at close range. A close encounter with a car radar may seem unlikely, but observatories are threaded by roads whose occasional downhill orientations provide opportunities for car radars to illuminate telescopes. RAS pleas to provide an easily-accessible off-switch for vehicular radars were roundly rejected by radar equipment manufacturers at WRC-15.

7.4.9 SPECTRUM NEWLY-ALLOCATED TO APPLICATIONS APPEARING OVERHEAD

Radio astronomy has taken advantage of a *de facto* segregation of radio spectrum use into frequency ranges used very near the ground – perhaps mobile but no higher than towers and buildings allow – and overhead from aircraft and satellites. All spectrum RAS shares with the mobile service is restricted to non-aeronautical mobile use below 70 GHz. This enables RAS to coordinate potential interference away over a broad range of spectrum using geographic separation and coordination, terrain shielding and radio quiet zones, etc., dealing in other ways with transmitters appearing overhead in other frequency bands.

Such distinctions are now blurring as aircraft drones, manned aircraft and cubesats are being allowed to communicate using mobile and mobile-satellite, fixed and fixed-satellite service bands that were previously not used aloft. Cubesats will downlink and satellites will inter-link in mobile-satellite spectrum. WRC-23 Agenda Item 1.14 may allow the operation of 5G base stations on high altitude platform stations (HAPS) at 20 km altitude.

7.4.10 SHARING DEDICATED PASSIVE SPECTRUM WITH ACTIVE SERVICES

As noted in Section 7.3.1 (see Figure 7.3.1), just 1-2% of the spectrum below 86 GHz is reserved for science including radio astronomy, rising to 10% from 90-200 GHz and 15% above. The spectrum currently reserved is a unique resource for science and human knowledge, and a constant lure for commercial operators who would like to transmit inside it and not have to avoid transmitting in it when using other frequency bands.

CEPT is conducting studies to allow the use of ultrawideband (UWB) short range devices (SRD) above 116 GHz, occupying a broad swath of spectrum up to 144 GHz and radiating inside the passive bands protected by footnote 5.340 of the RR (See Section 7.3.1). The spectrum regulator in the US has created special 10-yr temporary licenses to develop and market devices that transmit in or across passive bands above 95 GHz. Allowing transmitters into the passive bands is a significantly further step in the ongoing erosion of spectrum access for all sciences.

7.5 THE WAY FORWARD AND TWO RECOMMENDATIONS REGARDING NON-GSO SATELLITES

This is a time of extraordinary productivity and great expectation for future discovery. Planned flagship instruments SKA, ngVLA and smaller more specialized telescopes such as the ngEHT will probe the Universe before the formation of the first stars and galaxies, watch the ongoing formation of stars and planets in the Milky Way and take our viewpoint to the very edge of what is physically observable at the event horizon of black holes.

But it is also a time of unprecedented risk as the radio spectrum is exploited without adequate concern for the scientific enterprise. Radio astronomy has suffered the loss of allocated frequency bands to satellite interference for more than 40 years, but the number of satellites is increasing by factors of hundreds and thousands. The largest constellation up to 2019 had 75 satellites and caused the loss of an adjacent radio astronomy band (Figure 7.4.3) while the largest currently-launching system will have 4400 satellites. Various operators have requested to launch 30,000-50,000 satellites apiece. Risks to radio astronomy were discussed in Section 7.4 and the proliferation of satellites constitutes the greatest of these.

As ever it is incumbent on radio astronomy to adapt to changing circumstances and it will continue to do so, with new instruments, new observing techniques, more robust electronics and more sophisticated software as discussed in Section 7.5.1. But the *sine qua non* of our endeavor is access to spectrum in a degree that allows the inherent sensitivity of our instruments to be attained. Section 7.5.2 provides two recommendations that are needed to allow radio astronomy to survive in the presence of the expanding use of satellite radiocommunications.

7.5.1 WHAT RADIO ASTRONOMY CAN AND WILL DO, BY AND FOR ITSELF

The increasingly ubiquitous use of radiocommunication devices has resulted in a congested and worsening RFI environment. Regulatory protection is difficult even for the RAS allocations and almost impossible outside them, but radio astronomy is increasingly becoming wideband. Hence, we need to find ways to "inoculate" RAS to the ravages of the RFI "virus".

Radio astronomy will continue to operate as much as possible in remote locations using the terrain to shield it from direct line of sight contact with populated areas. It will operate inside radio quiet and coordination zones whenever possible, to avoid interference from terrestrial systems. But it will be increasingly necessary to observe in the presence of strong radiocommunication signals arising overhead from spaceborne transmitters that cannot be avoided geographically. Interferometry techniques mitigate interference that has different arrival times at different antennas, especially VLBI, but this technique loses its effectiveness for short baselines and distant interference sources such as satellites.

The first step in protecting RAS systems electronically is to ensure linearity in the operation of RAS receivers. If the receiver system goes non-linear (saturates), the resulting intermodulation products can wipe out the whole observing band.

Hence, the need for "robust" receivers i.e.

- Design the RF system's Low Noise Amplifiers (LNA) to tolerate higher input radiation power over a wide band. As RFI is often impulsive and narrow band, the total power over a wide band is not large and the system can be designed to remain linear. In extreme cases, some form of notch filtering could be considered but it is not an ideal solution because the addition of any element before the first amplifier will increase the noise temperature of the system.
- Design the digital part of the receiver to a high dynamic range to cope with the RFI spikes. This mostly necessitates digitizing with many bit levels, with 12-bit systems used in current cm-wave receiver designs. Of course this results in an avalanche of data (often Tbps), extremely wideband networking and large computer clusters to cope with the analysis of the data.
- Design RF and digital transport systems to the highest possible dynamic range and headroom.

A robust system that does not saturate preserves the radio astronomy signals and also measures accurately the RFI, which in turn enables RFI mitigation i.e.

- At a very basic level, the often narrow RFI signals might be excised in frequency and time, which enables use of the un-occupied spectrum, if sufficiently high time resolution can be accommodated during data-taking and data-logging.
- Measuring the RFI with a reference antenna can enable active RFI mitigation by subtracting the RFI signal from the telescope data to restore a usable spectrum. This has been demonstrated but requires significantly more development and is an expensive solution.

At the telescope operation level it is sometimes feasible to arrange operations to avoid known interference which may occur at particular times. This requires a level of coordination with other radio services that has not been utilized often by RAS. However, innovative new approaches are being considered. Currently, quiet zones have a mostly static model of coordination whereby once a given set of parameters is determined, those are the fixed requirements for the transmitter. In the new approach the transmitter requirements would change dynamically and coordination could be automated based on the frequency of the scientific observation being taken and the direction in the sky where the radio telescope is pointed. Additionally, this type of model could be enhanced via dynamic spectrum hopping. In the case of 5G, for example, with handsets enabled to operate in multiple bands, they could dynamically change their operating band within a radio quiet or coordination zone when the initial band would cause interference to the radio telescope.

7.5.2 RECOMMENDATIONS FOR PROTECTION OF RADIO ASTRONOMY FROM NON-GSO SATELLITES

As described in Sections 5.2 and 5.3, radio astronomy has engaged with the radio spectrum regulatory regime since 1958, one year after the launch of Sputnik, and has succeeded in securing exclusive rights to small fractions of the spectrum (Figure 3.1) upon which all passive radio science depends, including satellite remote Earth-sensing to study soil, water, weather, climate and global warming. Thus, loss of access to spectrum is not a problem for radio astronomy science alone.

Radio astronomy will always advocate for and defend its interests in the spectrum regulatory arena. But despite this, despite its broader public advocacy and outreach in support of scientific knowledge, and despite the public's inherent interest in preserving the value of its investment in radio astronomy, access to the spectrum is being eroded in the radio spectrum along with other wavebands. Radio astronomy defends its allocations in small portions of the spectrum, often with concessions from services transmitting in nearby bands, but faces grave problems as commercial exploitation of radio spectrum expands.

This situation has taken a perverse turn as indifferent radio spectrum regulators authorize the launch of mega-constellations in non-geostationary orbit that degrade the appearance of the night sky and hinder optical astronomy with unforeseen optical reflections. But these same constellations present the gravest threat to radio astronomy. If launched in the quantity now foreseen, it will be impossible to point anywhere in the sky without having one or more within a few degrees of the telescope beam. Satellite signals, already inherently at least 1010 times stronger than radio astronomy sources, will be collected and boosted by the radio astronomy antennas and amplified by receiver electronics.

How to accomplish the needed modification of current practice that sees spectrum merely as a resource from which to extract commercial value? Science must also be minded. As we discussed in Section 5.2, spectrum is a shared resource for everyone.

The following two recommendations distill the discussion and the experience of radio astronomers and radio astronomy spectrum managers into two practical tools that are needed to allow radio astronomy to continue to operate:

- **RAS1**: Non-GSO satellites should be required to be able to avoid direct illumination of radio telescopes and radio quiet zones, especially the radar and other high-power satellite applications that are capable of burning out radio astronomy's receivers;
- **RAS2**: Non-GSO satellites should be required to have sidelobe levels that are low enough that their indirect illuminations of radio telescopes and radio quiet zones do not interfere, individually or in the aggregate.

8. APPENDICES

APPENDIX A. DARK SKY OASES

A1. DARK SKY OASIS CLASSIFICATION SCHEME

The following table lists, for each of the six fundamental IUCN-DSAG classes, a recommendation for the threshold visual night sky brightness (NSB) at the zenith that defines the class and equivalent designation categories in the dark-sky certification programs of IDA, the Starlight Foundation, and the Royal Astronomical Society of Canada (RASC).

IUCN-DSAG Class	**V-band Zenith NSB (μcd m^{-2})**	**V-band Zenith NSB (mag arcsec^{-2})**	**IDA Category**	**Starlight Foundation Category**	**RASC Category**
1 Dark Sky Astronomy Site	<264	>21.7	International Dark Sky Sanctuary	Starlight Reserve (zenith >21.4 mag arcsec^{-2})	Nocturnal Preserve
2 Dark Sky Park	<360	>21.4	International Dark Sky Park	Starlight Landscape; Starlight Wilderness; Starlight Heritage Site; Starlight Astronomy Site	Dark Sky Preserve
3 Dark Sky Heritage Site	<660	>20.7	(none)	(none)	(none)
4 Dark Sky Outreach Site	<480	>21.1	Urban Night Sky Place[1]	Starlight Tourism Destination; Starlight Wilderness; Starlight Stellar Park and Stellariums; Starlight Camp (zenith >21.0 mag arcsec^{-2})	Urban Star Park
5 Dark Sky Reserve	<480	>21.1	International Dark Sky Reserve	Mixed Starlight Site	(none)

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[1] In practice, no upper limit for zenith NSB is imposed by IDA program guidelines as a requirement for obtaining this certification.

6a Dark Sky Community (urban)	<1000	>20.3	International Dark Sky Community[2]	(none)	(none)
6b Dark Sky Community (rural)	<750	>20.6	International Dark Sky Community	Starlight Oasis; Starlight Village (zenith >21 mag arcsec^{-2})	(none)

Table 1.3: Suggested zenith night sky brightnesses defining the IUCN-DSAG dark-sky place classes

Threshold zenith brightnesses are given in multiples of an assumed dark limit for the luminance of a night sky in the absence of anthropogenic light set only by natural sources.[3] There is some disagreement in the literature as to the value of this minimum zenith brightness in part because there is in some cases significant spatial and temporal variation in natural sources of light in the night sky. Chief among these sources in terms of contribution to night sky brightness is airglow, a chemiluminescent process in the Earth's atmosphere that can contribute as much as ~280 µcd m^{-2} of luminance to the total NSB in any given direction (Sternberg and Ingam 1972). Its intensity and distribution depend on upper atmosphere conditions and solar-geophysical conditions.

In the New World Atlas of Artificial Sky Brightness, Falchi et al. (2016) adopted a 'canonical' value of 174 µcd m^{-2}, or about 22.2 *V* magnitudes per square arcsecond. Crumey (2014) argued that "the darkest skies on Earth" have a zenith luminance of 171 µcd m^{-2}, but "a general approximation … representative of a truly dark sky" considering variations in airglow intensity and sky distribution is 200 µcd m^{-2} (≈22.0 *V* mag arcsec^{-2}), "though at a pristine site there may be regions of the sky that are darker than this".

This is, however, a theoretical lower limit that is rarely obtained in nature. In the experience of the authors, having made many measurements of NSB in different parts of the world and under a variety of conditions, the natural night sky is observed to vary in zenith brightness from around 200–250 µcd m^{-2} (≈22.0–21.8 *V* mag arcsec^{-2}). We therefore adopt a conservative global average, away from the Earth's polar regions, of 240 µcd m^{-2} (≈21.8 *V* mag arcsec^{-2}). We define this as one "night sky unit" (NSU).

Thresholds in multiples of this value are suggested in Welch (2021); we have adjusted the value of the NSU relative to Welch according to our preferred definition.

IUCN-DSAG Class	Threshold (NSU)
1	1.1
2	1.6
3	4.0
4	2.6

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[2] In practice, no upper limit for zenith NSB is imposed by IDA program guidelines as a requirement for obtaining this certification.

[3] This furthermore assumes that the sky is 'astronomically dark' (i.e., the Sun is at least 18° and the Moon at least 10° below the horizon); the air is clear (i.e., the atmospheric optical depth in the middle of the visual band $\tau \approx 0.1$); the Milky Way is not in the zenith and the observer is looking away from the ecliptic.

5	2.6
6a	4.0
6b	3.0

Table 1.4: IUCN-DSAG dark-sky place class definitions by zenith brightness given in night sky units (NSU).

We note that the values in the above tables are not intended to form the basis of regulations to control the brightness of the night sky over particular areas. Far from sources of light pollution, the brightness of the night sky, controlled by natural sources of light, is known to vary by a factor of two on timescales ranging from hours to years. For the purposes of defining conservation classifications of various sites, the guidelines above should be considered determinative only in the context of long-period night sky brightness monitoring programmes.

A2. TRADITIONAL AND MODERN LAMP TYPES USED IN OUTDOOR INSTALLATIONS

In 1417 houses in London were required to hang a lantern outside during the hours of darkness. This was presumably a wax candle, and represents the earliest introduction of street-lighting. Paris followed with a similar ordinance a century later, in 1524.

These early beginnings to municipal lighting would have hardly caused any significant light pollution. Lighting by reticulated coal gas came to London in 1807, to Baltimore in 1816 and to Paris in 1820. The 19th century was therefore the era of gas street-lighting in the major urban centres of Europe and North America. A typical gas mantle was very dim and emitted about 400 lumens, the same as a 25-watt incandescent light bulb.

Thomas Edison in the United States and Joseph Swan in England developed the first electric light bulbs using incandescent carbon filaments. Both were patented independently in 1879. A few years earlier Pavlov Yablochkov in Russia had devised a carbon arc lamp, and it was this lamp which was installed in Paris in 1878, the first city to have electric street-lighting. By 1881 as many as 4000 Yablochkov candles were installed in Paris. Carbon arc lamps were widespread in the United States by 1890. At about the same time, Edison incandescent bulbs were being used from the 1880s for street-lighting. These bulbs had a low efficiency, short life and yellow to orange colour. Edison and Swan each started companies for the manufacture of electric lights. These companies merged in 1883 with the formation of the Ediswan company.

Tungsten filament incandescent lamps were developed in 1904 and patented by Hungarian Sándor Just and Croatian Franjo Hanaman. They had brighter filaments operating at a higher temperature, and were filled with an inert gas such as argon or nitrogen.

Another type of arc lamp is the low-pressure sodium (LPS) lamp, in which light is emitted as the result of passing an electric current through a thin vapour of ionised sodium atoms. LPS technology was developed in the 1930s, and streetlights using this technology became common after World War 2. They emit almost monochromatic light at 589 nm, resulting in the well-known orange glow. Their colour temperature is about 1900 K, insofar as the concept of colour temperature can be applied to a non-thermal source with such a large departure from a black-body SPD. This value is similar to a typical carbon-filament incandescent lamp, but less than that of a tungsten filament (which is about 2450 K). Given their almost complete lack of short wavelength blue light, LPS luminaires have the least impact on night sky brightness among common lighting technologies.

A high-pressure sodium (HPS) arc lamp broadens the monochromatic orange light SPD of LPS, giving a more pleasing golden-yellow hue with better colour rendering to the human eye. HPS street-light luminaires were developed from 1965 and became widespread from that time. Another type of arc or gas discharge lamp is the mercury-vapour lamp, first patented in the 1890s. Its spectrum consists of a number of emission lines at discrete wavelengths, especially in the blue and ultraviolet; the high pressure under which the gas is maintained broadens the lines, rendering their perceived colour as bluish-white.A variation of the mercury-vapour lamp is the fluorescent lamp, in which the inside surface of a glass tube is painted with a fluorescent substance that converts ultraviolet light to visible light, thereby increasing the luminous efficacy and giving a more pleasing white light. Fluorescent lights were patented in 1931 and were marketed commercially by the General Electric Company in the U.S. from 1938. They were often used for street-lighting in the 1950s and 1960s, as well as for interior spaces such as offices and workshops.

Yet another variation of the mercury-vapour lamp is the metal halide lamp. Here a metal salt such as sodium iodide is added to the mercury vapour. In a metal halide lamp spectrum, orange sodium D lines are added to the line emission of mercury, giving a better luminous efficacy and improved colour rendition. Metal halide lamps are often used to light outdoor commercial or industrial spaces and car parks, as well as for flood lighting. They were first developed in the 1960s.

The first use of LEDs for street-lighting only came in 2006, almost half a century after their first invention. Ann Arbor in Michigan, where LEDs were first developed, was also the first to install LED street-lights. This required the first white LED to be devised, based on using a blue LED made from indium gallium nitride (InGaN) or gallium nitride (GaN) as the main semiconductor material, and coated with a phosphor made from yttrium aluminium oxide doped with cerium (known as Ce:YAG, or cerium-doped yttrium aluminium garnet semiconductor). The phosphor converts some of the blue or violet light into a broad spectrum of green, yellow and red. The result is an LED emitting light which appears as white to the human eye. LEDs are theoretically capable of emitting over 300 lumens of light per watt of electricity consumed, a vast improvement over the 16 lumens per watt efficacy for incandescent filament lamps, and are expected to operate for at least 100,000 hours in the field. For street-lights, this corresponds to about 25 years.

A3. ASTRO-TOURISM

'Astro-tourism' is sustainable in that it does not involve resource extraction. If darkness is preserved, it is infinitely renewable (Starlight, 2007)

Because natural darkness tends to be concentrated in underdeveloped and/or little-populated areas, astro-tourism necessarily contributes to rural economic development and overall development goals.

The biggest threat is often from the development that follows intense tourism interest in dark skies.

The challenge is how to sustainably grow this kind of tourism without damaging the very resource that tourists come to enjoy.

The French astronomer Camille Flammarion (1842-1925) was a great populariser of astronomy, and he had his private observatory at Juvisy-sur-Orge, 18 km south-east of Paris. He installed there a 24-cm refracting telescope where he was able to bring the beauty of celestial objects to the public, and to members of the Société Astronomique de France, which he founded.

In 1880, Flammarion wrote his well-known book *Astronomie Populaire* in which he extolled the beauty of a pristine night sky (Flammarion 1880). He was one of the founders of astro-tourism.

In spite of Flammarion's early recognition of celestial aesthetics, the strong interest in astro-tourism is very much a recent phenomenon, of the late 20th and 21st centuries. Astro-tourism constitutes the travelling of people to dark sky locations to admire the beauty of the night sky, and possibly to participate in a guided night-sky tour.

A3.1 STARLIGHT TOURIST DESTINATIONS

Astro-tourism epitomises the tendencies towards more meaningful tourism experiences, based on conservation of natural resources, knowledge, and science, potentially enriching the traveler and the host communities. In 2010, the Starlight Foundation unveiled for the first time the Starlight Tourism Certification System with the support of UNWTO. In recent years several UNESCO sites have been labelled by the Starlight Foundation as Starlight destinations, such is the case of biosphere reserves of La Palma, La Rioja, Fuerteventura, Sierra Morena, Gran Canaria, Monfragüe, Alto Turia, etc. (Spain), Fray Jorge (Chile) and South West Nova (Canada) or the Teide National Park, the first World Heritage site labelled. Responsible lighting and light pollution control are key requirements for the certification in these sites (Ref. *Alternative Ways of Lighting UNESCO Sites*, 2005).

As an example of good practices on astro-tourism we have chosen La Palma Island, **the world's first Starlight Reserve, was acknowledged in 2012 as a Starlight Tourist Destination;** this guarantees the possibility of enjoyable stargazing while learning something of the associated scientific, cultural, natural and environmental values. On 20 April 2007, **La Palma hosted the signing of the Starlight Declaration** in Defence of the Night Sky and the Right to Starlight (or La Palma Declaration) and on April 2017 hosted the X Anniversary of the Starlight Declaration, where the institutions signing the same, as well as other institutions invited, adopted resolutions and made a call facing the future.

La Palma possesses certain unique environmental features which have won it the distinction of being named a UNESCO World Biosphere Reserve. More than one third of its surface area is protected land, the highlight of which is the Caldera de Taburiente National Park. Its landscape is the result of a dramatic formation process that took millions of years, and houses a multitude of microclimates and surprisingly contrasting vegetation. At its highest point, over 2400m above sea level, the Roque de Los Muchachos Observatory rises above the "sea of clouds" where the atmosphere is clear and stable thanks to the Atlantic Ocean. Consequently, this is considered one of the best places on earth to observe the sky. In addition, La Palma was **the first place in the world to apply the Sky Law** promoted by the Institute of Astrophysics of Canary Island in 1988, a specific law was passed designed to protect the quality of the night sky for the purpose of astrophysical observation, which was a giant step forward in defence of the sky on a world-wide scale. This law protects La Palma from light, atmospheric and radioelectrical pollution, as well as preventing interference from aviation routes.

We can enjoy stargazing activities, guided night trails, visits to the astrophysics observatories of Roque de los Muchachos, etc. For all of them specialised personnel is needed. In La Palma the first course of **Starlight Guides** took place in 2012 and the second one in 2019, but the number of guides dedicated to the activity of stargazing has fallen short, especially when it coincides in dates with the visit of cruise ships. There is a demand for the training of specialised guides by specialised companies that have increased their activity in the last years.

To enjoy a unique experience, La Palma offers: hotels and country cottages that have basic instruments to enjoy our spectacular sky (El Pósito and Casa Emblemática San Sebastian have been awarded as Starlight Rural House and Hotel respectively); companies specialised in Astronomical Tours that have professional guides; organised visits to one of the most important Astrophysical Observatories in the world ; archaeoastronomy activities; night photography; thematic routes (wine and stars, moonlight hikes); solar observations; camping under the stars; activities with solar cooking; or the chance to simply stroll around discovering the sundials or to go shopping in stores where the protagonists are the stars. Some restaurants even include evocative flavours with names of planets, galaxies and constellations in their dishes.

There are more than 70 enterprises dedicated to astro tourism with annual revenues of about 30 million euros.

Astronomical resources:

A.3.1.1 Stargazing viewpoints network

These spaces located throughout the island's geography are equipped with information panels designed to interpret the night sky. The viewpoints are divided into 3 categories, depending on the darkness of the night sky. All of La Palma's municipalities have viewpoints dedicated to the observation of the local landscape during the day and astronomy during night, with themes that range from the interpretation of the sky (with its constellations, planets or the Moon), the calculation of equinoxes and solstices, up to a Solar System to scale, making an outdoor astronomy museum Some

Figure A.1. Stargazing resources at La Palma Island: walking and observing (http://www.starsisland-lapalma.es/en/walking-and-observing/). Map courtesy of Cabildo de La Palma.

of these observation points connect to hiking routes belonging to the nature trail network of La Palma.

A3.1.2 Stargazing trails

La Palma is an ideal island for lovers of hiking. In combination with the GR 131, four hiking trails have been signposted so you can walk while enjoying routes linked to the stars.

A3.1.3. Places of astronomical interest

Throughout the island's geography, places that have a special symbolism or connection with the sky and the stars are referenced: sundials, dark sky sites or places of great symbolism.

A3.1.4. Archeoastronomy

The Awara, the first settlers of the island, created various rock carvings, cairns, and other elements. According to new research these are related to ancient markers for the solstices, equinoxes and stellar alignments vital to the survival and religious beliefs of the population.

A3.2 ASTRO-TOURISM IN NEW ZEALAND

In New Zealand astro-tourism has grown strongly since the creation of the company Earth and Sky at Lake Tekapo in 2004 (since renamed the Dark Sky Project, in 2019). Approximately 1.5 million tourists travel through Tekapo annually, and a rough estimate is that 10 % of them come to see the night sky. In 2019 visitor guest nights in Mackenzie District accommodation reached 900,000 per year, a figure which has doubled in the period 2014 to 2019. Many astro-tourists visit nearby Mt John Observatory, a professional research facility operated by the University of Canterbury.

The growth of astro-tourism is very much a world-wide phenomenon, but New Zealand is seen as a world leader. This is a result of relatively unpolluted night skies, the Mackenzie District ordinance to control light pollution (first introduced in 1981), the presence of numerous astro-tourism companies in the Mackenzie Basin and the desire of many other communities in New Zealand to emulate the success of astro-tourism in the Mackenzie Basin.

In August 2019 Forbes magazine asked the question: 'Is astro-tourism the next Big Thing? – Incredible night-time outdoor adventures for Stargazers' (Forbes, 2019). The article urged tourists to visit a dark sky place to view the Milky Way, or an aurora or even an eclipse. Lonely Planet have jumped onto the band-wagon and published their first guide for astro-tourism (Stimac, 2019). The guide-book features many of the world's top locations for dark skies and star-gazing, including those in New Zealand and Australia.

Travel writers have also been quick to extol the delights of this new brand of educational scientific tourism. One of those is UK travel writer Anna Hart in the Telegraph (Hart 2018). She mentioned the top stargazing locations in the world, including the Aoraki Mackenzie in New Zealand.

In Italy, the website AstronomItaly, which has an English version (AstronomItaly, 2020) advises tourists how to find the best locations on Earth for stargazing. They also offer a certification programme for new dark sky localities, with applications solicited from observatories, planetariums, hotels and lodges, nature and national parks and villages, with a handful of certified places in each category

APPENDIX B. HISTORY OF LIGHT POLLUTION IMPACTS ON ASTRONOMY

B.1. HISTORY OF THE IMPACT ON THE FIELD OF ASTRONOMY: NINETEENTH CENTURY URBAN OBSERVATORIES AND THEIR FATE IN THE TWENTIETH CENTURY ELECTRIC LIGHT ERA

In Europe and in North America, many astronomical observatories were established or expanded during the nineteenth century. This was a century of great advances in telescope design, with achromatic refractors being the dominant and preferred technology from the 1820s when Fraunhofer's 24-cm aperture Dorpat telescope was installed at the Tartu Observatory in what is now Estonia (in 1824). The 15-inch (38-cm) Harvard refractor in Cambridge Mass. followed in 1847 and many others since, culminating in the Yerkes Observatory 40-inch refractor of 1897.

The great majority of these nineteenth-century observatories were in or near major cities and hence in an urban environment, which in many cases was having electric street lighting installed before the end of the century. Examples of major urban observatories established during or before the 19th century are the Royal Greenwich Observatory; the Paris Observatory; Allegheny Observatory in Pittsburgh, Ohio; Potsdam Astrophysical Observatory and many more. A survey indicates that 43 astronomical observatories were established in the nineteenth century, mainly in large cities of Europe and North America. Thirty-four of these were established in the second half of the nineteenth century. Just ten major observatories were operational in the world in the late 18th century. A useful list is found at Observatories (2020).

The statistics show a tremendous growth in observatory and telescope numbers from the mid-19th century onwards, concurrent with the beginnings of the new science of astrophysics from the 1860s. Nearly all these new institutions were in major cities, and ironically many were being established from the 1880s, just as the first electric street lighting was also being installed. The result was a catastrophic conflict between the requirements of astronomers for dark skies and the rush to illuminate cities with the new marvel of electric lighting, ostensibly to enhance safety and enable cities to commercial activities late into the night.

Today none of the urban observatories established before 1900 are still used for astronomical research observations. Light pollution put an end to that. Some are still the office headquarters for astronomers to analyse data or develop instrumentation (for example the Paris Observatory, the Royal Observatory Edinburgh). Some have been converted to museums or facilities for public outreach enabling the public to look through old telescopes (such as the Royal Observatory, Greenwich;, the Kuffner Observatory, Vienna and the Yerkes Observatory in Wisconsin). Others have closed altogether or moved to a better site, such as the Berlin Observatory (established 1830, moved to Babelsberg, Potsdam in 1906) and the Melbourne Observatory, established in 1862 and closed in 1945.

Only a few 19th century observatories which were sited on remote mountain tops are still used for research. Pic du Midi Observatory was established in 1878 at an altitude of 2877 m in the French Pyrenees and continues to be a world-class observational site for astronomical research. In 2013 the International Dark-Sky Association (IDA) gave accreditation to the surrounding Pic du Midi International Dark Sky Reserve which gives protection to the site from light pollution. The other famous mountain-top observatory still undertaking research is the Lick Observatory, which opened in 1881 on Mt Hamilton (altitude 1283 m) in California. It is now severely affected by light pollution from San Jose and the rest of Silicon Valley, and its future is in jeopardy.

B.2. HISTORY OF THE IMPACT ON THE FIELD OF ASTRONOMY: THE SEARCH FOR DARK OBSERVATORY SITES AWAY FROM LIGHT POLLUTION OF CITIES AND ON REMOTE MOUNTAIN TOPS

Charles Piazzi Smyth (1819-1900), the Astronomer Royal for Scotland, was the father of mountain-top astronomy. In 1856 he was funded by the British Admiralty to lead an expedition to Tenerife, where he established a temporary observing site on Alta Vista at 3300 m altitude, on the eastern slopes of the 3700-m high Teide. Here he used small telescopes to observe the diffraction rings and Airy disk of star images which are only seen in very steady air. He also observed the separation of close double stars such as alpha Piscium, an observation which was impossible from low altitude sites such as Edinburgh (Smyth, 1858, 1863).

By the end of the nineteenth century, it was realised that mountain-top observatories provided significant benefits for astronomy. At first the benefit was from sharper images arising from more steady air. However, in the twentieth century the additional benefit that came from darker skies away from light pollution was realised. As discussed above, mountain observatories were established at Pic du Midi (2877 m) in France in 1878 and on Mt Hamilton (1283 m) in California in 1881. These were the first two permanent astronomical observatories that enjoyed very dark skies at high altitude.

Mt Wilson Observatory was perhaps the most famous of the new mountain observatories of the early twentieth century. It was established from 1904 by George Ellery Hale on the San Gabriel Mountains near Pasadena, about 30 km north-east of downtown Los Angeles and only 10 km from central Pasadena (as the crow flies). It was the site for the famous 60-inch reflecting telescope of 1908 and 100-inch Hooker reflector of 1917. Mt Wilson was operated by the Carnegie Institution, but after 80 years of research, the light pollution made it no longer a viable site. The research observations were closed from 1984, although Georgia State University still runs an array of smaller telescopes on Mt Wilson.

Mt Wilson Observatory is probably the most successful optical observatory in the history of astronomy, and was made famous by the pioneering achievements of Edwin Hubble observing faint galaxies in the 1920s. These were observations that greatly benefitted from dark skies. In fact the first electric street lights in Los Angeles were installed in March 1916, but it is a reasonable assumption that the skies above Mt Wilson would have remained dark for most of the 1920s and even 1930s.

Perhaps surprisingly, the drive to establish further high altitude observatories at dark sites did not immediately follow the successful development of the Mt. Wilson Observatory outside of Los Angeles, California in the early 1900s. Probably two world wars and the economic depression of the early 1930s delayed their introduction in the first half of the twentieth century. Another major mountain-top observatory in the first half of the twentieth century was the Palomar Observatory at 1712 m on Palomar Mountain, which was established in 1936. It is about 100 km northeast of San Diego in California, and the site of the famous 200-inch (5-m) Hale telescope. It is also 150 km southeast of Los Angeles, so today is affected by light pollution, with the artificial light contribution in excess of 60% of the natural sky background when the two urban areas are not blanketed by marine layers (from Falchi et al. 2016). The Swiss also built the Sphinx Observatory on the Jungfraujoch at 3700 m in 1937. It was an ideal site for ultraviolet astronomy. These were the only mountain observatories of the first half of the twentieth century.

B.3. THE EFFECT OF ARTIFICIAL SKYGLOW ON ASTRONOMICAL OBSERVATIONS

Skyglow from ALAN arises from the scattering of light particles, or photons, by air molecules and aerosols, after they have been emitted from streetlights or other artificial light sources. Scattering is simply the change in direction of a photon as a result of its interaction with an air molecule, normally oxygen or nitrogen, or aerosol like a water droplet or dust particle.

The immediate result of scattering is a brightening of the night sky from artificial light at night. Not all photons are scattered – many go on up into space and leave the Earth, as attested by observations from satellites which show major cities pouring light into space. A bright night sky or skyglow affects astronomical observations because inevitably every observation of an astronomical object, be it star, nebula, galaxy or quasar also records skyglow photons mixed together with those from the object under study. The task of the astronomer is to interpret just the photons emitted by the astronomical body. In principle, a knowledge of the skyglow intensity should allow its contribution to be subtracted from the raw observation. In practice, there are difficulties in doing that.

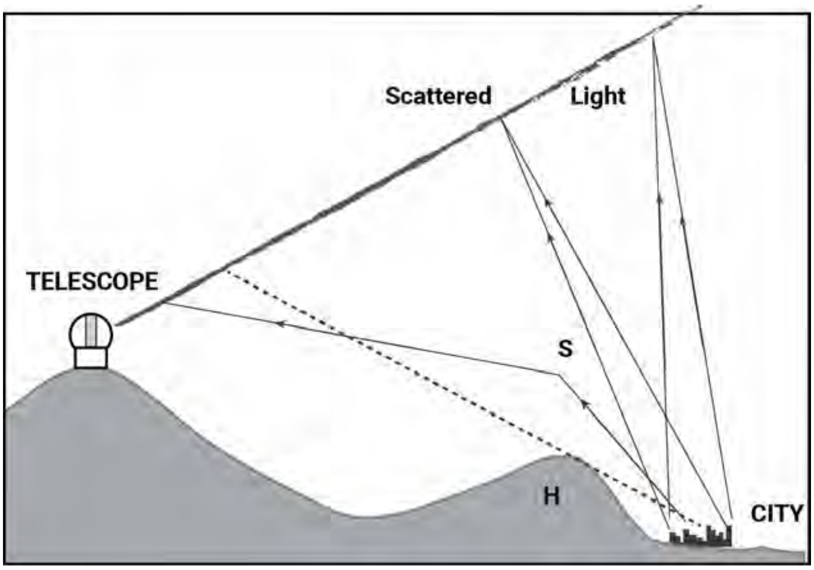

Fig. B.1. Mechanism of sky illumination from artificial lights. Light emitted by the city can reach the telescope either by direct scattering involving air molecules and aerosols located in the telescope field of view, or by multiple scattering in indirect paths such as that shown via the point S. Note that the hill H protects part of the telescope beam from direct illumination. Figure courtesy of Cayrel et al. (1980).

There are two ways of interpreting the effect of skyglow on astronomy. One approach is to consider that every observation requires a certain minimum contrast in order reliably to detect and deduce information about the astronomical source. The contrast C is just the ratio of the object's detected flux or surface brightness to that of the skyglow, or

$$C = S_{.} / S_{SG}$$

where $S_{.}$ is the recorded radiance of the astronomical image and S_{SG} that of the skyglow recorded in the same image area (including natural airglow). If we consider an observatory A where the skyglow is twice as bright as at observatory B, the contrast for a given object seen from A will be halved which may make the contrast too low for detection or for analysis. Observatory A will therefore have access to fewer objects than B. If the type of object is uniformly distributed throughout space, then a simple analysis shows that an increase of skyglow by a factor of 2.5 reduces the number of accessible objects by a factor of four.

A second analysis considers the noise in any physical measurement. Every measurement of a physical quantity has an uncertainty as a result of noise. In the case of astronomy, the noise is from the statistical uncertainty that the number of photons collected represents a true measure of an object's brightness. Both S_* and S_{SG} have noise. Our raw measurement is of $R = (S_* + S_{SG})$ and the noise is the combined noise from both sources. If S_{SG} is subtracted from R, then the remaining noise is still that of R and includes the skyglow noise. So our measurement of S_* is adversely affected with an extra dose of noise, even though the skyglow signal has been subtracted.

The report of Cayrel et al. (1980) noted that the natural airglow had emission lines, especially those of atomic oxygen at 557.7, 630.0 and 636.4 nm, and those of atomic sodium at 589.0 and 589.6 nm. The sharp peaks in airglow at these wavelengths meant that any artificial skyglow from lamps that also have emission lines at these same wavelengths can be tolerated. In particular, low pressure sodium street lights produce more or less monochromatic radiation at 589.0 and 589.6 nm (known as the Na D lines), and these meant that scattering from these lamps could be more readily tolerated, given that they leave the rest of the electromagnetic spectrum almost unaffected. Cayrel et al. recommended that skyglow equal to the airglow would be acceptable at the D lines, and hence low pressure sodium street lights were the recommended lamp type near astronomical observatories. These sources are no longer available, but the recommendation remains that (nearly) monochromatic sources are the best near observatories.

The physics of photon scattering by air molecules shows that the scattering is wavelength-dependent and goes as 1/4 a process known as Rayleigh scattering. Short wavelength blue photons (λ 450 nm) scatter about four times more readily than red photons (λ 650 nm), and ultraviolet ones (λ 350 nm) do so some ten times more than in the red. skyglow is therefore strongly weighted towards the blue end of the spectrum, which is also why the daytime sky is blue. This fact also strongly favours nearly monochromatic lights near 600 nm for street lighting, as their orange colour scatters relatively little compared to emissions from bluer lamps.

