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Recommendations to Keep Dark and Quiet Skies for Science and Society

Paper submitted by Chile, Ethiopia, Jordan, Slovakia, Spain and the International Astronomical Union

I. Introduction and Background

1. As requested by COPUOS, the UN Office of Outer Space Affairs, the International Astronomical Union (IAU) and Spain are organizing a Conference on "Dark and Quiet Skies for Science and Society", postponed to October 2021 as a result of the Covid-19 pandemic (See A/72/20). An online Workshop was held from 5 to 9 October 2020 to discuss initial findings and draft recommendations. The present Conference Room Paper (CRP) explains the issues astronomy faces and sets out those recommendations. The Scientific and Technical Sub-Committee is invited to comment on the recommendations proposed in this CRP. The comments will be reviewed after the Sub-Committee's meeting in April 2021. The CRP will then be revised and presented to the COPUOS Meeting in August 2021.

2. Astronomy is one of humanity's oldest sciences and underpins our exploration and use of outer space. Fantastic progress in understanding our Universe has been made possible by 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.

3. The knowledge that we acquire from the study of celestial phenomena not only provides a deeper understanding of our place in the Universe, but also leads 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 anthropogenic interference. Moreover, beyond science and technology, the pristine

* Reissued for technical reasons on 27 April 2021.

spectacle of the starry night sky has been inspirational to humankind since prehistoric times and this world cultural heritage should be zealously protected.

4. The online Workshop was very successful, with more than 970 registered participants, while each daily session was followed by between 250 to 380 online attendees. A draft report, prepared during the preceding months by internationally recognized experts, was made available to the registered participants prior to the event. All participants were then invited to submit written comments within one week of the Workshop's conclusion. Their comments were then used to finalize the Workshop Report.

5. The final Workshop Report represents the most up-to-date and authoritative analysis of the impact on astronomy by three classes of interference: artificial light at night (ALAN), the large number of low-Earth orbit (LEO) satellite trails, and radio-wavelength emission. (In the Workshop Report, ALAN is divided into three areas, dark skies oases, optical astronomy, and the bio-environment, described in Paragraph #8.) 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, detailed here: https://www.iau.org/static/publications/dqskies-book-29-12-20.pdf.

6. This CRP is drawn from the final Workshop Report. In preparing the CRP, all sources of electromagnetic interference that currently affect or endanger the visibility of the pristine night sky and the conduct of astronomical science have been considered, and the present report identifies measures that avoid or mitigate their negative impacts. The recommendations are technically and economically feasible and do not affect the main purposes behind the sources of interference, from providing safety-driven urban illumination to enabling space-based internet in remote areas.

7. The CRP is composed of a general executive summary followed by the topical executive summaries and recommendations in five areas: 1) The Impact of Satellite Constellations on the Science of Astronomy, 2) Protection of Dark Sky Oases, 3) Protection of Ground-Based Optical Astronomy Sites and Related Science, 4) Protection of the Bio-Environment, and 5) Protection of Radio Astronomy Sites and Related Science. (In this document the term "bio-environment" refers to flora and fauna, and humans, all of which can be affected by ALAN.)

II. General Executive Summary

8. This report analyses all types of artificial interference that may have a negative impact on the visibility of the night sky and astronomical science. The sources of interference can be logically grouped into three categories according to type. The first category refers to the impact of satellite constellations on the field of astronomy as well as the ability for people to view a pristine, starry night sky. The second category refers to the effect caused by the artificial emission of light during the night, also known as artificial light at night (ALAN). Illumination can be a great technological advantage to our society. However, excessive, ubiquitous and improperly directed illumination has significant negative impacts on dark skies oases, optical astronomy and the bio-environment (including human health). The third category is the effect on the field of radio astronomy. These categories will be detailed in five individual topical executive summaries in the next sections.

