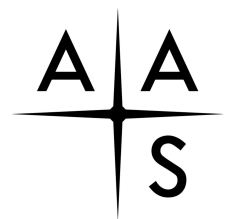


SATCON2

Working Group Reports



The SATCON2 workshop addressed a watershed moment in the transformation of space. In 2018, a few thousand operational satellites orbited the Earth. By 2030, there may be more than 100,000. A massive cloud of satellites presents significant to existential impacts on ground-based astronomy, and further impacts that extend to the environment, astro-tourism, and human health. While space offers many new frontiers and benefits to humanity, the sudden advance of spacefaring technology to the private sector comes with many side effects that should be carefully considered.

SATCON2 brought together members of many communities: astronomy, satellite operators, environmental and dark-sky advocates, and representatives from diverse and underrepresented communities. The distilled outcome of their deliberations can be found in the Executive Summary linked below. The details of their comprehensive work are presented in the working group reports.

The SATCON2 Scientific Organizing Committee and the many members of our working groups have prepared these reports in the hope that they will provide a roadmap for addressing the impact of the industrialization of space on all of us. We look forward to the collaborative work that awaits as a result of our recommendations.

The executive summary can be found [here](#) and the full SATCON2 website is [here](#).

The individual working group reports can be found at the links below:

- SATCON2 Observations Working Group Report
- SATCON2 Algorithms Working Group Report
- SATCON2 Community Engagement Working Group
- SATCON2 Policy Working Group Report

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SATCON2 Observations Working Group Report

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Purpose

The population of Earth-orbiting satellites is dramatically increasing with the advent of commercial satellite constellations that form global consumer communication networks. The impact of these satellite constellations on astronomy and the night sky depends strongly on the brightness of their constituent satellites, which is a complex function of time, attitude, orbital position, and wavelength.

In the optical, when observed well after sunset or before sunrise, satellites can reflect enough sunlight to be visible to the unaided eye. However, the impact extends out to longer wavelengths, with thermal emission at infrared wavelengths, and licensed and spurious emission at microwave and radio wavelengths.

Accurately predicting the location and brightness of a satellite for an observer or instrument on Earth is extremely difficult, and empirical observations are necessary to help build models of reflectivity and emission. The necessary preparations to observe satellites in order to constrain their brightness have significant overlap with the tools needed to avoid or model satellite contamination in astronomical observations. For more details, please see the Algorithms Working Group Report.

Of course, the impacts of hugely increased numbers of bright low-Earth orbit (LEO) satellites (LEOsats) are not limited to professional astronomical observers. There are a variety of different human traditions of astronomical observations and their uses, and humans have long relied on outer space to facilitate their life in the Earth system. This epistemic relationality extends beyond astronomy and can range from more traditional forms of navigation to current uses of satellite data to monitor climate change. All of these ways of knowing, importantly, can be impeded if the LEO is overwhelmed with light pollution and/or space debris. For more details, please see the Community Engagement Working Group Report.

The SATCON1 workshop studied the situation one year ago, in mid-2020, with a focus on mid-latitude observatories utilized by North America-based astronomers working at optical and near-infrared (NIR) wavelengths. The two main findings were that lower-altitude (below 600 km) satellites are strongly preferred, and that various mitigations can help but not fully avoid the impacts of satellite trails on science from present and future astronomy facilities. The published report following SATCON1 (Walker et al., 2020a; hereinafter the SATCON1 Report) further detailed 10 recommendations, three of which were specifically for observatories and satellite operators in collaboration. These are the focus of the SATCON2 Observations Working Group.

Recommendation 8. Support an immediate coordinated effort for optical observations of LEOsat constellation members, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations. Such observations require facilities spread over latitude and longitude to capture Sun-angle-dependent effects.

In the longer term, support a comprehensive satellite constellation observing network with uniform observing and data reduction protocols for feedback to operators and astronomical programs. Mature constellations will have the added complexity of deorbiting of the units and on-orbit aging, requiring ongoing monitoring.

Recommendation 9. Determine the cadence and quality of updated positional information or processed telemetry, distribution, and predictive modeling required to

achieve substantial improvement (by a factor of about 10) in publicly available cross-track positional determination.

Recommendation 10. Adopt a new standard format for publicly available ephemerides beyond two-line-elements (TLEs) in order to include covariances and other useful information. The application noted in Recommendation 2 should be compatible with this format and include the appropriate errors.

In this report, we outline implementation steps for SATCON1 Recommendations 8, 9, and 10. We take the liberty of expanding the scope beyond SATCON1's focus on mid-latitude optical/NIR astronomy, because LEOsat proliferation impacts observers worldwide at all latitudes. We recognize that a successful outcome will necessarily be supported by new policies governing the use of the sky across multiple jurisdictions, including the national and international level. For more details, please see the Policy Working Group Report.

We endorse the findings of the Dark and Quiet Skies for Science and Society Report and Recommendations (Walker et al., 2020b; hereinafter the D&QS Report), in particular Chapters 6 and 7 that pertain to satellite constellations and radio astronomy, respectively. This report is designed to build on the conclusions from the D&QS Report, not supersede it. To that end, we structure our implementation plan into three main areas: a new coordinated satellite observation hub (Section 1), building a training curriculum (Section 2), and establishing minimum best practices for all satellite constellation operators to share data with the astronomical community and the public (Section 3). We conclude with a few additional considerations (Section 4).

One likely avenue for implementation as described in this report may be through the establishment of a new International Astronomical Union (IAU) Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference¹ (hereinafter the IAU Centre). The Observations Working Group would like to emphasize that the implementation steps in this report require significant overall resources on as fast a timescale as possible. It is one thing to write down what must be done, and it is another to secure funding and direct appropriately skilled individuals to carry it out.

¹ <https://iau.org/news/announcements/detail/ann21039/>

1. Establishing and sustaining a coordinated satellite observation hub

The apparent brightness of visible satellites is critically dependent on the reflectivity of their surfaces. However, this is highly dynamic because it depends on the altitude, attitude (orientation), albedo, size, surface characteristics, specular versus diffuse reflections, self-shadowing, and the solar phase angle. To date, constellation operators do not provide comprehensive brightness models for their satellites. However, several measurements of LEOsat visual magnitudes have been made by different astronomical teams (e.g., Pomenis Observatory, Ckoirama Observatory, the Visible and Infrared Survey Telescope for Astronomy, and more) to assess their impact on optical and near-infrared astronomy.

Observations of Starlink satellites with no darkening mitigations show that they have typical apparent brightness in the magnitude 4–5 range (Mallama, 2020a; Otarola et al., 2020) and are easily visible with telescopes or even the unaided human eye. Observations of OneWeb satellites show typical brightness fainter than magnitude 6–7, but they are placed at a higher orbital height, around 1200 km (Mallama, 2020c; Zamora et al., 2020). Limited observations of DarkSat and VisorSat Starlink satellites indicate that the brightness-reduction mitigation measures implemented in the modified designs are effective, but do not achieve the SATCON1 brightness recommendation of 7th V magnitude at an orbital height of 550 km (see, e.g., Tyson et al., 2020; Tregloan-Reed et al., 2020; Mallama, 2020b). Observations of Starlink satellites in multiple spectral bands further show the satellites are brighter at longer wavelengths, and the efficacy of the DarkSat mitigation strategy experiment decreases in the near-infrared (Tregloan-Reed et al., 2021; D&QS Report).

While these ad hoc observing campaigns have been crucial for understanding the initial impacts of LEOsat constellations on astronomy and observers worldwide, in the longer-term, SATCON1 Recommendation 8 calls for a “*comprehensive satellite constellation observing network [...] for feedback to operators and astronomical programs.*” It notes that the regular launching, maneuvering, on-orbit aging, and deorbiting of LEOsats creates an ever-evolving population of satellites, which require ongoing monitoring. Current estimates indicate there will be numerous satellites visible to the unaided eye under dark skies in the next several years, sometimes to the point of saturating telescope CCD detectors, unless darkening measures are implemented. This conclusion is sound well beyond the level of uncertainty of the current photometric models. An immediate, coordinated, ongoing observational survey of LEOsats in different orbital configurations is therefore essential.

1.1 Introducing SatHub

We propose a “one-stop shop” to enable astronomers, community members, satellite operators, other interested groups, and the public to work together more effectively. This initiative, SatHub, will serve as a central coordination hub for characterizing the LEOsat population’s reflectivity, emission properties, positions/trajectories, and other properties over time. It will enable astronomers to build appropriate data processing pipelines to account for the effects on astronomical science programs, characterize both slow and rapidly varying brightness changes over time, and measure the effectiveness of experimental mitigations. As a global endeavor, SatHub will incorporate observations from a variety of facilities spread over latitude and longitude to capture Sun-angle-dependent effects, enable collaboration and feedback between multiple stakeholders, and encourage uniform observing and data reduction protocols alongside accessible data products and training opportunities.

To implement this, one of the first priorities for the forthcoming IAU Centre should be establishing a SatHub website. Different sections of the website can subsequently be built out to address different goals, as illustrated in Figure 1. The SatHub umbrella will encompass a user-friendly, accessible, and responsive interface with tools for accessing public data products and satellite orbital solutions, documented open source software to plan and process (or avoid) satellite observations, a curriculum to empower observers of all backgrounds to meaningfully contribute, and a real-time collaboration center. This latter portion will include a discussion forum, a means to request specific observations (e.g., for a satellite operator seeking to test the brightness of a new design), and a means to inform the community of the latest brightness measurements while they are still a work in progress and once they are published.

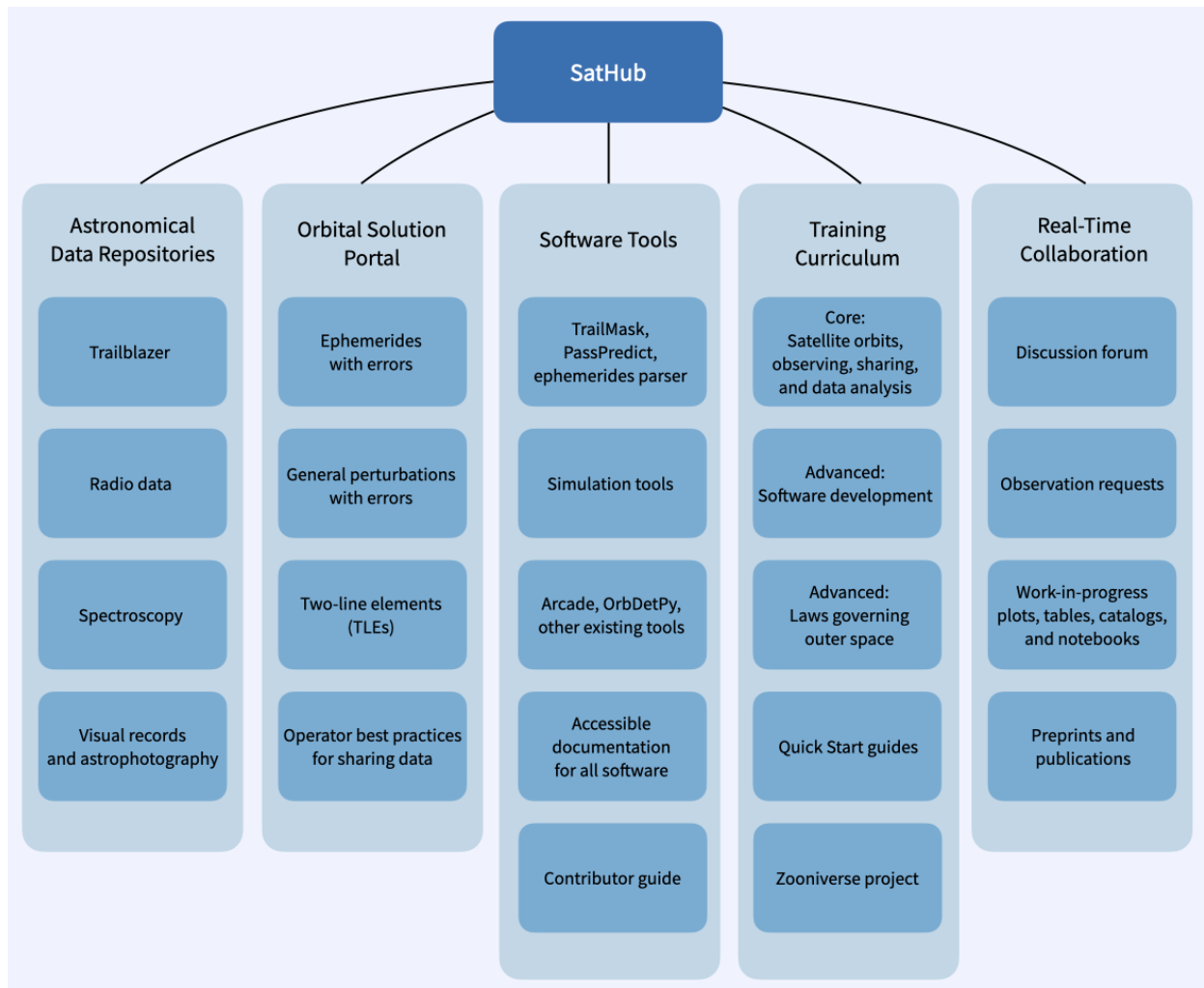


Figure 1. SatHub will include multiple components necessary to enable coordinated and sustained observation and analysis of bright satellites across the globe.

The primary goals of SatHub are as follows:

- Compile and share images, spectra, brightness measurements, other data products, and publications or other resources pertaining to non-classified satellite constellations, following CC BY-SA or similar free and publicly accessible licensing standards.

- Effectively educate observers with any experience level who wish to contribute to SatHub across all wavelength regimes (see Section 2).
- Provide tools to plan observations that account for the presence of satellites, and process images containing satellites, so it is straightforward to image or avoid satellites and measure satellite brightnesses.
- Provide tools to forecast and identify non-classified satellite constellations utilizing publicly available orbital solution information (see Section 3).
- Compile, document, and reference existing or in-development projects, software tools, and data repositories that directly relate to SatHub.
- Regularly inform the community about the evolving population of satellite constellations and their potential impact to different scientific studies.
- Establish and sustain dialogs with satellite operators, policymakers, and other stakeholders so future satellite design and operation has less unintentional impact on astronomy and dark skies.
- Sustain an accessible, responsive website as an evolving resource to accommodate the present and future needs of astronomy, the space industry, and observers worldwide.

Some examples of SatHub use cases follow. They are intended to be illustrative, but not exhaustive.

- An astronomer is planning an observing run for later in the week, and wishes to schedule high-priority observations of a certain target in a satellite-free viewing window. SatHub enables them to access PassPredict and forecast the windows when an input sky coordinate or field of view will have the fewest satellite crossings.
- An astronomy enthusiast enjoys participating in Zooniverse projects and wishes to help identify images with satellite streaks for a citizen science project. SatHub provides links to such projects and updates on resulting analyses and publications.
- A satellite operator has designed a new darkening treatment and wishes to learn how effective it is. Without revealing proprietary information, they use SatHub to share a list of experimental and control satellites for observers to target. Interested observers subsequently use SatHub to plan their observations and upload, coordinate, and analyze results from the experiment.
- An observer is reducing their CCD data and notices one or more satellite streaks in an image. They use SatHub as a resource for processing the image to minimize impact of the trails, uploading the image to aid in satellite brightness studies, and discussing strategies with others facing similar situations.
- A researcher wishes to use software in the public domain to calculate orbital ephemerides from TLEs (e.g., `pyorbital`² or `Skyfield`³). SatHub provides a place where tutorials or supplemental documentation for these tools can live, allows the researcher to ask questions of more experienced users or developers and begin developing their own software to improve or extend these existing tools.
- A student wishes to write a report on the impacts of satellite constellations on astronomy and the night sky. They complete the SatHub core training curriculum and participate in the discussion forum to learn both the historical context and the latest developments, and produce a well-researched report.
- An amateur astronomer highly experienced in visual magnitude estimation has meticulously recorded unaided eye brightnesses of satellites over many nights. SatHub allows them to share these observations with the broader community so they can be used to fill gaps or validate other observations with CCD instruments.

² <https://github.com/pytroll/pyorbital>

³ <https://rhodesmill.org/skyfield>

- A radio astronomer is writing a proposal for observing time. They use SatHub to estimate how many hours they need (and at what time of year, etc.) to successfully image their targets and minimize interference from satellites at their observing frequencies.
- A data scientist is interested in testing a new image feature detection algorithm. They use SatHub to access images from several astronomy databases in order to train and test their algorithm on streaks, point sources, extended sources, and artifacts.

In this Observations Working Group Report, we focus on implementing the Astronomical Data Repositories (Section 1.2), Training Curriculum (Section 2), and Orbital Solution Portal (Section 3) portions of SatHub. The Software Tools portion is largely addressed by the Algorithms Working Group Report, and we note that a significant number of tools already exist or are in development and should be at minimum linked to from SatHub (e.g., ARCADE⁴). We anticipate the establishment of an IAU Centre will enable many aspects of SatHub’s real-time collaboration needs.

1.2 Collecting satellite observations

As populations of LEOsats increase, observers of the night sky worldwide will more frequently encounter them. For optical telescopes with CCD imagers — and astrophotography more generally — they appear as bright streaks in images. The signatures of LEOsats in different kinds of telescopes (e.g., radio) and instruments (e.g., spectroscopy) manifest differently. The impacts of observable LEOsats on science and the human experience of the night sky can vary widely. Effectively implementing SATCON1 Recommendation 8 requires observers to share data affected by LEOsats in an accessible way.

1.2.1 Trailblazer

Trailblazer is an open data repository of astronomical images containing satellite trails⁵. Meredith Rawls (U Washington/Rubin Observatory) is leading development of this service with Dino Bektesevic (U Washington). It will be a living, queryable archive that welcomes uploads from anyone with recent FITS images with a valid World Coordinate System (WCS) affected by satellites. Trailblazer is being built publicly with open source tools, and will allow observational astronomers to salvage some scientific value from their satellite-streaked images, and it will give ready access to a user-friendly dataset to any group seeking to quantify scientific impacts of satellite trails.

A sustained funding source will be necessary to maintain and improve Trailblazer long-term. Nevertheless, a website with minimal functionality should exist by the end of 2021. The project is being developed in Django and utilizes Amazon Web Services. The main functionalities are file upload, thumbnail gallery display, and a query interface with a download option. When a new image is uploaded, a metadata database is populated containing critical information (exposure time, exposure duration, observatory location, sky location or WCS, and band or filter). All uploads will be required to accept a CC BY-SA or similar license that enables public sharing and reuse of all submitted data products. Trailblazer does not yet have plans for identifying linear features, matching satellite IDs to observed streaks, or measuring streak brightnesses.

Assembling a standardized dataset will enable these kinds of studies and inform more coordinated and planned observations and will better enable “dodging” or avoiding large numbers of satellites in certain situations. Planned observations of satellites are important to improve models, simulations, and satellite

⁴ <https://github.com/IBM/arcade>

⁵ <https://github.com/dirac-institute/trailblazer>

forecasting software, while avoidance includes preventing telescopes (both optical/NIR and radio) pointing in the direction of known satellites as well as determining retroactively if an observation suffers from satellite contamination.

1.2.2 Other satellite-impacted data in SatHub Astronomical Data Repositories

Trailblazer does not address all needs, including wavelengths outside visible/NIR, non-image data products, observations without a valid WCS, or file formats other than FITS (e.g., visual sightings or DSLR images). These kinds of observations also contain valuable information for characterizing satellite constellation populations and monitoring them over time. For example, preliminary studies (e.g., Tregloan-Reed et al., 2021) show that satellites darkened to meet the 7th V magnitude target from the SATCON1 Report tend to be significantly brighter in the NIR, but there are presently insufficient observations in other bands to write more specific darkening requirements for operators.

We propose that any new collection of images or data products affected with signatures of LEOsats coordinate with the existing satellite tracking community and make all data publicly accessible. A need exists for at least the collections outlined below.

1.2.2.1 Radio data affected by satellites

Radio observations are significantly impacted by emissions from satellites (see, e.g., the D&QS Report). Data products to collect may include FITS files/images, u,v interferometric data, time-ordered data, etc. Files should come with valid metadata to make it clear at which telescope, pointing direction, observing mode, and frequencies it was recorded. These may represent examples of ongoing interference from satellites, or transient events that have unknown sources. Ideally it would be known that the interference present in the data is caused by satellites, rather than terrestrial interference sources, but it is not always possible to guarantee this. When designing a campaign to collect impacted radio data, it is important to keep in mind that significant interference can occur at frequencies that satellites don't intentionally transmit at, because signals can be caused out-of-band by electronics on the satellite or poor filters for transmissions.

Radio astronomers may wish to gather information on bandwidth and time lost due to high power events (satellite crossing the main beam of a radio observatory) as well as residual radio frequency interference or signals originating in the side lobes of a radio observatory. We note that above frequencies of about 10 GHz, terrestrial weather patterns affect radio data. Optical depth measurements to account for this can be found by using nearby weather station records if it is not recorded directly in observation metadata.

1.2.2.2 Space-based observations from observatories in LEO

Satellite streaks have appeared in several Hubble Space Telescope images (Kruk et al., submitted to Nature Astronomy), and this is an area actively being studied. Some recent developments are presently being explored in a Zooniverse project⁶ led by Sandor Kruk (European Space Agency). Other existing and future space telescopes in LEO will likely be impacted by satellites too.

⁶ <https://www.zooniverse.org/projects/sandorkruk/hubble-asteroid-hunter/talk/2468/2083595>

1.2.2.3 Astrophotography and unaided eye observations

Many amateur astronomers and astrophotographers observe the sky without the use of research-grade telescopes and regularly see (or image) satellites. The American Association of Variable Star Observers (AAVSO) has a guide for visual star observations⁷ that we recommend as a starting point for this kind of campaign. In addition, astrophotographers already have tools for masking or removing satellite trails, image stacking, and similar techniques (e.g., Deep Sky Stacker⁸). Photographed satellite streaks for brightness measurements should ideally have accurate timing and location data, and could use a tool such as astrometry.net to learn where it was pointed in the sky. We encourage observers with all backgrounds to use SatHub to coordinate.

1.3 Funding SatHub

While we envision SatHub as a community-driven resource, creating and sustaining it will require significant funding. Funds are necessary for nearly all aspects of SatHub, most notably to pay for web hosting and key personnel to build and maintain each of five key portions shown in Figure 1. Funding is also needed to pay for telescope time, software developers, community-building experts, analysis of new and archival data, instructors, curriculum developers, forum moderators, industry liaisons, and more.

The forthcoming IAU Centre is an ideal home for SatHub. We encourage member and supporting institutions to commit resources to the core SatHub initiative. We strongly suggest satellite operators fund the Orbital Solution Portal section of SatHub, as having access to a wealth of data products and a means to request coordinated observations from astronomers will directly benefit industry partners. Finally, we anticipate supplementary funding may come from a variety of sources that each observer or team of observers applies for directly. These may include:

- Public funding from relevant agencies (e.g., NSF, NASA, or other national science funding bodies)
- Private funding from satellite operators or other industry partners
- Future licensing fees through regulatory bodies
- Cost-sharing arrangements among a group of parties (e.g., astronomy organizations, satellite operators, and regulators, potentially by paid memberships)
- Public-private partnerships
- Payments from interested parties requesting specific observations or novel data products
- Individual donations by members of the public or philanthropists

⁷ <https://www.aavso.org/visual-star-observing-manual>

⁸ <https://astrobackyard.com/deep-sky-stacker-settings>

2. Training professional astronomers, amateur astronomers, photographers, and others to contribute to satellite observing efforts

Effectively implementing SATCON1 Recommendation 8 requires more than just sharing affected data products and establishing SatHub. We must also train observers of all kinds to contribute to the global LEOsat monitoring campaign.

It is becoming increasingly clear that if the 100,000 or more LEOsats that have been proposed by private companies and governments across the world are deployed, no combination of mitigations can fully eliminate the impact of satellite trails on the science programs of current and planned ground-based optical, NIR, and radio astronomy facilities (SATCON1 Report). Additionally, astrophotography, amateur and backyard astronomy — indeed the very human experience of seeing and experiencing the beauty of the night sky — will all be increasingly affected. Mitigation of the most damaging impacts on scientific programs will require collaborations and changes at both ends of the spectrum:

1. Constellation Operators should:

- a. work towards reducing reflection through optimal satellite body orientation, Sun shielding, and surface darkening;
- b. provide accurate and timely ephemerides, and publish information about the satellites (brightness model, transmission bandpasses, etc.); and
- c. alert the community of changes in orbits (after an avoidance maneuver, for example).

2. Astronomers should:

- a. conduct observations to provide feedback to LEOsat operators;
- b. compile accurate brightness and timing information on LEOsats;
- c. perform simulations to predict visibility, brightness, and timing of satellites and
- d. develop software and hardware tools to mitigate the impact of satellite trails in science images.

Observing satellites can be quite challenging, and requires a slightly different approach than, say, observing variable stars or galaxies or exoplanet transits. One has to anticipate or calculate, based on available data, where the satellite is expected to be in the sky. The observer must then, with reasonable accuracy, point their telescope and/or camera in that direction before the satellite passes, and capture images with appropriate exposure times. Satellites are much closer to the observer than the more traditional targets and will leave a (bright) trail on the image. Tracking satellites is possible, but is quite challenging and will inevitably result in star trails.

As described in Section 1, SatHub will serve as a hub for astronomers and satellite operators to work together towards quantifying and cataloging various observational parameters (timing, satellite brightness, location, velocity, etc.) of non-classified satellite constellations. For SatHub to function smoothly and for it to evolve with the fast-changing LEO environment, a key piece of it must include training observers of all kinds to contribute to the global LEOsat monitoring campaign. To this end, we propose a training

curriculum addressing many aspects of satellite properties and observational techniques. It encompasses a crucial piece of SatHub and will be freely available online in various formats, such as web-based lessons and tutorial notebooks, as well as offered periodically at in-person or distributed (virtual/hybrid) events.

This curriculum will help establish uniformity in terminology and file formats. Such standards and best practices will in turn facilitate communication and cooperation among stakeholders worldwide (including both astronomers and satellite operators). We aim to create a sufficiently broad curriculum to connect similar initiatives around the globe, and prioritize communication and outreach.

The curriculum will point learners towards specific observing campaigns along the lines of similar campaigns associated with variable star observations (AAVSO⁹ and the TESS Follow-up Observing Program [TFOP]¹⁰) to involve members from both the professional and amateur astronomy community. The curriculum will consist of three components: a core curriculum, an advanced curriculum with a specialized set of modules, and a set of tutorials to get learners started with their first observations. The curriculum will be complemented with a citizen-science interface (modelled along the lines of Zooniverse) that allows for interested parties without access to observing equipment to make meaningful contributions by analyzing archival images.

After working through the curriculum, a learner should be able to:

- 1) Appreciate the different kinds of satellites in orbit, and the harmful impact of satellite mega-constellations on astronomy, stargazing, and our night skies;
- 2) Appreciate the purpose and importance of satellite observations;
- 3) Access and use existing satellite databases;
- 4) Efficiently use and contribute to SatHub;
- 5) Plan satellite observations based on criteria such as location, time, hardware (telescope, camera, etc.);
- 6) Carry out satellite observations using the hardware they have available to them;
- 7) Report serendipitous and planned observations (images, satellite-identifiers, time etc.) using the appropriate file format; and
- 8) Perform analysis on images to determine the timing, speed, and brightness of satellite trails.

While we strongly encourage observers who wish to contribute to SatHub to be well-versed in the core curriculum, it is not a formal requirement or prerequisite. Instead, the core curriculum is a tool designed to lower barriers to entry for successful SatHub collaboration and contributions. The curriculum will be divided into several modules as stated below. The advantage of the modular approach is that additional modules can be added and modified as needed, and the learner will have the freedom to skip certain modules that are not of interest to them.

2.1 Core curriculum

2.1.1 Artificial satellites: an overview

This module will provide an overview of the space industry, the types and purposes of artificial satellites, and the relatively recent developments related to LEOsat constellations and their impact on stargazing,

⁹ <https://www.aavso.org/observing-campaigns>

¹⁰ <https://tess.mit.edu/followup/apply-join-tfop/>

amateur, and professional astronomy. An overview of regional, national, and international laws and legal frameworks will also be provided. Each of these topics will be further discussed in detail in either the core modules or in the more advanced or specialized modules presented later.

This introductory module will consist of the following sections:

- History of the space industry
- Types of satellites:
 - Purpose
 - Orbital parameters
- Basics of radio frequency transmissions from satellites
- Satellite databases
- Impact of satellite constellations on astronomy
- Observing satellites: an overview
- Space law applicable to satellite orbits, as part of the broader international legal regime, as well as national legal frameworks
- Glossary of terms

2.1.2 Observing satellites

This module will cover the topics related to planning and observing satellites for the purpose of characterizing both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations of LEOsats. This module will also cover how to coordinate observations with other observers to set up a network of telescopes in order to improve the characterization of satellite brightness and timing.

Additionally, the module will cover unintentional or serendipitous observations, and will also be useful to learners to plan their telescope use to avoid satellites. The content of this module will also be intended for radio users to enable them to observe the magnitude of radio transmissions and occupancy in their sky.

This module will introduce software tools such as PassPredict, TrailMask, and the Test Data Suite proposed by the Algorithms Working Group. Learners will use PassPredict (or similar tools) to either identify potential satellite targets to observe or plan their astronomical observations to minimize satellite interference.

This module will consist of the following sections:

- Overview of software
- Planning observations
 - Hardware considerations
 - Software considerations
 - Identifying targets
 - Setting up
- Serendipitous observations
- Coordinated observations
- Radio frequency considerations

2.1.3 Reporting observations

For observations to be useful to the community vis-a-vis the characterization of satellite reflectivity, timing, radio frequency magnitude, and the effectiveness of mitigation strategies, it is necessary that the data are reported accurately and in standardized, readily usable format. This module introduces learners to the

different and most likely image types, the kinds of information needed *a priori*, and how to use SatHub to share data.

This module consists of the following sections:

- Image/data types: CCD/Radio (fits), DSLR (raw), CMOS (fits), other
- Header information: location, time, satellite information, etc.
- Sharing data (SatHub, likely with Trailblazer as an example)
- Licensing considerations (CC BY-SA or similar strongly recommended)

2.1.4 Image/data analyses

This module will introduce learners to data analyses and mitigation. By way of review, the learner will first be introduced to the available methods used to perform traditional photometry^{11,12}. The learner will then learn about novel ways to analyze satellite streaks or trails, i.e., how to use tools such as TrailMask to determine properties of the observed satellites: brightness, timing, variability, and so on. Additionally, a section is devoted to applying available tools to flag, mask, and repair the satellite trail to enable learners to extract as much astronomical data from their image as possible.

This module will contain the following sections:

- a) Aperture, PSF, and “streak” photometry
- b) Analyzing your observations
- c) Analyzing archival data
- d) Masking satellite trails from data

2.2 Advanced modules

2.2.1 Software development

This module will introduce the learner to the ways in which they can contribute towards developing new tools and improving existing tools related to LEOsats: observation planning, image calibration, satellite trail and comparison star analysis.

- Coordinating with SatHub’s software resources
- Contributing to PassPredict, TrailFix, and other software proposed by the Algorithms Working Group
- Contributing to existing repositories like CLEOsats¹³
- Best practices for accurate simulations of future LEOsat impacts.

2.2.2 Radio astronomy

This module will cover the interaction between radio astronomy and communications networks, with a specific focus on satellite constellations and sources of information about the interference that can be generated by satellites.

- Spectrum management 101: ITU-R Radio Regulations and national administrations
- Use of the radio spectrum by radio astronomy
- Spectrum allocation for various satellite constellations and other uses

¹¹ <https://photutils.readthedocs.io/en/stable/>

¹² <https://datacarpentry.org/astronomy-python/>

¹³ <https://github.com/CLEOsat-group>

- Accessing information from the International Telecommunications Union (ITU), the Federal Communications Commission (FCC), the UN Committee On the Peaceful Uses of Outer Space (COPUOS), and other databases
- Disentangling interference from LEOsats and other sources

2.2.3 International and national laws governing outer space

This module will introduce the learner to the relevant laws, treaties and legal approaches related to the legality of a private entity or a nation launching satellites into space. While a legal challenge initiated by the astronomy community seems unlikely to stop the already approved launches, it is possible that future launches could be stopped or deferred until LEOsat operators take into account the mitigation strategies developed by the astronomy community. Moreover, the intense competition between various LEOsat operators will inevitably lead to legal disputes and actions, and it is in the interest of the astronomy community to be aware of these developments.

This module will focus on the following (US) laws and international treaties that are relevant to LEOsat operators and, by extension, to astronomers:

- The Outer Space Treaty¹⁴ (1967),
- US Commercial Space Launch Competitiveness Act¹⁵ (2015),
- National Environmental Policy Act¹⁶ (1970)
- Ancestral Global Commons approach (Venkatesan et al., 2020)

2.3 Appendices

The following modules, proposed for the training curriculum, will provide observers with a wide variety of hardware as a quick start to observing satellites.

- Appendix A: Quick Start Recipe (DSLR Cameras)
- Appendix B: Quick Start Recipe (small, < 0.5-meter-class telescopes, CCD imaging)
- Appendix C: Quick Start Recipe (large, > 0.5-meter-class telescopes, CCD imaging)
- Appendix D: Citizen Science Projects (Zooniverse, Satellite Streak Watcher¹⁷, etc.)

An ideal timeline for the completion of the construction of this curriculum is about a year. This timeline is constrained by the timeline for development of SatHub and software tools proposed by the Algorithms Working Group. Nevertheless, it is prudent to make at least portions of this curriculum available as soon as possible — at least on the expected timescales of the deployment of satellite constellations, if not quicker.

We encourage the incorporation of elements of this curriculum into undergraduate and graduate astronomy laboratory exercises and projects. Other areas where this curriculum could be used are in a AAVSO “CHOICE” course¹⁸, as workshops before/during the AAS winter conference or other national conferences, or as fully fledged Carpentries-style modules like Foundations of Astronomical Data Science¹⁹.

¹⁴ <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html>

¹⁵ <https://www.congress.gov/bill/114th-congress/house-bill/2262/text>

¹⁶ <https://www.epa.gov/nepa>

¹⁷ <https://scistarter.org/satellite-streak-watcher>

¹⁸ <https://www.aavso.org/tags/choice-courses>

¹⁹ <https://datacarpentry.org/astronomy-python/>

3. Best practices for operators to publicly share satellite positions and trajectories

SATCON1 Recommendation 9 states we must “*Determine the cadence and quality of updated positional information or processed telemetry, distribution, and predictive modeling required*” to minimize impacts to astronomy. SATCON1 Recommendation 10 calls for “*a new standard format for publicly available ephemerides beyond [TLEs]*” in order to incorporate uncertainties and other useful information.

In general, the position of a satellite at a future time is forecast with a propagator algorithm that uses an orbital solution from the recent past. Orbital solutions may be in the form of either general perturbations, i.e., time-averaged Keplerian elements that include atmospheric drag computations (commonly represented in TLE format), or ephemerides, i.e., state vectors of position and velocity data (sometimes referred to as an orbit ephemeris message or OEM).

Orbital solution information is typically shared in the form of TLEs from radar observations and improved by ephemerides and supplemental TLEs from satellite operators. This is then used to forecast the ephemeris of the satellites and provide precise date, time, and sky position (Right Ascension and Declination) of each visible satellite from a particular observer's longitude and latitude. We note that in the future, the US Commerce Department's Open Architecture Data Repository may be responsible for sharing space situational awareness data²⁰. We encourage this to be fully public and coordinated with the SatHub initiative.

To implement SATCON1 Recommendations 9 and 10, we propose the following:

Detailed in Section 3.1:

- All operator-provided orbital solutions must include reasonable estimates of uncertainties, so observers with a variety of instrumentation can properly plan observations.
- Operators must publicly provide orbital solutions at a frequent and regular cadence for the benefit of observation planning and image masking.
 - The recommended minimum update cadence is every 8 hours or whenever a maneuver happens, whichever is first.
 - Operators should include future planned maneuvers whenever available.
 - Operators should begin providing this information as soon as they successfully communicate with newly launched satellites.

Detailed in Section 3.2:

- Operators should provide any other relevant metadata that may assist observers in assessing threats to optical and radio observations.
 - This may include, e.g., reflectivity, bidirectional reflectance distribution function (BRDF), effective isotropic radiated power (EIRP), transmission bandpasses, nominal flux density at different frequencies, etc.

²⁰ <https://spacenews.com/data-sharing-seen-as-critical-to-future-of-space-situational-awareness>

Detailed in Section 3.3:

- All operators should adopt a standard format for ephemerides (state vectors, i.e., position and velocity data), such as the plain text NASA Modified ITC Ephemeris format that SpaceX presently uses. (ITC is the International Telecommunications Corporation.)
- All operators should adopt the Celestrak-recommended format²¹ for general perturbations (Simplified General Perturbations No. 4 (SGP4) time-averaged Keplerian elements that include drag computations, i.e., the orbital solutions presently provided in TLE format).

Detailed in Section 3.4:

- Promptly establish a publicly-accessible Orbital Solution Portal website under the SatHub umbrella.
 - Satellite operators should pay for the hosting and upkeep of this portion of SatHub. Celestrak presently serves a function similar to this, but the public's ability to retrieve satellite orbital solutions should not be confined to one volunteer-run resource.
 - The Orbital Solution Portal should retain rather than overwrite past orbital solutions, so that data can be retroactively used for older observations, and also provide an easy lookup interface for retrieving data.
 - Operators and astronomers should work together to write an open-source software tool that translates between ephemerides, the Celestrak-recommended format for general perturbations, and old-style TLEs.

In the subsections that follow, we describe these critical implementation steps in more detail.

3.1 A measure of accuracy: frequent new orbital solutions with error bars

The accuracy in satellite forecasting codes depends on the accuracy of the general perturbation TLEs and the quality of the software used to calculate the satellite's future position and trajectory. Currently the accuracy of Starlink and OneWeb TLEs translates to an accuracy in position on the night sky of ≤ 30 arcminutes (see Figures 2 and 3). This is not adequate for the needs of the astronomical community and satellite forecasting software. Additionally, recent survey observations of OneWeb satellites by the CLEOsat group show that 1 in 40 observations resulted in a negative detection. This is due to an orbital maneuver made by the satellite after the public release of the TLE data. Therefore, we recommend operators maintain the frequency of the TLEs being released (every eight hours), but in addition release a new TLE after a satellite maneuver, allowing forecasting software to update the satellite's position and trajectory.

The introduction of error bars (uncertainties) with all orbital solution data is also essential to improve accuracy. This would protect critical optical observations, where a satellite trail could ruin an entire image, as well as radio astronomy, where the satellite radio beam can damage sensitive equipment.

New satellites launch regularly and many satellites in constellations change orbits very frequently. As a result, operators should begin sharing data as soon as they initially contact a newly launched satellite and indicate whenever a future maneuver is planned in advance.

