MITIGATING SATELLITE CONSTELLATION IMPACTS ON ASTRONOMY

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ABSTRACT

The protection of the dark and (radio) quiet sky is a key aspect of the European Space Agency Zero Debris Charter. The International Astronomical Union Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (IAU CPS) is one of the partners working to develop and implement technical and policy recommendations. In this contribution, we summarize and discuss existing recommendations and guidelines that are aimed at enabling the coexistence of satellite constellations and ground based astronomy. Many individuals and groups, including astronomers and industry partners, are working on strategies for more effectively sharing access to space. As a result, the IAU CPS recommendations touch on a variety of subjects ranging from satellite constellation design, to operational modes, to establishing standards for information sharing. The IAU CPS uniquely enables development of publicly accessible tools and services alongside these recommendations, and we endeavor to engage all parties in an open and constructive manner.

Keywords: ESA; Dark and Quiet Sky, Satellite Constellations, Astronomy, IAU CPS, Zero Debris.

1. INTRODUCTION

Historically, astronomers and the space industry have worked closely together. However, the establishment of satellite constellations has increased tensions between the fields [1, 2]. Astronomers became acutely aware of large satellite constellations and their potential impact on the night sky with the launch of the first Starlink satellites in May 2019. Satellites communicating with user terminals can appear as bright as the Sun to in radio observatories such as SKA-low [3]. Unintended electromagnetic radiation from satellites can also interfere with radio observations [4]. Large, direct-to-cell satellites that reflect sunlight back to the ground can be as bright as the brightest objects in the night sky [5]. The sunlight reflected off such satellites could cause partial "whiteouts" on CCDs in billion-dollar astronomical sky survey facilities such as the NSF-DOE Vera C. Rubin Observatory [6]. The congestion of low-Earth orbit presents additional challenges for adaptive optics, as artificial guide stars crucial for wave-front sensing must be turned off by default when satellites pass overhead to avoid damaging them [7]. It is well established that a large number of bright constellation satellites will permanently alter the appearance of the night sky [8, 9].

In response, more than 150 international experts from astronomy, industry, space policy, and the broader community set out to investigate potential and observed interference of satellites with astronomical observations. Multiple workshops (e.g. SATCON1 & 2), conferences (Dark & Quiet Skies 1 & 2) and symposia, such as the IAU Symposium 385: Astronomy and Satellite Constellations — Pathways Forward, have contributed to identifying key issues, proposing and implementing mitigation strategies, and involving all stakeholders [10, 11, 12, 13].

By integrating a zero-debris policy, for instance, that includes protections for the Dark and Quiet Sky, both communities, space industry and astronomy, are encouraged to continue to work together [14]. The Zero Debris Framework developed under the auspices of the European Space Agency is an initiative that represents a critical step toward sustainable space practices, ensuring that space remains accessible for scientific exploration and technological advancements.

2. THE IAU CPS

The **International Astronomical Union Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS)**[1] was established on 1

[1] cps.iau.org

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April 2022. Under IAU leadership, the CPS is co-hosted by the US National Science Foundation NOIRLab, the leading center for US ground-based optical astronomy, and the SKA Observatory (SKAO), an intergovernmental organization based in the UK responsible for developing the world's most advanced radio telescope networks in Australia and South Africa. The CPS now counts over 400 active international members associated with the following four divisions or hubs.

2.1. Industry and Technology Hub

The Industry & Technology Hub is focused on educating and informing the satellite industry partners about their possible impact on astronomy and recruiting satellite stakeholders to participate in the collaboration with the astronomical community. The Hub and its members are also actively exploring the tools and resources needed to assess satellite systems and implement effective, affordable, and accessible solutions that mitigate effects on astronomical discovery.

Members of the I&T hub enjoy access to several relevant services, for instance dedicated Astronomer Guides for industry partners, updated reading material on best practices and mitigation technologies, as well as observer networks to perform on-orbit brightness assessment.

A large fraction of the well established satellite constellation operators have joined the I&T hub and take advantage of the resources that are offered.

There is **no cost** for stakeholders in the satellite industry to join the Industry & Technology Hub - please visit cps.iau.org or email industry-tech@cps.iau.org.

2.2. Policy Hub

The aim of the Policy Hub is the study of national and international policies and regulations related to the use of space and in particular to satellite constellations. The Policy Hub coordinates and supports the work of national groups on these topics and assists actors in international policy forums such as the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) and the International Telecommunication Union (ITU).

Members of the Policy Hub have identified a lack of comprehensive regulation for satellite constellations in any country. Space-faring nations include certain aspects of a satellite operation and life-cycle in their regulations, but there is no consideration of the use of space as an environment or the potential impact that space objects can create on ground-based activities [11, 15, 16]. Several studies investigate potential frameworks to address the substantial challenges that arise from satellite constellations from a legal and policy standpoint [e.g., 17, 18, 19, 20, 21, 22]. IAU CPS efforts have resulted in the UN COPUOS recognizing that protecting the dark and quiet skies is an important and timely issue by taking up this discussion in 2025. The need to find balanced solutions, support research on satellite interference mitigation, and incorporate considerations on the cultural heritage of the night sky and the sustainable use of space is increasingly urgent.