A. The Impact of Satellite Constellations on the Science of Astronomy

9. The pending deployment of tens of thousands of communication satellites in LEO is a very recent technological capability. The main purpose of these satellite constellations is to provide low-latency communication networking to any inhabited region of the globe. While this endeavour may represent a huge advantage to society, the effect of fully deployed constellations on the visibility of the night sky and on

professional astronomical observations has not been adequately considered. Owing to their low orbits, a considerable number of satellites may be visible to the unaided eye, especially at low elevations above the horizon near 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. The impact is particularly dramatic for wide-field telescopes and automated surveys aimed at detecting moving objects, e.g., the COPUOS-supported International Asteroid Warning Network (IAWN). It is estimated that up to 30–40 per cent of the images taken by a wide-field telescope like the Simonyi Survey Telescope at Vera C. Rubin Observatory would be adversely impacted. 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 remit of the UN COPUOS. The situation is certainly complex, both from the technical point of view and in terms of the possible regulatory aspects. Therefore, a larger section of the report has been devoted to this matter.

B. Protection of Dark Sky Oases

10. It is unrealistic to re-establish a pristine night sky within the boundaries of a modern city, where street illumination is mandatory for public safety reasons. However, in order to protect the right of any citizen to enjoy the vision of the starry sky, we recommend that national and local governments establish a suitable number of "dark sky oases" and protect them from excessive ALAN. In order to protect them, especially if they are located near densely populated regions, urban illumination has to comply with a number of prescriptions that can mitigate the outward diffusion of light, including reducing the level of illumination to the minimum necessary to ensure public safety and directing the light sources only toward where light is 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 promote societal conservation of natural resources.

C. Protection of Ground-Based Optical Astronomy Sites and Related Science

11. 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 represent large public investments, and governments have an interest in protecting a suitable area surrounding each observatory by adopting and enforcing specific regulations. In many 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 a clear assurance of enforced protection from ALAN is included in international hosting agreements. This is one of the reasons why this matter is being brought to the attention of the UN Committee for the Peaceful Uses of Outer Space (COPUOS), which offers the best international forum in which to propose a uniform approach to the matter.

D. Protection of the Bio-Environment

12. In analysing the impact of ALAN on astronomical observations, it was noted that the same polluting sources affect not only the night sky, but also the environment in general and in particular biological life and human health. These effects have been analysed and a number of measures are recommended, some of which are germane to those recommended in the previous two cases. In addition, further study of the effects

of ALAN on the bio-environment is encouraged, in particular those effects produced by novel light sources such as various types of outdoor light-emitting diodes (LEDs).

13. The three cases above (dark skies oases, optical astronomy and the bio-environment) are presented and discussed within the same category (ALAN) because the recommendations, even if agreed to 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, this would greatly enhance the chances of their local implementation. The approach to regulating ALAN effects, however, differs substantially from those considered for the remaining two interference sources that impact astronomy: sunlight reflected from satellites in large “constellations” and interfering radio emissions.

E. Protection of Radio Astronomy Sites and Related Science

14. Radio astronomy has a long tradition of coping with interference caused by radio broadcasting and other artificial radio-wavelength emissions. Indeed, a number of international agreements have been signed at the level of the International Telecommunication Union (ITU) 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 from the regulatory point of view. New types of arrangements are needed that bridge the gap between the traditional sector of radio-frequency management, performed by the ITU and national communications regulators, and new approaches to regulating the physical parameters of spacecraft and their movements in space. Such arrangements could achieve the avoidance of illumination of radio antennas and radio-quiet zones around observatories with an overall reduction of interference.

III. Five Topical Executive Summaries

A. The Impact of Satellite Constellations on the Science of Astronomy

15. International Telecommunication Union (ITU) and national regulatory filings indicate that nearly 100,000 satellites could be launched into low Earth orbit (LEO) in the coming decade. Several companies have already begun construction and launch of satellite constellations. Without action from the international community, policymakers and industry, abundant LEO satellites will increasingly tarnish the pristine view of the natural night sky from our planet, and will increasingly imperil astronomical science.

16. As the number of satellites continues to grow, astronomy is facing a tipping point situation of increasing interference with observations and loss of science. While regulatory and technical mitigations are possible, no combination can fully avoid impacts on astronomical science. COPUOS is the primary international forum in which to address the need to create an international approach to equitably managing light and radio emissions from space and preventing undesired impacts. Without immediate action, all of humanity will lose a clear view of the Universe and its secrets.

17. More than 5,000 satellites will be above the local horizon at any given time at a typical dark sky observatory location (30 degrees latitude north or south), assuming that several of the largest constellation projects come to fruition. A few hundred to several thousand of these satellites will be illuminated by the Sun. Without the implementation of the proposed recommendations, these satellites will be detectable by even the smallest optical or infrared telescopes, depending on the hour of night

and the season. Moreover, up to several hundred satellites may be visible even to the unaided eye, particularly low on the horizon and in twilight hours.