²¹ <https://celestrak.com/NORAD/documentation/gp-data-formats.php>

3.1.1 Two case studies: validating orbital solutions through observations

Measuring the accuracy in the ephemerides derived from a TLE requires a large field of view and relatively short exposure time (a few seconds) to capture the start and end points of the satellite trail. With this type of observation, the position of the satellite as a function of time can be extracted from the image by integrating the angular velocity over the length of the satellite trail. Factoring in the telescope pointing error and correctly propagating uncertainties, it is possible to measure the accuracy of a TLE. An example is shown in Figure 2, where an observation of OneWeb-0210 obtained with the 0.6-meter telescope at Chungbuk National University Observatory, South Korea (courtesy of the CLEOsat group) provides a single measurement of the ephemeris-derived²² TLE accuracy to ~ 15 arcminutes.

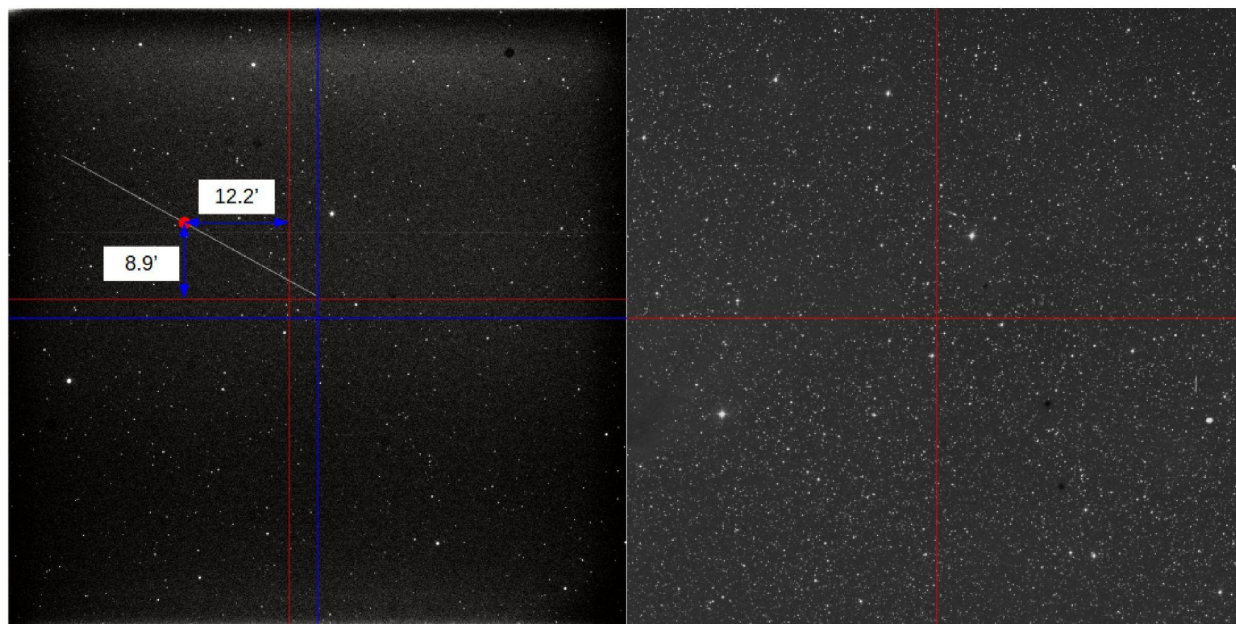


Figure 2. (Left) Observation of OneWeb-0210 obtained with the 0.6-meter telescope at Chungbuk National University Observatory, South Korea (courtesy of CLEOsat). The field of view is 72×72 arcminutes and the exposure time is two seconds. The image center is indicated by the blue crosshairs, while the red crosshairs show the forecast position of the satellite from a TLE. The red spot indicates the satellite's true position, which is 15.1 arcminutes off from the forecast position. (Right) A reference image from the ESO digital sky survey²³ centered on the TLE forecast position, which allows the telescope pointing uncertainty to be corrected for. The red crosshairs are in the same location in both images.

However, obtaining a robust measurement of TLE accuracy requires more than a single observation. One such attempt was performed by the Pomenis team led by Harrison Krantz (University of Arizona). Over 560 observations were conducted in the summer and autumn of 2020. Their analysis compared the trail centroid (assuming constant angular velocity) with the predicted TLE position of the satellite. Specifically, they measured the full uncertainty in the satellite positions, which is the sum of three error vectors: TLE accuracy, telescope pointing, and the uncertainties from the orbital equations. They concluded the statistical uncertainty in TLE accuracy is ± 3 arcminutes. Their results also show that the distribution tail

²² LEOsat Visibility Tool (LVT): <https://github.com/CLEOsat-group>

²³ <http://archive.eso.org/dss/dss>

extends beyond 0.5 degree, as shown in Figure 3, which is equivalent to the angular diameter of the Moon and larger than many telescope fields of view. The work by the Pomenis team used both operator-provided TLEs directly and the supplemental TLEs derived from operator-provided ephemerides, and actually found no discernible difference in the accuracy between the two types of TLE.

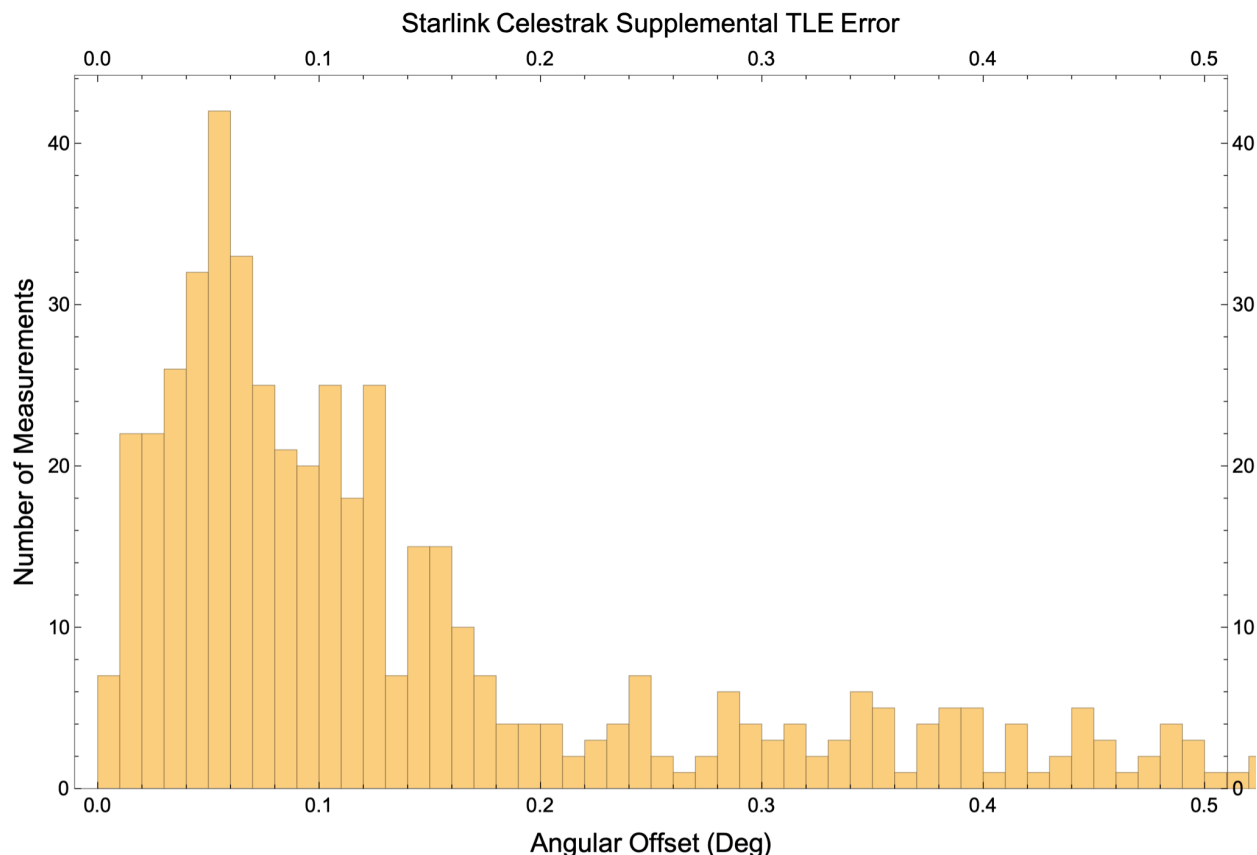


Figure 3. This histogram shows the error in satellite position measured from 567 observations made by Pomenis (University of Arizona) in the northern summer and fall of 2020. The angular offset is the difference between the expected satellite position as calculated from the most timely TLE and the satellite’s astrometric position measured in the captured image. The majority of satellites were within a few arcminutes of their expected position, although the tail of the distribution extends beyond 2 degrees. This plot utilized the Supplemental TLEs provided on Celestrak.com; comparison with the standard issue TLEs did not show significant differences.

Overall, these observations demonstrate that the current TLE system is wholly inadequate for the needs of astronomers in predicting the trajectories of satellites across the night sky. This is particularly true immediately after orbital maneuvers when a new TLE isn’t released until hours later. With rapid orbital solution data sharing after an orbital maneuver along with error bars, a more robust forecast will be possible. This will allow observers to assign different probability distributions and confidence levels for different satellite densities and reflective magnitudes for a given patch of sky at a given time range — a critical capability, whether the goal is to image a specific satellite or avoid as many as possible.

3.2 Additional operator provided metadata

For optical astronomy, the reflective brightness of the satellite is also a critical factor. For ultra-sensitive detectors like the Vera C. Rubin Observatory LSST Camera, laboratory studies indicate that an optical magnitude of at least $V \approx 7$ mag is needed to allow for non-linear image artefact correction to reduce the signal from the satellites to the same level as the background noise (Tyson et al., 2020). Darkening satellites is critical, but observers use more than just the V band. To allow forecasting models to accurately predict changes in satellite reflectivity as a function of time, operators should provide relevant metadata such as reflectivity and BRDF measurements in the optical to infrared (at least ~ 0.3 – 20 microns) range. This will better enable observers to assess the potential impact on their observations and/or detectors and take the appropriate action while observing or preparing to observe.

For radio astronomy, additional information is required from operators to allow for radio frequency interference analyses to be done. This includes EIRP, transmission bandpasses, and nominal flux density at different frequencies. Information about a satellite's beaming strategy would further help radio astronomers in planning observations to protect sensitive equipment. Radio astronomers also need to know satellite altitudes, as well as whether transmissions from LEOsats to ground stations are pointed “straight down” or if they are somehow inclined to advance or retard the transmission beam.

3.3 Improving and standardizing TLE and ephemerides formats

As discussed in Section 3.1, general perturbation orbital solutions (commonly in TLE format) need to be shared along with uncertainties. We propose adopting the Orbit Mean-Elements Message (OMM) format from CCSDS 502.0-B-2²⁴, as suggested by Celestrak, which contains the same information as a TLE but with an optional covariance matrix at the end of the file. Sharing general perturbation orbital solutions in this format, and requiring accompanying uncertainties, will accomplish the goal of adding error bars to general perturbation data.

In addition to general perturbation orbital solutions, which are time-averaged Keplerian elements, operator ephemeris files contain state vectors, which record satellite positions and velocities. However, at present, this information is shared publicly on a voluntary basis and there are different formats available. Presently, SpaceX provides Starlink orbital ephemerides to [Space-Track](#), and it is freely available to everyone who creates an account at that website. However, while OneWeb provides orbital ephemerides to Space-Track, these are only accessible by the owner/operators, not by the public or astronomers. We seek to simplify the situation by requiring all operators to use the same format, such as the plain text NASA modified ITC ephemeris format, which is currently used by SpaceX in their publicly released ephemeris files. If everyone uses the same format, ephemeris software can ingest data from all operators and avoid having to write code to handle each operator separately.

²⁴ Orbit Data Messages Recommended Standard, Blue Book, November 2009.

3.4 A central web portal for sharing and retrieving orbital solutions

To improve community collaboration among myriad stakeholders, especially satellite operators, we propose the Orbital Solution Portal aspect of SatHub (see Figure 1) to simplify how orbital solution data are collected and shared.

The key components of the Orbital Solution Portal are ephemerides with error bars, general perturbations with error bars, and equivalent general perturbation information in “old style” TLE format for backwards compatibility. Each of these must include functionality for efficiently uploading new orbital solutions as well as querying, filtering, downloading, and/or visualizing them. In addition, the portal should include a guide for operators to follow when designing their data formats and sharing protocols.

3.4.1 SatHub’s Orbital Solution Portal

Third-party websites such as Celestrak and Space-Track are presently the primary public-facing access points for observers and other interested parties to retrieve orbital solution data. We propose a more centralized and operator-supported portal to publicly share orbital solutions. In some ways, the data provided will be redundant, but it will utilize standard formats and clear documentation to markedly increase accessibility and usability and enable new researchers looking at satellites to get started more efficiently. It also avoids a single-point failure scenario should a resource outside of observers’ control cease functioning.

The Orbital Solution Portal will also deliver significant value to satellite operators who wish to avoid collisions with one another, collaborate with astronomers on darkening mitigation experiments, and more easily visualize their own constellation’s present and past states. The Orbital Solution Portal provides an opportunity for operators to contribute not only data, but also funding to operate a public service which serves their data in an accessible way.

In line with the Algorithms Working Group’s proposed ephemeris database, old orbital solution information should be archived for long-term longevity in the Orbital Solution Portal. This allows coincidentally observed satellites to be identified and characterized, and is particularly important for studies using archival survey data.

3.4.2 Astronomers and operators collaborating on open source software

At present, there are only a handful of satellite forecasting software packages available (e.g., OrbDetPy²⁵ and LEOsat Visibility Tool (LVT)²⁶). Satellite forecasting is important for both avoiding satellites and planning intentional observations of satellites, and historically, much of the software behind this capability is proprietary and inaccessible to outsiders. For example, Celestrak uses Systems Tool Kit (STK) to generate supplemental TLEs from operator-provided ephemerides, which in turn requires proprietary space weather data as another input.

²⁵ <https://github.com/ut-astris/orbdetpy>

²⁶ <https://github.com/CLEOsat-group>

In addition to key portions of the Software Tools aspect of SatHub, described in detail in the Algorithms Working Group Report, astronomers and operators should collaborate on an open source software package that parses various forms of orbital solution data. This tool should translate between spreadsheet/Comma-Separated Values (CSV) formats, backwards-compatible TLEs, general perturbations in the newer recommended format (Section 3.3), and ephemerides. It could also utilize GPS data when available to validate forecast positions, and utilize automated tests to verify that operator-generated orbital solution data are error-free upon release.

4. Additional considerations

In this report, we introduce and justify the urgent need for SatHub, a coordinated observing effort for satellite constellations that encompasses multiple aspects of work. In addition, the Observations Working Group identified a number of additional considerations that must be taken into account.

4.1 Planning for solar maximum

As the Sun approaches its next maximum activity level in 2024 or 2025, space weather events that affect the LEO environment will become more frequent. Increased solar activity will result in increased atmospheric scale height, which causes increased drag on LEOsats. In periods of greater solar activity, LEOsats will have to correct their altitudes much more frequently than they currently do in order to maintain operating altitudes.

Much more worryingly, extreme space weather events — which are most common during solar maximum — like coronal mass ejections and radio bursts could cause communication disruptions with LEOsats, and the high-energy charged particles could cause satellites to enter safe mode or even become fully disabled. With thousands of satellites in similar orbits that are relying on active collision avoidance, even a short window of time where many satellites are disabled or in safe mode could prove disastrous. Operators need to plan for this in order to avoid catastrophic collisions.

4.2 Satellite laser communications

The NIR laser communication wavelength is 1.550 nm, which is within the astronomical photometric *H* band (1.490–1.780 nm). Because communications require generation of the signal, leakage (direct line of sight or scattering) from satellite cross-links and down-links could cause a significant impact on astronomical data collections. Given the multi-billion dollar nature of the laser communications industry, the path forward may require a redefinition of the *H* band.

Various proposals have been circulated to add flashing light emitting diodes, either in the optical or the NIR, to all satellites as a means of positive identification or as a form of advertising. While these might or might not be visible to the unaided eye, the impact on images obtained by modest to large-aperture astronomical telescopes could be catastrophic. Should such a scheme be considered for an industry standard, the astronomical impact must be evaluated prior to deployment. The thought that every satellite would be equipped with a flashing light is a nightmare scenario for astronomers.

4.3 Adaptive optics and laser clearinghouse exclusion

At the time of writing, many Starlink satellites appear on the Laser Clearinghouse exclusion list. The point of this list is to indicate the orbits of certain satellites that could be damaged if they cross a powerful laser beam from, e.g., an astronomy adaptive optics (AO) system. Such systems are prohibited from operating when those satellites are overhead. It is our understanding that Starlink satellites do not need to be on this list and would likely not be damaged by AO lasers. Presumably other satellite constellations are similarly designed. The rapidly increasing number of satellites from multiple operators means that this issue ought to be remedied promptly to avoid hindering precise astronomical observations that utilize AO.

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SATCON2 Algorithms Working Group Report

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Introduction

This report is part of a collection of Working Group Reports from the [SATCON2](#) Conference.

The published report following SATCON1 (Walker et al., 2020) detailed 10 recommendations, three of which apply to the development of software; these three are the focus of the SATCON2 Algorithm Working Group:

Recommendation 1

Support development of a software application available to the general astronomy community to identify, model, subtract, and mask satellite trails in images on the basis of user-supplied parameters.

Recommendation 2

Support development of a software application for observation planning available to the general astronomy community that predicts the time and projection of satellite transits through an image, given celestial position, time of night, exposure length, and field of view, based on the public database of ephemerides. Current simulation work provides a strong basis for the development of such an application.

Recommendation 3

Support selected detailed simulations of the effects on data analysis systematics and data reduction signal-to-noise impacts of masked trails on scientific programs affected by satellite constellations. Aggregation of results should identify any lower thresholds for the brightness or rate of occurrence of satellite trails that would significantly reduce their negative impact on the observations.

We have attempted to transform these SATCON1 recommendations into a specific set of high-level software requirements with provisional names for convenience of reference. We note that each of these is a fairly major software effort if they are to be robust enough to support the community. However, in some cases relevant software already exists, and this document identifies those packages.

In brief, the SATCON1 recommendations call for the ability to flag, mask and repair satellite trails affecting astronomical data (a software tool we call TrailMask), to predict when satellite trails may or will affect specific observations (which we call PassPredict), and to simulate the effects of satellite trails so that the community can assess the scientific impact of those effects on astronomical research.

Our main focus is on ground-based optical images of all kinds. However, we also considered space-based images and spectroscopy. We did not consider the (important) effects of satellite constellations on radio astronomy, although the PassPredict tools should work for single-dish radio observations to the extent that sidelobes are not important.

We are mostly concerned with the large low-Earth orbit (LEO) satellite constellations. However, spacecraft at near-lunar distance are regularly seen by asteroid surveys, so we should consider MEO and GEO (medium Earth orbit and geosynchronous Earth orbit) cases too. Note that the fainter magnitude of high-orbit satellites is offset by their lower apparent angular velocity, leading to larger effective exposure time on a streak pixel.

In Figure 1 we note that the counts in a satellite streak will tend to be independent of exposure time, and so the measured magnitude of the streak will be fainter for longer exposures.

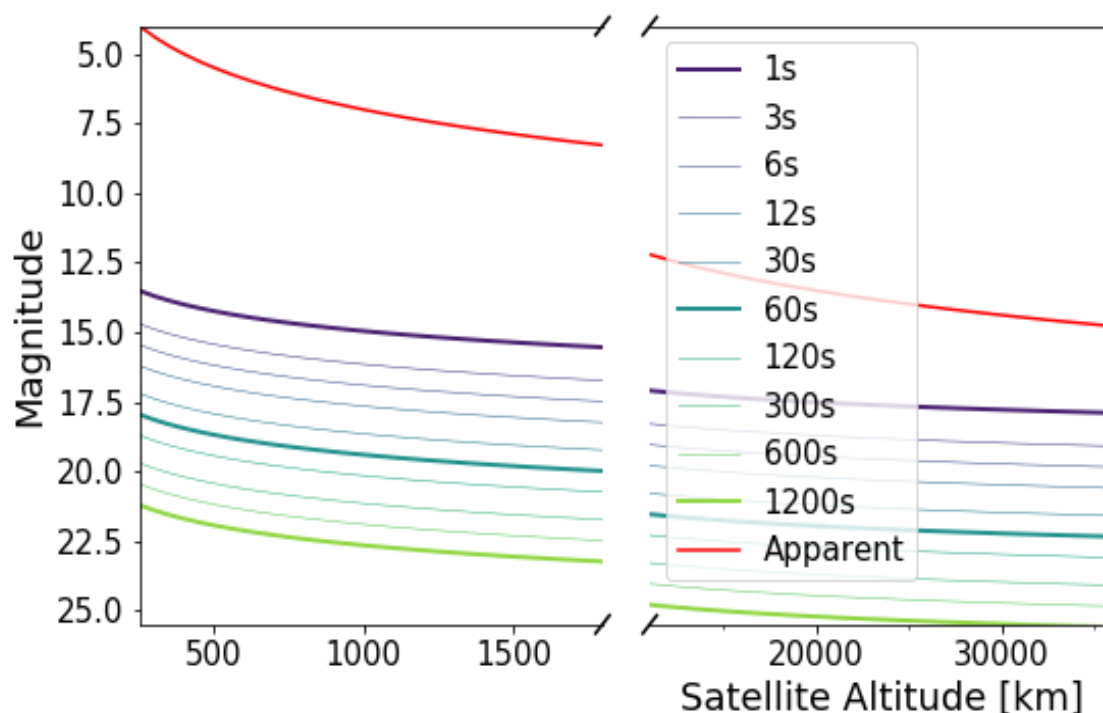


Figure 1. Effect of trailing on the effective magnitude of a satellite. Red: visual magnitude at zenith of an example satellite as a function of orbit altitude. Blue to Green: observed magnitude of the same satellite accounting for trailing, for a series of increasing exposure times and assuming a 1-arcsecond resolution element. In a given telescope/instrument, as exposure time increases, the number of counts detected from a faint (e.g., 15th magnitude) star will increase, but the number of counts in the satellite trail will not, assuming that the satellite crosses the field of view in a time that is short compared to the exposure time. Thus, the apparent brightness of the satellite trail will be comparable to stars of increasingly faint magnitude with increasing exposure. We assume this is a small telescope, so the spatial extent of the satellite (defocus + resolved size) is not accounted for.

The effects of streaks on optical imaging data were discussed in the SATCON1 Report (Walker et al., 2020). In this working group we also discussed the effects on other kinds of data, especially spectroscopy. Low-spectral-resolution fiber spectroscopy is especially vulnerable — the effect of a satellite streak is to add a solar spectrum to the target spectrum, and in the absence of any spatial information it may be hard to spot that your data has been affected. The limiting magnitude of low to medium resolution spectrographs are typically in the 20-25 range, comparable to the effective magnitudes of many satellites. ESO is planning a system with 3000 fibers at low resolution, and they estimate that the satellite contamination (when it occurs) will be up to 5-10 sigma above noise. This could be bad; 1000 sigma is easy to spot, 0.1 sigma can be ignored, but the intermediate range is difficult to notice and yet affects the scientific result. Higher resolution spectrographs have much shallower limiting magnitudes (15-20, even on large telescopes), and will therefore be essentially immune to the contamination by all but the brightest satellites. Finally, although exoplanet transit spectroscopy already has the problem of subtraction at the limits of S/N, its high spectral resolution will prevent significant contamination problems.

1. General Software Considerations

The astronomy software community is investing heavily in Python and in particular in the astropy suite. While we do not exclude other languages, applications developed in Python and compatible with astropy are more likely to be easily installed and usable by a broad audience.

External dependencies are sometimes necessary but each extra one adds maintenance overhead and often limits the potential user base; they should therefore be used judiciously.

Software-savvy astronomers will want to access the software by calling libraries (typically Python ones). However, less software-aware astronomers (both professional and amateur) will need command-line or web-based end-to-end tools which wrap these libraries in a simple interface. We must support both of these communities. In particular, a simple browser-based interface to the PassPredict and TrailMask tools discussed below (at least in their simple mode) is strongly recommended. We should also provide interfaces to planetarium applications (World Wide Telescope, OpenSpace, Stellarium).

If the software is to be used widely by astronomers, it should if at all possible be open-source, free, and free of restrictive licences. We should support a software ecosystem in which centrally developed reference implementations may exist, but interfaces are simple and well documented so that alternative implementations can be swapped in — this will allow us to leverage innovation by the community.

We encourage support of International Virtual Observatory Alliance (IVOA) protocols, and specifically pyVO, for retrieval of test datasets (and possibly of satellite prediction data if appropriate protocols exist). However, programs should always also allow import of datasets from a local disk.

Where appropriate (e.g., for satellite reflectance models) the software architecture should allow for user-model plugins (i.e., users can write their own model and have the software use that instead of the presupplied one).

1.1 Distribution and Documentation

The software will require user documentation and support. The obvious place to serve as a portal for software and documentation is the SatHub proposed in the Observations Working Group Report. We also recommend the development of related educational materials such as lesson plans to engage the school and university student communities.

2. Test Data Suite

The working group concluded that early development of a test dataset repository is a priority. Standard test datasets covering a range of cases will be needed during software development to validate algorithms and to compare the performance of different algorithms. Test datasets may also be of use to the Observations Working Group. The suite should be as small as possible (to be manageable) while still covering the needed range of test cases.

2.1 Image test data for TrailMask

The image test suite will be used to test TrailMask. It should include actual examples of images with satellite streaks, including the following cases:

- Large and small fields of view
- Large and small angular pixel sizes
- Short and long exposures
- Low and high background
- Professional and amateur telescopes
- Bright and faint streaks
- LEO and MEO/GEO satellite streaks
- Crowded and sparse fields
- Streaks that cross each other
- Optical and infrared data
- Mosaic frame and IFU (integral field unit) datasets
- Polarimetry data
- Simulated datasets (or real datasets with simulated streaks added) as needed — Vera C. Rubin Observatory has such data that could be used

Test cases should also include fiber spectroscopy and polarimetry examples. They should also include examples of false positives (e.g., comets/asteroids). The test case images should ideally be bias-/dark-subtracted and flat-fielded, although we should also include some uncalibrated images as test cases. It would be best if every test case consisted of a pair of images — one with the trail and one without, to test how well TrailMask works. All test cases should each be accompanied by a text description indicating their relevance (use cases etc.).

The test cases should also cover a range of telescopes and instrument types, including:

- All sky camera with a field of view > 150 degrees
- Commercial astrophotography lenses paired with DSLR, CCD, CMOS detectors
- Large CCD: 2k x 2k or larger with telescopes of various apertures from 1 to 30 metres (singly or in mosaics).

Image cases should include all metadata needed to perform different kinds of analysis — in particular observation time and pointing direction to support streak identification use cases. Use of at least the IVOA ObsCore DataModel is recommended as this will ensure that the developed software will work within a broad ecosystem. The metadata list should specifically include:

- Site (longitude, latitude, altitude in WGS84)
- Full image World Coordinate System (WCS) (ICRS etc; includes pixel scale.)
- Exposure start time and duration
- Filter (with documentation link to transmission curve)
- Optical setup (focal length, aperture, type)
- Photometric zeropoint (pixel values to Jansky or magnitude?)
- Gain noise / read noise

2.2 Satellite pass test data for PassPredict

A satellite pass test suite is needed to test PassPredict. The ObsCore data model should also be used here. Each test case should include:

- The observing conditions (telescope and camera parameters, pointing direction, date and time)
- A fixed test satellite database from which satellite ephemerides may be extracted, or (for some use cases) a single satellite ephemeris prediction (when you don't want to test the database part)

We should be able to (retro-)predict the passes of a few specific satellites at a specific epoch over a specific observatory and (if possible) predict their brightness.

2.3 Other Test Data

Test cases of secondary priority may include:

- Fiber spectroscopy and slit spectroscopy cases;
- Radio astronomy cases;
- Infrared astronomy cases; or
- TrailMask user-supplied cases, particularly if case is interesting/pathological.

We have not yet discussed what test cases would be needed for the simulation tools in the third SATCON1 recommendation above.

Effort required: establishing a repository where TestData can be organized and discovered should be done at one of the established astronomy data repositories. An upload and metadata registration system will require about 2 FTE (split across different expertise groups) with ongoing support requiring 0.25 FTE

3. Software projects

Here we discuss one by one the individual software algorithms that we see as responding to the SATCON1 recommendations. It is likely beyond the scope of this working group to choose or down-select a particular approach but we can provide some guidance on how such a selection might be made.

3.1 SATCON1 recommendation 1: TrailMask

Support development of a software application available to the general astronomy community to identify, model, subtract and mask satellite trails in images on the basis of user-supplied parameters.

As noted in Section 1, both programmatic and web-based interfaces should be provided. The latter will be of particular use to the hobbyist community.

3.1.1 Inputs and outputs

Required inputs:

- a) Image(s) where trails should be identified
- b) Image parameters (field of view, pixel size, flux calibration; would usually be in the image's header)
- c) Trail search parameters (width ranges, signal-to-noise ratio etc.; should come with reasonable default values if derivable from input b)

Additional, optional inputs (depending on the mode TrailMask is run in):

- d) Time and pointing of observation (for seeded mode)
- e) Prior information on where trails are expected to be present (for seeded mode)
- f) Simulated satellite traces planted on real images and also the images without the traces as the training set for deep learning models
- g) Real satellite traces in images — coming from the test data suite and elsewhere.
- h) Images from the same region as g) without the traces as an alternative training set for deep learning models

Outputs (depending on the mode, any combination of):

- 1) Catalog of identified trails, including some parameters (trail brightness estimates and brightness uncertainty estimates, start and end positions, width of the trail, and other parameters to be determined)
- 2) Mask file with flag set for each affected pixel
- 3) Images with trail affected pixels modified to minimize impact on data.

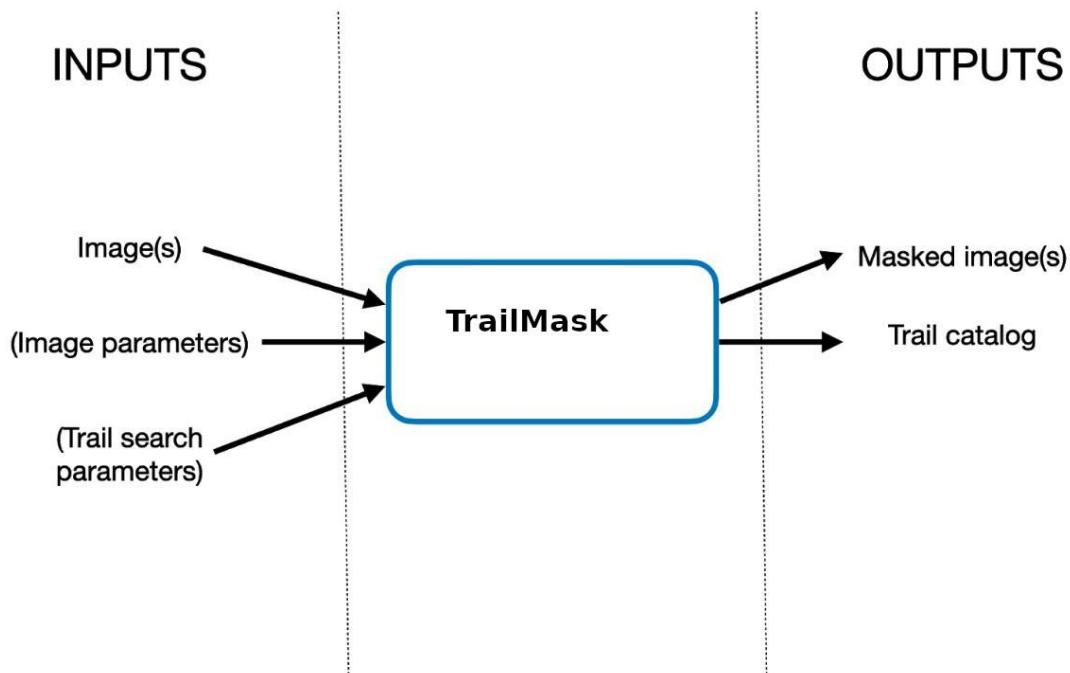


Figure 2. Schematic of TrailMask, when running in its simple configuration. In this example, since the user does not intend to use trail-subtracted images, the only outputs are the identified trail catalog and masked images.

3.1.2 Modes

TrailMask should support several modes, using different prior information and different desired outputs.

Prior information

- Run “seeded” with manual info about trail location and parameters, (optional input e)
- Run “seeded” using the output of PassPredict or similar
- Run “blind” without prior info on where the trails are

These different options ensure that one can deal with trails that were not predicted or were mispredicted.

Desired output

TrailMask should have the capability to find trails, mask every affected pixel, model the trails, and even minimize the noise signal. However, depending on use case, some or several of these options might be superfluous, or even undesirable. For instance, in many science cases where the noise properties must be very well understood, it is preferable to flag and ignore affected pixels rather than trying to recover them. In those cases, it would of course be wasteful for TrailMask to perform all the computations required to obtain all outputs. It is therefore crucial that the user be able to decide which combination of the various available outputs (1–3) they desire.

Approach

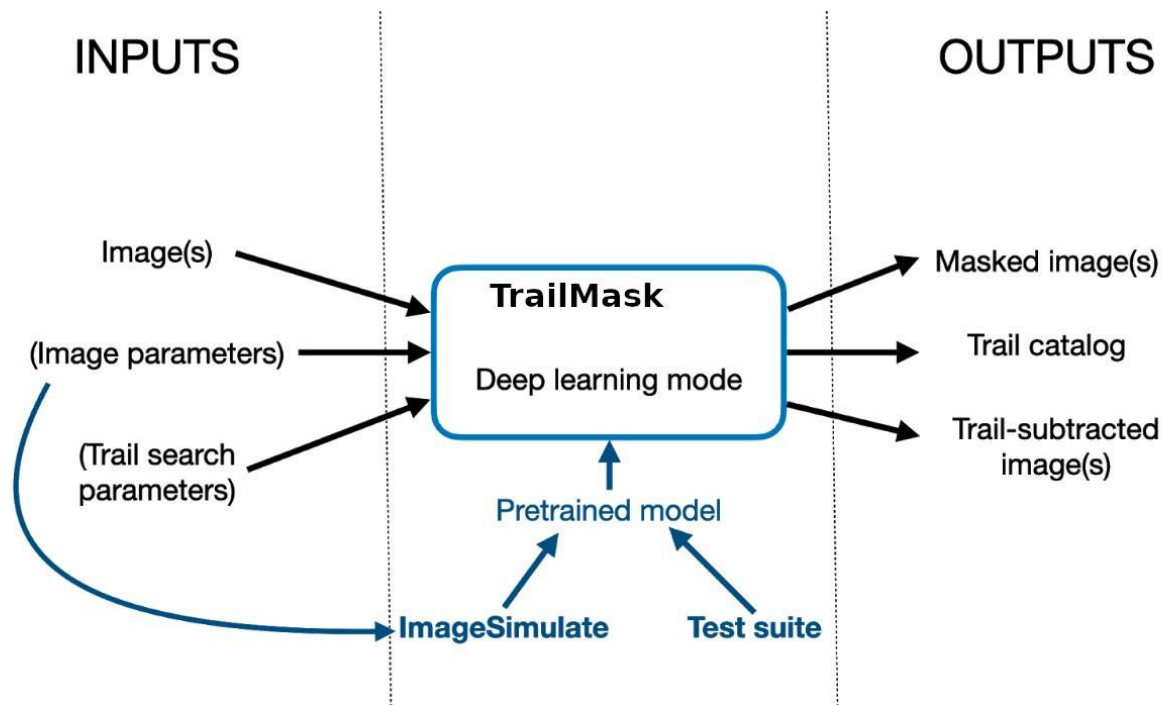


Figure 3. Schematic of TrailMask, when running in deep learning mode. If input images are too different from data used to train the pretrained model, but the user does not provide their own training data, TrailMask can rely on ImageSimulate (section 3.3.2) to provide extra training data.

When several frames of the same part of the sky are available, image differencing can be used to identify trail locations, and a simple median-stacking can be sufficient to remove the trail. TrailMask must also handle the case where only a single image is given as input. A simple, algorithmic approach should be available, and be able to produce satisfactory results for outputs 1 and 2. This could be based on the Hough Transform. However, modified methods may be needed to handle curved trails, which are especially likely to occur in space-based observations. Lastly, a more advanced, deep-learning-based method can be used, allowing for output 3 to be produced (and likely improving the quality of outputs 1 and 2). See Fig. 2 and Fig. 3 for schematic descriptions of these approaches.

Other considerations. How will the cutoff transverse to the trail be set? How will the algorithms behave on curved trails? How will ghosting be handled? For non saturated trails, can we assess whether faint sources can be detected under the trail?

A separate program under the TrailMask area might be a spectroscopy analysis tool to detect spectra showing contamination by a satellite spectrum (which will be close in shape to the solar spectrum).

Training data

The deep learning approach itself can run in several different modes. A pretrained model will be available as part of TrailMask. If the given input data are close enough for the model to be expected to perform well, this mode can be used without requiring any additional inputs. If not, appropriate training data can be used to generalize the model. These can be provided by the user (optional inputs f, or g+h), found in the test data suite if it contains images from a similar instrument, or be simulated in place by feeding input b to ImageSimulate (section 3.3.2 below).

TrailMask and the test data suite

To keep improving the pretrained model that is shipped with each TrailMask version, data from the test suite can be used. Conversely, in those cases where a user provides their own training data and at their discretion, these could be added to the test suite. This would require a certain level of interaction between TrailMask and the test suite, such that the former can query the suite, and potentially upload new data to it.

The use of processes that rely on databases of satellites will be inherently limited by the lack of availability of accurate orbits. Mitigation strategies for imaging should not rely on weakly available information. In addition, the goal of ‘TrailMask’ is twofold:

- Flag noise from satellite trails to reduce corruption in science analysis.
- Reduce/remove the noise that satellite trails insert into images.

Making images “look pretty” with various blending techniques is less important to the science mission. However, visual inspection of images is often important for analysis. Removal of satellite trails to allow deeper visual inspection (while ensuring the pixels impacted by the removal are flagged) is an important capability.

