United Nations

A/AC.105/1255

General Assembly

Distr.: General
5 November 2021

Original: English

Committee on the Peaceful Uses of Outer Space

Report on the United Nations/Spain/International Astronomical Union Conference on Dark and Quiet Skies for Science and Society

(La Palma, Spain (online), 3–7 October 2021)

I. Introduction

1. The Office for Outer Space Affairs of the Secretariat organized the United Nations/Spain/International Astronomical Union (IAU) Conference on Dark and Quiet Skies for Science and Society as an activity of the United Nations Programme on Space Applications.

2. In view of the coronavirus disease (COVID-19) pandemic, the conference was postponed from 2020 to 2021. The Office for Outer Space Affairs and the Government of Spain agreed to hold the conference as a hybrid event, with some attendees at Santa Cruz de La Palma and a broadcast of the event made available online for a larger number of participants. Owing to the eruption of the Cumbre Vieja volcano at La Palma that started on 19 September and disrupted activities on the island, the conference was ultimately held entirely online, from 3 to 7 October 2021.

3. The event was co-organized by the Government of Spain and IAU. It was supported by the Institute of Astrophysics of the Canary Islands as local organizer, and co-sponsored by the Council of La Palma, the town of Santa Cruz and the Starlight Foundation.

4. The present report describes the objectives of the conference and includes details of attendance and a summary of the presentations and discussions, as well as the conclusions and observations.

II. Background and objectives

5. In 2017, the Committee on the Peaceful Uses of Outer Space agreed that the Office organize, jointly with IAU, a conference on the general topic of light pollution.

6. In 2020, while travel was restricted during the COVID-19 crisis, the Dark and Quiet Skies for Science and Society online workshop was organized by the scientific organizing committee of the conference, from 5 to 9 October 2020. Participants discussed the impacts on astronomy of three classes of interference: (a) artificial light at night; (b) the large number of low-Earth orbit satellites; and (c) radio-wavelength emissions. In view of the initial findings and comments received, working groups of

the scientific organizing committee produced a report that was published by IAU in January 2021. Recommendations from the report were submitted by Chile, Ethiopia, Jordan, Slovakia, Spain and IAU to the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space at its fifty-eighth session, held in April 2021, in a conference room paper entitled “Recommendations to keep dark and quiet skies for science and society” (A/AC.105/C.1/2021/CRP.17).

7. The conference held from 3 to 7 October 2021 was focused on technical and policy actions associated with those recommendations, in particular, identifying which stakeholders and partners would need to collaborate to implement satisfactory solutions for the preservation of dark and quiet skies. The programme of the conference included presentations from working groups of the scientific organizing committee, talks by invited speakers and contributions selected through a call for abstracts.

8. The conference was an opportunity to listen to diverse views and for stakeholders to put forth suggestions, so that States members of the Committee could be better informed with regard to the various elements addressed.

III. Attendance

9. A total of 724 individuals, 32 per cent of whom were women, registered to attend the conference and were granted access to the online communication platform.

10. The following 76 countries were represented: Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Bangladesh, Belarus, Belgium, Brazil, Brunei Darussalam, Burkina Faso, Cameroon, Canada, Chad, Chile, China, Colombia, Croatia, Cyprus, Dominican Republic, Egypt, Ethiopia, France, Germany, Ghana, Greece, Guatemala, Honduras, Hungary, India, Indonesia, Iran (Islamic Republic of), Ireland, Italy, Japan, Jordan, Kenya, Lebanon, Libya, Malaysia, Malta, Mexico, Morocco, Nepal, Netherlands, New Zealand, Nigeria, Pakistan, Panama, Peru, Philippines, Poland, Portugal, Republic of Korea, Romania, Russian Federation, Saudi Arabia, Serbia, Slovenia, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Thailand, Tunisia, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, United Republic of Tanzania, United States of America, Uruguay, Venezuela (Bolivarian Republic of), Yemen and Zimbabwe. Taiwan Province of China was also represented at the conference.

11. Online attendance fluctuated, depending on the time zones around the world; at its peak, about 140 attendees were connected simultaneously.

12. Attendees were invited to use the online platform to ask questions in writing to speakers during discussions, and the organizers used the same interface to provide complementary information, whenever relevant.

IV. Programme

A. Overview

13. The programme comprised presentation sessions, round-table discussions and succinct presentations of posters. The various aspects of artificial light at night were discussed first, followed by discussions and recommendations relating to the impacts of satellite constellations on astronomy and on radio astronomy.

14. The display of posters, intended as the online equivalent of an in-person poster session, increased the number of initiatives presented and also enabled less experienced speakers to give presentations.

15. The total duration of the event was 28 hours over five days. It involved 69 individual speakers (22 women and 47 men).

16. All presentations given by the speakers were made available on the website of the Office for Outer Space after the event (www.unoosa.org/oosa/en/ourwork/psa/schedule/2021/2021_dark_skies.html).

B. Welcome and keynote

17. The event began with a welcome address from the Director of the Institute of Astrophysics of the Canary Islands, as local organizer and on behalf of Spain. He recalled that citizens of La Palma had supported astronomical activities for decades and regretted the exceptional circumstances that had led to the conference being held entirely online.