18. Initial studies of the unmitigated effects of satellites show a variety of impacts on astronomy from minor to severe, depending on the nature of the telescope and satellite system (Walker et al, 2020[1]; Hainaut & Williams, 2020[2]; Ragazzoni, 2020[3]; McDowell, 2020[4]; Tyson et al, 2020[5]). Observations with telescopes that view large portions of the sky will be severely impacted without substantial mitigations. While telescopes with narrow fields of view are less impacted, thanks to a lower probability that satellites will cross the field of view, observations with long exposure times and particularly in the hours close to twilight and low on the horizon are still significantly affected. Wide-field astrophotography will be affected, too. The impacts are not limited to ground-based observatories; space-based telescopes in LEO will also be affected, and in those cases, mitigations are more challenging to implement.

19. Observations conducted by radio observatories will also be harmed by satellite constellations. With the growing abundance of space-based transmitting objects above the horizon, radio astronomy faces a substantial loss unless preventative action is taken. Radio-quiet zones are impacted, and radio interference crossing frequency band boundaries poses a threat to the already limited set of frequency bands allocated to radio astronomy.

20. A set of recommendations are proposed to ensure that the development of national space economies can continue with minimal interference to the science of astronomy. They are formulated within a framework of shared stewardship, in which all space stakeholders acknowledge and assume their responsibility to conserve Earth’s pristine natural night-time landscapes, grow national space industries and a global space economy, and support fundamental scientific research. Governments, commercial enterprises, scientists, and those advocating the public interest must collaborate to balance their respective interests with those of the international community. Ultimately, this framework is underpinned by the Outer Space Treaty, ratified by 110 UN Member States. The Outer Space Treaty establishes clear principles of international cooperation and definitive obligations to consult in the event of harmful interference arising from space activities (Article IX). It also clearly recognizes the freedom to conduct scientific investigation in outer space (Article I). Astronomy, as one of the earliest space stakeholders, is a crucial part of this discussion.

21. These recommendations serve as guidelines to support states and other stakeholders in implementing urgently needed technical and policy mitigations that can foster the framework of shared stewardship and fulfil obligations inherent in the Outer Space Treaty. The recommendations reflect the collective input from observatories, industry, the astronomy community, science funding agencies, policymakers, regulatory agencies, and experts in international and space law.

22. Please note that the designation to distinguish the category of satellite constellation recommendations used here is “Sat_Con”. Some of the Sat_Con recommendations, as they are numbered in the Executive Summary of the full

[1] Walker, C., Hall, J., et al. (2020). Impact of Satellite Constellations on Optical Astronomy and Recommendations Toward Mitigations. Bulletin of the AAS. https://doi.org/10.3847/25c2cfeb.346793b

[2] 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

[3] 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

[4] 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

[5] Tyson, J. A., et al. (2020). Mitigation of LEO Satellite Brightness and Trail Effects on the Rubin Observatory LSST. http://arxiv.org/abs/2006.12417

Workshop Report, have been abridged in this Conference Room Paper. For the sake of clarity, the numbering has been maintained consistent between the two documents.

23. Sat_Con-3&7: Develop international collaboration and mitigation measures for transparent stewardship of the night sky. Develop mechanisms to (a) coordinate approaches across astronomy and industry communities and countries and (b) share information on industry interactions, mitigation solutions, and observational data. Raise awareness of the impacts on astronomy amongst satellite designers, investors, regulators, manufacturers and operators, and include impact mitigations as a core component of corporate social responsibility and sustainability strategies.

24. Sat_Con-4: Design satellite missions to minimize negative impacts on the pristine night sky and astronomical observations. Begin by 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, and scientific analysis shows that orbits on the order of 600 km or below offer a compromise between brightness and the length of time satellites are illuminated during the night. Then, minimize the number of satellites as second priority to altitude while maintaining safe operational practices, and minimize the time spent in orbit when not in service.