3.1.3 Relevant existing software

- Rubin Observatory’s satellite trail finder `maskStreaks.py`¹ — all open software.
 - Inputs: images with detection footprints
 - Outputs: images, with an additional mask bit for pixels that fall within streaks
 - Rough outline of the algorithm:
 - Uses Canny filter to make binary image of edges (the user could also provide a binary image instead of an image with detections and bypass this step)
 - Uses Kernel Hough Transform to find clusters of points and fit lines to each cluster
 - Takes sets of nearby lines as identifying the same streak
 - Fits a translated Moffat profile to the final lines
 - Adds mask bits
 - For now, the Rubin Observatory team are using it on the difference between single exposures (point spread function matched warps) and a static sky model
 - The current implementation requires the full Rubin Observatory artillery (the Science Pipelines) to be run, so it is clearly not an off-the-shelf solution. “Derubinizing” the algorithm itself should be a manageable task, if the community decides it is desirable.
- The CADC (Canadian Astronomy Data Center) Image Quality assessment process. In Teimoorinia et al. (2021) , it was presented as a process for the detection of trailed images but the satellite problem is similar.
- MaxiMask² is a CNN-based (convolutional neural network) trail identifier
- [Desai et al. \(2016\)](#) propose an algorithm that uses a deep co-added image of the same area of the sky as the exposure of interest
 - This may be too specific to sky survey-type observations to be of general use.
- [Gruen et al. \(2014\)](#) have a publicly available, modified version of SWarp to remove artefacts, including satellite trails.
 - This algorithm also supposes numerous exposures of the same area are available.

¹ https://github.com/lst/pipe_tasks/blob/master/python/lst/pipe/tasks/maskStreaks.py

² <https://github.com/mpaillassa/MaxiMask>

- StreakDet³, a European Space Agency (ESA) software package. It was developed to find space debris streaks, e.g., for on-board processing on an optical payload. It is available under a weak-copy left license and is not open source.
- Cosmic-CoNN (Xu et al., 2021) is a CNN architecture for cosmic ray detection, though as they say it should be easily generalizable to satellite trails. Especially relevant is their proof of generalization to other instruments with minimum input data for retraining once the pretrained model has been trained on a large volume of data (from Las Cumbres Observatory in their case). As they say, *“By expanding our dataset with more instruments from other facilities, we are confident to see an universal cosmic ray detection model that achieves better performance on unseen ground- based instruments without further training.”*

Effort required. The effort needed to produce a TrailMask process will be dependent on the path selected. Adoption of the Legacy Survey of Space and Time (LSST) pipeline based trailmask or similar pipeline to a generic environment will likely require around 2 FTE. Simple codes that remove trails via image stacking require nearly no effort but are only effective for stacks.

3.1.4 Future algorithms: deep learning

Deep learning/AI methods for both detection and removal of satellite trails are being developed and may provide a highly effective approach to solving the problem of detection and removal of trails.

A deep learning/AI implementation would have the following user modes:

- 1) Pretrained nets
- 2) User supplied training set (one could call the simulation tools discussed below to generate simulated data from observation parameters)

A deep learning generative model has been used by the CADC team to remove moving object trails; it uses the open source tensorflow library. However, designing the model is not easy. A deep learning model can be trained, with relevant data sets, to detect and model various objects in images, such as satellite traces in astronomical images. The models can then be used to remove the trails from the images using deep learning techniques. Tensorflow, an open-source machine learning platform, can provide a foundation for training deep learning models. Keras, a deep learning API (applications programming interface) written in Python, runs on top of TensorFlow's machine learning platform, focusing on enabling fast experimentation and easy implementation. With Keras, a trained model can be used easily as Python code, standalone, or a part of a pipeline.

The deep models that are trained on a single instrument are likely not generically applicable but they can be used as pre-trained models for trail detection on new instruments. Training for the new instrument can then be achieved using a smaller training data set. Two items needed to enable this transfer in learning are a database with some uniformity in accessibility and metadata associated with the training data.

Deep learning methods are also highly effective at learning in lower-dimensional representations, known as latent space representation. Images with similar characteristics lie near each other in latent space. The vector length is considerably smaller than the input image size, providing a compressed representation of the original image by removing complex dimensionality associated with astrophysically uninformative parts of the image space. The latent space vector can also be mapped back into the original space, restoring the original image (i.e., preserving fluxes, with possible random losses). The deep learning

³ <https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/1018/SDC7-paper1018.pdf>

model that creates the latent representation is trained such that the compressed latent representation contains astrophysically meaningful information. Simultaneously, the latent vector outputs of deep models provide a homogenous input for deep downstream models trained to solve astrophysical problems. A set of deep probabilistic deep models can learn "what is in the images".

Beyond use as homogenous inputs for deep learning, the latent space representations of the images themselves are also highly useful. A remarkable application of using latent space in deep models is to perform arithmetic methods on the latent space data. The algebraic manipulation has a visible manifestation when latent data are decoded back into the original image domain. For example, suppose we have a set of latent space vectors of particular sky images containing contamination from satellite tracks and another set of images for the same sky but without these tracks. The latent space vectors can be subtracted from each other. Once subtracted, the leftover latent data will only represent the satellite tracks. These new latent satellite vectors can act as versatile models; for example, they can be subtracted from other contaminated images to remove undesirable tracks.

As an example of deep learning methods (that can also be generalized to the satellite problems), the top panel of Figure 4 shows two different images with different pixel problems. The blue and red marks show two moving objects. The bottom panel shows the same images where the images have been denoised, and the problems have also been removed without damaging the sources in the images.

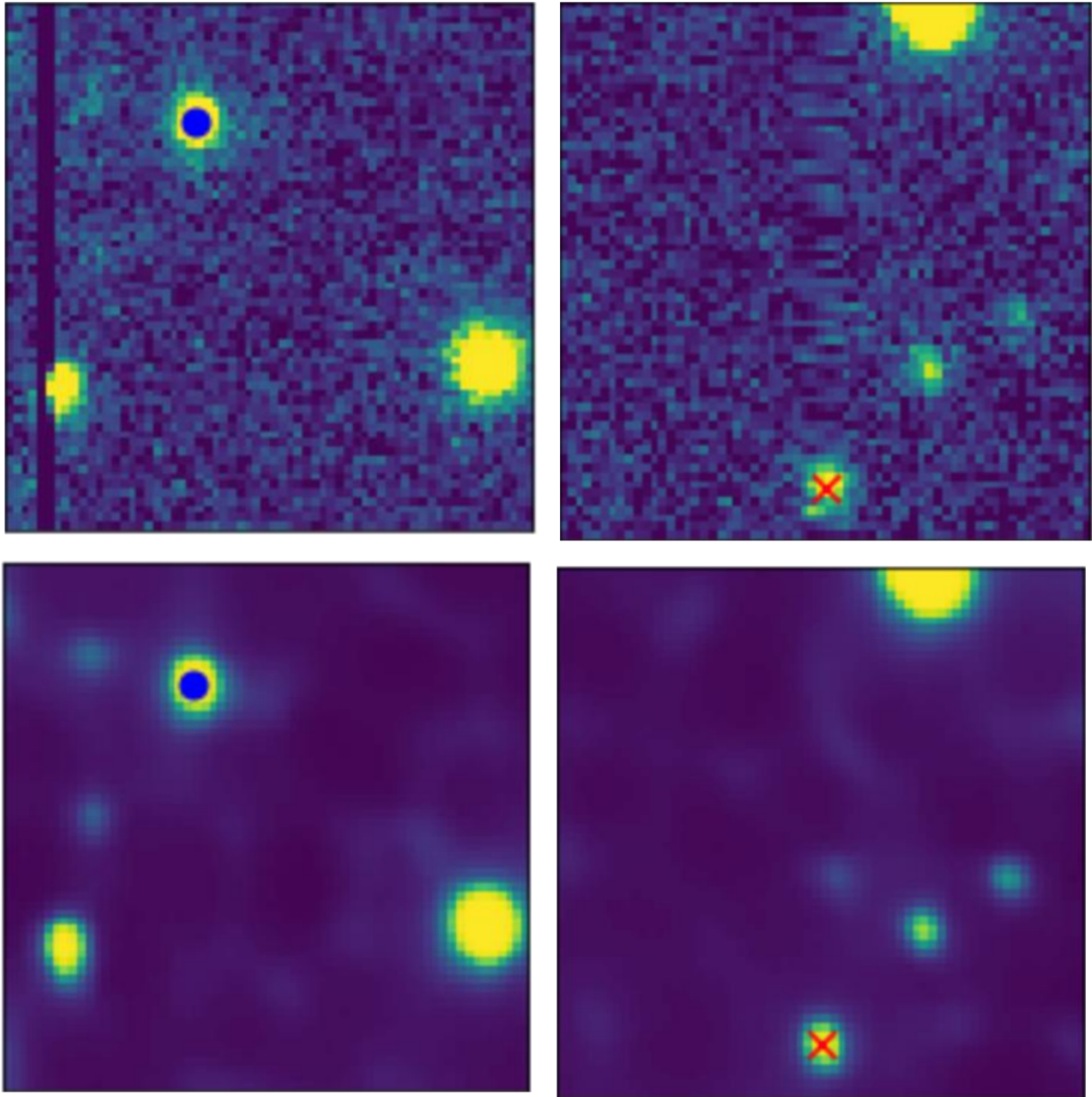


Figure 4. Examples of deep learning methods. In the top row are two different images with different pixel problems. The blue and red marks show two moving objects. The bottom row shows the same images after they have been denoised, and the problems have also been removed without damaging the sources in the images.

As another example, the deep models can also be used as a content-based recommendation system capable of filtering images based on the desired content (see Teimoorinia et al., 2021). In Figure 5 (a Self Organizing Map), different sources of a set of astronomical images are modeled by a deep model. The model is capable of recognizing images with bad pixels (e.g., the sources similar to node (1, 12)), images with a bad focus problem (e.g., node (2, 1)) or images with satellite tracks (e.g., node (23, 1)).

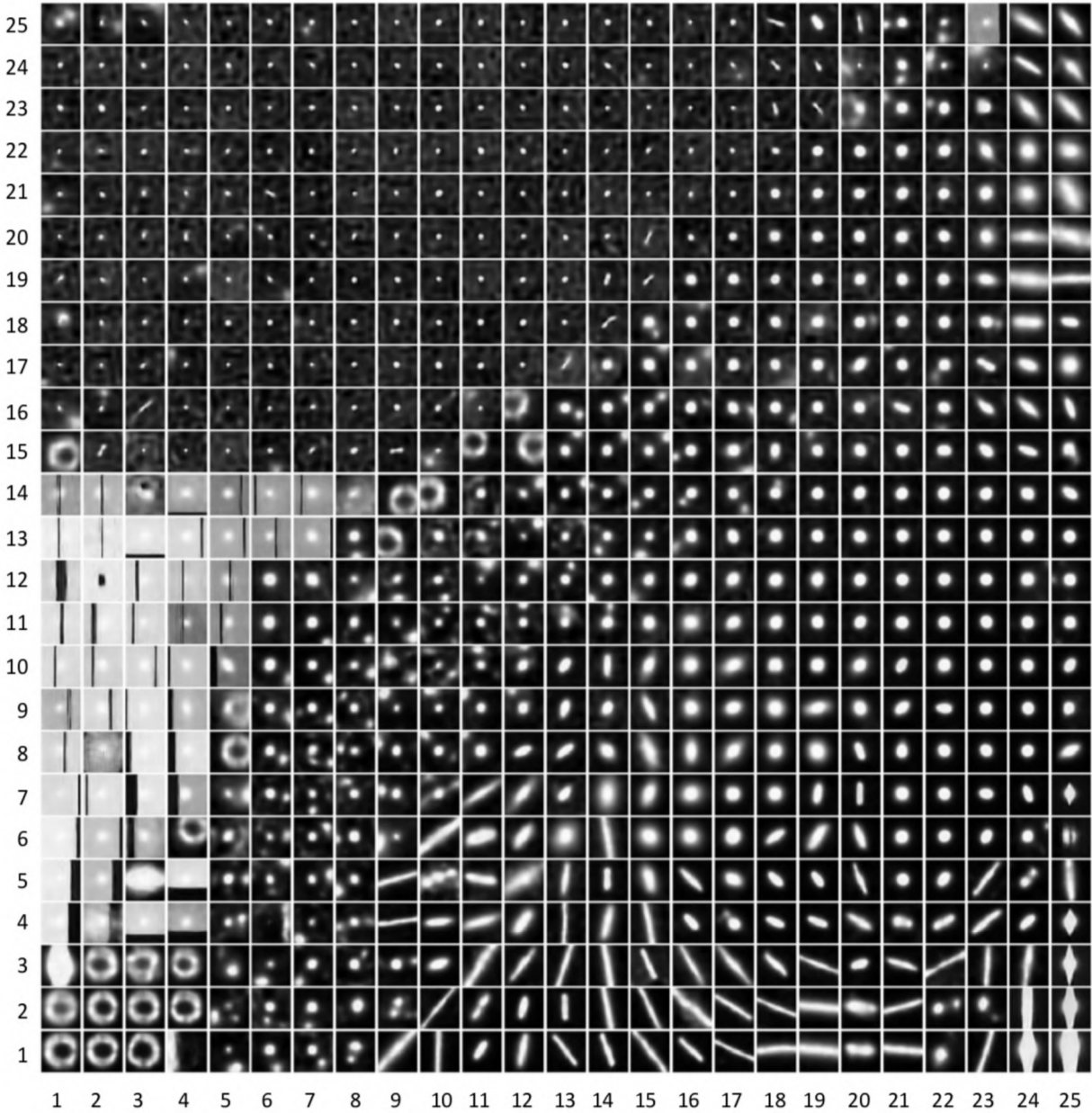


Figure 5. A Self Organizing Map showing different sources for a set of astronomical images modeled by a deep learning model. The model is capable of recognizing images with bad pixels (e.g., the sources similar to node (1, 12)), images with a bad focus problem (e.g., node (2, 1)) or images with satellite tracks (e.g., node (23, 1)).

3.2 SATCON1 recommendation 2: PassPredict

Support development of a software application for observation planning available to the general astronomy community that predicts the time and projection of satellite transits through an image, given celestial position, time of night, exposure length, and field of view, based on the public database of ephemerides. Current simulation work provides a

strong basis for the development of such an application.

A browser-based interface will enable astronomers to predict what satellites will intersect with any given single observation. However, to be effective as a mitigation strategy, astronomers will need to use an interface optimized for planning observations in advance, adjusting either the pointing and/or the timing of the observation to minimize the number of satellite tracks or even (if possible) shifting the observation to a different observatory location/instrument field of view. This will mean multiple queries to the database with adjusted parameters for each observation. Together with the need for intensive observing programs and rapid response to transient events, this implies the need for an interface accessible from programs (i.e., an API) which would handle large batch requests with inputs and outputs in a parseable format (e.g., JSON). Deployment of a queryable system via the IVOA TAP protocol would leverage several existing application tools, such as pyVO. This program will be computationally intensive and may benefit from optimisations (such as grouping calculations of satellites in similar orbits) and from use of parallelization and GPUs.

3.2.1 Inputs and Outputs

Inputs:

- A. Ephemeris database (real or simulated) and in-orbit satellite list
- B. Observatory parameters: latitude, longitude, height
- C. Observation schedule parameters (right ascension, declination, date/time, exposure time, field of view, aperture)
- D. Satellite physical and optical properties (bidirectional reflectance distribution function [BRDF] etc.) including software model to predict brightness (advanced mode only)
- E. Streak minimum brightness threshold (advanced mode only)
- F. Photometric bands in which to estimate brightness (advanced mode only)
- G. Possibly, Satellite attitude ephemeris (needed to use the BRDF)

Outputs:

1. Transit list: Satellite catalog number, time, probability, trail parameters+uncertainties.
 - a. Trail parameters include satellite magnitude, trail surface brightness, trail width, trail start and end location.

The predicted trail location on the image may be too uncertain to be useful for actual predictions, but will be required for simulation exercises.

Accuracy requirements on inputs:

- We consider two levels of accuracy: COARSE — enough to say if the field of view is affected; and FINE — enough to say where the streak will be in the field of view (ideally to the pixel level).
- For COARSE accuracy we require about 10-arcminute fidelity, corresponding to about 1 km at the satellite. For FINE accuracy we would like arcsecond fidelity, corresponding to meter-level knowledge of the cross-track satellite position.
- The along-track angular velocity of the satellite is large, the time to cross the field of view being on the order of a second. The along-track requirements on the prediction accuracy may be somewhat weaker, but confirming this requires a more accurate calculation involving the transverse angular velocity of the streak in the detector frame.
- Requirements on the observatory parameters are similar to those on the satellite: kilometer for coarse, meter for fine.

- Requirements on the observation parameters include at least 1 second absolute accuracy on the exposure start and end time, to match the coarse requirement for satellite position.

Accuracy requirement on methods (and so outputs):

- For FINE accuracy refraction and aberration must be accounted for.
- For brightness calculations in advanced mode, 0.1 magnitude is probably more than good enough to assess the scientific impact of streaks.

3.2.2 Modes

PassPredict will have three modes:

- Simple mode, predicting position but not brightness. This should include support for a browser-based interface as well as an API.
- Advanced mode, predicting brightness of the satellite as well.
- A posteriori mode, for identifying streaks or (importantly) possibly compromised fiber spectra — in archives.
 - Note that *post facto* operator ephemerides are often more accurate than predictive ones, in contrast to two-line elements (TLEs) which are never improved retrospectively.

One could separate out the “position [and optionally brightness] of satellite vs time” part from the “what does the streak look like on the image?” part and make them two separate programs.

3.2.3 PassPredict: Considerations for the ephemeris database

The ephemeris database will be an interface to a variety of data inputs:

- The list of satellites to be considered. Each satellite (with a few exceptions that we aren’t interested in) may be labelled by its number in the US satellite catalog. This is a 9-digit integer (currently all but a few objects use only 5 digits, but that’s about to change). Tables are available to look up the satellite name and owner as a function of catalog number, and to look up which catalog numbers are currently in orbit rather than re-entered. Note that for efficiency our database should avoid requesting fresh orbital data for a satellite which has now re-entered, so it needs to keep track of such events.
- The orbital solutions for each satellite.
- A curated list of active satellites and their current status (in orbit, orbit raising, operational, failed, etc.) is desirable. Such lists are currently maintained by unfunded enthusiasts but there is no sustainable project to support this in the long term. One can find the list of all satellites in orbit by filtering the space-track catalog; at a minimum we should provide software to do this and cache it on a weekly basis, rather than running a space-track query every time PassPredict is run. Additional information on the status of each satellite will be needed for assessments of the overall impact of the constellations and such a list should be supported and maintained by the astronomical community. In addition to the usual catalog-numbered satellites, some numbers are reserved for so-called ‘analyst satellites’. These are objects not identified with a specific launch and can be thought of as analogous to unnumbered minor planets. The analyst numbers are arbitrarily re-used. The megaconstellation satellites we are mostly concerned with will probably not be in the analyst list, so it is not urgent to consider them.

3.2.3.1 Orbital Solutions

The position of a satellite at a future time is predicted by an algorithm called a “propagator”, using an orbital solution at some given past epoch. For accurate predictions the epoch used should be only a few days old, at most a week, especially in low orbits (since drag effects and atmospheric density are not predictable on long timescales). The propagator that you need depends on the model used to generate the orbital solution. There are two main sources of orbital solutions:

- Operator orbit solutions for their own active satellites determined by active tracking of the satellite radio signal or derived from onboard GPS receivers
- Passive (radar or optical) tracking of satellites, including inactive satellites and debris. This is systematically done by US Space Force 18th Space Control Sqn (18SPCS) and the Russian Space Forces’ SKKP, and is now also being done by commercial companies LeoLabs and ExoAnalytics, and to some extent by ESA. For brighter satellites optical and radio-transmission tracking is also done by hobbyists.

The orbital solutions used are typically one of several types:

- GP (General Perturbations) mean elements. These are time-averaged Keplerian elements using a model called SGP4 which takes a simple drag model and some other perturbations into account. GP elements used to be provided in TLE format but are now also available in JSON and other formats.
- SP (Special Perturbation) state vectors — the state vector (position plus velocity) at an epoch in a particular frame. These state vectors are not directly observed but are derived from orbit fits using high-fidelity force models.
- SP ephemerides — sets of predicted state vectors vs time which can be interpolated using Lagrange or Hermite polynomials.
- Other forms of state vector ephemerides, including those from NASA or the International Laser Ranging Service (ILRS).

The elements or state vectors are given in one of several reference frames. The most common ones are:

- EME2000 (The astrodynamical name for J2000)
- TEME (True Equator Mean Equinox, sort-of-but-not-quite equator of date). Space-Track TLEs are in TEME.
- ITRF (International Terrestrial Reference Frame, rotating with Earth)

Availability of data, all of which is updated approximately daily:

- GP/TLE data are available from 18SPCS via the public website⁴ for all satellites except secret US satellites, whose GP/TLE data are instead made available by hobbyists⁵.
- The SP data from 18SPCS are available to operators by special arrangement with Space Force but not to the public. Such a special arrangement usually comes with restrictions that would be incompatible with our needs.
- Some researchers (e.g., M. Jah, UT Austin) have access to LEO Labs data for academic research, but they are in general not free.

⁴ <https://space-track.org>

⁵ notably <https://www.prismnet.com/~mmcants/tles>

- Some operators (notably Starlink, OneWeb, GPS) make their GP/TLE data available publicly. TLE versions of these data are available on T.S. Kelso's Celestrak site⁶.
- SP ephemeris files (several GByte per day) for SpaceX Starlink satellites are publicly available⁷.

One of the conclusions from all our previous and current work is that our proposed PassPredict tools will need orbital information allowing for position accuracy of the order of an arcminute for imaging applications and general purpose evaluation. This is equivalent to knowing the position of a LEO satellite with a precision of ~ 200 m. For spectroscopy, the requirements would be even more stringent, on the order of an arcsecond or ~ 5 m. These levels of precision cannot be provided by the publicly available elements in GP/TLE format. However, the information is available to the spacecraft operators, possibly with an even higher precision.

We therefore recommend that the orbital parameters (suited to high fidelity models, with covariance/uncertainty information) be reliably made available by the satellite operators to the observatories. Should the full precision orbital data be commercially sensitive information, they could of course be degraded/truncated, to a precision allowing for sub-arcminute uncertainty on the position. The detailed exchange of requirements resulting in such an arrangement can be part of the ongoing dialogue and cooperation between the astronomical community and the space industry.

3.2.3.2 Accuracy, maneuvers, and operator data

Most orbital data, including TLEs, have no accuracy or uncertainty information. Some orbital solution data formats allow provision of uncertainties in the form of a time series of position-velocity 6×6 covariance matrices.

Satellite operators regularly perform maneuvers to maintain or change their orbits (e.g, ESA performs weekly manoeuvres — “burns” — for its Earth observation satellites; and SpaceX adjusts the orbits of its Starlink satellites frequently for orbit raising and slot relocation). These maneuvers cannot be predicted by external observers and, of course, make existing orbit predictions obsolete. There is now a mechanism by which operators can inform 18SPCS of planned trajectories and maneuvers and allow 18SPCS to make these predictions available to other operators (but not to the public). In addition to incorporating planned burns, operator orbital predictions are often based on on-board GNSS receivers, are more accurate than passive tracking by surveillance systems, and may include covariance data.

GP data are given in ASCII TLE 80-characters-per-line format inherited from punch card days; they are also available in JSON and other representations. Ephemeris data formats include: CCSDS Orbit Ephemeris Message (OEM), NASA ITC, and ILRS CPF. CPF is used by the satellite laser ranging community who often prefer the ITRF frame. More details of the formats are given in the appendix.

3.2.4 PassPredict simple mode: detailed requirements for inputs

- Observatory location. For a ground based observatory, the station location shall be provided either in a geodetic frame using latitude, longitude and height (e.g., in degrees and meters) or in a geocentric Earth-fixed cartesian frame (ITRF) using x,y,z coordinates. For space-based telescopes, an ephemeris is required. For compatibility with the ground-based case, this should also be in geodetic or ITRF frame versus time. Alternatively we may want to support doing all the

⁶ <https://celestrak.com/NORAD/elements/supplemental>

⁷ <https://space-track.org> (under 'Public Files')

calculations in inertial TEME or ICRS frames. The exposure times of space observatories are typically very long compared to the time it takes for the observatory position to change significantly.

- Observation schedule.
- The centre pointing of the telescope during exposure shall be defined with azimuth and elevation or topocentric ICRS (or TEME) right ascension and declination.
- The field of view shall be defined using a radius in degrees in the case of a circular shape, horizontal and vertical dimensions for a rectangular shape or using a polygon to allow arbitrary shapes
- The pixel size shall be given in arcseconds.

3.2.5 PassPredict: algorithm

We can search for passes using a brute force grid search with fixed time steps, or by using a root search algorithm (Oltrogge, Kelso & Seago, 2011). Batch or individual requests could be generated by existing tools which support observation requests, but they would need updating to provide an interface.

For each satellite, we calculate the position at a series of time steps specified by the user. For each step, we perform the following steps:

1. Calculate the geocentric satellite position and uncertainty (interpolating state and covariance from the ephemeris or propagating TLE and using a fixed uncertainty estimate). Note that covariance interpolation can lead to unphysical results (results which are non-positive-definite or have negative variance). See the astroplan package (<https://astronplan.readthedocs.io/en/latest/>) for approaches to handling this.
2. Calculate the difference vector between the observatory location and the satellite position.
3. Transform this to a unit vector (the “line of sight”) in the observatory topocentric frame.
4. Determine the telescope field of view at this time in the topocentric frame.
 - a. There remain detailed issues to resolve: how to handle aberration and refraction; whether we convert the FOV from apparent to true RA/Dec, or conversely convert the satellite vectors from true to apparent. An observing schedule is normally given in true RA/Dec rather than apparent, so the former approach seems better.
 - b. If the line of sight is within the field of view, the satellite is geometrically observable (Alfano, Negron & Moore, 1992).
5. Calculate the satellite topocentric angular velocity in the instrument frame.
 - a. This is not necessarily tracking at the sidereal rate; however, this is unlikely to be a significant issue.
6. Calculate the geocenter-Sun vector from, e.g., the JPL ephemeris.
7. Subtract the satellite-geocenter vector to obtain the satellite-Sun unit vector.
8. Compare the geocenter-Sun vector and Earth radius to see if the Sun is above the horizon as seen by satellite — if so, it is illuminated.

In simple mode:

1. Output the result line if the satellite is geometrically observable.
2. Keep track of whether the satellite was observable at the previous time step; if so, it’s the same streak and has the same streak ID (identification) number. If not, increment the streak ID number.
3. The result line indicates: satellite catalog number; streak ID number; predicted topocentric right ascension and declination at the time step; a flag to say whether the satellite is illuminated or not; the location of the streak in the field of view.

In advanced mode:

1. Use the BRDF (and attitude model if available) to determine the predicted magnitude in specified bands. Add to the output line.
2. Use the angular velocity and pixel size to predict the surface brightness of the streak per pixel. Add to the output line.

3.2.6 Available software for PassPredict simple mode

Table 1: The table below identifies a variety of existing software that may have capabilities relevant to the PassPredict effort.

	Package	Capabilities
Main candidates for orbit calculations	GMAT (NASA)	TLE propagation, OEM interpolation, frame conversion, position prediction (GMAT, n.d.)
	Orekit	OEM interpolation, frame conversion. The code is from a French company (CSGroup). OreKIT is used in Moriba Jah's Orbit DetPy (Iyer, 2019).
	OrbitDetPy	Wrapper on OreKIT with useful functionality, from UT Austin group https://github.com/ut-astris/orbdepy (Iyer, 2019) and https://github.com/IBM/arcade (IBM/U of Texas).
Wrappers for observation requests	Astropy.astroplan	Observation planning
	TOM Toolkit	Observation planning (Street et al 2018)
Other packages of interest	STK	AGI; not free or open source
	Freeflyer	A.i.-solutions; not free or open source
	ERFA	Astropy; frame conversion routines
	Slrfield	Satellite laser ranging pass predictions https://pypi.org/project/slrfield
	PROOF	ESA; uses GP/TLE to compute individual topocentric pass predictions with configurable observatory parameters, including instrument field of view, etc. It is an open source Fortran code with a Java interface.
	Monte	JPL (not open source)

Notes: STK and Freeflyer are widely-used industry-standard packages of particular note. R. Street (Las Cumbres Observatory) noted an interest in building a component to the LCO TOM Toolkit to wrap the U. Texas OrbitDetPy work.

3.2.7 PassPredict advanced mode — considerations

In order to predict the apparent brightness of satellites a model for the reflectance distribution must be provided. The brightness can be predicted in a deterministic way using a satellite model or some

approximation (e.g., a look-up table) assuming knowledge of the attitude state. Operators could be encouraged to share their attitude states using, e.g., the CCSDS ADM formats (similarly to ephemeris files). Many operators also follow some attitude law which could be considered in the code. Alternatively, the brightness can be bounded statistically irrespective of the attitude state, e.g. based solely on Sun-phase angle.

It would be helpful if operators made available BRDFs, satellite models, and attitude control profiles to allow us to make detailed brightness predictions.

Effort required. We have not made a level of effort estimate for the PassPredict work. The existing relevant software suggests that the actual software development will be a smaller job than TrailMask; however, a robust system to manage and interface with the ephemeris data will likely take significant and continuing resource investment.

3.3 SATCON1 recommendation 3: Simulation Tools

Support selected detailed simulations of the effects on data analysis systematics and data reduction signal-to-noise impacts of masked trails on scientific programs affected by satellite constellations. Aggregation of results should identify any lower thresholds for the brightness or rate of occurrence of satellite trails that would significantly reduce their negative impact on the observations.

3.3.1 EphemSimulate

To model the effects of future constellations, we need to be able to go from a constellation description to a simulated ephemeris database; EphemSimulate would do this.

Inputs:

- A. Constellation shell parameters
- B. Observation date

Outputs

- 1. Simulated ephemeris database

A typical constellation description defines a number of layers with fixed altitude and inclination (see Fig. 6 for an example). Each layer specifies the number of orbital planes and number of satellites per plane. We can assume that the planes are evenly spaced and that the satellites in a single plane are on average evenly spaced along the orbit (possibly with some rule for adding some randomness to the phases along the orbit). This allows us to instantiate a suitable set of orbital elements for each satellite in the constellation. For this purpose (to assess the impact of a particular new constellation design), perfect circular Keplerian orbits are likely a sufficiently accurate representation; detailed propagation models are not needed.

Since the deployment of Starlink it has become clear that satellites may spend a significant fraction of their lifetime in ascent and descent orbits and in plane-adjusting drift orbits at intermediate altitudes, so simulations may want to include these effects as well.

MODEL VII: Chinese GW Constellation (2021 revision, 12992 satellites)

Layer	Element	Altitude (km)	Inclination (deg)	No of planes	Sats per plane	Total sats
A	1	590	85.0	16	30	480
A	2	600	50.0	40	50	2000
A	3	508	55.0	60	60	3600
B	4	1145	30.0	48	36	1728
B	5	1145	40.0	48	36	1728
B	6	1145	50.0	48	36	1728
B	7	1145	60.0	48	36	1728

Figure 6. Typical example constellation definition, in this case for a proposed Chinese constellation.

The output of this tool could then be passed to PassPredict or a similar algorithm to model the observability of the constellation at a given observatory and date. In an advanced mode, we should also predict the satellite brightness. Simulations should include cases for professional observations and also of the effect on the naked-eye sky. As to existing software, various unpublished research codes exist but would need to be modified to generate the ephemeris database output and improved to be robust enough for general use.

3.3.1.1 PassProbability

We can use the approach of EphemSimulate in a statistical mode to predict the average density of satellite passes on the sky in a given situation. We call this tool PassProbability. This can be used for long-term impact studies or as a quick alternative to the computation-intensive PassPredict to estimate the probability that a given observation will be affected by a satellite trail. Bassa et al. (2021, in preparation) have generated an analytic satellite density model that can be used to go from the constellation definitions to probability sky maps and calendars. The probability that an observation will be affected varies by orders of magnitude with only slight changes in the observation parameters.

We can consider two modes of output:

1. A Probability Map (Figure 7) which shows the fraction of exposure lost due to satellite trails as a function of celestial position. A value greater than 1 indicates that the exposure is entirely lost.
2. A Probability Calendar (Figure 8). Here we calculate the probability of exposure loss for a specific target (in this case, the Large Magellanic Cloud) as a function of time of night and observation date. The idea is to plan the optimal dates for an observing run. The solar elevation is indicated by the blue contours; yellow-green slanted lines indicate the elevation of the target, with elevations below 20 degrees considered unobservable and shaded in gray. The color scale indicates the expected fraction of exposures lost.

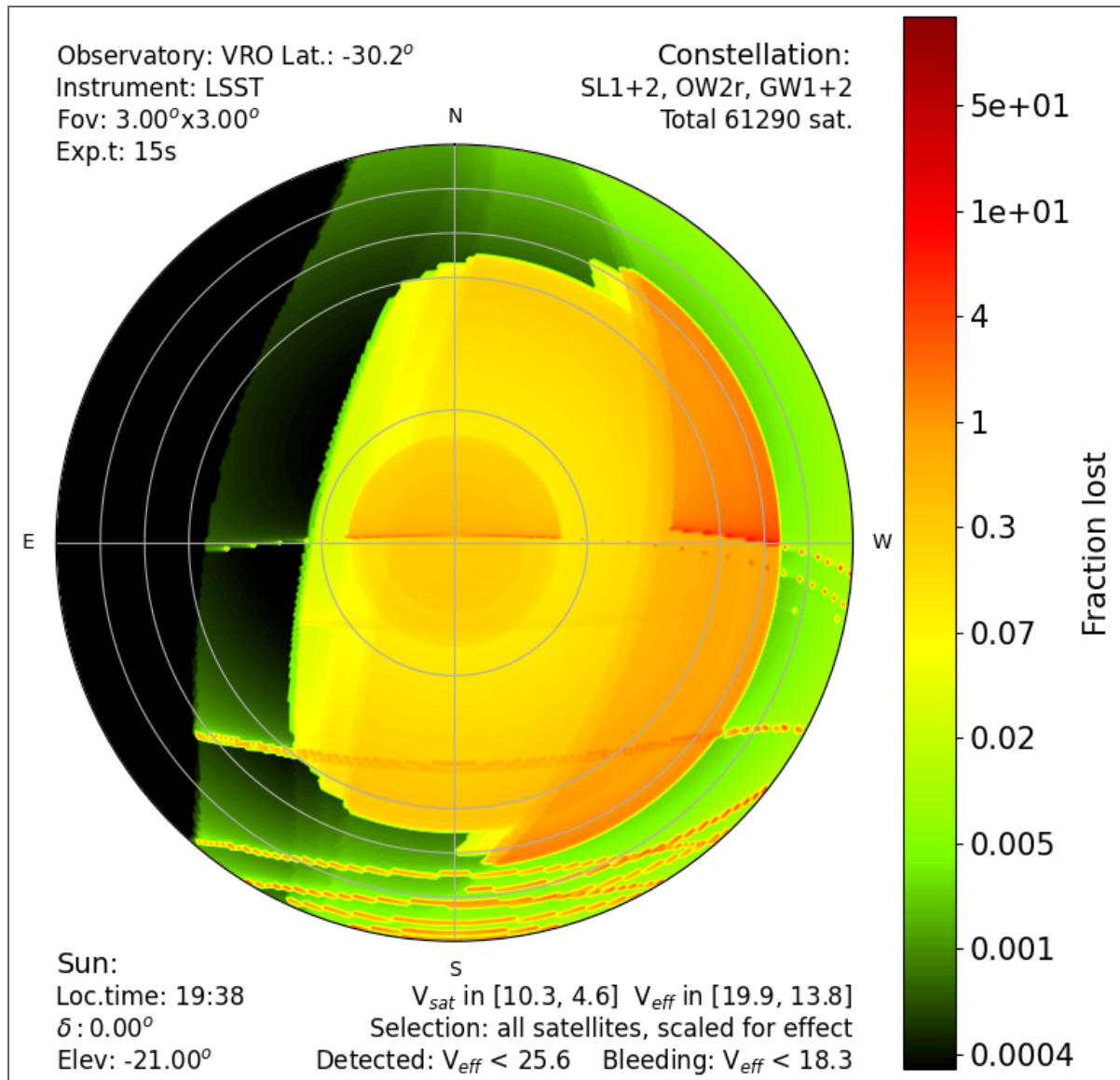


Figure 7. An example probability map displaying fraction of exposure lost due to satellite trails as a function of celestial position.

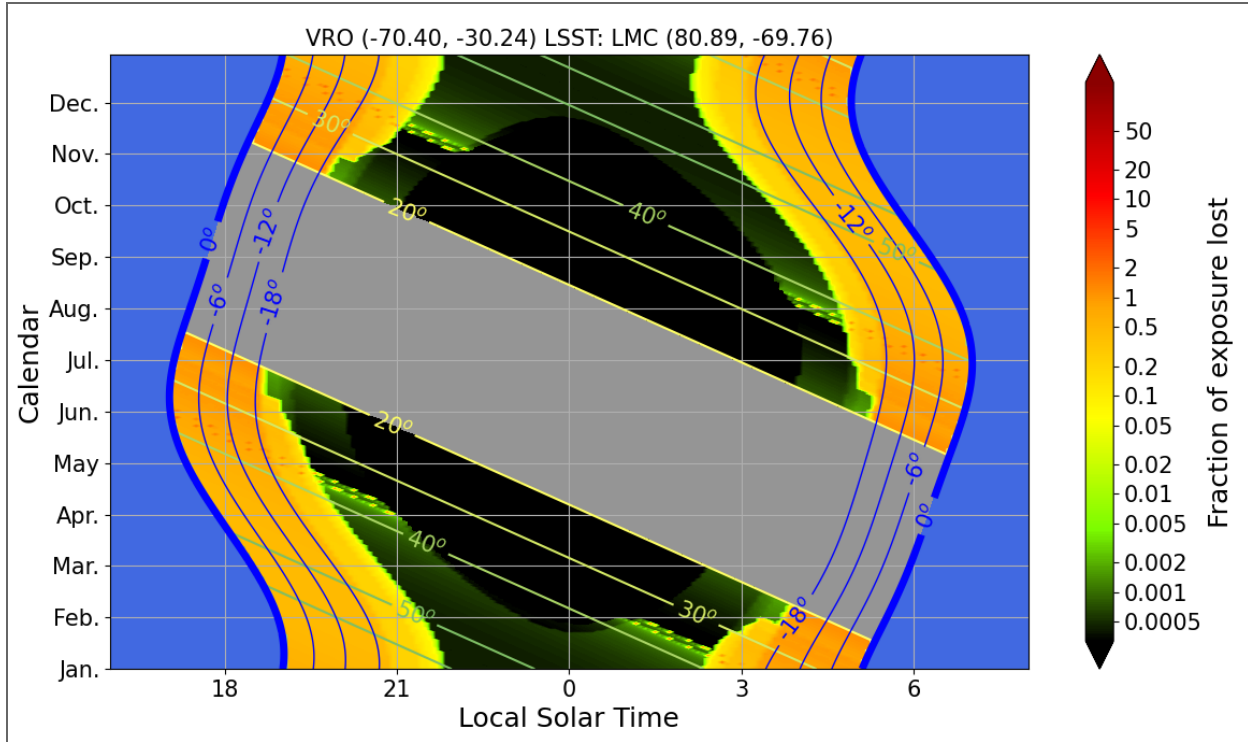


Figure 8. A Probability Calendar displaying the probability of exposure loss for a specific target (in this case, the Large Magellanic Cloud) as a function of time of night and observation date.