Finally we note that the brightness of skyglow at an observatory depends on the distance *r* to a town and its population *P*. In various models, the polluting skyglow declines rapidly with distance *r* and is proportional to the population *P* and hence to the number of streetlights, assumed to be low pressure sodium.

B.4. INSTRUMENTATION AND TECHNIQUES FOR MEASURING NIGHT SKY BRIGHTNESS AND SKY BACKGROUND IN ASTRONOMICAL OBSERVATORIES AND TRENDS WITH TIME

B.4.1 SENSING NIGHT SKY BRIGHTNESS

There are two basic approaches to measure and monitor night sky brightness (NSB): look upward from the ground, or look down from Earth orbit. The former mode involves direct sensing of the radiance of the night sky, while the latter mode predicts the night sky radiance seen from the ground by sensing the upward-directed radiance of light escaping the Earth's atmosphere and applying a model of how light propagates through the atmosphere. Ground-based measurements are model-independent but typically limited geographically and temporally. We focus here largely on the ground-based approach, but briefly comment on new capabilities for remotely sensing NSB.

Direct measurements of NSB from the ground involve sensors that integrate the flux of light through a known solid angle, within some wavelength range, and over some length of time. These divide into two types: single-channel devices, and multichannel devices. Table D1 summarises a variety of both types of device.

Instrument	Manufacturer	Type	Sensor(s)	Bandpass	Reference
Sky Quality Meter (SQM)	Unihedron (Canada)	Single-channel; wide- (SQM) and narrow-field (SQM-L)	TSL237 light-to-frequency (LTF) converter	Native (modified Johnson-Cousins *V*)	Cinzano (2005, 2007)
CoSQM A color hack to the SQM	Cégep de Sherbrooke (Canada) Free online documentation.	Multi-channel; narrow-field including the standard SQM-L measurement to be retro-compatible with historical database	TSL237 light-to-frequency (LTF) converter with filter wheel	RGBY color filters	Aubé (2020)
Telescope Encoder and Sky Sensor WiFi (TESS-W)	Universidad Complutense de Madrid (Spain)	Single-channel	TSL237 LTF	Native (modified Johnson-Cousins *V* with enhanced red response)	Zamorano et al. (2017)
Digital single-lens reflex (DSLR) + fisheye lens	Various	Multi-channel	Complementary metal- oxide semiconductor (CMOS)	Broadband RGB	Hoot (2007)
Astronomical camera + lens or telescope	Various	Multi-channel	CMOS or charge-coupled device (CCD)	Various	Duriscoe et al. (2007); Falchi (2010); Aceituno et al. (2011)

Table B.1. Summary of several devices for measuring the brightness of the night sky.

B.4.1.1. Single-channel devices

Single-channel devices are patterned on photoelectric photometers used by astronomers for almost a century. These devices rely on simple and well-understood physics, require little electric current to operate, and are usually small enough to be easily portable. They typically employ light-to- frequency (LTF) converters whose output is a signal pulse stream, the frequency of which is linearly proportional to received light intensity. Their light response is determined in the laboratory, with on-board lookup tables relating measured frequency to light intensity tied to calibrated light sources. Since the response of LTF converters is also sensitive to the ambient operating temperature, sensing of the air temperature is required to properly correct the measured frequency. This is usually done on board the measurement device.

Most commercially available devices have their own photometric passbands modeled on Johnson-Cousins *V*. Researchers have experimented with other filters, but V was chosen to match the bulk of existing literature data and the human visual response to light under photopic conditions.

Infrared blocking filters are often used in combination with the quantum efficiency profile of the semiconductor material of the LTF to achieve the desired effective passband. Optics such as lenses may be used to constrain the opening angle defining the device's angular field of view. Although single-channel device measurements indicate only the brightness of the night sky averaged across a fairly large acceptance angle, some authors report creating crude two-dimensional maps of NSB by interpolating spot measurements from these devices. (Zamorano et al. 2014)

Single-channel devices have a number of advantages, including ease of use; portability; a physically simple sensing mechanism; temperature compensation; good repeatability; rapid capture and display of data; and relatively long historical basis. However, their use also involves certain drawbacks. In order to sense a sufficient amount of yield a measurable signal, they must integrate light over a fairly large solid angle. They yield no valuable spatial resolution in most applications, making them generally unsuitable for monitoring the behaviour of light domes near the horizon. Lastly, there are differences among commercially available devices in terms of photometric passbands that complicate comparison of results among different device types.

B.4.1.2. Multi-channel devices

Multichannel detectors consist either of arrays of light-sensitive elements whose output is multiplexed through one or more signal amplifiers or of panchromatic detectors

behind a filter wheel equipped with filters of various spectral coverage. The ideal example is a spectroradiometer, which provides a complete set of information about the wavelength-dependent brightness of the night sky in any given direction. However, the current generation of such devices is too slow for capturing time- resolved NSB data, and they tend to be prohibitively expensive. One more commonly encounters cameras capturing two-dimensional images, particularly commercial digital single-lens reflex (DSLR) cameras and mirrorless interchangeable lens cameras (MILC). Some are operated with photometric filters to yield a particular effective passband, while others use Bayer filter mosaics to capture native (pseudo-)true-colour images through the combination of broadband red-, green- and blue-filtered data. Other initiatives using non-imaging sensors are also alternatives to the DSLR camera (e.g. CoSQM project).

The main advantage imaging devices have over non-imaging devices is the ability to produce two-dimensional images with some amount of angular resolution. They are often paired with very wide angle lenses to capture views with solid angles as large as 2π steradians (180°) in a single exposure, while others build up multiple-image mosaics with angular offsets between exposures so that the results can later be "stitched" together in software. As a result, these devices provide significantly more spatial information about the distribution of NSB than do non-imaging devices. But the data from imaging devices are more complex to interpret for the non specialist.

Depending on the pixel scale of the detector, star images may be sufficiently sampled that flux calibration can be performed using spectrophotometric standard stars; other imaging systems make use of lab calibrations from reference light sources and employ integrating spheres for illumination of the camera and lens. Spatial distortion information for particular lens and camera combinations can be used to correct lens aberrations after the fact in software. (Mohar 2015; Kolláth & Dömény 2017)

Multichannel imaging devices have certain drawbacks. Due to sensor size and pixel scale, they generally have limited angular resolution. When imagers are used with fisheye lenses to capture all-sky data in single exposures, significant spatial distortions are induced near the horizon. Their multi-spectral functionality is usually limited to a few broad passbands. And, lastly, there is as yet no standard, SI-traceable reporting unit for night sky measurements.

B.4.1.3. Colour considerations

An adjunct issue to the brightness of the night sky is its spectral power distribution (SPD). As the preceding discussion suggests, the sensed NSB is the result of integrating, with respect to wavelength, the convolution of the SPD of the night sky with the spectral bandpass of the measuring device. The SPD of the night sky is a complex function of the various physical processes from which it results; it is further modulated by wavelength-dependent scattering during the transit of night sky light through the Earth's atmosphere. Measurements of NSB in both radiometric and photometric units are therefore strongly dependent on the night sky's spectrum. (Bará et al. 2020) Because most devices used to sense NSB have relatively large spectral bandpasses, the response of those instruments interact with the night sky SPD in complex ways and call for careful consideration when interpreting measurements. (Sánchez de Miguel et al. 2017)

Some reports (e.g., Jechow et al. 2019, 2020) indicate the use of metrics such as the correlated colour temperature (CCT) of the night sky as a means of characterizing its spectral qualities. While CCT is an appropriate representation of the spectra of thermal sources, its utility diminishes as the SPDs of sources become increasingly non-thermal. Since many NSB components, such as airglow and aurorae, have decidedly non-thermal SPDs, the use of CCT alone is unlikely to give reliable colour information about the night sky.

B.4.1.4. Data modeling

Modeling of observations can assist with their analysis and interpretation. For example, Duriscoe (2013) reported successfully recovering the anthropogenic component of NSB from mosaicked all-sky image data by subtracting 2-D models of natural sources of light. To the extent that construction and application of such models can be automated, they hold the promise of rapidly disentangling natural sources of light in the night sky from artificial sources for the purposes of modeling the angular and temporal evolution of skyglow.

For spectrally resolved measurements, it is possible to model the natural components of NSB in wavelength space to subtract and remove them, leaving behind only the spectrum of artificial light sources. From a decomposition of the night sky spectrum, Kolláth et al. (2020) determined that the 'continuous' component of the natural sky (zodiacal light, scattered starlight and airglow pseudo-continuum) is nearly constant at all visible wavelengths and has a spectral radiance of ~2 nW m^{-2} sr^{-1} nm^{-1}.

There are a handful of additional approaches to the modeling NSB that add other inputs to the direct sensing of light. A recent example, provided by Kolláth & Kolláth (2020), used raw backscatter data from a laser ceilometer to provide inputs to Monte Carlo simulations of sky radiances measured simultaneously from the ground using calibrated cameras. The authors applied this technique to infer the vertical structure of the radiance distribution of the night sky.

B.4.1.5. Remote sensing of night sky brightness

The use of remote sensing platforms (namely, Earth-orbiting satellites) to infer NSB from direct measurements of upward radiance offers a number of attractive qualities. Chief among these is the ability to collect information about NSB from essentially anywhere on Earth, which decouples NSB measurement and monitoring from the deployment of ground-based sensors. Falchi et al. (2016) provided such a global data product. They calibrated the radiance-NSB relationship using many thousands of ground-based NSB measurements, but their predictions are sometimes inaccurate. This may be the result of models assuming a flat Earth, and which therefore do not take into account the screening effect of topography, or due to the fact that locally variable atmospheric turbidity can induce scattering effects for which models can't account.

Diffuse light around cities in remote sensing imagery from Earth orbit was long thought to result from a combination of sensing artifacts and low spatial resolution, (L.Imhoff et al. 1997; Li & Zhou 2017) but it is now recognised as a real signal corresponding to light scattered in the atmosphere. Kocifaj & Bará (2020) showed that certain aerosol properties, such as the particle size number distribution, can be successfully retrieved from orbital radiometry of the angular radiance distribution of the scattered light near cities. Sánchez de Miguel et al. (2020) recently found a strong correlation between the zenith NSB measured on the ground and orbital radiance measurements at both low and high resolution. They suggested that "it should be possible to create maps of regional sky brightness, or even global sky brightness maps" based on radiance measurements from the newest generation of orbital radiometers.

However, there are other problems with existing satellite remote sensing platforms. For example, VIIRS-DNB has no spectral sensitivity shortward of 500 nm, so the instrument is effectively blind to the strong peak in white LED light emissions near 450 nm. This limits what can be reliably inferred concerning short-wavelength light sources within the data set. (Bará, Lima and Zamorano 2019)

B.4.1.6. Night sky brightness measurement units

NSB measurements found in the literature are reported in several different, and sometimes confusing, units. Although one occasionally finds illuminances reported in SI units like microlux, the majority of measurements are given in luminance (surface brightness) terms. As a further complication, measurements can be either radiometric or photometric depending on whether they refer broadly to the entire visible spectrum or instead are weighted by the spectral response of the human eye, respectively.

Some units characterizing NSB in luminance and radiance terms are as follows:

- **Candela per square metre** (cd m^{-2}), a linear, SI unit informally called the "nit". The unit is based on the SI unit of luminous intensity (candela) and the SI unit of area (metre). The CGS equivalent is the **stilb** (1 stilb = 10^{4} nits).
- **Lambert** (L), a linear, non-SI unit defined as π^{-1} cd cm^{-2} (= 3183 cd m^{-2}).
- **S$_{10}$(vis)**, a linear, non-SI unit defined as the surface brightness of 10th *V* magnitudes per square degree.
- **Magnitude per square arcsecond** (mag arcsec^{-2}, or mpsa), a logarithmic, non-SI unit defined such that if an area on the sky contained only exactly one magnitude *N* star in each square arcsecond, the sky brightness would be *N* mag arcsec^{-2}.
- **Night Sky Unit (NSU)**, a linear, non-SI unit representing the average zenith NSB away from the ecliptic assuming quiescent airglow conditions and the absence of skyglow (~0.2 mcd m^{-2} in the astronomical *V* band). It is sometimes called a "Natural Sky Unit" or a "sky".
- **Dark Sky Unit (DSU)**, a linear, non-SI unit (but traceable to SI units) representing a band-averaged spectral radiance in which 1 DSU = 1 W m^{-2} sr^{-1} m^{-1}. (Kolláth et al. 2020)

Of these, the magnitude per square arcsecond is most often encountered, being the native reporting unit of, among other devices, the popular Sky Quality Meter. Transformations between, e.g., magnitude per square arcsecond and the SI candela per square meter have been derived so that astronomical brightnesses in, e.g., *V* magnitudes can be approximately transformed to photometric values. Noting that the relationship between these quantities depends on the spectral power distribution of the source, Bará et al. (2020) derived the transformation equation and calibrated it using zero-point luminances determined from a variety of skyglow spectra.

B.4.2 MONITORING NIGHT SKY BRIGHTNESS

In the present context, "monitoring" of NSB refers to its repeated measurement to look for trends on timescales ranging from minutes to years. Monitors, like sensing devices, fall into two general categories: those that function autonomously, and those whose operation requires human attendants.

Autonomous monitors are sensing devices fitted into weatherproof housings with their own electric power supplies and, optionally, network connections. Some of them save their measurements to on-board memory, while others relay them to another location for storage via a local network or the Internet. At present, autonomous monitors tend to be single-channel devices with few requirements for field calibration. Attempts to construct autonomous all-sky imagers have tended to leverage existing facilities marketed to amateur astronomers as cloud sensors; other, purpose-built devices, such as the ASTMON system (Aceituno et al. 2011), are intended as fully robotic instruments whose data acquisition and reduction are automated and which function as permanent monitors.

Attended monitors may function automatically, but require a human operator for their setup and maintenance. This is usually because the monitoring device is not permanently installed and lacks equipment to make it durable in the natural environment. The operator may also direct details of the data collection protocol (e.g., manually switching slides in a rotating filter wheel). An example of this is the Road Runner system, in which a single-channel sensing device is mounted to the roof of an automobile and collects NSB data continuously while the vehicle is driven. (Rosa Infantes 2011) Another example is the U.S. National Park Service Night Sky Team (NPS NST) imaging method: its camera, situated on an automatic 'go-to' mount, executes an imaging programme automatically, but it must be transported to each measurement site and set up by NPS NST staff. (Duriscoe et al. 2007) There is also considerable human effort required to reduce, analyse, and report the resulting data.

Monitoring entails the concerns of data handling, transmission and storage, as well as reduction and analysis. Some autonomous monitors log NSB data to on-board storage media, which must be periodically retrieved and copied by human attendants. Other systems, such as TESS-W, make use of wireless networking and transmission of measurements to a central storage location via the Internet, leaving them vulnerable to network interruptions; unless the data are separately captured and stored on the local network, they are simply lost. There are also concerns about data reporting formats, although some effort has been put into designing and promoting a protocol for recording and reporting NSB data.

B.4.2.1. Temporal sampling frequency

Other monitoring considerations involve the frequency of data collection, both in the temporal and spatial senses. Given the timescales on which the natural NSB is known to vary, sampling frequency is important so as to fully understand the brightness range of the natural night; the same applies to skyglow, which tends to vary in slower and more predictable ways. The presence of skyglow can 'stabilise' NSB if it significantly exceeds natural sources of light in the night sky in terms of radiance, as in many bigger cities. In such cases, only weak variations exist from night to night once the anthropogenic signal overwhelms the natural signal. This situation makes it such that NSB monitors typically perform best in urban environments, while potentially giving ambiguous information in naturally dark locations.

Various approaches to visualizing NSB time-series data are suggested in the literature. Perhaps the most common method is the NSB densitogram, commonly referred to as a ‘jellyfish plot’. In this representation, the NSB is plotted against the local time, and each pixel is colour-coded to represent the number of observations in a time series that fall into that particular (time, NSB) bin. It is a convenient way to both compress a lengthy time series into a single plot as well as to quickly discern between typical and atypical NSB conditions.

This kind of data visualisation helps inform efforts to characterize night sky quality at a given location and follow its evolution in time. For example, Bará et al. (2019) suggest that a well-sampled jellyfish plot can be used to extract meaningful sky quality metrics. However, the authors conclude:

> *It is clear that no single value of the NSB can be taken as fully representative of the variety of conditions at any given observation site, much like no single air temperature or wind speed could be attributed to it with a claim of completeness. As a matter of fact, the NSB results from the interaction between the light emitted by artificial and natural sources and the changing meteorological conditions, whose combined variability is larger than any of its individual factors.*

There have been some limited efforts made to apply, e.g., Fourier analysis techniques to time-domain measurements of NSB. For example, Puschnig et al. (2019) used fast Fourier transform frequency analysis of nightly mean NSB measurements made using a network of Sky Quality Meters in Austria. From this analysis they concluded that the circalunar periodicity of NSB, of biological importance to a number of nocturnal species, essentially disappears for maintained zenith brightnesses higher than about 16.5 mag arcsec^{-2} (~32 mcd m^{-2}).

Bará et al. (2019) further considered whether the NSB sampling rate on a timescale of minutes influences the average indicators using measurement collected in long (e.g., yearly) time periods, concluding that it does not. Resampling a series of zenith brightnesses obtained with Sky Quality Meters in one-minute readings to sampling intervals of five and ten minutes, they found that the the maximum absolute difference of the full width at half-maximum (FWHM) of the darkest peak in a histogram of time-series NSB values was < 0.0009 mag arcsec^{-2} for a five-minute sampling interval and < 0.0017 mag arcsec^{-2} for a ten-minute sampling interval. These values are well below the measured precision of the SQM (~ 5%).

Recently, Grauer et al. (2019) found evidence for significant variations in the natural NSB background, even near solar minimum, that correlate in time at observing stations separated by thousands of kilometres.

However, the question of which temporal NSB sampling frequencies are sufficient to yield a sense of the typical night sky quality is not well formed because there is yet no general agreement as to what we mean by ‘typical’. If this were clearly and definitively decided, a simple analysis would easily reveal the optimal sampling parameters to yield the desired metric.

B.4.2.2. Spatial sampling frequency

Characterizing the typical NSB across a large geographic area demands consideration of the proper spatial sampling frequency in order to ensure uniform results, especially with respect to acceptable measurement uncertainties. To date there is one published study on this subject by Bará (2017), based on data from Falchi et al. (2016). Bará found that a useful rule of thumb is that one measurement per square kilometre is sufficient to constrain the zenith NSB at any point in a sampled region to a precision of ±0.1 V mag arcsec^{-2} rms. However, the author notes that “exact reconstruction of the zenithal night sky brightness maps from samples taken at the Nyquist rate seems to be considerably more demanding."

B.4.3 EXAMPLES OF TRENDS IN NIGHT SKY BRIGHTNESS NEAR ASTRONOMICAL OBSERVATORIES

A key point to note is that solar activity drives the airglow contribution to natural skyglow to vary during the 11-year solar cycle. Based particularly on data reported by Krisciunas (1997) and Krisciunas et al. (2007), as well as other long-cycle measurements, both Benn and Ellison (2007) and Walker and Schwarz (2007) conclude that the mean *V*-band zenith sky brightness at new moon brightens by ~ 0.4 - 0.5 mag arcsec^{-2} from solar minimum to solar maximum. The airglow variation corresponds directly to the 10.7 cm solar radio flux variation, while the small auroral contribution can lag by some 2 years. (Roach and Gordon 1973) The most recent solar minimum was in 2008, with another ending currently in 2020.

Sky brightness monitoring for professional observatories continues to be reported in the astronomy literature. Neugent and Massey (2010) compared spectrophotometry for Kitt Peak National Observatory over a two-decade interval, comparing samples from 1988, 1999 and 2009, with azimuthal sampling to gauge the impact of urban growth. Sampling at 30° elevation in the azimuth toward the adjacent city of Tucson, Arizona, was ~ 30% brighter than the zenith observation. Corrected for solar activity, the zenith sky brightness in both Johnson-Cousins *B* and *V* bands increased by ~ 10% in the first decade interval from an essentially pristine level fainter than 21.9 mag/sq. arcsec, then remained constant for the second decade sample. The Falchi et al. (2016) analysis found that Kitt Peak has an ALAN contribution of 8.4% in *V*-band, consistent with the 10% measurement. Downtown Tucson is ~ 66 km along the line-of-sight from the summit of Kitt Peak. The population of the Tucson metropolitan area increased ~ 28% over the first decade interval, and another 17% over the second decade. Local governments in the Tucson metropolitan area have strict and somewhat regularly updated outdoor lighting codes for the purpose of protecting southern Arizona observatories and for which local astronomy leadership more actively advocated in the second decade interval. One may conclude that such codes can have an effect in counteracting the effect of population growth in adjacent urban centres on artificial skyglow at observatories.

Walker and Schwarz (2007) reported on a combination of measurement and modeling for Cerro Tololo and Cerro Pachon in north-central Chile. The modeling was based on the population growth of the nearby cities of La Serena/Coquimbo (66 km distant) and Ovalle (59 km) as well as very nearby villages. The corresponding growth of artificial light contribution to zenith *V*-band was modeled to increase from ~ 2% in 1992 to ~ 9% in 2002. With the introduction of their national regulatory framework and active engagement of astronomy leadership with local governments for implementation, the expectation is that current levels of artificial zenith skyglow are ~6% for Cerro Tololo and ~ 2% for Cerro Pachon. The Falchi et al. (2016) determination for Cerro Tololo was ~ 6%. Several sky brightness measurements are reported, based on reduction of scientific imaging data. The scatter is large, and correction would be required for dependences on solar activity and ecliptic latitude (as well as more frequent sampling) to determine whether the improvement at the few percent level has been verified. The two studies discussed here seem to support correlations between skyglow trends at observatories and regional outdoor lighting policies.

Patat (2008) reported six years of monitoring for Cerro Paranal in northern Chile. This intrinsically dark site allowed measurement of trends in sky brightness with solar cycle, and the excitation and variation of atmospheric emission on short timescales and seasonally. The study was based on the sky recorded in images and spectra taken for scientific purposes. The amplitudes of all the natural variations considerably exceed the Falchi et al. (2016) ALAN determination of □0.1% from local mines.

B.5 OVERVIEW OF CIE PUBLICATIONS AND WORKS ON LIGHTING RECOMMENDATIONS AND OBTRUSIVE LIGHT

At the international level, recommendations for various lighting applications are developed and provided by the International Commission on Illumination (CIE). The CIE has a strong technical, scientific and cultural foundation and is an independent non-profit organisation. The CIE is recognised by the CIPM, the International Organisation for Standardisation (ISO) and the IEC as a standardisation body across its scope , publishing international standards for basic research on light and lighting. Many national and regional regulations and norms are based on or refer to CIE publications, these being:Technical Reports, International Standards, Technical Notes, and Position Statements.

This annex gives an overview of CIE publications with outdoor lighting recommendations which are the most relevant in relation to the limitation of adverse effects of ALAN as unnecessary spill light and skyglow. Current CIE work items in the field are mentioned in this annex, too.

The environmental lighting zones comparison table shows the categories from CIE and other organizations of usage and class of protection.

IES-IDA Lighting Zone (IDA 2011)	**IES Environmental Zone** (IES 2014)	**CIE Environmental Lighting Zone** (CIE 2017)	**Description**	**Examples**
LZ0	E1 (Intrinsically Dark Areas)	E0 (Intrinsically Dark)	Parks and similar protected areas where controlling light pollution is a high priority. No artificial light at night is expected in this zone, and its use is often prohibited.	UNESCO Starlight Reserves; IDA International Dark Sky Parks; major astronomical observatories.
LZ1	E1 (Low Ambient Lighting)	E1 (Dark)	Areas where lighting might adversely affect flora and fauna or disturb the character of the area. The vision of human residents and users is adapted to low light levels. Lighting may be used for safety and convenience but it is not necessarily uniform or continuous. After curfew, most lighting should be extinguished or reduced as activity levels decline.	National parks; UK Areas of Outstanding Natural Beauty

LZ2	E2 (Moderate Ambient Lighting)	E2 (Low District Brightness)	Areas of human activity where the vision of human residents and users is adapted to moderate light levels. Lighting may typically be used for safety and convenience but it is not necessarily uniform or continuous. After curfew, lighting may be extinguished or reduced as activity levels decline.	Sparsely inhabited rural areas; villages or relatively dark outer suburban locations
LZ3	E3 (Moderately High Ambient Lighting)	E3 (Medium District Brightness)	Areas of human activity where the vision of human residents and users is adapted to moderately high light levels. Lighting is generally desired for safety, security and/or convenience and it is often uniform and/or continuous. After curfew, lighting may be extinguished or reduced in most areas as activity levels decline.	Small town centres; suburban locations
LZ4	E4 (High Ambient Lighting)	E4 (High District Brightness)	Areas of human activity where the vision of human residents and users is adapted to high light levels. Lighting is generally considered necessary for safety, security and/or convenience and it is mostly uniform and/or continuous. After curfew, lighting may be extinguished or reduced in some areas as activity levels decline.	Town and city centres and other commercial areas with high levels of nighttime activity

Table B.2 Summary of IDA, IES and CIE lighting and environmental zones.

ULR and UFR limits by usage zone are given in the following table.

Light Technical Parameter	Type of installation	Environmental Zone				
		E0	E1	E2	E3	E4
Lighting Environment		Intrinsically dark	Dark	Low district brightness	Medium district brightness	High district brightness
Upward Light Ratio (ULR)		0 %	0 %	2.5 %	5 %	15 %
Upward Flux Ratio (UFR)	Road	N/A	2 %	5 %	8 %	12 %
	Amenity	N/A	N/A	6 %	12 %	35 %
	Sports	N/A	N/A	2 %	6 %	15 %

Table B.3. Maximum values of Upward Light Ratio (ULR) of luminaires and Upward Flux Ratio (UFR) of lighting installations

B.5.1. Overview of selected CIE publications on lighting recommendations

CIE 115:2010 'Lighting of Roads for Motor and Pedestrian Traffic' presents a structured model developed for the selection of the appropriate lighting classes (M, C, or P) for roads for motorised traffic, conflict areas and areas for pedestrians. This model is based on the luminance or illuminance concept, taking into account the different parameters relevant for the given visual tasks. Applying for example time dependent variables like traffic volume or weather conditions, the model offers the possibility to use adaptive lighting systems. This Technical Report highlights the importance of power consumption and environmental aspects in road lighting which with improved performance of luminaires and control gears make it possible to introduce adaptive lighting.

CIE 236:2019 'Lighting for Pedestrians: A Summary of Empirical Data' concerns lighting for roads where pedestrians are the primary road user. Lighting guides recommend certain criteria for design such as target illuminances. The bases of these recommendations are, however, largely unstated or were not published in international magazines and got lost. The aim of this report is therefore to provide a summary of credible, empirical evidence of the effects of changes in lighting on the visual impressions and visual performance of pedestrians, as a basis for future revisions to design standards.

CIE S 015/E:2005 'Lighting of Outdoor Workplaces' specifies requirements for lighting of tasks in most outdoor work places and their associated areas in terms of quantity and quality of illumination. In addition recommendations are given for good lighting practice. All usual visual tasks are considered. The standard gives detailed information on lighting design criteria. Fifteen tables specify the lighting requirements for various areas, tasks and activities.

CIE 083:2019 'Guide for the Lighting of Sports Events for Colour Television and Film Systems, 3rd Edition' provides quality aspects to be fulfilled for colour television and colour film in sports lighting applications including vertical illuminance, uniformity of horizontal illuminance, flicker, colour temperature and colour rendering of the lighting together with lighting requirements on the surrounding spectator areas. New Technical Report on general requirements for sports lighting is being prepared by the Technical Committee CIE TC4-57 'Guide for Sports Lighting'.

CIE 234:2019 ‘A Guide to Urban Lighting Masterplanning’ is providing guidance about the objectives and underlying principles relating to the lighting aspects of the urban nightscape. It deals with the visual, organisational, environmental, and technical elements of these aspects of urban planning. This guide identifies the lighting planning criteria that should be considered when initiatives are being taken in relation to new or existing lighting in urban areas or newly planned conurbations. Guidance is provided to both the functional and expressive aspects of lighting. This publication is intended to support those decision makers who are required to initiate, promote, and manage the night-time image of their city and who require a masterplan to provide a sound basis for long term lighting developments.

CIE 094-1993 ‘Guide for Floodlighting’ aims to provide information on how to use exterior lighting for the decoration of the night-time urban landscape. Of the many applications of lighting in an urban environment, this guide deals with those having a purely aesthetic and decorative purpose. Such lighting can be used every night, as is often the case in the lighting of monuments, public art, commercial buildings, or used only periodically on the occasion of a festival or public gathering. The lighting of natural sites, parks, and gardens is also dealt within this guide. This guide provides tools for the exterior lighting designer and ideas for the town architect. For those who have to make the decisions on expenditure, this guide explains the possibilities of combining outdoor beautification with economical and energy friendly decorative lighting. Update of this publication is currently dealt in the Technical Committee CIE TC4-59 ‘Guide for Lighting Urban Elements’.

B.5.2. Overview of CIE publications on obtrusive light

CIE 001-1980 ‘Guidelines for minimizing urban skyglow near astronomical observatories’ has been prepared jointly with IAU. Purpose of this publication is to stimulate collective action that minimises the degradation of the astronomical environment near cities. The problem and its solutions are stated in a manner that provides a basis for understanding, cooperation, and action by astronomers, lighting engineers and public authorities. The report explains the effect of man-made skyglow, the degree of glow likely to be produced by lighting near an observatory, the level above which skyglow should not be allowed to rise, and how it can be contained by good lighting practice and public ordinances.

CIE 126-1997 ‘Guidelines for minimizing skyglow’ gives general guidance for lighting designers and policy makers on the reduction of the skyglow. The report discusses briefly the theoretical aspects of skyglow and it gives recommendations about maximum permissible values for lighting installations in relation to the needs of astronomical observations - casual sky viewing included. These values must be regarded as limiting values. Lighting designers should do all possible to meet the lowest specifications for the design unless the specific installation requires relaxation. Other uses of the open air areas at night will usually result in less stringent skyglow requirements. Practical implementation of the general guidance is left to National Regulations.

CIE 150:2017 ‘Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations, 2nd Edition’ is intended to help formulate guidelines for assessing the environmental impacts of outdoor lighting and to give recommended limits for relevant lighting parameters to contain the obtrusive effects of outdoor lighting within tolerable levels. As the obtrusive effects of outdoor lighting are best controlled initially by appropriate design, the guidance given is primarily applicable to new installations; however, some advice is also provided on remedial measures which may be taken for existing installations. This guide refers to the potentially adverse effects of outdoor lighting on both natural and man-made environments for people in most aspects of daily life, from residents, sightseers, transport users to environmentalists and astronomers.

CIE 150 recommends maximum permitted values of average surface luminance on building facade L_b and luminance of signage L_s for each of the environmental zones. For building façade luminance, values lower than 0.1 cd m^{-2} are required within zones E0 and E1, 5 cd m^{-2} is limit for the zone E2, 10 cd m^{-2} for E3 and maximum 25 cd m^{-2} is permitted in the zone E4. Allowed sign luminances are higher but their size is usually much smaller. Less than 0.1 cd m^{-2} is required for zone E0, 50 cd m^{-2} for E1, 400 cd m^{-2} for E2, 800 cd m^{-2} for E3 and 1000 cd m^{-2} is the maximum permitted value within the zone E4. These values apply both for pre- and post-curfew except that in Zones 0 and 1 the values shall be zero post curfew. The values for signs do not apply to signs for traffic control purposes.

B.5.3. Current CIE works related to obtrusive light problems

TC 4–58 'Obtrusive Light from Colourful and Dynamic Lighting and its Limitation' aims to provide guidelines for the implementation and usage of colourful and dynamic lighting in outdoor applications aiming at limitation of obtrusive light with respect to astronomical observations, humans and night-time environment. To develop metrics for obtrusive light from colourful and dynamic lighting systems and to propose suitable methods for limitation or prevention of obtrusive light from such systems.

TC 4–61 'Artificial Lighting and its Impact on the Natural Environment' deals with effects of artificial lighting on the natural environment, including impacts on flora and fauna and aims to provide guidance on ways to minimise these effects. This would be accomplished by making recommendations on light levels, spectral distributions, and other specific considerations of a broad range of organisms as well as specific habitats.

TC 4–62 'Adaptive Road Lighting' aims to analyze needs, specify recommendations, develop methodology and promote application of adaptive road lighting based on various conditions and input data from field sensors and interconnected systems with respect and tailored to specific requirements of different user groups and user patterns.

DR 4–53 'Environmental Aspects of Obtrusive Light from Outdoor Lighting Installations' aims to analyze contents of current CIE publications and progress in current Technical Committees dealing with obtrusive light problems and to suggest concerted actions in order to harmonise development of new CIE publications in the field. This reportership also aims to identify potential gaps in research and recommendations and to prepare new work items to fill-in these gaps. As a result of this activity, a new Technical Committee on measurement of obtrusive light is in preparation.

B.5.4. CIE Research Topics with relevance to obtrusive light problems

Light and lighting technologies are essential to modern daily life, touching on its every aspect. These technologies require well-founded knowledge, both fundamental and applied, to ensure that they can be used with confidence in their safety and quality. CIE publications provide that confidence. They are based on the strongest available scientific evidence and follow a rigorous review and ballot process. To develop consensus-based documents fit for the future requires that scientists engage now in building the knowledge base that will support them.

The current priority research topics of the CIE that need immediate attention by the research community in support of developments in lighting technology and application can be found on the CIE website, (http://cie.co.at/research-strategy). Topics that relate to human capabilities and ecological systems, whether fundamental or applied, would all benefit from also addressing diversity and inclusion dimensions. Publications in the peer-reviewed literature on these topics will provide the basis for the next generation of CIE technical reports and standards.

Some of the current research topics that have some relevance to the effects, management and/or measurement of obtrusive light are:

a Recommendations for Healthful Lighting and Non-Visual Effects of Light
b Integrated Glare Metric for Various Lighting Applications
c Adaptive, Intelligent and Dynamic Lighting
d Support for Tailored Lighting Recommendations
e Metrology for Advanced Photometric and Radiometric Devices

B.6. CHALLENGES OF RELATING SAFETY TO NIGHTTIME LIGHTING

Among the causes of light pollution is the popular belief that the use of outdoor light at night necessarily improves road and traffic safety and discourages or prevents the perpetration of both violent and property crimes. While under certain circumstances the careful application of outdoor lighting may improve nighttime safety, this belief is otherwise not grounded in peer-reviewed scientific evidence. Some studies find evidence for a positive correlation in which crime or road collisions decrease after application of lighting treatments, (Bullough, Donnell & Rea 2013; Wanvik 2009a) while others find either a negative correlation, (Morrow & Hutton 2000) none at all, (Marchant 2004; Sullivan & Flannagan 2002; Marchant 2011) or equivocal results. (Wanvik 2009b) A few authors turn the question around and ask whether reducing outdoor lighting in areas prone to either crime or road collisions leads to poorer outcomes, finding little or no such evidence. (Steinbach et al. 2015)

Among the practical barriers to a clear determination of the effect of outdoor lighting on public safety is an inability to model whatever underlying mechanism may exist. Jackett and Frith (2013) note that “no well-established dose-response relationship to lighting parameters exists from which one can deduce benchmark levels of lighting for safety.” One consequence, as Fotios and Gibbons (2018) write, is that “recommendations for the amount of light [for drivers and pedestrians] do not appear to be well-founded in robust empirical evidence, or at least do not tend to reveal the nature of any evidence.”

A separate issue regarding road traffic is whether automotive lighting itself is a source of objectionable light pollution, specifically in relation to its utility as a means of ensuring public safety. There is little research to date on the overall contribution of automobile lights to light pollution, although early work suggests that the impact is non-trivial. (Lyytimäki, Tapio & Assmuth 2012; Bará et al. 2018; Gaston & Holt 2018) Also, researchers are only beginning to contemplate the implications for the need for future installations of roadway lighting as the result of the introduction of autonomous (self-driving) vehicles. (Stone, Santoni de Sio & Vermaas 2019)

APPENDIX C - BIO-ENVIRONMENT

C.1. THE EXCESSIVE AND IMPROPER USE OF COLORFUL AND DYNAMIC LIGHTING

More and more LED flood lighting and landscape functional lighting are used/applied outdoors either in the downtown city center or even in the urban area all over the world in order to attract more tourists or to serve for illumination purposes or for advertisement purposes. The correct usage and proper installation of LED luminaires could bring positive effects and result, however, if they are used in the excessive and improper way, they may possibly bring a new source of light pollution that may affect astronomy observation, ecological system, floras and faunas, wildlife mating and birds migrating.

The problem is becoming more severe when the urban city planners found out they are not able to divide distinctive districts into residential, workings and commercial areas. Hence the excessive usage of LED media facades in the shopping area may cause light intrusion into the resident area through the window, and that may cause sleep disorder, bringing negative emotional impact. Analyzing the satellite data of outdoor night lighting in Korea provided by the National Environmental Information Center of Korea and the Korean Community Health Survey data, it was found that night outdoor lighting was significantly related to depression symptoms and suicidal behaviors of Korean adults. In 2018, CIE released an international standard CIE S026/E:2018 CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light on non-visual effects.

There is strong scientific evidence that light is not only essential for vision but also achieves important biological effects relevant for human health, performance and well-being that are not dependent on visual images. These effects depend on the spectral power distribution, the spatial distribution, the timing and the duration of the light exposure. They also depend on person-specific parameters such as an individual's circadian phase and history of light exposure. Light is the main synchronizer of the human biological clock. It can shift the phase of the circadian rhythm and determines the timing of the sleep/wake cycle. Light can cause acute suppression of the nocturnal release of melatonin. There are also reports that light can increase heart rate, improve alertness, alleviate seasonal and non-seasonal depression, influence thermoregulation, and it can affect the electroencephalogram (EEG) spectrum.