25. Sat_Con-5: Design satellites to minimize negative impacts on the pristine night sky and astronomical observations. This can be implemented by: (a) guaranteeing that all satellites appear fainter than 7.0 Vmag + 2.5 × log10(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 dynamic variations and specular flares; (c) incorporating the capability for dynamic orientation changes in order to reduce brightness in the specific direction of an observatory, particularly for time sensitive events; (d) minimizing antenna sidelobe emissions such that their indirect illumination of radio observatories and radio quiet zones do not interfere, whether individually or in the aggregate; and (e) preventing direct illumination of radio observatories and radio-quiet zones with a satellite's main antenna beam.

26. Sat_Con-6: Conduct operations to minimize the impacts on astronomical observations. 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 trajectories.

27. Sat_Con-13-15: Ensure that satellite licensing requirements, guidelines, and operational standards take into account impacts on astronomy. These must include the impacts on multiple stakeholders, including astronomical activities, and be coordinated with existing worldwide satellite regulations, guidelines, and procedures that relate to radio astronomy and space debris mitigation.

28. Sat_Con-16: Support the development of shared space domain decision intelligence. At a minimum, parties must collect data of proposed satellite constellations and existing orbiting space objects, model satellites and their operations and behaviours in the space environment, and estimate uncertainties to assess the impact of satellite constellations on ground-based astronomical observations. Incentivizing satellite operators to make the needed data freely and publicly accessible is encouraged.

29. Sat_Con-10&12: Provide funding for understanding and mitigating impacts on astronomy. At the forefront, these financial impacts will include increased overheads in terms of additional observing time and science losses. This includes providing specific vehicles to fund the development of software and hardware mitigations, additional telescopes, and technology developments in detectors and receivers. It also involves taking steps to evaluate, formalize and report to governments the overall impacts on science research and capital investments. Additionally, financial

incentives are required to encourage consultation and collaboration between the space industry, observatories, and the astronomy community.

30. Sat_Con-17: Investigate policy measures that can account for negative externalities of space industrial activities. In particular, these measures must include impacts on astronomical activities. Stakeholders need to develop incentives and inducements for industry and investors.

B. Protection of Dark Sky Oases

31. This section discusses the nature and causes of a bright night sky resulting from light pollution, otherwise known as artificial light at night (ALAN), and recommends mitigations to protect dark sky areas. ALAN has an adverse effect for professional astronomers, for amateur astronomers, for astro-tourists, for those who hold a cultural value for a starry night sky and for those who want to admire the beauty of a pristine and dark night sky. ALAN also has a number of additional adverse effects including reduced safety at night, wasted electric power, environmental harm and adverse effects on human health.

32. 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, the use of lighting for commercial locations such as factory yards, ports and sports facilities and the floodlighting of buildings of heritage value.

33. 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 unaided eye at night. In recognition of the value of dark skies for the economy, for science, for promoting culture, for environmental protection, for human well-being and for promoting astro-tourism, many national and regional governments have created 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 by 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 and the Starlight Foundation.

34. The birth of the Starlight Declaration[6] in April 2007 launched a means of recognizing the value of a starlight vista as an inspiration of humankind and as an essential element in the development of scientific thought in all civilisations. The Declaration's main aim is to strengthen the importance of clear skies for humankind, emphasizing and introducing the value of this endangered heritage for science, education, culture, technological development, nature conservation, astro-tourism and, obviously, as a quality-of-life factor.

35. This paper adopts the International Union for the Conservation of Nature (IUCN) classification scheme, which groups dark sky oases into six classes according to their primary uses (such as astronomical research, astro-tourism, heritage values, wilderness areas used for public education and outreach, etc.). In May 2020 there were 223 dark sky oases covering more than 20 million hectares with accreditation for their dark skies. The number is growing steadily every year.

36. The effects of ALAN on dark sky oases depend very much on the type of light source used in surrounding areas. A key issue is the dominant rise of white light-emitting diode (LED) lamps, which have significant blue emission that is largely absent from sodium arc lamps. (Here blue light is defined as that with a wavelength less than 500 nm.) The harmful effects of ALAN in brightening the night sky are

[6] https://www.starlight2007.net/index_option_com_content_view_article_id_185_itemid_80_lang_en.html.

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.

37. A number of countries and localities over the last fifty years have recognized the need to mitigate the effects of ALAN and have enacted lighting ordinances or bye-laws. 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.

38. In order to support an internationally recognized approach to reducing ALAN at dark sky oases, this paper proposes recommendations in the following two categories.