3.3.2 ImageSimulate

We need to provide base images to add simulated trails to. One could argue that you can just use existing images and no basic image simulation tool is needed. However, it is useful to have the capability to create images with known (because simulated) source properties (e.g., faint sources with a variety of known magnitudes) to properly assess detection thresholds.

Inputs:

- A. Observation parameters, the same as fed to PassPredict
- B. Base image (e.g., from archive for desired telescope)
- C. List of additional sources to simulate with a point spread function and/or thumbnail image

Output:

1. Simulated image (no trails, but with added test sources)

Existing software:

- Skymaker, from the Astromatic package (the software for the Canada France Hawai'i Telescope's MegaCam; also the same team as SExtractor, SCamp etc.)
- GalSim (GalSim-developers, 2012) is a very widely used tool in wide-field optical cosmology
- The official simulation suite for the LSST Dark Energy Science Collaboration is DC2. It actually uses GalSim under the hood. (LSST Dark Energy Science Collaboration, 2021)

GalSim is an open-source software library to perform image simulations. It can be used either through its python interface, or as an executable, configurable through YAML files. Most of the computation-heavy parts of the code are written in C++ for performance. In its simplest configuration, GalSim uses simple

parametric models for both galaxies (e.g., Sersic, exponential) and point spread functions (e.g., Moffat). The former can also be generated from real Hubble Space Telescope images (provided the instrument for which images are to be simulated has a larger point spread function). The latter can be created as the convolution of an optical and an atmospheric point spread function. The optical part can be simulated if the user provides a set of instrument related parameters. Alternatively, an external calibration image of the point spread function can be used. The positions and parameters of the objects to be simulated can be read from a catalog. Several options also exist for noise, detector effects and WCS. The simulated image outputs are usually stored in FITS files. At present, it does not handle simulation of several image artefacts, including trails due to satellites.

3.3.3 TrailSimulate

To assess impacts of satellite trails on science, we need to create simulated images with specific trail properties. This tool will require detailed (probably instrument-dependent, plugin) models of the appearance of trails and related instrumental effects.

A first mode of the tool would be driven by a specific satellite pass prediction.

A second mode might be to give the code a trail occurrence distribution as a function of brightness (e.g., 10 trails per square degree per hour uniformly distributed between magnitudes 4 and 6) rather than a PassPredict output. We will refer to this as the “rate input mode”.

Inputs:

- A. Transit list from PassPredict run on output from EphemSimulate or (rate input mode) rate of trails as a function of brightness
- B. Observation parameters, the same as fed to PassPredict
- C. Simulated image without trails
 - a. Must be consistent with B.
- D. Model (code) for generating trails including CCD and optical side effects

Outputs:

- 1. Simulated image with trails
- 2. Fraction of image pixels affected (including by side effects)

Existing software. We are not aware of any existing software that would address this issue.

3.3.4 TrailAssess

We need to assess what the scientific impact of trails has been on our images. One way to do this is to take two images of the same field, one unaffected and one affected (either with trails, or still degraded after trail removal). These could be real images (with different epochs), or a pair of simulated images with and without trails. One metric of the effect on science is to detect and parameterize sources in the field, and compare the derived source list and source parameters before and after degrading the image with trails.

Inputs:

- A. Simulated image without trails, output from ImageSimulate
- B. Simulated image with trails, output from TrailSimulate or from TrailMask (with trails removed at some level)
- C. Trail catalog (from TrailMask)

D. Data reduction parameters, to be determined

Outputs:

1. Point source detection list with source parameters for both images
2. Extended source detection list with source parameters for both images
3. Detection efficiency and photometric accuracy for both lists
4. Sensitivity limit for both lists
5. Derived output: percentage degradation in source detection efficiency vs brightness percentage degradation in detection threshold.

3.3.5 Simulation assessment

This is not a software application per se. We are also tasked with aggregating the simulation results generated by the tools described in the preceding subsection. and interpreting them, summarizing them for the community.

We will need to define a set of simulations to cover the relevant parameter spaces and provide sufficient data for an assessment, then actually run the simulations. Then we need to generate summary trend plots and tables versus time of year, observatory location, etc., for different types of observation/science, different telescopes, and for different constellation scenarios. These will allow us to provide recommendations on desired limits on trails and make progress on suggesting corresponding limits on various types of satellite.

4. Implementation Timescale

Specifying an exact timetable for the implementation of the software tools described above lies outside the capabilities of this Working Group, and the conceptual outline of the packages is not yet sufficiently detailed to allow credible planning of implementation timescales. However, the Working Group emphasizes the importance of these tools' being available to the astronomical community on a timescale commensurate with that of the development of the satellite constellations; the tools need to be available before the need for them is so pressing that observations are severely disrupted. Bearing in mind that software development projects frequently take significantly longer than originally expected, the Working Group stresses the urgent need to invest in the development of these tools.

5. Cross-Group Coordination

We will need to continue coordination with the Observations Working Group on the issue of publicly accessible satellite positional information, which is a key input for some of the above software. The Policy Working Group could argue for national policies to support the availability of the needed inputs.

We welcome further input from the Community Engagement Working Group about what stakeholders, if any, will need to access the software beyond the professional and hobbyist observer community, and what implications that has for the interfaces.

6. Conclusions

We summarize our findings in the following conclusions:

1. We re-emphasize SATCON1 recommendations 1 to 3. New tools are critical to partially mitigate the constellation impacts on astronomy. The PassPredict software will allow astronomers to determine which observations may be affected and in conjunction with simulations may allow quantification of the degradation of science data expected in a particular situation. The TrailMask software will allow some science to be salvaged from some affected datasets and reduce the chance of spurious results being published. A large simulation and modeling effort will allow the community to assess impacts of current and future constellations on both ground- and space-based observations and establish recommended constraints on the design of constellations.
2. In the report we have provided a moderately detailed analysis of requirements, interfaces and algorithms that may serve as a starting point for software implementation.
3. Some software already exists to help with parts of these tasks. However, much of it is specialized to particular instruments or situations, and needs to be generalized.
4. There are gaps where no suitable software exists, and a significant software development effort is warranted. Project management, documentation, user support and maintenance will all be important and will require substantial resources and funding. Educational materials (e.g., lesson plans) are also desirable.
5. To support the diverse community of night-sky users, software must be provided in several forms: libraries (integrated with core astronomy interfaces like the Astropy project), applications for data pipelines, web services and planetarium-compatible services.
6. We conclude that there is an urgent need to develop a set of test cases, including example datasets covering a wide range of instrument and satellite-trail properties which can serve as a standard test suite for the development of the software and as benchmark comparisons for both archival and new sources of data.
7. We endorse the SatHub concept developed by the Observations Working Group. SatHub provides a natural home for curated software (and links to external software), satellite catalog and ephemeris access, test data, and documentation. This aspect of SatHub, like the others, will need continuing development, support and maintenance at a professional level.
8. The constellations are being launched now but software takes time to develop. Resources should be made available as soon as possible.
9. If the satellite constellations are deployed as planned we find that no software solution can fully mitigate the impact on astronomical observations. The problems with spectroscopic observations are particularly hard to solve. It is likely that many ground-based observatories around the world will be forced to make a significant investment in hardware such as auxiliary spotting cameras or other solutions to deal with the problem of satellite streaks. However, the effects of satellite constellations on a given observatory will depend on specifics such as aperture, etendue, pixel size, observing strategy, and other factors; for some the impact will be small and mitigations will not be required, while for others the impact will be serious. Each observatory will need to make its own assessment.

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Appendix A: Ephemeris file formats

1.1 File formats

Common ephemeris formats are CCSDS OEM, NASA ITC format, or ILRS CPF. They provide additional information such as the used frame (e.g., EME2000, TEME, ITRF), interpolation method and order, and manoeuvre epochs. ILRS CPF files are used within the satellite laser ranging community for station predictions. Operators of laser ranging stations often prefer the ITRF frame to simplify the computation (as there is no need for any frame conversions).

1.1.1 Example CCSDS OEM

File extracted from the standard.

```
CCSDS_OEM_VERSION = 2.0
CREATION_DATE = 1996-11-04T17:22:31
ORIGINATOR = NASA/JPL

META_START OBJECT_NAME = MARS GLOBAL SURVEYOR
OBJECT_ID = 1996-062A
CENTER_NAME = MARS BARYCENTER
REF_FRAME = EME2000
TIME_SYSTEM = UTC
START_TIME = 1996-12-28T21:29:07.267
USEABLE_START_TIME = 1996-12-28T22:00:02.5
USEABLE_STOP_TIME = 1996-12-30T01:18:02.5
STOP_TIME = 1996-12-30T01:28:02.267
INTERPOLATION = HERMITE
INTERPOLATION_DEGREE = 7
META_STOP

1996-12-28T21:29:07.267 -2432.166 -063.042 1742.754 7.33702 -3.495867 -1.041945
1996-12-28T21:59:02.267 -2445.234 -878.141 1873.073 1.86043 -3.421256 -0.996366
1996-12-28T22:00:02.267 -2458.079 -683.858 2007.684 6.36786 -3.339563 -0.946654
...
1996-12-30T01:28:02.267 2164.375 1115.811 -688.131 -3.53328 -2.88452 0.88535

COVARIANCE_START

EPOCH = 1996-12-28T21:29:07.267
COV_REF_FRAME = EME2000
3.3313494e-04
4.6189273e-04 6.7824216e-04
-3.0700878e-04 -4.2212341e-04 3.2319319e-04
-3.3493650e-07 -4.6860842e-07 2.4849495e-07 4.2960228e-10
-2.2118325e-07 -2.8641868e-07 1.7980986e-07 2.6088992e-10 1.7675147e-10
-3.0413460e-07 -4.9894969e-07 3.5403109e-07 1.8692631e-10 1.0088625e-10 6.2244443e-10

EPOCH = 1996-12-29T21:00:00.000
COV_REF_FRAME = EME2000
3.4424505e-04
4.5078162e-04 6.8935327e-04
-3.0600067e-04 -4.1101230e-04 3.3420420e-04
-3.2382549e-07 -4.5750731e-07 2.3738384e-07 4.3071339e-10
-2.1007214e-07 -2.7530757e-07 1.6870875e-07 2.5077881e-10 1.8786258e-10
-3.0302350e-07 -4.8783858e-07 3.4302008e-07 1.7581520e-10 1.0077514e-10 6.2244443e-10

...

COVARIANCE_STOP
```

1.1.2 Example CPF

File extracted from the format description.

```
H1 CPF 1 AIU 2005 11 16 4 8201 gps35
H2 9305401 3535 22779 2005 11 15 23 59 47 2005 11 20 23 29 47 900 1 1 0 0 0
H9
10 0 53689 86387.000000 0 -13785362.868 -12150743.695 19043830.747
10 0 53690 887.000000 0 -13656536.158 -14288496.731 17628980.237
10 0 53690 1787.000000 0 -13618594.073 -16250413.260 15908160.431
10 0 53690 2687.000000 0 -13647177.924 -18001187.561 13911910.138
10 0 53690 3587.000000 0 -13712868.344 -19511986.614 11675401.577
10 0 53690 4487.000000 0 -13782475.931 -20761369.576 9237779.852
...
99
```

1.1.3 Example NASA Modified ITC Ephemeris format

Dummy file content.

```
created:2021-01-01 01:00:00 UTC
ephemeris_start:2021-01-01 02:00:00 UTC ephemeris_stop:2021-05-03 02:00:00 UTC step_size:60
ephemeris_source:blend
UNW
202100102000.000 -5000.000000000 1000.000000000 3000.000000000 1.500000000 -5.000000000 4.000000000
1.000000000e-01 -1.000000000e-02 1.000000000e-03 -1.000000000e-04 -1.000000000e-05 1.000000000e-06 1.000000000e-06
-1.000000000e-07 1.000000000e-08 1.000000000e-09 -1.000000000e-10 1.000000000e-11 -1.000000000e-12 -1.000000000e-13
1.000000000e-14 -1.000000000e-15 1.000000000e-16 1.000000000e-17 1.000000000e-18 -1.000000000e-19 1.000000000e-20
2021001020100.000 -5200.000000000 700.000000000 3200.000000000 1.700000000 -5.300000000 4.200000000
1.000000000e-01 -1.000000000e-02 1.000000000e-03 -1.000000000e-04 -1.000000000e-05 1.000000000e-06 1.000000000e-06
-1.000000000e-07 1.000000000e-08 1.000000000e-09 -1.000000000e-10 1.000000000e-11 -1.000000000e-12 -1.000000000e-13
1.000000000e-14 -1.000000000e-15 1.000000000e-16 1.000000000e-17 1.000000000e-18 -1.000000000e-19 1.000000000e-20
...
```


Appendix B: Glossary of Abbreviations

Abbrev.	Full Title	Type	URL for further information
18SPCS	18th Space Control Squadron, US Space Force	Organization	https://en.wikipedia.org/wiki/18th_Space_Control_Squadron
ADM	-	Satellite data format	
API	Applications Programming Interface	Software term	
BRDF	Bidirectional Reflectance Distribution Function	Optics term	
CADC	Canadian Astronomy Data Center	Organization	https://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/en/
CCD	Charge coupled device	Astronomical detector	
CCSDS		Orbit data format	https://public.ccsds.org
CPF	-	Orbit data format	https://ilrs.gsfc.nasa.gov/data_and_products/formats/cpf.html
CNN	Convolutional Neural Network	Algorithm	https://en.wikipedia.org/wiki/Convolutional_neural_network
EME2000	Earth Mean Equator 2000	Coordinate System	https://en.wikipedia.org/wiki/Earth-centered_inertial
ESA	European Space Agency	Organization	https://esa.org
FOV	Field of view	Astronomy term	
FTE	Full Time Equivalent	Management term	https://en.wikipedia.org/wiki/Full-time_equivalent
GEO	Geosynchronous Earth Orbit	Orbit category	https://en.wikipedia.org/wiki/Geostationary_orbit
GNSS	Global Navigation Satellite System	Navigation term	
GP	General Perturbations	Orbit theory	
GPU	Graphics Processing Unit	Computer hardware	https://en.wikipedia.org/wiki/Graphics_processing_unit

ICRS	International Celestial Reference System	Coordinate system	https://en.wikipedia.org/wiki/International_Celestial_Reference_System_and_Frame
IFU	Integral Field Unit	Astronomical detector	https://en.wikipedia.org/wiki/Integral_field_spectrograph
ILRS	International Laser Ranging Service	Organization	
ITC	International Telecommunications Corporation	Orbit data format	https://platform.leolabs.space/documentation/ephemerides_file_formats
ITRF	International Terrestrial Reference Frame	Coordinate system	
IVOA	International Virtual Observatory Alliance	Organization	https://ivoa.net
JPL	Jet Propulsion Laboratory	Organization	https://www.jpl.nasa.gov/
JSON	-	Software protocol	https://www.json.org
LEO	Low Earth Orbit	Orbit category	https://en.wikipedia.org/wiki/Low_Earth_orbit
LSST	Legacy Survey of Space and Time	Astronomical survey	https://www.lsst.org
MEO	Medium Earth Orbit	Orbit category	https://en.wikipedia.org/wiki/Medium_Earth_orbit
NASA	National Aeronautics and Space Administration	Organization	https://nasa.gov
OEM	Orbit Ephemeris Message	Orbit data format	
pyVO	-	Software protocol	https://pyvo.readthedocs.io
S/N	Signal-to-noise	Data analysis	
SKKP	Tsentr Kontroly'a Kosmicheskya Prostranstva	Organization	https://en.wikipedia.org/wiki/Main_Centre_for_Reconnaissance_of_Situation_in_Space
SP	Special Perturbations	Orbit theory	
TAP	Table Access Protocol	Software protocol	https://www.ivoa.net/documents/TAP/
TEME	True Equator Mean Equinox	Coordinate System	https://docs.astropy.org/en/stable/api/astropy.coordinates.builtin_frames.TEME.html

TLE	Two Line Elements	Orbit data format	
WCS	World Coordinate System	Software protocol	https://www.atnf.csiro.au/people/mcalabre/WCS/
WGS84	World Geodetic System 1984	Geodetic frame	https://gisgeography.com/wgs84-world-geodetic-system/
WWT	World Wide Telescope	Web application	https://worldwidetelescope.org/webclient/
YAML	-	Software language	https://yaml.org

SATCON2 Community Engagement Working Group

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1. Summary and Overview

This report is part of a collection of Working Group Reports from the [SATCON2](#) Conference.

1.1 Charge

The SATCON2 Community Engagement Working Group aimed to engage a broad and diverse swath of stakeholders in dark skies and near-Earth space who are impacted by large mega-constellations of tens of thousands of low-Earth orbit (LEO) satellites, beyond professional astronomy alone. The working group consisted of 22 members across 23 time zones including professional and amateur astronomers, members of sovereign Indigenous/First Nations communities, dark-sky advocates, planetarium professionals, and environmental/ecological non-governmental organizations. We set out to work together towards a new and effective conceptual, ethical, legal, and regulatory framework for the protection and sustainability of space and the night sky as a global cultural, natural and scientific commons. Community Engagement Working Group members invested thousands of volunteer hours in working group meetings, listening sessions with impacted constituencies, numerous conversations, developing, conducting and analyzing surveys, and finalizing our results and recommendations.

1.2 Constituencies

For SATCON2, the Community Engagement Working Group focused on five specific constituencies that had not previously been explicitly included in SATCON1 or other policy discussions about satellite constellations, including some groups traditionally excluded from political and economic power:

1. Astrophotography and Astro-Tourism
2. Amateur Astronomy
3. Indigenous Communities and Perspectives
4. Planetariums
5. Environmental and Ecological Concerns

They shared their feedback, needs and recommendations during listening sessions and conversations before the workshop and during dedicated sessions at the workshop.

We acknowledge that there remain many constituencies and perspectives not included in the Community Engagement Working Group that may prove important players in future negotiation and policy-making, such as telecommunication companies, space contractors, economic development groups, ground-based internet equipment suppliers, and Internet service providers.

The largest group not included explicitly in the Community Engagement Working Group is the population of humans world-wide who admire, cherish, view, connect with, seek solace from, practice traditional religion and culture with, navigate by, are inspired by, and need the stars, the Milky Way, and unpolluted night skies. Our principles and recommendations include them implicitly, and we call for explicit consideration of the rights of humanity to see the stars in all future space activities including satellite constellations.

We emphasize that these reports represent the needs and perspectives of individuals, specific communities, and those who were able to offer feedback and participate. Our compiled report does not

speak for all members of any constituency, or all examples of a group, e.g., all Native American tribal communities or all environmental groups.

Last, we honor all the voices and communities who offered their time and feedback for the months leading up to the SATCON2 workshop and this report. This included many who have been historically marginalized and are overloaded by disproportionate fallout from climate change and the pandemic. We are grateful for their uncompensated labor in a time of loss, crisis fatigue, and global pain, in which we are quickly approaching our and our planet's ability to cope — much like overcrowded low-Earth orbits.

1.3 Background and Context

In early 2020 much of work and life as we knew it ground to a halt with the arrival of the COVID-19 pandemic on the global stage. But one activity continued unceasingly at pre-pandemic levels: the relentless launch of satellite constellations by private operators, while the world was roiled by climate change, economic collapse, racial injustice and of course, the still ongoing pandemic.

The 18 months leading up to SATCON2 revealed widening inequalities among all these factors, including the dire need for affordable accessible broadband for all as education, work and much of daily life went online. Globally available cheap broadband is the main promise and potential from companies such as Starlink, OneWeb and others. It remains to be seen whether this promise is fulfilled, but in the process we stand to clutter LEO orbits with hazardous space debris, blind our ground-based telescopes to the cosmos, imperil life and well-being with falling rocket bodies and increasing greenhouse gas emissions — and lose dark skies for all of humanity and all flora and fauna over the next few years. The impacts will likely affect a broad swath of constituencies across humanity, beyond professional astronomy alone. By invoking the democratization of space, the commons of space itself — as enshrined in the Outer Space Treaty of 1967 (OST) — continues to be claimed piecemeal by corporations in a longstanding pattern of unchallenged, unregulated “progress” on our collective behalf. We are reminded of this through regular headlines on space billboards and space tourism; the SATCON2 workshop week in mid-July was itself bracketed by the brief space adventures of Richard Branson, Jeff Bezos and their crews. Some working group members contrasted that billionaire space race with the two-week Red Road to DC¹, which began during the SATCON2 workshop week, and involved the journey of a 25-foot Native American totem pole through sacred Indigenous lands from Washington state to Washington DC, highlighting historical and continuing exclusion and erasure of marginalized communities and culture.

We view this report as the beginning, rather than the end, of a conversation that is long overdue. We urge active ongoing engagement among federal agencies, private and state actors in space, professional societies and especially organizations and communities representing the diversity of stakeholders in our shared skies, so we can co-create a new, ethical, sustainable approach to space exploration rather than the current regulatory maze of siloed concerns enabling business as usual.

1.4 Common Themes and Principles

We identified common themes that recurred and resonated across the Community Engagement Working Group's five subgroups. Collectively, the Community Engagement Working Group offers the following observations and principles:

1. The skies and space belong to everyone. Space is a global commons.

¹ <https://redroadtodc.org/>

2. All people are impacted by changes in the sky. Nearly all consulted for SATCON2 had already noticed a dramatic rise in satellite constellation sightings in the past two years, and were worried.
3. Many communities see the unchecked actions of space actors as colonization expanded to a cosmic scale during a time of global crisis.
4. The sky must be considered part of the environment and the current National Environmental Policy Act (NEPA) exemption for the satellite constellation industry must end.
5. Ecosystems depend on the night sky and on each other.

1.5 Recommendations

The Community Engagement Working Group offers the following nine recommendations to decision-makers, regulators, the satellite industry, researchers, and all communities affected by satellite constellations.

1. Duty to consult

Satellite operators must first consult all impacted groups, including the sovereign American Indian / Alaska Native nations and global Indigenous communities, before launching satellites. Industry must fully consider the concerns of Indigenous nations, including sovereignty, transparency, written agreements, and jurisdiction of treaties in space. Space belongs to us all and we need to listen to all constituencies impacted by satellite constellations. The OST establishes space as a global commons, and the American Astronomical Society (AAS) mission statement emphasizes inclusivity, sustainability, and the importance of humanity's understanding of the Universe.

2. Need for more information and communication

Communities want more information and dialogue. Astronomers and other parties concerned about the impacts of LEO satellite constellations need to engage, listen, share, and act with affected constituencies, government agencies, and cultural, grassroots, and political leaders. Decision-makers and private satellite operators must intentionally invite the voices and groups that have historically been excluded from the power structure and decision-making regarding space activity. Involving youth is a key aspect to co-creating solutions together to protect the Earth and skies that they will inherit.

3. Engage with industry

Astronomers and other interested and affected groups need to continue to engage with the satellite industry to build relationships and find common ground. The Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference proposed by the International Astronomical Union (IAU) is one possible venue for such engagement.

4. Recognize and rebalance power structures

Decision-makers and advocates for the regulation of LEO satellites should recognize the economic, legal, and political structures that continually affect technology choices. The regulatory process must take those power structures into account to optimize societal and environmental benefit with equity — power over a global commons comes with responsibilities to the global good. The social systems of economic and technological opportunities that enable satellite constellations focus on technological solutions; but there is only so much back-correcting that software can do to remove satellite streaks in images, or that engaging affected communities in dialogue, reports, and conferences can do to make amends once

irreparable damage is done to the sky and to communities — just as removing plastics from the ocean is proving an impossible task. We urge the broad inclusion of all affected communities in meaningful dialogue from the start.

At the same time, there has been an enormous amount of volunteer labor from mainstream astronomy, communities and institutions devoted to addressing the challenges posed by satellite constellations. Funding for training and FTEs from agencies and industry is needed for continued efforts in the future.

5. Learn from the past

History offers valuable lessons on many issues of concern with satellite constellations, including environmental concerns, loss of millennia-old practices, and the painful legacies of colonization. The past century in particular offers ample examples of disruptive technologies that have been developed first and regulated only later, with varying degrees of cost, benefit, risk, and impact, e.g., telephones, trains/planes/cars, fossil fuels, and the Internet itself. Examples of global challenges requiring international collaboration include damage to the ozone layer, for which corrective action has been largely successful, and climate change, for which a global course of corrective action has remained elusive. We must learn from those examples as we grapple with the satellite constellation challenge.

6. “Science vs. Internet” is a false choice

Affordable broadband is crucial to almost all aspects of 21st century work and life, and some communities welcome satellite broadband. However, we must not assume that LEO satellite constellations are the only option, or that sacrificing the night sky is an acceptable trade-off. Industry and government agencies must develop a meaningful assessment of viable alternatives to satellite broadband, including ground-based fiber, from the aspects of cost, infrastructure and environmental impact. Satellite operator business models may not accurately assess the profitability of satellite constellation broadband Internet and its affordability for low-income users; in Mexico, Starlink currently charges roughly four times more than ground-based broadband, and one recent study found only a small overlap between global populations that need broadband and those that can afford to pay market rates for it. Costs of satellite constellations that are put on society — such as coping with space debris after satellite collisions or bankruptcies and environmental costs from launches, operations, and deorbiting — should be fully considered in the true cost of satellite constellations, rather than left as externalities.

7. Better international regulation and globally coordinated oversight/enforcement

We need coordinated international regulation of the satellite constellation industry with oversight and enforcement, in contrast to the current regulatory maze of siloed issues enabling business as usual. Most of the constituencies polled by the Community Engagement Working Group want industry to slow down until meaningful solutions can be developed in consensus, involving youth and communities. The fallout from unregulated unchecked satellite constellation launches includes dramatic predicted increases in all of the following: space debris, radio frequency interference, orbital traffic and collisions, environmental fallout in the upper atmosphere or oceans after satellite decommissioning, and global sky brightness (not just individual satellite streaks) washing out fainter stars or meteors, and undermining dedicated dark sky parks and preserves.

8. Slow or stop satellite constellation launches until problems are resolved

We strongly urge that the pace of launches be slowed or stopped until the issues can be much more fully understood and meaningful solutions to proven and likely problems can be developed in consensus. All the constituencies we polled and consulted are already noticing a dramatic rise in the number of satellites seen, when the number of satellites in orbit is currently only 5–10% of what is planned to be launched in the next decade. We need to plan for and mitigate both the known impacts of satellite constellations and a broad array of unintended consequences from them for many human endeavors.

9. Continued active engagement and conversation

The Community Engagement Working Group views the SATCON2 workshop as the beginning, rather than the end, of a long overdue conversation that was prompted by satellite constellations, but that extends to far broader issues of preserving space and the night sky as a scientific, environmental and cultural commons for humanity. The Community Engagement Working Group urges active engagement and long-term relationship-building among industry, leadership, all space actors and communities representing the diversity of stakeholders in our shared skies so we can co-create an inclusive, ethical, and sustainable approach to space.

1.6 Subgroup reports

The reports from our five constituencies follow this overview. We emphasize that these reports represent the needs and perspectives of individuals, specific communities, and those who were able to offer feedback and participate. Our compiled report does not speak for all members of any constituency, or all examples of a group, e.g., all Native American tribal communities or all environmental groups. We acknowledge that we ran out of time and resources to include many perspectives at the workshop and in this report and that they still need to be honored, including the role of aesthetics, culture, heritage, art, storytelling, and humanity in our connection to the skies. There are other issues that we could do only peripheral justice to, including rural economic development, an assessment of alternatives to satellite broadband, the digital divide etc. Rather than being a comprehensive or conclusive document, this report shares early findings as we begin a long-term process of building relationships and listening to communities' needs and perspectives on the impact of LEO satellite mega-constellations, co-creating new ways for how we collectively approach space in the coming years.

2. Astrophotography, Astrotourism and Broader Implications of a Global Rise in Night Sky Brightness

The primary authors of this section and subgroup members are:

John Barentine (International Dark-Sky Association and Dark Sky Consulting, LLC)

Ruskin Hartley (International Dark-Sky Association)

Jessica Heim (University of Wales Trinity St. David and Consortium for Dark Sky Studies)

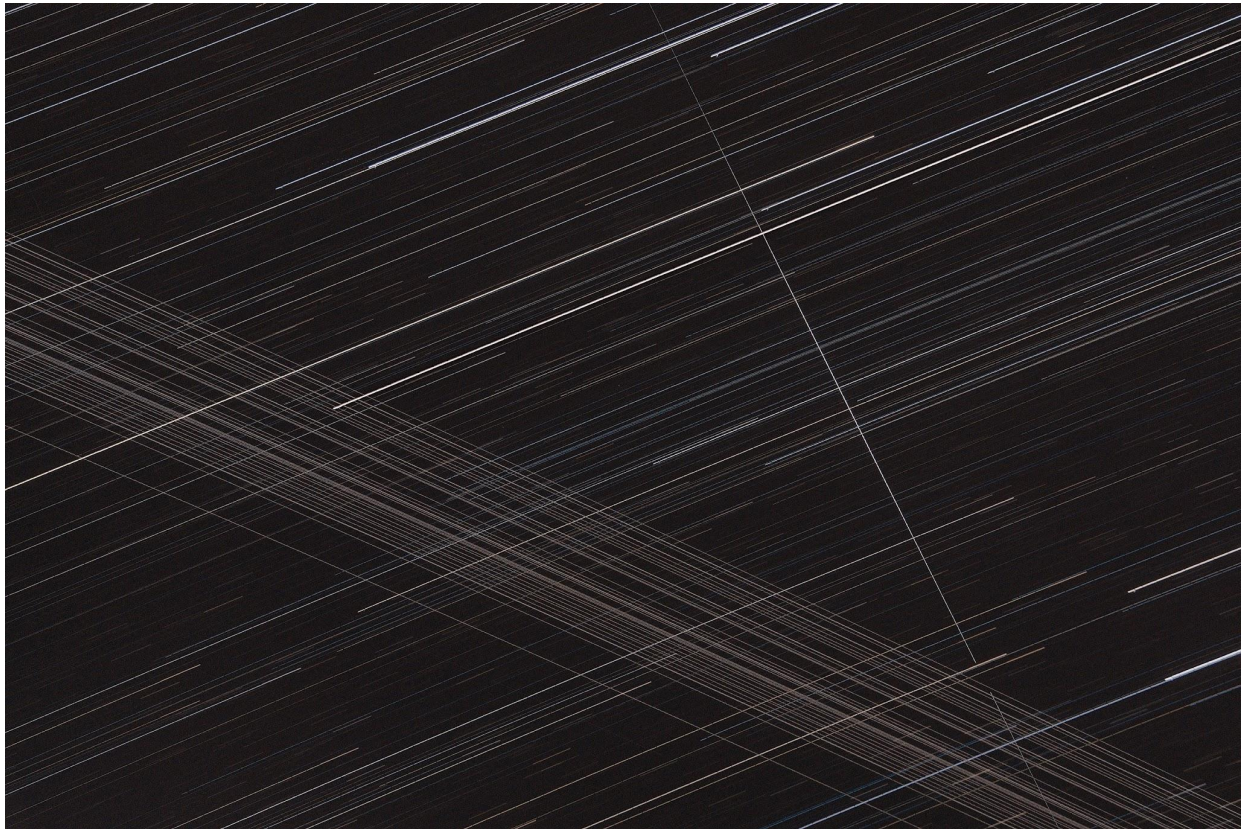


Figure 1. 39 Starlink satellites from Flight 10 appear as trails (upper left to lower right) across this 87-second photograph of the night sky made on 11 August 2020. The more vertical line at right is a trail from a Chinese Long March 2C rocket body. Image by Martin Bernardi, licensed under CC BY-SA 4.0.

2.1 Astrophotographers

Members of the astrophotography community were on the front line when the subject of satellite mega-constellations first entered the global public consciousness after the initial SpaceX Starlink launch in May 2019. Before the first group of 60 Starlink objects was raised to its final, 550-km station and the satellites were still flying in close proximity, their tendency to leave multiple parallel streaks in astrophotos (e.g. Fig. 1) was exploited by world media to suggest that Starlink represented a serious or even

existential threat to ground-based astronomy.² Later it was revealed that not even space-based astrophotography was immune to the threat, as it was found that the Hubble Space Telescope, orbiting below on-station Starlink objects, experienced the same satellite trails in its images.³

In SATCON1, we explored the potential for large satellite constellations to yield negative impacts on astronomical images ranging from wide-field “nightscapes” to deep imaging through telescopes to casual astrophotography employing the cameras built into mobile devices.⁴ Using the best information available at the time in terms of the expected number and brightness of objects planned for launch in the 2020s, we rated their impacts to various modes of astrophotography from “negligible” to “fatal”. In the latter case, the expected victim was nightscape photography, which we expected to “*suffer the same problem as high- $A\Omega$ telescopes, albeit with considerably smaller apertures.*” Assuming the fully built SpaceX Starlink and OneWeb constellations, simulations suggested an average of two satellite trails per square degree would appear in every 60-second exposure taken near the horizon. From this we concluded that “*we do not see how wide-field astrophotography can be performed to current standards with the projected density and brightness of the steady-state configurations of the Starlink2 and OneWeb constellations.*”

For SATCON2, we contacted both amateur and professional astrophotographers to obtain information on their attitudes toward large satellite constellations. We took a cue from the online-survey approach of the Community Engagement Working Group’s subgroup aimed at soliciting opinions from the amateur astronomy community. However, our survey⁵ was marketed differently from the survey to broadly defined “amateur astronomers”. While there certainly is some overlap between the groups, the astrophotography survey was aimed mainly at individuals who are less likely to identify as amateur astronomers and more as landscape photographers for whom the night sky is another backdrop. Consequently there were more responses from “nightscape” photographers than from those who engaged in planetary or deep-sky astrophotography, usually with the aid of telescopes.

The survey was distributed through our professional networks and social media. We received 21 responses. First we asked about geographic location. As expected, the respondents were overwhelmingly from North America (43%) and Europe (37%). The vast majority of respondents (81%) described their work as “amateur/hobbyist”, which we take to mean they identified their work to be recreational in nature rather than professional/other work. Other roles mentioned included (semi-)professional photographer (33%) and “citizen scientist” (24%); we note that respondents could choose more than one option. About an equal number of participants said they took wide-field/landscape astrophotographs (76%) as compared to those who used long-focus lenses or telescopes to take deep-sky (71%) or planetary astrophotographs (57%). Far fewer engaged in speciality astrophotography, such as imaging asteroids (5%).

² For examples of media stories illustrated by such images, see “Astronomy group calls for urgent action on SpaceX Starlink satellites”, New Scientist, 3 June 2019 (<https://www.newscientist.com/article/2205172-astronomy-group-calls-for-urgent-action-on-spacex-starlink-satellites/>); Satellite constellations: Astronomers warn of threat to view of Universe, BBC, 27 December 2019 (<https://www.bbc.com/news/science-environment-50870117>); and Latest Starlink Plans Unveiled By Elon Musk And SpaceX Could Create An Astronomical Emergency, Forbes, 11 December 2019 (<https://www.forbes.com/sites/startswithabang/2019/12/11/elon-musk-spacex-unveil-latest-starlink-plans-creating-an-astronomical-emergency/?sh=3e0755c1287e>)

³ A proliferation of space junk is blocking our view of the cosmos, research shows, Washington Post, 27 April 2021 (<https://www.washingtonpost.com/business/2021/04/27/starlink-light-pollution/>). The original Hubble image shown in the story can be found in the Space Telescope Archive at <https://archive.stsci.edu/cgi-bin/mastpreview?mission=hst&dataid=IEDK12A0Q>.

⁴ Barentine, J. (2020) *Concerns of the non-professional astronomy community and adjacent night-sky stakeholders*, appendices to *Impact of Satellite Constellations on Optical Astronomy and Recommendations Toward Mitigations*, NOIRLab Technical Document 004 (<https://noirlab.edu/public/products/techdocs/techdoc004/>), pp. 106-108.

⁵ Available on <https://forms.gle/ZEMDNzHY3uoC1F2J9>

The overwhelming majority of survey participants (90%) rated the impacts of moving objects on their work as "moderate", "significant" or "severe". Less than 10% said the impacts were "zero" or "minimal". As expected, astrophotographers identified wide-field images of various targets as being most prone to the consequences of moving objects; over half cited subjects such as star trails, constellations and panoramas as examples. Of these, nightscapes featuring the Milky Way were mentioned most often, by three-quarters of participants.

It is not at all surprising — although perhaps the result of selection bias and a small sample size — that 100% of survey respondents described the impacts of satellites and other moving objects on their astrophotography as "more" than they were five years ago. It is reasonable to conclude that this is mainly the result of the launch of ~ 1800 SpaceX Starlink objects in the interim, which constitute nearly all of the larger, and brighter, objects launched into near-Earth space in the same period.

We asked those who said they felt the impact was more in recent years (i.e., 100% of respondents) to estimate the increase as a percentage over the baseline conditions of five years ago. We were surprised at the diversity of responses to this question, which was deliberately phrased as a free response rather than pre-established ranges of numbers. A small majority (61%) of respondents estimated the impact as +50% in the past five years, which turns out to be in rough proportion to the increase in the number of bright objects in near-Earth space in the same time period. With fewer responses each, other suggestions ranged from +5% to +200%.

Next we asked respondents to rate the significance of the impacts of satellites and moving objects in terms of the burden their presence in images imposed on astrophotographers needing to remove them from their images in post-processing. About 95% of respondents indicated that some burden or disadvantage is imposed on their work by satellites and other moving objects in the night sky. Of these, a clear majority (76%) labeled the burden "moderate" to "significant". Curiously, none rated the burden as "severe", a label we defined as a condition in which moving objects essentially made their astrophotography work impossible.

We also asked astrophotographers to speculate on the future. We did not presume that survey respondents had any detailed knowledge of satellites, and we gave them very little information so as to attempt to not bias the results. In order to ask them about the potential for changes in impacts in the future, we provided them with relative numbers of existing functional satellites before the first Starlink launch and a total for the number of Starlink objects launched to date. A significant majority (86%) of respondents said that they felt there was an approaching threshold in terms of the number of bright objects orbiting the Earth at which their astrophotography would suffer irreparable harm. None of the respondents indicated they did not think such a threshold existed, but a few (14%) admitted that they did not know. For those who answered "yes" to the previous question, we asked them if they cared to venture a guess as to the size of the number. Responses to this question varied wildly, suggesting that the answers are no more than speculations. One respondent simply wrote that it was "very difficult to estimate".

The last substantive question was free-response: "Please provide any comments/suggestions you have regarding large satellite constellations, including additional information you would like to receive, ideas for mitigating effects, etc." We received six responses, reproduced here in their entirety:

Ban them !!!!!!!!!!!!!!!!!!!!!!! Space could be for exploration and not for commercial use.