The Policy Hub is also working with a group associated with UN COPUOS Science and Technology SubCommittee called the "Group of Friends of the Dark and Quiet Sky for Science and Society" (GoF). The GoF is an initiative that was launched by the UN COPUOS Delegations of Chile and Spain. Members of this group came together to raise awareness in a UN context following the 60th session of the Scientific and Technical Subcommittee (STSC) and the 66th session of COPUOS in 2023.

2.3. Community Engagement Hub

The Community Engagement (CE) Hub aims to establish a forum for the thoughtful and respectful discussion of satellite constellations with all affected groups. While the other hubs of the CPS are highly focused on addressing aspects of satellite constellations as they affect professional astronomy, the CE Hub seeks to broaden this, as the emerging changes to the night sky will impact all of humanity.

The CE hub builds bridges connecting the professional astronomical community with other affected parties around all issues relating to dark and quiet skies. For example, the CE hub has established relationships with Indigenous leaders, hosted successful town halls, and created the SatCons 101 training series.

2.4. SatHub

SatHub fosters collaboration between astronomers, observers, satellite operators, and more, advancing a scientific understanding of satellite impacts and developing mitigation strategies that may be useful for astronomers and the wider community [23]. Key achievements so far include multiple successful observation campaigns of satellite constellation prototypes by amateur and professional observers, leading to publications [e.g. 5, 24, 25], the development of SatChecker, a satellite pass prediction tool for forecasting satellite transits through specific fields of view [26], and the launch of the Satellite Constellation Observation Repository (SCORE), allowing observers to share brightness data in a standardized format under an open-access CC-BY license.

While IAU CPS SatHub members are successfully developing tools that enable astronomers and observers to provide feedback to satellite constellation operators, proactive engagement from companies is still needed.

In the remaining sections, we therefore summarize current IAU CPS recommendations [13, 27] aimed at satellite operators toward the goal of ensuring satellites and astronomy may coexist with minimal, well-understood interference.

3. IAU OPERATIONAL DATA SHARING RECOMMENDATIONS

Astronomy focused mitigation technologies that are currently under development by the community, such as field-of-view avoidance, require accurate and timely information that can only be provided by satellite constellation operators. The implementation of the following recommendations would enable such services.

3.1. Providing Accurate Ephemerides and Attitude

Satellite operators should share high-quality ephemeris and attitude data in a standardized format to support astronomy observation planning, i.e.

a) Provide attitude and ephemeris updates that enable accurate prediction of satellite positions in advance. Classical Two Line Elements and attitude predictions should be updated at least every 8 hours.

b) Disclose planned maneuvers to improve prediction accuracy.

c) Maintain attitude uncertainty below 0.05 degrees.

d) Ensure ephemeris prediction accuracy meets astronomy observation planning needs, i.e. below 1-arcsecond cross-track on sky (3σ) and below 1-second timing uncertainty (along track, 3σ).

e) Provide uncertainties with the nominal spacecraft states.

A switch to higher fidelity dynamical models for satellites could alleviate frequent update requirements. If that is considered, the use of standardized formats to transmit satellite ephemerides such as CCSDS OEM including uncertainty covariances is recommended. A detailed description of the dynamical model that is used to generate high-fidelity orbit predictions would also need to be made publicly available.

4. IAU OPTICAL BRIGHTNESS MITIGATION RECOMMENDATIONS

The rapid increase in bright satellite constellations poses significant challenges for optical astronomical observations. Satellites can reflect sunlight in the morning hours before sunrise and during the evening after sunset, therefore substantially shortening the time available to astronomers to perform optical observations. Potentially hazardous asteroids are, for example, more likely to be discovered during these times [28]. To address these and related concerns, the IAU CPS has established a set of recommendations aimed at mitigating the impact of satellite constellations.

4.1. Minimize Impact of Satellite Reflected Sunlight

In order to minimize the impact of sunlight reflected by satellites on optical astronomical observations, the following guidelines are suggested:

a) In order to minimize interference with current astronomical instruments as well as to preserve the night sky as cultural heritage satellites in operational orbit should not be visible to the unaided eye. More precisely, for satellites in Low Earth Orbit, optical brightness should appear fainter than

$$V > 7 + 2.5 \log_{10} \left(\frac{A}{550 \text{ km}} \right), \tag{1}$$

for $A > 550$ km for ground-based observers. Satellites in lower orbits are recommended to be fainter than $V > 7$mag. Here, V is the optical magnitude in the Johnson V-filter, and A is the satellite altitude above mean sea level. For details on the derivation, see [29]. In narrow (color) band filters the following brightness limits for satellites based on current astronomical observatories should be enforced:

- u-band (367 nm): 5.5 mag
- g-band (467 nm): 7.0 mag
- r-band (622 nm): 6.9 mag
- i-band (755 nm): 6.8 mag
- z-band (870 nm): 6.7 mag
- y-band (1004 nm): 6.2 mag

The above magnitude thresholds are limits beyond which large optical surveys such as the NSF-DOE Vera C. Rubin Observatory, experience large-scale non-correctable effects during data collection [30]. The IAU, thus, recommends satellites to be designed as faint as possible and develop improved or alternative tracking techniques.

b) Operators should provide public radiometric visibility models based on materials reflectivity and bidirectional reflectance distribution function (BRDF). This can help astronomers judge which satellite observatory geometries need to be avoided.

c) Validation of brightness models should be conducted through ground-based observations of satellites throughout their life cycle.