18. A welcome address from a representative of IAU followed, on behalf of the scientific organizing committee. The speaker reminded the audience that a detailed report from the online workshop held in October 2020 was available on the IAU website (www.iau.org/static/publications/dqskies-book-29-12-20.pdf). It contained recommendations, the implementation of which would be further discussed during the conference.

19. After welcoming attendees, a representative of the Office for Outer Space Affairs explained the rationale for holding the conference. He explained the specificities of the work of the Committee and how the topic of dark and quiet skies had been brought to its attention by a number of delegations. At its fifty-eighth session, the Scientific and Technical Subcommittee had encouraged the Office to engage with all relevant stakeholders, such as IAU and others, on the topic and present the outcomes of that engagement, including findings for furthering the discussion on the matter, to the Subcommittee for consideration. In that regard, the present conference could provide input to a focused discussion on opportunities for international cooperation. In accordance with the agreement reached by the Subcommittee at its fifty-eighth session, the Office for Outer Space Affairs would also organize the industry symposium at the fifty-ninth session of the Subcommittee, in 2022, on the topic of dark and quiet skies.

C. Artificial light at night

20. Session 1 concerned the growing threat of artificial light at night and how it affected the natural world. Light pollution was a contributing factor to major challenges such as the extinction of insects and the unnecessary emission of carbon dioxide. Besides affecting astronomy, it had an impact on human cultural heritage by erasing the night sky. Artificial light at night, especially blue light from light-emitting diode lighting, had been increasing fast, and further increases were projected. Ecological niches were directly affected, as artificial light changed the way in which animals chose their habitat, foraged and migrated. Light affected circadian rhythms, which affected hormones and seasonal rhythms, which directly affected reproduction. In oceans, light interfered with the migration of zooplankton, which avoided light. Animals that used stars to navigate, especially migratory birds that used the light of the Milky Way, lost time and energy when that reference was removed. Artificial light at night also affected the whole physiology of insects; its responsibility for population decrease was now being studied. Awareness of the negative impact on human health was also increasing slowly. Light pollution should be reduced in an integrated manner, not merely by reducing the temperature of lighting but also by considering where and when lighting was truly required. Light pollution was an issue that could be solved in a manner that would spare resources. While some cities saved energy and reduced cost when designing outdoor lighting to reduce the pollution created locally, space-based pollution caused by satellites reflecting light was an emerging threat and one that required international collaboration.

21. Session 2 addressed the protection of astronomical sites. The experience of several astronomical observatories was presented. As they were often funded by

several countries and built in another, the astronomy community considered that international agreement on measures to protect astronomical sites from artificial light at night was necessary. The four speakers explained their experience, as follows:

(a) In the United States, the newest observatories had been located at sites where light pollution was limited; however, measures should be aimed at reversing the current increase in such pollution by matching illumination to need, with active control to reduce light when not needed, including through caps and curfews. No light should be projected above the horizontal plane. In zones close to observatories (e.g. within 30 km), the use of certain colours of light should be justified, with concentric zones of increasing levels of restrictions. Lighting design should not exceed 20 per cent of the minimum strictly required for safety, with the light flux directed where it was required and designed specifically for the local environment;

(b) In Spain, a sky law had been signed to protect the darkness of the sky in the Canary Islands and corresponding regulations had come into force in 1992. The protected area included the whole island of La Palma and parts of Tenerife; the Sky Quality Protection Technical Office ensured that the measures were enforced, with continuous monitoring and inspections in the field. The regulatory framework was made possible thanks to strong support at the political level, strong communication efforts and local support from the islands' populations;

(c) Morocco had started a project to create a dark sky reserve in the Atlas region in 2018, protected from light pollution from Marrakesh, Agadir and Ouarzazate. The project had started by measuring lighting from localities and assessing the issues. Recognition was expected to be obtained from the International Dark-Sky Association in 2023;

(d) In China, actions were under way to create dark sky protection standards at the national level and to convince local governments to implement lighting caps. Some air traffic routes had been modified to protect astronomy. Ultimately, observatories might need to be moved to new sites in less-populated areas. For radio astronomy, China was measuring and mitigating radio-frequency interference and was looking at creating radio quiet zones.

22. Session 3 covered the impact of artificial light at night on the biological environment, on the circadian rhythms of humans and fauna, and on human health overall. Outdoor artificial light at night was a pollutant and should be considered as such: rather than continue to try to reduce artificial light at night feature by feature, a global approach, with scientifically defined thresholds and coordination at the international level, would be more effective, as artificial light at night continued to grow worldwide. Light pollution, for the most part, was due to poorly planned and poorly controlled light. The speakers explained the impact of light on the human circadian rhythm: the rhythm was slightly longer than 24 hours and was readjusted by light every day. Melatonin, which determined the body clock, was inhibited by light during the day, and light during the night disrupted its secretion. The World Health Organization had declared circadian disruption a class 2 carcinogen, owing to its link to a variety of diseases. Some medical societies had therefore recommended removing blue light from lighting sources to protect human health. Evidence had started to accumulate that human cancer cells developed when melatonin was suppressed, and similar effects had been observed in other species of animals. A speaker explained that technology to reduce that negative impact on health already existed; however, the lighting industry was not currently required to assess the environmental impact of their technology and might not welcome such a constraint.