39. Firstly, for the six classes of dark sky oasis recognized by the International Union for the Conservation of Nature, values of the maximum desirable night sky brightness are proposed. These are aspirational values; in particular locations they 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 natural background (applicable in the vicinity of astronomical research observatories) to four times the natural background for protected dark sky sites closer to urban areas.

40. Secondly, a number of technical lighting recommendations are made which will assist dark sky locations to realize the night 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.

(i) Recommendations

41. We recommend the levels of night sky brightness considered appropriate for different dark sky place classes to be as defined by the International Union for Conservation of Nature (IUCN) Dark Skies Advisory Group (DSAG) (in §4.1 and Appendix 1 of their report). The International Astronomical Union (IAU) and the International Commission on Illumination recommend that for astronomical observatories the sky brightness should be no more than 10 per cent beyond the airglow background at a zenith angle of 45º, airglow being typically 174 to 250 (micro candela per square meters, Falchi et al. 2016) (µcd m-2) in brightness. 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 the abatement of light pollution. Recommended limiting night sky brightness values in µcd m-2 are also quoted in visual magnitudes per square arcsecond (mag arcsec-2). These recommended values are consistent with those also recommended by IUCN.

42. DS_Oas-1: Dark Sky Astronomy Site, DSAG class 1: no more than 10 per cent more than airglow, or <260 µcd m-2 (>21.7 mag arcsec-2).

43. DS_Oas-2: Dark Sky Park, Starlight Reserve, DSAG class 2: no more than 50 per cent more than airglow, or <360 µcd m-2 (>21.4 mag arcsec-2).

44. DS_Oas-3: Dark Sky Heritage Site, DSAG class 3: no more than 2.75 times the airglow, or <660 µcd m-2 (>20.7 mag arcsec-2).

45. DS_Oas-4: Dark Sky Outreach Site, Starlight Tourist Destination, Starlight Stellar Park, 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).

46. DS_Oas-5: Dark Sky Reserve, Starlight Wilderness, Starlight Village, DSAG class 5: similar to outreach sites, <480 µcd m-2 (>21.0 mag arcsec-2).

47. DS_Oas-6: Dark Sky Community, urban, DSAG class 6a: the recommended limit is 4 times the airglow for protected sites in and near urban areas, or <1000 µcd m-2 (>20.3 mag arcsec-2).

48. 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, or <750 µcd m-2 (>20.6 mag arcsec-2).

49. It is recognized that these recommendations may not be realizable in all protected areas and that each area will have its own challenges and circumstances. Values of night sky brightness may be more or less than these recommendations in individual locations. In addition, the following practical recommendations for exterior lighting in protected dark sky oases are made:

50. DS_Oas-8: In all instances, the default condition should be no artificial light. Specific uses justifying light should then be additive once other non-lighting interventions are exhausted.

51. 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.

52. DS_Oas-10: If phosphor-converted amber LED or white 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.

53. 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.

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

55. DS_Oas-13: No development in or near highly ecologically sensitive sites should be permitted.

56. DS_Oas-14: Monitoring of night-time conditions in and near dark sky oases is encouraged through a combination of ground-based and remote sensing methods.

57. DS_Oas-15: Active management of natural night-time darkness as a natural resource is encouraged through recognized conservation best practices.

58. DS_Oas-16: Restoration plans should be implemented when night sky brightness thresholds are routinely exceeded.

C. Protection of Ground-Based Optical Astronomy Sites and Related Science

59. 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 a cost per unit light-collecting area some two orders of magnitude lower than those launched into orbit. And they provide critical data for planetary defence and key aspects of space situational awareness.

60. 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 (ALAN). In the past

decade alone, the globally averaged rate of increase in artificial sky brightness was 2 per cent per year in terms of both lit area and total radiance, double the rate of world population growth during the same period.

61. More recently, a new factor impacting natural night sky integrity has emerged. This impact is from 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 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 fuelling elastic demand for the consumption of light, leading to higher overall light emissions.

62. The International Astronomical Union (IAU) has defined the upper limit of artificial light contribution for a professional observatory site to be considered adequate for true dark-sky observing to be <10 per cent above the natural background at an elevation of 45° in any azimuthal direction. Modern professional observatories have been located at remote, high-altitude sites that are significantly below this limit of artificial light contamination.

