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Dark and quiet skies, astronomy and large constellations: addressing emerging issues and challenges

Conference Room Paper on the Protection of Dark and Quiet Skies for science and society

Presented by Belgium, Bulgaria, Chile, Colombia, Germany, Mexico, Peru, Spain, Switzerland, the United Kingdom, African Astronomical Society, Committee on Space Research, European Astronomical Society, European Organization for Astronomical Research in the Southern Hemisphere, International Academy of Astronautics, International Astronomical Union, and Square Kilometre Array Observatory

Summary

Many companies and space agencies are building and launching space objects in low Earth orbits (LEO). Their purpose varies from providing communications services, remote sensing services, or low-latency broadband internet access, all beneficial applications of space technology and in line with the United Nations Sustainable Development Goals (SDGs), such as bridging the digital divide. However, the rapid growth of large satellite constellations poses challenges for astronomical research from streaks of reflected sunlight for optical telescopes to increased power potentially swamping faint astronomical signals for radio telescopes. The growth in number of satellites also impacts amateur astronomers, and the general connection between humanity and the night sky, including for Indigenous communities.

Given the unique nature of this topic, no single nation or entity can drive meaningful change without the coordinated action and cooperation of governments, satellite owner-operators or manufacturers, and astronomers from around the world. The United Nations Committee on the Peaceful Uses of Outer Space is well suited to address the challenge to optical and infrared astronomy and has the appropriate

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mandate, technical expertise, and processes necessary to achieve results under the five-year Agenda Item.

This paper offers suggestions to Member States for immediate actions that they can take to support the coexistence of satellite constellations and astronomical research.

I. Introduction and Background

1. “Dark and Quiet Skies, astronomy and large constellations: addressing emerging issues and challenges” was established at the 67th session of the Committee on the Peaceful Uses of Outer Space in 2024 as a five-year Agenda Item for the Scientific and Technical Subcommittee beginning in February 2025.

2. The “Group of Friends of the Dark and Quiet Skies for Science and Society” (GoF) is an initiative focused on the impact of satellites and satellite constellations on astronomy and the night sky. It was established by the Committee delegations of Chile and Spain following broad support from Member States to advance the protection of Dark and Quiet Skies as discussed by many delegations at the 60th session of the Scientific and Technical Subcommittee and the 66th session of the Committee in 2023.

3. The GoF was created during a special session of the IAU Symposium 385 Astronomy and Satellite Constellations: Pathways forward in La Palma (Canary Islands) on October 6, 2023, and now includes 17 Member States and six Permanent Observers.

4. Member States and Permanent Observers from the Committee that have supported or are interested in exploring support for “Dark and Quiet Skies for Science and Society” are welcome to join the Group of Friends. Delegations can appoint their representatives from their government, academy or private sectors.

5. Additional information can be found in the GoF’s Terms of Reference, which details how the group aims to promote awareness of the issue and discuss adoption of best practices among relevant stakeholders.

6. The GoF operates through a Steering Committee (SC) representing all the member delegations and organizations; it appoints Focus Groups of technical and policy experts to articulate issues.

II. Impacts and Mitigations

A. Impact of Satellite Constellations on Optical/Infrared Astronomical Science

7. Streaks in astronomical images from reflected sunlight off satellites compromise astronomical data quality, particularly for images obtained in twilight and at lower elevation in the sky. These streaks interfere with the discovery and tracking of small solar system bodies like near-Earth objects and comets, as they can mask or distort the appearance of faint objects, making identification and orbital calculations more difficult. For time-domain astronomy, which aims to track variable sources and transient events (e.g. supernovae or other highly energetic phenomena) there is a higher risk of detecting false positives due to streak-induced background variability (e.g. satellite glints). This reduces observational accuracy and wastes valuable resources. It also interferes with the discovery of unexpected astronomical phenomena.

8. For time-critical observations, like those tracking gravitational wave events, satellite streaks can disrupt astronomers’ ability to pinpoint optical counterparts in real-time, potentially missing very short-lived phenomena. While some propose space-based observatories as a solution, construction and operational constraints

mean they cannot fully replace the capabilities that the combination of ground-based and LEO telescopes (like Hubble Space Telescope) provide, given the higher costs of deployment in space further away from the Earth, and the complexity of maintenance of observatories in these locations. Additionally, orbit-based telescopes are not without satellite streaks, especially those in LEO. Collaborative strategies are needed to mitigate the impact of satellite streaks on critical astronomical discoveries, as ground-based astronomy remains irreplaceable in the study of the universe.