23. Session 4 addressed dark sky oases, presenting best practices from Germany, New Zealand and Spain and explaining how to design environmentally responsible lighting. Beyond astronomers and star-gazing enthusiasts, public health stakeholders were now involved in the issue. Air glow was measured in candela per square metres (luminance), and any value above 1 microcandela per square metre meant a light-polluted sky, meaning that about 80 per cent of the world's population lived in areas polluted by light. Astronomical observatories should ideally be situated in areas with

no more than 10 per cent above the natural airglow, while other areas could tolerate brighter levels, but local governments were poorly equipped to tackle or informed about what was a global crisis. Strong guidelines, such as a lighting convention, applicable to dark sky oases and to urban environments, would enable States to follow globally established protocols. A sustainable development goal could also be defined about the quality of the night sky, as proposed by the Starlight Foundation in Spain. Astrotourism had developed steadily. For example, about 10 per cent of the total revenue from tourism in La Palma came from astrotourism. In New Zealand, astrotourism had been developed in the Tekapo area, with similar results. Astrotourism could compensate for the seasonality of tourism and help prevent depopulation. In Germany, where about 44 per cent of the population could not see the Milky Way, measuring sky brightness in natural parks had motivated the decision to create dark sky reserves, and an increasing number of communities were interested in joining them. The ministries of the environment of Denmark, Germany and the Netherlands were in the process of reducing light emissions in the United Nations Educational, Scientific and Cultural Organization World Heritage site of the Wadden Sea. Interdisciplinary research into light development was currently in the early stages of development and research had not yet been translated into law. Environmentally responsible lighting design was needed to improve street lighting, buildings and sport facility lighting, advertisements, landscape lighting, safety and security lights and event lighting. Policy publications to date tended to address only some parameters. Easily available tools to measure lighting were needed, with guidelines for responsible illumination, a regulatory framework and more funding for interdisciplinary research.

24. Two posters were presented, about mitigation of light pollution in Uruguay and on the effect of artificial light at night on animal communication systems.

25. Session 5 covered measuring and modelling artificial light at night. Measurements for regional monitoring could be taken from space, from aircraft or on the ground, with simple devices that measured sky brightness in a single direction. Such devices were available for purchase and could be used in networks, once calibrated. Other devices, such as fisheye lenses, were readily available and affordable tools that produced an “all sky” measurement. A natural sky model was required to assess additional light resulting from artificial light at night: such a model was under development on the basis of satellite observations, while other models accounted for various components of light pollution (direct light, indirect light and what was reflected or scattered by aerosols and molecules, such as sea salt or soot). Such a model was very complex and computation-intensive; a simplified version suitable for non-experts was under development.

26. Three posters were presented. They addressed the measurement of light pollution in Indonesia, where it was a relatively new topic, a proposal to establish an astronomical observatory in the south of Tunisia and how to measure changes in the spectral and angular emission of cities’ lighting infrastructure to monitor how regulation was applied.

27. Session 6 was a synthesis of the recommendations proposed to reduce artificial light at night. The recommendations on what was needed to protect astronomical sites, dark sky oases and the bio-environment were very similar. Instead of proposing many separate technical recommendations, it was proposed that the following principles could be considered: (a) develop a lighting masterplan and efficient design; (b) use adaptive control and spectral tuning of the light, notably to limit blue light; (c) define nominal and adaptive lighting classes for outdoor areas with research-based recommendations for each safety-related level of lighting; (d) adopt a zoning system with associated limits; (e) limit skyglow for protected areas; (f) limit lighting of buildings’ facades and colourful illumination, shielding all outdoor light; (g) measure and monitor light with a standardized metrology system; (h) plan commercial and military flights to exclude zones near observatories; (i) support research, especially interdisciplinary research between lighting, medical and environmental research, on

the effects of artificial light at night; and (j) define long-term targets, with a strategy to ensure mitigation of unwanted effects.

28. The summary was followed by three presentations. The International Commission on Illumination worked with the International Committee for Weights and Measures and the International Organization for Standardization; it brought together experts from academia and industry to develop position statements, technical publications and international standards, balancing the interests of various stakeholders. Enforcement of laws required legislation based on well-defined and traceable measurements. In turn, the measurements required a defined measurement quantity, suitable devices and a definition of uncertainty and instrument-conformity assessment processes. The instruments currently used had often been designed for a different purpose: they need suitable calibration, traceability and ways to evaluate uncertainty in measurements. The "Guidelines for minimizing sky glow" were a long-standing publication by the International Commission on Illumination and had been adopted by some regulators and legislators. The Commission had also defined an urban lighting masterplan and lighting zones as part of a policymaking framework document. During the discussion, some scepticism was expressed as to whether the standards were evidence-based and concerns were raised about conflict of interest. The representative of the Commission clarified that documents were approved by consensus among all members and that older documents would need updating now that new research was available.

29. Session 7 introduced policy proposals and legal options. During the discussion, experts proposed treating artificial light at night as a pollutant. Should it be recognized as such, the associated environmental laws and regulations at the international, national and regional levels would apply. An admissible quota of artificial light at night could be defined with, for instance, taxation or a cap-and-trade scheme. The idea of an environmental impact assessment was repeatedly mentioned during the discussion: it would force stakeholders to consider their impact and would enable the public to engage in the process. When discussing the relevance of excess lighting, the speakers stressed that light prevented the observation of outer space. As outer space was an enabler and an inspiration for science, the Committee on the Peaceful Uses of Outer Space was a vehicle for raising awareness about the need to reduce artificial light at night for a wide range of reasons.