They are unneeded. In the 90s the Iridium needed less than 100 satellites to cover the world. Now there are 10s of thousands needed? Looks like the technology in 30 years went backwards.

The industry is unsustainable for many reasons.

Governments should impose a moratorium on all mega-constellations and negotiate an international framework to better regulate low orbit. It's a shambles and shouldn't be allowed to happen.

There has been an interesting discussion about aluminium oxide from burned satellites and their impact on the earth's albedo and thus global climate. We will be deploying tons of it in the atmosphere in the coming years. This should be a) regulated and b) part of the overall bill (counter /compensating measures). We also need a broader discussion in the general public about this side effect.

Every satellite needs a deorbit system. Also more analysts on the benefit to risk of having them.

From the survey responses, and in consideration of the small sample size and potential for selection bias, we conclude the following:

- Like amateur astronomers, astrophotographers report impacts to their work imposed by large satellite constellations, namely Starlink.
- Many astrophotographers see a future in which the number of relatively bright objects orbiting Earth will affect their work to the point that it simply cannot be done effectively anymore.
- They seem frustrated by the status quo, and several indicated clearly that they preferred a moratorium on launches or other steps to be taken to limit the number of objects in orbit.
- While we can't say how representative these views are of all astrophotographers, the results largely mirror the privately expressed opinions of many astrophotographers related to us as anecdotes about impacts on their work.

2.2 Astrotourism professionals

Astrotourism, broadly defined, is a form of sustainable tourism that engages clients in activities related to stargazing and astronomy, including terrestrial night-sky phenomena such as aurora watching. Usually classified alongside other forms of “ecotourism” or “green tourism”, astrotourism has as its object the resource of the night sky, and it is usually pursued in places with relatively little light pollution. It offers participants content outside the realm of more traditional, destination-based tourism and fuses elements of outdoor/adventure tourism with resort and amenity activities.

There is little to date in the tourism and hospitality literature studying astrotourism, but limited evidence suggests great growth and revenue potential.⁶ It is hypothesized that astrotourism can drive rural economic development, especially in economically depressed regions where former industries have departed as a result of globalization, natural resource exhaustion and other influences. The astrotourism field itself remains nascent despite growing public interest; as an indicator, no professional organization of astrotourism operators has yet emerged. It is not known how many people in the world are employed in

⁶ For recent case studies, see, e.g., Mitchell, D., & Gallaway, T. (2019). *Dark sky tourism: economic impacts on the Colorado Plateau Economy, USA*. *Tourism Review*, 74(4), 930–942. <https://doi.org/10.1108/tr-10-2018-0146> and Rodrigues, A. L. O., Rodrigues, A. & Peroff, D. M. (2014). *The Sky and Sustainable Tourism Development: A Case Study of a Dark Sky Reserve Implementation in Alqueva*. *International Journal of Tourism Research*, 17(3), 292. <https://doi.org/10.1002/jtr.1987>.

astrotourism, but anecdotally we understand this number to be far fewer than those who engage in amateur astronomy or astrophotography as avocations.

In order to solicit opinions about the impacts of large satellite constellations on the work of astrotourism professionals, we contacted individuals in our professional networks with whom we have had previous communications about their work. For this report, we conducted interviews with five people, all of whom agreed to be identified by name and affiliation:

- Roy Alexander ([AstroVentures CIC](#) and [Battlesteads Dark Sky Observatory](#), UK)
- Etta Danemann ([Visit Dark Skies](#), Germany)
- Sabine Frank ([Verein Sternenpark Rhön e.V.](#), Germany)
- Catherine Johns ([Kielder Observatory](#), UK)
- Samuel Singer ([Wyoming Stargazing](#), US)

In their respective roles, their work ranges from those who provide nighttime star tours on a freelance basis to those who operate small private observatories open to the public. The respondents have work experience in astrotourism ranging from eight to 15 years. They work in astrotourism on a part-time or full-time basis, showing that while for some it has become their primary means of earning a living, others are working in this space in a way that supplements their income or engages their interests beyond their main paid jobs. While some own astrotourism businesses that employ other people, others are either sole proprietors or work essentially as freelancers. Business owners employ between two and 12 individuals on a full-time basis, and have help from others who are employed part-time, are self-employed, or serve in a volunteer capacity.

The respondents offer a wide array of astrotourism products and services to their clients. Most provide some kind of in-person "star tours," telescope viewing, or comparable kinds of programming. Some mentioned more specific activities like astrophotography, light pollution education and aurora watching. However, not all astrotourism follows this model. For instance, Danemann's company markets an "audio experience" to parks and similar places for self-guided stargazing adventures. Johns reports that Kielder Observatory is branching into this space as well, offering "immersive and digital" experiences in addition to its usual educational activities. The respondents reported a wide range of visitor/guest totals each year, ranging from 2500 to 25,000 before the COVID-19 pandemic began.

We asked whether the appearance of satellites in the night sky affects the respondents' work in astrotourism, and if so, what the significance of the effect is now. The respondents mostly reported no effect at all, or a net-positive effect in terms of engaging the curiosity of guests. One (Singer) specifically noted that satellites "frequently interfere" with his company's astrophotography offerings.

Of the respondents who are field practitioners of astrotourism, all noted that the appearance of satellites in the night sky has increased in recent years; two rated the status quo as "much more" than in the past. Frank summarized the effect on visual observations of the night sky: *"It's simply the multitude of satellites moving across the sky at different speeds that change the view and also distract the participants, especially since the brightness is often as great as that of stars."* Alexander compared the situation to the past, in which *"apart from the ISS, spotting satellites would need an app and you'd have to be sharp-eyed to spot them. Now they're all over the place"* (e.g., Fig. 2)

We then asked whether the respondents were aware of their guests'/clients' attitudes toward satellites. All suggested that guests or users of their products are curious about satellite constellations like Starlink and some enjoy seeing them. *"Guests tend to be excited to see satellites,"* Alexander wrote. *"The ISS and Starlink in particular put on a good show, and on dark sky nights there's normally a couple of guests who*

end up informally competing to see who can count the most.” Despite presenting a nuisance to the astrophotographers among his guests, Singer noted “they are a welcomed added attraction to the stargazing programs. Guests are excited to see them.”

Often it seems that astrotourism experiences are when these people for the first time pause to consider the implications of such large numbers of objects orbiting Earth. This suggests that astrotourism may be a route to increasing the overall public awareness of the issue of the sustainable use of outer space. Alexander described engaging with guests on the topic of satellites: *“Everyone tends to feel that space is getting too cluttered, that there might come a time where the sky is just crawling with sat tracks and most people are unhappy with the way billionaires can just launch whatever they like with impunity.”* Frank described her guests as *“impressed and curious”* with the mega-constellation phenomenon. *“People want to know a lot of information. Especially the Starlink satellites are causing some anxiety and some participants are a bit afraid.”* Johns reported her guests at Kielder Observatory *“love seeing them and it’s an interesting opener to a discussion around the sustainability of space. The Starlink trains are especially spectacular in this regard.”*⁷

We were curious as to whether, compared to the situation now, astrotourism operators envisioned a time in the future when the number of satellites might be sufficiently large as to disrupt or negatively impact their businesses. Responses to this question were mixed, with some suggesting relatively little impact to their business to those who say it may adversely affect specific activities like astrophotography. For Alexander, this time is *“not in the near future”*, but he suspects that *“there will come a time where if the skies are allowed to become more busy, our type of visual and amateur-astrophotography evenings will be negatively impacted by too many visible satellites.”* Singer wrote that while he didn’t think that satellites will impact his visual stargazing programs, he expected that *“they will become more and more of a nuisance with imaging.”* Danemann suggested that the potential of programs like Starlink to bring broadband internet into remote areas where astrotourism often takes place *“might even be positive”* for her business. And Johns raised the possibility of a link between casual attitudes among the public regarding the visual pollution of the night sky represented by satellites and a lack of concern for sources of terrestrial light pollution as they may affect the accessibility of the night sky. *“The clear and present danger is a lack of joined-up thinking around dark skies as an asset beyond astrotourism leading to ill-conceived lighting schemes,”* wrote Johns. She further mentioned that Kielder Observatory is developing a “Dark Skies NE” plan, referring to the northeast of England, to address this concern on a regional basis.

The attitudes of these astrotourism professionals largely mirror those of amateur astronomers, astrophotographers, and general supporters of dark-skies initiatives. They expressed concern for the future accessibility of the night sky, although none specifically cited potential negative effects on their businesses as a reason for concern. Some argued for new regulations, or strengthening of existing regulations, having to do with the use of near-Earth space. Singer wrote that *“more regulations are necessary to prevent abuses of the use of low-earth and mid-earth orbits for satellites,”* while Alexander opined that *“billionaires shouldn’t be able to just launch what the heck they like, when they like, in some kind of space one-upmanship. There needs to be more regulation.”*

Frank pointed out that the increasing commercialization of near-Earth space *“is against the common good”* associated with the accessibility of the natural night sky. Danemann further suggested that the real harm of large numbers of satellites may be in simply redirecting the gaze of viewers from the natural to

⁷ “Starlink trains” refers to the configuration of newly launched Starlink objects that are physically grouped together in their initial parking orbits. At ~ 300 km altitude, they are brighter than the same objects after reaching their 550-km station orbits approximately 90 days later.

the artificial: *“A night sky full of satellites would direct visitor interest to the space close to Earth, thus harming the exposure to the vast Universe with its life-changing eternity aspect.”*

Our limited survey of a few astrotourism professionals in the US and Europe points to something of a double-edged sword in how large satellite constellations affect the nature of their business: while the public is excited to see satellites swarming about overhead, that phenomenon can also detract from the experience of viewing the wonders of a dark night sky. It may motivate some customers while alienating others. Astrotourism professionals seem to be situated along the sidelines of the public debate about the issue of satellite constellations, cautiously observing developments that may influence their businesses for better or worse and whose full ramifications are not yet known.

What is the potential for loss of astrotourism revenue as night skies become brighter? There are no published data on astrotourism potential as a function of night sky conditions, although it seems anecdotally that pristine night skies are not a precondition for running a successful astrotourism enterprise. Accessibility of the resource is an important concern based on the premise that certain tourists are willing to travel across the world and spend significantly to see “pristine” night skies; others would be willing to stay closer to home and spend less on each visit but might choose to visit more often.

At present, we do not have anything even like a heuristic model of astrotourism spending that can suggest how the monetary value of nighttime darkness scales with metrics such as night sky quality. But we raise the alarm that a global rise in night sky brightness from satellites and space debris (collectively, “space objects”) will be akin to a rising tide that lifts all boats. It seems reasonable to expect that such increasing worldwide night sky brightness will tend to diminish the value of *all* “dark-sky” sites, particularly those that are now thought of as pristine such as dedicated dark-sky parks and preserves. This will impact millenia-old human observations of the Milky Way, meteor showers and more, which we elaborate on and attempt to quantify below. This is also yet another way that satellites and space debris will impact Indigenous sky traditions and storytelling, which have had an increasing role in recent years in astrotourism tours and stargazing initiatives at International Dark Sky Parks designated by the International Dark-Sky Association.⁸

2.3 Rising diffuse night sky brightness from satellites and space debris

Concerns raised to date about the impact of large satellite constellations on the night sky have tended to focus on the streaks or trails of light they produce, whether observed visually as discrete, moving points of light or recorded on various electronic detectors. However, we are only beginning to examine the contribution of space objects in elevating the global diffuse brightness of the night sky⁹, much as the collective light of millions of individual stars too faint to detect by the human eye yields the familiar, glowing clouds of the Milky Way. A recently published study estimates that, prior to the first SpaceX launch in 2019, these objects yielded an increase of *“approximately 10 per cent ... over the brightness of the night sky determined by natural sources of light”*, equivalent to a zenith luminance contribution of $20 \mu\text{cd m}^{-2}$. Coincidentally, the IAU and the International Committee on Illumination consider an

⁸ National Parks Are Embracing Indigenous Astronomy, Outside Online, 12 July 2021 (<https://www.outsideonline.com/adventure-travel/national-parks/national-parks-indigenous-stars/>).

⁹ Kocifaj, M., Kundracik, F., Barentine, J. C. & Bará, S. (2021). *The proliferation of space objects is a rapidly increasing source of artificial night sky brightness*. Monthly Notices of the Royal Astronomical Society: Letters, 504(1), L40. <https://doi.org/10.1093/mnrasl/slab030>.

astronomical observatory site whose night-sky brightness exceeds 10% above background at zenith angles $\leq 70^\circ$ to be light-polluted.¹⁰

According to the Union of Concerned Scientists, as of 1 April 2020 there were a total of 2666 satellites in orbit around Earth, of which 1918 were in LEO.¹¹ Assuming the number above for the total steady-state number of new LEO satellites in space in the 2020s, the total would reach about 50,000 satellites. If the population of debris objects increases according to the current size distribution, then the number of LEO objects in 2030 should be a factor of about 25 times higher than it is now. That would yield an average zenith luminance contribution from space objects of around $500 \mu\text{cd m}^{-2}$, or 250% above the natural background. As we detail below, if this scenario were fully realized, it would cause significant degradation of detail in visual observations of the Milky Way, a diminution of the number of stars visible to the unaided eye by a factor of about two, the disappearance of roughly half of the meteors in major annual events like the Leonid meteor shower, and the inability to view faint auroral displays.

At a combined total of natural plus space objects background of $\sim 700 \mu\text{cd m}^{-2}$, the brightness of the night sky at the zenith in this scenario would rival that at a site moderately impacted by terrestrial skyglow: 20.7 V magnitudes per square arcsecond, a value three times higher than the natural background alone. This condition is described by Class 4 on the qualitative Bortle Scale of night sky quality.¹² Only half the number of stars would be visible in the night sky relative to what would be visible in the absence of space-object light pollution.¹³ This reduction in the visibility of stars is akin to a global view of the night sky that lies somewhere between typical suburban and rural skies.¹⁴ We emphasize that this is only a lower limit to the stars being erased, assuming that crowded conditions in LEO lead to more frequent debris-generating collisions. This estimate further assumes that future satellites will have optical properties broadly like those of today. Although SpaceX has demonstrated a reduction in the total reflectivity of its Starlink objects through engineering innovations,^{15,16} the long-term choices made by industry regarding mitigating solutions are not guaranteed. Without binding legal regulations that impose mitigation targets, it remains a purely voluntary matter whether operators pursue these solutions.

Other than the loss of stars, there is also the potential for increased target observation times for professional astronomy as higher backgrounds require longer integration times to reach a specific signal to noise ratio. Last but not least, there will be reduced viewing of celestial phenomena that have united human observations across the ages, including, e.g., the Milky Way, meteor showers and aurorae.

The brightest parts of the Milky Way become just visible to the unaided eye at the zenith around a brightness of $2000 \mu\text{cd m}^{-2}$ (~ 19.5 V magnitudes per square arcsecond, or $m_V \text{ arcsec}^{-2}$). At $800 \mu\text{cd m}^{-2}$

¹⁰ Cayrel R., et al. (1980). *Guidelines for minimizing urban sky glow near astronomical observatories*. CIE 001-1980.

¹¹ Geospatial World, *How many satellites orbit Earth and why space traffic management is crucial* (<https://www.geospatialworld.net/blogs/how-many-satellites-orbit-earth-and-why-space-traffic-management-is-crucial/>, accessed 23 August 2021)

¹² For a description of the Bortle Scale, see Bortle, John E. (February 2001), *Gauging Light Pollution: The Bortle Dark-Sky Scale*, Sky & Telescope. Sky Publishing Corporation.

¹³ This assumes ~ 9000 stars brighter than the canonical unaided eye limit of magnitude +6.5 spread over the entire sky (Hoffleit, D.; Jaschek, C., eds. 1991. *The Bright Star Catalogue*. New Haven: Yale University Observatory) and the relationship between the luminance of the night sky and limiting visual magnitude given in Schaefer, B. E. (1990). *Telescopic limiting magnitudes*. Publications of the Astronomical Society of the Pacific, 102, 212. <https://doi.org/10.1086/132629>.

¹⁴ Note that Kocifaj et al. assumed the pre-Starlink rate of growth for new satellite launches to estimate a zenith brightness of $25 \mu\text{cd m}^{-2}$ in 2030 — some 20 times less than what we might more realistically expect in the age of mega-constellations.

¹⁵ Horiuchi, T., Hanayama, H. & Ohishi, M. (2020). *Simultaneous Multicolor Observations of Starlink's Darksat by the Murikabushi Telescope with MITSuME*. The Astrophysical Journal, 905(1), 3. <https://doi.org/10.3847/1538-4357/abc695>.

¹⁶ Mallama, A. (2021). *The Brightness of VisorSat-Design Starlink Satellites*, arXiv:2101.00374.

(20.5 m_V arcsec⁻²), depending on the presence of light domes on the horizon, most of the Milky Way is visible from horizon to horizon. But the visual appearance of the Milky Way with richness of detail does not begin until the zenith brightness is around 400 μcd m⁻², (~ 21.2 m_V arcsec⁻²). In terms of factors above the assumed natural background of ~ 200 μcd m⁻² (~ 21.9 m_V arcsec⁻²), these represent thresholds of about 10, 4 and 2 times, respectively.¹⁷

Observing meteor showers and aurorae are also popular activities at dark-sky sites. While the brightest meteors are visible from even the most light-polluted cities, dark sites excel at providing the opportunity to see relatively large numbers of meteors during a given night. Faint meteors tend to dominate these numbers, and so the resulting effect is rather dependent on night-sky brightness. Keeping in mind that every step brighter in sky brightness in terms of magnitudes per square arcsecond is a factor of approximately 2.5 toward higher backgrounds, and given the brightness distribution of meteors in major annual showers, a brightening of the night sky from any source means a significant reduction in the number of observable meteors. For example, Brosch et al. (2004) found for the Leonid meteor shower (population index ~ 2) a broad distribution of apparent magnitudes peaking around +5.¹⁸ For a site where the unaided-eye limiting magnitude equalled +5, corresponding to a night-sky brightness ~ 10 times higher than the natural background, approximately 40% of Leonids would be invisible.

The odds of seeing any particular auroral display are similarly decreased as the night-sky background brightens. This phenomenon is readily evident to aurora watchers impacted by the presence of moonlight, which even at relatively small lunar phases can quickly wash out faint auroral displays and those that are close to the horizon. Fainter aurorae (International Brightness Coefficients¹⁹ I and II) have surface brightnesses comparable to that of airglow, and thus would be rendered invisible under a modest amount of sky brightness from any source. If the background were routinely elevated, whether from terrestrial skyglow or the diffuse glow of space objects, it would sharply reduce the potential to see the aurorae at moderately high northern/southern latitudes, reducing the number of nights a year when the phenomenon might be visible.

¹⁷ Conversions between SI (cd m⁻²) and ‘astronomer’ luminance units (m_V arcsec⁻²) were made here according to the calibrations in Bará, S., et al. (2020). Magnitude to luminance conversions and visual brightness of the night sky. *Monthly Notices of the Royal Astronomical Society*, 493(2), 2429–2437. <https://doi.org/10.1093/mnras/staa323> and Fryc, I., et al. (2021). On the Relation between the Astronomical and Visual Photometric Systems in Specifying the Brightness of the Night Sky for Mesopically Adapted Observers. *LEUKOS*, 1–12. <https://doi.org/10.1080/15502724.2021.1921593>.

¹⁸ Brosch, N., et al. (2004). *Meteor light curves: the relevant parameters*. *Monthly Notices of the Royal Astronomical Society*, 355(1), 111. <https://doi.org/10.1111/j.1365-2966.2004.08300.x>

¹⁹ A classification system introduced by Seaton, M. J. (1954) *Excitation processes in the aurora and airglow 1. Absolute intensities, relative ultra-violet intensities and electron densities in high latitude aurorae*. *Journal of Atmospheric and Terrestrial Physics*, 4(6), 285, [https://doi.org/10.1016/0021-9169\(54\)90060-4](https://doi.org/10.1016/0021-9169(54)90060-4) and extended in Hunten, D. M. (1955) *Some photometric observations of auroral spectra*. *Journal of Atmospheric and Terrestrial Physics*, 7, 141, [https://doi.org/10.1016/0021-9169\(55\)90121-5](https://doi.org/10.1016/0021-9169(55)90121-5).



Figure 2. Starlink trails from objects deployed during Flight 6 are seen in this panoramic view of the night sky. Photo by Mike Lewinski, licensed under CC BY 2.0.

2.4 Other skywatchers and broad implications

This type of stakeholder may not have any specific scientific, cultural, hobby-related or religious connection to the night sky. They may not engage in astrotourism or participate in amateur astronomy, but they think of access to the night sky as something that adds value to their lives and may contribute positively to their overall sense of wellbeing.²⁰ They don't necessarily have any equipment to view the night sky, and typically do so with their unaided eyes. And they may have a sense that what makes the night sky special is that it is (literally) above Earthly concerns and that the value they perceive is independent of whether they understand any of it. In that way, its value is largely aesthetic, like visual art. But it isn't seen as a luxury or a frivolity; research suggests that people are willing to exchange things of value for access to nighttime darkness.²¹

What we all stand to lose as the night sky brightens around the world is the initial attachment to these ideas; in other words, if people never experience something first hand, it is less likely that they will assign it value, much less take any action to protect it when threatened.²² In the case of both terrestrial light pollution and enhanced night-sky brightness attributable to space objects, viewers may see an

²⁰ For one well-studied example, see Blair, A. (2016). *Sark in the Dark: Wellbeing and Community on the Dark Sky Island of Sark*. Sophia Centre Press.

<http://sophia-project.net/SophiaProjectNews/issues/2016-vol10-sark-in-dark.php>.

²¹ Simpson, S. N., & Hanna, B. G. (2010). *Willingness to pay for a clear night sky: use of the contingent valuation method*. Applied Economics Letters, 17(11), 1095, <https://doi.org/10.1080/00036840902817508>.

²² Amel, E., et al. (2017). *Beyond the roots of human inaction: Fostering collective effort toward ecosystem conservation*. Science, 356(6335), 275, <https://doi.org/10.1126/science.aal1931>.

unwelcome reminder of the extent to which humans have modified and transformed Earth, often for the worse. Although spotting individual satellites or the International Space Station can be entertaining or inspiring to some viewers, a steady stream of swarming artificial lights in the night sky diminishes the experience by making them routine or even perhaps annoying. A future transformation of the night sky in this way threatens to fundamentally rewrite the story of the relationship between humanity and the night sky, yet there has been virtually no outreach to this global community of night sky stakeholders. Often these communities are invisible to policymakers and have no seat at the tables around which policy decisions are made affecting the night sky; some authors have suggested that this amounts to a form of “astrocolonialism,”²³ while others have labeled it “cultural genocide”.²⁴

That this concern exists, requiring the attention of stakeholders through events like SATCON2, begs the question of who should bear the burdens associated with this fundamental paradigm shift in our approach to the use of orbital space near Earth. These are not old issues on newly expanded scales; rather, they are entirely new uses of near-Earth space whose scope and consequences we have barely begun to understand. Most launches now take place from US territory and are thus governed by US law and space policy; however, communities impacted by private commercial activities in space are being told to accept the consequences of these activities while the industry carrying them out faces a weak regulatory environment in the same regard. For example, it is arguable that a significant burden has already been placed on astrophotographers, whose work is adversely affected after the launch of only a few percent of the planned total of nearly 100,000 objects in LEO this decade.

It is clear at this point in time that we do not have a full accounting for all of the known and potential harms associated with a vast increase in the number of LEO satellites expected in the 2020s. It may be further argued that the current international space policy framework is inadequate to address these concerns, and combined with the advent of low-cost commercial launches it has led to a sense in which near-Earth space is the new Wild West where the priority of access is determined by who is the first to arrive. To the extent that near-Earth space represents a kind of commons, as implied by the language of the OST²⁵, there is now a strong possibility of a tragedy of that commons in which individual users of that space, unhindered by social strictures or meaningful international regulation, simply act in their own self-interest and diminish the resource through their largely uncoordinated activities.²⁶ Debate over the nature of this commons and the sustainability of its use has fragmented the participants into idealist and conformist factions²⁷, further muddying the waters as we collectively search for some kind of fair and amicable agreement on the shared use of the resource of near-Earth space. However, all sides seek **regulatory clarity and certainty, which seems to be the best hope for achieving some kind of consensus moving forward.**

²³ *SpaceX's Satellite Megaconstellations Are Astrocolonialism, Indigenous Advocates Say*, Vice, 5 October 2021 (<https://www.vice.com/en/article/k78mnz/spacexs-satellite-megaconstellations-are-astrocolonialism-indigenous-advocates-say>)

²⁴ Hamacher, D.W., de Napoli, K. & Mott, B. *Whitening the Sky: light pollution as a form of cultural genocide*, arXiv:2001.11527 (10 January 2020)

²⁵ Resolution adopted by the United Nations General Assembly, 2222 (XXI). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies. (<https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html>)

²⁶ See, e.g., Hardin, G. (1968), *The Tragedy of the Commons*. Science. 162 (3859): 1243, <https://doi.org/10.1126/science.162.3859.1243>.

²⁷ Verstegen, S. & Hanekamp, J. (2005), *The sustainability debate: Idealism versus conformism—the controversy over economic growth*, Globalizations, 2 (3): 349

3. Survey of the Amateur Astronomy Community Regarding Impacts of Satellite Constellations

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The members/attendees of the Amateur Astronomy Subgroup are:

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3.1 Overview

Our working group pursued input from as wide a range of constituencies as possible regarding their views about the impact of large satellite constellations. This report summarizes information gleaned from the amateur astronomy community. As this is an international community, it seemed best to utilize a survey that could be broadly disseminated across the world, relatively rapidly accumulate information that could be analyzed, and provide quantitative and open-ended qualitative information on viewpoints and attitudes.

3.2 Data Collection

A survey was created using the *Google Forms* tools, which was viewed as the quickest and easiest way to generate an instrument that could be broadly distributed and be compatible across many software platforms across the world. The survey questions are shown in the appendix. As the goal was to “take the pulse” of the amateur astronomy community as broadly as possible, and to allow for some level of analysis, the survey asked several key demographic questions: the primary type of observing of the respondent (visual, astrophotography, both); the level of participation in research activities; and the home country. Questions asked about the degree to which the observing activities of the respondent were impacted by satellite constellations, and the degree to which these satellites affected their appreciation of the night sky (each using a 5-level Likert scale). Open-ended questions for comments and a totally optional opportunity to supply an email address completed the survey.

The link to the survey generated by *Google Forms* was posted on as many sites and distributed as widely as we could to reach a broad constituency of amateur astronomers across the world. The distribution was as follows:

- The website and Facebook page of the Mountains of Stars public science education and outreach program²⁸
- Through the Night Sky Network, posted by the Astronomical Society of the Pacific both in their newsletter and on their social media sites
- Through the American Association of Variable Star Observers (AAVSO), via their online Forum and social media
- Posted to the Astronomical League for distribution to member clubs
- Posted to the Cloudy Nights online forum
- The e-mail lists of several astronomy clubs, including the Springfield Telescope Makers and the Amateur Telescope Makers of Boston.

In each case, the postings also asked recipients to further distribute the survey link as broadly as possible.

As of this writing (19 August 2021) some 564 responses from 37 countries have been collected. A breakdown of respondents is summarized in Figure 3.

²⁸ <https://www.mountainsofstars.org>; <https://facebook.com/mountainsofstars>

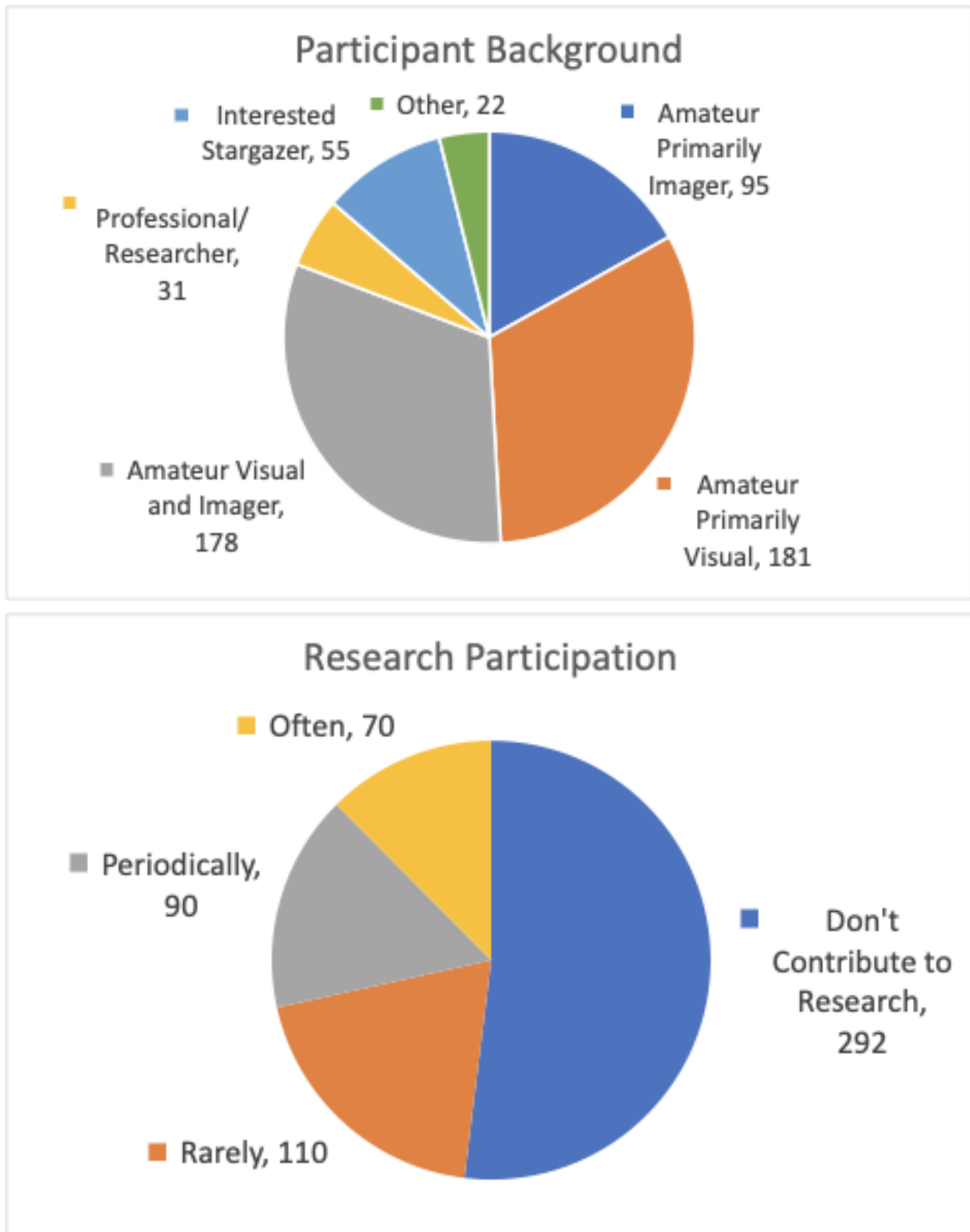


Figure 3. Breakdown of survey participant backgrounds and their contributions to astronomical research.

3.3 Summary of Results

In aggregate, respondents viewed the impact on their observing activities as moderate, with a mean value of 2.6 (+/- 1.3) out of 5 and the impact on their appreciation of the sky as moderate, but somewhat higher, 2.82 (+/- 1.5). The distributions are shown in Figures 4 and 5.

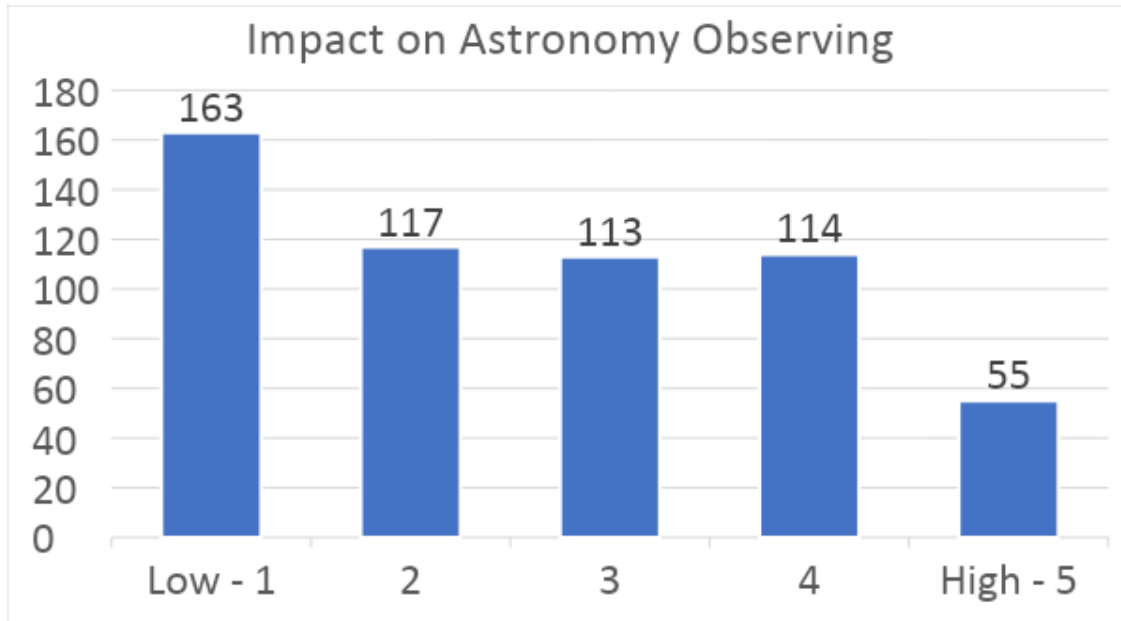


Figure 4. Bar chart displaying the number of survey participants reporting impacts on their observing activities.

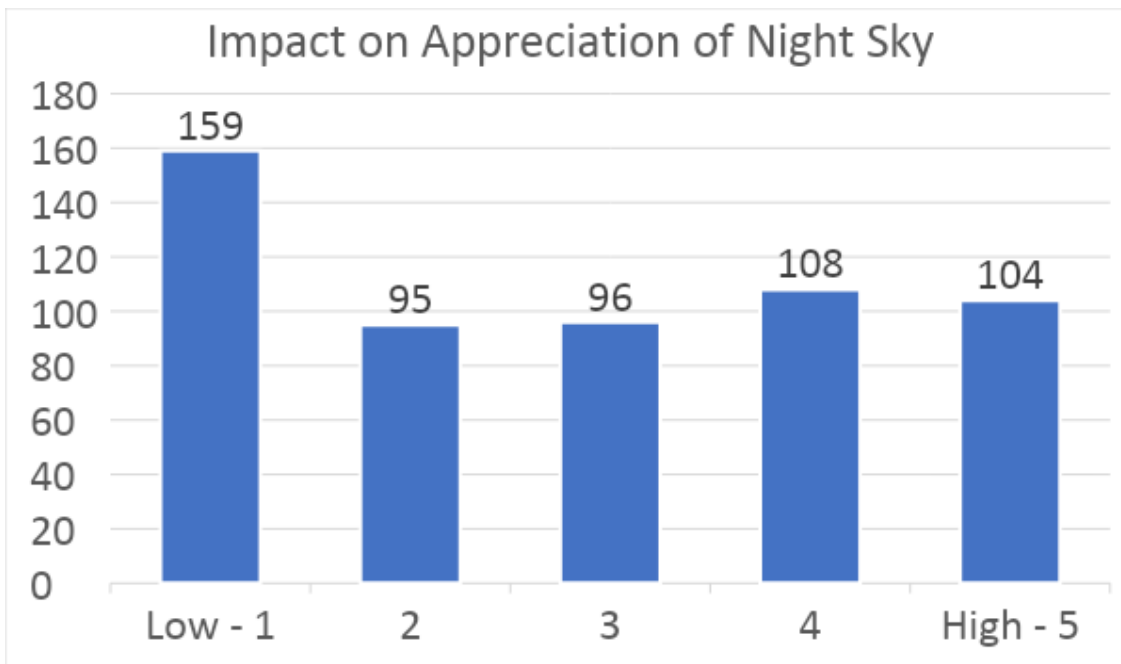


Figure 5. Bar chart displaying survey participants' perception of impact on their appreciation of the night sky.

3.4 Open Ended Comments

Respondents were given the option to submit open-ended comments on their view of both satellite constellations and the potential impact. Comments spanned a wide spectrum. A selection of comments, covering different viewpoints, are highlighted below:

I'm concerned about the current "gold rush" to populate space with micro satellites before governments across the globe put some form of control in place. Right now, it seems left to entrepreneurs with the wealth and means to do so. Commercial interests risk dominating scientific interests and the public good. There really needs to be some global coordination in this area. This could be a limit on the number of satellites, minimum standards for albedo and methods for retrieval such as space salvage — possibly a mix of all. Ultimately the space around our planet should be treated the same as a National Park, with a balance between usage and conservation.

It's only the beginning and the real impacts may come when there are tens of thousands in the sky

The sky should be open for everybody worldwide and not only to those who sent up satellites

It's incredible. I am living at a latitude of 54° north ... and there are always up from 30% to 50% of my photographed single frames "infected" by satellite trails I can't remove by algorithm ... I have to eliminate them by hand ... it's terrible

I reject frames to mitigate the effect on stacked final images, but [it] is another source of data reduction to go with weather, seeing, light pollution etc.

I understand the issues (I'm a satellite engineer at NASA) that a large constellation will have on professional wide field ground based arrays but for the amateur astrophotographer this really isn't a problem. I shoot mainly wide field and I have only had the occasional run-in with Starlink. For the most part I'm just as likely to have a non-Starlink satellite pass through my 3–5-minute exposures. In 2020, I took more than 123 hours of data. This year, in just six months, I already have more than what I collected last year. I've rarely even removed a sub-exposure with a satellite trail because the modern pixel rejection algorithms are so good.

Astronomical research — especially photometry and spectroscopy of transient targets — will be/is being seriously impacted. Unlike pretty picture astrophotography, in which satellite trails can be removed through processing, time-series photometry requires all those sub-frames, and cannot tolerate pixel replacement algorithms to mask the satellites. There are sometimes transient events that happen before astronomical twilight, well over toward the western or eastern horizon, so the argument that the satellites will only be visible/detectable for a short period after sunset or before sunrise isn't valid for this type of research.

I also don't understand why each company needs its own constellation. Seems much more environmentally responsible to send up a much smaller fleet and share between companies.

I'm concerned with the interference to astronomical observations caused by these satellites. Also concerning is the amount of space satellites/debris to be managed to keep astronauts and those of us on the ground safe.

For now, my enjoyment of night viewing has been enhanced with Starlink satellite trains passing overhead. Looks like an alien invasion and at times, surprisingly bright.

I really think that complaining about satellites while ignoring ground based light pollution is just being penny wise and pound foolish. Light pollution makes a much more serious impact.