9. There are several additional domains where amateur astronomers contribute to astronomy through professional-amateur collaborations which are more and more impacted:

(a) Meteor statistics and Zenithal Hourly Rate which contribute to the knowledge of the ejected materials and processes from comets as the Earth crosses their ejecta clouds;

(b) Comet photometry requiring the integration of the total flux from the complete coma, which could be compromised by noise from adjacent satellite streaks;

(c) Accurate photometry of stellar occultations by solar system objects requiring a stable background.

10. The downstream impacts to astronomy from atmospheric effects from launches and re-entries are under investigation. Deployment and maintenance of constellations with thousands of satellites with short individual operational lifetimes requires frequent launches and re-entries. Although the volume of material burning up in the atmosphere is smaller than that deposited by meteors to date, the composition of the material is very different and the rate of heavy metals deposited by satellites may be surpassing the natural influx. Should the abundance of materials like alumina in the upper atmosphere sharply increase (with aluminium and other metals from spacecraft already detected), there is the possibility of reducing observational transparency in the stratosphere and increasing light diffusion from the high atmospheric layers. Detailed modelling and atmospheric measurement campaigns are required to assess this effect. Any increased creation of space debris would present an uncontrolled source of stray light in the case of large objects with unpredictable light curves. We also note that observatories within a few hundred kilometres of launch facilities may be impacted by the glowing contrails for each launch, potentially limiting observing directions. This impact needs further quantification.

B. Rationale for limits on brightness and orbital deployment

11. While various limits have been proposed for maximum acceptable satellite brightness, the International Astronomical Union (IAU) currently recommends each satellite to appear fainter than 7th magnitude. This recommendation is being implemented in national laws, e.g. the French Space Operation Act. (A “magnitude” is a traditional way to characterize steps in brightness, with first magnitude stars representing the brightest few stars in the sky). At 7th magnitude, satellites should be invisible to the unaided eye. It is essentially impossible to avoid all effects on astronomical science, as large telescopes can see objects millions of times fainter than this. However, for the most sensitive wide field camera systems currently planned, disrupting effects become dramatically worse at brighter than 7th magnitude, as electronic effects in detectors lead to multiple “ghost streaks”. In establishing that performance goal, astronomers assumed that satisfying the operating condition for the telescope with the largest “grasp” of collecting area and field of view would be sufficient for most other professional telescopes.

12. It is the case that even if the steady state typical brightness is fainter than 7th magnitude, satellites may be much brighter than this during their specific “orbit raising” phase, and very bright glints may occur as the viewing angle towards satellites changes. In addition, apparent flickering from reflection from irregular surfaces creates a challenge in data analysis. The largest impact on science is not from

lost sky survey area (caused by masked trails), but from the systematic errors introduced by unmasked trails at the limit of detection.

13. Public workshops established a recommendation on the orbital height of constellations, but this was based exclusively on minimizing sunlight streaks in the dark sky for the largest professional observatories. Constellations at lower orbital height need more satellites to provide ground coverage for the communications missions, which seems to suggest that constellations at higher orbits would require fewer satellites and therefore would have a lesser impact. However, at visible light wavelengths, satellites can only be seen when they are reflecting sunlight. This "twilight window" is much shorter for satellites at low orbit heights, especially for most observatories stationed at low latitudes on the Earth's surface. Satellites at lower orbit heights also move more quickly through the focal planes of telescopes and may be more out-of-focus, resulting in a larger angular size and a lower brightness per pixel. This means that for optical astronomy, lower constellation orbital heights would be preferable. Further simulations are valuable to expand on those already in hand addressing the scientific impact on a mix of different programs, including those done in astronomical twilight such as Near-Earth Object detection and tracking, from each different parameter of a constellation configuration (the number of satellites, the orbital height distribution, etc.).

C. Current status of mitigations of satellite brightness

14. Satellite operators and manufacturers have taken steps to mitigate the effect that the Sun's reflection from satellite surfaces can have on astronomical observations. Several technological solutions and techniques have been experimented with and adopted. For example, some operators deflect or diffuse sunlight using dielectric mirror films or innovative surface shapes. Darkening of certain components, especially those with complex geometry, also stands as an effective approach if the thermal effects can be managed. In addition, satellite operators have implemented flight operation strategies such as methods for minimizing tumbling or for pointing the solar arrays away from the Sun when crossing the terminator as well as for adjusting spacecraft orientation during orbit raise, all of which can help reduce reflectivity. Some satellite operators have chosen lower orbital heights. Importantly, some satellite operators share their satellite ephemerides with astronomers to help adapt observation schedules, and thereby minimize disruptions from satellite reflections.

15. Numerous optical observations indicate that these mitigation strategies have helped satellite operators and manufacturers to reduce the apparent magnitude of their satellites. All satellites also remain visible to large optical telescopes during standard operations, hence additional mitigation efforts may be required.