Exposure to light elicits fast responses (i.e. in the range of milliseconds and seconds) in the pupillary reflex or in brain activity recommending proper lighting at the appropriate time. However, because this type of light pollution (due to colorful and dynamic lighting) is still relatively new, there is still a lack of quantitative assessment and scientific research on the influence of that and how to quantify them.

The excessive usage of outdoor lighting in mountains and also more and more lighting shows and parks are created can affect the circadian effects of trees, plant physiology and plant ecosystem, it may have an effect in the form of delaying the growth and defoliation period of these plants. Similar adverse impacts of night lighting can affect animal physiology and activity (disturb feeding, reproduction and orientation. Again, because we are dealing with new source of colorful and dynamic light source, more study and scientific research should be carried out in order to make quantitative assessment of the negative effects. The excessive light emitted from the media screen also can produce glare that may influence the actual safety (disability glare) and the comfort (discomfort glare) of the pedestrians.It can also divert the attention of the drivers, through creation of the glare and distractions, that compromise traffic safety.

In September 2018, A new TC named TC4-58 Obtrusive Light from Colourful and Dynamic Lighting and its Limitation was established to provide guidelines for the implementation and usage of colorful and dynamic lighting in outdoor applications aiming at limitation of obtrusive light with respect to astronomical observations, humans and night-time environment and to develop metrics for obtrusive light from colorful and dynamic lighting systems and to propose suitable methods for limitation or prevention of obtrusive light from such systems.

C.2. SUMMARY OF RESEARCH METHODS AND THE APPLIED ARTIFICIAL LIGHT AT NIGHT REGIME

Table C.1: Summary of the research method of the referred articles and the applied artificial light at night regime. (Reviews are excluded)

Publication	**Method**	**ALAN example**
Baker & Richardson 2006	In situ experiment	Flashlight, illuminating frogs in an area of 1m² at 52-120 lx
Berge et al. 2020	In-situ monitoring	Lights used were normal working lights representative for any ship operating in the dark
Bolton et al. 2017	In-situ monitoring	Array of 4050 lm warm white LED spotlights installed under a wharf in 45°. Less intense than normal harbour illumination.
Brüning et al. 2018a	Laboratory experiment	1 lx, fluorescent bulbs
Brüning et al. 2018b	Field experiment	Experimental streetlight: 13.3 to 16.5 lx at the water surface and 6.8–8.5 lx at 50 cm depth
Cabrera-Cruz et al. 2018; 2019	Modell of Birds of the World geodatabase to obtain geospatial data characterizing the presence, origin and seasonality of 10,423 bird species around the world Data from nine weather surveillance radars in the eastern United States to estimate altitudes at five quantiles of the vertical distribution of birds migrating at night over urban and non-urban areas during five consecutive spring and autumn migration seasons.	Light pollution map: mosaic of six geotiff tiles from the Earth Observation Group (EOG) at NOAA National Geophysical Data Center to create a complete dataset of ALAN for the entire world
Cathey & Campbell 1975	In situ monitoring	Streetlight
Ciach & Fröhlich 2019	In-situ monitoring city of Krakow (PL)	Urban light pollution

Cravens et al. 2018	Field experiment	Experimental lights: 50-W LED, producing 4,200 lm at 5,500 K at 3 m height
Davies et al. 2012	Field experiment	High-pressure sodium streetlights
De Young et al. 2017	Laboratory experiment	Nighttime: 0-5 lx
Dominoni et al. 2013	Laboratory experiment	Daytime: 250-1250 lx Nighttime: 0.3 lx vs 0.0001 lx
Grubisic et al. 2017,2018	Artificial streamside flumes on a sub-alpine stream.	White LED stripes 20 lx
Henn et al. 2014	Field experiment	1482 lx; standard error (SE) = 533] intensely illuminated a 1 × 4 m area and were placed 1 m upstream of the drift net
Knop et al. 2017	Field experiment	experimental streetlight
Kwak et al. 2017;2018	Experimental setup	3 years exposure of 1, 3 and 50 µmol m-2 s-1
LeTallec et al. 2013	Cage experiments	light intensity: 24.2+/-0.9 nmol photons.s−1.m−2 corresponding to a high pressure sodium lamp streetlight located 50 m in front of the cages and positioned 8 m above the ground
Longland 1994	Laboratory foraging arena	0.5 to 0.4 lx dark control, 5.5 lx illuminated patches
Macgregor et al. 2017	In situ monitoring	Streetlight: 2.3 lx (range 0.2–12.1 lx) vs 0.1 lx at the ground
Macgregor et al. 2019	Field experiment	Streetlight HPS vs. cold white LED, full vs. part night lighting
Manfrin et al. 2018	Field experiment	Experimental streetlight
Masetti 2018	In situ monitoring	Streetlight
Matzke et al 1936	In situ monitoring	Streetlight
Meravi et al. 2018	In situ monitoring	Leaves close to streetlight receiving 340–360 lx
Nitschke et al. 2016	Laboratory experiment	8 h light/16 h dark short day cycle vs. extended cycles of 32h, light intensities of 120 to 170 µmol m-2 s-1, using a combination of Philips SON-T Agros,400W, and Philips Master HPI-T Plus, 400 W/645 lamps
Oyang et al. 2017	Field experiment	Experimental streetlight: 8.2 +/- 0.3 SEM lx at ground level beneath the light posts

Palmer et al. 2017	In-situ monitoring	Streetlight: 4.000K LED vs. HPS
Perkin et al. 2014	Artificial indoor flume	416 to 0 lx
Riley et al. 2015	Laboratory experiment	8, 4, 2 and 1 lx vs 0.1 lx
Robert et al. 2015	In situ monitoring	Marine base illumination vs bushland
Rotics et al. 2011	Field enclosure experiments	Approximately 2 lx, similar to light pollution measured about 40 m from an illuminated road junction in the study area. 70-watt yellow metal halide lamps at 3 m height.
Torres et al. 2020	In-situ experiment	Experimental streetlight: 0.2 lx diffused, cool-white LED light
Van Grunsven et al. 2018	Field experiment	Experimental streetlight

C.3 MINORITY VIEWPOINTS

C.3.1 S. BARÁ

S. Bará: Vote against recommendation 5.5.9. Spectral content of the emitted light. According to our present knowledge, a recommendation on spectral power distributions for the preservation of biodiversity and human health should contain a sharp call for the reduction of the absolute blue content until limits strictly compatible with these goals. Balancing environment and health against other needs is a social choice problem outside the scope of this group. Presenting 4000 K outdoor sources as simply less preferable than 3000 K, instead of strongly discouraging their use does not represent the growing consensus of the scientific community.

S. Bará: Vote against recommendation 5.5.12. Urgent research topics. The last paragraph of this recommendation (about interdisciplinarity/multidisciplinarity) fails to recognize the actual richness of research methods developed by several scientific communities, presenting as an example of multidisciplinarity a set of methods strongly biased toward the ones used by the lighting engineering community. I adhere to the text of the last draft before the final version:

> "Studies should use the correct and appropriate light quantities and metrics, and lighting research methods, that are highly interdisciplinary and deserve careful discussion because in many cases are currently not properly used (an example of methods used by the lighting engineering community can be found in LEUKOS Vol 15, 2019, Special issue 2-3, Lighting research methods). Methods used by the light pollution, environment and health research communities are also available in the literature at large. Finding a common language across different scientific, technical and clinical traditions is essential to ensure the results can be communicated between disciplines and implemented."

C.3.2 LJM SCHLANGEN

LJM Schlangen wishes to express his view that in section 5.2 certain formulations within the text of this report are not a good representation of the heterogeneous results in the scientific literature, and can present viewpoints and opinions for which he believes there is no scientific consensus at present. In this respect he would like to note the following:

- Outdoor satellite-assessed outdoor LAN exposure levels are reported to be correlated with urban environmental exposures, but need not be a good proxy for indoor evening or night-time personal exposures (Huss et al., 2019).
- Due to the spectral tuning abilities of modern LED technology, CCT by itself is not a sufficient metric to provide guidance on what light to use at a particular time of day or night (Souman et al., 2018).
- The melanopsin action spectrum (see Fig. 5.2) provides a good model for predicting circadian responses (melatonin suppression and phase shifting) in humans: for instance, the melanopic equivalent daylight (D65) illuminance (melanopic EDI, see CIE S 026:2018 (CIE, 2018)) threshold at which 50% of the full melatonin suppression response is achieved ranges between approximately 10 lx and 300 lx, pending exposure duration and experimental context (Brown, 2020). Moreover, there is a large interindividual variability in sensitivity to light around bedtime: the (photopic) illuminance at which 50% suppression of the hormone melatonin occurs can vary over an order of magnitude across individuals (6 lux in the most sensitive individual, 350 lux in the least sensitive individual) (Phillips et al., 2019). Closing

eyelids (for instance when going to sleep) strongly attenuates light reaching the eyes/retinas (> 99.5% for blue/green light and > 90% for red light) (Ando and Kripke, 1996; Bierman et al., 2011).

- LJMS believes it is not yet possible to draw general conclusions from the scientific literature on the (causal) role of blue light (at night) from indoor and outdoor lighting installations in retinal pathologies.

References/footnotes:

Ando, K., and Kripke, D.F. (1996). Light attenuation by the human eyelid. *Biol. Psychiatry* 39(1), 22-25.

Bierman, A., Figueiro, M.G., and Rea, M.S. (2011). Measuring and predicting eyelid spectral transmittance. *J Biomed Opt* 16(6),067011. doi: 10.1117/1.3593151.

Brown, T.M. (2020). Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions. *Journal of Pineal Research* n/a(n/a), e12655. doi: 10.1111/jpi.12655.

CIE (2018). "CIE S 026:2018 CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light", in: *International Standard.* (http://www.cie.co.at/publications/cie-system-metrology-optical-radiation-iprgc-influenced-responses-light-0 doi: 10.25039/S026.2018).

Huss, A., van Wel, L., Bogaards, L., Vrijkotte, T., Wolf, L., Hoek, G., et al. (2019). Shedding Some Light in the Dark-A Comparison of Personal Measurements with Satellite-Based Estimates of Exposure to Light at Night among Children in the Netherlands. *Environ Health Perspect* 127(6), 67001. doi: 10.1289/EHP3431.

Phillips, A.J.K., Vidafar, P., Burns, A.C., McGlashan, E.M., Anderson, C., Rajaratnam, S.M.W., et al. (2019). High sensitivity and interindividual variability in the response of the human circadian system to evening light. *Proceedings of the National Academy of Sciences*, 201901824. doi: 10.1073/pnas.1901824116.

Souman, J.L., Borra, T., de Goijer, I., Schlangen, L.J.M., Vlaskamp, B.N.S., and Lucassen, M.P. (2018). Spectral Tuning of White Light Allows for Strong Reduction in Melatonin Suppression without Changing Illumination Level or Color Temperature. *Journal of Biological Rhythms* 33(4), 420-431. doi: 10.1177/0748730418784041.

C.3.3 A.K. Jägerbrand

CRediT statement (Contributor Roles Taxonomy): development and design of the recommendations (5.5 Recommendations), analysis of the intellectual content in the recommendations, preparation, creation and presentation of the recommendation, writing the original draft (jointly with Costis Bouroussis), reviewing and editing of the recommendations. I also contributed with editing, reviewing, and commenting on the executive summary.

Authorship contribution according to the ICMJE recommendations: Apart from the text on the recommendations, I did not contribute with conception, design, analysis, or interpretation of data, nor did I draft the text. I have revised the recommendations critically for intellectual content, as well as the executive summary mainly regarding the recommendations. The views, thoughts, and opinions in the other parts of the text belong to individual members of the group and do not, in my opinion, necessarily reflect individuals in the group. Therefore, I do not agree to be accountable for all aspects of the work in this report.

In addition, the input to the recommendations comes from various previous research in the area and is therefore not solely based on the sections prior to the recommendations in this report. This work includes, for example, a thorough systematic review on the ecological impact of LED lighting and recommendations of countermeasures for sensitive species and areas with a focus on the Nordic countries that was published in 2018 by Jägerbrand.

Minority report

This report lacks objective information on the benefits of lighting for human health, despite not specifically stating that this was beyond the scope of the report. However, such benefits are critical for our understanding for the need of outdoor lighting and how we can make the lighting design more environmentally friendly without resulting in negative impacts on human health in terms of, for example, traffic safety, feelings of safety, safety for pedestrians and cyclist, physical exercise, well-being and the ability to live an active and modern life. For future work in this area it is important to use scientifically establish thresholds on the need of lighting for human activities and functions and use this knowledge to minimize and reduce the ecological impact. Moreover, the positive impacts of outdoor lighting on human health must be evaluated and analyzed jointly with the negative impacts to fully view the outdoor lighting from a sustainable and holistic perspective. For example, it is important to properly investigate if the benefits of ALAN overweigh the negative impacts in evaluations of well-being/quality of life, or in terms of established monetary evaluations, for example, VSL, value of a statistical life.

This report did not use scientifically established methods for literature reviews, such as, for example, PRISMA (Preferred reporting items for systematic reviews and meta-analyses). Reviews that do not use established scientific methods will limit the readers ability to assess its strengths and weaknesses. Selective reporting can result in bias towards scientific papers only showing negative impacts on humans and the biota, and may also give the impression of a consensus within the scientific community irrespective of if there is such a consensus or not. My opinion is therefore that the report should inform the readers about the possibility of bias in a transparent way, thus ensuring that readers are not inadvertently misled.

C.3.4 P. SANHUEZA

For human health and the environment, the spectral content of the emitted light must be with no blue emission or with a concrete very restrictive and specific limit. When saying minimum values of blue light, there is no concrete limit being suggested. Some could easily perceive that 15% of blue is correct, especially if we compare with the neutral or cold white sources. Of course, CCT below 2200 K is better than 3000 K or 4000 K. Also 4000 K is better than 5000 K and so on. The evolution of LED technology allows us to illuminate with no blue content, with good CRI, reasonable efficiency and similar cost of the typical 3000 K sources. Based on this, there is no practical justification to limit ourselves in our recommendations when referring to the spectral content of the emitted light.

I suggest:

As a general rule, all areas that must be illuminated should be illuminated with sources having the minimum amount of blue emission possible **or directly with no blue emission. An amount of 1% or less in the range 380 – 500 nm in respect of the human visible spectrum (380 – 780 nm) can be considered as zero emissions from a practical perspective. This SPD restriction must be combined with dimming control.**

Also:

Tunable white luminaries, with variable CCT (e.g. 2200 -3000 K) and variable luminous flux, **can only be used in commercial districts, non residential areas neither parks or other green areas,** only if not affecting the surrounding wild areas outside human settlements.

Appendix D. Satellite Constellations

D.1 Technical details on the simulations

This Appendix provides a somewhat more detailed and technical description of the simulations that support this report.

D.1.1 The constellation model

All large satellite constellation projects rely on large numbers of satellites, each placed on quasi-circular orbits organised in shells. Each shell is defined by its altitude over the Earth surface and by the inclination of its orbits relative to the equator. Inside each shell, the number of orbital planes, the distribution of their ascending nodes, and the phase distribution of spacecraft along each plane are decided aiming to provide the best land coverage, which implies that the projections of the individual satellites on the Earth's surface are distributed in the most uniform way allowed by the laws of orbital mechanics. Under these conditions, all satellite shells exhibit perfect axial symmetry around the rotation axis of the Earth: the average density of satellites projected on the ground is a function only of latitude. Not only that, but, also, the latitudinal density distribution is also symmetric with respect to the equatorial plane (north and south hemispheres of each shell are reflections of each other).

The first decision to be taken in order to perform a simulation is to select the composition of the constellation, in terms of the number of shells and their individual parameters: inclination, altitude, and number of satellites. For the simulations described in this report, we have adopted a reference design composed from the most recent information provided by the two projects that have already started the launch of spacecrafts: Starlink and OneWeb. We will refer to this composition as the SL2+OW2 profile. It is described in Table D.1.

Altitude [km]	**Inclination [deg]**	**Number of planes**	**Number of satellites**
Starlink Generation 2 (based on May 2020 filings)			
328	30	84	7 178
334	40	84	7 178
345	53	84	7 178
360	97	40	2 000
373	75	20	1 998
499	53	40	4 000
604	148	12	144
614	116	18	324
OneWeb Phase 2 (based on May 2020 filing)			
1 200	87.9	36	1 764
1 200	40	32	23 040
1 200	55	32	23 040

Table D.1 Characteristics of the constellations used in this study

The Starlink Generation 2 (SL2) project includes 30 000 satellites in several shells with different altitudes and inclinations, all of them placed in true low Earth orbit (LEO), ranging from 328 to 614 km. OneWeb Phase 2 (OW2), in contrast, has declared its plans to place all its almost 48 000 satellites at a single common altitude of 1200 km above the Earth surface, in shells that differ in the number of spacecraft and orbital inclination.

Independently of the final shape that will be adopted by these two projects, these profiles have been selected for the simulations because they include two different populations in respect of altitude, and the total number of satellites, about 80 000, amounts to a quantity intermediate between the smallest proposals (some 10 000 spacecraft) and the most crowded scenarios (that may amount, globally, to some 100 000 active satellites in orbit).

D.1.2. SIMPLIFICATIONS AND ASSUMPTIONS COMMON TO ALL MODELS

The accurate prediction of the position of a real satellite would require using sophisticated models of orbital dynamics that include a detailed description of the Earth's gravitational potential, the shape of the Earth's surface, atmospheric drag, lunisolar perturbations and even radiation pressure. None of these is needed for our purposes. We aim to statistical predictions on the number and general kinematic characteristics of the satellites observed, which means that all the refinements and details of the complex models for the prediction of individual spacecraft would be averaged out: the same conclusions are reached considering just purely circular orbits in a spherically symmetric potential and without additional perturbations of any kind (atmospheric or gravitational).

This makes conceptually simple the task of following the position of each spacecraft in the reference constellation. The remaining complexity to predict the observation circumstances is of purely geometric character and is fully deterministic. An additional complication arises from the high number of satellites implied, which requires applying smart algorithmic choices to limit computing times.

In this section we are dealing only with optical astronomy, which means that we are interested in the observation of sunlight reflected by the satellites. Given a location on Earth (the symmetry in longitude means that only latitude is relevant), first of all we have to identify, at each shell, which satellites are above the local horizon. But, in general, only a subset of the satellites above horizon will be detectable: those that receive direct sunlight. This leads to one of the main features that have to be included in all models: the Earth's shadow. This trait has been included in the models in different ways: cylindrical approximation or true conical shape, hard (no penumbra) or soft (with penumbra) borders. These different shadow models do not lead to significant differences in the results.

D.1.3. THREE KINDS, TWO APPROACHES

We present results from simulations that, geometrically, belong to one of three kinds.

D.1.3.1. All-sky simulations

A: All-sky bulk satellite count. For a location on Earth (defined by its latitude φ), a day of the year (that specifies the declination δ of the Sun, ie its angular distance to the celestial equator), the local solar time sets the elevation h of the Sun above (or below) the local horizon. For each satellite, we compute the position (azimuth and elevation), and apparent angular velocity, distance, and illumination by the Sun (including phase angle). A photometric model may allow predicting the apparent brightness for detectable spacecraft. Then, satellites matching some criteria (eg, above the horizon, brighter than a limit) are counted.

The geometry of the problem implies some symmetries: the same satellite counts are obtained interchanging the signs of latitude and sun declination, and the same results arise when the Sun has elevation h towards the West (before midnight) or towards the East (after midnight).

Repeating this over a whole night produces the simplest result from this approach: the evolution number of satellites detectable (above the horizon and illuminated) as a function of local time. in successive steps along a whole day and/or night: the U-shaped graphics similar to those shown in Figs. 6.1.1 and 6.1.3.

A useful variation consists in counting only the satellites above a specific elevation over the horizon (for instance 20° or 30°), above which most observations take place. Comparing these counts one gets some rough indication about the distribution of satellites on the sky, as can be seen in the results included in the main report.

Additional refinements may lead to counts of satellites according to intervals of apparent speed or apparent brightness (if available).

D.1.3.2. Pointing-oriented simulations

P: Pointing-oriented simulation. Of course, location (φ), Sun declination (δ; time of the year) and Sun elevation (h) have to be fixed but now, also, a specific pointing direction is also given (in terms, for instance, of azimuth and elevation of the telescope, or through the coordinates linked to the celestial sphere: right ascension and declination). A size for the field of view (FOV) is also given. In principle, only the solid angle (the "piece" or "area" of sky) is relevant, independently of its shape. Most simulations deal with circular FOVs but the results do not depend on this. Then, P-kind simulations proceed registering the satellites that cross the field of view during a certain integration time. Additional parameters such as angular speed, position angle of the trail and apparent brightness may also be recorded.

P-kind simulations allow assessing the impact of satellite constellations on true astronomical observations configured under realistic conditions, if reasonable integration times and FOVs are given as input.

D.1.3.3. Spatially resolved simulations

S: Spatially resolved simulation. This kind of simulation may be understood as the result of performing P-kind tests for a whole grid of positions on the sky under the same local conditions. The density of the grid would determine the spatial resolution of the resulting map that may, or may not, cover the whole local celestial sphere. A whole sequence of S tests along a whole night would provide a series of graphs, or a movie, with the spatially resolved equivalent to the U-shaped graphs derived from the elementary A-kind simulations.

D.1.3.4. Discrete and analytical approaches

All three kinds of simulations may, in principle, be devised through two very different computational approaches. The most immediate idea, and that followed by most researchers up to now, consists in the D, or discrete approach, based on following the path of all individual satellites in their orbits. This may be conceptually simpler and implies a natural series of computation steps very easy to understand. However, the D approach is computationally costly, especially when dealing with huge constellations such as SL2+OW2 (even implementing smart turnarounds). Also, the intrinsically granular, quantum character of the constellations makes it necessary to perform several (normally many) iterations to smooth out the effects caused by the spatial texture of the satellite shells. Although this is true for the tree kinds of simulations (A, P and S), it may be specially relevant for pointing-oriented computations, where small FOVs and/or short integration times usually lead to small number statistics, unless a large number of shots are simulated through the discrete approach.

The symmetries of the problem, as described in Sect. D.1.3.1, suggest that an analytical approach, based on average densities, should be possible. Let us consider one individual satellite in a circular orbit with inclination i. If we take the average over a long period of time, the satellite behaves as a fuzzy cloud that may be described as a density probability function. That function would be scalable to the population of the complete shell just multiplying by the number of satellites that it contains. The A, analytical approach, is based on such density functions as primary inputs, with computation on the orbital position of individual satellites no longer necessary. The density functions may be simple, uniform approximations (Hainaut & Williams 2020), which have shown their suitability in different contexts, but even the simplest geometrical considerations show that the true density functions should show a dependence with latitude, displaying a minimum at the equator and reaching a maximum for latitudes with absolute value equal to the orbital inclination i. The exact functional form of this latitudinal dependency has been worked out by C. Bassa and it is the basis of his results, also included in this report.

D.1.4. RELIABILITY AND SOURCES OF UNCERTAINTY

The readers of this document may be well acquainted with assessment studies on other environmental problems of many kinds. Of course, light pollution counts among the relevant environmental issues, and the effects of satellite large constellations is just one of its most recent dimensions. Often, environmental studies related to climate or ecology are affected by a considerable degree of uncertainty. In contrast, the simulation of the effects of satellite large constellations on the observation of the night sky (whether with professional or with amateur means) allows a direct and very reliable prediction of the effects, due to the following circumstances:

The problem arises from artificial satellites of the Earth, whose behaviour is very well known and is described (to the accuracy required) by simple laws based on classical celestial mechanics.

The effect depends on the laws of optics and on the techniques of observational astronomy, also perfectly known to the degree of accuracy required by the problem.

The relation among cause and effect is direct, strictly linear and does not imply other side effects or external physical systems, making the computation directly deterministic.

Even though the computations implied in the simulations are far from trivial, they are based on techniques that have been developed for many decades and that are used on a daily basis to predict the position and observation circumstances of all artificial satellites of Earth. No new tools are needed, and their accuracy and suitability are tested beyond any doubt.

In the specific case of satellite large constellations, the simulations performed to assess specifically this case have been done by several individuals, using strictly independent computer codes, logical implementations and complementary models, always leading to coincident predictions.

Of course, as in any other problem of scientific modelling of reality, some sources of uncertainty remain. However, it is important to note that they do not affect the conclusions and recommendations stated in this report, and that the margin for improvement is relevant mainly for technical and very specialised purposes. The sources of uncertainty affecting this simulation work are of two kinds, that may be classified as “external” and “internal”.

The main external source of uncertainty is the lack of definition of the constellation projects themselves. The satellite large constellations are still under development, only two of the dozen or so announced projects have launched a part of their spacecraft fleet and, even in those cases, the final architecture of their systems is not fully known, in part due to industrial secrecy and in part to the fact that the details change as the projects develop, in response to the experience gained in the process. As we detail in the main report, we have approached the limitation of the lack of complete information carefully selecting a case of study that is realistic, scalable and that covers all the relevant variables.

Simulating the observation of spacecraft from the ground implies predicting their positions, apparent motions and their apparent brightness. These variables can easily be computed with an accuracy more than sufficient for our goals of statistical assessment.

A somewhat larger degree of uncertainty affects the photometric predictions, but this margin does not affect the conclusions stated in this report. The photometric predictions will be improved in the future as a result of the observational efforts (see the section of this report devoted to this subject) and, also, thanks to the detailed information about the photometric behaviour of the satellites that may be provided by their operators. These improvements will be of interest for specific applications. The magnitude estimates included in some of our simulations are drawn from simple models such as that in Hainaut & Williams (2020).

Finally, several conclusions are related not to the photometric predictions yielded by the simulations, but to the known characteristics of the detectors of light (human eye and astronomical devices), which allows setting up certain limitations and thresholds. Their translation into design features of the spacecraft is a task that would lay on the engineering side.

D.2. TECHNICAL DETAILS OF OBSERVATIONS

D.2.1. INTRODUCTION

There are generally two reasons to observe satellites now and in the future: 1) to characterize the satellites and their behavior, and 2) to assess and understand their impacts on current and future science. While there is a growing awareness in astronomy of the need for these observations, to date they have been few and relatively uncoordinated. The primary finding of this report is that an organized, coordinated effort going forward is needed. Satellite brightness is dynamic and highly dependent on numerous parameters. A single observation and photometric measurement is not sufficient to fully characterize the satellite's brightness. The same satellite may appear significantly brighter or dimmer at a different time or even to a different observer at the same time but different geographic locations.

To first order, a satellite can be considered as a simple uniform sphere with purely diffuse reflection. As the satellite's relative position to the observer changes the satellite's apparent brightness changes, for instance increased range decreases brightness while, reducing the phase angle increases brightness. However, the reality is much more complicated. Satellites are not uniform spheres and have many surfaces with various levels of specularity. In addition to the relatively simple orbital geometry, we must consider satellite structure and attitude. In some cases, minute changes in satellite orientation yield dramatic changes in apparent brightness. Thus, in order to characterize satellite brightness, we must measure the photometric brightness in a variety of geometries and orientations.

D.2.2 OBSERVATION STRATEGIES & TELESCOPES USED FOR OBSERVATIONS

D.2.2.1 Technical Challenges

Making accurate photometric measurements of LEO satellites includes a number of challenges:

- The satellites are particularly observable around the twilights, i.e. after sunset and before sunrise while they are best illuminated. This best time opportunity window for observing the satellites last about 1 to 3 hours. However, depending on the season, those satellites at relatively high orbital height (800 km or higher) can reflect the sunlight even in the middle of the night as reported by the SATCON1 Modelling WG.
- The satellites are fast moving; ~1° per second (variable as a function of the azimuth and elevation of the satellites from the observer's point of view)
- Need precise telescope control including pointing and timing
- Accuracy of the Two-Lines Ephemeris (TLE) data that describes the motion of the satellites along their respective orbits.

These challenges are explained in a bit more detail in the subsequent paragraphs describing the observation strategies.

D.2.2.2 Planning and predicting the pass of satellites above the horizon

Tracking satellites and predicting their positions is a mature science led by the US Space Command which maintains a catalog of objects in orbit and actively tracks over 17,000 objects. Satellite trajectories are published in a format called a Two Line Element set (TLE) which is a standardized set of two 69 character strings which includes the orbital elements and time epoch needed to calculate the position of a satellite at any point in time. Due to uncertainty in the orbital propagation, the predictions from a given TLE become less accurate with increasing time from the original epoch.

```
STARLINK-1260
1 45404C 20019AW  20264.29700302 -.00018979  00000-0 -13000-2 0  2643
2 45404  52.9987  98.7688 0001660  88.4598  38.3140 15.05595957    11
```

```
ONEWEB-0033
1 45142C 20008M   20264.56388889 -.01446998  00000-0 -13590+1 0  2641
2 45142  87.7934  93.5018 0017007 211.6239 131.1901 13.83012493    12
```

Table D.2.1. TLE data for the Starlink-1260 and OneWeb-0033 on 2020-09-20

Line 1		
Field	Column	Information
1	01 – 01	Line number
2	03 – 07	Satellite catalog number
3	08 – 08	Classification (U=Unclassified; C=Classified; S=Secret)
4	10 – 11	International designator (last two digits of the year was launched)
5	12 – 14	International designator (launch number in the given year)
6	15 – 17	International designator (piece of the launch)

7	19 – 20	Epoch year (last two digits of year)
8	21 – 32	Epoch day (day of the year, and fractional portion of the day)
9	34 – 43	First derivative of mean motion
10	45 – 52	Second derivative of mean motion (decimal point)
11	54 – 61	Drag term (Radiation pressure coefficient)- (decimal point)
12	63 – 63	Ephemeris type
13	65 – 68	Element set number. Incremented when a new TLE is generated
14	69 – 69	Checksum
Line 2		
Field	Column	Information
1	01 – 01	Line number
2	03 – 07	Satellite catalog number
3	09 – 16	Inclination, degrees
4	08 – 25	Right Ascension of the Ascending Node (degrees)
5	27 – 33	Eccentricity (decimal point)
6	35 – 42	Argument of Perigee (degrees)
7	44 – 51	Mean anomaly (degrees)
8	53 – 63	Mean Motion (revolutions per day)
9	64 – 68	Revolution number at epoch (revolutions)
10	69 – 69	Checksum

Table D.2.2. Information content in the TLE data

TLEs generated by the US Space Command are publicly available on SpaceTrack.org. Other third party publishers distribute the same TLEs and some from other sources. One source of note is Celestrak.com, a site run by Dr. T.S. Kelso. Celestrack coordinates with satellite operators, such as SpaceX, to utilize first-party telemetry data to compute Supplemental TLEs that differ from those published on SpaceTrack, which are based on observational data.

There are numerous software tools and code libraries available to calculate a satellite ephemeris from a TLE. Some tools make approximations during the orbital propagation calculations and are not as accurate as others. For many satellites these differences are minor and inconsequential, however for fast moving LEO satellites these errors are more prominent. The best software tools utilize the same SGP4 orbital models which are used to originally create the TLE. One such tool is a Python library called Skyfield (Rhodes 2019).

The Starlink satellites move with an apparent angular velocity of up to 2 degrees per second. The exact angular velocity depends on the satellite’s orbit and range. Successfully capturing an image of a Starlink satellite requires accurate ephemeris calculation and precise timing. A timing or clock error of just one second can result in a missed observation.

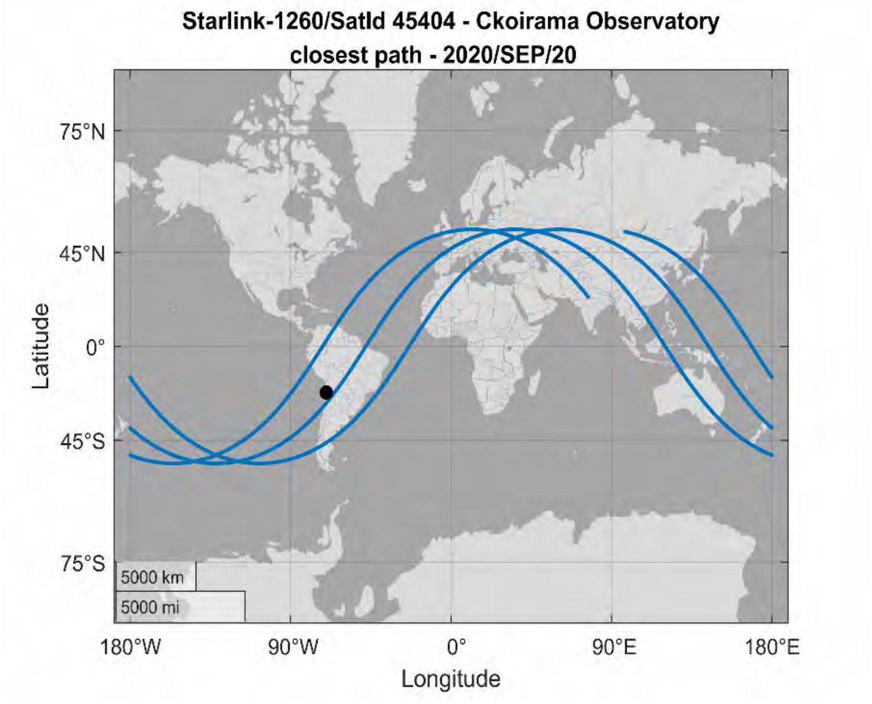

Figure D.2.1. Path of Starlink-1260 across the globe. Data shown is for the date 2020-09-20 between 6 and 12 GMT. The dot, in each figure, shows the location of the Ckoirama Observatory in northern Chile.

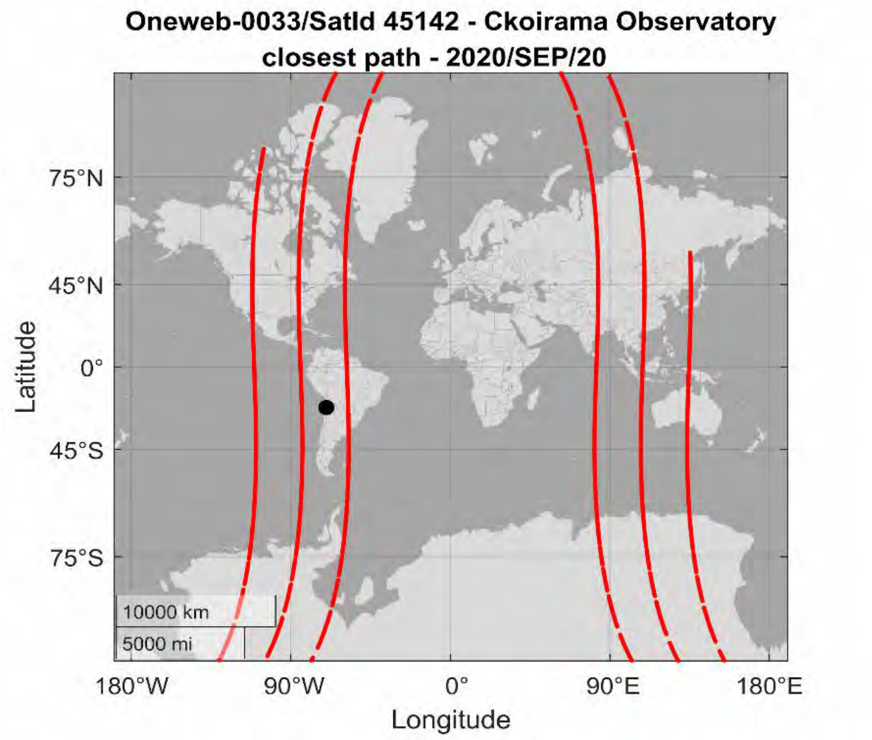

Figure D.2.2. Path of OneWeb-0033 across the globe. Data shown is for the date 2020-09-20 between 6 and 12 GMT. The dot, in each figure, shows the location of the Ckoirama Observatory in northern Chile.

As an illustration of some of the concepts alluded in the previous paragraphs, Figure D.2.1. and Figure D.2.2. show the projected paths of satellites Starlink-1260 (SatId 45404) and Oneweb-0033 (SatId 45142) nearby the Ckoirama Observatory, in northern Chile, owned and operated by the

Universidad de Antofagasta. The paths for the Starlink and OneWeb satellites were computed using as a reference the TLE data shown in Table 3.1. Like this, several other satellites already in orbit around our planet are visible from a given location on the planet at a given time. For observation of any of those satellites, the user will use the TLEs to predict the satellite positions above the horizon and will set to observe them at specific positions along their track. For the satellites used in this example, Figure D.2.3. shows the rate at which the satellites change azimuth and elevation angles, in degrees/second, as well as their corresponding azimuth and elevation as a function of elapsed time, in seconds, since the satellites become visible above the horizon.

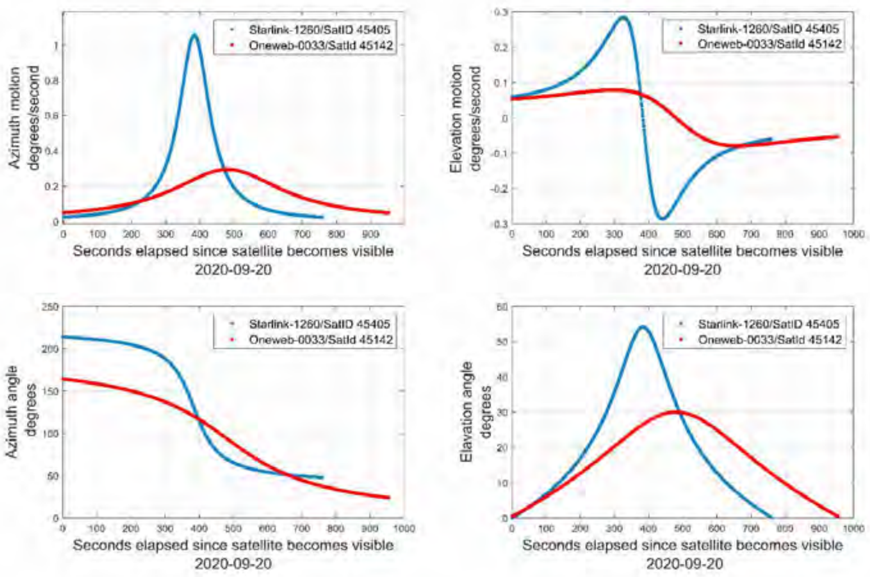

Figure D.2.3. Azimuth, elevation angular motion (top plots) and azimuth and elevation position above the horizon (bottom plots) for satellites Starlink-1260 (550 km orbital height at the time of the observation) and OneWb-0033 (960 km orbital height at the time of the observation), as seen from the location of the Ckoirama Observatory in northern Chile.