30. The three speakers discussed options for implementation, such as economic incentives based on self-interest, cap-and-trade schemes and a "light tax". No single model of governance would work everywhere, at all levels. Using existing legal infrastructure, such as incorporating artificial light at night into guidance and regulations on environmental law and health law, would be the easiest approach. As objections would be raised and then exemptions granted, implementation should take place gradually, in phases. Preventive measures stopping inappropriate lighting or banning poor products should be implemented together with reactive measures relying on well-resourced enforcement bodies, to prevent deliberate misuse and transfer remediation costs to the light owner. Enforcement needed simple metrics, such as reading a label, rather than technical measurements. Education was critical but laws also needed to be in place at various levels, from international laws to local ordinances. While a treaty could be initiated by States, local advantages stemming from keeping the sky dark would justify local decisions, for instance in rural areas interested in astrotourism.

31. Session 8 provided examples of national and regional implementation of national policies limiting artificial light at night:

(a) The observatories in northern Chile were being threatened by an increase in artificial light at night in nearby cities. Chile had decided to ban blue light in the region and restrict the lighting of sports facilities. A new law was in development; however, enforcement remained an issue. Astrotourism was well developed in northern Chile and involved the local communities; they, in turn, clearly had an interest in protecting dark skies;

(b) In Spain, in addition to the law protecting the Canary Islands, laws existed at the regional level. Light pollution fell under the umbrella of environmental law, but without any remediation mechanism, and Spanish legislators saw a formal difference between atmospheric pollution and light pollution;

(c) In Portugal, artificial light at night along the coast had increased significantly, not in correlation with population increases, mostly as a result of changes to light-emitting diode technology. Education programmes in schools were used to raise awareness. Parliament had discussed but not yet legislated upon the issue, while the Portuguese environmental agency had no competence in artificial light at night;

(d) Various laws on light pollution existed in Italy, at the regional level. Lombardy had been a forerunner, with 25,000 signatures collected to request a law; however, it needed updating to take blue light into account and the total amount of light produced also needed to be controlled;

(e) In the south-western United States and Hawaii, a regulatory patchwork determined who had control over lighting and where, without overriding federal law. Flagstaff was the first “international dark sky city” to implement ordinances to minimize light pollution, and Hawaii had implemented various laws at the local level, requesting shielding and limits on spectrum. It was often possible to reach a good outcome without legal requirements, especially as retrofitting streetlights brought financial savings;

(f) France had implemented a law on energy saving in January 2020, to reduce artificial light at night with specific measures. The National Association for the Protection of the Night Sky and Environment had also developed a label of “starry villages and towns” that had been adopted by 13,000 places that switched off public lights during certain times, for instance between 11 p.m. and 5 a.m.;

(g) In Germany, the decrease in insect populations had led the Government to define an action programme. Laws existed at the regional level, with restrictive measures and a concept of “insect-friendly” lighting (time-limited, directed downwards only, temperature lower than 3,000 kelvin and no ultraviolet light). The federal nature protection law of June 2021 included the concept of protecting animals from artificial light at night but what may be illuminated when was not regulated, and there was no “lighting police”.

32. Session 9 was a round-table discussion during which panellists discussed how to produce a document with recommendations, and how to best bring the topic to the attention of the Committee on the Peaceful Uses of Outer Space. Working within existing frameworks might lower resistance to change: examples of successful legislation against artificial light at night already existed and peer pressure might convince Governments to act. Linking the issue to human health made it universal. More efforts to raise awareness would be beneficial, as convincing local populations was key for implementation and compliance. Technically, the recommendations were very clear; they needed to state explicitly whether the main goal was to stop the growth in or reduce entirely artificial light at night. Various channels could be used to present the case to Governments and speakers noted that, while many acknowledged that satellites were an issue relevant to the Committee on the Peaceful Uses of Outer Space, artificial light at night still needed to be recognized in a similar manner. As many places did not have access to outer space other than for watching the stars, there should be a discussion on whether being able to see the stars was part of the use of outer space.

D. Satellite constellations

33. Session 10 addressed observations of satellite constellations and what kind of data and software processing would be required for astronomers to mitigate their impacts. While space traffic management was a fundamental issue for constellations,

two aspects were important for astronomy: reflected sunlight and the impact of radio frequencies. Open data repositories for astronomical data products affected by satellites were under development. In terms of sharing data in such repositories, astronomers would prefer satellite operators to provide orbital information every eight hours, in a standardized manner, with error bounding. Some speakers explained their activities to inform astronomers and educators about satellite constellation observations. Software was being developed to help plan observations with minimal disturbance, or to quantify the impact of satellites on observation data. That activity was well defined but needed volunteers and resources to proceed. The many spacecraft of future constellations would have an impact on observations, sometimes drastically: some satellites were dark enough not to create a trail but still obscured their background. In specific situations, such as observing the transit of Venus or Mercury in front of the Sun, observation could not wait for the satellite to leave the telescope’s field of view. Astronomers would continue working with all interested operators and hoped that satellite operators would fund the development of data repositories or that States would provide funding for that research.