16. Other concerns relate to some phases of flight such as orbit raising and deorbiting. Indeed, power generation and drag minimisation must be prioritized at orbit raising, and end-of-life operations such as satellite passivation during deorbiting may prevent operational mitigation measures. Drag sails used in controlled de-orbiting can increase reflectivity, exacerbating visibility issues during satellite disposal phases. Observations of current constellations indicate that, while some satellite operators and manufacturers have reduced brightness through mitigation measures, many satellites remain highly visible, without any mitigation strategies, causing significant disruption to ground-based astronomy.

17. To encourage efforts, the IAU Centre for the Protection of Dark and Quiet Sky (or CPS) has created an Industry and Technology Hub which is fostering collaboration between the astronomical community and satellite operators and manufacturers to further study and encourage the implementation of mitigating measures of constellations' effect on astronomers' observations. First results are encouraging and confirm the willingness of satellite companies to cooperate and work on additional mitigation options. It is important for satellite operators and manufacturers to share

sufficient information, while honouring proprietary nature of aspects of their design, on the geometry and make-up of their satellites or to provide accurate brightness models, so that the astronomical community can undertake realistic simulations of the impact on their data and science.

18. Astronomy benefits from safe and sustainable practices in space operations, such as effective space traffic coordination and space situational awareness. In addition to the benefits of better understanding when space objects will be in view of telescopes, it is important to minimize the creation of space debris to avoid additional sunlight streaks and increase in diffuse skyglow from impacting astronomical data collection.

D. Collaborative efforts to mitigate the impact of satellites on radio astronomy observations

19. The unique roles of the Committee and ITU-R are clear and distinct with respect to the protection of radio astronomy. However, the proposed and future mitigations may require action by both bodies and coordination is likely necessary without creating conflict between their mandates.

20. The impact on the radio-quiet sky needs a different consideration, as all satellites above the horizon are detectable by sensitive radio telescopes. Such telescopes are usually sited in remote locations and are often afforded additional protection by local and national regulations against interference by ground-based transmitters. While the radio regulation is the domain of the ITU-R, this topic is highlighted for information to the Committee. There are three distinct issues:

(a) Interference from allocated radiocommunication service applications can enter into bands allocated to the radio astronomy service and have detrimental effects. This case is well-regulated at the ITU-R in terms of protection criteria and calculation methods;

(b) Modern radio astronomy requires using very sensitive and large-bandwidth receivers. Therefore, receivers can become saturated if an intense signal is entering the system (even at frequencies which are not of interest or are not protected);

(c) Satellites can produce unintended electro-magnetic radiation (UEMR), which can be thought of as “leakage radiation” from electronics on board a satellite that are not immediately related to the desired radio transmissions. While the Radio Regulations of the ITU-R urge administrations to avoid interference to radio services stemming from UEMR (Article 15.12), UEMR is not considered in any of the international regulatory procedures (such as satellite filing processes).

21. The challenge to radio astronomy observations has been internationally recognized at the ITU-R. For the exchange of information about global systems, including satellite constellations, the Radiocommunication Assembly in 2023 called for a worldwide database of Radio Quiet Zones. This database is maintained by the ITU-R and member states are encouraged to submit details regarding rules they have established to protect their radio astronomy facilities. This database will facilitate voluntary avoidance of established RQZs by satellite operators.

22. The ITU-R World Radio Conference 2027 (WRC-27) Agenda Item 1.16 is focused on studies on the technical and regulatory provisions necessary to protect radio astronomy operating in specific Radio Quiet Zones (and in frequency bands allocated to the radio astronomy service on a primary basis globally) from aggregate radio-frequency interference caused by non-geostationary satellite orbit systems.

23. Geodetic Very Long Baseline (Radio) Interferometry (Geo-VLBI), as the most accurate technique to measure positions on Earth and its position in the Universe, can also be impacted by satellite constellation interference. The United Nations General Assembly Resolution 69/266 tasks the Geo-VLBI community to provide data products such as the Celestial and Terrestrial Reference Frames, as well as Earth

orientation parameters, which are of utmost importance to society and research, including monitoring of global change or applications of space and satellite navigation. The United Nations Global Geodetic Centre of Excellence was established in Bonn, Germany and may serve as a coordinator of concerns related to geodesy (https://ggim.un.org/UNGGCE/). Radiofrequency concerns are being addressed at the ITU-R.

24. The density of microwave emission generated by the satellite constellations creates microwave background noise orders of magnitude stronger than the weak cosmic signals. Observations of the CMB (Cosmic Microwave Background) by ground-based instruments become impossible. No mitigation for this type of impact has been determined yet.