Figure D.2.3. helps to illustrate a couple of things: first the relatively faster angular motion, and shorter visibility time, of the Starlink satellite with respect to the OneWeb satellite. This difference, in a good part, is due to the difference in orbital height of the satellites, 550 km and 1200 km, respectively. Satellites at higher orbital height change azimuth and elevation at a somewhat lower rate, which also makes them easier for tracking. In this example the Starlink satellite was above the observer's horizon for about 13 minutes, while the OneWeb satellite was available for about 16 minutes. The effective maximum angular motion rates, azimuth and elevation, as well as visible time above the horizon depends on the relative position of their respective orbital path to the observer, at that date and time of the observation.

D.2.2.3 TLE Accuracy

To what accuracy does the observer need to know the orbital ephemeris (TLE) of the satellites, to be able to detect them in the field of view of an imaging device? The answer to this question depends on how large the field of view of the detector is. The TLE of the satellites get updated a few times per day.

The web site (Kelso n.d.), makes two sets of TLE data available, that we can refer as the Standard and Supplemental TLE sets. The Standard TLE are produced from radar observational data and are the same as those issued by Space Track. On the other hand, the Supplemental are derived from first-party telemetry data provided by cooperating satellite operators. Celestrak publishes Supplemental TLEs for both OneWeb and Starlink satellites.

An analysis of TLE accuracy has been done based on the large amount of LEOsats observations conducted by the POMENIS Telescope team. During the automated processing of images from the POMENIS Observatory the satellite's astrometric position is accurately measured on the images. To determine the TLE accuracy post-observation, the satellite expected on-sky position of the imaged satellite, based on its TLE is compared with the actual position of the satellite in the image. The actual position is obtained based on an astrometry analysis. The TLE information used to estimate the expected on-sky position can be as old as 48 hours. The angular positional error is then estimated, as the difference between the expected and the actual position of the satellite in the image. With this post-observation analysis, we can compare the accuracy of TLEs from different sources. The quoted error measurements encompass all possible errors including errors in the astrometry, observing geographic location, and orbit propagation, not just errors in the TLEs themselves.

D.2.2.3.1 Estimated overall accuracy in the determination of the satellite positions using Standard TLE including other possible sources of errors

For a total of 565 satellite observations done with the POMENIS Telescope, the mean satellite positional error is found to be 0.61 degrees with a standard deviation of 2.4 degrees. This is a large average error with an even larger distribution however does not accurately describe the typical errors. As shown in Figure D.2.4, the typical error is less than 0.2 degrees. The tail of the distribution extends out to 10 degrees with a few outliers of even larger errors resulting in the large mean and standard deviation. Excluding the tail of the distribution (errors greater than 0.2 degrees) yields a mean error of 0.07 degrees with a standard deviation of 0.04 degrees. The predicted position of the

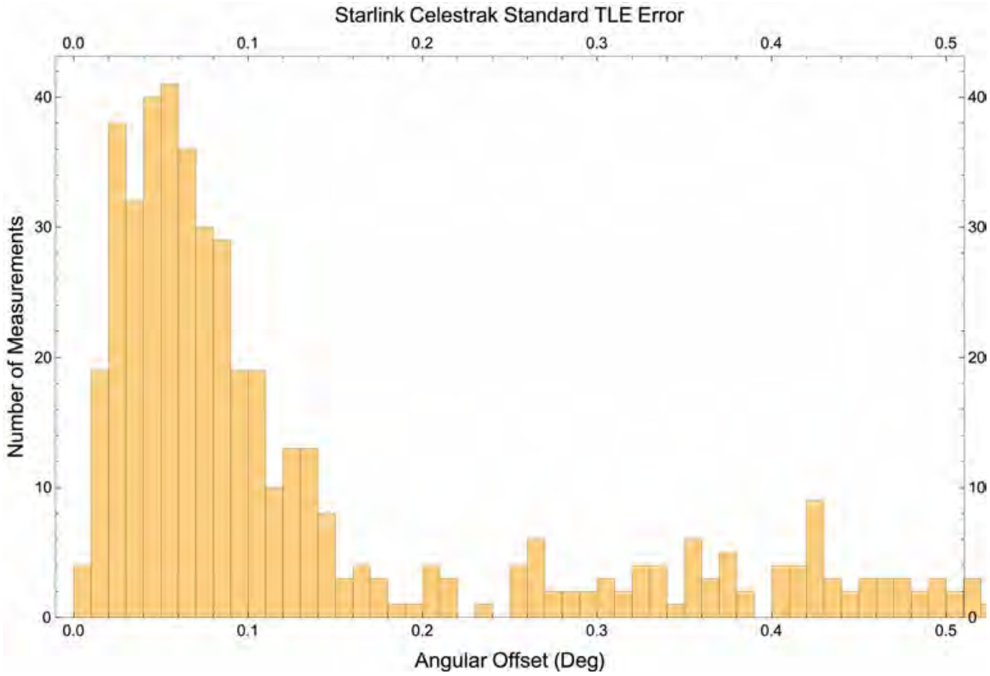

Figure D.2.4. The majority of TLE predictions are less than 0.2 degrees off from the actual satellite position. Large errors are present and extend all the way to 10 degrees with a few outliers even larger.

satellites decreases with TLE age, the time difference from when a TLE is published and the time of observation. There is not a large difference in typical error though but there is an increase in the number of outliers.

D.2.2.3.2 Estimated overall accuracy in the determination of the satellite positions using Supplemental TLE including other possible sources of errors

For a total of 567 satellite observations done with the POMENIS Telescope, the mean satellite positional error is found to be 0.29 degrees with a standard deviation of 0.44 degrees (see Figure D.2.5.) . This is better than the standard issue TLEs, but similarly the typical error is less than 0.2 degrees. Excluding the tail of the distribution (errors greater than 0.2 degrees) yields a mean error of 0.08 degrees with a standard deviation of 0.05 degrees.

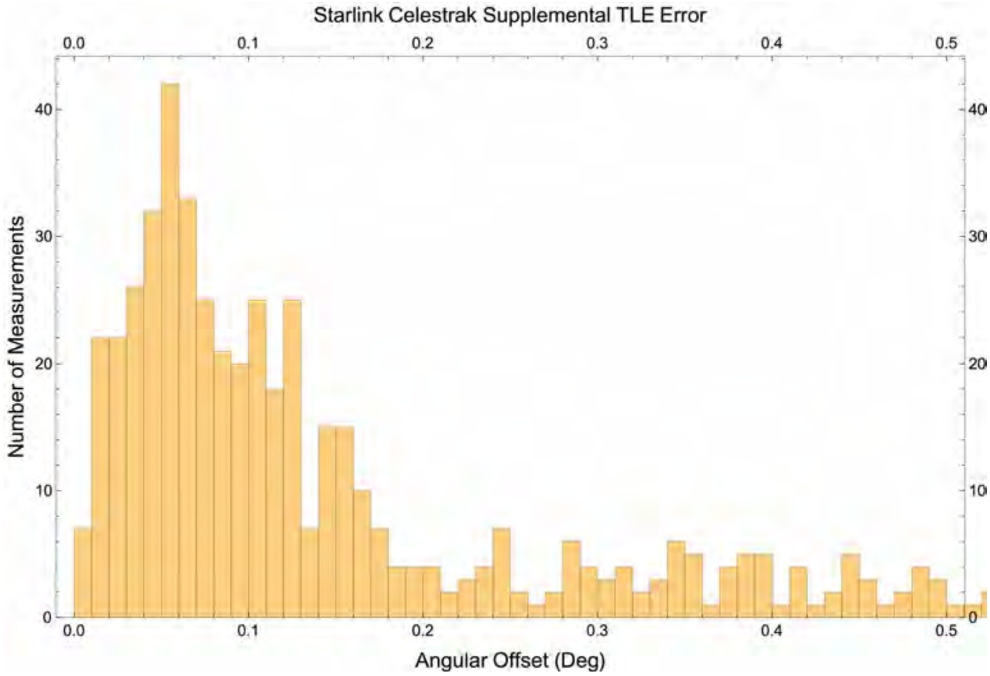

Figure D.2.5. The majority of TLE predictions are less than 0.2 degrees off from the actual satellite position. Large errors are present and extend all the way to >2.5 degrees, the limit of the telescope's FOV and thus ability to measure.

D.2.2.3.3 On the positional errors and TLE accuracy, conclusion

Consequently, including all sources of errors that may affect the accurate determination on the pass of a satellite across the field of view of an imaging telescope/camera setup, the mean positional error is in the order of 5 arcmin. Therefore, for imaging setups with a field-of-view of a few tens of arcminutes in size, this uncertainty can be managed and the likelihood of capturing the satellites at a given time and position in the sky increases. For imaging devices of field of view smaller than 10 arcmin, the advice is to use the best coordinates known for the telescope to be used for the imaging of the satellites, as well as the newest TLE information data when estimating the pass of a satellite of interest to be observed. In general, this advice applies to anyone interested in tracking and imaging satellites. The experience of the Ckoirama Telescope LEOsats observations team, is to use TLE a few days in advance as to plan the best observing window for the satellites of interest. Then, a few hours prior to actual observation, the celestial coordinates of the satellite are recalculated using the latest Celestrak Supplemental TLE data.

It is also important to keep in mind, There is likely to be a larger error in TLE propagation for Starlink/OneWeb satellites in the deployment phase. More reliable, and accurate TLE data is likely found for satellites already at their nominal orbital height and nominal attitude.

Another important consideration is that the satellites angular motion needs to be also taken into account. So far, we have been imaging satellites whose angular motion across the field of view of the imaging device, at the time of the observation, is around 1000 to 2000 arcsecs/sec. Consequently, for a telescope/camera setup with a 15 arcmin field of view (900 arcsecs), the satellite will take less than 1 second of time to cross the imaging field. The advice is to schedule the observing blocks, and plan the exposure times, such that the telescope as already slewed to the right celestial coordinates, is tracking sideral (so stars are round and easier to handle for photometry calibration), and the camera is already taken an exposure at the moment the satellite is expected to cross the field of view. We have learned that accomplishing this process is not easy when using telescopes with automatic schedulers of the observations. For planning the observing block, the time for the telescope to slew into position, and uncertainties in the overhead time taken for cameras to accomplish the readout and store of a previous image, confabulate as to be able to schedule the observing sequence such that the camera will be in exposure mode when the satellite of interest is at the expected position on the sky.

D.2.3 OBSERVING TECHNIQUES

There are two techniques for imaging satellites. One technique is to drive the telescope to track the satellite. If well-tracked this method results in higher sensitivity for detecting the satellite and produces more data as the satellite can be imaged many times during the course of its flyover pass. If a high-speed camera is used it is possible to produce high-resolution time-domain data and record events like flares and glints.

Unfortunately tracking on a fast-moving LEO satellite is difficult and requires a high-performance telescope mount. Additionally, since the telescope is tracking the satellite, the background stars become streaked, as illustrated in Figure D.2.6, making photometry and astrometry difficult to do accurately.

The second option is called ‘Wait and Catch’. The telescope is pointed to where a satellite will be and tracks sidereal. Then the camera is triggered to catch the satellite as it flies through the FOV. This results in a streaked satellite and static background stars, as shown in Figure D.2.7. Ideally the entire satellite streak will be visible within the image frame. This simplifies the photometric analysis and provides unambiguous timing information as we can definitively determine the satellite’s position at the beginning and end of the timed exposure, as well as the effective exposure time. This approach was used to estimate the accuracy of TLE data shown in Figure D.2.4 and Figure D.2.5.

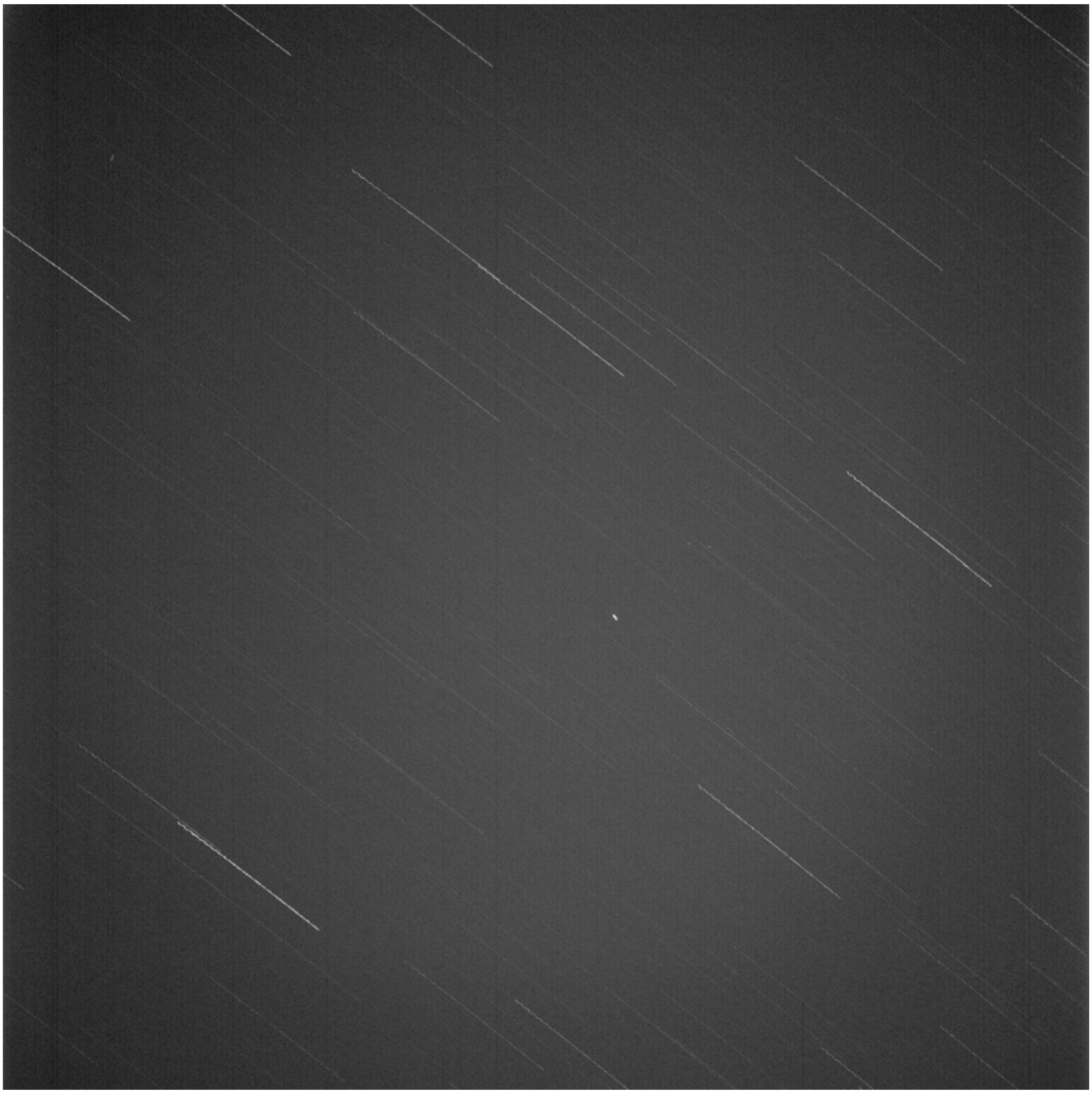

Figure D.2.6. Starlink-1130 being tracked by the POMENIS Observatory on 16 May 2020. The background stars are severely streaked and often overlap making photometry and astrometry difficult to do accurately.

If the entire streak is not in the image, then the summed flux cannot be directly compared to the background stars. It is possible to compute the satellite's angular velocity from the orbital elements and determine the effective exposure time (e.g. Tregloan-Reed et al. 2020a) though this method introduces a source of error which could be significant, for long exposure times.

Fortuitously, a streaked satellite image contains very high-resolution time domain data albeit over a short duration of time. Though this short time is enough to capture some transient events like glints and flares (see Figure D.2.8), and possibly glean information about the satellite's orientation and reflectivity.

Figure D.2.7 Starlink-1212 as imaged by the POMENIS Observatory on 23 May 2020.

Figure D.2.8. Starlink-1408 exhibiting a flare event on 28 August 2020. This flare exceeded 0th magnitude in brightness, enough to saturate the detector pixels with only a 2 ms effective exposure time per pixel. Image by the POMENIS Observatory.

D.2.3.1 Summary of the techniques used for calibration of the images

The observed reflective brightness of a LEOsat is dependent on the satellite range to the observer (r), the solar incidence angle (θ) and observer angle (Φ) of the satellite, due to the diffused reflected flux. The solar phase angle (α) is the angle between the observer and the Sun measured from the satellite vertex point. Therefore, to allow a direct comparison of the reflective brightness between LEOsats requires a correction for θ and Φ, whilst normalized to a standard range. When observed at local zenith (airmass = 1) r is equal to the orbital height (Horb). Therefore, to normalize the magnitude of the satellites to the nominal Horb, 550 km requires scaling the magnitudes by −5 log(r/550).

The observer phase angle is the angle between the observer and the unit normal of the Earth facing surface of the satellite (see Figure 4.4). Tregloan-Reed et al, 2020a, gives an equation to approximate Φ using the straight line distance between the observer and the satellite footprint, nadir (η), LEOsat elevation (e) and Horb:

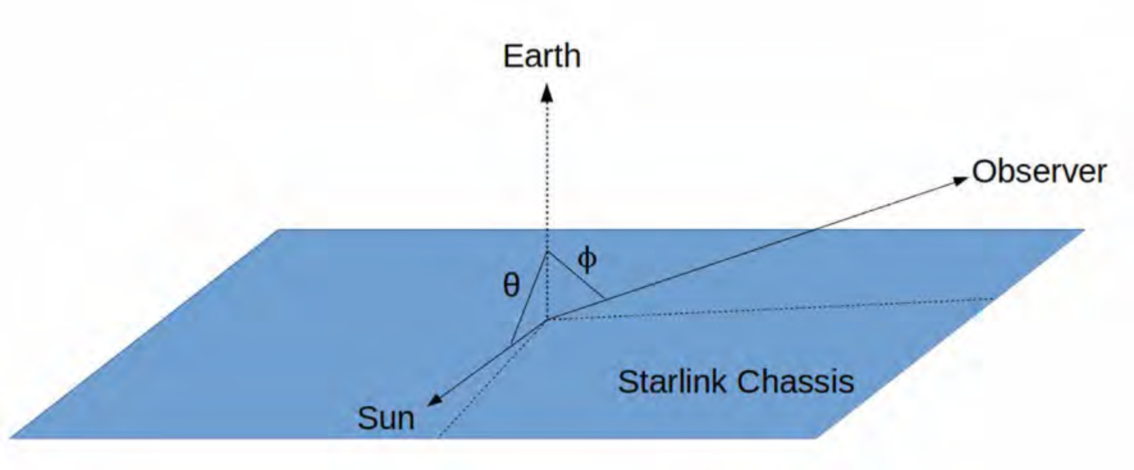

Figure D.2.9. Diagram depicting the Earth facing side of the Starlink chassis. The unit normal points toward Earth at the nadir. The vectors towards the Sun and observer are shown along with θ and φ.

The solar incidence angle (see Figure D.2.10) can be calculated by evaluating the solar elevation angle (αs) at the satellite nadir. As shown in Figure D.2.10 the body of the satellite is parallel to the tangent to the Earth's surface at the nadir. With the Sun at infinity, the two vectors from the Sun to the satellite chassis and from the Sun to the satellite nadir can be approximated as parallel. Therefore, θ + αs = 90 degrees when αs is evaluated at the satellite nadir.

Most of the observed reflective light from a complex body like a Starlink satellite is diffused. This effect can be approximated by using a Bidirectional Reflectance Distribution Function (BRDF). As the majority of LEOsat observations are from a single point along the satellite trajectory path, the BRDF can be estimated using a parameterized BRDF model from Minnaert 1941:

$$R = \left(\frac{cos\theta_{sat}cos\varphi_{sat}}{cos\theta_{ref}cos\varphi_{ref}}\right)^{(k-1)}$$

where θsat and Φsat are the solar incidence and observer angles for the LEOsat, respectively. While θref and Φref are the solar incidence and observer angles for the reference orientation. R is the ratio of the solar phase attenuation and k is the Minnaert exponent and ranges from 0 to 1 with k = 1 representing a perfect lambertian surface. To approximate a dark surface, we set k = 0.5 following Stamnes et al. 1999.

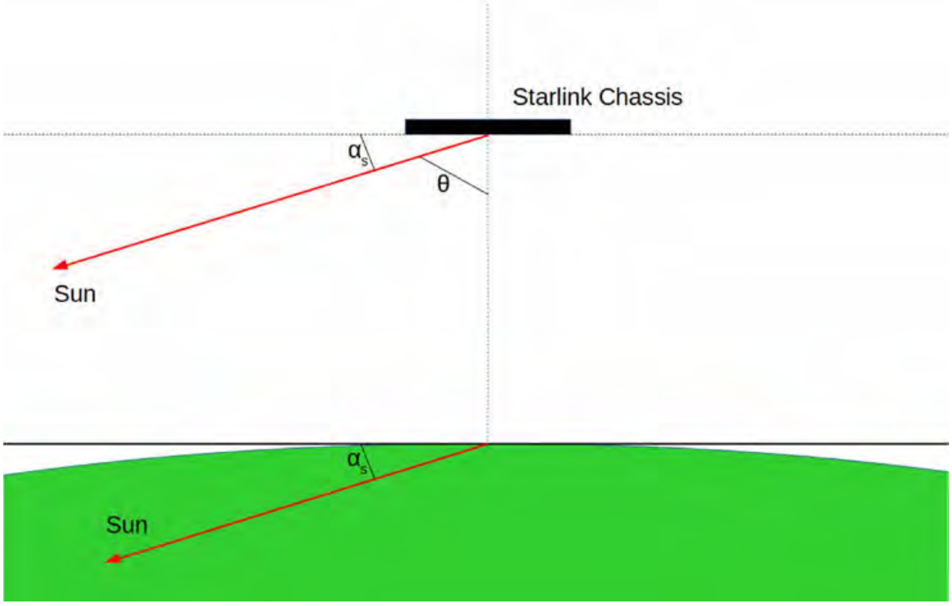

Figure D.2.10. Diagram depicting the Starlink chassis parallel to the tangent at the nadir. The vectors from the Sun to both the satellite chassis and nadir are approximated as being parallel and form the angle αs with the Starlink chassis and the tangent at the nadir, allowing θ + αs = 90°.

The brightness magnitudes in this report list the magnitude as observed, i.e. at the satellites' zenith angle and range from the observer at the moment of the observations, as well as their corresponding magnitudes corrected to the zenith (at their corresponding orbital height). The brightness magnitudes have also been corrected for the solar incidence and observer angles. For direct comparisons these angles need to be calibrated to a universal orientation. As the range is calibrated to local zenith then it serves to calibrate the orientation to the true orientation of the satellites if observed at local zenith. As can be seen in Figure D.2.7 at local zenith the observer is directly below the satellite, and so, the observer angle is zero. For the solar incidence angle, we chose a value of 75°, corresponding to a solar elevation angle of -15° below the horizon (halfway through astronomical twilight). These corrections help normalize the results and be able to compare the relative brightness of satellites of different design or different constellations.

The magnitudes are reported as the total flux collected from these satellites in the imaging system in various well-known astronomical spectral bands. The spectral band information is important since it helps provide information on the effectiveness of the mitigation strategies, intended to reduce the brightness of satellites across the astronomical spectral bands from the visible/optical to the near-infrared.

D.2.4 OBSERVATIONS TO DATE

A. Starlink Satellites in optical/visible, near infrared, spectral bands
   a. Pre-Mitigation v0.9, v1.0 satellites
   b. Darksat

        c. Visorsat
    B. OneWeb satellites in optical/visible spectral bands

D.2.4.1 Observations: Brief Introduction

Currently there are only two active so-called mega-constellations of LEO satellites in orbit. These are Starlink and OneWeb constellations, respectively. As of 20 September 2020, there are 74 OneWeb satellites deployed at an orbital height of about 1000 km, and 684 Starlink satellites deployed at an orbital height of about 550 km (some of the Starlink LEOsats have been deorbited and had reentered into the Earth's atmosphere already). These satellites were launched in the period from 27 February 2019 and 21 March 2020, and 24 May 2019 until 3 September 2020, respectively.

In the particular case of the Starlink constellations of satellites, two of the satellites are implementing design modifications intended to test mitigation strategies to make them fainter when illuminated by the sun rays. These satellites are dubbed Darksat (Starlink-1130; SatId 44932), and Visorsat (Starlink-1436/SatID 45713), respectively. Darksat was launched on 7 January 2020 and Visorsat on the 4 June 2020. Following the test of Visorsat, newer Starlink satellites feature the same sun-visor technology starting with the launch on 7 August 2020.

Very important for the astronomy community, has been to observe as many of the Starlink and OneWeb satellites as to determine their brightness magnitude under various states of the satellite deployment. This report summarizes observation of these satellites mainly from the following astronomical observatories:

- Ckoirama Observatory, using the Chakana Telescope (60 cm aperture), Antofagasta Region/Chile. This is operated by the Astronomy Center (Centro de Astronomía, CITEVA) of the Universidad de Antofagasta.
- Cerro Tololo Inter-American Observatory, Victor M. Blanco Telescope (3.6 m apertura), Coquimbo Region/Chile. Using the DECAM camera. This is operated by the Association of Universities for Research in Astronomy (AURA) and funded by the USA's National Science Foundation.
- European Southern Observatory, VISTA Telescope (4.0 m aperture)
- Steward Observatory, University of Arizona, POMENIS Telescope (180 mm aperture), Arizona.
- Las Cumbres Observatory, 0.4 m telescope at the Haleakala Location (Maui, HI).
- Calar Alto Observatory Spain, using the Zeiss 1.23m telescope. The telescope was operated in remote[1].

The following sections describe the observations of the Starlink and Oneweb satellites. The results of such observation are summarized later in the Results section of this document.

D.2.4.2 Observations from the Ckoirama Observatory, Universidad de Antofagasta, Chakana Telescope

D.2.4.2.1 Starlink Satellites

The Ckoirama observatory is located in the Atacama desert in northern Chile. It is owned and operated by the Centro de Astronomía (CITEVA), Universidad de Antofagasta, Chile. The observatory contains the Chakana 0.6m telescope, equipped with a FLI ProLine 16801 camera. The filter

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[1] Special thanks to Luigi Mancini (Department of Physics, University of Rome 2, Italy), Thomas Henning, Martin Schlecker, Lizxandra Flores, and Jonas Syed (Max Plank Institute for Astronomy, Heidelberg, Germany)

wheel contains three scientific filters: Sloan g’ (475.4 nm), r’ (620.4 nm), and i’ (769.8 nm). The CCD covers a field of view of 32.4 × 32.4 arcmin with a pixel scale of 0.47 arcsec pixel−1 (Char et al. 2016).

In early March 2020 the Chakana 0.6-m telescope was used to observe two Starlink LEO satellites, Starlink-1113 and Starlink-1130 (DarkSat). The observations were performed on three nights, with a different spectral band filter on each night (see Figure D.2.11). The objective of the observations was to measure the reduction in reflective brightness of DarkSat as a function of wavelength.

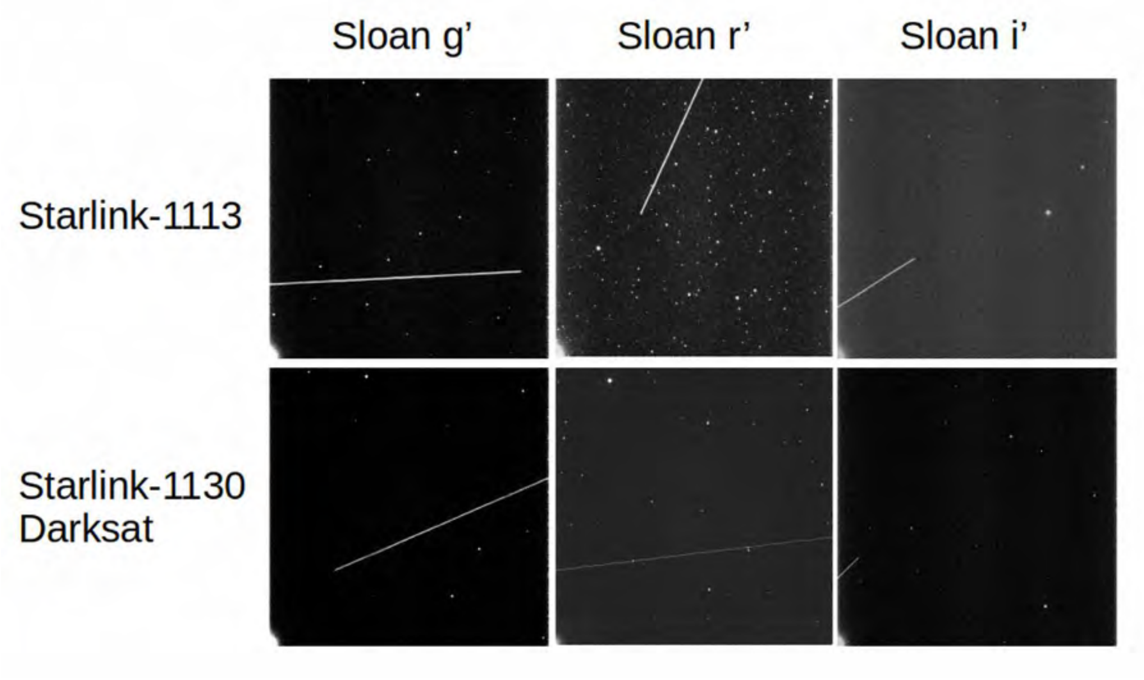

Figure D.2.11. Starlink-1113 and 1130 (DarkSat) observed from Ckoirama, Chile on 5 March 2020 (Sloan r’), 6 March 2020 (Sloan g’) and 7 March 2020 (Sloan I’).

Prior to the Chakana observations a satellite telemetry code was developed to determine the ephemerides of the satellite and of the Sun, using the coordinates of the observatory. The telemetry code downloads the latest TLE data from the celestrak.com website. The code is written in Python and makes use of the Pyorbital package from the PyTroll project.

D.2.4.3 Observations from the European Southern Observatory, VISTA Telescope

D.2.4.3.1 Starlink Satellites

VISTA (Visible and Infrared Survey Telescope for Astronomy, see Sutherland et al. 2015) is a 4m class telescope designed for wide-field surveys in the southern hemisphere. The telescope is situated at ESO’s Cerro Paranal Observatory in Chile. The telescope is equipped with VIRCam (VISTA InfraRed CAMera). VIRCam has a 1.65 degree diameter field of view with a mean pixel scale of 0.339 arcsec pixel−1. The camera has five broad band filters Z, Y, J, H, and Ks along with three narrow band filters. Each ‘footprint’ consists of 16 images from the 16 CCD chips. A standard observation consists of five ‘footprints’, with a slight dither. This allows for objects which fall in the gaps between each chip to be observed at least once. Once the raw data has been collected, they are processed by the calibration pipeline at Cambridge Astronomy Survey Unit (CASU).

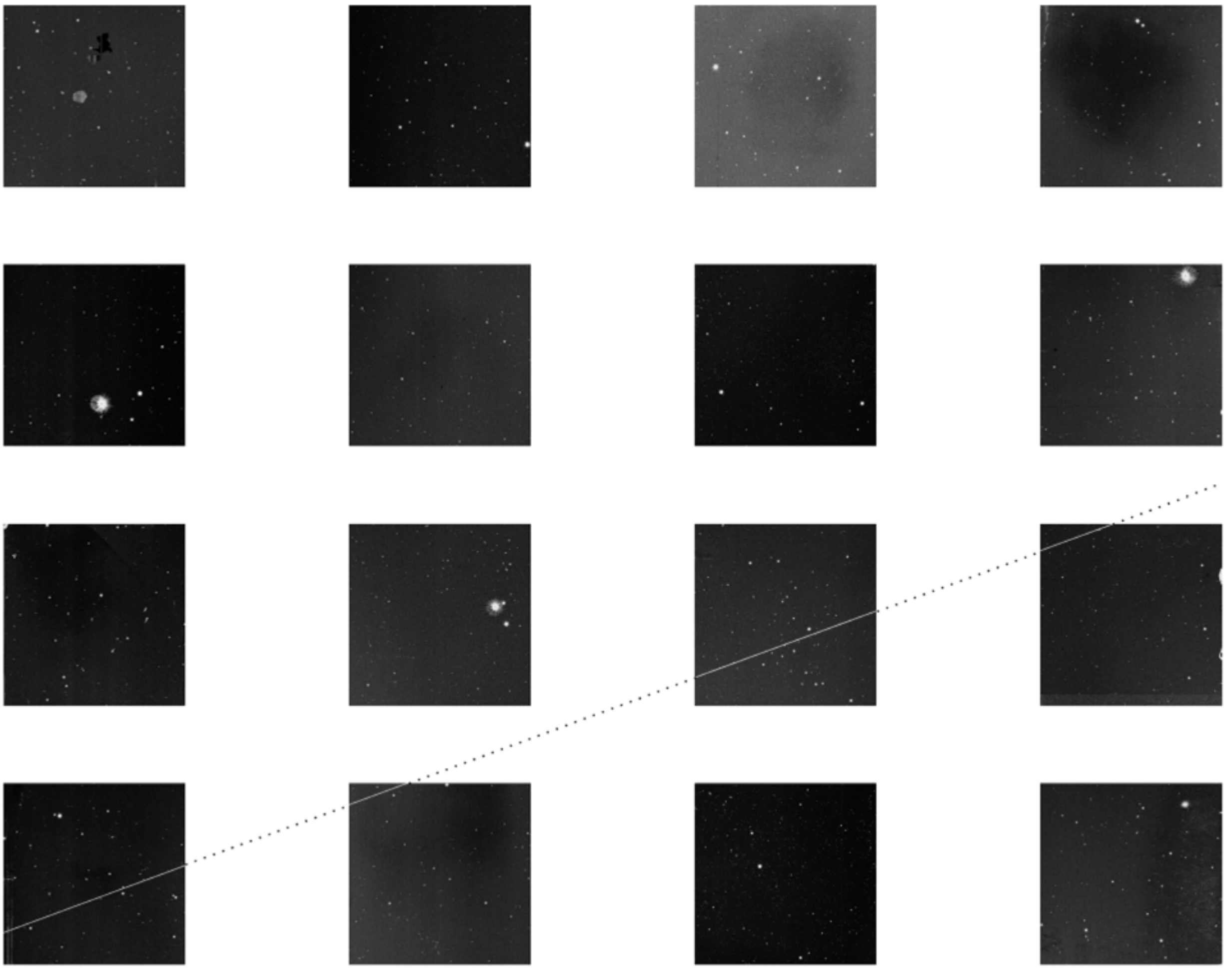

Figure D.2.12 NIR image of DarkSat taken using a J filter with VIRCam on the 4m VISTA telescope, ESO Cerro Paranal Observatory, Chile. The 16 CCD images (11.6 x 11.6 arcmins) are arranged in geometric order and the gaps between the detectors are to scale. With the horizontal and vertical gaps between the detectors corresponding to 10.4 arcmins and 4.9 arcmins, respectively. The dotted line represents the satellite trail falling within the detector gaps.

On the evening (local time) of 5 March 2020, VIRCam was used to observe both Starlink-1113 and Starlink-1130 (DarkSat) (see Figure D.2.12) in the NIR J-band (1250 nm), while on the evening (local time) of 7 March 2020 both LEO satellites were observed in the NIR Ks-band (2150 nm). The observations were in coordination with the observations at the Ckoirama observatory, to obtain magnitude measurements of a pre-mitigation Starlink LEO satellite and DarkSat across a wide wavelength range, from the optical to NIR.

D.2.4.4 Observations from Steward Observatory, POMENIS Telescope

The POMENIS Observatory (Pierce et al. 2018) is a unique system that was developed specifically to perform synoptic surveys of Earth satellites such as Starlink. The 180 mm Takashi astrograph provides a 4.2 x 4.2 degree FOV on a 3056 x 3056 CCD imager with a 7-color filter wheel. The system is fully robotic and automated, allowing for remote operation and intelligent automated observing. The telescope is housed in a unique portable trailer-mounted enclosure allowing for relocation for different projects or observing programs. The POMENIS Observatory is most often located at the summit of Mt Lemmon near Tucson.

The wide FOV and robotic operation of POMENIS make it particularly capable of imaging

fast-moving satellites like Starlink. POMENIS can image dozens of Starlink satellites every clear night, limited only by the overhead between targets, i.e. camera readout and slew time.

Planning Starlink observations with POMENIS utilizes a custom Python software program1. This program relies on the Skyfield code library for ephemeris calculation. The software downloads the newest Starlink TLEs from Celestrak and computes all the observable satellite passes for the forthcoming night. To be observable, a satellite pass must be above the horizon limit (20 deg) and be illuminated by sunlight, i.e. not in shadow. After determining all the observable passes, the software selects a subset of these to observe based on a priority weighting scheme, time availability, and overhead needed between observations. The software outputs an ACP observing plan, a script which the POMENIS telescope uses to autonomously observe the satellites. The software is currently configured to image the satellites at the peak of their flyover pass.