34. Session 11 continued the review of satellite observations, with inputs from eight speakers. Observations in Chile, coordinated with the Republic of Korea, Spain and Viet Nam, compared the brightness of satellites of various design of the Starlink and OneWeb constellations and measured whether their magnitude was fainter than seven. Others carried out simulations of satellites’ apparent magnitude: the higher their orbit, the brighter they were. The Near-Earth Object Surveillance Satellite measured the brightness of satellites from space: it had found no difference in brightness between the various Starlink designs and more variability among OneWeb satellites. When on the dayside of the Earth, the earthshine illuminated the spacecraft and the backside of the solar array was very bright. Some spacecraft of remote sensing constellations also exceeded magnitude seven. Satellites crossed the field of view of space-based telescopes as well: for the CHaracterising ExOPlanets Satellite (CHEOPS) space telescope, which characterized exoplanets with high-precision photometry during transit across a star, only about 0.2 per cent of images contained satellite trails because the telescope had a small field of view and short exposure. The impact on science was negligible, but satellites were already affecting space-based astronomical observations. In addition to the instrument’s field of view, the orbit of the telescope determined how affected its observations would be. Another speaker produced simulations of satellite trails seen by various telescopes on Earth, as a function of the exposure time and field of view of the instrument. That work could be adapted to model the impact on space telescopes. Another speaker reviewed the impact on science of existing telescopes with large fields of view, proposing parameters to characterize those observations.

35. Overall, the reflectivity of a spacecraft was complex to assess as its shape and materials varied; surfaces in carbon fibre reflected light much less than metal. Keeping records was required to assess how evolutions in design between spacecraft generations affected astronomy. A speaker explained the impact on ground-based facilities in the United States, where the Vera Rubin Observatory was the most affected because of its large field of view. Domestic rules coordinated radio quiet zones on the ground around radio telescopes, but satellites passed overhead and affected their observations: when observing in radio bands was not protected for astronomy, no location on Earth was remote enough to not be affected by satellites. For optical observation, no combination of mitigation would prevent trails appearing. The satellite constellation workshops of the United States National Science Foundation and the American Astronomical Society had developed recommendations and the Foundation could support the development of software to help schedule observations.

36. Session 12 involved the presentation of algorithms and software tools for astronomers to know when satellites would leave a trail in the image. So far, volunteers had developed a prototype with minimum capabilities and a test suite to collect feedback from the community before developing more robust and capable

versions. Technology existed to mask the trails but, as the number of satellites increased, the information provided publicly on a satellite's position was not accurate enough for astronomers' needs. To mitigate streaks, it was useful to know the satellite brightness, in addition to the background image and the satellite position. One speaker gave a demonstration of the Worldwide Telescope from the National Observatory of China, which was a public version of the Virtual Observatory, an international initiative for online research and education for astronomy. The software computed satellite visibility and could be further developed to model the field of view of a given telescope.

37. Two speakers assessed how the proliferation of space objects had increased night sky brightness and how to model future evolutions. The collective light of objects individually below the threshold of detection still contributed light in the sky, especially for detectors with a large field of view. Current satellites had caused an increase by a factor of 4.5 in 20 years, resulting in about 16 microcandela per square metre now, while the natural night sky was about 200. It did not yet prevent visibility of the Milky Way from a dark sky place, but the visibility of some objects in some regions of the sky might be affected and such a proportion corresponded to what some standards considered light pollution. In 15 years, the additional presence of 64,000 satellites would increase the sky brightness by a few per cent. In the theoretical event of all those 64,000 satellites breaking down to debris of 1 millimetre as a result of collisions, the sky brightness caused by constellations would increase by a factor of 14, and by larger factors if the debris were smaller.

38. In the ensuing discussion, it was concluded that tools were needed but that astronomers also needed policy actions to preserve the night sky. Astronomers considered advertising their efforts through the media to reach software developers who could contribute to those efforts. As policy processes progressed very slowly, it might be more effective to convince industry to help and start citizen-science initiatives.

39. Session 13 presented the point of view of satellite operators and the satellite manufacturing industry. Operators needed to consider the impacts on astronomy very early in their design, as any changes during development would be more costly to implement or cause significant delay to the project. The cost might even be prohibitive. While industry had been assessing how to reduce the brightness of spacecraft, satellite radiofrequency signals needed to go through any material used for shielding reflected sunlight: such technical constraints reduced options and no satellite manufacturer had yet produced a design with brightness maintained below magnitude seven. Engineering teams in the satellite manufacturing industry could model various materials in laboratories to assess their reflectivity and specialized companies could do measurements on materials and computer simulations before launch, but that required an additional budget. Ultimately, assessment in real conditions could only happen once the satellite had been launched. Tools to predict visibility after launch would need to be further developed.

40. The satellite industry had been discussing how to raise awareness of the impact on astronomy among space systems designers and regulators; there was already a high level of concern within the industry about how to implement space safety measures. After launch, industry actors could make data available to astronomers to support observations; however, some information on satellite location was sensitive and operators might not want to provide it. Most of the data required by astronomers could probably be given, provided it was kept secure. A dialogue was in progress about recommendations that needed further discussion. For instance, visibility might be reduced at altitudes below 600 km, but lower orbits automatically required more satellites to provide the same service. Industry would prefer an approach based on meeting performance metrics, rather than prescriptive approaches.