63. The goal of the framework of recommendations proposed in this section of the paper 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.

64. Each observatory site has its own circumstances, so achieving the goal will require a regional lighting plan with a specific approach based on detailed modelling. Protection of the site may entail land-use zoning that restricts development and the ultimate tightening of regulations with time to reduce light pollution. An approach of quality lighting design is strongly advocated to match the illumination level to need, limiting unnecessary spectral content and taking advantage of precise optical control to reduce spill light. A key aspect of observatory 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 framework of recommendations 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.

65. Many professional observatories see measurable impacts of "light domes," the dome-shaped glowing night sky area over conurbations, at distances even in excess of 300 km. The International Commission on Illumination (CIE) provides 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 controlling night-time lighting and reducing energy costs.

66. 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 skyglow. The near zone is an area within a radius of approximately 30 km, depending on local conditions. The framework of recommendations has the following provisions:

(a) Exclusive use of luminaires with no light emitted above the horizontal;

(b) Limiting lamp spectral content in the blue and near-ultraviolet region (below 500 nm);

(c) Limiting the maintained average illuminance;

(d) Implementation of curfews and light-level controls;

(e) Defining the minimum utilance ratio;

(f) Designing and mounting luminaires to minimize direct and reflected light in the direction of observatories; and

(g) 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. (A lumen is an SI unit of the rate of flow of radiant energy, specifically in the visible spectrum. Ideally, areas or zones closest to observatories have stricter lighting ordinances. Caps are maximum values.)

67. Observatories on the most remote mountaintops encounter lighting for special uses 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 proximity to the observatories. Best practice design and associated regulation can limit up-lighting, manage spectral output, and limit total luminous output.

68. There are strong corollary benefits that incentivize 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 night-time safety, and possible benefits to human health.

(i) Recommendations for observatories and their extended protected zones

69. For all the following specific recommendations for the protection of observatory sites, if current applicable regulations or regionally referenced professional lighting authorities impose 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. Whenever professional standards or recommendations offer a range, the guidance presented here is to stay within 20 per cent 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 by using motion-activated sensors for night-time traffic and activity.

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

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

72. Opt_Ast-3: Such sky-monitoring data should be collected under uniform protocols and reported in “dark sky units” (dsu: 1 dsu = 1 nW m−2 sr−1 nm−1), with standard calibration traceable to the SI system.

73. 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 in the near zone, as well as the extent of the area of protection.

74. 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.

75. Opt_Ast-6: All luminaires must provide no direct illumination above the horizontal.

76. Opt_Ast-7: No architectural lighting or electronic message displays emitting light above the horizontal should be permitted in Environmental Zones E0, E1, or E2 within the extended protected area.

77. Opt_Ast-8: The blue light content (i.e., the ratio of light emitted below 500 nm to the total light emitted over all wavelengths) should be null. Lighting devices should

use quasi-monochromatic sources emitting their maximum radiant flux (in W nm-1) in the 585–605 nm spectral range and having a Full Width at Half Maximum (FWHM) smaller than 18 nm. If modest colour rendition is approved as a necessity, sources with broader spectral bandpasses (FWHM of ~100 nm) can be used in those exceptional cases.

78. Opt_Ast-9: The maintained average illuminance for periods of active use should not be higher than 20 per cent above the minimum maintained average illuminance suggested in technical norms/recommendations published by CIE or the Illuminating Engineering Society (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.

79. Opt_Ast-10: Avoid exceeding luminance or illuminance limits by more than 20 per cent in design, and plan for active control and maintenance to achieve nearly constant light output.

80. Opt_Ast-11: A maximum possible reduction of the total light levels, with a target of at least 66 per cent 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 per cent or less of the maintained average luminance or illuminance.

81. Opt_Ast-12: The utilance ratio should be at least 75 per cent.

82. Opt_Ast-13: Luminaires should be designed and mounted to minimize direct and reflected light propagating in the direction of observatories.

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

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

(ii) Recommendations for more distant urban areas impacting observatories

85. Opt_Ast-16: Follow, and minimize high-side deviation to no more than 20 per cent 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.

86. Opt_Ast-17: Follow and minimize high-side deviation to no more than 20 per cent 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.

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

88. 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), with application of curfew-time reductions in lighting levels.