POMENIS has observed Starlink satellites on a limited basis since February 2020 and began nightly observations in late May 2020. The system was offline from June to August 2020 due to wildfire activity. See examples of the images in Figure 5.3 and Figure 5.4. The system also began observing OneWeb satellites in August 2020. The entire system now runs autonomously including planning observations, recording images, and processing data. The current observations are 3-second exposures through the V filter.

Due to the small aperture and sensitivity limit of POMENIS, the current software pipeline struggles to determine brightness measurements for satellites dimmer than about 6th magnitude.

D.2.4.4.1 Starlink Satellites

To date POMENIS has captured hundreds of images of Starlink satellites. Processing the images with the current automated software pipeline yields a total of 567 measurements. The mean brightness of all the measured Starlink satellites is 4.7 magnitude with a standard deviation of 0.85 (see Table 3). When normalized to a nominal orbital height of 550 km and corrected by the solar incidence and sat-observer angles, the mean brightness of all the satellites observed is 4.0 mag in V spectral band as shown in Table 2.3. Figure D.2.15 and Figure D.2.16 show the histograms for the satellites magnitude distribution as observed, and once the magnitudes have been normalized to Horb=550 km and corrected by the solar illumination and view perspective of the observer, respectively. In particular the broader peak in the distribution shown in Figure D.2.15 is results of the various elements contributing to the brightness of the satellite at the moment of observations, such as their range, and relative orientations respect to the sun and view angle of the observer.

	As Observed			**Normalized**		
Satellites	**Mean**	**Standard Deviation**	**Range**	**Mean**	**Standard Deviation**	**Range**
All Starlink	4.7	0.85	0.0 - 7.1	4.0	0.84	-0.4 - 6.9
Starlink Below 550 km	4.5	1.3	1.5 - 7.1	4.2	1.4	0.6 - 6.9
Starlink Above 550 km	4.7	0.75	0.0 - 6.8	3.9	0.69	-0.4 - 6.2

Table 2.3. Mean brightness magnitude of Starlink satellites as surveyed by the POMENIS Observatory in Johnson V spectral Band.

Figure D.2.13. Starlink-1226 with the Orion Nebula as imaged by the POMENIS Observatory on 7 September 2020.

Figure D.2.14. Starlink-1021 (top) and Starlink-1049 (bottom) as imaged by the POMENIS Observatory on 20 Feb 2020. Although these two satellites are at the same range and flying side-by-side, 1049 is significantly darker. This is likely due to differences in satellite orientation.

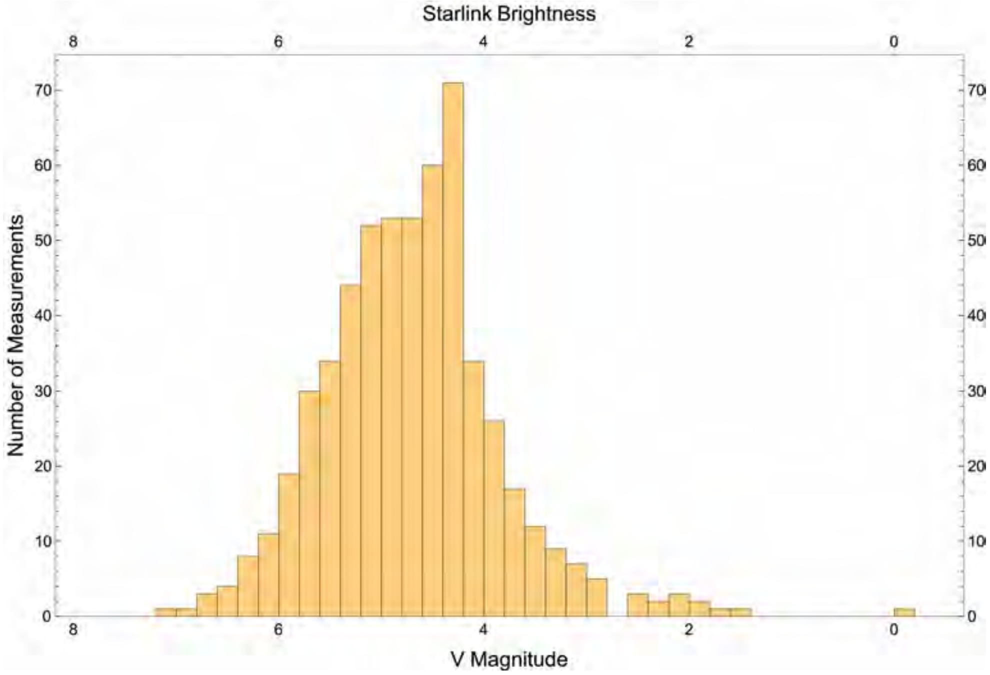

Figure D.2.15. A histogram of 567 Johnson V magnitude measurements of Starlink satellites imaged by the POMENIS Observatory from May to September 2020. The mean of all 567 measurements is 4.7 with a standard deviation of 0.85. This broad distribution of values demonstrates the varied brightness of Starlink satellites which depends on numerous geometric factors. Note there are additional observations of Starlink satellites that are fainter than 6th magnitude for which the SNR is too low to be processed by the current software pipeline.

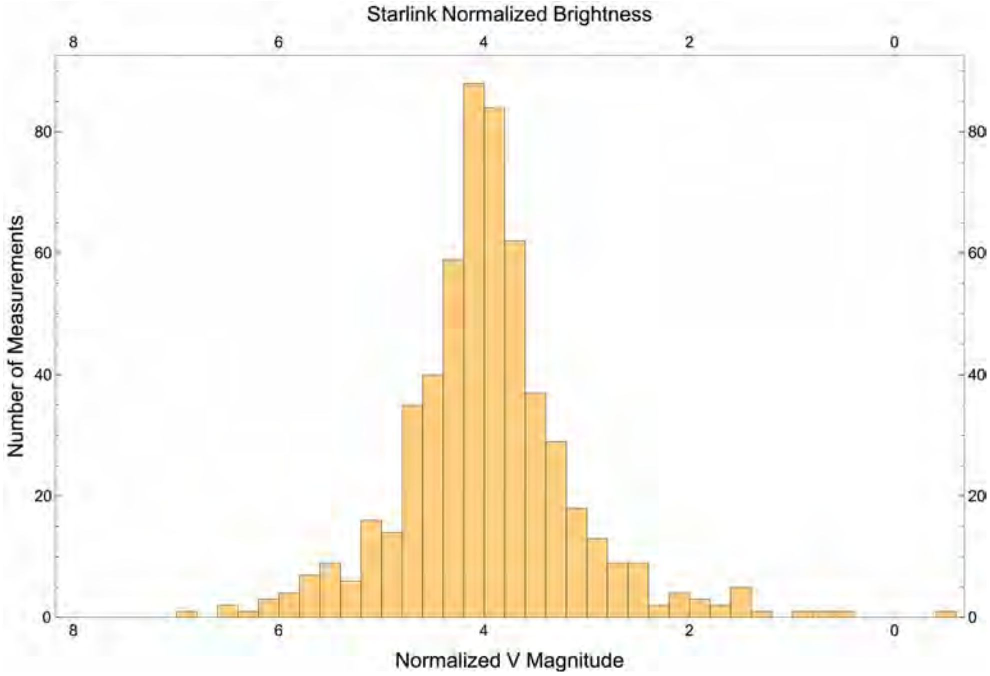

Figure D.2.16. Satellites magnitudes in Johnson V spectral band, normalized to an orbital height of 550 km and calibrated by the effects of different solar illumination angle (solar incidence) and satellite view angle from the perspective of the observer. The histogram shows the distribution of 567 V magnitude measurements of Starlink satellites imaged by the POMENIS Observatory from May to September 2020. The mean of all 567 normalized and calibrated measurements is 4.0 with a standard deviation of 0.84.

D.2.4.4.1.1 Visorsat

The POMENIS Observatory has made 5 measurements of Visorsat, see Table D.2.4. For all these images Visorsat was too faint to be detected by the automated software pipeline. These images were instead processed with the same pipeline but with a manually defined photometric aperture for the satellite streak.

Time (UTC)	**V Magnitude**	**Range (km)**	**Orbit (km)**
2020-08-27 02:42:25	6.8±0.81	1005	552
2020-09-15 11:29:57	7.7±1.21	1057	551
2020-09-16 11:24:26	7.2±0.77	813	551
2020-09-17 11:18:54	6.4±0.61	629	551
2020-09-17 11:20:28	6.1±0.23	923	551

Table D.2.4. Brightness magnitude of Visorsat satellites in Johnson V spectral band, imaged by the POMENIS telescope.

D.2.4.4.1.2 Other Visored Satellites

Beginning with the L9 launch on 7 August 2020, SpaceX is including the visor technology tested on Visorsat on all Starlink satellites. The POMENIS Observatory has captured many images of these satellites. However, in all the images the satellites are too faint to be measured by the current software pipeline. This indicates these satellites are typically fainter than about 6th magnitude, approximately the threshold where the software struggles to detect the satellite streak.

D.2.4.4.2 OneWeb Satellites

The POMENIS Observatory began observing the OneWeb satellites in August 2020 and has successfully captured over 100 images. However, in the majority of the images the satellites are too faint to be measured by the current software pipeline. This indicates the OneWeb satellites are typically fainter than about 6th magnitude, approximately the threshold where the software struggles to detect the satellite streak.

This does not mean that the OneWeb satellites are always faint. Table D.2.5. lists 8 successful measurements showing the OneWeb satellites are occasionally brighter.

Satellite	Time (UTC)	V Magnitude	Range (km)	Orbit (km)
ONEWEB-0061	2020-08-15 03:34:31	5.2±0.17	668	583
ONEWEB-0046	2020-08-15 03:36:48	5.6±0.12	649	584
ONEWEB-0019	2020-08-15 03:38:53	3.3±0.07	622	582
ONEWEB-0080	2020-08-15 03:42:32	4.1±0.08	601	583
ONEWEB-0094	2020-08-20 03:20:56	4.6±0.12	585	585
ONEWEB-0054	2020-08-22 03:50:14	4.4±0.07	771	741
ONEWEB-0028	2020-08-22 03:52:53	5.7±0.17	706	688

ONEWEB-0028	2020-09-06 02:41:43	6.5±0.20	819	818

Table D.2.5. Brightness magnitude of OneWeb satellites in Johnson V spectral band, imaged by the POMENIS telescope.

D.2.4.5 Observations from Cerro Tololo Inter-American Observatory, Victor Blanco 4-meter Telescope

D.2.4.5.1 Starlink Satellites

The Dark Energy Camera (DECam) is a 60-CCD wide-field visible imager on the Víctor M. Blanco 4-meter Telescope at Cerro Tololo Interamerican Observatory in Chile. It is one of two main precursor instruments used for verifying and validating the LSST Science Pipelines by Rubin Observatory Data Management. Tyson et al. 2020, obtained about 30 minutes of observations of Director's Discretionary Time as part of the DECam Local Volume Exploration (DELVE) Survey on the night of 5–6 March 2020, about 1 hour after sunset. The five 120-second exposures in g-band were timed to image five Starlink satellites transit near zenith. All five Starlinks were launched in January 2020, and one of them is DarkSat (Starlink-1130). Using the LSST Science Pipelines, Tyson et al. 2020 reduced the data and measured airmass-corrected (zenith-extrapolated) stationary satellite magnitudes.

They also report solar phase angle, stellar PSF, background surface brightness, average satellite trail profile FWHM, raw trail surface brightness, satellite angular speeds, exposure-time-corrected trail surface brightness (with satellite velocities computed assuming a 550 km circular orbit), stationary trail magnitude (before and after airmass correction), derived distance between the telescope and the satellite, and derived approximate size of the satellite. For more details on the analysis, please see] Section 6 in Tyson et al. 2020.

The main conclusion from this analysis is that DarkSat is 6.1 g mag AB at zenith while its four siblings are all around 5.1 g mag AB at zenith. (See Figure D.2.17) In addition, the satellite trail is wider than the stellar PSF, because satellites at 550 km altitude are out of focus. The trail width is also a function of the telescope's primary mirror size, so the same Starlink observed with Rubin Observatory's 8.4-m mirror would result in trails that are even wider.

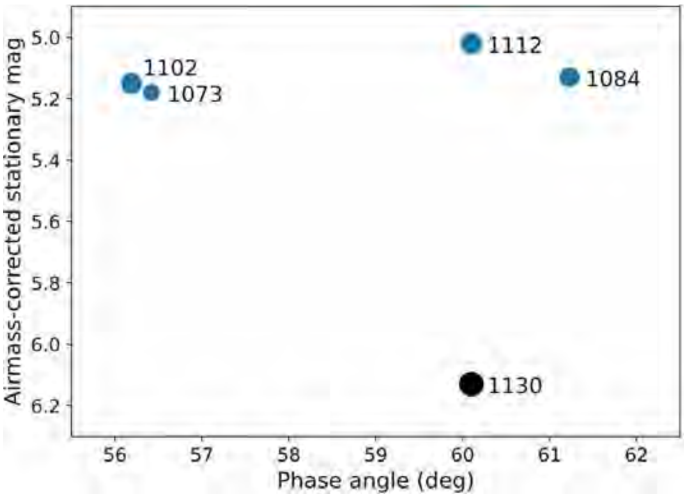

Figure D.2.17. Apparent stationary g band magnitude of five recent Starlink satellites in the "on station" main operational phase extrapolated to zenith as a function of solar phase angle. DarkSat (black) was measured to be 1 mag fainter than its four bright siblings launched in January 2020 (blue), which are in turn about 0.5 mag fainter than the older v0.9 Starlinks. Measurement errors are the symbol sizes (Tyson et al. 2020).

D.2.4.6 Observations from Las Cumbres Observatory (LCO), 0.4m-04 Telescope at the Haleakala Site

D.2.4.6.1 Starlink, VisorSat Satellite

Of great importance has been to determine the brightness magnitude of the Visorsat (Starlink-1436/SatID 45713), since this includes the latest mitigation strategy from the SpaceX/Starlink consortium to make the Starlink satellites fainter. On 14 September 2020 at 14:47:24.437s UT an image of Visorsat (see Figure D.2.18), in SDSS g' spectral band, was performed using the 0m4-04 telescope at the LCOGT node, At Haleakala (HI), of Las Cumbres Observatory (Brown et al. 2013) (see Figure D.2.19).

The observations, conducted under proposal DDT2020B-003, used a 0.4m telescope consisting of an RCS tube and 3-element optics, mounted in LCO equatorial C-ring mounting. The optics consists of a primary, secondary and Corrector plate (Meade) with LCO focus mechanism driving corrector plate/secondary. The camera used for the observation is a SBIG STL-6303 with a 29.2x19.5 arcmin field of view and pixel size of 0.571 arcsecs/pixel.

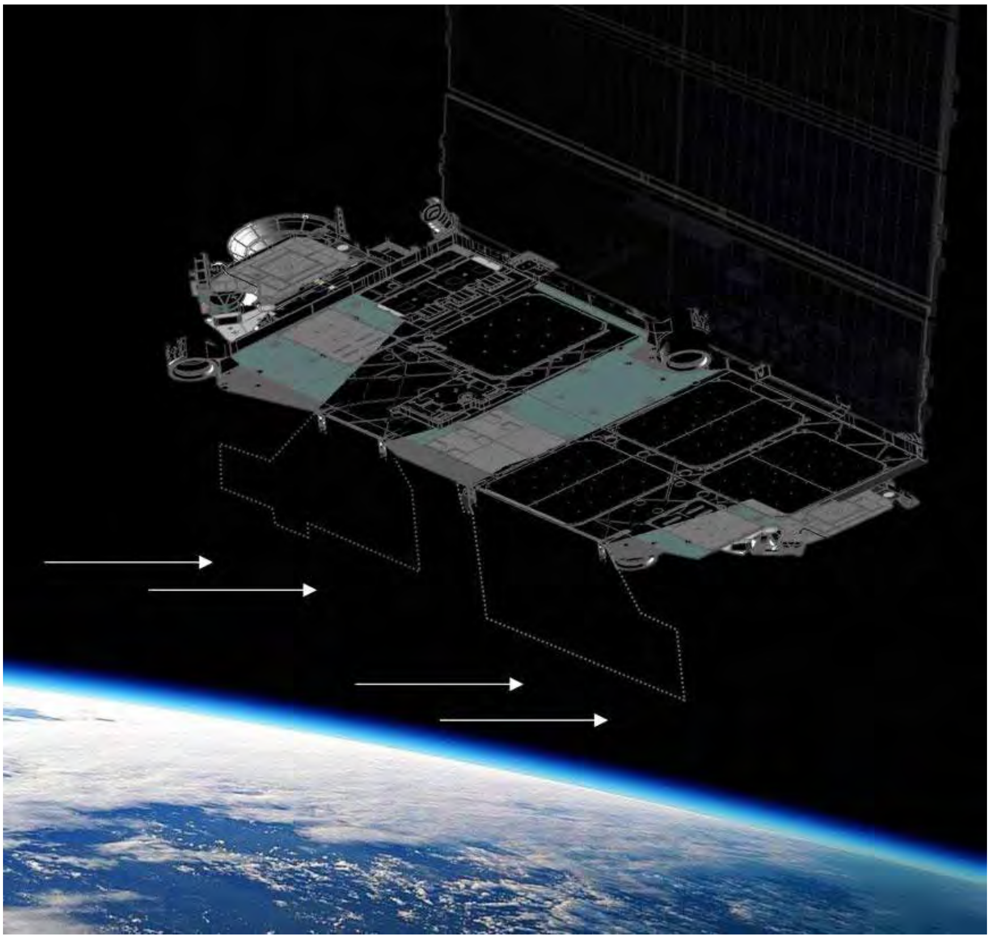

Figure D.2.18. Artist depiction of VisorSat, Starlink satellite (c) SpaceX.

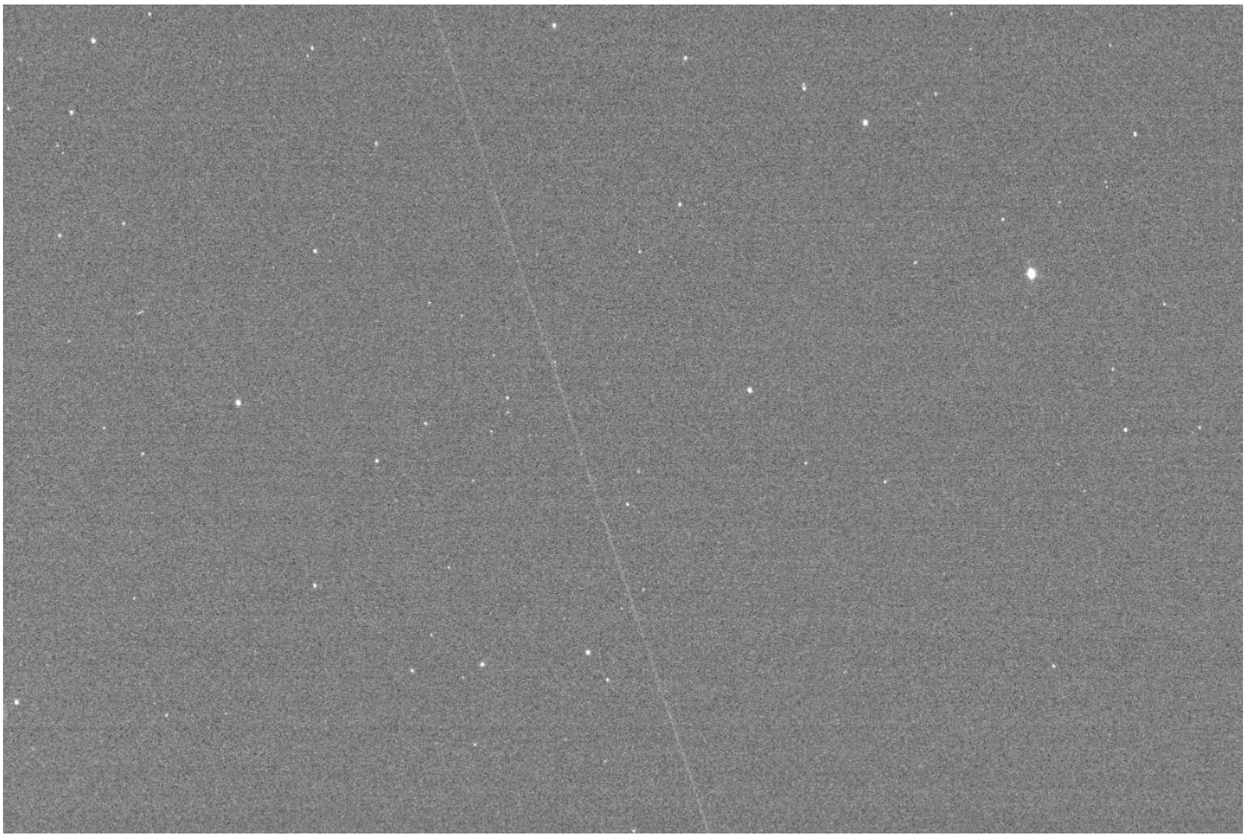

Figure D.2.19. Starlink-1436 (Visorsat, SatID 45713) as imaged by the 0m4-04 telescope at the LCOGT node, At Haleakala (HI), of Las Cumbres Observatory on 14 September 2020.

D.2.4.7 Observations from Calar Alto Observatory Spain, 1.23m Telescope

D.2.4.7.1 Starlink Satellites

During September and October the Zeiss 1.23m telescope based at the Calar Alto observatory (Barrado et al. 2011), Spain has been performing observations of Visorsat and other sibling Starlink satellites. To date, the observations have captured Visorsat and Starlink-1405. The observing procedure used is the same employed at the Ckoirama observatory.

The Zeiss telescope uses a CCD DLR-MKIII camera with a 21.4 by 21.4 arcmin FoV, with a pixel size of 0.314 arcsec pixel-1. The observations used a Johnson V filter. Future observations are planned to use the Johnson U, R, and I filters. This will provide the first U-band magnitude measurements of LEOsats. Figure D.2.20 shows Starlink-1405 observed in the morning twilight on 14 September 2020 with a 14 second exposure. Figure D.2.21 shows an image of Starlink-1436 (Visorsat). The image also shows a serendipitous detection of Starlink-1348 (upper-middle) that at the time of the observation was at 386 km orbital height. Current information on this satellite, shows fluctuations in the orbital height around 350 km, obtained from a website cured by Dr. Jonathan MacDowell (McDowell n.d.). The observation took place in the morning twilight on 20 September 2020 using a 10 second exposure.

Figure D.2.20. Starlink-1405 as imaged by the Zeiss 1.23m telescope at Calar Alto, Spain on 14 September 2020.

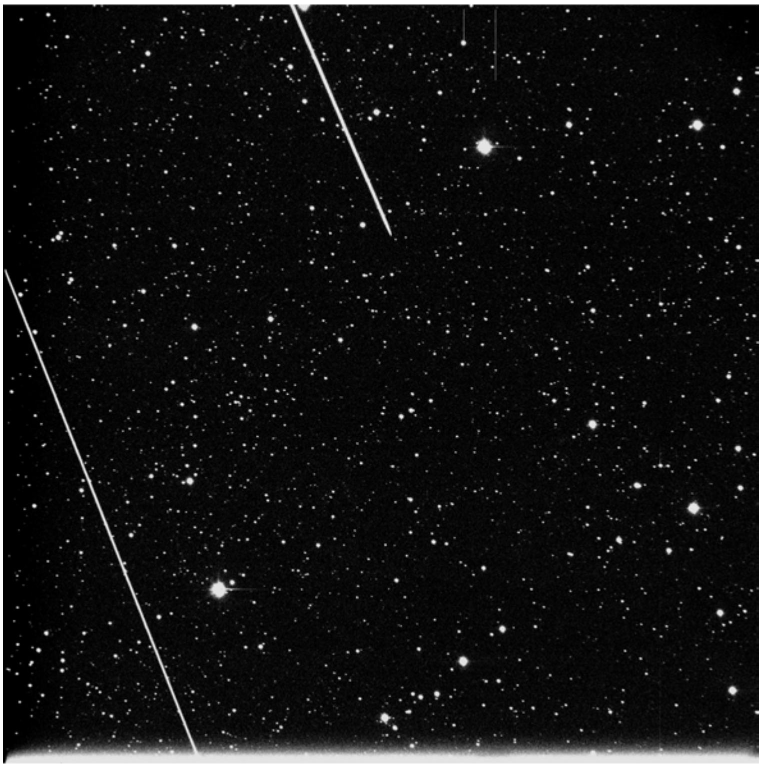

Figure 5.11. Starlink-1436 (Visorsat) as imaged by the Zeiss 1.23m telescope at Calar Alto, Spain on 20 September 2020. Visorsat (at 555 km orbital height) is the trail seen in the bottom left. A second trail from in the upper middle corresponds to Starlink-1348 (at 386 km orbital height).

D.2.5 DATA ANALYSIS AND RESULTS

The spectral bands and their width, for the telescopes/camera setups used to image the satellites whose magnitudes are included in this report, are listed in Table D.2.6.

The observations conducted by the various teams, using the various facilities listed in the previous section, are summarized in Table 6.2. These values are calibrated to local zenith and the orientation set out in the Observing Techniques section. Results from published work are numbered [1] Tregloan-Reed et al. (2020a); [2] Tregloan-Reed et al. (2020b); [3] Tyson et al. (2020). We also include yet unpublished observations of Visorsat from the facilities described in the observation section.

VERY IMPORTANT: The results in Table 6.2, include the magnitude of the satellites as observed using filters at different astronomical spectral bands. Each spectral band has its own central wavelength and bandpass (as shown in Table 6.1). Consequently, care needs to be taken when establishing comparisons of the magnitude of the satellites reported.

D.2.5.1 Starlink Satellites

The magnitudes, as observed and the calibrated magnitudes (normalized to an orbital height of 550 km, and by the solar incidence and satellite-observer view angle at the time of the observations) are included in Table D.2.7.

Observatory Telescope	Spectral Band	Central Wavelength micrometers	Bandpass width micrometers
Ckoirama Obs	SDSS g’	0.477	0.149
Ckoirama Obs	SDSS r’	0.623	0.140
Ckoirama Obs	SDSS i’	0.763	0.140
ESO/VISTA	NIR J	1.254	0.172
ESO/VISTA	NIR Ks	2.149	0.309
CTIO/BLANCO/DECAM	g band	0.483	0.156
POMENIS telescope	Astrodon Johnson V band	0.549	0.168
Calar Alto Obs.	Johnson V band	0.549	0.168
Las Cumbres Obs	SDSS g’	0.477	0.149

Table D.2.6. Characteristics of the spectral bands (filters) used in the imaging of satellites included in this report.

There are empirical corrections in the technical literature (e.g. Jordi et al. 2006) to convert magnitudes between known astronomical filters. An approximation that can be used for reflected light to convert from Johnson V to the SDSS g’ spectral band (bulk of the sat observations done) is V = SDSSg’ + 0.286 mag. We do not use this conversion in the document, it is only given as a reference for the reader. Here we report the magnitudes as observed by the various telescopes and camera setups.

LEOsat	Time (UTC)	Facility	Filter	Observed Magnitude	Range (km)	Solar incidence (⌧)	Observer angle (⌧)	Calibrated Magnitude At 550 km orbital height	Reference
Starlink-1113	2020/03/06 00:15:26	Ckoirama	Sloan g’	6.59±0.05	941.62	78.3	47.2	5.75±0.05	1
Starlink-1113	2020/03/05 00:20:37	Ckoirama	Sloan r’	5.46±0.05	718.89	72.0	35.9	4.90±0.05	2
Starlink-1113	2020/03/07 00:11:55	Ckoirama	Sloan i’	5.43±0.04	880.06	79.3	48.9	4.82±0.04	2
Starlink-1113	2020/03/05 00:14:54	ESO VISTA	NIR J	5.10±0.01	1004.76	76.7	51.8	4.12±0.01	2
Starlink-1113	2020/03/07 00:09:07	ESO VISTA	NIR Ks	4.65±0.02	885.43	81.4	49.8	4.15±0.02	2
Starlink-1130 (Darksat)	2020/03/06 00:30:22	Ckoirama	Sloan g’	7.46±0.04	976.50	76.5	50.6	6.52±0.04	1
Starlink-1130 (Darksat)	2020/03/05 00:34:27	Ckoirama	Sloan r’	6.50±0.02	866.39	73.3	45.1	5.64±0.07	2
Starlink-1130 (Darksat)	2020/03/07 00:27:01	Ckoirama	Sloan i’	6.33±0.03	991.73	77.4	51.9	5.40±0.03	2
Starlink-1130 (Darksat)	2020/03/05 00:29:55	ESO VISTA	NIR J	5.65±0.01	1063.91	75.5	54.8	4.50±0.01	2
Starlink-1130 (Darksat)	2020/03/07 00:23:58	ESO VISTA	NIR Ks	5.63±0.02	1146.11	78.2	57.7	4.50±0.02	2
Starlink-1102	2020/03/06 00:05	Blanco 4m	g band	5.21	565	79.1	16.3	5.35	3
Starlink-1073	2020/03/06 00:15	Blanco 4m	g band	5.46	625	77.7	28.6	5.36	3
Starlink-1112	2020/03/06 00:30	Blanco 4m	g band	5.86	810	75.6	44.6	5.23	3
Starlink-1084	2020/03/06 00:35	Blanco 4m	g band	6.15	878	76.4	48.8	5.41	3
Starlink-1130 (Darksat)	2020/03/06 00:30	Blanco 4m	g band	6.97	810	76.1	45.3	6.36	3
Starlink-1436 (Visorsat)	2020/08/27 02:42:25	POMENIS	V	6.8±0.81	1005	77.1	53.2	5.89±0.81	
Starlink-1436 (Visorsat)	2020/09/15 11:29:57	POMENIS	V	7.7±1.21	1057	73.6	54.9	6.54±1.21	
Starlink-1436 (Visorsat)	2020/09/16 11:24:26	POMENIS	V	7.2±0.77	813	70.2	44.9	6.36±0.77	
Starlink-1436 (Visorsat)	2020/09/17 11:18:54	POMENIS	V	6.4±0.61	629	68.0	27.7	6.01±0.61	

Starlink-1436 (Visorsat)	2020/09/17 11:20:28	POMENIS	V	6.1±0.23	923	73.1	50.2	5.15±0.23	
Starlink-1436 (Visorsat)	2020/09/14 14:46:28	LCO 0.4m	Sloan g’	7.39±0.18	982	75.3	24.5	6.41±0.21	
Starlink-1436 (Visorsat)	2020/09/20 04:43:04	CAHA 1.23m	Johnson V		882	72.4	50.9	6.43±0.08	
Starlink-1405	2020/09/14 03:52:55	CAHA 1.23m	Johnson V	5.74±0.09	876	69.2	50.1	4.80±0.10	
Starlink-1348	2020/09/20 04:43:04	CAHA 1.23m	Johnson V	4.40±0.10	850.8	72.4	53.1	3.54±0.10 (#) 2.48±0.10 (&)	

Table D.2.7. Summary of LEO satellites observed and calibrated magnitudes for observations performed from the various observatory/telescopes facilities included in this report.

Notes:

For the case of Starlink-1348 two calibrated magnitudes are reported in the last row of Table D.2.7: (#) normalized/calibrated to an orbital height of 550 km, and (&) normalized/calibrated to the actual orbital height of the satellite at the time of the observation 386 km

D.2.5.2 OneWeb Satellites

The POMENIS Observatory began observing the OneWeb satellites in August 2020 and has successfully captured over 100 images. However, in the majority of the images the satellites are too faint to be measured by the current software pipeline. This indicates the OneWeb satellites are typically fainter than about 6th magnitude, approximately the threshold where the software struggles to detect the satellite streak. This does not mean that the OneWeb satellites are always faint. Results are shown in Table D.2.5. earlier in this report.

The observed magnitudes shown in Table D.2.5., are at the range of the actual observations. If we were to normalize these brightness magnitudes to a nominal altitude of 550 km, we would obtain V band magnitudes in the range of 3.0 to 5.6. This range of magnitudes doesn’t account for the calibration by the solar illumination angle and satellite view angle perspective at the time of the observations. Nevertheless, the results seem to indicate that OneWeb satellites reflect the light of the sun more efficiently, i.e. brighter, than the Starlink satellites. We can’t draw a definitive conclusion until we make an attempt to observe a larger number, out of the 74 launched, of these satellites. The fact that the normalized to 550 km magnitudes range is so large (2.6 magnitudes – a range of almost 11 in photon flux detected) may imply that the OneWeb satellites reflected the light of the sun differently depending on the surfaces being illuminated.

D.2.5.3 Efficiency of mitigation strategies, to name a few: re-orientation of satellites during deployment, darkening treatments (Darksat), reduced reflection (Visorsat).

Observations of the special satellite, Starlink-1130 (Darksat), a first mitigation strategy by the Starlink team to make the satellites dimmer, were performed earlier in 2020 (January and March) and results of its brightness magnitude were first published in the pee-review literature in the work of Tregloan-Reed et al. 2020a. The calculated and reported magnitude of the satellite, normalized to zenith and calibrated by solar illumination and observer view angle, was confirmed in the independent work of Tyson et al. 2020.

Observations of Darksat, and of another pre-mitigation satellite (STARLINK-1113) show that after correcting for the solar incidence and observer phase angles whilst normalising the range to the orbital height, 550 km (one airmass), Darksat is dimmer than STARLINK-1113 in both the optical and NIR (observations done with the Ckoirama and ESO/VISTA telescopes). However, the results also show that both satellites increase in reflective brightness with increasing wavelength (towards redder bands) and the effectiveness of the darkening treatment used for Darksat reduces with increasing wavelength. The results show that between 475.4 nm (Sloan g') and 2150 nm (Ks) Darksat increases in reflective brightness by 2.02 mag (≈ 6.4 times brighter). While STARLINK-1113 increases in reflective brightness by 1.60 mag (≈ 4.4 times brighter).

The reduction in reflective brightness between Darksat and STARLINK-1113 is ≈ 51 % (475.4 nm), ≈ 49 % (620.4 nm), ≈ 41 % (769.8 nm), ≈ 30 % (1250 nm), and ≈ 28 % (2150 nm). Figure 22 shows that the effectiveness of the darkening treatment used for Darksat, reduces from the optical to the NIR (Figure D.2.22).

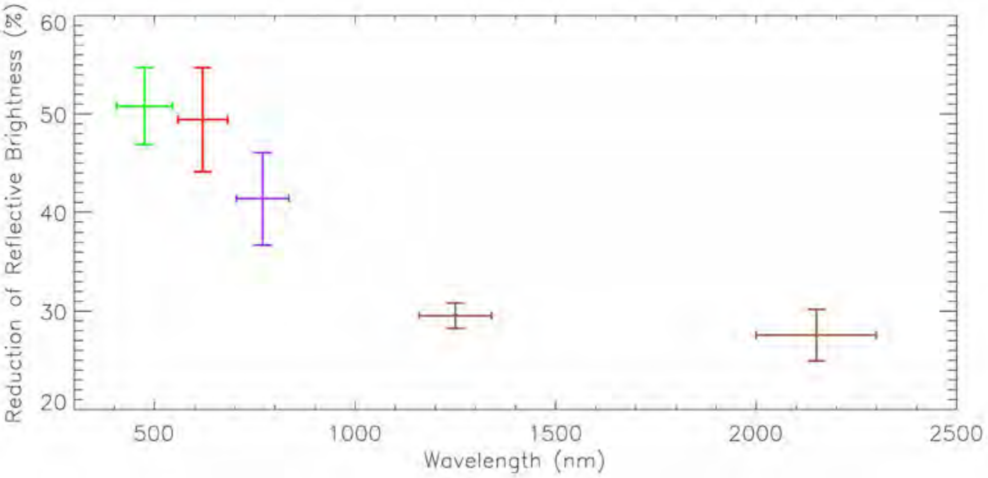

Figure D.2.22. Reduction of reflective brightness between Darksat and STARLINK-1113 for the Sloan g' (green), Sloan r' (red), Sloan i' (purple), J (brown), and Ks (brown) calibrated results (adapted from Tregloan-Reed et al. (2020a,b)). The horizontal error bars represent the FWHM of the passband filters, while the vertical error bars represent the uncertainty in the reduction.

Regarding VisorSat, the observations to date show that the calibrated magnitudes obtained are:

- POMENIS telescope: 5.4±1.21 (weighted mean from V filter observations)
- POMENIS telescope without bright outlier 6.1 +/- 0.4 mag (weighted mean from V filter observations)
- Las Cumbres Observatory 0m4-04 Telescope: 6.41±0.21 (SDSS g' filter)
- Calar Alto Observatory, 1.23m telescope, 5.33±0.08 mag (only one observation in Johnson V filter))

These magnitudes are all normalized to an orbital height of 550 km and calibrated by the solar incidence and observer view angle.

The larger uncertainty in the POMENIS results for VisorSat is that the observations were too faint to be detected by the automated POMENIS's software pipeline. Therefore, the images were instead processed with the same pipeline but with a manually defined photometric aperture for the satellite streak and this may have introduced a larger uncertainty. The observation at Las Cumbres observatory, using the 0.4m-4 telescope (at their Haleakala, HI, site) was also of relatively low signal-to-noise ratio, but the analysis done independently by three pipelines people show a much lower uncertainty.

Regarding the Visorsat mitigation strategy (as depicted in the rendering view shown in Figure 5.8 is that its magnitude, when scaled to the 550 km orbital height can be taken as similar to the Darksat solution, all within the respective uncertainties in the measurements. Consequently, none of these strategies so far are yet achieving a conclusive normalized brightness magnitude at 550 km of 7.0 or fainter as advised in Recommendation #5 of the SATCON1 Workshop Report (Walker at al 2020).