41. The discussion was focused on how to define suitable measures: the engineering and operational constraints proposed needed to be informed and realistic. The proposal by astronomers to target magnitude seven originated in the impossibility of

recovering astronomical data, but before such a rule could be adopted, technical feasibility needed to be demonstrated. An environmental impact assessment could possibly be requested before launch, as a precondition in the regulatory process. In such a case, responsibility would shift to the national authorities. Such measures might affect the financial viability of satellite services, and some operators already faced funding difficulties. The dialogue with astronomers needed to continue in order to determine feasible options jointly.

42. Session 14 provided an overview of policy implementation in various countries. Diverging interests between telecommunication projects and astronomy were not new: in 1961, Project West Ford had created a historical precedent when astronomers opposed the plan to send millions of metal dipole antennae into orbit. In addition to a space agency, separate stakeholders usually oversaw science spending, granted orbital licences and regulated the use of the radio spectrum. In the United Kingdom, the Royal Astronomical Society had brought questions to Parliament after the Government's purchase of parts of OneWeb made the company integral to its space strategy. At the European level, astronomers had held meetings with members of the European Parliament and wanted to initiate a public campaign about the societal impact of losing dark skies, covering heritage and cultural traditions. A group of experts had been preparing recommendations for IAU with case studies from 25 countries. The speaker illustrated those elements with the situation in Argentina, Canada and the United Arab Emirates. There was a strong push to support the growth of the space economy in many countries and concerns about sustainability often did not translate into specific measures. Many States invested considerable human and financial resources into astronomical activities without an appropriate forum at the national level to balance the interest in astronomical activities with commercial activities.

43. A legal discussion followed on how to define "the environment"; for instance, whether it included Lagrange points or the surface of Mars, and whether the legal concept of protecting solar system bodies from contamination by Earth life could be extended to celestial bodies. From the perspective of an attorney working in litigation, the fact that astronomy involved economic activities, with investments in scientific research, was a relevant line of argument against increasing the brightness of the sky, when addressing Governments. Other arguments could consider that the re-entry of satellites created aluminium oxide that affected the atmosphere, or that orbits were a natural resource and the Earth's environment should be regulated as such.

44. A representative of ITU provided an overview of how the radio frequency spectrum and associated orbits were regulated. Light was not considered part of radio frequencies so was not regulated by ITU. The Radio Regulations were an international treaty developed through conferences since 1906 and amended by consensus among all signatories; changes were prepared ahead of world radio conferences within study groups. Participants in study groups represented member States but also included researchers and representatives of academia and the private sector. Registrations of satellite networks with ITU were done by national administrations, not operators directly; every frequency and associated orbit used in space needed to be coordinated before entering the Master International Frequency Register. Current provisions of the Radio Regulations to register a satellite network did not comprise any specific review of environmental concerns. Whenever technical coordination was required to resolve an identified risk of signal interference, operators and national authorities discussed and coordinated directly, before informing ITU of their agreement. As operators submitted their initial requests at an early stage of the design, the requests reflected their estimated needs. Initial filings might contain more physical satellites and radiofrequency beams, while the filings registered in the Master Register closely reflected the use of spectrum and orbits. The Radio Regulations did not stipulate a maximum number of satellites: as long as a new system met the requirements to operate without causing unacceptable interference to others, it could be registered. The protection of existing services and the introduction of new ones were equally important for technical compatibility studies. ITU aimed to avoid warehousing of

spectrum and orbits by theoretical projects that did not materialize: each satellite network was to be brought into use within seven years. Since 2015, the rules had been adapted to constellations: the principles of protection of other services and of "first come, first served" remained applicable, while deployment milestones, after bringing the first satellite into use, needed to be declared to ITU.

45. The speakers discussed how Governments could require operators to take responsibility and how any country wishing to protect astronomy could include such considerations as part of its licensing regime for satellite operators.

46. Session 15 was focused on international policy. One speaker discussed whether to consider astronomy a form of use of space protected by the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, and whether the principle of non-appropriation contained in the Treaty could apply if satellite constellations excluded others from using the same orbit. Principles of environmental law were reviewed, such as prevention of transboundary harm, the precautionary principle, the polluter-pays principle, and sustainable use. Private actors were not directly bound by public international law, but States had an obligation to regulate their activities, assess compliance with applicable international environmental law and consider sustainability; non-governmental activities should be subject to some form of obligation to consult affected States parties. The concepts of corporate responsibility could apply to private activities, also in outer space: the Space Sustainability Rating was a voluntary tool that could encourage such practices.

47. In the ensuing discussion, the absence of enforcement mechanisms to police offenders after a launch was noted. States needed to consider all stakeholders with legitimate interest and, rather than international law, it should be a concern at the national level during the process of licensing space activities. The threat of space debris had been discussed for many years by the Committee on the Peaceful Uses of Outer Space, while astronomy's predicament was more recent: several States were currently updating their regulations to consider space debris, providing an opportunity to also consider the broader impact on the environment. Space was recognized as a global commons in the Common Agenda[1] recently published by the Secretary-General and newcomers could not push others away. The ITU advance notification process required those wishing to launch a new initiative to coordinate with those affected to resolve the conflict, in a bilateral process between States. Speakers discussed whether space law might evolve in the same way as the law of the sea, with a specialized international tribunal to settle disputes, or towards arbitration.