89. Opt_Ast-20: For Zones E2 and E3 impacting observatories, do not exceed American National Standards Institute (ANSI)/IES standards for maximum luminances for illuminated signs. Take all recommended measures to reduce skyglow from internally illuminated signs and electronic message displays. For E3 Zones, do not exceed the CIE maximum standard permitted luminance levels for building façades, and prohibit façade lighting in E0, E1, and E2 Zones in the extended area impacting observatories.

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

91. 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.

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

93. Opt_Ast-24: Sharply limit the 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/near-UV content available (colour index G > 2) when colour rendition is necessary.

D. Protection of the Bio-Environment

94. 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.

95. 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 cause retinal damage.

96. Epidemiological studies show a 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 exposure 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.

97. 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.

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

99. 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 for food webs and habitat use. The impact of ALAN on the nocturnal organism level can cascade into ecosystems and can also affect diurnal 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.

100. 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. The brightening of the night sky caused by ALAN scattered within the atmosphere results in elevated skyglow levels hundreds of kilometres away from

cities and towns, where it can negatively impact ecosystems in otherwise remote and unlit natural areas.

101. Thirteen recommendations have been compiled to mitigate the impacts of ALAN on humans, flora, and fauna.

102. Bio_Env-1: Areas to be illuminated: Governing bodies (e.g., countries, states, counties, etc.) should define the criteria for deciding 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.

103. Bio_Env-2: Geographical framework to mitigate light pollution: Maximum admissible values of the indicators of deterioration of the night-time 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.

104. Bio_Env-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.

105. Bio_Env-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 per cent the minimum requirement of the usage class as specified in relevant scientifically-supported documents or standards.

106. Bio_Env-5: Lighting control and adaptive lighting: All new and renovated outdoor lighting installations should incorporate means to control 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.

107. Bio_Env-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.

108. Bio_Env-7: Intrusive light: Light entering indoor living areas during night-time should be minimized and ideally eliminated.

109. Bio_Env-8: Glare control on roads and in outdoor working places: Glare levels should be controlled and reduced below the recommended maximum levels.

110. Bio_Env-9: Spectral content of the emitted light: The spectral content of the emitted light, especially the blue and near-UV content, should be carefully selected for the intended application to minimize negative impacts on the surrounding environment. Melanopsin-activating blue light content should be minimized. This approach is useful for both humans and vertebrates where the circadian timing system has a similar spectral sensitivity to that of 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.

111. Bio_Env-10: Directionality of light, light modulation, floodlighting, 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 colour façades such as light-emitting diode (LED) billboards are strongly discouraged.

112. Bio_Env-11: ALAN monitoring measurements: ALAN that affects humans and the environment should be carefully assessed and monitored via field measurements. ALAN measurements and skyglow monitoring should be implemented in international, national or local regulations. Mitigation and possibly restoration measures should be applied when scientifically justified thresholds are exceeded.

113. Bio_Env-12: Urgent research topics: Interdisciplinary research among lighting, medical, and environmental research communities is urgently needed in the following fields and should be encouraged:

(a) Effects of ALAN on human health, flora and fauna, visibility levels and public safety;

(b) Thresholds for impacts of ALAN on humans and natural species, especially for protected and threatened species;

(c) Measurement, monitoring and impact assessment of ecological effects of ALAN;

(d) Studies on impact of new technologies including adaptive lighting, and other characteristics of light such as light modulation (flicker) and glare.

114. Scientific analysis of the need to update or adjust current technical guidelines and studies should use the correct and appropriate light quantities and metrics, and highly interdisciplinary 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.

115. Bio_Env-13: Strategic targets:

(a) Establish standards to prevent unwanted impacts on human health and the environment.

(b) Establish specific regulations for outdoor lighting within each country.

(c) Establish an accreditation system for outdoor lighting installations.

(d) Ensure that new installations and renovations follow the relevant regulations.

(e) Review and revise the lighting requirements for illuminating roads and highways and the lighting legislation to consider environmental effects of ALAN.

(f) Minimize the negative effect of outdoor lighting on vision, human health and natural species.

(g) 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.

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

(i) Develop a scale of ecological classes of dark skies to show the differential impact of light on ecosystems and species across the territory.

(j) 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.