3.5 Analysis and Discussion

There is some correlation between those who conducted research or were regular imagers and the most negative views of satellite constellations and their impact on their observing programs. The comments made by respondents were generally targeted at limiting or eliminating satellite constellations — generally, approaches that are not likely to happen. Several asked that the satellites be painted black, or not be launched at all. A number of respondents noted that internet accessibility is, fundamentally, a good thing, and the astronomy community is a small, special interest group that should merely accept the satellites. There is no doubt a sampling bias in such surveys; those who have the strongest opinions (pro or con) are more likely to respond.

As there was a need to conduct this process over a relatively short time period, we recognize that there were questions that could have been asked but were not posed. These include (a) a measure of the familiarity of respondents with satellite constellations in general, and (b) a measure of the anticipated impact of satellite constellations as they grow in scale. A number of respondents addressed the latter on their own in their responses, noting that while satellite constellations *currently* may not pose a major barrier to their observing or astrophotography, they were concerned about what the future could bring. If a follow-up survey is administered when a larger number of satellites has been launched, these two questions will be valuable in parsing the responses and correlating the degrees of impact and attitudes about satellite constellations.

It is heartening that over 560 respondents around the world took the time to respond to this survey. Nevertheless, it would take substantial resources to fully analyze the data (using software such as SPSS) to identify potential correlations between observer type and attitude towards and impact of satellite constellations, for example, and the other cross-tabulations that such a data set offers, and must be weighed against any potential value such an analysis would have in addressing satellite constellations.

3.6 Input and follow-up from Town Hall discussion

The participants in the SATCON2 Town Hall Breakout Room offered both opinions on the current state of affairs and a number of concrete plans of action. There was concern that amateur astronomers are being blindsided; in particular, not enough information is being distributed to the community. Related to this, it was suggested that there has not been sufficient modeling of actual satellites since SATCON1. Concerns were voiced that the problem will become significantly enhanced in the future, as larger launch vehicles make it possible to launch hundreds of small satellites at a time. Discussion ensued around the fact that visibility of satellites depends on latitude and inclination of the orbit, so some regions will be more affected than others. More tracking is needed; the existence of a UK program was noted. Heavens Above also

shows which satellites are up, including Starlinks. It was suggested that this could be used to gauge the number/impact of them. In general, amateur astronomers may have to become more proactive (less “meek” in the words of one participant).

In terms of concrete actions, a suggestion was made to reorient satellites in order to lower their reflectivity when passing over major observatories. Another way of attacking the problem is to increase availability of broadband fiber optics and 5G internet, thus reducing the need for many of these satellites. In particular, politicians should be contacted and used as advocates (e.g., Senator Shaheen). Fiber optic technology is currently preferred to satellites in some locations (e.g., New Hampshire) because it is more durable, less weather-dependent, carries more kinds of data, provides better uploads, and is a better long-term investment. Therefore local economic development organizations could be helpful partners in finding a long-term solution to the explosion of satellite constellations. In turn, concerned citizens should be encouraged to make their preference for fiber over satellite known to their local governments, utility companies, and economic development agencies.

Returning to the issue of educating the amateur community (and beyond) about the problem, it was requested that a central information hub be created. Information about satellites that could be useful for planning observing runs would be helpful. It was suggested that the AAS provide follow-up to this meeting, for example creating an email list for attendees to stay in touch if desired. The leadership of the AAS should use their political and corporate connections to aid in the push for fiber over satellite; a partnership would serve both astronomical and corporate interests. It was also suggested that the amateur astronomy and astrophotography communities work together in educating their members, as they have shared interests and parallel concerns.

Finally, we need to hold the satellite constellation operators responsible; they should be more transparent with their plans, and explain to the general public and politicians clearly and honestly what the benefits, dangers, and trade-offs are of satellite constellation implementation. Politicians should hold operators to international agreements protecting the night sky at optical and radio wavelengths, not merely to the strict letter of the law, but to the spirit as well. Members of the general public should hold their elected representatives responsible in this regard.

While this survey and related public fora focused on the impact of satellite constellations on amateur astronomers, it must be noted that the division between amateur and professional astronomy is fuzzy, at best. Organizations such as the AAVSO and the Center for Backyard Astrophysics demonstrate the important follow-up work done by amateur astronomers, contributing literally millions of data points to our understanding of the Universe. A threat to amateur astronomy is therefore a threat to professional astronomy, interfering with our ability to both understand the Universe and effectively guard against unexpected threats from outer space (including both deorbiting satellites and near-Earth asteroids).

3.6 Survey Form

Here we include the text of the survey to the amateur astronomy community.

Impact of Large Satellite Constellations on Astronomy

As individuals engaged with the night sky, you are in an important position to help guide efforts to understand the impact of large satellite constellations on astronomy and enjoyment of the night sky. Data obtained through this survey will be used to inform the writing of the SATCON2 report - which will be used as part of our effort to address the impacts of satellite constellations on astronomy.

*** Required**

1. In what country are you located? *

2. I would characterize myself as: *

Mark only one oval.

- ☐ Professional astronomer/researcher
- ☐ Amateur astronomer - primarily visual
- ☐ Amateur astronomer - visual + imager
- ☐ Amateur astronomer - primarily imager
- ☐ Interested stargazer/appreciator of the night sky
- ☐ Other: _____

3. I contribute to research programs, such as variable star light curves, exoplanet confirmations, supernova searches, etc. *

Mark only one oval.

- ☐ Often
- ☐ Periodically/occasionally
- ☐ Rarely
- ☐ Don't contribute to professional research

4. My general sense of large satellite constellations (such as Starlink and OneWeb) is: *

Mark only one oval.

- ☐ A major issue impacting professional and amateur astronomy
- ☐ A modest issue impacting professional and amateur astronomy
- ☐ A minimal issue impacting professional and amateur astronomy

5. My observing has been affected by large satellite constellations (e.g., Starlink) *

Mark only one oval.

	1	2	3	4	5	
Little to no impact	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Substantial impact

6. My appreciation and enjoyment of the night sky has been negatively affected by large satellite constellations: *

Mark only one oval.

	1	2	3	4	5	
Very little	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Very much

7. Please provide any comments/suggestions you have regarding large satellite constellations, including additional information you would like to receive, ideas for mitigating effects, etc.

8. If you are willing to contribute additional thoughts/information to this project, please provide your e-mail address. This information is not required, and will not be shared outside of this study.

This content is neither created nor endorsed by Google.

Google Forms

4. Perspectives from Indigenous Communities

The primary authors of this section and subgroup members are, in alphabetical order of last name:

Fernando Avila Castro (Mestizo / Universidad Nacional Autónoma de México)
David Begay (Diné, Indigenous Education Institute and U. of New Mexico)
Juan-Carlos Chavez (Yaqui/Sonora, affiliate at the Blue Marble Space Institute of Science)
Alvin Harvey (Diné, MIT)
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Annette Lee (Ojibwe and D(L)akota, St. Cloud State University)
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Hilding Neilson (Mi'kmaw, University of Toronto)
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International perspectives on this report's topics were offered by Hilding Neilson, Fernando Avila Castro and Michele Bannister (non-Indigenous (Pākehā), University of Canterbury, New Zealand).

This report shares a summary of perspectives and needs as directly stated by our Indigenous colleagues and conference participants at SATCON2, primarily through the Community Engagement Working Group. We emphasize that these speakers and participants speak for themselves and their own experiences only, not their whole community or all Indigenous peoples or tribal nations.

We also respectfully draw the reader's attention to the References and Further Reading section at the end, which includes a brief (incomplete) compilation of articles co-authored by this subgroup's members and others on Indigenous perspectives in space and related report topics, as well as recent articles featuring subgroup members that draw attention to the ongoing role of satellite constellations in "astro-colonialism" and space as an environmental commons.

Opening the workshop, Dr. Chavez began by drawing attention to our relationship with Mother Earth and Father Sky, asking that we honor their gifts and take responsibility for our actions and choices as we began this conversation. He invited all those working on these issues to bring our best intentions to this journey, and to seek ways to heal and learn from the past so we can do better and be better as beloved communities. He ended by seeking permission to continue in a good way so that our desire to progress does not come at the cost of elders or with ideals of empire, but so we can proceed in ways that honor our interconnectedness.

4.1 Key Themes

Some key themes that emerged from the morning talks and the afternoon Town Hall and breakout room on Indigenous and international perspectives are described below.

Indigenous peoples are part of sovereign nations — they are not special interest groups. Satellite constellations that are visible by the unaided eye on Earth will impact Indigenous peoples. The SATCON1 report noted in passing that the satellites might affect wayfinding practiced by different Indigenous peoples. It is commendable that the SATCON2 working groups included greater discussion about how

Indigenous peoples might be harmed by or benefit from these satellites, including the voices of some Indigenous peoples. However, Indigenous peoples were included in the discussion as a special interest group along with amateur astronomers, astrophotographers, and others. This is inappropriate because Indigenous peoples in Canada and the United States are groups of sovereign nations with rights highlighted by treaties and the United Nations Declaration of the Rights of Indigenous Peoples. Consulting and including Indigenous peoples in a working group is a positive step from the SATCON1 report, but more work is needed for that discussion to be nation-to-nation and not colonizer-to-Indigenous peoples.

Altered relationship with the cosmos. Indigenous workshop speakers shared that “*satellites literally interrupt our relationship with the stars and ceremonial ways of connecting with them*”, “*Stars are our ancestors and erasing them is erasing our tellings and scientific-cultural traditions*”, and “*Land, sky and oceans are relationships, a verb*”. Speakers emphasized the need for a relational ethical approach to space built on consensus and consultation. There is also a profound shift in our view of the stars as a fixed sphere, as we introduce more human-made moving objects into this realm.

A new form of colonization. The perspectives of Indigenous peoples with respect to outer space and the expected rapid growth of satellite constellations are important and necessary. Indigenous peoples from around the globe have observed the night sky since time immemorial and have a sophisticated and complex relationship with the visible night sky. As sovereign peoples and cultures, the rapid growth of these satellite constellations can have a significant and negative impact on this relationship. Many Indigenous stories are written in the stars. Light pollution has acted to erase Indigenous stories and identities — again — disconnecting these peoples from the night sky, mirroring the painful history of colonization in which Indigenous peoples lost their land and water. Speakers viewed light pollution as erasing their stories and satellites as rewriting them. They shared successful collectives to honor and preserve ancestral knowledge about Indigenous star stories and sky traditions, including Pai Pai star stories²⁹ from the bilingual 68 Voices project³⁰ based in Mexico, and the highly successful nonprofit Native Skywatchers³¹ founded by astronomer-artist Dr. Annette Lee. Speakers also raised the disproportionate impact of colonization, climate change and COVID19 on Indigenous communities.

Duty to consult. Indigenous peoples and nations must be consulted and their decisions should be respected. Many nations might view these satellites as inappropriate and as another form of pollution or colonization, but many nations might view the benefits of the satellites, such as access to broadband internet, as being valuable to their communities. However, it is not the purview of the workshop report authors, or academia and industry, to dictate the impact of these LEO satellites on Indigenous peoples. As such, the discussion would be better served as a nation-to-nation dialogue that includes consultation and consent.

Urgent need for cultural competency in space agencies and space actors. The accelerating situation with satellite constellations and the use of near-Earth space reveals an urgent need for space policy and scientific programs rooted in cultural competency and sensitivity to cultural traditions. NASA could lead the way by having an Office of Tribal Affairs or an Office of Cultural Protocol. Such an office could address ongoing practices around sensitive issues (e.g., what is heritage and who gets to define it; the thriving export business of human remains and ashes to near-Earth space). Several participants also suggested that NASA is missing an opportunity for due diligence on a major international issue: engaging sovereign nations in space exploration. NASA has much to learn from Indigenous ways of knowing and integrative scientific-cultural practices such as wayfinding, which have reflected for millennia the relatively new NASA

²⁹ <https://68voces.mx/pai-pai-el-origen-de-los-celos>

³⁰ <https://68voces.mx/>

³¹ <https://www.nativeskywatchers.com/>

values of Inclusion and Mission Success. Participants shared that a talking circle with NASA leadership is needed — something that has been very rich when allowed to happen — rather than the current approach of being sent in circles when Indigenous scientists and communities wish to be heard.

We can also learn from inclusive or creative approaches in other countries, e.g., in New Zealand, a small yet highly active spacefaring nation. Recent major national shifts in cultural competency include the official declaration³² of the heliacal rising of Matariki (The Pleiades) as a national holiday honoring Māori calendrical and cultural traditions. In addition, national initiatives in New Zealand are required to protect and enact Māori principles and incorporate Māori in economic and cultural development, as per Te Tiriti o Waitangi | the Treaty of Waitangi. The New Zealand government has to consider how any policy affects Māori empowerment and communities, including for instance in science implementation and funding.³³ New Zealand has five dark-sky reserves at present, for culture, astrotourism, and science; iwi-owned astrotourism in the largest reserve contributes to rural economic development, and the increased visibility of satellites there has been noted.

Legal and policy issues in space in the context of treaties with Sovereign Indigenous Nations. A growing number of issues need legal clarification and explicit addressing³⁴. These include: how do we define the environment of the Earth, where does Earth end and space begin, and what is the legal jurisdiction of Earth's laws? What are the legal obligations for state and private actors in space given existing treaties with sovereign Indigenous nations? We need written agreements between industry, spacefaring countries and Indigenous nations that respect these treaties and these communities' sovereignty. Such agreements must be transparent and include cost analysis so that agreements are not dependent on a new generation of leaders and people. Looking at New Zealand's approach once more, Aotearoa (the Maori name for New Zealand) is a new Artemis Accords signatory with public statements³⁵ emphasizing Māori principles of sustainability and stewardship of natural resources, as applied to outer space, which is termed an environment. Legal scholars are yet to answer the broader legal question of whether night skies are implicit in the multiple existing agreements and treaties between state actors and Indigenous peoples.

Systematic studies are needed on the viability of satellite broadband and outcomes for economic development. Two of our subgroup members drew attention to the unfolding situation as regards satellite broadband in their countries.

In Mexico, as an example, Dr. Avila Castro shared that as of July 2021, according to official data³⁶ 31% of the working population earns 3700 pesos a month or less, or approximately a third of the population earns \$185 USD or less a month at current exchange rates of \$1 USD = 20 pesos. Only 2% of the working force earns 18,700 pesos (\$925 USD) a month. The announced price of Starlink in Mexico is the same as in the USA: An initial \$500 USD (10,000 pesos) and a monthly fee of \$99 USD (2,000 pesos). With this information we can easily see that Starlink is completely out of reach of the vast majority of the population. On the other hand, Mexico has 84 million internet users which is around 70% of the overall population. In urban areas, internet coverage is acceptable and affordable through cellular (3G, 4G), and ground-based internet (DSL, cable, optic fiber). As with other services, rural areas are the ones left behind so it could be argued that Starlink could fill those gaps in coverage. However, rural areas have the

³²<https://www.mbie.govt.nz/business-and-employment/employment-and-skills/employment-legislation-reviews/matariki/matariki-public-holiday/>

³³http://www.maramatanga.co.nz/sites/default/files/Rauika%20Ma%CC%84ngai_A%20Guide%20to%20Vision%20Ma%CC%84tauranga_FINAL.pdf

³⁴ E.g., <https://www.nature.com/articles/d41586-021-01954-4>

³⁵ <https://www.beehive.govt.nz/release/space-exploration-soars-artemis-accords>

³⁶ Data come from the National Institute of Statistics, Geographical Information (INEGI), and the Federal Institute of Telecommunications (IFT).

lowest incomes meaning that satellite internet is completely unaffordable for them. Even if resources are pooled to share a satellite link for the whole community, infrastructure has to be acquired, installed, and maintained (routers, cables, WiFi antennas, etc) and at that point it makes more sense to solve the last mile problem through conventional internet access. But let's expand the scenario even further, e.g., that Starlink is installed and operating through a community effort. What is going to happen if the Starlink project doesn't pan out and has to shut down the service? Now the community has invested a lot of money, only to be left with some proprietary antennas that are no longer useful. This is what technological colonization means in a developing country. You no longer own the infrastructure or services — they are owned instead by a private company in a foreign country³⁷. So for the developing world, satellite internet in this form does not have a real market to expand, nor does it have a long term benefit for the people. However, people in these countries will suffer the increase in light pollution, and the loss of their traditional tales and stories in the skies. Any short-term benefits from satellite broadband may therefore be eclipsed by long-term economic and other impacts, with no clear path of recovery.

In the case of the nation of Canada, Dr. Neilson shared that access to broadband internet has been promised by governments for years³⁸. To that end the Canadian government has committed support to the satellite company Telesat³⁹ which currently has a constellation of about 300 LEO satellites in space to provide broadband internet access to almost two million Canadians who lack affordable access. Most of this access will impact large areas of Canada with small population densities who are disproportionately Indigenous. At the time of writing, it is unclear whether and how many communities have been consulted about this.

Nuanced approaches without appropriation are required. Indigenous peoples have their own governance, rights and needs. Both academia and industry should avoid statements emphasizing preferred narratives around satellite constellations. We must avoid such appropriations of Indigenous perspectives and needs, or misinterpreting them for pre-determined uses — this is a real issue now that astronomers are at the receiving end of colonization. Nuanced approaches that engage in long-term relationships and listening with communities are needed, recognising that consensus building happens differently in each community and culture. This is not a single issue across all Indigenous peoples (e.g., cultural sky traditions); rather, this is a complex tradeoff between broadband access, economic development, cultural heritage, and survival (many Indigenous peoples do not have access to clean water or other basic necessities).

We end by sharing that the co-Chairs of the Community Engagement Working Group were invited into extended dialogue with a circle of Oceania wayfinders ranging from Hawai'i to Aotearoa and many Pacific communities, starting in the week of the SATCON2 workshop. It would be inappropriate to attempt to summarize these conversations this early in the process, but we honor the wayfinders' gracious invitation into dialogue as we collectively move forward to preserve the health and integrity of the ocean above us as well as the ocean between our lands.

We express gratitude and support for these Indigenous perspectives offered at SATCON2. We hope that we can listen, consult, learn from the past and co-create an ethical sustainable future in space that honors our interconnection and does not come at the expense of things that belong to us all.

³⁷ More broadly, fiber optic cables can serve multiple data-carrying functions in multiple formats for multiple providers and users from individuals to corporations to governments for multiple decades. In contrast, satellite dishes to access satellite broadband internet are fixed to one household account with one private provider corporation using one format of data transmission, and are prone to rapid obsolescence.

³⁸ <https://crtc.gc.ca/eng/internet/internet.htm>

³⁹ <https://www.telesat.com/about-us/>

5. Planetariums and the Satellite Constellation Challenge

The primary authors of this section are:

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Ryan Wyatt (California Academy of the Sciences)
Ka Chun Yu (Denver Museum of Nature & Science)
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The primary attendees of the SATCON2 Community Engagement Working Group breakout session on planetariums were:

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James Sweitzer (Science Communication Consultants, USA)
Patrick Seitzer (University of Michigan)
Rosemary Walling (Marie Drake Planetarium)
David Galadi Enriquez (Calar Alto Observatory)
Andreas Haenel (Museum am Schölerberg)

5.1 Introduction

Planetariums deliver accurate, dark, artificial starry skies on demand. In an era when the natural night sky is under threat from light pollution and now satellite constellations, planetariums could well become a leading method to communicate the satellite constellation challenge and educate a broad range of people, whether they live in urban or rural areas, about these problems. Unfortunately, some 83% of the world's population live under light polluted skies. Few have ready access to natural dark sky sites either. Planetariums might therefore be the only starlight refuges we have to educate the public. These “domed cosmic classrooms” should not be regarded as a separate, threatened community, but rather as trusted voices for the protection of the night sky.

We are now approaching the 100th anniversary of the first modern planetarium, in Munich, Germany. Today, planetariums number 4000 worldwide in nearly 90 countries. They include fixed and portable domes with both digital systems and traditional opto-mechanical projectors. More than 1700 of the planetariums are now digitally full-dome capable. The advantage of full-dome video systems is that they can display either real-time simulations or pre-rendered videos of virtually anything that can be visualized for a hemisphere. Displaying simulations of artificial satellites and showing their impact should be a straightforward task for contemporary planetariums.

Aside from their technical capabilities and broad geographic reach, planetariums connect with larger in-person astronomical audiences than any other mode by nearly two orders of magnitude. Current pre-COVID estimates top out at over 100 million global planetarium attendees per year. In contrast, a quarter of a million students are enrolled in American introductory astronomy courses. Planetariums also reach a truly international audience with programs in their native language. And unlike online media, planetarium experiences generally include contact with real astronomers, educators and experts. For much of the world, planetariums *are* the face of astronomy.

5.2 Assessing satellite constellation impacts in planetariums

Along with their worldwide distribution and ability to reach large audiences, planetariums also offer four programmatic and technical opportunities and one organizational bonus for the community concerned about the impact of satellite constellations.

1. The technical capabilities of planetariums allow them to share visualizations that accurately illustrate satellite constellations. What better way to understand the problem than to see and compare for oneself? Planetariums have been teaching children and adults to identify constellations in the night sky for nearly a century. Simulating the challenge of light pollution has long been a staple of planetariums. Augmenting that natural sky with a new set of realistic-looking, artificial lights in motion is a straightforward task for planetariums.
2. Planetariums are natural venues to celebrate the many cultural dimensions of humanity's relationship with the night sky. They regularly present programming that addresses celestial practices and beliefs of diverse cultures today, as well as the traditional views of the past. This practice of featuring indigenous storytelling and culturally-rooted star shows and sky traditions is well developed in many planetariums. These programs have proven to be among the most popular with audiences. Planetariums offer a familiar and trusted venue to celebrate our common heritage and respect for the dark night sky. The planetarium world also realizes it must go beyond traditional approaches to cultural stories and instead become places for giving people and groups a chance to speak for themselves. The yearly Live Interactive Planetarium Symposium (LIPS) meetings are a natural forum for engendering such programs.
3. During the fulldome digital planetarium revolution of the past twenty years, ambitious shows have been developed with sophisticated visualizations able to tackle subjects that would never have been approached in the past. Planetarium show content now ranges from storytelling for children to accurate visualizations of the bending of light around the supermassive black hole in M87. Storylines can be as complex as those seen on NOVA, the popular documentary television series. For example, Big Astronomy, an ambitious planetarium show with a broad perspective on the enterprise of research astronomy including a number of social and cultural themes, also includes Vera C. Rubin Observatory, which will be extremely vulnerable to satellite constellations because of its large etendue.

Many planetariums also offer live presentations that augment pre-recorded shows like Big Astronomy. This offers an opportunity for planetariums to contextualize the effect of satellite constellations in terms of topics addressed by the shows. A "live section" following Big Astronomy, for example, could highlight the effect of satellite constellations on the Rubin Observatory Legacy Survey of Space and Time (LSST) program, followed by tips on how audience members can act to preserve dark skies. Live segments can be considered as "rapid deployment presentations" for timely topics like satellite constellations.

4. Planetariums can deliver emotional astronomy experiences and be used for artistic performances. Although they are admittedly "second best" to stunning dark night skies in nature, they are on-demand and accessible to even the most light-polluted populations. They bring the night sky experience to the people. All planetariums, no matter what the show they are presenting, know the power of the stars. Ironically, this *affective* capability of planetariums might prove to be the most important factor for addressing the satellite constellation challenge. This is because we

face a challenge to motivate the public similar to the one the environmental movement has had to deal with for decades. The British environmental writer Michael McCarthy argues that engendering an emotional connection to nature may prove to be the best approach for engaging the general public:

We should offer up not just the notion of being sensible and responsible about [nature], which is sustainable development, nor the notion of its mammoth utilitarian and financial value, which is ecosystem services, but a third way, something entirely different: we should offer up what it means to our spirits; the love of it. We should offer up its joy.

The planetarium community also offers an organizational bonus. Although widespread and institutionally diverse, they are a relatively close-knit group. This means that any programming created for planetariums or for professional development programs can be distributed via well-established organizational channels. A prime channel is the International Planetarium Society (IPS). This organization can, with coordinated and adequately funded programs, reach nearly every planetarium in the world. The IPS has already connected with the SATCON2 Community Engagement Working Group and initiated the formation of an educational working group of their own. In addition, other planetarium communities of practice, such as LIPS, support professional development with a focus on how to engage audience members.

5.3 Recommendations

During the SATCON2 online meeting and subsequent discussions, the following specific thoughts regarding planetariums were offered, some of which can be used as action items for the coming months and years. (Because planetariums operate primarily within educational, nonprofit organizations they will require financial, partnership, and in-kind support to legitimize and achieve the actions outlined below.)

- Convene a group of planetarians, astronomers, system operators and software developers who can begin the task of creating databases of orbital elements and algorithms for rendering satellite visibility that can be shared among the different software vendors. (Several in the breakout group volunteered to help and the list of others who need to be in this group, such as planetarium software vendors, has been assembled.)
- Produce short, “live presenter” planetarium content that can be added in the near future to shows that are already running in multiple planetariums. This can be done in the coming year. For example, Big Astronomy could be augmented with short live sections that might show how Vera C. Rubin Observatory would be impacted. Other add-on live segments could be developed and added to other pre-rendered programs.
- Begin production planning for a more comprehensive, pre-rendered show that includes a more complete discussion of satellites and the challenges of the commercialization of near space.
- Start creating content and activities for professional development opportunities for the planetarium community. As of late summer 2021, planetarians are still meeting remotely. The hope would be to have such content ready for the renewed in-person meetings in 2022 and beyond.
- Establish a “satellite event” portal where the planetarium and amateur astronomy communities could share the information they need to help their audiences learn about satellites first hand. This would also allow opportunities for these two communities to connect and collaborate.
- The IPS is interested in progressive ways to use planetariums to give agency and voice to many who have not had a chance to be represented in their theaters. The satellite constellation challenge could be a welcome catalyst for new discussions about the night sky we all share.

- Planetariums worldwide will be celebrating the 100th anniversary of the first planetarium between 2023 and 2025. In April of 2024 an important total solar eclipse will be seen in North America. The challenges presented by satellite constellations should be folded into the educational efforts over the coming years.

Satellite constellations pose threats to our celestial commons and heritage in ways that are unprecedented. Good decision making and effective solutions will require a well-informed and educated public. The planetarium community has the capacity to be an important contributor to this effort. They have been trusted conveyors of the messages of the stars for over three generations. Now is the time for them to begin to prepare future generations for a more sustainable and equitable space habitat.

6. Environmental and Ecological Impacts of Satellite Constellations

The primary authors of this section and subgroup members are:

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The Environmental Impacts subgroup of the SATCON2 Community Engagement Working Group researched and discussed numerous aspects of environmental and ecological impacts of satellite mega-constellations, held a virtual listening session with the Sierra Club, held dedicated presentation and discussion sessions during the SATCON2 workshop, and reached out to numerous individuals with expertise in environmental conservation and related concerns. Here we report the main issues and themes that surfaced from those inquiries and discussions.

We offer three main recommendations, summarized here and expanded below:

1. Earth-orbiting space should be considered part of Earth's environment, legally and otherwise.
2. Satellite constellations should not be exempt from NEPA review.
3. Sovereignty should be respected with regard to space and the night sky.

6.1 Historical, political, and environmental context

Just as the SATCON2 conference got underway to grapple with the challenges posed by Elon Musk's SpaceX Starlink and other mega-constellations of LEO satellites, news headlines around the world highlighted the race to space by two other billionaires, Jeff Bezos of Blue Origin and Richard Branson of Virgin Galactic. At the same time, much of the American and Canadian west was suffering from record-breaking heat waves and wildfires, as was Greece, while other areas, including parts of Germany and Belgium, saw massive and fatal flooding following unprecedented torrential rainfall, all exacerbated by anthropogenic climate change. Several members of the Community Engagement Working Group and people interviewed pointed out the ironic contrast between the dire material needs of the vast majority of the Earth's population and the indulgences of some of the richest men in the world, as if the wealthy were literally escaping a planet on fire by means unavailable to most people. Others drew parallels between the current space race, including the development of satellite constellations, and the long history of colonial imperialism over the last millennium: the new natural resource up for grabs is space itself, to be exploited and capitalized by the highest bidders and the quickest and largest private corporations.

International legal and philosophical conception of the need to protect space for all humanity was enshrined, soon after the advent of the Space Age, in the OST. The OST lays the foundation for peaceful international cooperation and universal access to space, but it contains no explicit reference to the need for environmental protection against harm from human activities in space. More than 50 years later, facing the prospect of a rapid and manifold expansion and commercialization of activity in space, the United Nations Office of Outer Space Affairs (UNOOSA) issued the first Guidelines for the Long-Term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space (UN COPUOS 2021). Guideline A.2 reads in part:

In developing, revising or amending, as necessary, national regulatory frameworks, States and international intergovernmental organizations should...:

- b: Implement space debris mitigation measures, such as the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, through applicable mechanisms;*
- c: Address, to the extent practicable, risks to people, property, public health and the environment associated with the launch, in-orbit operation and re-entry of space objects;*

Gilbert & Vidaurri (2021) study existing national and international case law and conclude that consideration of the NEPA should be applied to space activities — contrary to the practice of the US Federal Communications Commission (FCC), which is to disregard environmental impacts when considering applications by satellite operators for licenses to launch and operate satellite constellations. Sutherland (2021) describes the process by which NASA applies NEPA, in contrast to the FCC. Cirkovic (2021a,b) argues for a new “cosmolegal” conception of space and space law that recognizes the limitations of traditional terrestrial legal frameworks and the potential risks from overcrowding of orbits, space debris, and possible contamination of other planets by human activity in space. Comparisons between the problems of space debris, satellite constellations, and climate change become even more concrete given the prediction that increasing levels of atmospheric CO₂ will reduce drag on LEO satellites, making them stay in orbit longer (O’Callaghan, 2021).

Thus there is growing concern about the environmental impacts of satellite constellations, and precedent for implementing regulation and national and international law to control, mitigate, minimize, or eliminate those impacts.

6.2 Environmental harm from satellite constellations

Environmental harm from satellite constellations occurs during all three phases of satellite constellation lifetimes. Below we summarize the major impacts we found in the literature and from our discussions.

- I. Impacts to the natural and human environment identified or predicted from launching satellite constellations include:
 - a. Large quantities of CO₂, NO_x, water vapor, and other greenhouse gases and toxic substances are produced by combustion of liquid and/or solid fuel during rocket launches (see Dallas et al., 2020 for a comprehensive review). Depending on the type of fuel used and the size of the launching rocket, up to 300 tons of CO₂ can be produced per launch. The breakdown of water vapor released in the stratosphere leads to depletion of the ozone layer (Marais, 2021).
 - b. Combustion of kerosene fuel produces black carbon, and combustion of solid rocket fuel produces soot and alumina, both of which can affect the albedo (reflectivity) of Earth’s atmosphere to sunlight (Lawler & Boley, 2021).
 - c. Pollution associated with rocket launches, including over sensitive habitats such as the Gulf Coast in Texas and Cape Canaveral in Florida, negatively impacts humans and wildlife alike. Rocket launching facilities that are placed in environmentally delicate areas and/or near low-income or marginalized people raise questions about environmental justice and equity, e.g., the SpaceX spaceport near Boca Chica, TX (Sandoval & Webner, 2021).
 - d. Falling debris and explosions associated with failed rocket launches have raised concerns and protest among neighbors of proposed launching sites, e.g., Little Cumberland Island, Georgia, where Camden County plans a new spaceport (Marvar, 2021).

- II. Impacts on the natural and human environment identified or predicted from operating LEO satellites at orbit-raising and final station altitude include:
- a. Possible disruption of various species' ability to navigate using the stars. A wide range of species are suspected or known to use the stars and even the Milky Way to navigate (e.g., Foster et al., 2018; Sokol, 2021; Fritts 2021), from dung beetles (Foster et al., 2021) to bats (Stone, Harris & Jones, 2015), harbor seals (Mauck et al., 2008), and migratory songbirds (Emlen, 1967; Wiltshko et al., 1987; Pakhomov, Anashina & Chernetsov, 2017). The possibility that the proliferation of bright artificial LEO satellites could lead to the disruption of migration by many millions or billions of individual animals (Lintott & Lintott, 2020) is still new enough just two years after the first launch of Starlink satellites that no peer-reviewed studies have been published yet reporting confirmed impacts of satellite constellations on animals; however, numerous members of the working group felt that there was sufficient reason to be concerned about such possible effects on animals that the precautionary principle should apply, and that launches should be halted unless and until the effects are demonstrated to be negligible.
 - b. Interference with the timeless and profound human experience of regarding the starry sky. The night sky is a fundamental part of nature, and one that provides us with solace, inspiration, and connection with countless generations before us and, one hopes, yet to come. The human right to see the naturally dark, unpolluted, starry night sky has been articulated in the Declaration in Defense of the Night Sky and the Right to Starlight (Starlight Foundation, 2007), and Resolution B5 in Defence of the Night Sky and the Right to Starlight (International Astronomical Union, 2009), and by the US National Park Service, which operates an extraordinarily popular Night Skies program whose motto is "Half the Park is After Dark" and whose philosophy is that naturally dark skies are, like clean air and clean water, a natural resource to which every human has a right (National Park Service, 2021). Satellite constellations have the potential to dramatically and irrevocably alter the naked-eye appearance of the night sky (e.g., Lawler, Boley & Rein, 2021; Lawler and Boley, 2021; Skibba, 2021).
 - c. Earth-orbiting satellites know no national boundaries, and several Community Engagement Working Group members pointed out the need to respect the sovereignty of other nations, including Native American and other Indigenous peoples, who may regard outer space and the night sky as part of the environment, even if the FCC does not.
 - d. The rise in overall night-sky brightness due to the combined light from many thousands of satellites, even if individually invisible to the naked eye, may already be a significant new form of light pollution; Kocifaj et al. (2021) calculate that the night sky may already be as much as 10% brighter than natural as a result of the integrated reflected light from all artificial objects currently in orbit, including fewer than 2000 Starlink satellites out of more than 10,000 planned; that contribution to overall sky brightness will inevitably grow as more satellite constellations are put in orbit. Reasonable estimates based on planned satellite constellations just in the 2020's imply that the night sky could be artificially brightened by as much as 250%, erasing the view of the Milky Way and more than half of naked-eye visible stars (see the Astrophotography subgroup report of the Community Engagement Working Group). The circadian rhythms of humans and animals are generally thought to be controlled by the perception of integrated and diffuse light such as from the sky (Brown, 2016), rather than from individual light sources, and many species are sensitive to extremely low levels of light, well below 1 lux (e.g., Walbeek et al., 2021). Therefore an overall elevation of night sky brightness by satellite constellations may have profound and negative effects on many or most species of flora and fauna on Earth. Again, the field is too new for there to be published empirical studies yet, but Community

Engagement Working Group members argued that the precautionary principle should apply.

- e. Some interviewees indicated that any potential impacts on the integrity and continuance of Earth Observation (EO) satellites from orbital debris collisions and especially a potential debris cascade (the Kessler syndrome) due to overcrowding of orbits would be points of major concern to the environmental and ecological justice community, from scientists and activists to policy makers. Many of those EO satellites operate in LEO. For decades, EO satellites have provided data that have helped humanity understand, appreciate and protect the planet's atmosphere and ecosystems. They have exposed the vulnerability of our planet and the limits of our natural resources. They provided evidence and now the means to monitor our progress, or lack thereof, in tackling the climate and biodiversity crises. Whether directly or indirectly, whether knowingly or not, these constituents have benefited from EO observations in their work on ecosystems, natural resources, wildlife biodiversity, agriculture, food security, transportation, weather, water and air quality, light pollution, wildfires, disaster response, smart growth, climate adaptation, energy transition, social justice, and much more.

Unfortunately, because the focus on identifying and communicating impacts and mitigations related to satellite mega-constellations has been primarily on astronomy, most of the communities working on environmental, ecological and social justice issues (including non-profit organizations) are largely unaware of the challenges that thousands of new LEO satellites, and associated space debris, could pose to current and future EO satellites.

While intentional and meaningful outreach to these communities has only recently started, questions from them so far have included:

- Who is bearing the burden of costs associated with tracking these many objects, mitigating potential issues, and the loss or reduction of public benefits, if the operations of EO satellites are compromised?
 - Will future launches of EO satellites be affected or reduced by more congested LEOs?
 - How will cascading collision events, especially with untracked debris, affect the EO satellites we have come to depend on in respect of issues of great environmental importance, such as monitoring pollution and land cover changes affecting people and wildlife?
 - What sustainability and carrying capacity studies are being carried out, if any, to ensure the safety and health of the planet's atmosphere and the equitable access to near-Earth orbits, especially among marginalized communities?
- f. Community Engagement Working Group members pointed out that even with sophisticated decommissioning plans in place, individual satellite operators can go, and already have gone, bankrupt, potentially leaving thousands of satellites stranded in orbit, perhaps for thousands of years. This is perhaps analogous to leaving wrecked cars by the side of the highway indefinitely, a practice no modern society accepts.

III. Impacts on the natural and human environment identified or predicted from decommissioning LEO satellites include:

- a. Aluminum and rare-earth metals deposited mostly in the atmosphere and the oceans but also on land during re-entry of satellites, either planned or accidental. Boley & Byers (2021) estimate that from the eventual re-entry of the fewer than 2000 Starlink satellites

already in orbit as of this writing, the deposition of aluminum into the atmosphere will exceed that from all natural causes, primarily the steady rain of small asteroids and micrometeoroids (roughly 50 tons per day), that Earth collects (e.g., Rojas et al., 2021).

- b. The greatly increased likelihood, given the numbers of satellites planned in LEO, of unplanned or uncontrolled re-entries resulting in the direct impact of satellites or satellite fragments with the ground, possibly causing direct injury or loss of life to humans or animals. Residents of the Pacific Northwest got a dramatic demonstration of such a scenario when a SpaceX Falcon 9 made an uncontrolled re-entry into the atmosphere, producing a spectacular fireball witnessed by thousands (Ives, 2021).

The Community Engagement Working Group makes the following recommendations regarding the proven or plausible impacts on the human and natural environment of launching, operating, and decommissioning LEO satellite constellations:

1. **Earth-orbiting space should be considered part of Earth's environment, legally and otherwise.** There was a strong consensus that the region of space occupied by Earth-orbiting satellites and the night sky should be considered an integral part of the environment and of the human experience of the natural world. To limit the concept of the environment to the surface of Earth and its atmosphere but to exclude the starry night sky or even objects passing through the atmosphere en route to or returning from LEO is to make an arbitrary distinction that defies common sense and universal experience.
2. **Satellite constellations should not be exempt from NEPA.** There was strong consensus that NEPA, which the FCC has so far declined to invoke in considering licence applications by potential operators of satellite constellations, should in fact be applied, and that environmental impact studies should be required components of such license applications.
3. **Sovereignty should be respected with regard to space and the night sky.** Even if the FCC does not consider space to be part of the environment or subject to NEPA review, other nations can and do consider space, the starry sky, the Milky Way, the planets and the Moon to be part of the environment, nature, cosmology, cultural and spiritual heritage and practice. Introducing satellite constellations to the night sky, especially if bright enough to be seen naked eye, thus threatens the autonomy and wellbeing of people of other sovereign nations including Indigenous and First Nations people, and undermines the concept of space as a commons as enshrined in the OST.