48. Session 16 was attended by representatives of astronomers and of the space industry and by policy experts for a round-table discussion about satellite constellations. While using satellite constellations to bridge the digital divide was a positive contribution to enable science, speakers discussed whether there was a market for all satellite constellation projects. Industry had seen increasing demand for satellite Internet and enthusiasm for the service, with technology evolving towards 5G networks and connected objects: low latency required low Earth orbit constellations rather than geostationary satellites. Putting numerous objects into orbit and moving to a consumer-electronics approach for space created problems similar to the "tragedy of the commons" seen in economical science with the pollution of the oceans and the upper atmosphere. A speaker noted that the rules on space activities were decades-old even though the industry was innovating quickly. Technology was being developed, together with international guidelines, to deorbit spacecraft safely, and space sustainability required rules. Licensing operators should include risk assessments so that States knew what risk they were taking and the potential impact on the public purse. The largest constellations were aware of the issue with astronomy and tried to propose best practices that could be implemented by all operators, such as modelling and testing of brightness before launch. Monitoring what happened in orbit remained necessary to enforce rules; however, one speaker stressed that there

[1] Available at www.un.org/en/un75/common-agenda.

might be issues with tracking some objects or challenges related to export control laws preventing the sharing of such data.

49. One speaker noted that the Guidelines for the Long-term Sustainability of Outer Space Activities did not specifically address constellations, because the challenges they raised were still being discussed. It was not clear whether States saw astronomy as a space activity, or whether the drafters of the Outer Space Treaty had astronomy in mind. Rather than launching a debate on how to interpret the Treaty, the speaker recommended a pragmatic approach through national legislation in States that authorized space activities and had an interest in astronomy. Some States heavily invested in astronomy were also involved with constellations. The United Nations had not handled space debris mitigation by developing a new treaty, but rather best practices and guidelines that some States were choosing to integrate into their national regulatory framework. Speakers wondered whether States with astronomical observatories could define regulation as part of the licensing process at the national level, with sanctions for non-compliance. It was suggested that gathering supportive evidence of the impact on astronomy, then formulating recommendations in simple terms, would help the astronomy community raise the matter with Governments.

E. Radio astronomy

50. Session 17 summarized the situation for radio astronomy. Radio astronomy surveyed broad frequency ranges and large sky areas with high sensitivity, because some phenomena were very faint and only visible at some frequencies. When satellites had started to create interferences with observations, astronomers had manually modified radio telescope antennae to filter out extraneous radiation. Years later, the large number of satellites overwhelmed telescopes, with side effects difficult to foresee, accumulated noise was strong enough to overwhelm filtering and receivers would have to be redesigned. The radar operations of remote sensing satellites could also saturate, or even destroy, radio astronomy telescopes if they emitted directly into the receivers. The number of satellites with radars on-board had increased massively, to several hundred. While radio astronomers tried to contact newcomers in the field directly to warn them of the damage they might cause, new threats were emerging: satellites that would convert solar radiation to distribute electricity on Earth were under study and, although the Radio Regulations protected passive science on the far side of the Moon, missions were being prepared with telecommunications and navigation satellites in orbit there.

51. To preserve radio astronomy, artificial radiation (whether light or radio waves) should not be produced if not needed and should not be detectable where it was not used. Satellites should avoid direct illumination of radio quiet zones, with measures to reduce emissions from their antenna side lobes.

52. Protecting radio astronomy required resources in various spectrum management bodies; the few astronomers working on spectrum management could not match the vastly larger resources devoted to the topic by private companies. Incentives were needed for younger generations to get involved, because work on spectrum management did not contribute to advancing a scientific career. Going to remote parts of the planet to avoid interference was no longer an option: cosmic microwave background measurements, which were essential for fundamental physics, saw geostationary satellites as brighter than the sun in the data. There was concern that satellite constellations would similarly contaminate data and many experiments, funded by public funding, would be significantly affected. Modifying receivers or avoiding looking at satellites was not feasible for all telescopes, while observing for longer to compensate for the loss of data directly increased the cost of science.

53. Limits to intentional emissions were regulated by ITU and administrations in each State, while unintended electromagnetic radiation limits were adopted nationally. For a satellite, electromagnetic radiation tests focused on compatibility with the launcher; no specific consideration was paid to protecting radio astronomy

bands. That was not an issue with very few satellites, but in an area of mass production, the maximum tolerated electromagnetic radiation in a radio astronomy band would need to decrease as satellite numbers increased, otherwise satellites could close the spectral windows of observations for radio astronomy forever.

54. A speaker explained how radio signals were used to detect meteors and the ionized trail they created in the atmosphere: information was obtained from reflection and the scattering of a radio wave by the trail. Several highly sensitive radars were used around the world for that purpose.