(k) Develop standardized methods for measuring ALAN and skyglow and establish them in the relevant national or international standards

E. Protection of Radio Astronomy Sites and Related Science

(i) *Discovery*

116. 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 prebiotic chemistry there. There are no other sources of such knowledge.

(ii) *Technology and invention*

117. 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 tens to hundreds of kilometres, or disconnected and crossing continents for Very Long Baseline Interferometry (VLBI). VLBI was used in 2017 to image the shadow of the supermassive black hole at the centre 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.

118. 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 techniques 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 damaging or destroying sensitive detectors of radio frequencies.

119. 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 centres 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 scale of millimetres. 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, VGOS , is a key driver in the recommendations here.

(iii) *How the laws of physics render radio antennas vulnerable to interference*

120. One very important fact 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 20o of a transmitter to be sure not to boost its signal.

121. 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.

(iv) Regulation of the radio spectrum

122. 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.

123. The mechanisms and institutions that support compatible use of the radio spectrum by multiple stakeholders are 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, and 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.

124. Radio astronomers discussed the need for spectrum management soon after the characteristic emission from hydrogen atoms at 1420 MHz (the HI line) was discovered in 1953. The International Astronomical Union (IAU), the International Union of Radio Science (URSI) and the Committee on Space Research (COSPAR) formed the Inter-Union Committee for the Allocation of Frequencies (IUCAF) under the aegis of the International Council for Science (ICSU) (now the International Science Council, ISC) and radio astronomy was given the sole allocation of the 1400–1427 MHz band at a meeting in Geneva in 1959–1960.

(v) Spectrum management has made accommodations for radio astronomy and vice versa

125. 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’s use of spectrum is so unusual that the rules regarding the radio astronomy service are still evolving at the International Telecommunication Union Radiocommunication Sector (ITU-R).

126. An example of spectral protection that has been implemented in radio astronomy are the so-called “passive” frequency bands. These bands are exclusively allocated for scientific observation and forbidden to transmitters: 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.

127. Only 1–2 per cent of the spectrum is set aside for science below 50 GHz, where almost all commercial radio communication occurs, rising to 10–15 per cent 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.

128. 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.

(vi) Risks to radio astronomy

129. The wide variety of risks to radio astronomy operation ranges 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.

130. The risks from satellites stand out for many reasons. Satellites operate beyond national control and appear overhead during observing, even 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 number of radar and radiocommunication satellites in low-Earth orbit (LEO) is expected to grow by two to three orders of magnitude over the coming years. Therefore, the measures currently used to protect radio astronomy are ill-suited for the future.

131. Radio astronomy has a long history of interaction with radiocommunication satellites. 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. The first GPS and GLONASS global positioning satellites used unfiltered transmitters that interfered over wide portions of the radio spectrum. The continued interference in a radio astronomy band from a second generation of Iridium mobile phone satellites operating in nearby (not shared) spectrum has withstood remediation despite complaints to the highest authorities.

132. Some 5–10 per cent of the satellites in a LEO constellation are above the horizon at any one time. The Iridium constellation with 66 operational and 3–4 instantaneously visible satellites has caused 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 as many.

133. 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 ~ 8.3o and on average it will be impossible for a radio telescope to point on the sky without having a satellite within about 4o of the main beam. With 50,000 satellites in orbit, one will always be within 1.3o. This is in addition to the aggregate interference from the sidelobes of the other satellites. These satellites must be rendered invisible to radio telescopes.

(vii) The Way Forward and Two Recommendations Regarding non-geostationary orbit (GSO) Satellites

134. Section 7.5 of the Workshop Report describes some of the technological innovations 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.

135. 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 LEO. 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.

136. Two recommendations have been formulated for steps necessary to allow continued radio astronomy observations, 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.

137. 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 a radio astronomy receiver.

138. 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.

IV. Conclusions

139. Considering the significance of dark and quiet skies for science and society and the complexity and urgency of safeguarding them, it is proposed that IAU and UNOOSA engage with relevant stakeholders, intersessionally, on the matter of Dark and Quiet Skies, to form consensus on expert-recommendations and report back to COPUOS STSC 2022. In this regard, the results of the Conference on “Dark and Quiet Skies for Science and Society” planned for October 2021 can serve as an input to this exchange and focused discussions on opportunities for international cooperation.