The Starlink team also adopted other mitigation strategies intended to decrease the brightness of the satellites during the deployment phase, i.e. before they reach their nominal orbital height and nominal attitude. The observations done with the POMENIS telescope, plotted as a function of month through year 2020, are shown in Figure D.2.23.The results are shown separately for the satellites in deployment phase (below 550 km) and those that have already achieved the nominal orbital height and are distributed around 550 km. The results are not conclusive, but they seem to indicate that the Starlink team mitigation strategy to find a better orientation geometry during the deployment phase of the satellites may have contributed to shift their overall magnitudes towards fainter values.

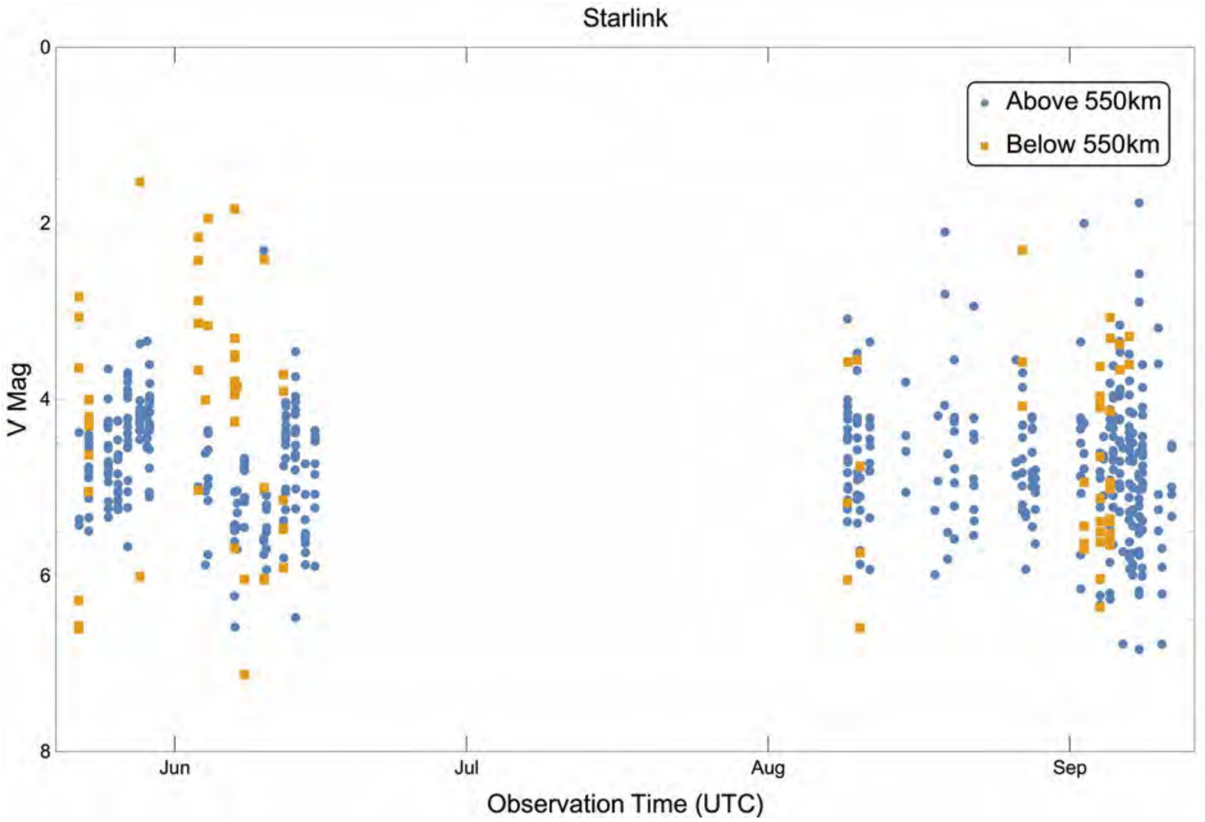

Figure D.2.23. This plot shows the Starlink observed magnitudes, in a Johnson V filter, by the date of observation. The satellites below 550 km observed early in the summer show a brighter and larger distribution of magnitudes than those observed later. This may be a result of SpaceX’s mitigation plan to orient the satellites differently during the deployment phase. Alternatively, this may be the result of a sampling bias due to the limited opportunities to observe the satellites during the deployment phase. The telescope was not operating from mid-June to August due to wildfire activity.

9. REFERENCES

9.1 Dark Sky Oases References

AMIDSR. (2020), Aoraki Mackenzie International Dark Sky Reserve. https://darkskyreserve.org.nz. Accessed 23 July 2020.

AstronomItaly (2020). Accessed 19 March 2020. English version at https://www.astro-tourism.com/ Accessed 19 March 2020.

Bará, S., Aubé, M., Baretine, J. & Zamorano, J. (2020). Magnitude to luminance conversions and visual brightness of the night sky. *Monthly Notices R Astron. Soc.*, 493(2), 2429-2437.

Barentine, J. (2016). Going for the Gold: Quantifying and Ranking Visual Night Sky Quality in International Dark Sky Places. *International Journal of Sustainable Lighting*, 18, 9–15. https://doi.org/10.26607/ijsl.v18i0.16.

Barentine, J. (2021). National and Sub-National Laws, Bylaws and Ordinances. in Welch, D. (ed.), *The World at Night: preserving natural darkness for heritage conservation and night sky appreciation. Best Practice Protected Area Guidelines*. Gland, Switzerland: International Union for the Conservation of Nature.

Blair, A. (2018). An Exploration of the Role that the Night Sky Plays in the Lives of the Dark Sky Island Community of Sark. *Journal of Skyscape Archaeology*, 3(2), 236–252. https://doi.org/10.1558/jsa.34689.

Bortle, J. (2001). *Sky and Telescope*, 101, 126. No doi.

Cayrel, R., Graham-Smith, F., Fisher, A. & de Boer, J. (1980). GuideLines for minimizing Urban Sky Glow near Astronomical Observatories. Publication IAU/CIE No. 1. No doi.

Cinzano, P., Falchi, F., & Elvidge, C. (2001). The first World Atlas of the artificial night sky brightness. *Monthly Notices of the Royal Astronomical Society*, 328(3), 689–707. https://doi.org/10.1046/j.1365-8711.2001.04882.x.

Crumey, A. (2014). Human contrast threshold and astronomical visibility. *Monthly Notices of the Royal Astronomical Society*, 442(3), 2600–2619. https://doi.org/10.1093/mnras/stu992.

Dalton, A., del Solar, D., and Barentine, J. (2021a). The IDA International Dark Sky Places Program. in Welch, D. (ed.), *The World at Night: preserving natural darkness for heritage conservation and night sky appreciation. Best Practice Protected Area Guidelines*. Gland, Switzerland: International Union for the Conservation of Nature.

Dalton, A., del Solar, D., and Barentine, J. (2021b). Yeongyang Firefly Eco Park International Dark Sky Park. in Welch, D. (ed.), *The World at Night: preserving natural darkness for heritage conservation and night sky appreciation. Best Practice Protected Area Guidelines*. Gland, Switzerland: International Union for the Conservation of Nature.

DSAG. (2020). IUCN Dark Skies Advisory Group. http://darkskyparks.org/dark-skies-and-nature-conservation/#2. Accessed 16 July 2020.

DSP (2020). World list of dark sky places maintained by IUCN DSAG. http://darkskyparks.org/dsag/2020-05-31_DSAG_word_list.htm. Accessed 21 July 2020.

Dudley, N. (Editor) (2008). Guidelines for Applying Protected Area Management Categories. Gland, Switzerland: IUCN.

Elvidge, C., Erwin, E., Baugh, K., Ziskin, D., Tuttle, B., Ghosh, T., & Sutton, P. (2009). Overview of DMSP nightime lights and future possibilities. *Proceedings of the 2009 Joint Urban Remote Sensing Event*. https://doi.org/10.1109/urs.2009.5137749.

Falchi, F.; Cinzano, P.; Duriscoe, D.; Kyba, C.; Elvidge, C.; Baugh, K.; Portnov, B.; Rybnikova, N.; Furgoni, R. (2016). The new world atlas of artificial night sky brightness. *Science Advances*, 2, 1-25. http://doi.org/10.1126/sciadv.1600377.

Fotios, S., & Gibbons, R. (2018). Road lighting research for drivers and pedestrians: The basis of luminance and illuminance recommendations. *Lighting Research & Technology*, 50(1), 154–186. https://doi.org/10.1177/1477153517739055.

Gallaway, T. (2010). On Light Pollution, Passive Pleasures, and the Instrumental Value of Beauty. *Journal of Economic Issues*, 44(1), 71–88. https://doi.org/10.2753/jei0021-3624440104.

Grauer, A., Grauer, P., Davies, N., & Davies, G. (2019). Impact of Space Weather on the Natural Night Sky. *Publications of the Astronomical Society of the Pacific*, 131(1005), 114508. https://doi.org/10.1088/1538-3873/ab370d.

Haworth, D. (2003). How Many Stars You Can Observe. http://www.stargazing.net/david/constel/howmanystars.html. Accessed 20 July 2020.

Hart, A. (2018). The rise of astro-tourism: Why your next adventure should include star-gazing. *The Telegraph*, 11 July 2018. https://www.telegraph.co.uk/travel/comment/astro-tourism-new-sustainable-travel-trend/. Accessed 16 March 2020.

Haworth, D. (2003). How many stars can you observe? http://www.stargazing.net/david/constel/howmanystars.html. Accessed 23 Feb 2020.

Huang, Q., Yang, X., Gao, B., Yang, Y., & Zhao, Y. (2014). Application of DMSP/OLS Nighttime Light Images: A Meta-Analysis and a Systematic Literature Review. *Remote Sensing*, 6(8), 6844–6866. https://doi.org/10.3390/rs6086844.

International Dark-Sky Association (IDA). (2018). International Dark Sky Reserve program guidelines. https://www.darksky.org/wp-content/uploads/2018/12/IDSR-Guidelines-2018.pdf. Accessed 17 September 2020.

International Dark-Sky Association (IDA). (2020). Light Pollution. https://www.darksky.org/light-pollution. Accessed 16 July 2020.

International Dark-Sky Association (IDA). (2020). Energy Waste. https://www.darksky.org/light-pollution/energy-waste/. Accessed 16 July 2020.

Lee, T., Miller, S., Turk, F.,, Schueler, C., Julian, R., Deyo, S., Dills, P., & Wang, S. (2006). The NPOESS VIIRS Day/Night Visible Sensor. *Bulletin of the American Meteorological Society*, 87(2), 191–200. https://doi.org/10.1175/bams-87-2-191.

Lamptech. (2020). Spectral properties of the sodium discharge. http://www.lamptech.co.uk/Documents/SO%20Spectral.htm. Accessed 9 March 2020.

Marín, C. (ed.) (2009), Starlight Reserve Concept. UNESCO-WHC, Mab Urban Ecology Programme of UNESCO, IAU, UNWTO, OTPC-IAC, CIE.

Marín, C. & Jafari, J. (eds). (2007). StarLight: a Common Heritage. International Initiative in Defence of the Quality of the Night Sky and the Right to Observe the Stars. Tenerife, Spain: Starlight Initiative, Institute of Astrophysics of the Canaries (IAC).

Marín, C., Ceregioli, P., Fayos-Solá, E., & Gallardo Campos, A. (2015). *Alternative ways of lighting UNESCO sites. Save energy and recover the stars*, Ed. Starlight Foundation & iGuzzini. https://www.dropbox.com/s/1w9kmttai6mumdj/LightingUNESCOsitesLRweb.pdf?dl=0

Mitchell, D., & Gallaway, T. (2019). Dark sky tourism: economic impacts on the colourado Plateau Economy, USA. *Tourism Review*, 74(4), 930–942. https://doi.org/10.1108/tr-10-2018-0146.

Pollard, N. E., van Bommel, W., Diaz Castro, J., Lecocq, J., Pong, B.-J., & Walkling, A., (2017), CIE 150:2017 Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations, 2nd Edition, Vienna Austria: International Commission on Illumination. DOI 10.25039/TR.150.2017.

RASC. (2020). Royal Astronomical Society of Canada. https://www.rasc.ca/. Accessed 16 July 2020.

Ruggles, C. (ed.) (2017). Heritage Sites of Astronomy and Archaeoastronomy in the Context of the World Heritage Convention: A Thematic Study no. 2. Publ. by ICOMOS and the IAU.

Ruggles, C. & Cotte, M. (eds.) (2010). Heritage Sites of Astronomy and Archaeoastronomy in the Context of the World Heritage Convention: A Thematic Study. Publ. by ICOMOS and the IAU.

Schreuder, D.A. (1998). *Road lighting for safety.* London: Thomas Telford Publishing.

Simpson, S., & Hanna, B. (2010). 2010, Willingness to pay for a clear night sky: use of the contingent valuation method. *Applied Economics Letters*, 17(11), 1095–1103. https://doi.org/10.1080/00036840902817508.

Spoelstra, H. (2002). A sky brightness nomogram. http://www.darkskiesawareness.org/nomogram.php. Accessed 16 July 2020.

Starlight Foundation. (2007). The Starlight Declaration, publ. by the Starlight Foundation. https://fundacionstarlight.org/. Accessed 3 March 2020.

Starlight Reserve Concept. (2009). UNESCO.WHC, MaB, IAU, UNWTO, OPTC-IAC, CIE. https://www.fundacionstarlight.org/

Starlight Foundation. (2020). https://fundacionstarlight.org. Accessed 17 July 2020.

Sternberg, J., & Ingham, M. (1972). Observations of the Airglow Continuum. *Monthly Notices of the Royal Astronomical Society*, 159(1), 1–20. http://doi.org/10.1093/mnras/159.1.1.

Stimac, V. (2019). Dark Skies: A Practical Guide to Astrotourism. Carlton, Australia: Lonely Planet.

Stolton, S., Shadie, P. and Dudley, N. (2013). IUCN WCPA Best Practice Guidance on Recognising Protected Areas and Assigning Management Categories and Governance Types, Best Practice Protected Area Guidelines Series No. 21, Gland, Switzerland: IUCN.

Sweatman, M., & Coombs, A. (2019). Decoding European Palaeolithic Art: Extremely Ancient knowledge of Precession of the Equinoxes. *Athens Journal of History*, 5(1), 1-30. No doi.

Varela, A., Muñoz-Tuñón, C., Sánchez, F. & Martínez, L. (2012). Dark sky over a bright landscape: a starlight reserve for the Mackenzie Basin, pp. 229-234. In *Proceedings of the Third International Starlight Conference, New Zealand*, Eds. Hearnshaw, J., Pollard, K. & Head, M.

Welch, D. (2013). Dark Sky Places Class System. Gland, Switzerland: International Union for the Conservation of Nature. http://darkskyparks.org/dsag/2013-3-26_DSAG_class_system.pdf (accessed 28 August 2020)

Welch, D. (ed.) (2021). The World at Night: preserving natural darkness for heritage conservation and night sky appreciation. Best Practice Protected Area Guidelines. Gland, Switzerland: International Union for the Conservation of Nature. In preparation.

9.2 Optical Astronomy References

Aubé, M., Roby, J., & Kocifaj, M. (2013). Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility. *PLoS ONE*, 8(7), e67798. https://doi.org/10.1371/journal.pone.0067798.

Aubé, M. (2015). Physical behaviour of anthropogenic light propagation into the nocturnal environment. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 370(1667), 20140117. https://doi.org/10.1098/rstb.2014.0117.

Aubé, M. (2016). The LED outdoor lighting revolution: Opportunities, threats and mitigations for urban and rural citizens. *53rd International Making Cities Livable Conference on Caring, for our Common Home: Sustainable, Healthy, Just Cities & Settlement*, Vatican city, Rome, Italy.

Aubé, M., Simoneau, A., Wainscoat, R., & Nelson, L. (2018). Modelling the effects of phosphor converted LED lighting to the night sky of the Haleakala Observatory, Hawaii. *Monthly Notices of the Royal Astronomical Society*, 478(2), 1776–1783. https://doi.org/10.1093/mnras/sty1143.

Aubé, M. (2020). CoSQM, a color hack to the SQM instrument, https://lx02.cegepsherbrooke.qc.ca/~aubema/index.php/Prof/CoSQMEn

Aubé, M., Simoneau, A., Muñoz-Tuñón, C., Díaz-Castro, J., Serra-Ricart, M. (2020). Restoring the night sky darkness at Observatorio del Teide: First application of the model Illumina version 2, *Monthly Notices of the Royal Astronomical Society*, 497(3), 2501–2516. https://doi.org/10.1093/mnras/staa2113.

Aceituno, J., Sánchez, S. F., Aceituno, F. J., Galadí-Enríquez, D., Negro, J. J., Soriguer, R. C., & Gomez, G. S. (2011). An All-Sky Transmission Monitor: ASTMON. *Publications of the Astronomical Society of the Pacific*, 123(907), 1076–1086. https://doi.org/10.1086/661918.

Bará, S. (2017). Characterizing the zenithal night sky brightness in large territories: how many samples per square kilometre are needed? *Monthly Notices of the Royal Astronomical Society*, 473(3), 4164–4173. https://doi.org/10.1093/mnras/stx2571.

Bará, S., Rodríguez-Arós, Á., Pérez, M., Tosar, B., Lima, R., Sánchez de Miguel, A., & Zamorano, J. (2018). *Lighting Research & Technology*, 51(7), 1092–1107. doi:10.1177/1477153518808337.

Bará, S., Rodríguez-Arós, Á., Pérez, M., Tosar, B., Lima, R., Sánchez de Miguel, A., & Zamorano, J. (2018). Estimating the relative contribution of streetlights, vehicles, and residential lighting to the urban night sky brightness. *Lighting Research & Technology*, 51(7), 1092–1107. https://doi.org/10.1177/1477153518808337.

Bará, S., Aubé, M., Barentine, J., & Zamorano, J. (2020). Magnitude to luminance conversions and visual brightness of the night sky. *Monthly Notices of the Royal Astronomical Society*, 493(2), 2429–2437. https://doi.org/10.1093/mnras/staa323.

Barentine, J., Walker, C., Kocifaj, M., Kundracik, F., Juan, A., Kanemoto, J., & Monrad, C. (2018). skyglow changes over Tucson, Arizona, resulting from a municipal LED street lighting conversion. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 212, 10–23. https://doi.org/10.1016/j.jqsrt.2018.02.038.

Benn, C, and Ellison, S.L., 2007, La Palma Night Sky Brightness, La Palma Technical Note 115, http://www.ing.iac.es/Astronomy/observing/conditions/skybr/skybr.html

Bessell, M. (1990). UBVRI passbands. *Publications of the Astronomical Society of the Pacific*, 102, 1181. https://doi.org/10.1086/132749.

Brown, R. (2010). *World On the Edge: How to Prevent Environmental and Economic Collapse*. New York: W.W. Norton & Company.

Bullough, J., Donnell, E., & Rea, M. (2013). To illuminate or not to illuminate: Roadway lighting as it affects traffic safety at intersections. *Accident Analysis & Prevention*, 53, 65–77. https://doi.org/10.1016/j.aap.2012.12.029.

Cao, C., De Luccia, F., Xiong, X., Wolfe, R., & Weng, F. (2014). Early On-Orbit Performance of the Visible Infrared Imaging Radiometer Suite Onboard the Suomi National Polar-Orbiting Partnership (S-NPP) Satellite. *IEEE Transactions on Geoscience and Remote Sensing*, 52(2), 1142–1156. https://doi.org/10.1109/tgrs.2013.2247768.

Cayrel, R. (1979). 50. Identification and Protection of Existing and Potential Observatory Sites. *Transactions of the International Astronomical Union*, 17(1), 215–223. https://doi.org/10.1017/s0251107x00010798.

Cayrel, R., Graham-Smith, F., Fisher, A. & de Boer, J. (1980). Guidelines for minimizing urban skyglow near astronomical observatories. Publication IAU/CIE No. 1. Paris: Commission Internationale de l'Eclairage. No doi.

Cinzano, P. (2005). Night Sky Photometry with Sky Quality Meter, Tech. Rep. 9, Istituto di scienza e tecnologia dell'inquinamento luminoso. No doi. http://www.lightpollution.it/download/ sqmreport.pdf.

Cinzano, P. (2007). Report on Sky Quality Meter, version L, Tech. rep., Istituto di scienza e tecnologia dell'inquinamento luminoso. No doi. http://unihedron. com/projects/sqm-l/sqmreport2.pdf

Cinzano, P., Diaz Castro, F. J. (2000). *Memorie della Società Astronomia Italiana*, 71, 251. No doi. https://ui.adsabs.harvard.edu/abs/2000MmSAI..71..251C.

Collison, F, & Poe, K. (2013). "Astronomical Tourism": The Astronomy and Dark Sky programme at Bryce Canyon National Park. *Tourism Management Perspectives*, 7, 1–15. https://doi.org/10.1016/j.tmp.2013.01.002.

Commission Internationale de l´Eclairage (CIE). (1980). CIE 001-1980, "Guidelines for minimizing urban skyglow near astronomical observatories", Paris: Bureau Central de la CIE.

Commission Internationale de l'Eclairage (CIE). (2019). CIE 083:2019, "Guide for the Lighting of Sports Events for Colour Television and Film Systems, 3rd Edition", Vienna: Bureau Central de la CIE.

Commission Internationale de l'Eclairage (CIE). (1993). CIE 094-1993, "Guide for Floodlighting", Vienna: Bureau Central de la CIE.

Commission Internationale de l'Eclairage (CIE). (2010). CIE 115:2010, "Lighting of Roads for Motor and Pedestrian Traffic", Vienna: Bureau Central de la CIE.

Commission Internationale de l'Eclairage (CIE). (1997). CIE 126-1997, "Guidelines for minimizing skyglow", Vienna: Bureau Central de la CIE.

Commission Internationale de l'Eclairage (CIE). (2017). CIE 150:2017, "Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations, 2nd Edition". Vienna: Bureau Central de la CIE. https://doi.org/10.25039/TR.150.2017.

Commission Internationale de l'Eclairage (CIE). (2019). CIE 234:2019, "A Guide to Urban Lighting Masterplanning". Vienna: Bureau Central de la CIE. https://doi.org/10.25039/TR.234.2019.

Commission Internationale de l'Eclairage (CIE). (2019). CIE 236:2019, "Lighting for Pedestrians: A Summary of Empirical Data", https://doi.org/10.25039/TR.236.2019.

Commission Internationale de l'Eclairage (CIE). (2005). S 015/E:2005, "Lighting of Outdoor Workplaces", CIE Vienna: Bureau Central de la CIE.

Commission Internationale de l'Eclairage (CIE). (2011). CIE S 017/E:2011, "International Lighting Vocabulary (ILV)", Vienna: Bureau Central de la CIE.

Duriscoe, D. (2013). Measuring Anthropogenic skyglow Using a Natural Sky Brightness Model. *Publications of the Astronomical Society of the Pacific*, 125(933), 1370–1382. https://doi.org/10.1086/673888.

Duriscoe, D. (2016). Photometric indicators of visual night sky quality derived from all-sky brightness maps. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 181, 33–45. https://doi.org/10.1016/j.jqsrt.2016.02.022.

Duriscoe, D., Luginbuhl, C., & Moore, C. A. (2007). Measuring Night-Sky Brightness with a Wide-Field CCD Camera. *Publications of the Astronomical Society of the Pacific*, 119(852), 192–213. https://doi.org/10.1086/512069.

Duriscoe, D., Luginbuhl, C., & Elvidge, C. (2013). The relation of outdoor lighting characteristics to skyglow from distant cities. *Lighting Research & Technology*, 46(1), 35–49. https://doi.org/10.1177/1477153513506729.

Falchi, F. & Bará, S. (2020). Protecting the night sky darkness in astronomical observatories: a linear systems approach. arXiv:2008.09928.

Falchi, F., Cinzano, P., Duriscoe, D., Kyba, C., Elvidge, C., Baugh, K., Portnov, B., Rybnikova, N. A., & Furgoni, R. (2016). The new world atlas of artificial night sky brightness. *Science Advances*, 2(6), e1600377. https://doi.org/10.1126/sciadv.1600377.

Fotios, S., & Gibbons, R. (2018). Road lighting research for drivers and pedestrians: The basis of luminance and illuminance recommendations. *Lighting Research & Technology*, 50(1), 154–186. https://doi.org/10.1177/1477153517739055.

Galadí-Enríquez, D. (February 2018). "Beyond CCT: The spectral index system as a tool for the objective, quantitative characterization of lamps". *Journal of Quantitative Spectroscopy and Radiative Transfer*. 206, 399–408. https://doi.org/10.1016/j.jqsrt.2017.12.011.

Garrett, J., Donald, P., & Gaston, K. (2020). *Animal Conservation*, 23(2), 153–159. doi:10.1111/acv.12480.

Garrett, J., Donald, P., & Gaston, K. (2020). skyglow extends into the world's Key Biodiversity Areas. *Animal Conservation*, 23(2), 153–159. https://doi.org/10.1111/acv.12480.

Gasparovsky, D., Janiga, P., Dubnicka, R., Novak, T. (2018). Potential of energy savings in traffic-flow controlled street lighting systems. Proceedings of CIE 2018 Topical Conference on Smart Lighting, 123-132. https://doi.org/10.25039/x45.2018.

Government of Chile. (2012). Decreto 43, "Establishing an Emission Standard for the Regulation of Light Pollution, Composed from the Revision of Decree No. 686, of 1998, of the Ministry of Economy, Development and Reconstruction". https://www.leychile.cl/Navegar?idNorma=1050704&idParte=0.

Government of Spain. (1988). Law 31/1988, "On Protection of the Astronomical Quality of the Observatories of the Canary Islands Institute of Astrophysics". https://www.iac.es/en/documents/ley-311988-proteccion-de-la-calidad-astronomica-de-los-observatorios-del-instituto-de-astrofisica-de-canarias. Accessed 22 September 2020.

Government of Spain. (1992). Real Decreto 243/1992, "By which the Regulation of Law 31/1988, of October 31, on the protection of the astronomical quality of the observatories of the Instituto de Astrofísica de Canarias is approved". https://www.boe.es/diario_boe/txt.php?id=BOE-A-1992-8705. Accessed 22 September 2020.

Grauer, A., Grauer, P., Davies, N., & Davies, G. (2019). Impact of Space Weather on the Natural Night Sky. *Publications of the Astronomical Society of the Pacific*, 131(1005), 114508. https://doi.org/10.1088/1538-3873/ab370d.

Hänel, A., Posch, T., Ribas, S.J., Aubé, M., Duriscoe, D., Jechow, A., Kollath, Z., Lolkema, D.E., Moore, C., Schmidt, N., Spoelstra, H., Wuchterl, G., Kyba, C.C.M. (2018). Measuring night sky brightness: methods and challenges. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 205, 278. https://doi.org/10.1016/j.jqsrt.2017.09.008

HAO 2020, List of Highest Astronomical Observatories, *Wikipedia*, https://en.wikipedia.org/wiki/List_of_highest_astronomical_observatories.

Hölker, F., Moss, T., Griefahn, B., Kloas, W., Voight, C., Henckel, D., Hänel, A., Kappeler, P., Völker, S., Schwope, A., Franke, S., Uhrlandt, D., Fischer, J., Klenke, R., Wolter, C., & Tockner, K. (2010). The Dark Side of Light: A Transdisciplinary Research Agenda for Light Pollution Policy. *Ecology and Society*, 15(4), 13. No doi. http://www.ecologyandsociety.org/vol15/iss4/art13/.

Hoot, J. (2007). Photometry With DSLR Cameras. In The Society for Astronomical Sciences 26th Annual Symposium on Telescope Science, held May 22-24, 2007 at Big Bear, CA, pp. 67-72. http://articles.adsabs.harvard.edu/pdf/2007SASS...26...67H .

Illuminating Engineering Society (IES): ANSI/IES RP-39-19 Recommended Practice: Off-Roadway Sign Luminance. https://webstore.ansi.org/standards/iesna/ansiiesrp3919.

International Dark-Sky Association (IDA). (2018). International Dark Sky Sanctuary programme guidelines. https://www.darksky.org/wp-content/uploads/2018/12/IDSS-Guidelines-2018.pdf, accessed 27 August 2020.

International Dark-Sky Association (IDA). (2019). Guidance for Electronic Message Centers. https://www.darksky.org/wp-content/uploads/2019/10/EMC-Guidelines-IDA2019-1.1.pdf

Jackett, M., & Frith, W. (2013). Quantifying the impact of road lighting on road safety — A New Zealand Study. *IATSS Research*, 36(2), 139–145. https://doi.org/10.1016/j.iatssr.2012.09.001.

Jechow, A., Hölker, F., & Kyba, C. (2019). Using all-sky differential photometry to investigate how nocturnal clouds darken the night sky in rural areas. *Scientific Reports*, 9(1). https://doi.org/10.1038/s41598-018-37817-8.

Jechow, A., Kyba, C., & Hölker, F. (2020). Mapping the brightness and color of urban to rural skyglow with all-sky photometry. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 250, 106988. https://doi.org/10.1016/j.jqsrt.2020.106988.

Jones, B. (2018). Spillover health effects of energy efficiency investments: Quasi-experimental evidence from the Los Angeles LED streetlight programme. *Journal of Environmental Economics and Management*, 88, 283–299. https://doi.org/10.1016/j.jeem.2018.01.002.

Kocifaj, M., & Bará, S. (2020). Aerosol characterization using satellite remote sensing of light pollution sources at night. *Monthly Notices of the Royal Astronomical Society: Letters*, 495(1), L76–L80. https://doi.org/10.1093/mnrasl/slaa060.

Koen, E., Minnaar, C., Roever, C., & Boyles, J. (2018). Emerging threat of the 21st century lightscape to global biodiversity. *Global Change Biology*, 24(6), 2315–2324. https://doi.org/10.1111/gcb.14146.

Kolláth, Z., & Dömény, A. (2017). Night sky quality monitoring in existing and planned dark sky parks by digital cameras. *International Journal of Sustainable Lighting*, 19(1), 61–68. https://doi.org/10.26607/ijsl.v19i1.70.

Kolláth, Z., Cool, A., Jechow, A., Kolláth, K., Száz, D., & Tong, K.-P. (2020a). Introducing the dark sky unit for multi-spectral measurement of the night sky quality with commercial digital cameras. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 253, 107162. https://doi.org/10.1016/j.jqsrt.2020.107162.

Kolláth, K., & Kolláth, Z. (2020). On the feasibility of using ceilometer backscatter profile as input data for skyglow simulation. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 253, 107158. https://doi.org/10.1016/j.jqsrt.2020.107158.

Kolláth, Z., Száz, D., Tong, K.-P. & Kolláth, Z. (2020b). The Colour of the Night Sky. *Journal of Imaging,* 6(9), 90. https://doi.org/10.3390/jimaging6090090.

Krisciunas, K. (1997). Optical Night-Sky Brightness at Mauna Kea over the Course of a Complete Sunspot Cycle. *Publications of the Astronomical Society of the Pacific*, 109, 1181. https://doi.org/10.1086/133993.

Krisciunas, K., Semler, D., Richards, J., Schwarz, H., Suntzeff, N., Vera, S., & Sanhueza, P. (2007). Optical Sky Brightness at Cerro Tololo Inter-American Observatory from 1992 to 2006. *Publications of the Astronomical Society of the Pacific*, 119(856), 687–696. https://doi.org/10.1086/519564.

Kyba, C., & Lolkema, D. (2012). A community standard for recording skyglow data. *Astronomy & Geophysics*, 53(6), 6.17-6.18. https://doi.org/10.1111/j.1468-4004.2012.53617.x.

Kyba, C., Hänel, A., & Hölker, F. (2014). Redefining efficiency for outdoor lighting. *Energy and Environmental Science*, 7(6), 1806–1809. https://doi.org/10.1039/c4ee00566j.

Kyba, C., Kuester, T., Sánchez de Miguel, A., Baugh, K., Jechow, A., Hölker, F., Bennie, J., Elvidge, C., Gaston, K., & Guanter, L. (2017). Artificially lit surface of Earth at night increasing in radiance and extent. *Science Advances*, 3(11), e1701528. https://doi.org/10.1126/sciadv.1701528.

L.Imhoff, M., Lawrence, W., Stutzer, D., & Elvidge, C. (1997). A technique for using composite DMSP/OLS “City Lights” satellite data to map urban area. *Remote Sensing of Environment*, 61(3), 361–370. https://doi.org/10.1016/s0034-4257(97)00046-1.

Li, X., & Zhou, Y. (2017). Urban mapping using DMSP/OLS stable night-time light: a review. *International Journal of Remote Sensing*, 38(21), 6030–6046. https://doi.org/10.1080/01431161.2016.1274451.

Luginbuhl, C., Boley, P., & Davis, D. (2014). *Journal of Quantitative Spectroscopy and Radiative Transfer* 2014;139, 21–26. doi:10.1016/j.jqsrt.2013.12.004.

Luginbuhl, C., Boley, P., & Davis, D. (2014). The impact of light source spectral power distribution on skyglow. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 139, 21–26. https://doi.org/10.1016/j.jqsrt.2013.12.004.

Luginbuhl, C., Duriscoe, D., Moore, C., Richman, A., Lockwood, G., & Davis, D. (2009). From the Ground Up II: skyglow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona. *Publications of the Astronomical Society of the Pacific*, 121(876), 204–212. https://doi.org/10.1086/597626.

Lyytimäki, J., Tapio, P., & Assmuth, T. (2012). Unawareness in environmental protection: The case of light pollution from traffic. *Land Use Policy*, 29(3), 598–604. https://doi.org/10.1016/j.landusepol.2011.10.002.

Marchant, P. (2004). A Demonstration That the Claim That Brighter Lighting Reduces Crime Is Unfounded. *British Journal of Criminology*, 44(3), 441–447. https://doi.org/10.1093/bjc/azh009.

Marchant, P. (2011). *Radical Statistics*, 104, 39–48. No doi. https://www.radstats.org.uk/no104/Marchant2_104.pdf.

Marchant, P. (2017). Why Lighting Claims Might Well Be Wrong. *International Journal of Sustainable Lighting*, 19(1), 69–74. https://doi.org/10.26607/ijsl.v19i1.71.

Marchant, P. (2019). Do brighter, whiter street lights improve road safety? *Significance*, 16(5), 8–9. https://doi.org/10.1111/j.1740-9713.2019.01313.x.

Masana, E., Carrasco, J. M., Bará, S., & Ribas, S. J. (2020). A Gaia map of the natural sky brightness. *Contributions to the XIV.0 Scientific Meeting (virtual) of the Spanish Astronomical Society, held 13-15 July 2020, online at* https://www.sea-astronomia.es/reunion-cientifica-2020, id.234. Bibcode: 2020sea..confE.234M.

Mitchell, D., & Gallaway, T. (2019). Dark sky tourism: economic impacts on the Colorado Plateau Economy, USA. *Tourism Review*, 74(4), 930–942. https://doi.org/10.1108/tr-10-2018-0146.

Mohar, A. (2015). Sky Quality Camera as a Quick and Reliable Tool for Light Pollution

Monitoring. Book of Abstracts, International Conference on Light Pollution Theory, Modelling and Measurements, May 26 – 28, Jouvance, Quebec, Canada, eds. M. Aubé, J. Roby, M. Kocifaj, & O. Domingue, 47. No doi. https://lx02.cegepsherbrooke.qc.ca/~aubema/LPTMM//uploads/Main/Abstract-booklet-lptmm-2015.pdf.

Morrow, N., & Hutton, S. (2000). The Chicago Alley Lighting Project: Final Evaluation Report. Illinois Criminal Justice Information Authority. No doi. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.508.9242&rep=rep1&type=pdf.

Patat, F. (2008). The dancing sky: 6 years of night-sky observations at Cerro Paranal. *Astronomy & Astrophysics*, 481(2), 575–591. https://doi.org/10.1051/0004-6361:20079279.

Puschnig, J., Wallner, S., & Posch, T. (2019). Circalunar variations of the night sky brightness – an FFT perspective on the impact of light pollution. *Monthly Notices of the Royal Astronomical Society*, 492(2), 2622–2637. https://doi.org/10.1093/mnras/stz3514.

Roach, F. & Gordon, J. (1973). *The Light of the Night Sky*. Dordrecht, Netherlands: Reidel.

Rosa Infantes, D. (2011). The RoadRunner System. In Fourth International Symposium for Dark Sky Parks, Montsec, Spain. No doi. http://darkskyparks.splet.arnes.si/files/2011/09/RoadRunner.pdf.

Sánchez de Miguel, A., Aubé, M., Zamorano, J., Kocifaj, M., Roby, J., & Tapia, C. (2017). Sky Quality Meter measurements in a colour-changing world. *Monthly Notices of the Royal Astronomical Society*, 467(3), 2966–2979. https://doi.org/10.1093/mnras/stx145.

Sanchez de Miguel, A., Kyba, C., Zamorano, J., Gallego, J., & Gaston, K. (2020). The nature of the diffuse light near cities detected in nighttime satellite imagery. *Scientific Reports*, 10(1). https://doi.org/10.1038/s41598-020-64673-2.

Schroer, S., & Hölker, F. (2014). Light Pollution Reduction: Methods to Reduce the Environmental Impact of Artificial Light at Night. In *Handbook of Advanced Lighting Technology*, eds. Karlicek, R., Sun, C.-C., Zissis, G., & Ma, R., 1-17. Cham, Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-319-00295-8_43-1.

Smyth, C.P. (1858). Teneriffe, An Astronomer's Experiment: or, Specialities of a Residence Above the Clouds. London: Lovell Reeve.

Smyth, C.P. (1863). Astronomical Observations made at the Royal Observatory, Edinburgh Vol XII 1863.

Steinbach, R., Perkins, C., Tompson, L., Johnson, S., Armstrong, B., Green, J., Grundy, C., Wilkinson, P., & Edwards, P. (2015). The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis. *Journal of Epidemiology and Community Health*, 69(11), 1118–1124. https://doi.org/10.1136/jech-2015-206012.