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SATCON2 Policy Working Group Report

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1. Executive Summary

This report is part of a collection of Working Group Reports from the [SATCON2](#) Conference.

The charge to the SATCON2 Policy Working Group was to review existing national policies and legislative frameworks. With the SATCON1 recommendations as context, the group was charged to assess policy options to serve the diverse requirements of astronomy, the satellite industry, and other communities.

1.1 International Law and Treaties

The international shared use of “outer space” has a heritage in the international approach to Antarctica. The Antarctic Treaty articulates three core principles: peaceful use, scientific exploration, and protection of certain identified components of the Antarctic environment. The last two principles provide policy support to the need to protect Earth’s dark skies. And all three principles are mirrored in the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (the “Outer Space Treaty”, hereinafter the OST), elaborated within the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS). The OST is a legally binding instrument for the States that have signed and ratified it (110 ratifications and 23 signatures to date). The foundational principle of the OST and related UN space treaties, namely the freedom of exploration and use of space, has been recognized as customary international law, binding all States.¹ The last sentence of Article I states that “[t]here shall be freedom of scientific investigation in outer space” and that “States shall facilitate and encourage international co-operation in such investigation.” This aspect is exceptionally relevant to mitigating the impact that satellite constellations may have on astronomy, which could be partially mitigated with a continuous exchange of information and data. Article IX of the OST suggests that the US and other parties to the OST have an obligation to implement activities in space with “due regard” to the corresponding interests of other States in respect of potential light pollution created by satellite constellations. This language could also be used to encourage other States to adopt licensing conditions that will lessen the impact of satellite constellations on astronomy — anywhere in the world — to the greatest degree practicable.

Another of the most relevant limitations to the activities of States and other actors in the exploration and use of outer space can be found in Article II of the OST, which establishes that “Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.” The conditions for a safe, stable and sustainable environment should not ignore considerations regarding the impact that space activities, albeit coordinated, can have on ground-based activities and should not overlook the application of fundamental principles of international law for the development of exploration and use of space, such as the non-appropriation principle, correlated with freedom of access, principles of fairness and regard for the interests of other actors. A change would therefore be necessary at the international level to ensure that the first-come, first-served allocation practices for non-geostationary orbits are gradually replaced with more equitable procedures capable of responding to the emerging needs prompted by the spread of satellite constellations.

¹ <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/status/index.html>

The legal principles contained in Article VI of the OST, namely (a) State responsibility for national space activities, including those pursued by nongovernmental entities; and (b) authorization and continuing supervision of such activities by a State, provide two important safeguards for the conduct of space activities by non-governmental entities of a State. The US position has always been that private agencies would not be free to engage in space programs without governmental permission and continuing governmental supervision. Evidence of current and potential interference to astronomy is being submitted by the American Astronomical Society (AAS) and other stakeholders, so the obligation of the US government to maintain “continuing supervision” could be interpreted, at the very least, as demanding a thorough inspection into this matter and further consideration of appropriate measures to safeguard its own interests as well as those of all its actors, governmental and non-governmental entities alike. In the event of transboundary impact/harm/damage (present as well as future), it is recognized that the US maintains the view that States will not necessarily be responsible for the liability of private entities/actors; however, Article VI of the OST suggests that this position cannot be taken in respect of space activities. **A good starting point would be to conduct due diligence concerning the activities of commercial satellite operators, specifically as regards the impact of in-orbit operation of such activities.**

Astronomy plays an integral role in planetary defense, a core mission of COPUOS. Thus, as a policy consideration, planetary defense considerations support the inclusion, as a condition of licensing, of an obligation to reduce the impact (if any) of satellite constellations on telescopes used for planetary defense to the greatest degree practicable. Altogether, we do not expect large constellations to prevent planetary defense from operating. Rather, they could under certain conditions cause delays in the identification of objects, which could have widespread ramifications if an object is on an Earth-impact trajectory. This will further affect responses by numerous US government agencies and could delay an internationally coordinated response.

The Working Group considered whether planetary protection policy (PPP) might provide considerations for the impacts of satellite constellations on astronomy. The motivation is that satellite constellations have the potential to contaminate the night sky and cause harm to astronomical observations, as well as enjoyment of the night sky. As astronomy is one of the foremost ways we study and explore space and is advanced by multiple agencies within States, activities that “*would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space,*” in the language of OST Article IX, are intended to be subject to international consultations.

1.2 US National Law

A variety of existing local, state and national regulations and laws, coupled with the policy rationales for those measures, support the inclusion, as a condition of licensing commercial satellites and in particular satellite constellations, of an obligation to reduce the detrimental effect of such satellites on astronomy to the greatest degree possible.

In the US, a growing number of federal, state and local ordinances and regulations are being implemented to address the threats posed by light pollution. The main thrust of these efforts is to address the persistent light pollution generated by terrestrial lighting fixtures and:

- the consequential effect on wildlife;
- the aesthetic impact on recreational viewing of the night sky;
- related energy consumption; and
- in some cases, the effect on astronomy.

These regulations and ordinances are localized, deal with persistent lighting fixtures and generally cover light visible to the naked eye. Conversely, satellite constellations generate diffuse or reflected light that is generally visible to the naked eye in dark skies only temporarily, post-launch and prior to orbit raise. Additionally, the cumulative effect of all satellites and debris results in an overall brightening of the sky that, while not detectable by the naked eye, may be observed with astronomical instruments. However, the goal — to preserve the environment for astronomy — remains the same and only the means to achieve the goal will differ. Nineteen US states, plus Washington, DC and Puerto Rico have enacted laws to address light pollution. Many localities are referring to the principle-based outdoor lighting model ordinance of the International Dark-Sky Association and the Illumination Engineering Society in establishing their regulatory frameworks.

Federal agencies are now also taking affirmative steps to protect the sky at night from light pollution. The federal system of protected lands has grown, and agencies have come to recognize that a naturally dark, star-filled sky is an intrinsic part and a critical aspect of the park or wilderness experience. While the focus of the federal system is on the visual experience of visitors, the fact must be recognized that light pollution that can ruin aesthetic experiences will also be ruinous to astronomy. Certainly, to those who benefit from astronomical research — which, it may be argued, is nearly everyone — utilitarian concerns may be considered to be vastly more important than scenic. Consequently, an effort to protect the beauty of the skies can, by inference, be considered to require the protection of the astronomical value of the skies.

Directly relevant as the basis for federal agency protection of full natural landscapes, including the dark night sky, are The Antiquities Act of 1906 establishing National Monuments, The Organic Act of 1916 creating the National Park Service (which now has a Natural Sounds and Night Skies Division), and the Wilderness Act of 1964 with a system now including 803 wilderness areas. The three most recent declarations of National Monuments contained specific reference to the value of pristine night skies.

There are several precedents in Federal regulation and agency policy implementation for protecting dark and quiet skies. 51 USC 50911 explicitly prohibits space-based advertising visible to the naked eye. Congress authorized NASA in 2005 to conduct sensitive surveys in service of planetary defense against near-Earth asteroids. The very fact that light pollution may have an effect on planetary defense supports the need to include as a condition of licensing an obligation to reduce the impact of satellite constellations on astronomy to the greatest degree possible. A National Radio Quiet Zone (RQZ) in West Virginia is established by federal statute. Although it is protected from radio interference only by stationary sources, the principle of having a sensitive zone meriting special protection is valuable.

The National Space Traffic Management (STM) Policy articulates the principles for a safe, stable and sustainable operational space environment. The US National Oceanic and Atmospheric Administration (NOAA) and Federal Aviation Administration (FAA) have recently revised their policies to take these STM principles into account, as did the US Federal Communications Commission (FCC) as part of their licensing considerations. There are three implications for licensing requirements. One is the precedent that these agencies can and do consider at least one aspect of in-orbit operations as a condition of licensing. Another is that aggregate effects can and should be taken into account, relevant to the cumulative impact of all orbital material in brightening the diffuse sky glow. The third is that the FCC can pursue regulations that address perceived issues of the space environment without invoking or relying explicitly on environmental statutes like the National Environmental Policy Act of 1969 (NEPA).

1.3 Considerations Regarding Orbit as Environment

Article III of the OST makes clear that States must carry out activities in outer space in accordance with international law. The effect of this concept was articulated in the the 2018 Guidelines for the Long-Term Sustainability of Outer Space Activities (LTSG) which indicate that States should build upon principles of international law “*when developing and conducting their national activities in outer space.*” In particular, the LTSG recommends that in drafting national legislation, States should address to the extent practicable risks to the environment associated with in-orbit operating and support the idea of minimizing the impacts of human activity on the outer space environment.

The LTSG can be interpreted as requiring, as part of the licensing process, due diligence in respect of potential environmental harm — or the preparation of an environmental impact statement (EIS). A 2018 report prepared by the Secretary General of the UN concluded that the “prevention principle” — the prevention of transboundary harm to the environment — is a well-established rule of customary international law. The UN report further concluded that the prevention principle creates a duty to undertake an Environmental Impact Assessment (EIA) prior to engaging in activities which pose a risk of transboundary harm.

The concept of prevention of transboundary damage suggests that States have a responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or areas beyond the limits of natural jurisdiction. While the US has stated its position that a State is not in general liable for transboundary harm caused by private entities, this precept cannot apply to space activities given the OST Article VI construct which makes States responsible for the private activities of their nationals in space.

As established by SATCON1, large satellite constellations create an environmental impact due to the light pollution generated as a result of the reflectivity factor of the spacecraft. If one accepts the prevention principle as a rule of Customary International Law, adding the OST Article VIII statement that space objects remain within the jurisdiction and control of the State Party who launched it, then it can be surmised that States must work to assure their nationals reduce the potential environmental impact of their in orbit activities.

US law also considers the effect of human activity on the natural environment. NEPA was enacted in recognition, by the US Congress, of the “*profound impact of [hu]man’s activity on the interrelations of all components of the natural environment*”. Within NEPA, the Council on Environmental Quality (CEQ) was created to review all government programs in light of national environmental policy. All federal agencies must consult with the CEQ and complete EISs in respect of any actions that will have a significant effect on the environment.

However, certain definitions used within US environmental policy are unclear, including the definition of “human environment.” While the term suggests a narrow concept of the environment, namely as it directly affects humans, the definition itself places no limits on the concept of natural or physical environment, leaving open the argument that, the use of the word “human” aside, NEPA is intended to cover all of Earth, its orbital environment and all other celestial bodies.

Within these strictures, it is recognized that the FAA construes NEPA and the CEQ Implementing Regulations broadly and indicates, among other things, that it recognizes light emissions as possibly in the environmental impact category. The FCC, which licenses satellite constellations, does not consider its licensing activities to require EISs.

We note that the processes inherent in the application of NEPA address a concern articulated in the Community Engagement report. Consultation is required with impacted stakeholders, which could be extended to indigenous communities with respect to their cultural relationship with natural dark skies. That process could then satisfy some expectations of the UN Declaration on the Rights of Indigenous Peoples (UNDRIP). We also note that the practical production of a full EIS can be a costly and time-consuming endeavor, of concern to industry in a highly competitive environment.

1.4 Industry Perspective

Within the SATCON2 Policy Working Group, the Industry Subgroup brought together industry representatives, astronomers and others to explore the feasibility of recommendations for implementation and where appropriate, to consider how best to advance and refine them. The Industry Subgroup included discussants from SpaceX, Amazon/Kuiper, OneWeb and OneWeb/Airbus, Telesat, AST&Science, and the Satellite Industry Association. The context was to ensure that satellite operators with a sense of a corporate responsibility had access to sufficient insight to astronomical concerns, analytical tools and testing, and cross-industry collaboration for information sharing on mitigation techniques to develop satellite systems mindful of their effect on astronomy. The conclusions do not represent official corporate policy, but rather the continuation of needed technical discussion between industry and the astronomical/dark sky community. They are also an expression of industry intent to be responsive to the technical recommendations of SATCON1 to the extent that solutions are possible and practical, and to generate broader awareness of the impact of their operations on observations and practices dependent on a traditional dark sky.

The Industry Subgroup concluded that satellite operators were more likely to adopt voluntary practices or mitigation tools if they engaged with astronomers early in their project cycle, before spacecraft designs were finalized and when modifications to architectures, spacecraft design or operations could be introduced at less cost or schedule impact. Further, the group concluded that more work was required to ensure that analytical tools, test facilities and observational data are widely available to satellite operators, and are cost-effective, so that their adoption does not disrupt either budgets or schedule for their project.

Building on SATCON1 and the primary concern of brightness, the Industry Subgroup recommends that astronomers continue to develop a hierarchy of additional characteristics of spacecraft, operations and/or altitude for satellites/constellation systems that would indicate to owner/operators either that they have a low/no concern from a reflection perspective, or that they have a high level of concern. These may include key characteristics that exclude/capture a constellation, such as the altitude, number of satellites, design of satellites, and the satellites' shape, surface or materials used. Astronomers should perform the same exercise on the recommendations that apply to them.

The Industry Subgroup also explored the possibility of recommending designs, materials and operations to limit impact on astronomy from cubesats and smaller satellites for remote sensing or Earth imaging. Commercial communications are being launched in larger numbers in the near term and typically weigh more than even the new generation of commercial remote sensing satellites, and should certainly remain

the primary for technical work and stakeholder outreach. However, little technical work has been undertaken on the impact of cubesats and commercial remote sensing satellites, and deployments of both types of satellites are growing rapidly. Developing clear and early guidance would improve awareness and voluntary adoption of techniques among operators of these additional types of satellites that could lessen the impact on astronomy. All projects should be given guidance to minimize reflectivity. All satellite projects should be encouraged to minimize nadir-facing specular surfaces and maintain robust orbital attitude control to minimize flares and glints.

Given that each proposed satellite constellation to date features distinct spacecraft designs, orbital architecture and business model, the assessment of visibility, potential to disrupt optical observation and potential for effective mitigation approaches at pre-deployment phases are best assessed in a customized way, constellation by constellation. A centralized hub for communicating such evaluations would help reduce confusion and speed the process for assessing mitigation strategies. The International Astronomical Union (IAU) has taken the lead in establishing a “Centre for the Protection of the Dark Sky from Satellite Constellation Interference.” It is recommended that operators, as a first step, share and publish their experience and lessons learnt across the community, in order to build understanding of mitigation design techniques and foster innovation in new concepts.

Industry R&D efforts can be focused on the most impactful problems if guided by the development of an “impact metric” to depict the relative effect of satellite visibility on various astronomy fields, not just the types of telescopes or observations, but also their frequency or proliferation. While this may be a problematic value judgement for the astronomy community to adopt broadly, it could be considered on a constellation-by-constellation basis as part of the SatHub concept discussed elsewhere in the SATCON2 workshop.

Ideally, modeling and testing for impacts on astronomy would become routine for satellite constellations, and all satellite operators would interject into the design phase a step to model their spacecraft to predict accurately the likely visibility well before designs are set and any test articles are fabricated. Further, prior to deployment, any demonstration satellites would ideally be subjected to ground testing, as well as the kind of systematic observation measurements of brightness once launched. While testing for reflection and albedo during the development stage is a worthwhile goal, these are relatively new engineering protocols. Given the newer nature of this consideration, additional experience and development are needed to allow for a mature capability to the point where willing satellite operators can readily access reliable and cost effective testing tools.

Satellites deorbiting as part of their end of life (EOL), a requirement for space safety, present several complications for astronomy. For mature constellations that require continuous replacement and EOL maneuvers of satellites, the deorbiting satellites could lead to a non-negligible addition to the bright satellite population. This is expected to be more acute for long deorbiting timescales, even when adhering to the 25-year rule. Moreover, satellites that are passively deorbiting are expected to tumble, which will cause variations in satellite brightness, with the possibility of bright transients. Such variations have the potential to cause significantly greater data loss than those under active control meeting the recommended brightness limit. On-orbit aging of satellites, whether active or defunct, could further lead to changes in satellite brightness or variability. For these reasons, satellite operators should deorbit their satellites as soon as practicable upon satellites reaching their end of mission, consistent with the US government’s Orbital Debris Mitigation Standard Practices (ODMSP) 4-1(a).

Because the technical and practical inquiry into mitigation techniques is still at an early stage, the Industry Subgroup endorses an outcome-driven focus for any mitigation recommendations and guidelines, rather than overly prescriptive language that stipulates a specific technology or technique. The community should continue its work to establish data-driven, well-defined standards and requirements based on continued research, modeling, and analytical efforts, and promote meeting these desired performance-based outcomes. With such dynamism and iteration in mitigation techniques and ongoing work to evaluate their effectiveness, recommendations should incentivize further innovation and leave room for variations in mitigation approaches that may be suitable for different types of constellations and operators.

2. Introduction

Both the SATCON1 and the subsequent Dark and Quiet Skies Workshops identified various recommendations for operators of satellite constellations to consider in order to mitigate their impact on optical astronomy. An emphasis of the SATCON2 Workshop was on paths to implementation of the technical recommendations of SATCON1.

The charge to the SATCON2 Policy Working Group was to review existing national policies and legislative frameworks. With the SATCON1 recommendations as context, the group was charged to assess policy options to serve the diverse requirements of astronomy, the satellite industry, and other communities.

To address these charges, the Working Group focused on three specific areas and structured the work through three subgroups with overlapping membership: international law and policy; US national law and policy; and industry perspective. All three focused their attention on the current playing field, whether in law, policy, or practice, of satellites' effects on ground-based astronomy.

2.1 Industry Subgroup

Within the SATCON2 Policy Working Group, the Industry Subgroup brought together industry representatives, astronomers and others to explore the feasibility of these earlier recommendations for implementation and, where appropriate, to consider how best to advance and refine them. The Industry Subgroup included discussants from SpaceX, Amazon/Kuiper, OneWeb and OneWeb/Airbus, Telesat, AST&Science, and the Satellite Industry Association. Co-conveners were Chris Hofer of Amazon/Kuiper and Patricia Cooper, an industry advisor. The subgroup set out to identify viable tools that willing satellite owner/operators can readily use to evaluate, test, mitigate and field spacecraft in a manner that limits impact on ground-based optical astronomy.

The context was to ensure that satellite operators with a sense of a corporate responsibility had access to sufficient insight to astronomical concerns, analytical tools and testing, and cross-industry collaboration for information sharing on mitigation techniques to develop satellite systems mindful of their effect on astronomy. The conclusions do not represent official corporate policy, but rather the continuation of needed technical discussion between industry and the astronomical/dark sky community. They are also an expression of industry intent to be responsive to the technical recommendations of SATCON1 to the extent that solutions are possible and practical, and to generate broader awareness of the impact of their operations on observations and practices dependent on a traditional dark sky.

The Industry Subgroup noted that since SATCON1 took place in 2020 considerable progress has been made to raise awareness within the communications satellite sector that large constellations of satellites can have adverse impacts on astronomical discovery. Active outreach and engagement by the AAS, the Satellite Industry Association, the National Science Foundation (NSF), the IAU, along with regular discussions at conferences and frequent coverage in trade press and even mass media have improved the likelihood that new satellite operators in the US will consider their impact on astronomical observation when developing a new satellite system. In addition to SpaceX's active engagement over the past two years, others currently deploying or planning satellite broadband constellations are now participating in policy and technical discussions, including Amazon's Kuiper, OneWeb, and others. Further work remains

to engage other newer satellite operators and those proposing constellations for purposes other than communications and broadband.

2.2 International Subgroup

The goal of the authors within the International Law and Policy Subgroup was to:

- identify how international obligations are implemented by US regulatory and policy mechanisms, with specific regard to international space law and international environmental law;
- identify any gaps; and
- suggest where the implementations could be strengthened.

The Convener was Giuliana Rotola, with Vice-Convener Andrew Williams, both of the European Southern Observatory. The members sought a few case studies of space and environmental regulations in other countries to provide supportive comparisons to the US case. There are, at present, no international/multilateral/bilateral agreements or formal understandings of any kind addressing the issue of interference with astronomy. This issue did not emerge until large constellations began deploying into low Earth orbit (LEO). The findings of the authors are preliminary and will be further developed.

2.3 US National Subgroup

The goal of the US National Subgroup was solely to make the policy case for including as a condition of licensing an obligation to reduce detrimental effects² of satellite constellations on astronomy to the greatest degree practicable. The Convener was Michelle Hanlon, co-Director of the Center for Air and Space Law at the University of Mississippi School of Law, with Vice-Convener Joshua Smith, JD, LLM candidate in Air and Space Law at the University of Mississippi. The subgroup considered the FAA and the FCC to be the two agencies most likely to administer such licenses.

The subgroup focused narrowly on the impacts on astronomy of increased light pollution as generated by:

1. the increase in artificial light caused by the sheer volume of satellites which redirect sunlight, adding to the diffuse natural glow of the night sky;
2. reflectivity issues of the individual satellites; and
3. the increase in visual disruption due to the sheer volume of space objects.

² We note that 40 CFR § 1508.8; 48 USC §§4321 *et. seq.* define the term “effects” to include:

A. *Direct effects, which are caused by the action and occur at the same time and place.*

B. *Indirect effects, which are caused by the action and are later in time or farther removed in distance, but are still reasonably foreseeable. Indirect effects may include growth inducing effects and other effects related to induced changes in the pattern of land use, population density or growth rate, and related effects on air and water and other natural systems, including ecosystems.*

Effects and impacts as used in these regulations are synonymous. Effects includes ecological (such as the effects on natural resources and on the components, structures, and functioning of affected ecosystems), aesthetic, historic, cultural, economic, social, or health, whether direct, indirect, or cumulative. Effects may also include those resulting from actions which may have both beneficial and detrimental effects, even if on balance the agency believes that the effect will be beneficial.

The US National Subgroup found a growing recognition of the detrimental effect of light pollution both as an aesthetic matter and specifically as it interferes with astronomy, as evidenced by the implementation of local, state and national ordinances, laws and regulations.

Rationale for the implementation of licensing conditions can also be found in relation to the role astronomy plays in respect of planetary defense, to the extent any detrimental effect is found.

The US National Subgroup made note of the concern that unilateral licensing conditions may cause satellite operators to seek licenses in jurisdictions without such constraints and found that national responsibilities imposed by international treaties may be used to counter this concern. Members also acknowledged that the US is a very attractive market for telecommunications, a benefit which may offer a counterbalance against costs related to an elevated regulatory burden.

The US National Subgroup also considered STM and RQZs as possible models for the development of licensing conditions.

With respect to each policy rationale, a balance must be achieved. The effect and the level of impact reduction must be weighed against the use of satellite constellations to provide broadband to unserved areas of the world providing important life-saving and educational opportunities where they previously did not exist and where other infrastructure possibilities are too impractical to pursue or would be worse for the environment. Moreover, satellites in general are also integral to national security and planetary defense measures.

The US National Subgroup approached its analysis from three different angles:

1. focusing on how satellite constellations are impacting the terrestrial human environment.
2. conceptualizing LEO as part of the human environment; and
3. embracing the perception that LEO is an environment that needs to be protected.

The US National Subgroup did not reach consensus with respect to points two and three.

2.4 Full Policy Working Group

This paper combines the findings of each of the subgroups. The full considerations of each subgroup are contained in the subsequent sections. We also note that there are two outstanding issues that are beyond the current remit but will require consideration:

1. the reality that there currently exists no national or international regulation of on-orbit activities of any kind beyond the OST restriction on the placement of weapons and the general concepts of due regard, harmful contamination, and harmful interference; and
2. the need to aggregate impact and the application of such aggregation in an equitable manner across industry and sovereign States.³

³ See *Friends of the Earth, Inc. v. US Army Corps of Engineers*, 109 F.Supp.2d 30,43 (D.D.C. 2000) (“*the significant cumulative impacts of the multiple casino projects along the coast that the Court has discussed above warrant the preparation of an EIS*”). Here, the court noted that the goal of examining the cumulative impacts of a project is to prevent an actor from engaging in an activity that has a minimal impact on the environment but, when combined with the activity of other actors, results in a significant impact on the environment. *Id.*

In the Policy Working Group's positive engagement among satellite industry representatives, legal/policy scholars and astronomers, no consensus was reached regarding the standards and requirements that might be imposed as part of the licensing conditions. The Policy Working Group takes note of the industry perspective that:

1. such conditions should ultimately be data-driven, well-defined standards and requirements based on continued research, modeling and analytical efforts to better inform and understand this new research area, and encourage operators to share data with the astronomy community;
2. licensing requirements should focus on general design approaches, strategies and performance-based metrics that enable operators to innovate with different mitigation strategies and should not rely on specific, overly-prescriptive mitigations; and
3. over-zealous regulations could result in satellite systems obtaining licenses outside of the US, creating a situation where the US has even less control over constellation impacts.

The structure of the report is as follows: Section II offers a global perspective on efforts and current legal regimes that could be used to mitigate the effects of orbital light pollution; Section III looks specifically at the US laws and policies within its jurisdictional territory regarding light pollution, generally, and how they might be applied to light pollution in orbit; Section IV introduces the industry perspective as prepared by the Industry Subgroup; Section V offers considerations regarding the consideration of orbit as environment; Section VI identifies some key concerns raised in the policy analysis; and Section VII articulates the industry perspective on the challenges of mitigating impacts.

3. International Law and Treaties

3.1 Antarctic Treaty

By the 1940s, seven countries had made territorial claims in Antarctica.⁴ Another five countries operated in Antarctica without making territorial claims.⁵ Moreover, these five countries disregarded the territorial claims made by other countries.⁶ Eventually, the US realized that continuing territorial claims could lead to problems and, in 1947, issued a policy statement advocating international action and agreement to address the Antarctic territorial problem.⁷ In 1959, the US convened the Antarctic Conference that included the countries maintaining operations or claims in Antarctica.⁸ At the Conference, the participating countries adopted the Antarctic Treaty.⁹

The Antarctic Treaty contains fourteen articles.¹⁰ Arguably, the underlying principle of the Treaty establishes Antarctica as a region to be used for peaceful purposes.¹¹ To that end, the Treaty prohibits any claims of sovereignty (though it allowed claims existing at the time of the Treaty's coming into force to remain) and militarization. Indeed, it specifically prohibits military bases or fortifications. It also prohibits nuclear explosions, testing, and waste within the region.¹²

Two additional principles emerge from the Antarctic Treaty. With respect to science endeavors, Articles II and III of the Antarctic Treaty protect the freedom of scientific investigation in Antarctica (Article II) and require cooperation and transparency between State Parties in their scientific research (Article III). Indeed, the Treaty makes clear that scientific observations and results from Antarctica shall be exchanged and made freely available. Article IX reaffirms these concepts and the importance of “*scientific cooperation*,” “*scientific research*” and “*scientific expeditions*” in Antarctica. Additionally, Article IX introduced an environmental component to the Treaty. Specifically, it required further discussion on the “*preservation and conservation of living resources in Antarctica*.”¹³

In essence, the Antarctic Treaty articulates three core principles: peaceful use, scientific exploration, and protection of certain identified components of the environment in Antarctica. Though the Treaty discusses the first two principles more thoroughly and explicitly, the third principle nonetheless clearly emerges — if

⁴ Jonathan Blum, *The Deep Freeze: Torts, Choice of Law, and The Antarctic Treaty Regime*, 8 EMORY INT'L L. REV. 667, 670 (1994); Ottavio Quirico, *Climate Change, Regionalism, and Universalism: Elegy For The Arctic and The Antarctic?*, 35 AM. U. INT'L L. REV. 487, 491 (2020). The countries making territorial claims were Argentina, Australia, Chile, France, Norway, New Zealand, and Great Britain (United Kingdom).

⁵ These were Belgium, Japan, South Africa, the Soviet Union, and the United States.

⁶ Colin Diehl, *Antarctica: An International Laboratory*, 18 B.C. ENVTL. AFF. L. REV. 423, 433.

⁷ Blum, *supra* note 3, at 671.

⁸ Quirico, *supra* note 3, at 492.

⁹ *Id.* Following ratification, it required member states to ensure their activities did not violate the Treaty and encouraged them to implement measures consistent therewith.

¹⁰ Antarctic Treaty, Dec. 1, 1959, 12 UST. 794, 402 U.N.T.S. 71 [hereinafter Antarctic Treaty].

¹¹ Articles I and V of the Antarctic Treaty make clear that Antarctica shall be used solely for peaceful purposes and that State Parties shall not place or test nuclear weapons in the region.

¹² Antarctic Treaty, art. V.

¹³ *Id.*, art. IX.

only as an invitation for further discussion. Each of these three principles contributes to the OST that followed less than a decade later. As articulated below, the last two principles provide policy support to the need to protect Earth's dark skies.

3.2 The Outer Space Treaty: Freedom of Exploration and Use, and Limitations

Indeed, the principles of the Antarctic Treaty connect to those of the OST, elaborated within the United Nations Committee on the Peaceful Uses of Outer Space ("COPUOS"), and which entered into force in 1967.¹⁴ The OST is a legal instrument that is binding on the States that have signed and ratified it (110 ratifications and 23 signatures to date¹⁵), with the foundational principles of the OST and related UN space treaties regarded as customary international law, binding *all* States¹⁶.

Additional international developments moved the international community toward a space treaty. After the launch of the first artificial satellite in 1957, the international community and, more specifically, the United Nations recognized a need to establish regulations regarding space activities.¹⁷ In 1961, as the joint initiative of the US and the former Soviet Union, the United Nations established COPUOS. The United Nations tasked COPUOS with establishing regulations for the peaceful uses, scientific exploration, and protection of space and celestial bodies.¹⁸ COPUOS directed its Legal Subcommittee to consider and enact rules that would be harmonious between the actors of the international community that intended to use space. The same year, the United Nations General Assembly adopted Resolution 1721 relating to the peaceful uses of outer space.

In 1962, following comments from Soviet Chairman Krushchev, US President Kennedy proposed cooperation with the former Soviet Union on space science which led to agreement on four specific projects. Both countries also expressed their intentions "*not to station in outer space any objects carrying nuclear weapons or other kinds of weapons of mass destruction.*"¹⁹ The next year, the United Nations General Assembly adopted Resolution 1884 on the Question of General and Complete Disarmament that specifically acknowledged the expressions of the US and Soviet Union as well as calling upon all States to do the same. The United Nations General Assembly also adopted Resolution 1962 on the Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space.²⁰

¹⁴ Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, Jan. 27, 1967, 18 UST. 2410, 610 U.N.T.S. 205 [hereinafter Outer Space Treaty].

¹⁵ "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies". United Nations Office for Disarmament Affairs https://treaties.unoda.org/t/outer_space.

¹⁶ Jakhu, Ram S. and Freeland, Steven, The Relationship Between the Outer Space Treaty and Customary International Law (2016). <http://dx.doi.org/10.2139/ssrn.3397145>.

¹⁷ Chairman, Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space (COPUOS), *Treaty On Principles Governing The Activities Of States In The Exploration And Use Of Outer Space, Including The Moon And Other Celestial Bodies*, at 1, (2008).

¹⁸ *Id.*

¹⁹ G.A. Res. 1884 (XVII), Question of General and Complete Disarmament (Oct. 17, 1963).

²⁰ Chairman, Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space (COPUOS), *Treaty On Principles Governing The Activities Of States In The Exploration And Use Of Outer Space, Including The Moon And Other Celestial Bodies*, at 2 (2008).

Subsequently, in 1966, US President Johnson announced the need for a treaty relating to the exploration of space and proposed that international discussions begin to facilitate that purpose.²¹ In doing so, he proposed six elements to be included:

(1) freedom of exploration, (2) prohibition of claims of sovereignty, (3) freedom of scientific investigation and international cooperation, (4) studies to avoid harmful contamination, (5) mutual assistance among astronauts in case of need, and (6) a ban on the stationing of weapons of mass destruction, weapons tests and military maneuvers on celestial bodies.²²

These elements echo the Antarctic Treaty principles of peaceful purposes,²³ scientific exploration, and matters related to the environment.²⁴

In fact, congressional testimony supporting adoption of the treaty that followed President Johnson's directive clearly indicates that the Antarctic Treaty served as a foundation for the OST.²⁵ US Ambassador Arthur J. Goldberg made clear that the authors of the provisions focused on arms control, prohibitions on military fortifications, maneuvers, and weapons on celestial bodies, and the use of celestial bodies only for peaceful purposes drew from the corresponding provisions of the Antarctic Treaty.²⁶ A review of the relevant articles in the treaties further demonstrates this connection.²⁷ Specifically, Article IV of the OST correlates directly to Article I of the Antarctic Treaty in articulating that each respective area shall not be militarized and shall only be used for scientific and peaceful purposes.²⁸

Further, Ambassador Goldberg stated that the provisions for "*freedom of scientific investigation in outer space*," "*international co-operation in such investigation*"²⁹ and the ability to use military in such investigations originate from the Antarctic Treaty.³⁰

Article I of the OST establishes which activities are allowed in space, affirming the freedoms of exploration and use of outer space, the freedom of access to all the areas of celestial bodies, and the freedom of scientific investigation in outer space. Astronomical observations and satellite constellations constitute two legitimate ways of exploring and using outer space. However, coordination mechanisms are required to limit the impact and negative consequences caused by the interference between the two activities.

²¹ *Id.* at 151.

²² *Id.*

²³ In his United States Senate testimony in favor of the Outer Space Treaty, then-NASA Administrator James Webb indicated that the drafters adopted a principle first articulated in the National Aeronautics and Space Act of 1958. *Treaty on Outer Space: Hearings Before the Committee on Foreign Relations United States Senate*, 90th Cong. 157-158 (1967) (Referring to National Aeronautics and Space Act of 1958, P. L. No. 85-568, 72 Stat. 426-438, § 102).

²⁴ See *supra* and generally Antarctic Treaty art. 1, 2, and 4, Dec. 1, 1959, 12 U.S.T. 794, 402 U.N.T.S. 71.

²⁵ 90th Cong., *supra* note 1, at 80 (testimony of Deputy Secretary of Defense Cyrus R. Vance).

²⁶ *Id.* at 149, 153.

²⁷ Not surprisingly, the procedural provisions in the OST reflect nearly verbatim those of the Antarctic Treaty. Outer Space Treaty, art. 13-17; Antarctic Treaty, 11-14.

²⁸ Outer Space Treaty, art. I; Antarctic Treaty, art. 4.

²⁹ Outer Space Treaty, art. 1.

³⁰ 90th Cong., *supra* note 21 at 53, 154.

The scope of the following analysis is to verify whether the US national space legislation and policies meet the obligations deriving from the treaty mentioned above or whether the relevant provisions need further implementation. As stated in Article I:

*The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the province and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all (human)kind. Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies. There shall be freedom of scientific investigation in outer space, including the Moon and other celestial bodies, and States shall facilitate and encourage international cooperation in such investigation.*³¹

The fundamental freedoms recalled by Article I are not absolute but subject also to the freedoms of other actors, whether their activities are ground-³² or space-based. Indeed, the first limitations indicated by Article I are that such activities must take place for the benefit and in the interests of all countries. These must also happen on the basis of equality and in accordance with international law.³³ Such consideration is recalled in Article III of the OST, which affirms the applicability of international law, including the Charter of the United Nations, to the activities of exploration and use of outer space.³⁴

The last sentence of Article I states that “[t]here shall be freedom of scientific investigation in outer space” and that “States shall facilitate and encourage international co-operation in such investigation.”³⁵ This aspect is exceptionally relevant to mitigating the impact that satellite constellations may have on astronomy, which could be partially mitigated with a continuous exchange of information and data.

Further, Article XI of the OST and Article III of the Antarctic Treaty detail international scientific cooperation in reporting experiments and respecting the research of other countries.³⁶

Finally, with respect to the principle relating to matters of the environment, Article IX of both the Antarctic Treaty and the OST articulate their respective concerns.³⁷ The Antarctic Treaty focuses on the “*preservation and conservation of living resources in Antarctica*.” Within the OST, Article IX requires

³¹ Outer Space Treaty, art. I.

³² Ground-based activities can be considered “space activities” when they are supporting a space activity in-orbit, or directly associated with it. [Citation for explanatory footnote?]

³³ COLOGNE COMMENTARY ON SPACE LAW # (Stephan Hobe, Bernhard Schmidt-Tedd, Kai-Uwe Schrogl eds., 2009). [need pin cite-Art I]

³⁴ Outer Space Treaty, art. III.

³⁵ This principle recalls the similar dictate of the earlier Antarctic Treaty of 1959, which revolves around the same direction. It states that “*Freedom of scientific investigation in Antarctica and cooperation toward that end... shall continue....*” The Antarctic Treaty also goes beyond this statement, affirming that in addition to the original signatories, the participation in the Treaty is limited to actors who can demonstrate their scientific interest in Antarctica by carrying out meaningful scientific research. This principle could not similarly be applied to space, given the freedom of access established in Article I OST. However, both treaties support research and science concepts and cooperation, emphasizing how collaboration, the exchange of data, observations, and results are essential for scientific development. See *Antarctic Treaty System*, SCAR, <https://www.scar.org/policy/antarctic-treaty-system/> (last accessed Aug. 21, 2021).

³⁶ Outer Space Treaty, art. XI; Antarctic Treaty, art. 3.

³⁷ Outer Space Treaty, art. IX; Antarctic Treaty art. 9.

States Parties to conduct exploration of celestial bodies in a manner such as to avoid their contamination as well as to avoid adverse changes in Earth's environment, albeit through the introduction of extraterrestrial material.

It is noteworthy that unlike the Antarctic Treaty, the OST recognizes in Article I the importance of both “*exploration*” and “*use*” of outer space for peaceful purposes. Throughout the treaty, the word “*exploration*” is tied to the word “*use*” of space. The treaty is specifically designed to balance scientific research with other benefits to be derived from the “*use*” of space.

3.2.1 Article IX of the Outer Space Treaty

The environmental protection arising from Article IX of the OST deserves a bit more focused attention. Article IX states in relevant part:

*In the exploration and use of outer space, ... States Parties to the Treaty ... shall **conduct all their activities in outer space, ... with due regard to the corresponding interests of all other States Parties to the Treaty.** States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination ... If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, ... would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space ... it shall undertake appropriate international consultations before proceeding with any such activity or experiment....*³⁸

At the outset, States Parties to the OST must: 1) “*conduct **all** their activities* [whether by government agencies or non-governmental entities]³⁹ *in outer space with due regard to the corresponding interests of all other States Parties to the Treaty;*”⁴⁰ and 2) presumably avoid harmful interference with the activities of another.

Per the Permanent Court of Arbitration,

... the ordinary meaning of “due regard” calls for the [first State] to have such regard for the rights of [the second State] as is called for by the circumstances and by the nature of those rights. The Tribunal declines to find in this formulation any universal rule of conduct. The Convention does not impose a uniform obligation to avoid any impairment of [the second State’s] rights; nor does it uniformly permit the [first State] to proceed as it wishes, merely noting such rights. Rather, the extent of the regard required by the Convention will depend upon the nature of the rights held by [the second State], their importance, the

³⁸ *Id.* (emphasis added).