55. Session 18 was a round-table discussion between radio astronomers and a representative of the Radiocommunication Bureau of ITU, looking at the roles of ITU and the Committee on the Peaceful Uses of Outer Space. Spectrum management had evolved from an environment with a handful of participants to a situation of competing demands from operators, with high-power radars and transmitters on high-altitude platforms. Satellite communications had become a large business and the operation of satellites had moved from Governments, which were the interface of ITU, to private companies. Spectrum management practices had not progressed as quickly as the technology had evolved. The speakers considered that more discussion was required on the roles of the ITU Radio Regulations and the Committee. Astronomers would need to contact their own administrations, which were entitled to propose changes to the Radio Regulations, starting with preparatory studies before proposing agenda items at a world radio conference at which those regulations evolved. The representative of ITU clarified that radio frequencies above 3,000 GHz were not regulated, but that studies were possible at any frequency, including optical links. It was considered that, as the Radio Regulations did not currently include formal limits to the number of objects launched into space, while the Office for Outer Space Affairs, on behalf of the Secretary-General, was charged with maintaining the Register of Objects Launched into Outer Space, the Committee on the Peaceful Uses of Outer Space would be the proper place to discuss the topic. Discussion on the sustainable use of space at the United Nations level was also the work of the Committee.

56. Participants in the discussion stressed that some problems were particularly acute, such as how to keep observing the microwave background, and required joint solutions, possibly involving international scientific entities such as the Committee on Space Research. Authorizing a constellation had wide-ranging consequences that had not been foreseen.

V. Observations and recommendations

57. At the last session, chaired jointly by representatives of the Office for Outer Space Affairs and IAU, the various views on the actions that could be initiated after the event were summarized. A discussion followed, involving representatives of each of the groups of experts that had prepared inputs for the conference.

58. The recommendations raised about artificial light at night were combined with those on the protection of observatories, of dark sky oases and of the bio-environment. The world was gradually blinding itself to the dark sky, with ramifications for human health and the functioning of nature at night, in addition to astronomy:

(a) For special protected areas, the total amount of light that is acceptable needs to be defined, with ways of measuring lighting and stopping the increase. Technical means exist to direct and reduce light, with usage-based dynamical zoning adjusting light level, without exceeding what is strictly needed. Practicalities on how to reach that goal are under discussion: engineers, planners and policymakers would want quantitative guidance for technical design that organizations such as the International Commission on Illumination could provide; however, quantitative requirements would need to be adjusted to circumstances;

(b) A cultural change is needed: natural darkness should be the baseline and lighting added only when necessary. Public opinion would be more likely to endorse this change if people were able to see what the natural state of the night sky was;

(c) Astronomical science requires observations from the ground for the success of space-based science. If measures to support science were implemented against misdirected light, other areas, such as health and the bio-environment, but also the detection of near-Earth objects, would benefit.

59. Recommendations about satellite constellations addressed several aspects:

(a) To mitigate loss, astronomers would need to mutualize data and software and obtain information on precise satellite positions to predict when satellites would cross the field of view. Masking software is complex to develop and might introduce artefacts into the data. Before mitigation services become available for professional use, this effort needs to be funded;

(b) Satellite operators and the manufacturing industry have been engaged in discussions with astronomers on a voluntary basis. Both sides need to engage, from the inception of satellite projects, and develop mitigation jointly. Governments could encourage this coordination while industry should continue to develop laboratory testing and modelling, sharing data and best practices;

(c) National space policies could consider the brightness of space objects in the licensing and authorization procedures that are at the heart of how States implement their obligations under the Outer Space Treaty. Some States stipulate environmental concerns relative to space activities. Similarly, international standards could be developed to define the brightness of space objects and how to implement a limit;

(d) Increased funding will be required for astronomy to develop mitigation, but also for industry, for which the topic is new;

(e) At the international level, while astronomy could be considered a form of use of outer space, so are telecommunications; therefore, a balance needs to be found between the necessities of individual States. A consultation process could be considered, with guidelines that would take astronomy into consideration.

60. The recommendations for radio astronomy consider that, whether it is artificial light at night or reflection from satellites, unwanted emissions into radio telescopes should not be produced. Difficulties are particularly critical for radio astronomy disciplines such as studying the microwave background, where the Radio Regulations cannot solve the problem:

(a) Satellites should be required to avoid direct illuminations of radio telescopes and radio quiet zones. Direct illumination is a consequence of how the satellites are operated and their orientation, as well as antenna side lobe levels;

(b) Recommendations do not specifically refer to spectrum management and ITU. Since the registration of objects launched into outer space is governed by the legal regime of outer space as developed by the Committee on the Peaceful Uses of Outer Space and as the Office for Outer Space Affairs maintains the Register of Objects Launched into Outer Space, the Committee would be the proper place to discuss the presence of so many satellites in orbit.

61. The speakers stressed the central role of the Committee on the Peaceful Uses of Outer Space and discussed how to link the various issues. Some States members had advocated for a single issue/item for discussion on the agenda of the Scientific and Technical Subcommittee session in 2022, with the suggested wording of “General exchange of views on the effect of satellites upon astronomy”. The various views and proposals discussed at the present conference could provide input to such a discussion on opportunities for international cooperation.

62. It was noted that interested States members of the Committee on the Peaceful Uses of Outer Space might consider submitting a working paper proposing actions.

VI. Conclusions

63. The Conference on Dark and Quiet Skies for Science and Society discussed a wide-ranging set of measures that could be taken to reduce the impact of sources of light pollution and interference on optical and radio astronomy.

64. Representatives of the Permanent Mission of Spain to the United Nations, IAU and the Office for Outer Space Affairs concluded the conference by thanking all involved in preparing the event and expressed their solidarity with the people of La Palma.

65. Participants were encouraged to provide written feedback using a dedicated online form and IAU announced the creation of a dedicated centre to structure initiatives.