Many factors affect how bright a satellite appears. The orbital altitude of constellation satellites is one of them. Recommendations regarding constellation design and operation are summarized in the following section.

4.2. Constellation Design Considerations

Where possible and safe, operators should prioritize lower orbital altitudes with as few satellites as possible to reduce their impact on optical astronomy [27, 29]. This means:

a) Operating satellites below 600 km whenever practicable.

b) Selecting the lowest feasible altitude to minimize illumination duration and brightness.

c) Evaluating and sharing the carrying capacity of different orbital shells.

d) Minimizing the number of satellites as far as possible.

Constellation design should also consider how satellite attitude can be optimized to avoid unnecessary reflection of sunlight toward the ground.

4.3. Minimizing Flares and Glints

Satellite operators should take measures to reduce high-amplitude flares, which can interfere with astronomical observations [31]. Recommendations include:

a) Designing satellites to minimize brightness fluctuations for small changes in sun/viewing angle.

b) Sharing flare modeling predictions to aid observation planning (e.g. via BRDFs).

c) Choosing materials with reflection slowly varying with illumination and viewing angles.

d) Providing a radiometric variability model based on reflectance properties.

e) Conducting ground-based validation of in-orbit flare occurrences compared to modeling predictions.

Understanding and predicting the flaring and glinting behavior of satellites is crucial to enable astronomy centered mitigation strategies such as field-of-view avoidance.

4.4. Minimizing Visibility During Mission Lifetime

Since satellites can be particularly bright during orbit raising and reentry, operators should strive to minimize the visibility of satellites throughout their lifetime. Corresponding activities entail:

a) Conducting orbit raising and deorbiting as quickly as practicable while following space sustainability protocols.

b) Providing a deorbiting plan that minimizes sunlight reflectance toward Earth.

c) Modeling and validating apparent brightness during transition phases.

d) Implementing voluntary plans to reduce visibility during orbit raising and deorbiting phases.

e) Making use of non-reflective drag sails where feasible to expedite deorbiting.

4.5. Suitable Tradeoffs

Preferred mitigation strategies should avoid light pollution of observers rather than trade off between different frequency bands. Converting incident sunlight to thermal emission can block atmospheric windows in the infrared, for instance, from 3–4 and 8–14 micrometers. This should be avoided, as it negatively affects ground-based IR astronomy.

5. IAU RADIO ASTRONOMY PROTECTION RECOMMENDATIONS

In contrast to satellite constellation effects in optical bands, which is mostly due to reflected sunlight, radio astronomy is subject to both intended and unintended emissions from satellites [3, 4, 32]. Combating satellite interference with Radio Astronomy requires, therefore, somewhat different approaches to the ones discussed so far.

5.1. Radio Quiet Zones and Observatories

Governments and industry should collaborate to protect radio observatories by methods such as:

a) Develop internationally agreed mechanisms to protect radio quiet zones from satellite transmissions where possible to avoid the direct illumination of radio telescopes by satellites.

b) Avoid transmissions at frequencies adjacent to those reserved for Radio Astronomy Services (RAS).

c) Minimize antenna sidelobe levels to avoid indirect interference.

d) Support ongoing development of simulations to calculate equivalent power flux densities at radio observatories.

e) Support development of improved low noise amplifiers that are more robust to high input power from satellites.

We note that even if all these recommendations are followed perfectly, adverse effects will be present to some degree. Similar to optical astronomy, accurate modeling of radio emissions by satellites requires technical details known to the constellation operators.

5.2. Sharing Technical Information

Satellite operators should share relevant metadata to help astronomers assess and mitigate potential radio interference. Key parameters include (but are not limited to):

a) Effective isotropic radiated power (EIRP),

b) Transmission frequencies and bandpasses, including information about known spurious and out-of-band emissions,

c) Measured spectral masks and nominal flux density at different frequencies,

d) Measurements of unintentional electromagnetic radiation.

Such data, if made available, would help astronomers to produce suitable, independent mitigation strategies. Avoiding unintended emissions altogether would be the preferred solution.

6. CONCLUSION

Implementing the current IAU CPS recommendations as summarized here would constitute a giant step toward enabling the successful coexistence of satellite constellations and ground-based observational astronomy. Mitigating adverse effects will take all parties working together toward preserving access to the night sky and low-Earth orbit for many generations to come. The IAU CPS provides an excellent platform for constructive conversations and collaboration to this end. Please learn more and join us at cps.iau.org.

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