Stone, T., Santoni de Sio, F., & Vermaas, P. (2019). Driving in the Dark: Designing Autonomous Vehicles for Reducing Light Pollution. *Science and Engineering Ethics*, 26(1), 387–403. https://doi.org/10.1007/s11948-019-00101-7.

Sullivan, J., & Flannagan, M. (2002). The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. *Accident Analysis & Prevention*, 34(4), 487–498. https://doi.org/10.1016/s0001-4575(01)00046-x.

Treanor, P. (1973). A simple propagation law for artificial night-sky illumination. *The Observatory*, 93, 117. No doi. http://articles.adsabs.harvard.edu/pdf/1973Obs....93..117T.

Walker, A. & Schwarz, H. (2007.) Night Sky Brightness at Cerro Pachon. Unpublished. No doi. http://www.ctio.noao.edu/site/pachon_sky/. Accessed 22 September 2020.

Walker, M. (1977). The effects of urban lighting on the brightness of the night sky. *Publications of the Astronomical Society of the Pacific*, 89, 405. https://doi.org/10.1086/130142.

Wanvik, P. (2009a). Effects of road lighting: An analysis based on Dutch accident statistics 1987–2006. *Accident Analysis & Prevention*, 41(1), 123–128. https://doi.org/10.1016/j.aap.2008.10.003.

Wanvik, P. (2009b). Effects of Road Lighting on Motorways. *Traffic Injury Prevention*, 10(3), 279–289. https://doi.org/10.1080/15389580902826866.

Zamorano, J., Sánchez de Miguel, A., Rosillo, M., & Tapia, C. (2014). NixNox procedure to build Night Sky Brightness maps from SQM photometers observations. *Universidad Complutense de Madrid Preprints*, 26982. No doi. https://eprints.ucm.es/26982/

Zamorano, J., García, C., Tapia, C., Sánchez de Miguel, A., Pascual, S., & Gallego, J. (2017). STARS4ALL Night Sky Brightness Photometer. *International Journal of Sustainable Lighting*, 18, 49–54. https://doi.org/10.26607/ijsl.v18i0.21.

Junta de Andalucía (2019), "Spectral G index", technical handbook: http://www.juntadeandalucia.es/medioambiente/portal_web/web/temas_ambientales/atmosfera/contaminacion_luminica/5_iluminacion/indice_espectral_G/indexG_descrip.pdf

9.3 Bio-environment References

American Academy of Neurology’s 68th Annual Meeting in Vancouver, Canada, April 2016

American Medical Association. 2012.

Anisimov, V.N., Baturin, D.A., Popovich, I.G., et al. 2004. Effect of exposure to light-at-night on life span and spontaneous carcinogenesis in female CBA mice. Int J Cancer. 111:475-479.

Anbalagan, M., Dauchy, R.T., Xiang, S., et al. 2019. Disruption of the circadian melatonin signal by dim light at night promotes bone-lytic breast cancer metastases. Presented at: ENDO 2019; March 23-26, 2019

ANSES. 2010. Opinion of the French Agency for Food, Environmental and Occupational Health & Safety, ANSES Opinion, October 19, 2010. Archived April 29, 2014

Azam, C., Le Viol, I., Julien, J. F., Bas, Y., & Kerbiriou, C. (2016). Disentangling the relative effect of light pollution, impervious surfaces and intensive agriculture on bat activity with a national-scale monitoring program. *Landscape ecology*, *31*(10), 2471-2483.

Azam, C., Le Viol, I., Bas, Y., Zissis, G., Vernet, A., Julien, J. F., & Kerbiriou, C. (2018). Evidence for distance and illuminance thresholds in the effects of artificial lighting on bat activity. *Landscape and Urban Planning*, *175*, 123-135.

Baker, B. J., & Richardson, J. M. L. (2006). The effect of artificial light on male breeding-season behaviour in green frogs, Rana clamitans melanota. *Canadian Journal of Zoology*, *84*(10), 1528-1532.

Bará S, Lima RC, Photons without borders: quantifying light pollution transfer between territories, International Journal of Sustainable Lighting 20(2), 51-61 (2018) DOI:10.26607/ijsl.v20i2.87

Bará S, Rigueiro I, Lima RC. Monitoring transition: expected night sky brightness trends in different photometric bands. Journal of Quantitative Spectroscopy and Radiative Transfer, 239 (2019) 106644. https://doi.org/10.1016/j.jqsrt.2019.106644

Barghini, A., and B. A. S. de Medeiros. 2012. UV radiation as an attractor for insects. Leukos 9:47–56.

Bauer, S. E., S. E. Wagner, J. Burch, R. Bayakly, and J. E. Vena. 2013. A case-referent study: light at night and breast cancer risk in Georgia. International Journal of Health Geographics 12:23.

Beauchamp, G. 2007. Exploring the role of vision in social foraging: what happens to group size, vigilance, spacing, aggression and habitat use in birds and mammals that forage at night? Biological Reviews 82:511–525.

Bedrosian, T. A., Fonken, L. K. & Nelson, R. J. 2016. Endocrine effects of circadian disruption. Annual Review of Physiology 78:109–131.

Bedrosian, T. A., Fonken, L. K., Walton, J. C. &Nelson, R. J. . 2011. Chronic exposure to dim light at night suppresses immune response in Siberian hamsters. Biology Letters 7:468–471.

Behar-Cohen, F., Martinsons, C., Viénot, F., Zissis, G., Barlier-Salsi, A., Cesarini J.P. et al. 2011. Light-emitting diodes (LED) for domestic lighting: any risks for the eye? Prog Retin Eye Res; 30: 239–257.

Beier, P. 1995. Dispersal of juvenile cougars in fragmented habitat. Journal of Wildlife Management 59:228–237.

Beier, P. 2006. Effects of artificial night lighting on terrestrial mammals. Pages 19–42 in C. Rich and T.

Longcore, editors. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.Bennie, J., Davies, T. W., Cruse, D., & Gaston, K. J. (2016). Ecological effects of artificial light at night on wild plants. *Journal of Ecology*, *104*(3), 611-620.

Beniashvili, D.S., Benjamin, S., Baturin, D.A., et al. 2001. Effect of light/dark regimen on Nnitrosoethylurea-induced transplacental carcinogenesis in rats. Cancer Lett. 163:51-57.

Bennie, J., Davies, T. W., Cruse, D., Inger, R., & Gaston, K. J. (2015). Cascading effects of artificial light at night: resource-mediated control of herbivores in a grassland ecosystem. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1667), 20140131.

Bennie, J., T. W. Davies, D. Cruse, and K. J. Gaston. 2016. Ecological effects of artificial light at night on wild plants. Journal of Ecology 104:611–620.

Berge, J., Geoffroy, M., Daase, M., Cottier, F., Priou, P., Cohen, J. H., ... & Vogedes, D. (2020). Artificial light during the polar night disrupts Arctic fish and zooplankton behaviour down to 200 m depth. *Communications Biology*, 3(1), 1-8.

Bird, S., and J. Parker. 2014. Low levels of light pollution may block the ability of male glow-worms (Lampyris noctiluca L.) to locate females. Journal of Insect Conservation 18:737–743.

Blair, A. (2018). An Exploration of the Role that the Night Sky Plays in the Lives of the Dark Sky Island Community of Sark. Journal of Skyscape Archaeology, 3(2), 236–252. https://doi.org/10.1558/jsa.34689.

Blake, D., A. M. Hutson, P. A. Racey, J. Rydell, and J. R. Speakman. 1994. Use of lamplit roads by foraging bats in southern England. Journal of Zoology (London) 234:453–462.

Blask, D.E. 2009. Melatonin, sleep disturbance and cancer risk. Sleep Med Rev.; 13:257-264.

Blask, D.E., Brainard, G., Gibbons, R., Lockley, S., Stevens, R. & Motta, M.E. 2012. Light Pollution: Adverse Health Effects of Nighttime Lighting, Report 4 Of The Council On Science And Public Health (A-12). American Medical Association.

Blask, D.E., Brainard, G.C., Dauchy, R.T., et al. 2005. Melatonin-depleted blood from premenopausal women exposed to light at night stimulates growth of human breast cancer xenografts in nude rats. Cancer Res. 65:11174-11184.

Blask, D.E., Dauchy, R.T., Sauer, L.A., et al. 2003. Growth and fatty acid metabolism of human breast cancer (MCF-7) xenografts in nude rats: impact of constant light-induced nocturnal melatonin suppression. Breast Cancer Res Treat .79:313-320.

Blask, D.E., Hill, S.M., Dauchy, R.T., et al. 2011. Circadian regulation of molecular, dietary, and metabolic signaling mechanisms of human breast cancer growth by the nocturnal melatonin signal and the consequences of its disruption by light at night. J Pineal Res. 51:259-269.

Blask, D.E., Sauer, L.A., Dauchy, R.T., et al. 1999. Melatonin inhibition of cancer growth in vivo involves suppression of tumor fatty acid metabolism via melatonin receptor-mediated signal transduction events. Cancer Res. 59:4693-4701.

Bliss-Ketchum, L. L., C. E. de Rivera, B. C. Turner, and D. M. Weisbaum. 2016. The effect of artificial light on wildlife use of a passage structure. Biological Conservation 199:25–28.

Boldogh, S., D. Dobrosi, and P. Samu. 2007. The effects of the illumination of buildings on house-dwelling bats and its conservation consequences. Acta Chiropterologica 9:527–534.

Bolton, D., Mayer-Pinto, M., Clark, G. F., Dafforn, K. A., Brassil, W. A., Becker, A., & Johnston, E. L. (2017). Coastal urban lighting has ecological consequences for multiple trophic levels under the sea. *Science of the Total Environment*, *576*, 1-9.

Borniger, J.C., McHenry, Z.D., Abi Salloum, B.A. & Nelson, R.J. 2014. Exposure to dim light at night during early development increases adult anxiety-like responses. Physiol Behav. 133:99-106. doi:10.1016/j.physbeh.2014.05.012

Brzezinski, A. 1997. Melatonin in humans. N Engl J Med 336:186-95.

Briggs, W. R. 2006. Physiology of plant responses to artificial lighting. Pages 389–411 in C. Rich and T. Longcore, editors. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, DC.

Brillhart, D. B., and D. W. Kaufman. 1991. Influence of illumination and surface structure on space use by prairie deer mice (Peromyscus maniculatus bairdii). Journal of Mammalogy 72:764–768.

Brown, T. M. (2020). “Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions.” Journal of Pineal Research n/a(n/a): e12655.

Brüning, A., Hölker, F., Franke, S., Kleiner, W., & Kloas, W. (2018a). Influence of light intensity and spectral composition of artificial light at night on melatonin rhythm and mRNA expression of gonadotropins in roach Rutilus rutilus. *Fish physiology and biochemistry*, *44*(1), 1-12.

Brüning, A., Kloas, W., Preuer, T., & Hölker, F. (2018b). Influence of artificially induced light pollution on the hormone system of two common fish species, perch and roach, in a rural habitat. *Conservation Physiology*, *6*(1), coy016.

Butler, M. P., and R. Silver. 2011. Divergent photic thresholds in the non-image-forming visual system: entrainment, masking and pupillary light reflex. Proceedings of the Royal Society of London, Series B: Biological Sciences 278:745–750.

Cabrera-Cruz, S. A., Smolinsky, J. A., & Buler, J. J. (2018). Light pollution is greatest within migration passage areas for nocturnally-migrating birds around the world. *Scientific reports*, *8*(1), 3261.

Cabrera-Cruz, S. A., Smolinsky, J. A., McCarthy, K. P., & Buler, J. J. (2019). Urban areas affect flight altitudes of nocturnally migrating birds. *Journal of Animal Ecology*, *88*(12), 1873-1887.

Cajochen, C., Frey, S., Anders, D., et al. 2011. Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance. J Appl Physiol. 110:1432-8.

Cappuccio, F.P., Miller, M.A., Lockley, S.W., Eds. 2010. Sleep, health and society: From Aetiology to Public Health, Oxford, UK: Oxford University Press.

Carić, H., Mackelworth, P., 2014. Cruise tourism environmental impacts – the perspective from the Adriatic Sea. Ocean & Coastal Management 102, 350–363.

Carrillo-Vico, A., Guerrero, J. M., Lardone, P. J., & Reiter, R. J. (2005). A Review of the Multiple Actions of Melatonin on the Immune System. Endocrine, 27(2), 189–200. https://doi.org/10.1385/endo:27:2:189.

Cathey, H.M.; Campbell, L.E. (1975) Security lighting and its impact on the landscape. J. Arboric. 1, 181–187.

CBS-13 TV. 2014. Davis Will Spend $350,000 To Replace LED Lights After Neighbor Complaints, October 21, 2014 10:11 PM, Sacramento.

Chaban, M.A.V. 2015. LED Streetlights in Brooklyn Are Saving Energy but Exhausting Residents. March 23, 2015, New York Times.

Chapman, A.D. (2006). Numbers of living species in Australia and the World. Australian Biological Resources Study. ISBN 978-0-642-56850-2.

Cho, Y., Ryu, SH., Lee, B.R., Kim, K.H., Lee, E. & Choi, J. 2015. Effects of artificial light at night on human health: a literature review of observational and experimental studies applied to exposure assessment. Chronobiol Int. 32(9):1294-1310. doi:10.3109/07420528.2015.1073158

Cho, Y., Ryu, S.H., Lee, B.R., Kim, K.H., Lee, E. & Choi, J. 2015. Effects of artificial light at night on human health: a literature review of observational and experimental studies applied to exposure assessment. Chronobiol Int. 32(9):1294-1310. doi:10.3109/07420528.2015.1073158

Ciach, M., & Fröhlich, A. (2019). Ungulates in the city: light pollution and open habitats predict the probability of roe deer occurring in an urban environment. *Urban Ecosystems*, *22*(3), 513-523.

CIE Reference Standard S 026, 2018 http://cie.co.at/publications/cie-system-metrology-optical-radiation-iprgc-influenced-responses-light-0

Clarke, J. A. 1983. Moonlight's influence on predator/prey interactions between Short-eared Owls (Asio flammeus) and deermice (Peromyscus maniculatus). Behavioral Ecology and Sociobiology 13:205–209.

Contín, M. A., Benedetto, M. M., Quinteros-Quintana, M. L. & Guido, M. E. 2016. Eye, 30, 255–263.

Council on Science and Public Health Report 4. Light pollution. Adverse effects of nighttime lighting. 2012. American Medical Association, Annual Meeting, Chicago, IL.

Cravens, Z. M., Brown, V. A., Divoll, T. J., & Boyles, J. G. (2018). Illuminating prey selection in an insectivorous bat community exposed to artificial light at night. *Journal of Applied Ecology*, *55*(2), 705-713.

Cullen, P., & McCarthy, T. K. (2000, December). The effects of artificial light on the distribution of catches of silver eel, Anguilla anguilla (L.), Across the Killaloe eel weir in the lower River

Czeisler, C. A., T. L. Shanahan, E. B. Klerman, H. Martens, D. J. Brotman, J. S. Emens, T. Klein and J. F. Rizzo, III (1995). "Suppression of melatonin secretion in some blind patients by exposure to bright light." N. Engl. J. Med 332(1): 6-11.

Da Silva, A., J. M. Samplonius, E. Schlicht, M. Valcu, and B. Kempenaers. 2014. Artificial night lighting rather than traffic noise affects the daily timing of dawn and dusk singing in common European songbirds. Behavioral Ecology 25:1037–1047.

Da Silva, A., M. Valcu, and B. Kempenaers. 2015. Light pollution alters the phenology of dawn and dusk singing in common European songbirds. Philosophical Transactions of the Royal Society of London B: Biological Sciences 370:20140126.

Dauchy, R.T., Sauer, L.A., Blask, D.E., et al. 1997. Light contamination during the dark phase in "photoperiodically controlled" animal rooms: effect on tumor growth and metabolism in rats. Lab Anim Sci. 47:511-518.

Dauchy, R.T., Blask, D.E., Sauer, L.A., Brainard, G.C., Krause, J.A. 1999. Dim light during darkness stimulates tumor progression by enhancing tumor fatty acid uptake. Cancer Lett. 144:131-136.

Dauchy, R.T., Dupepe, L.M., Ooms, T.G., et al. 2011. Eliminating animal facility light-at-night contamination and its effect on circadian regulation of rodent physiology, tumor growth and metabolism: a challenge in the relocation of a cancer research laboratory. J Am Assoc Lab Anim Sci. 50:326-336.

Davies, T. W., Bennie, J., & Gaston, K. J. (2012). Street lighting changes the composition of invertebrate communities. *Biology letters*, *8*(5), 764-767.

De Jong, M., Caro, S. P., Gienapp, P., Spoelstra, K., & Visser, M. E. (2017). Early birds by light at night: effects of light color and intensity on daily activity patterns in blue tits. *Journal of biological rhythms*, *32*(4), 323-333.

De Molenaar, J. G., M. E. Sanders, and D. A. Jonkers. 2006. Road lighting and grassland birds: local influence of road lighting on a Black-tailed Godwit population. Pages 114–136 in C. Rich and T. Longcore, editors. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.

Dijk, D. J., T. L. Shanahan, J. F. Duffy, J. M. Ronda and C. A. Czeisler (1997). "Variation of electroencephalographic activity during non-rapid eye movement and rapid eye movement sleep with phase of circadian melatonin rhythm in humans." J Physiol 505 (Pt 3): 851-858.

Dominoni, D., M. Quetting, and J. Partecke. 2013a. Artificial light at night advances avian reproductive physiology. Proceedings of the Royal Society B: Biological Sciences 280:20123017.

Dominoni, D. M., E. O. Carmona-Wagner, M. Hofmann, B. Kranstauber, and J. Partecke. 2014. Individual-based measurements of light intensity provide new insights into the effects of artificial light at night on daily rhythms of urban-dwelling songbirds. Journal of Animal Ecology 83:681–692.

Dominoni, D. M., M. Quetting, and J. Partecke. 2013b. Long-term effects of chronic light pollution on seasonal functions of European Blackbirds (Turdus merula). PLoS ONE 8:e85069.Dominoni, D., Quetting, M., & Partecke, J. (2013). Artificial light at night advances avian reproductive physiology. *Proceedings of the Royal Society B: Biological Sciences*, *280*(1756), 20123017.

Duffy, J. F. and K. P. Wright, Jr. (2005). "Entrainment of the human circadian system by light." J Biol Rhythms 20(4): 326-338.

Durrant, J., Green, M. P., & Jones, T. M. (2019). Dim artificial light at night reduces the cellular immune response of the black field cricket, Teleogryllus commodus. Insect Science, 27(3), 571–582. https://doi.org/10.1111/1744-7917.12665.

Eisenbeis, G. 2006. Artificial night lighting and insects: attraction of insects to streetlamps in a rural setting in Germany. Pages 281–304 in C. Rich and T. Longcore, editors. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.

Eisesbeis, G. 2006. Artificial night lighting and insects: attraction of insects to streetlamps in a rural setting in Germany. Pages 281–304 in C. Rich and T. Longcore, editors. Ecological consequences of artificial night lighting. Island Press, Washington, DC.

European Green Deal. 2019. Accessed September 2020. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu/eu-biodiversity-strategy-2030_en

European Union. 2012. Scientific Committee on Emerging and Newly Identified Health Risks. Health Effects of Artificial Light. March 4, 2012 http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_033.pdf

Evans, J.A. & Davidson, A.J. 2013. Health consequences of circadian disruption in humans and animal models. Prog Mol Biol Transl Sci. 119:283-323.

Falchi, F. and Bará S. 2020. Protecting the night sky darkness in astronomical observatories: a linear systems approach. https://arxiv.org/abs/2008.09928

Falchi, F., Cinzano, P., Elvidge, C.D., Keith, D.M. & Haim, A. 2011. Limiting the impact of light pollution on human health, environment and stellar visibility. J Environ Manage. 92:2714-22.

Falkenberg, J. C., and J. A. Clarke. 1998. Microhabitat use of deer mice: effects of interspecific interaction risks. Journal of Mammalogy 79:558–565.

Ffrench-Constant, R. H., R. Somers-Yeates, J. Bennie, T. Economou, D. Hodgson, A. Spalding, and P. K. McGregor. 2016. Light pollution is associated with earlier tree budburst across the United Kingdom. Proceedings of the Royal Society B: Biological Sciences 283:20160813.

Filipski, E., Delaunay, F., King, V.M., et al. 2004. Effects of chronic jet lag on tumor progression in mice. Cancer Res. 64:7879-7885.

Filipski, E., Innominato, P.F., Wu, M., et al. 2005. Effects of light and food schedules on liver and tumor molecular clocks in mice. J Natl Cancer Inst. 97:507-517.

Fonken, L. K., & Nelson, R. J. 2014. The effects of light at night on circadian clocks and metabolism. Endocrine Reviews 35:648–670.

Fonken, L. K., Workman, J. L., Walton, J. C., Weil, Z. M., Morris, J. S.Haim, A. & Nelson, R. J. 2010. Light at night increases body mass by shifting the time of food intake. Proceedings of the National Academy of Sciences, USA 107:18664–18669.

Fontaine, C., Dajoz, I., Meriguet, J., & Loreau, M. (2005). Functional diversity of plant–pollinator interaction webs enhances the persistence of plant communities. *PLoS Biol*, *4*(1), e1.

Foster, J. J., Smolka, J., Nilsson, D. E., & Dacke, M. (2018). How animals follow the stars. *Proceedings of the Royal Society B: Biological Sciences*, *285*(1871), 20172322.

Frank, K. D. 1988. Impact of outdoor lighting on moths: an assessment. Journal of the Lepidopterists' Society 42:63–93.

Frank, K. D. 2006. Effects of artificial night lighting on moths. Pages 305–344 in C. Rich and T. Longcore, editors. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.

Frey, J. K. 1993. Nocturnal foraging by Scissor-tailed Flycatchers under artificial light. Western Birds 24:200.

Gangwisch, J.E. 2009. Epidemiological evidence for the links between sleep, circadian rhythms and metabolism. Obes Rev. 10 Suppl 2:37-45.

Garcia-Saenz, A., Sánchez de Miguel, A., Espinosa, A., Valentin, A., Aragonés, N., Llorca, J., Amiano, P., Martín Sánchez, V., Guevara, M., Capelo, R., Tardón, A., Peiró-Perez, R., Jiménez-Moleón, J. J., Roca-Barceló, A., Pérez-Gómez, B., Dierssen-Sotos, T., Fernández-Villa, T., Moreno-Iribas, C., Moreno, V., … Kogevinas, M. (2018). Evaluating the Association between Artificial Light-at-Night Exposure and Breast and Prostate Cancer Risk in Spain (MCC-Spain Study). Environmental Health Perspectives, 126(4), 047011. https://doi.org/10.1289/ehp1837.

Garcia-Saenz, A., de Miguel, A. S., Espinosa, A., Costas, L., Aragonés, N., Tonne, C., Moreno, V., Pérez-Gómez, B., Valentin, A., Pollán, M., Castaño-Vinyals, G., Aubé, M., & Kogevinas, M. (2020). Association Between Outdoor Light-at-night Exposure and Colorectal Cancer in Spain. Epidemiology, 31(5), 718–727. https://doi.org/10.1097/ede.0000000000001226.

Garrison, M.M., Leikweg, K. & Christakis, D.A. 2011. Media use and child sleep: the impact of content, timing, and environment. Pediatrics. 128:29-35.

Gaston, K. J., T. W. Davies, J. Bennie, and J. Hopkins. 2012. Reducing the ecological consequences of night-time light pollution: options and developments. Journal of Applied Ecology 49:1256–1266.

Gaston, K. J., J. Bennie, T. W. Davies, and J. Hopkins. 2013. The ecological impacts of nighttime light pollution: a mechanistic appraisal. Biological Reviews 88:912–927.

Gehring, J., P. Kerlinger, and A. M. Manville, II. 2009. Communication towers, lights, and birds: successful methods of reducing the frequency of avian collisions. Ecological Applications 19:505–514.

Gibbons, R.B & Edwards. C.J. 2007. A review of disability and discomfort glare research and future direction. Presented at the 18th Biennial TRB Visibility Symposium, College Station TX, United States, 17–19 April.

Goertz, J. W., A. S. Morris, and S. M. Morris. 1980. Ruby-throated Hummingbirds feed at night with the aid of artificial light. Wilson Bulletin 92:398–399.

Goodspeed, D., E. W. Chehab, A. Min-Venditti, J. Braam, and M. F. Covington. 2012. Arabidopsis synchronizes jasmonate-mediated defense with insect circadian behavior. Proceedings of the National Academy of Sciences of the United States of America 109:4674–4677.

Grimm, C., Wenzel, A., Williams, T., Rol, P., Hafezi, F., Remé, C et al. 2001. Rhodopsin-mediated blue-light damage to the rat retina: effect of photoreversal of bleaching. Invest Ophthalmol Vis Sci 42: 497–505.

Grimm, C. & Reme, C.E. 2013. Light damage as a model of retinal degeneration. Methods Mol Biol; 935: 87–97.

Grubisic, M., Singer, G., Bruno, M. C., van Grunsven, R. H., Manfrin, A., Monaghan, M. T., & Hölker, F. (2017). Artificial light at night decreases biomass and alters community composition of benthic primary producers in a sub-alpine stream. *Limnology and Oceanography*, *62*(6), 2799-2810.

Grubisic, M., Singer, G., Bruno, M. C., van Grunsven, R. H., Manfrin, A., Monaghan, M. T., & Hölker, F. (2018). A pigment composition analysis reveals community changes in pre-established stream periphyton under low-level artificial light at night. *Limnologica*, *69*, 55-58.

Grubisic, M., Haim, A., Bhusal, P., Dominoni, D. M., Gabriel, K. M. A., Jechow, A., Kupprat, F., Lerner, A., Marchant, P., Riley, W., Stebelova, K., van Grunsven, R. H. A., Zeman, M., Zubidat, A. E., & Hölker, F. (2019). Light Pollution, Circadian Photoreception, and Melatonin in Vertebrates. Sustainability, 11(22), 6400. https://doi.org/10.3390/su11226400.

Hagen, O., and V. R. Viviani. 2009. Investigation of the artificial night lighting influence in firefly (Coleoptera: Lampyridae) occurrence in the urban areas of Campinas and Sorocaba municipalities [extended abstract]. Pages 1–2 in Anais do IX Congresso de Ecologia do Brasil, São Lourenço.

Hansen, J., Stevens, R.G. 2011. Case–control study of shift-work and breast cancer risk in Danish nurses: Impact of shift systems. Eur J Cancer. Aug 16. [Epub ahead of print]

Hattar, S., Liao, H.W., Takao, M., Berson, D.M. & Yau, K.W. (2002). Melanopsin-containing retinal ganglion cells: architecture, projections, and intrinsic photosensitivity. Science, 295 (5557), 1065–70. Bibcode: 2002Sci...295.1065H. doi:10.1126/science.1069609. PMC 2885915. PMID 11834834.

Havlin, J. 1964. Zur Lösung der Amselfrage [The solution to the blackbird question]. Angewandte Ornithologie 2:9–14.

Henn, M., Nichols, H., Zhang, Y., & Bonner, T. H. (2014). Effect of artificial light on the drift of aquatic insects in urban central Texas streams. *Journal of Freshwater Ecology*, *29*(3), 307-318.

Higuchi, S., Motohashi, Y., Liu, Y., Ahara, M. & Kaneko, Y. 2003. Effects of VDT tasks with a bright display at night on melatonin, core temperature, heart rate, and sleepiness. J Appl Physiol. 94:1773-1776.

Hoffman, A.E., Yi, C.H., Zheng, T., et al. 2010. CLOCK in breast tumorigenesis: genetic, epigenetic, and transcriptional profiling analyses. Cancer Res. 70:1459-1468.

Hoffmann, J., Schirmer, A., & Eccard, J. A. (2019). Light pollution affects space use and interaction of two small mammal species irrespective of personality. *BMC ecology*, *19*(1), 1-11.

Hölker, F., T. Moss, B. Griefahn, W. Kloas, C. C. Voight, D. Henckel, A. Hänel, P. M. Kappeler, S. Völker, A. Schwope, S. Franke, D. Uhrlandt, J. Fischer, R. Klenke, C. Wolter, and K. Tockner. 2010a. The dark side of light: a transdisciplinary research agenda for light pollution policy. Ecology and Society 15:article 13.

Hölker, F., C. Wolter, E. K. Perkin, and K. Tockner. 2010b. Light pollution as a biodiversity threat. Trends in Ecology and Evolution 25:681–682.

Howell, J. C., Laskey, A. R., & Tanner, J. T. (1954). Bird mortality at airport ceilometers. *The Wilson Bulletin*, 207-215.

Hurley, S., D. Goldberg, D. Nelson, A. Hertz, P. L. Horn-Ross, L. Bernstein, and P. Reynolds. 2014. Light at night and breast cancer risk among California teachers. Epidemiology 25:697–706.

Huss, A., van Wel, L., Bogaards, L., Vrijkotte, T., Wolf, L., Hoek, G. & Vermeulen, R. 2019. Shedding Some Light in the Dark—A Comparison of Personal Measurements with Satellite-Based Estimates of Exposure to Light at Night among Children in the Netherlands. Enviro. Health Persp. 127, 6. doi.org/10.1289/EHP3431.

IARC. 2010. Monographs on the Evaluation of Carcinogenic Risks to Humans. Painting, Firefighting, and Shiftwork. Volume 98. http://monographs.iarc.fr/ENG/Monographs/vol98/index.php

Illuminating Engineering Society RP-8 – Guide to Roadway Lighting http://www.ies.org/? 2014

Inger, R., Bennie, J., Davies, T.W., Gaston, K.J. (2014) Potential Biological and Ecological Effects of Flickering Artificial Light. PLoS ONE 9(5): e98631. doi:10.1371/journal.pone.0098631

JAMA Psychiatry. doi:10.1001/jamapsychiatry.2020.1935 Published online July 8, 2020.

James, P., Bertrand, K.A., Hart, J.E., Schernhammer, E., Tamimi, R. M. & Laden, F. 2017. Outdoor Light at Night and Breast Cancer Incidence in the Nurses' Health Study II. Environmental Health Perspectives, August 17, 2017, doi: 10.1289/EHP935

Kantermann, T. & Roenneberg, T. 2009. Is light-at-night a health risk factor or a health risk predictor? Chronobiol Int; 26: 1069–1074.

Kempenaers, B., P. Borgström, P. Loës, E. Schlicht, and M. Valcu. 2010. Artificial night lighting affects dawn song, extra-pair siring success, and lay date in songbirds. Current Biology 20:1735–1739.

Keshet-Sitton,A., Or-Chen, K., Huber, E. & Haim A. 2016a. Illuminating a risk for breast cancer: A preliminary ecological study on the association between streetlight and breast cancer. Integr Cancer Ther.

Kim, Y.J., Lee, E., Lee, H.S., Kim, M., Park, M.S. 2015. High prevalence of breast cancer in light polluted areas in urban and rural regions of South Korea: An ecologic study on the treatment prevalence of female cancers based on National Health Insurance data. Chronobiol Int 32(5):657–667.

Klem, D., Jr. 1990. Collisions between birds and windows: mortality and prevention. Journal of Field Ornithology 61:120–128.

Kloog, I., A. Haim, and B. A. Portnov. 2009. Using kernel density function as an urban analysis tool: investigating the association between nightlight exposure and the incidence of breast cancer in Haifa, Israel. Computers, Environment and Urban Systems 33:55–63.

Kloog, I., A. Haim, R. G. Stevens, M. Barchana, and B. A. Portnov. 2008. Light at night co-distributes with incident breast but not lung cancer in the female population of Israel. Chronobiology International 25:65–81.

Kloog, I., A. Haim, R. G. Stevens, and B. A. Portnov. 2009. Global co-distribution of light at night (LAN) and cancers of prostate, colon, and lung in men. Chronobiology International 26:108–125.

Kloog, I., B. A. Portnov, H. S. Rennert, and A. Haim. 2011. Does the modern urbanized sleeping habitat pose a breast cancer risk? Chronobiology International 28:76–80.

Kloog, I., R. G. Stevens, A. Haim, and B. A. Portnov. 2010. Nighttime light level co-distributes with breast cancer incidence worldwide. Cancer Causes & Control 21:2059–2068.

Knop, E., Zoller, L., Ryser, R., Gerpe, C., Hörler, M., & Fontaine, C. (2017). Artificial light at night as a new threat to pollination. *Nature*, *548*(7666), 206-209.

Kocifaj and Barentine (2020). Submitted to *Science Advances*.

Kolligs, D. 2000. Ökologische Auswirkungen künstlicher Lichtquellen auf nachtaktive Insekten, insbesondere Schmetterlinge (Lepidoptera) [Ecological effects of artificial light sources on nocturnally active insects, in particular on moths (Lepidoptera)]. Faunistisch-Oekologische Mitteilungen Supplement 28:1–136.

Koo, Y.S., Song, J.Y., Joo, E.Y. et al. 2016. Outdoor artificial light at night, obesity, and sleep health: Cross-sectional analysis in the KoGES study. Chronobiol Int. 33(3):301-14.

Korkmaz, A., Topal, T., Tan, DX. & Reiter, R.J. 2009. Role of melatonin in metabolic regulation. Rev Endocr Metab Disord. 10:261-70.

Kotler, B. P. 1984. Effects of illumination on the rate of resource harvesting in a community of desert rodents. American Midland Naturalist 111:383–389.

Kramer, K. M., and E. C. Birney. 2001. Effect of light intensity on activity patterns of patagonian leaf-eared mice, Phyllotis xanthopygus. Journal of Mammalogy 82:535–544.

Kumar, P., Ashawat, M. S., Pandit, V., & Sharma, D. K. (2019). Artificial Light Pollution at Night: A Risk for Normal Circadian Rhythm and Physiological Functions in Humans. Current Environmental Engineering, 6(2), 111–125. https://doi.org/10.2174/2212717806666190619120211.

Kupprat, F., Hölker, F., & Kloas, W. (2020). Can skyglow reduce nocturnal melatonin concentrations in Eurasian perch?. *Environmental pollution* , *262*, 114324.

Kurvers, R. H., Drägestein, J., Hölker, F., Jechow, A., Krause, J., & Bierbach, D. (2018). Artificial light at night affects emergence from a refuge and space use in guppies. *Scientific Reports*, *8*(1), 1-10.

Kwak, M.; Je, S.; Cheng, H.; Seo, S.; Park, J.; Baek, S.; Khaine, I.; Lee, T.; Jang, J.; Li, Y.; et al. (2018) Night light-adaptation strategies for photosynthetic apparatus in Yellow-Poplar (Liriodendron tulipifera L.) exposed to artificial night lighting. Forests 9, 74.

Kwak, M.J.; Lee, S.H.; Khaine, I.; Je, S.M.; Lee, T.Y.; You, H.N.; Lee, H.K.; Jang, J.H.; Kim, I.; Woo, S.Y.

(2017) Stomatal movements depend on interactions between external night light cue and internal signals activated by rhythmic starch turnover and abscisic acid (ABA) levels at dawn and dusk. Acta Physiol. Plant. 39, 162.

Kyba, C. C. M., Ruthtz, T., Fischer, J., and Hölker, F. (2011), Lunar skylight polarization signal polluted by urban lighting, Geophys. Res., 116, D24106, doi:10.1029/2011JD016698

Kyba, C. C. M. et al. (2017). Artificially lit surface of Earth at night increasing in radiance and extent, Science Advances, 3:e1701528, doi:10.1126/sciadv.1701528

La Sorte, F. A., D. Fink, J. J. Buler, A. Farnsworth, and S. A. Cabrera-Cruz. 2017. Seasonal associations with urban light pollution for nocturnally migrating bird populations. Global Change Biology 23:4609–4619.

Lack, D. 1965. The life of the robin. H. F. & G. Witherby, London.

Le Tallec, T., Perret, M., & Théry, M. (2013). Light pollution modifies the expression of daily rhythms and behavior patterns in a nocturnal primate. *PloS one*, *8*(11), e79250.

LED Lighting Facts – A Program of the United States Department of Energy http://www.lightingfacts.com/

Lewanzik, D., & Voigt, C. C. (2014). Artificial light puts ecosystem services of frugivorous bats at risk. *Journal of applied ecology*, *51*(2), 388-394.

Lewis, A. & Gibbons, R., et al. 2016. Applicability of mesopic factors to the driving task. Lighting res technology, 48(1):70-82

Lewy, A., Wehr, T., Goodwin, F., Newsome, D., & Markey, S. (1980). Light suppresses melatonin secretion in humans. Science, 210(4475), 1267–1269. https://doi.org/10.1126/science.7434030.

Li, Q., Zheng, T., Holford, T.R., Boyle, P., Zhang, Y. & Dai, M. 2010. Light at night and breast cancer: results from a population-based case-control study in Connecticut, USA. Cancer Causes Control. 21:2281-2285.

Lie, J.A.S., Kjuus, H., Haugen, A., Zienolddiny, S., Stevens, R.G. & Kjærheim, K. 2011. Night work and breast cancer risk among Norwegian nurses: Assessment by different exposure metrics. Am J Epidemiol. 173:1272-1279.

Lissoni, P., Rovelli, F., Malugani, F., Bucovec, R., Conti, A. & Maestroni, G.J. 2001. Antiangiogenic activity of melatonin in advanced cancer patients. Neuro Endocrinol Lett. 22:45-47.

Lloyd, J. E. 2006. Stray light, fireflies, and fireflyers. Pages 345–364 in C. Rich and T. Longcore, editors. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.

Longcore, T., and C. Rich. 2004. Ecological light pollution. Frontiers in Ecology and the Environment 2:191–198.

Longcore, T. 2010. Sensory ecology: night lights alter reproductive behavior of blue tits. Current Biology 20:R893–R895.