III. Policy Considerations

25. The Committee already engages on several topics regarding the operation and effects of satellites in orbit, including space debris, the use of nuclear-power sources, and the long-term sustainability of outer space activities. The Committee's work on these topics has resulted in comprehensive guidelines and frameworks meant to guide the international community's efforts to address these issues, including the Debris Mitigation Guidelines, the Safety Framework for Nuclear Power Source Applications in Outer Space, and the Guidelines for the Long-Term Sustainability of Outer Space Activities of the Committee. These significant achievements were accomplished by leveraging the unique convening power of the Committee to bring together government, policy, legal, and technical experts from more than one-hundred nations. The Committee should rely on similar procedures and processes to promote efforts advancing the work under this agenda item to understand and address the challenges posed by satellites and large satellite constellations on astronomy and the night sky, while considering the scope and mandate of the Committee and other United Nations Agencies. Indeed, the inclusion of the dedicated agenda item "Dark and quiet skies, astronomy and large constellations: addressing emerging issues and challenges" for consideration by the Scientific and Technical Subcommittee during its sessions from 2025 to 2029 is a substantive step towards addressing this issue.

IV. Possible Actions by Member States

26. The unintended consequences of the proliferation of satellite constellations have included negative impacts on activities dependent on Dark and Quiet Skies. The delegations and organizations supporting this Conference Room Paper therefore recommend the following actions to be considered by Member States:

(i) To encourage and provide resources or incentives to support collaboration among administrations, satellite owners, operators and manufacturers and astronomers to develop, implement and test effectiveness of mitigating effects on astronomy;

(ii) To encourage and provide funding or incentives for research to inform policy, best practices, and guidelines based on scientific understanding;

(iii) To foster consultation and coordination between satellite owners, operators, and manufacturers and impacted scientific agencies.

27. The Annex provides specific suggestions for implementation.

Annex

Possible Implementation Actions by Members States include:

A. Increasing the accuracy of predictions of position and optical brightness.

1. Sharing of accurate and current positional information for telescope pointing avoidance as needed and post-hoc sunlight streak removal.

2. Establishment of laboratories for measurement, such as the Bi-directional Reflectance Distribution Function (BRDF) of satellite surface materials for predicting brightness at different angles of viewing and illumination and utilization of an anechoic chamber to understand broadband radio emissions.

3. Development of software to model and predict apparent brightness (as a function of phase angle and viewing angle) and observational verification of modelling predictions.

4. Coordinated tests between satellite operators and astronomy facilities to assess the effectiveness of mitigation measures.

B. Taking steps to reduce optical brightness.

1. Supporting development of coating materials that can be implemented on satellite surfaces towards reducing satellite brightness.

2. Promoting satellite designs which minimize the impact (size of satellite, geometry, orientation of components).

3. Consider all phases of launch, operation, and re-entry to minimize brightness and associated operational parameters.

C. Understanding the impact.

1. Support general research to understand impacts on all affected stakeholders, both professional and non-professional.

2. Support research to model the scientific impact of sunlight streaks (in the interest of defining thresholds for harm) and to examine the impacts on a distribution of high-priority scientific programs for different constellation configurations in terms of number of satellites and orbital altitude.

3. Support research to model the impact of launches and re-entries on stratospheric chemistry (hence atmospheric transparency for astronomical observations) to determine impact on astronomical observations.

4. Support research to model the loss of observing time from atmospheric after-glow of launches or re-entries.

5. Support research to model the scientific impact of increase in diffuse skyglow from the growing population of space debris.

D. Research support for new technologies and approaches.

1. Support development of new technologies considering the trade-offs among impacts to optical, infrared and radio astronomy, such as development of more resilient optical detectors and technologies for reducing the impact by man-made transmissions from satellites to radio astronomy observatories, including the radio quiet zones of highest relevance to astronomy.

E. Promoting collaboration and consultation, including with commercial or non-governmental satellite operators and manufacturers.

1. Promote fora for exchange of information on astronomical needs and industry capabilities, one example being the IAU CPS Industry and Technology Hub.

2. Offer ways for satellite owners, operators and manufacturers to demonstrate publicly their efforts to mitigate impacts on Dark and Quiet Skies, for example, through extension of the Space Sustainability Rating.

3. Gather information, follow activities and participate in the processes at ITU-R, CISPR, ISO, and other international organisations that assess and act on the impact of complementary issues such as radio emissions, in particular unintended radio emission, on astronomy.

4. Develop or support existing organizations that engage, assess, and share with broader stakeholders and communities affected by satellites' effects on the night sky.

5. Participate in workshops and gatherings that explore broader impacts, such as the IAU Symposium IAUS 399: Indigenous Astronomy in the Space Age | IAU.

6. Consider licensing or regulatory approaches that facilitate coordination and/or mitigations by satellite operators to limit potential impacts to astronomy.