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, S. A. Gauthreaux, Jr., M. L. Avery, R. L. Crawford, A. M. Manville, II, E. R. Travis, and D. Drake. 2012. An estimate of avian mortality at communication towers in the United States and Canada. PLoS ONE 7:e34025.

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, S. A. Gauthreaux, Jr., M. L. Avery, R. L. Crawford, A. M. Manville, II, E. R. Travis, and D. Drake. 2013. Avian mortality at communication towers in the United States and Canada: which species, how many, and where? Biological Conservation 158:410–419.

Longcore, T., H. Aldern, J. Eggers, S. Flores, L. Franco, E. Hirshfield-Yamanishi, L. Petrinec, W. Yan, and A. Barroso. 2015. Tuning the white light spectrum of light emitting diode lamps to reduce attraction of nocturnal arthropods. Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences 370:20140125.

Longcore, T., and C. Rich. 2017. Artificial Night Lighting and Protected Lands: Ecological Effects and Management Approaches (Revised August 2017). Natural Resource Report NPS/NRSS/NSNS/NRR—2017/1493. National Park Service, Fort Collins, Colorado.

Longland, W. S. (1994). Effects of artificial bush canopies and illumination on seed patch selection by heteromyid rodents. *American Midland Naturalist*, 82-90.

Lopes, J., Arnosti, D., Trosko, J.E., Tai, M.-H. & Zuccari D. 2016. Melatonin decreases estrogen receptor binding to estrogen response elements sites on the OCT4 gene in human breast cancer stem cells. Genes & Cancer, Vol. 7 (5-6).Lougheed, T. 2014. Hidden Blue Hazard? LED Lighting and Retinal Damage in Rats, Environ Health Perspect. DOI:10.1289/ehp.122-A81

Lowe, R. H. (1952). The influence of light and other factors on the seaward migration of the silver eel (Anguilla anguilla L.). *The Journal of Animal Ecology*, 275-309.

Lucas, R.J., Peirson, S.N., Berson, D.M., et al. 2014. Measuring and using light in the melanopsin age. Trends Neurosci. 37:1-9.

Ludvigsen, M., Berge, J., Geoffroy, M., Cohen, J. H., Pedro, R., Nornes, S. M., ... & Johnsen, G. (2018). Use of an autonomous surface vehicle reveals small-scale diel vertical migrations of zooplankton and susceptibility to light pollution under low solar irradiance. *Science advances*, *4*(1), eaap9887.

Luginbuhl, C. B., Walker, C. E. & Wainscoat, R. J. (2009). Lighting and astronomy. Physics Today 62, 12, 32 https://doi.org/10.1063/1.3273014

Lunn, R. M., Blask, D. E., Coogan, A. N., Figueiro, M. G. , Gorman, M. R., Hall, J. E., Hansen, J., Nelson, R. J., Panda, S. & Smolensky, M. H. 2017. Health consequences of electric lighting practices in the modern world: a report on the National Toxicology Program’s workshop on shift work at night, artificial light at night, and circadian disruption. Science of the Total Environment 607:1073–1084.

Macgregor, C.J.; Evans, D.M.; Fox, R.; Pocock, M.J.O. (2017) The dark side of street lighting: Impacts on moths and evidence for the disruption of nocturnal pollen transport. Glob. Chang. Biol. 23, 697–707.

Macgregor, C.J.; Pocock, M.J.O.; Fox, R.; Evans, D.M. (2019) Effects of street lighting technologies on the success and quality of pollination in a nocturnally pollinated plant. Ecosphere 10, e02550.

Macgregor, C. J., M. J. O. Pocock, R. Fox, and D. M. Evans. 2015. Pollination by nocturnal Lepidoptera, and the effects of light pollution: a review. Ecological Entomology 40:187–198.

Mao, L., Summers, W. , Xiang, S. Yuan, L., Dauchy, R.T., Reynolds, A., Wren-Dail, M.A., Pointer, D., Frasch, T., Blask, D.E. & Hill, S.M. 2016. Melatonin Represses Metastasis in Her2-Postive Human Breast Cancer Cells by Suppressing RSK2 Expression Mol Cancer Res; 14(11)

Marchant, P., J. D. Hale, and J. P. Sadler. 2020. Does changing to brighter road lighting improve road safety? Multilevel longitudinal analysis of road traffic collision frequency during the relighting of a UK city. Journal of Epidemiology and Community Health.

Marquioni-Ramella, M.D. & Suburo, A.M. 2015. Photo-damage, photoprotection and age-related macular degeneration. Photochem Photobiol Sci; 14: 1560–1577.

Massetti, L. Assessing the impact of street lighting on Platanus x acerifolia phenology. Urban For. Urban Green. 2018, 34, 71–77.

Matzke, E.B.(1936) The effect of street lights in delaying leaf-fall in certain trees. Am. J. Bot. 23, 446–452.

Mazur, M. M., & Beauchamp, D. A. (2006). Linking piscivory to spatial–temporal distributions of pelagic prey fishes with a visual foraging model. *Journal of Fish Biology*, *69*(1), 151-175.

McFarlane, R. W. 1963. Disorientation of loggerhead hatchlings by artificial road lighting. Copeia 1963:153.

McLaren, J. D., J. J. Buler, T. Schreckengost, J. A. Smolinsky, M. Boone, E. E. van Loon, D. K. Dawson, and E. L. Walters. 2018. Artificial light at night confounds broad-scale habitat use by migrating birds. Ecology Letters 21:356–364.

Meravi, N.; Kumar Prajapati, S. (2018) Effect street light pollution on the photosynthetic efficiency of different plants. Biol. Rhythm Res. 5167–75.

Meyer, L. A., and S. M. P. Sullivan. 2013. Bright lights, big city: influences of ecological light pollution on reciprocal stream–riparian invertebrate fluxes. Ecological Applications 23:1322–1330.

Miles, W., Money, S., Luxmoore, R., & Furness, R. W. 2010. Effects of artificial lights and moonlight on petrels at St Kilda. Bird Study *57*(2): 244–251.

Miller, M. W. 2006. Apparent effects of light pollution on singing behavior of American Robins. Condor 108:130–139.Manfrin, A., Lehmann, D., van Grunsven, R. H., Larsen, S., Syväranta, J., Wharton, G., ... & Hölker, F. (2018). Dietary changes in predators and scavengers in a nocturnally illuminated riparian ecosystem. *Oikos*, *127*(7), 960-969.

Moaraf, S., Vistoropsky, Y., Pozner, T., Heiblum, R., Okuliarová, M., Zeman, M., & Barnea, A. (2020). Artificial light at night affects brain plasticity and melatonin in birds. *Neuroscience Letters*, *716*, 134639.

Motta, M. et al. 2012. Council on Science and Public Health Report 4. Light pollution. Adverse effects of nighttime lighting. American Medical Association, Annual Meeting, Chicago, IL. 2012.

Mukhin, A., V. Grinkevich, and B. Helm. 2009. Under cover of darkness: nocturnal life of diurnal birds. Journal of Biological Rhythms 24:225–231.

Narisadam, K., & Schreduder, D. (2004). Light Pollution Handbook. Groningen, The Netherlands: Springer Netherlands 966p. ISBN 978140206669 https://doi.org/10.107/978-1-4020-2666-9

Nightingale, B., Longcore, T., & Simenstad, C. A. (2006). *Artificial night lighting and fishes* (pp. 257-276). Washington, DC: Island Press.

Nitschke, S.; Cortleven, A.; Iven, T.; Feussner, I.; Havaux, M.; Riefler, M.; Schmülling, T. (2016) Circadian stress regimes affect the circadian clock and cause jasmonic acid-dependent cell death in cytokinin-deficient arabidopsis plants. Plant Cell 28, 1616–1639.

Nobel Prize Medicine website: https://nobelprizemedicine.org. Accessed 2020 Oct 01.

Novotny, V.; Basset, Y.; Miller, S. E.; Weiblen, G. D.; Bremer, B.; Cizek, L; Drozd, P. (2002). “Low host specificity of herbivorous insects in a tropical forest”. Nature. 416 (6883): 841–844. doi:10.1038/416841a.

Nowak, J.Z. 2014. AMD—the retinal disease with an unprecised etiopathogenesis: in search of effective therapeutics. Acta Pol Pharm. 71: 900–916

Obayashi, K. 2018. Bedroom Light Exposure at Night and the Incidence of Depressive Symptoms. Am J Epidemiol. 187(3):427-434.

Obayashi, K., Saeki, K. & Kurumatani, N. 2018. Bedroom light exposure at night and the incidence of depressive symptoms: a longitudinal study of the HEIJO-KYO Cohort. Am J Epidemiol. 187(3): 427-434. doi:10.1093/aje/kwx290

Ohayon, M.M. & Milesi, C. 2016. Artificial outdoor nighttime lights associate with altered sleep behavior in the American general population. Sleep. 39(6):1311-1320. doi:10.5665/sleep.5860

O'Leary, E.S., Schoenfeld, E.R., Stevens, R.G., et al. 2006. Electromagnetic Fields and Breast Cancer on Long Island Study Group. Shift work, light at night, and breast cancer on Long Island, New York. Am J Epidemiol. 164:358-366.

Organisciak, D.T., Jiang, Y.L., Wang, H.M., Pickford, M. & Blanks, J.C. 1989. Retinal light damage in rats exposed to intermittent light. Comparison with continuous light exposure. Invest Ophthalmol Vis Sci; 30: 795–805

Ouyang, J.Q.; de Jong, M.; van Grunsven, R.H.A.; Matson, K.D.; Haussmann, M.F.; Meerlo, P.; Visser, M.E.; Spoelstra, K. Restless roosts: Light pollution affects behavior, sleep, and physiology in a free-living songbird. Glob. Chang. Biol. 2017, 23, 4987–4994.

Owens, A. C., Cochard, P., Durrant, J., Farnworth, B., Perkin, E. K., & Seymoure, B. (2020). Light pollution is a driver of insect declines. *Biological Conservation*, *241*, 108259.

Owens, A.C.S. & Lewis, S.M. (2018). The impact of artificial light at night on nocturnal insects: A review and synthesis. Ecology and Evolution. 2018;8:11337–11358. DOI: 10.1002/ece3.4557

Owens, J., Maxim, R., McGuinn, M., Nobile, C., Msall, M. & Alario, A. 1999. Television-viewing habits and sleep disturbances in school children. Pediatrics. 104;e27

Palmer, M., R. Gibbons, R. Bhagavathula, D. Davidson, and D. Holshouser. 2017. Roadway Lighting's Impact on Altering Soybean Growth: Volume 1. 0197-9191, Illinois Center for Transportation/Illinois Department of Transportation.

Patel, P.C. 2019. Light pollution and insufficient sleep: evidence from the United States. Am J Hum Biol. 31(6):e23300. doi:10.1002/ajhb.23300

Pauley, S.M. 2004. Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue. Med Hypotheses; 63: 588–596.

Pauwels, J., Le Viol, I., Azam, C., Valet, N., Julien, J. F., Bas, Y., ... & Kerbiriou, C. (2019). Accounting for artificial light impact on bat activity for a biodiversity-friendly urban planning. *Landscape and Urban planning*, *183*, 12-25.

Perkin, E. K., Hölker, F., Heller, S., & Berghahn, R. (2014). Artificial light and nocturnal activity in gammarids. *PeerJ*, *2*, e279.

Phillips, A. J. K., Vidafar, P., Burns, A. C., McGlashan, E. M., Anderson, C., Rajaratnam, S. M. W., Lockley, S. W., & Cain, S. W. (2019). High sensitivity and interindividual variability in the response of the human circadian system to evening light. Proceedings of the National Academy of Sciences, 201901824. https://doi.org/10.1073/pnas.1901824116.

Pietroiusti, A., Neri, A., Somma, G., et al. 2010. Incidence of metabolic syndrome among night-shift healthcare workers. Occup Environ Med. 67:54-57.

Polak, T., C. Korine, S. Yair, and M. W. Holderied. 2011. Differential effects of artificial lighting on flight and foraging behaviour of two sympatric bat species in a desert. Journal of Zoology 285:21–27.

Poulin, C., Bruyant, F., Laprise, M. H., Cockshutt, A. M., Marie-Rose Vandenhecke, J., & Huot, Y. (2014). The impact of light pollution on diel changes in the photophysiology of Microcystis aeruginosa. *Journal of plankton research*, *36*(1), 286-291.

Rawson, H. E. 1923. A bird's song in relation to light. Transactions of the Hertfordshire Natural History Society and Field Club 17:363–365.

Rebke, M., Dierschke, V., Weiner, C. N., Aumüller, R., Hill, K., & Hill, R. 2019. Attraction of nocturnally migrating birds to artificial light: The influence of colour, intensity and blinking mode under different cloud cover conditions. Biological Conservation 233: 220-227.

Reiter, R.J., Tan, D.X. & Fuentes-Broto, L. 2010. Melatonin: a multitasking molecule. Prog Brain Res. 181:127-51.

Resco, V., J. Hartwell, and A. Hall. 2009. Ecological implications of plants' ability to tell the time. Ecology Letters 12:583–592.

Rich, C., and T. Longcore, editors. 2006. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.

Riley, W. D., Davison, P. I., Maxwell, D. L., Newman, R. C., & Ives, M. J. (2015). A laboratory experiment to determine the dispersal response of Atlantic salmon (Salmo salar) fry to street light intensity. *Freshwater Biology*, *60*(5), 1016-1028.

Riou, S., and K. Hamer. 2008. Predation risk and reproductive effort: impacts of moonlight on food provisioning and chick growth in Manx Shearwaters. Animal Behaviour 76:1743–1748.

Ritonja, Jennifer, Michael A. McIsaac, Eric Sanders, Christopher CM Kyba, Anne Grundy, Emilie Cordina-Duverger, John J. Spinelli, and Kristan J. Aronson. "Outdoor light at night at residences and breast cancer risk in Canada." European Journal of Epidemiology (2020)1-11

Robert, K. A., Lesku, J. A., Partecke, J., & Chambers, B. (2015). Artificial light at night desynchronizes strictly seasonal reproduction in a wild mammal. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1816), 20151745.

Rodriguez, A., & Rodriguez, B. 2009. Attraction of petrels to artificial lights in the Canary Islands: effects of the moon phase and age class. Ibis 151(2):299–310.

Rodríguez, A., Burgan, G., Dann, P., Jessop, R., Negro, J. J., & Chiaradia, A. 2014. Fatal attraction of short-tailed shearwaters to artificial lights. PLoS One 9(10):e110114.

Rodríguez, A., García, D., Rodríguez, B., Cardona, E., Parpal, L., & Pons, P. 2015. Artificial lights and seabirds: is light pollution a threat for the threatened Balearic petrels?. Journal of Ornithology 156(4):893-902.

Rodríguez, A., Dann, P., & Chiaradia, A. 2017. Reducing light-induced mortality of seabirds: high pressure sodium lights decrease the fatal attraction of shearwaters. Journal for Nature Conservation 39:68-72.

Rohweder, D. A., and P. R. Baverstock. 1996. Preliminary investigation of nocturnal habitat use by migratory waders (Order Charadriiformes) in northern New South Wales. Wildlife Research 23:169–183.

Rotics, S., Dayan, T., & Kronfeld-Schor, N. (2011). Effect of artificial night lighting on temporally partitioned spiny mice. *Journal of Mammalogy*, *92*(1), 159-168.

Rowan, W. 1938. London starlings and seasonal reproduction in birds. Proceedings of the Zoological Society of London A108:51–78.

Russo, D., Cistrone, L., Libralato, N., Korine, C., Jones, G., & Ancillotto, L. (2017). Adverse effects of artificial illumination on bat drinking activity. *Animal Conservation*, *20*(6), 492-501.

Rybnikova, N., Haim, A., Portnov, B.A. 2015. Artificial light at night (ALAN) and breast cancer incidence worldwide: A revisit of earlier findings with analysis of current trends. Chronobiol Int 32(6):757–773,

Rybnikova, N., & Portnov, B. A. (2018). Population-level study links short-wavelength nighttime illumination with breast cancer incidence in a major metropolitan area. Chronobiology International, 35(9), 1198–1208. https://doi.org/10.1080/07420528.2018.1466802.

Rydell, J. (2006). Bats and their insect prey at streetlights. Pages 43–60 in C. Rich and T. Longcore, editors. Ecological Consequences of Artificial Night Lighting. Island Press, Washington, D.C.

Rydell, J., Eklöf, J., & Sánchez-Navarro, S. (2017). Age of enlightenment: long-term effects of outdoor aesthetic lights on bats in churches. *Royal Society open science*, *4*(8), 161077.

Saini, C., Hutton, P., Gao, S., Simpson, R. K., Giraudeau, M., Sepp, T., ... & McGraw, K. J. (2019). Exposure to artificial light at night increases innate immune activity during development in a precocial bird. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *233*, 84-88.

Sainz, R.M., Mayo, J.C., Rodriguez, C., et al. 2003. Melatonin and cell death: differential actions on apoptosis in normal and cancer cells. Cell Mol Life Sci. 60:1407-1426.

San-Jose, L. M., R. Séchaud, K. Schalcher, C. Judes, A. Questiaux, A. Oliveira-Xavier, C. Gémard, B. Almasi, P. Béziers, A. Kelber, A. Amar, and A. Roulin. 2019. Differential fitness effects of moonlight on plumage colour morphs in barn owls. Nature Ecology & Evolution.

Schernhammer, E.S., Hankinson, S.E. 2009. Urinary melatonin levels and postmenopausal breast cancer risk in the nurses' health study cohort. Cancer Epidemiol Biomarkers Prev. 18:74-79.

Schroer, S., Huggins, B. J., Azam, C., & Hölker, F. (2020). Working with inadequate tools: Legislative shortcomings in protection against ecological effects of artificial light at night. *Sustainability*, *12*(6), 2551.

Scigliano, E. 2013. Seattle's new LED-lit streets Blinded by the lights, Crosscut, March 18, 2013.

Shang, Y.-M., et al. 2014. White light–emitting diodes (LEDs) at domestic lighting levels and retinal injury in a rat model.. Environ Health Perspect 122(3):269–276.

Shannon. In *Biology and Environment: Proceedings of the Royal Irish Academy* (pp. 165-169). Royal Irish Academy.

Sheppard, C., and G. Phillips. 2015. Bird-Friendly Building Design, 2nd Ed., American Bird Conservancy, The Plains, Virginia.

Shuboni, D., and L. Yan. 2010. Nighttime dim light exposure alters the responses of the circadian system. Neuroscience 170:1172–1178.

Sick, H., and D. M. Teixeira. 1981. Nocturnal activities of Brazilian hummingbirds and flycatchers at artificial illumination. Auk 98:191–192.

Siu, T.L., Morley, J.W. & Coroneo, M.T. 2008. Toxicology of the retina: advances in understanding the defence mechanisms and pathogenesis of drug- and light-induced retinopathy. Clin Experiment Ophthalmol; 36: 176–185

Skaf, J. R. G., E. T. Hamanishi, O. Wilkins, S. Raj, and M. M. Campbell. 2010. The impact of artificial night lighting in an urban environment on plant photosynthesis and gene expression. Plant Biology 2010. American Society of Plant Biologists and Canadian Society of Plant Physiologists, Montréal, Canada.

Škvareninová, J., M. Tuhárska, J. Škvarenina, D. Babálová, L. Slobodníková, B. Slobodník, H. Středová, and J. Minďaš. 2017. Effects of light pollution on tree phenology in the urban environment. Moravian Geographical Reports 25:282–290.

Smolensky, M.H., Sackett-Lundeen, L.L. & Portaluppi, F. 2015. Nocturnal Light Pollution and Underexposure to Daytime Sunlight: Complementary Mechanisms of Circadian Disruption and Related Diseases. Taylor & Francis.

Spoelstra, K., van Grunsven, R. H., Ramakers, J. J., Ferguson, K. B., Raap, T., Donners, M., ... & Visser, M. E. (2017). Response of bats to light with different spectra: light-shy and agile bat presence is affected by white and green, but not red light. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1855), 20170075.

Squires, W. A., & Hanson, H. E. (1918). The destruction of birds at the lighthouses on the coast of California. *The Condor*, *20*(1), 6-10.

Stevens, R.G. 1987. Review and Commentary: Electric power use and breast cancer: a hypothesis. Am J Epidemiol. 125:556-561.

Stevens, R.G. 2009. Light at night, circadian disruption, and breast cancer: assessment of existing evidence. Int J Epidemiol. 38:963-970

Stevens, R.G., Brainard, G.C., Blask, D.E., Lockley, S.W. & Motta, M.E. 2014. Breast cancer and circadian disruption from electric lighting in the modern world. CA Cancer J Clin. 64:207-18.

Stevens, R.G., Hansen, J., Costa, G., et al. 2011. Considerations of circadian impact for defining ‘shift work’ in cancer studies: IARC Working Group Report. Occup Environ Med. 68:154- 162.

Stone, E. L., S. Harris, and G. Jones. 2015. Impacts of artificial lighting on bats: a review of challenges and solutions. Mammalian Biology-Zeitschrift für Säugetierkunde 80:213–219.

Stone, E. L., G. Jones, and S. Harris. 2009. Street lighting disturbs commuting bats. Current Biology 19:1123–1127.

Stone, E. L., G. Jones, and S. Harris. 2012. Conserving energy at a cost to biodiversity? Impacts of LED lighting on bats. Global Change Biology 18:2458–2465.

Stracey, C. M., B. Wynn, and S. K. Robinson. 2014. Light pollution allows the Northern Mockingbird (Mimus polyglottos) to feed nestlings after dark. The Wilson Journal of Ornithology 126:366–369.

Straif, K., Baan, R., Grosse, Y., et al. 2007. Carcinogenicity of shift-work, painting, and fire-fighting. Lancet Oncol. 8:1065-1066.

Stothard, E. R., et al. (2017). “Circadian Entrainment to the Natural Light-Dark Cycle across Seasons and the Weekend.” Curr Biol 27: 1-6. ;

Sustek, Z. 1999. Light attraction of carabid beetles and their survival in the city centre. Biologia (Bratislava) 54:539–551.

Sutherland, D. R., and M. Predavec. 1999. The effects of moonlight on microhabitat use by Antechinus agilis (Marsupialia: Dasyuridae). Australian Journal of Zoology 47:1–17.

Sweater-Hickcox, K., Narendran, N., Bullough, J.D., & Freyssinier, J.P. 2013 Effect of different coloured luminous surrounds on LED discomfort glare perception. Lighting Research Technology. 45(4):464-75.

Szaz, D., Horvath, G., Barta, A., Robertson, B. A., Farkas, A., Egri, A., ... & Kriska, G. (2015). Lamp-lit bridges as dual light-traps for the night-swarming mayfly, Ephoron virgo: interaction of polarized and unpolarized light pollution. *PLoS One*, *10*(3), e0121194.

Tabor, R. A., Brown, G. S., & Luiting, V. T. (2004). The effect of light intensity on sockeye salmon fry migratory behavior and predation by cottids in the Cedar River, Washington. *North American Journal of Fisheries Management*, *24*(1), 128-145.

Telfer, T. C., Sincock, J. L., Byrd, G. V., & Reed, J. R. 1987. Attraction of Hawaiian seabirds to lights: conservation efforts and effects of moon phase. Wildlife Society Bulletin (1973-2006) 15(3):406-413.

Thomas, R. J., T. Székely, I. C. Cuthill, D. G. C. Harper, S. E. Newson, T. D. Frayling, and P. D. Wallis. 2002. Eye size in birds and the timing of song at dawn. Proceedings of the Royal Society of London B 269:831–837.

Tillmann, J. E. 2009. Fear of the dark: night-time roosting and anti-predation behaviour in the grey partridge (Perdix perdix L.). Behaviour 146:999–1023.

Titulaer, M., K. Spoelstra, C. Y. M. J. G. Lange, and M. E. Visser. 2012. Activity patterns during food provisioning are affected by artificial light in free living great tits (Parus major). PLoS ONE 7:e37377.

Topping, M. G., J. S. Millar, and J. A. Goddard. 1999. The effects of moonlight on nocturnal activity in bushy-tailed wood rats (Neotoma cinerea). Canadian Journal of Zoology 77:480–485.

Torres, D., Tidau, S., Jenkins, S., & Davies, T. (2020). Artificial skyglow disrupts celestial migration at night. Current Biology 30, R1–R3.

Travlos, G.S., Wilson, R.E., Murrell, J.A., et al. 2001. The effect of short intermittent light exposures on the melatonin circadian rhythm and NMU-induced breast cancer in female F344/N rats. Toxicol Pathol.29: 126-136.

Upham, N. S., and J. C. Hafner. 2013. Do nocturnal rodents in the Great Basin Desert avoid moonlight? Journal of Mammalogy 94:59–72.

Van den Heiligenberg, S., Deprés-Brummer, P., Barbason, H. et al. 1999. The tumor promoting effect of constant light exposure on diethylnitrosamine-induced hepatocarcinogenesis in rats. Life Sci.;64:2523-2534.

Van Doren, B. M., K. G. Horton, A. M. Dokter, H. Klinck, S. B. Elbin, and A. Farnsworth. 2017. High-intensity urban light installation dramatically alters nocturnal bird migration. Proceedings of the National Academy of Sciences 114:11175–11180.

van Grunsven, R. H., Jähnichen, D., Grubisic, M., & Hölker, F. (2018). Slugs (Arionidae) benefit from nocturnal artificial illumination. *Journal of Experimental Zoology Part A: Ecological and Integrative*

Physiology, *329*(8-9), 429-433.

van Langevelde, F., J. A. Ettema, M. Donners, M. F. WallisDeVries, and D. Groenendijk. 2011. Effect of spectral composition of artificial light on the attraction of moths. Biological Conservation 144:2274–2281.

Vasquez, R. A. 1994. Assessment of predation risk via illumination level: facultative central place foraging in the cricetid rodent Phyllotis darwini. Behavioral Ecology and Sociobiology 34:375–381.

Viviani, V. R., M. Y. Rocha, and O. Hagen. 2010. Fauna de besouros bioluminescentes (Coleoptera: Elateroidea: Lampyridae; Phengodidae, Elateridae) nos municípios de Campinas, Sorocaba-Votorantim e Rio Claro-Limeira (SP, Brasil): biodiversidade e influência da urbanização. Biota Neotropica 10:103–116.

Voigt, C. C., Roeleke, M., Marggraf, L., Pētersons, G., & Voigt-Heucke, S. L. (2017). Migratory bats respond to artificial green light with positive phototaxis. *PLoS One*, *12*(5), e0177748.

Voigt, C. C., Azam, C., Dekker, J., Ferguson, J., Fritze, M., Gazaryan, S., ... & Lewanzik, D. (2018). Guidelines for consideration of bats in outdoor lighting projects. Bonn: Eurobats Publ, (8).

Vos, J. J. 2003. “On the cause of disability glare and its dependence on glare angle, age and ocular pigmentation,” Clin. Exp. Optom. 86(6), 363–370.

Walls, H.L., Walls, K.L., & Benke, G. 2011. Eye disease resulting from increased use of fluorescent lighting as a climate change mitigation strategy. Am J Public Health. 101: 2222–2225.

Walmsley, L., Hanna, L., Mouland, J., Martial, F., West, A., Smedley, A. R., Bechtold, D. A., Webb, A. R., Lucas, R. J., & Brown, T. M. (2015). Colour As a Signal for Entraining the Mammalian Circadian Clock. PLOS Biology, 13(4), e1002127. https://doi.org/10.1371/journal.pbio.1002127.

Wang, T., and D. M. Shier. 2018. Effects of anthropogenic lighting on San Bernardino kangaroo rat (Dipodomys merriami parvus) foraging behavior, persistence and fitness. Revised final report to U.S. Fish and Wildlife Service. San Diego Zoo Institute for Conservation Research, San Diego, California.

Wang, T. B., and D. M. Shier. 2017. Effects of anthropogenic lighting on Pacific pocket mouse (Perognathus longimembris pacificus) foraging behavior, persistence and fitness. Final Report prepared for Wildlife Management Branch Environmental Security Dept. Marine Corps, Base Camp Pendleton. San Diego Zoo Institute for Conservation Research, San Diego.

Wang, W., J. Y. Barnaby, Y. Tada, H. Li, M. Tör, D. Caldelari, D.-u. Lee, X.-D. Fu, and X. Dong. 2011. Timing of plant immune responses by a central circadian regulator. Nature 460:110–114.

Williams, C. B. 1936. The influence of moonlight on the activity of certain nocturnal insects, particularly of the family Noctuidae, as indicated by a light trap. Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences 266:357–389.

Wright, K.P. Jr, McHill, A.W., Birks, B.R., Griffin, B.R., Rusterholz, T. & Chinoy, E.D. 2013. Entrainment of the human circadian clock to the natural light-dark cycle. Curr. Biol. 23:1554-8.

Wu, J., Dauchy, R.T., Tirrell, P.C., et al. 2011. Light at night activates IGF-1R/PDK1 signaling and accelerates tumor growth in human breast cancer xenografts. Cancer Res. 71:2622- 2631.

Wu, J., Seregard, S. & Algvere, P.V. 2006. Photochemical damage of the retina. Surv Ophthalmol; 51: 461–481.

Xiao, Q., Gee, G., Jones, R.R., Jia, P., James, P. & Hale, L. 2020. Cross-sectional association between outdoor artificial light at night and sleep duration in middle-to-older aged adults: The NIH-AARP Diet and Health Study. Environ Res. 180:108823. doi:10.1016/j.envres.2019.108823.

Xiao, Q., James, P., Breheny, P., Jia, P., Park, Y., Zhang, D., Fisher, J.A., Ward, M.H. & Jones, R.R. 2020. Outdoor light at night and postmenopausal breast cancer risk in the NIH-AARP diet and health study. International Journal of Cancer.

Yandan Lin. Model predicting discomfort glare caused by LED road lights. 28 July 2014 | Vol. 22, No. 15 | DOI:10.1364/OE.22.018056 | OPTICS EXPRESS 18056

Yurk, H., & Trites, A. W. (2000). Experimental attempts to reduce predation by harbor seals on out-migrating juvenile salmonids. *Transactions of the American Fisheries Society*, *129*(6), 1360-1366.

Zhang, S., X. Chen, J. Zhang, and H. Li. 2014. Differences in the reproductive hormone rhythm of tree sparrows (Passer montanus) from urban and rural sites in Beijing: the effect of anthropogenic light sources. General and Comparative Endocrinology 206:24–29.

Zubidat, A. E., R. Ben-Shlomo, and A. Haim. 2007. Thermoregulatory and endocrine responses to light pulses in short-day acclimated social voles (Microtus socialis). Chronobiology International 24:269–288.

Zubidat, A. E., R. J. Nelson, and A. Haim. 2010. Differential effects of photophase irradiance on metabolic and urinary stress hormone concentrations in blind and sighted rodents. Chronobiology International 27:1–29.

9.4 Satellite Constellations References

Barrado, D., Thiele, U., Aceituno, J., Pedraz, S., Sanchez, S. F., Aguirre, A., Alises, M., Bergond, G., Galadi, D., Guijarro, A., Hoyo, F., Mast, D., Montoya, L., Sengupta, C., de Guindos, E., & Solano, E. (2010). *The Calar Alto Observatory: current status and future instrumentation*. https://arxiv.org/abs/1012.2099

Bastida Virgili, B., Dolado, J. C., Lewis, H. G., Radtke, J., Krag, H., Revelin, B., Cazaux, C., Colombo, C., Crowther, R., & Metz, M. (2016). Risk to space sustainability from large constellations of satellites. *Acta Astronautica*. https://doi.org/10.1016/j.actaastro.2016.03.034

Brown, T. M., Baliber, N., Bianco, F. B., Bowman, M., Burleson, B., Conway, P., Crellin, M., Depagne, É., De Vera, J., Dilday, B., Dragomir, D., Dubberley, M., Eastman, J. D., Elphick, M., Falarski, M., Foale, S., Ford, M., Fulton, B. J., Garza, J., … Willis, M. (2013). Las Cumbres Observatory Global Telescope Network. *Publications of the Astronomical Society of the Pacific*. https://doi.org/10.1086/673168

Catalina Sky Survey, https://catalina.lpl.arizona.edu

Char, F., Unda-Sanzana, E., Colque, J., Fossey, S., and Rocchetto, M. (2016). Ckoirama, the first Chilean--state owned observatory under desert skies. *Boletin de la Asociacion Argentina de Astronomia La Plata Argentina*, 58 200.

Daehnick, C., Klinghoffer, I., Maritz, B., Wiseman, B. (2020). *Large LEO satellite constellations: Will it be different this time?* https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/large-leo-satellite-constellations-will-it-be-different-this-time

ESA's Annual Space Environment Report (2019), Space Debris Office, Issue3.2. Reference: GEN-DB-LOG-00271-OPS-SD. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

Hainaut, O. R., & Williams, A. P. (2020). Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains. *Astronomy and Astrophysics*. https://doi.org/10.1051/0004-6361/202037501

Inter-Agency Space Dedbris Coordination Committee. (2007). IADC Space Debris Mitigation Guidelines. *IADC Space Debris Mitigation Guidelines*.

Grigorevskij, V.M. (1959). About Methods of Photometry of Artificial Earth's Satellites. Byulleten' Stantsii Nablyudenia ISZ, 7, 14.

Hot-wiring the Transient Universe III, Wozniak, Graham, Mahabal, & Seaman, eds, https://www.slac.stanford.edu/econf/C131113.1/

Hot-wiring the Transient Universe VI, Margutti, R., et al, https://sites.northwestern.edu/hotwired6/

Jordi et al. 2006 Jordi, K., Grebel, E.K., and Ammon, K. (2006). Empirical color transformations between SDSS photometry and other photometric systems. Astronomy and Astrophysics, 460(1), 339. 10.1051/0004-6361:20066082

Las Cumbres Observatory, https://lco.global

Minnaert, M. (1941). The reciprocity principle in lunar photometry. The Astrophysical Journal, 93 403. 10.1086/144279

McDowell, J. C. (2020). The Low Earth Orbit Satellite Population and Impacts of the SpaceX Starlink Constellation. *The Astrophysical Journal*. https://doi.org/10.3847/2041-8213/ab8016

McDowell, J. (2020b), private communication based on the analysis of data publicly available at https://planet4589.org/space/stats/megacon/starbad.html

Moore, J. G. (1959). Photometric Observations of the Second Soviet Satellite (1957 β1). *Publications of the Astronomical Society of the Pacific*. https://doi.org/10.1086/127354

Pan-STARRS, https://www.ifa.hawaii.edu/research/Pan-STARRS.shtml

Pearce, E., Avner, L., Block, A., Krantz, H., and Rockowitz, K. (2018). POMENIS: A Small Portable Astrograph for Synoptic SSA. The Advanced Maui Optical and Space Surveillance Technologies Conference, 56.

Ragazzoni, R. (2020). The Surface Brightness of MegaConstellation Satellite Trails on Large Telescopes. *Publications of the Astronomical Society of the Pacific*. https://doi.org/10.1088/1538-3873/abaca8

Rascon, M., Jannuzi, B., Neff, D., Teran, J., Hinz, P., Zaritsky, D., Martin, H. M., Kingsley, J., Angel, R., Davison, W., Oh, C. J., Kim, D. W., Pearce, E., Connors, T., Alfred, D., Christensen, E., Assenmacher, W., Peyton, K., Males, J., … Adriaanse, D. (2018). *An inexpensive turnkey 6.5-m observatory with customizing options*. https://doi.org/10.1117/12.2313889

Rhodes, B. (2019). Skyfield: High precision research-grade positions for planets and Earth satellites generator. Astrophysics Source Code Library, ascl:1907.024.

Souvari, J.M. (1979). Photometry of Artificial Satellites Application to the Ground Electro-Optical Deep Space Surveillance (GEODSS) Program. MIT Lincoln Laboratory Technical Note 1979-61.

Stamnes, K., Thomas, G., & Stamnes, J. (1999). *Radiative Transfer in the Atmosphere and Ocean.* Cambridge University Press.

Sutherland, W., Emerson, J., Dalton, G., Atad-Ettedgui, E., Beard, S., Bennett, R., Bezawada, N., Born, A., Caldwell, M., Clark, P., Craig, S., Henry, D., Jeffers, P., Little, B., McPherson, A., Murray, J., Stewart, M., Stobie, B., Terrett, D., … Woodhouse, G. (2015). The Visible and Infrared Survey Telescope for Astronomy (VISTA): Design, technical overview, and performance. *Astronomy and Astrophysics*. https://doi.org/10.1051/0004-6361/201424973

Tyson, J. A., Ivezić, Ž., Bradshaw, A., Rawls, M. L., Xin, B., Yoachim, P., Parejko, J., Greene, J., Sholl, M., Abbott, T. M. C., & Polin, D. (2020). *Mitigation of LEO Satellite Brightness and Trail Effects on the Rubin Observatory LSST*. http://arxiv.org/abs/2006.12417

Tregloan-Reed, J., Otarola, A., Ortiz, E., Molina, V., Anais, J., González, R., Colque, J.P., and Unda-Sanzana, E. (2020). First observations and magnitude measurement of Starlink's Darksat. Astronomy and Astrophysics, 637 L1. https://doi.org/10.1051/0004-6361/202037958

Tregloan-Reed, J., Otarola, A., Unda-Sanzana, E. et al. (2020). Under review in Astronomy and Astrophysics. arXiv e-prints, arXiv:2011.01820, https://arxiv.org/abs/2011.01820

Vera C. Rubin Observatory, https://www.lsst.org

Walker, C., Hall, J., Allen, L., Green, R., Seitzer, P., Tyson, ., Bauer, A., Krafton, K., Lowenthal, J., Parriott, J., Puxley, P., Abbott, T., Bakos, G., Barentine, J., Bassa, C., Blakeslee, J., Bradshaw, A., Cooke, J., Devost, D., … Yoachim, P. (2020). Impact of Satellite Constellations on Optical Astronomy and Recommendations Toward Mitigations. *Bulletin of the AAS*. https://doi.org/10.3847/25c2cfeb.346793b