³⁹ Outer Space Treaty, art. VI (emphasis added). Article VI of the OST expressly states that each State shall be responsible for its national activities whether “*carried on by governmental agencies or by non-governmental entities.*” *Id.* at art. VI.

⁴⁰ Outer Space Treaty, art. IX.

*extent of the anticipated impairment, the nature and importance of the activities contemplated by the [first State], and the availability of alternative approaches.*⁴¹

This language suggests that the US and other States Parties to the OST have an obligation to consider the corresponding interests of other States in respect of potential light pollution created by satellite constellations. This language could also be used to encourage other States to adopt licensing conditions that will lessen the impact of satellite constellations on astronomy — anywhere in the world — to the greatest degree possible.

Additionally, Article IX of the OST compels States Parties to at least engage in a consultation prior to causing harmful interference with the activities of another. Again, this provision can be read to indicate that the US and other States Parties to the OST have an obligation to consider the corresponding interests of other States in respect of potential light pollution created by satellite constellations. This language could also be used to encourage all States to adopt licensing conditions that will lessen the impact of satellite constellations on astronomy — anywhere in the world — to the greatest degree possible.

3.2.2 Article II and the Non-Appropriation Principle

Another of the most relevant limitations to the activities of States and other actors in the exploration and use of outer space can be found in Article II OST, which establishes “**Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.**”⁴²

The term “*national*” recalls what is subsequently stated in Article VI of the OST regarding the international responsibility of States for national activities, and therefore can be interpreted to impose on them an obligation to verify that such appropriation activities do not take place by their own national actors or by the organizations to which they belong.⁴³

In the current interpretation, no use or occupation of outer space could, in fact, constitute appropriation of outer space since it refers only to a limited part of it.⁴⁴ However, there are two considerations to make: the first is that although legitimate, these uses of space and partial occupations must always be read also in the light of the other provisions of the treaty, and therefore must, in any case, occur according to principles of fairness and having regard to the interest of the other actors. Secondly, satellite constellations raise new questions about the possibility of using large portions of outer space, whose access, use, and scientific investigation are hindered to other stakeholders, including the astronomy community.

Indeed, the current allocation practices for orbital slots and frequency spectrum in the low orbital region, including the FCC assigning procedures, are based on a “first come, first served” principle, which in the

⁴¹ In the Matter of the South China Sea Arbitration (Republic of the Philippines v People’s Republic of China), para. 742 (12 July 2016) *citing* Chagos Marine Protected Area Arbitration (Mauritius v United Kingdom), para. 519 (18 March 2015).

⁴² Outer Space Treaty, art. II (emphasis added).

⁴³ COLOGNE COMMENTARY ON SPACE LAW, *supra* note 30, at #. [Need pin cite – art II]

⁴⁴ *Id.*

long term could cause the exclusion of some space actors and an appropriation of orbital planes by satellite constellation operators while the satellites in those constellations remain in orbit.

The US Space Policy Directive (SPD) 3, published in June 2018 and concerning STM, refers to the volume of space used by large constellations, promoting best practices for improving strategies for STM, and favoring the coordination of satellite operators.⁴⁵

The United States should explore strategies that will lead to the establishment of common global best practices, including:

A common process addressing the volume of space used by a large constellation, particularly in close proximity to an existing constellation;

A common process by which individual spacecraft may transit volumes used by existing satellites or constellations; and

A set of best practices for the owner-operators of utilized volumes to minimize the long-term effects of constellation operations on the space environment (including the proper disposal of satellites, reliability standards, and effective collision avoidance).⁴⁶

However, improving coordination between in-orbit activities does not necessarily mitigate harmful interference with ground-based astronomical activities.

One potential way to address the management of satellite constellation volume is to limit orbital slots. Other common processes could be established that also include other actors, including ground-based astronomy, such as providing public data about spacecraft trajectories. Purely technical solutions, such as better orbit determination, may only displace the problem, or from the astronomer's point of view, make the problem worse, as more satellites might safely occupy a given volume.

It was noted that SPD 3 considers the promotion of best practices within the context of national interests.

Given the significance of space activities, the United States considers the continued unfettered access to and freedom to operate in space of vital interest to advance the security, economic prosperity, and scientific knowledge of the Nation.⁴⁷

To that end, SDP 3 itself promotes principles that encourage the safe and sustainable operation of the outer space environment, affirming:

Safety, stability, and operational sustainability are foundational to space activities, including commercial, civil, and national security activities. It is a shared interest and responsibility of all spacefaring nations to create the conditions for a safe, stable, and operationally sustainable space environment.⁴⁸

The conditions for a safe, stable and sustainable environment, however, should not ignore considerations regarding the impact that space activities, albeit coordinated, can have on ground-based activities and should not overlook the application of fundamental international principles of law for the development of exploration and use of space, such as the non-appropriation principle mentioned earlier, correlated with freedom of access, principles of fairness and regard for the interests of other actors.

⁴⁵ Space Policy Directive-3 of June 18, 2018, 83 Fed. Reg. 28969 (Jun. 21, 2018).

⁴⁶ *Id.*

⁴⁷ *Id.*

⁴⁸ *Id.*

3.2.3 Article VI and the Obligation to Maintain “Continuing Supervision” over National Space Activities

Historically noted as a core compromise to achieve fruition,⁴⁹ the legal principles contained in Article VI of the OST,⁵⁰ namely (a) international responsibility for national space activities; and (b) authorization and continuing supervision of such activities by a State, provide two important safeguards for the conduct of space activities by non-governmental entities of a State. The US position has always been that private agencies would not be free to engage in space programs without governmental permission and continuing governmental supervision.⁵¹ And indeed, the US has the most robust space regulatory framework in the world.

For the purposes of this report, the obligation of the US government to maintain “continuing supervision” over the space activities of its private actors assumes prime importance. In the view of the authors of this paper, such an obligation entails the attention of the US government in ascertaining the impact of in-orbit operational phases of commercial satellites of large-scale constellations.

At this juncture, the authors of this paper note with appreciation all actions (legislative, policy, directives, and implementation) of the US government in pursuance to its overall objective of safe and sustainable use of outer space by authorizing and licensing the space activities of its private actors,⁵² including its efforts to sustain the conduct of EIAs for its space activities:

§ Council on Environment Quality, Executive Order of the President – Regulations for Implementing the Procedural Provisions of the National Environmental Policy Act, 40 CFR Parts 1500 – 1508;

⁴⁹ See generally, Comm. on the Peaceful Uses of Outer Space, Summary Record of the Twenty-Second Meeting, 4–5, U.N. Doc. A/AC.105/C.2/SR.22 (April 26, 1963); see also, Letter from the Permanent Representatives of the Union of the Soviet Socialist Republics and the United States of America, U.N. Doc. A/5482 (Aug. 22, 1963).

⁵⁰ Outer Space Treaty, art. VI (“*States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty.*”)

⁵¹ Comm. on the Peaceful Uses of Outer Space, Summary Record of the Twenty-Second Meeting, U.N. Doc. A/AC.105/C.2/SR.20 (27 June 1963) at 12: “*The sixth principle in the United States draft declaration dealt with international responsibility. It was recognized that in some instances a governmental authority might choose to license a private firm to carry out activities in space. Such private agencies would not be free to engage in space programmes without governmental permission and continuing governmental supervision. The principle of national responsibility for national space activities was embodied in the United States Communication Satellite Act of 1962*”; see also, Comm. on the Peaceful Uses of Outer Space Verbatim Record of the Thirtieth Meeting, 4-5, U.N. Doc. A/AC.105/PV.30 (Dec. 8, 1964).

⁵² See e.g., 51 USC § 50906 (2010). In the US, the Commercial Space Launch Act of 1984 (CSLA) authorized the FAA to license the launch and re-entry of expendable and reusable vehicles, as well as the operation of a launch or re-entry site by a US citizen irrespective of whether the launch site is within or without the US.

§ NASA's Project Review Model based on NASA NPR 8580.1A – Implementing the National Environmental Policy Act and Executive Order 12114 (please also see Annex I at the end of this document); and
§ FAA Order 1050.1F, Paragraphs 3-1.2 (15), and 3-1.3 (2).

However, it is also equally important to note that while the National Aeronautics and Space Administration (NASA) — a US governmental entity, and thus outside the scope of regulation under Article VI of the OST — conducts separate assessments pertaining to the environmental impact of its activities (governmental projects, defense applications, etc.). The FAA conducts similar assessments pertaining to (i) issuance of a commercial space launch site operator license; (ii) launch licenses; and (iii) experimental permits to support activities requiring the construction of a new commercial space launch site on undeveloped land. A gap, identified by the authors, is the requirement to conduct an EIA of space activities of commercial entities (which entities satisfy, for the US government, the international responsibility criterion under Article VI of the OST⁵³) pertaining to their on-orbit operations in the outer space environment.

Moreover, authors of this paper note that it is not particularly relevant here to discuss and debate the terminology (“environmental impact assessment” or “impact of human activities in Earth environment as well as the outer space environment”) as it is being sufficiently covered in other sections of the entire report and also being presented as different options for the US government to pick and choose as per its policy initiative and requirements.⁵⁴ It is also important to note here that the manner in which national laws implement a State’s international obligation relating to authorization and continuing supervision does not in any way affect the nature of that obligation under international law.⁵⁵

The LTSG provides, in Guideline A.3 (supervise national space activities), the need for States to supervise the space activities of its non-governmental entities, and to (a) develop specific procedures and requirements to address safety and reliability of outer space activities *during all phases of a mission life cycle*; (b) assess all risks to the long-term sustainability of outer space activities associated with the space

⁵³ Outer Space Treaty, art. VI (“*States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty.*”)

⁵⁴ See G.A. Res. 68/74, para. 4 (Dec. 16, 2013) (“*The conditions for authorization should be consistent with the international obligations of States, in particular under the United Nations treaties on outer space, and with other relevant instruments, and may reflect the national security and foreign policy interests of States; the conditions for authorization should help to ascertain that space activities are carried out in a safe manner and to minimize risks to persons, the environment or property and that those activities do not lead to harmful interference with other space activities; such conditions could also relate to the experience, expertise and technical qualifications of the applicant and could include safety and technical standards that are in line, in particular, with the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space.*”)

⁵⁵ See Vienna Convention on the Law of Treaties, art. 27, May 23, 1969 1155 U.N.T.S. 331; see also, 51 USC § 60122 (wherein the regulations governing the licensing of private remote sensing systems in the US note that the “*responsibility falls to the [US] Government with respect to the activities in outer space of private entities subject to US jurisdiction*”, and such responsibility is fulfilled through issuing and enforcing licenses for the “*operations of such systems*”).

activities conducted by [an] entity, in *all phases of the mission life cycle*, and take steps to mitigate such risks to the extent feasible.⁵⁶

Evidence of current and potential interference to astronomy is being submitted by the AAS and other stakeholders, so the obligation of the US government to maintain “continuing supervision” could be interpreted, at the very least, as demanding a thorough inspection into this matter and further consideration of appropriate measures to safeguard its own interests as well as those of all its actors, governmental and non-governmental entities alike. As discussed in relevant sections below, a good starting point would be to conduct due diligence into the activities of commercial satellite operators, and specifically regarding the impact of in-orbit operation of such activities.

3.3 Equitable Access to Orbital Resources

A change would likewise be necessary at the international level to ensure that the first-come, first-served allocation practices are gradually replaced with more equitable procedures capable of responding to the emerging needs prompted by the spread of satellite constellations.

As mentioned above, current allocation practices for orbital slots in non-geosynchronous orbits are solely based on coordinated allocation mechanisms, which respond to the needs of efficiency in orbit distributions, but not to equitable interests. There is, however, no formalized allocation procedure for non-geostationary satellites. Rather, there are only International Telecommunications Union (ITU) requirements to coordinate around certain frequencies.⁵⁷

On the other hand, considerations of equitable access are considered for allocating radio frequency spectrum and orbital slots in geostationary orbit (GSO), as provided by article 44 of the Constitution of the ITU, which states:

1. *Member States shall endeavor to limit the number of frequencies and the spectrum used to the minimum essential to provide in a satisfactory manner the necessary services. To that end, they shall endeavor to apply the latest technical advances as soon as possible.*
2. *In using frequency bands for radio services, Member States shall bear in mind that radio frequencies and any associated orbits, including the geostationary-satellite orbit, are limited natural resources and that they must be used rationally, efficiently and economically, in conformity with the provisions of the Radio Regulations, so that countries or groups of countries may have equitable access to those orbits and frequencies, taking into account the special needs of the developing countries and the geographical situation of particular countries.*

The recognition of GSO's limited nature and the consequent determination to establish a system that guarantees the allocation and use of this resource rationally, efficiently and economically, and based on the principle of equity, occurs during the World Administrative Radio Conference for Space

⁵⁶ Comm. on the Peaceful Uses of Outer Space, Guidelines for the Long-term Sustainability of Outer Space Activities, Guideline A.3, paras 2(b-c), U.N. Doc. A/AC/105/2018/CRP.20 (emphasis added.) [hereinafter LTSG]

⁵⁷ See *Non-geostationary satellite systems*, ITU, <https://www.itu.int/en/mediacentre/backgrounders/Pages/Non-geostationary-satellite-systems.aspx> (last accessed Aug. 17, 2021).

Telecommunications, held in Geneva in 1971. The final acts of the Conference, at Resolution No. Spa2-1, affirm:⁵⁸

The World Administrative Radio Conference for Space Telecommunications (Geneva, 1971),

- *considering that all countries have equal rights in the use of both the radio frequencies allocated to various space radiocommunication services and the geostationary satellite orbit for these services;*
- *taking into account that the radio frequency spectrum and the geostationary satellite orbit are limited natural resources and should be most effectively and economically used;*
- *having in mind that the use of the allocated frequency bands and fixed positions in the geostationary satellite orbit by individual countries or groups of countries can start at various dates depending on requirements and readiness of technical facilities of countries;*

Resolves

1. *... that the registration with the I.T.U. of frequency assignments for space radiocommunication services and their use should not provide any permanent priority for any individual country or groups of countries and should not create an obstacle to the establishment of space systems by other countries;*
2. *that, accordingly, a country or a group of countries having registered with the I.T.U. frequencies for their space radiocommunication services should take all practicable measures to realize the possibility of the use of new space systems by other countries or groups of countries so desiring;*
3. *that the provisions contained in paragraphs 1 and 2 of this Resolution should be taken into account by the administrations and the permanent organs of the Union.*

These considerations indeed find their basis in the immediately preceding ratification of the OST in 1967, to guarantee the respect of the fundamental freedoms recalled, in particular by Article I, and the relative limitations, such as the prohibition of national appropriation established in Article II, and to ensure that the exploration and use of outer space are effectively provinces of all humankind and that equal benefits and rights are granted to all countries, regardless of their level of economic and technological development.⁵⁹ The current assignment procedures in the GSO, which do not allow the permanent assignment of orbital positions, are in any case due to the physical characteristics of this orbit, which is spatially limited and offers an optimal position for certain services, basically communication services, characteristics that cannot always be found in different orbits, such as LEO. However, the emergence of mega-constellations of satellites could call these considerations into question, given the progressively higher number of objects in orbit, their permanence, and the consequent inaccessibility to the same resources in an equitable manner by other actors, including the astronomy community.

⁵⁸ ITU, FINALS ACTS OF THE WORLD ADMINISTRATIVE RADIO CONFERENCE FOR SPACE TELECOMMUNICATIONS 311-12 (1971).

⁵⁹ Matteo Cappella, *The principle of equitable access in the age of mega-constellations*, in # Legal Aspects Around Satellite Constellations (Annette Froelich ed., 2019).

3.4 Astronomy and Planetary Defense

Astronomy plays an integral role in planetary defense. Thus, as a policy consideration, planetary defense considerations support the inclusion, as a condition of licensing, of an obligation to reduce the impact (if any) of satellite constellations on telescopes used for planetary defense to the greatest degree possible.

Planetary defense involves the detection and characterization of Near-Earth Objects (NEOs) and, if needed, the mitigation or management of Earth impacts. While a NEO making impact is functionally in line with a traditional natural disaster, it is rhetorically linked to an act of war.⁶⁰

Large satellite constellations may impact the effectiveness of planetary defense, which relies on astronomy as one of its principal tools. As discussed in the US policy section below, such interference has broad implications for public policy and disaster management.

International coordination for planetary defense is through the United Nations Office of Outer Space Affairs (UNOOSA). Upon the recommendation of the COPUOS, two collaborative bodies were established to strengthen international cooperation on NEO studies: the Space Mission Planning Advisory Group (SMPAG) and the International Asteroid Warning Network (IAWN).

SMPAG is an advisory group composed of space agencies from Member States. As UNOOSA explains:

*[SMPAG's] responsibilities include laying out the framework, timeline and options for initiating and executing response activities, informing the civil-defense community about the nature of impact disasters and incorporating that community into the overall mitigation planning process through an impact disaster planning advisory group.*⁶¹

Two things should be kept in mind: SMPAG is advisory only and does not have any decision-making authority; and SMPAG does not have direct industry involvement, and the roles of industry and [NewSpace](#) on planetary defense efforts are not internationally coordinated.

The second forum for international cooperation on planetary defense is IAWN, which is a:

*virtual network linking together the institutions performing functions such as discovering, monitoring and physically characterizing the potentially hazardous near-Earth object population and maintaining an internationally recognized clearing house for the receipt, acknowledgment and processing of all near-Earth object observations.*⁶²

Participation in the IAWN network is open to applicants, requiring a signed commitment to IAWN's charter and Statement of Intent. The IAWN Steering Committee decides whether to admit the applicant as a member. As a result of this process, IAWN network participation ranges from amateur astronomers, to

⁶⁰ Andrea Harrington, *National and International Security in Space: International Law Implications of Space Force and Planetary Defense*, 48 GA. J. INT'L. COMP. L. 767, 770 (2020).

⁶¹ SMPAG, UNOOSA, <https://www.unoosa.org/oosa/en/ourwork/topics/neos/smpag.html> (last accessed Aug. 21, 2021).

⁶² IAWN, UNOOSA, <https://www.unoosa.org/oosa/en/ourwork/topics/neos/iawn.html> (last accessed Aug. 21, 2021).

major observatories and national space agencies.⁶³ IAWN's role is one of information sharing and cooperation, but again it does not have decision-making authority.

Fostering international cooperation and maintaining efficient ways to promote information sharing is of general importance to the international community, as demonstrated by UN General Assembly Resolution 73/91:

[The General Assembly] reiterates the importance of information-sharing in discovering, monitoring and physically characterizing potentially hazardous near-Earth objects to ensure that all countries, in particular developing countries with limited capacity for predicting and mitigating a near-Earth object impact, are aware of potential threats, emphasizes the need for capacity-building for effective emergency response and disaster management in the event of a near-Earth object impact, and notes with satisfaction the work carried out by the International Asteroid Warning Network and the Space Mission Planning Advisory Group to strengthen international cooperation to mitigate the potential threat posed by near-Earth objects, with the support of the Office, serving as the permanent secretariat of the Advisory Group” (paragraph 10).⁶⁴

Nonetheless, despite a general view of the importance of planetary defense, there is a lack of international policy. Decision making is ultimately a national matter. Thus, as discussed in the US policy section, the 2018 US National NEO Preparedness Strategy and Action Plan (AP) Goal 1: Enhance NEO Detection, Tracking, and Characterization Capabilities will be directly affected. Mistaking a satellite as an NEO is not the concern. Rather, it is the loss of detection efficiency as a direct result of data loss. A way to think about the effects of data loss is, instead, a loss of time. As the AP explains:

Early detection and characterization of hazardous NEOs increases the time available to make decisions and take effective mitigating action, and it is the first priority for planetary defense.⁶⁵

Indeed, a persistent theme that arises from the planetary defense tabletop exercises, held every two years, is the need for observational follow up after the discovery of a potential impactor. Through the participation of multiple IAWN members, some inefficiencies in data collection can be tolerated. However, the initial discovery of a *hazardous* impactor could be delayed.

There could also be issues with “precoveries,” i.e., an often-used technique that relies on searching through archival data for the object, which had previously missed detection. Such lack of detections will be common for faint objects, and precoveries rely on having information about where the object should be, within some uncertainty. The object might not even be noticeable in a single image, relying instead on combining multiple images to obtain sufficient signal relative to the noise. If large fractions of archival data cannot be searched for faint objects, then this important component of planetary defense could be partially compromised.

⁶³ *Id.*

⁶⁴ G.A. Res. 73/91, International Co-operation in the Peaceful Uses of Outer Space (Dec. 18, 2018); see also Comm. on the Peaceful Uses of Outer Space, Report of the Scientific and Technical Subcommittee on its fifty-fourth session (Jan. 10–Feb. 10, 2017).

⁶⁵ <https://www.nasa.gov/sites/default/files/atoms/files/ostp-neo-strategy-action-plan-jun18.pdf>

Altogether, we do not expect mega-constellations to prevent planetary defense from operating. Rather, it will cause delays in the identification of objects, under certain conditions, which may have widespread ramifications if an object is on an Earth-impact trajectory. This will further affect responses by numerous US government agencies and could delay an internationally coordinated response.

3.5 Astronomy, Planetary Protection, and the Contamination of the Night Sky

The authors considered whether PPP might provide considerations for the impacts of satellite constellations on astronomy. The motivation is that satellite constellations have the potential to contaminate the night sky and cause harm to astronomical observations, as well as the enjoyment of the night sky. As PPP seeks to protect Earth from “*harmful contamination*” due to space activities, it is instructive to examine whether PPP might be applied in this context.⁶⁶

PPP was developed to address the potential for spaceflight and space exploration missions to contaminate the Moon and other celestial bodies, compromising future missions. It was also developed to address concerns over the introduction of potentially dangerous extraterrestrial matter to Earth. The Committee on Space Research (COSPAR) is the primary international forum for developing international PPP, and its policy is written to guide compliance with Article IX of the OST; namely,

*States Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose.*⁶⁷

The most recent COSPAR PPP was updated and approved in 2017.⁶⁸ The preamble of the PPP notes that:

*COSPAR maintains and promulgates this planetary protection policy for the reference of spacefaring nations, both as an international standard on procedures to avoid organic-constituent and biological contamination in space exploration, and to provide accepted guidelines in this area to guide compliance with the wording of this UN Space Treaty and other relevant international agreements.*⁶⁹

What the above makes clear is that while COSPAR PPP is concerned with “*harmful contamination*,” it does so in the context of introducing extraterrestrial materials to Earth or contaminating celestial bodies with organic material from Earth. With this scope, COSPAR PPP is not inherently intended to protect Earth from other forms of harmful contamination resulting from space exploration.

⁶⁶ G. Kminek, C. Conley, V. Hipkin, H. Yano, *COSPAR’s Planetary Protection Policy* (2017), available at <https://cosparhq.cnes.fr/assets/uploads/2019/12/PPPolicyDecember-2017.pdf>.

⁶⁷ Outer Space Treaty, art. IX.

⁶⁸ G. Kminek, C. Conley, V. Hipkin, H. Yano, *COSPAR’s Planetary Protection Policy* (2017), available at <https://cosparhq.cnes.fr/assets/uploads/2019/12/PPPolicyDecember-2017.pdf>.

⁶⁹ G. Kminek, C. Conley, V. Hipkin, H. Yano, *COSPAR’s Planetary Protection Policy* (2017), available at <https://cosparhq.cnes.fr/assets/uploads/2019/12/PPPolicyDecember-2017.pdf>.

COSPAR PPP itself sets forth guidelines, and it is the responsibility of States to establish their own PPP requirements. In December 2020 the US released its National Strategy for Planetary Protection (US NSPP)⁷⁰ which is intended to address, in part, the 2020 National Space Policy call “[to develop] *national and international planetary protection guidelines, working with scientific and commercial partners, for the appropriate protection of planetary bodies and Earth from harmful biological contamination.*”⁷¹

The US NSPP states that:

*The practice of planetary protection is grounded in the premise that life may exist beyond the Earth’s biosphere. Should life exist elsewhere in the universe, measures to avoid the introduction of external contaminants are necessary in order to protect life on Earth and ensure the validity of any scientific study related to such a discovery. In essence, planetary protection refers to the policies and practices related to two aspects of space exploration. First, planetary protection aims to protect future scientific investigations by limiting the forward biological contamination of other celestial bodies by terrestrial lifeforms. Second, planetary protection aims to protect Earth’s biosphere by preventing the backward biological contamination of Earth by returning spacecraft and their payloads.*⁷²

Again, we see that the emphasis of PPP as written is on biological contamination through the introduction of organic material and is not intended to protect Earth from other forms of harmful contamination.

However, it must be kept in mind that PPP, including COSPAR PPP and the US NSPP, is policy that is intended to augment Article IX of the OST:

*States Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose.*⁷³

Here, we see the reference to adverse changes in the environment of Earth resulting from “*the introduction of extraterrestrial matter.*” This is consistent with PPP. In contrast, “*harmful contamination*” is not so clearly defined and requires further clarification. With this in mind, PPP results from only one interpretation of “*harmful contamination.*” This phrasing is also used to describe how we should “*pursue studies of outer space*” and “*conduct exploration.*” Article IX continues:

If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with

⁷⁰ Nat’l Space Council, *National Strategy for Planetary Protection* (2020).

⁷¹ President Donald Trump, National Space Policy, Dec. 9, 2020, *available at* <https://www.space.commerce.gov/policy/national-space-policy/> (last accessed Aug. 21, 2021) [hereinafter US National Space Policy 2020].

⁷² Nat’l Space Council, *supra* note 68, at 2.

⁷³ This is text from article IX OST

*any such activity or experiment. A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities in the peaceful exploration and use of outer space, including the moon and other celestial bodies, may request consultation concerning the activity or experiment.*⁷⁴

As astronomy is one of the foremost ways we study and explore space and is advanced by multiple agencies within States, activities that “*would cause potentially harmful interference with activities [of other States Parties] in the peaceful exploration and use of outer space*” are intended to be subject to international consultations.

Finally, as described in the US policy section of this document, Article IX clearly implies that the environments of space and the Moon and other celestial bodies are intended to have some protections. Thus, it can be suggested that States Parties to the Treaty are obligated to avoid harming environments beyond Earth, including orbital environments.

3.6 IDA/IES Model Lighting Ordinance Limits Light Pollution

The International Dark-Sky Association (IDA) and the Illuminating Engineering Society (IES) created the Five Principles for Responsible Outdoor Lighting Practices⁷⁵ which offer principles for safe outdoor lighting that limits light pollution.

In 2011 the IDA and the IES drafted a Model Lighting Ordinance (MLO).⁷⁶ The MLO was drafted in response to the growing number of states passing light pollution regulations that had little cohesion, making it difficult to assess the success of the laws. The MLO seeks to help municipalities reduce light pollution through the development of lighting standards to reduce glare, light trespass and skyglow. The MLO implements lighting zones to allow governments to adjust the stringency of lighting regulations. In summary, the zones are:

1. LZ0: no ambient light. To include natural areas where there should be no human-created lighting, e.g., rural areas, parks, wildlife preserves, etc.
2. LZ1: low ambient lighting. Lighting is permitted for safety but should not be continuous, e.g., rural or agricultural areas, sparsely populated, wildlife preserves in populated areas, business parks.
3. LZ2: moderate ambient lighting. Lighting is permitted for safety but should not be continuous, e.g., neighborhoods, businesses, churches, schools, industrial areas.
4. LZ3: moderately high ambient lighting. Lighting is often uniform or continuous as desired for safety, security or convenience, e.g., business zones, heavy industrial areas.

⁷⁴ Article IX again OST

⁷⁵ IDA, *Light to Protect the Night* (2020) available at <https://www.darksky.org/wp-content/uploads/2020/06/Light-to-Protect-the-Night-IDA-and-IES.pdf>

⁷⁶ *Joint IDA-IES Model Lighting Ordinance 1,6* (2011) available at <https://www.darksky.org/our-work/lighting/public-policy/mlo/>

5. LZ4: high ambient lighting. Lighting is considered necessary and is mostly continuous or uniform, e.g., high-intensity business/industrial.

The MLO includes a Backlight, Uplight, and Glare classification to create light shielding standards.⁷⁷ The MLO also suggests that it is best implemented as an “overlay zoning” ordinance so that it may be implemented into existing land-using zoning ordinances.

⁷⁷ *Id.* at 3.

4. US National Law

In the United States, a growing number of federal, state and local ordinances and regulations are being implemented to address the threats posed by light pollution. The main thrust of these efforts is to address the persistent light pollution generated by terrestrial lighting fixtures and:

- the consequential effect on wildlife;
- the aesthetic impact on recreational viewing of the night sky;
- related energy consumption; and
- in some cases, the effect on astronomy.

These regulations and ordinances are localized, deal with persistent lighting fixtures and generally cover light visible to the naked eye. Conversely, satellite constellations generate diffuse or reflected light that is generally visible to the naked eye only temporarily, post-launch and prior to orbit raise. Additionally, the cumulative effect of all satellites and debris results in an overall brightening of the sky that, while not detectable by the naked eye, may be observed with astronomical instruments.

However, the goal — to preserve the environment for astronomy — remains the same and only the means to achieve the goal will differ.

4.1 Astronomy Protected from Light Pollution by Local and State Laws

Nineteen US states, plus Washington DC and Puerto Rico, have enacted laws to address light pollution.⁷⁸ The stated legislative purposes include energy reduction, preservation of aesthetics and the protection of science. Most state regulations are narrowly limited to outdoor lighting on the grounds of state buildings or public roadways. They commonly require one or more of the following:

1. The shielding of light fixtures to make light eliminate downward rather than upward/outward.
2. Low-glare or low-wattage lighting
3. Timing regulations, for example, lighting only on for a certain amount of time.
4. The adoption of IES⁷⁹ guidelines.

Some states regulate light pollution through zoning codes. There are 27 dark skies parks and preserves located in twelve states (primarily in the western United States).

Some states specifically identify astronomical interests, as described below.

4.1.1 Arizona

The urtext for protection of astronomical sites came first from the City of Flagstaff in 1958 and the City of Tucson and surrounding Pima County in 1973. Those updated codes have remained model ordinances

⁷⁸ See Annex I for a complete list.

⁷⁹ See subsection II.B below.

for the rest of the world. They prescribe control of spectral output and limits on total outdoor light per area per legal parcel dependent on distance from the observatories.⁸⁰

The City of Flagstaff was designated by the IDA as the world's first Dark Sky Community. The City of Tucson / Pima County's code articulates the modern purpose:

*The purpose of this code is to preserve the relationship of the residents of the City of Tucson, Arizona and Pima County, Arizona to their unique desert environment through protection of access to the dark night sky. Intended outcomes include continuing support of astronomical activity and minimizing wasted energy, while not compromising the safety, security, and well being of persons engaged in outdoor night time activities. It is the intent of this code to control the obtrusive aspects of excessive and careless outdoor lighting usage while preserving, protecting, and enhancing the lawful nighttime use and enjoyment of any and all property. It is recognized that developed portions of properties may be required to be unlit, covered, or have reduced lighting levels in order to allow enough lumens in the lighted areas to achieve light levels in accordance with nationally recognized recommended practices.*⁸¹

4.1.2 Hawai'i

Act 185 (2015) established the Dark Skies Protection Advisory Committee, comprising 13 members tasked with identifying and evaluating light pollution-related issues. The Committee's 2020 report essentially stated that they needed more time to complete the task. Interestingly, Hawai'i places the bulk of its lighting regulations in Title 13 Chapter 201 (Department of Business, Economic Development, and Tourism). At the county level, Hawai'i County on the Big Island has stringent lighting ordinances designed to protect the many observatories on Maunakea. The ordinances divide lighting into three categories (Class I, II, III) from least to most essential.⁸²

4.1.3 New Mexico

The Night Sky Protection Act regulates outdoor night lighting “to preserve and enhance the state's dark sky while promoting safety, conserving energy and preserving the environment for astronomy”.⁸³

4.1.4 Texas

Regulation of outdoor lighting (both mandatory and permissive) “must be designed to protect against the use of outdoor lighting in a way that interferes with scientific astronomical research of the observatory or military and training activities of the military installation, base, or camp.”⁸⁴

⁸⁰ City of Flagstaff Division 10-50.70: Outdoor Lighting Standards; 2012 City of Tucson / Pima County Outdoor Lighting Code

⁸¹ Pima County Ordinance 2012-14 Exhibit A:

https://webcms.pima.gov/UserFiles/Servers/Server_6/File/Government/Development%20Services/Building/OLC.pdf.

⁸² Haw. County Code § 14-50 (2017).

⁸³ NM Stat § 74-12-2 (2019).

⁸⁴ Tex. Local Government Code § 240.032(c)

4.1.5 Puerto Rico

The Light Pollution Prevention and Control Program, administered by the Puerto Rico Environmental Quality Board, is intended to “*prevent and control light pollution from night skies for the enjoyment of all our inhabitants, the benefit of scientific research, astronomy...[to] promote darkness to be able to appreciate the light of the stars...*”⁸⁵

4.2 Astronomy Protected from Light Pollution at Federal Level

4.2.1 Protecting Aesthetics Implies Need to Protect Astronomy

The Federal Government has a long history of recognizing and protecting natural landscapes for their scenic value. In 1872 the United States Congress and President Grant designated Yellowstone as the first National Park and the first conservation area of its kind in the world. In establishing the park, the legislation declared that the area would be preserved “*for the benefit and enjoyment of all people.*”⁸⁶ The act provided for “*all timber, mineral deposits, natural curiosities, or wonders within said park, and their retention in their natural condition.*”⁸⁷

Over the intervening years, the federal system of protected lands has grown, and agencies have come to recognize that a naturally dark, star-filled sky is an intrinsic part and critical aspect of the park or wilderness experience. While the focus of the federal system is on the visual experience of visitors, the fact must be recognized that light pollution that can ruin aesthetic experiences will also be ruinous to astronomy. Certainly, to those who benefit from astronomical research — which, it may be argued, is nearly everyone — utilitarian concerns may be considered to be vastly more important than scenic. Consequently, an effort to protect the beauty of the skies can, by inference, be considered to require the protection of the astronomical value of the skies.

In any event, federal agencies are now taking affirmative steps to protect the sky at night from light pollution.

4.2.1.1 The Antiquities Act of 1906

In 1906 the Antiquities Act was enacted.⁸⁸ This authorized the President of the United States to “*declare by public proclamation historic landmarks, historic and prehistoric structures, and other objects of historic or scientific interest that are situated upon the lands owned or controlled by the Government of the United*

⁸⁵ PR Laws 1 § 8032 (2019) (translated from Spanish).

⁸⁶ We want to acknowledge that in setting Yellowstone aside as a National Park, the Government forcibly removed the Tribes who had called the landscape home. The National Park Service was founded on the myth of the American wilderness as a place untouched by people. The reality is that the landscape had been populated for at least 15,000 years by Native peoples. See David Treuer, *Return the National Parks to the Tribes*, ATLANTIC, <https://www.theatlantic.com/magazine/archive/2021/05/return-the-national-parks-to-the-tribes/618395/> (May 2021).

⁸⁷ An Act Establishing Yellowstone National Park, 17 Stat. 32 (1872).

⁸⁸ American Antiquities Act of 1906, 16 USC. § 431-433.

*States to be national monuments...*⁸⁹ Bear Lodge Butte, also known as Devils Tower, was established as the first National Monument. Since then, 200 have been created, 69 of which have now been incorporated into the National Parks system or other protected lands systems.

While this Act does not mention light pollution or the protection of dark skies, it lays an early foundation for the preservation of sites of scientific interest and also introduces the need to balance protection with and assure that protection “*be confined to the smallest area compatible with proper care and management of*”⁹⁰ the area to be protected.

4.2.1.2 The Organic Act of 1916

By 1916 the Department of the Interior was overseeing 14 national parks, 21 national monuments, and the Hot Springs and Casa Grande Ruin reservations, but it lacked a unified organization to manage them. This changed with the creation of The National Park Service (NPS) through the Organic Act of 1916.⁹¹ The Act directs the NPS to:

*...conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations.*⁹²

Today, the National Park System comprises more than 400 areas covering more than 84 million acres in 50 States, the District of Columbia, American Samoa, Guam, Puerto Rico, Saipan, and the Virgin Islands.

4.2.1.3 The Natural Sounds and Night Skies Division

The Natural Sounds and Night Skies Division⁹³ was established within the NPS. Its goal is to support units across the NPS system in the stewardship of natural sounds and night skies. It recognizes that the soundscape, alongside the quality of the nighttime environment, is an intrinsic part of the scenery and ecosystem of Park units.

The division recognizes the night sky as a natural resource, a cultural resource, and an economic resource.⁹⁴ Since 2001 the Division has measured and inventoried night sky conditions in approximately 100 parks. Maintaining the dark night sky above many national park units is a high priority for the NPS. Their policy is to preserve, to the greatest extent possible, the natural night sky of parks, which are natural resources and values that exist in the absence of human-caused light.⁹⁵

⁸⁹ *Id.* at § 431.

⁹⁰ *Id.*

⁹¹ Organic Act of 1916, 16 USC. § 1 *et. seq.*

⁹² *Id.* at § 1.

⁹³ Natural Sounds and Night Skies Division, NPS, <https://www.nps.gov/orgs/1050/index.htm> (last accessed Aug. 27, 2021).

⁹⁴ Night Sky Resources, NPS, <https://www.nps.gov/subjects/nightskies/resources.htm> (last accessed Aug. 27, 2021).

⁹⁵ Managing Lightscapes, NPS, <https://www.nps.gov/subjects/nightskies/management.htm> (last accessed Aug. 27, 2021).

4.2.1.4 Lightscape Management

The 2006 NPS Management Policies include the following language:

The Service will preserve, to the greatest extent possible, the natural lightscapes of parks, which are natural resources and values that exist in the absence of human-caused light....The stars, planets, and earth's moon that are visible during clear nights influence humans and many other species of animals, such as birds that navigate by the stars or prey animals that reduce their activities during moonlit nights.

...

*The Service will ... shield the use of artificial lighting where necessary to prevent the disruption of the night sky ...*⁹⁶

Over the past decade, many National Park units have taken steps to invest in new infrastructure to reduce the impact of artificial light at night to protect the environment and enhance the visitor's appreciation of the park at night. Night sky programming is one of the most popular interpretive programs in many parks.

Moreover, many National Park units are now recognized as International Dark Sky Parks, and many more are pursuing designation

4.2.1.5 The Wilderness Act of 1964

In September 1964, the Wilderness Act was signed into law by President Lyndon Johnson.⁹⁷ The Act defines wilderness as:

*A wilderness, in contrast with those areas where man and his own works dominate the landscape, is hereby recognized as an area where the earth and its community of life are untrammelled by man, where man himself is a visitor who does not remain.*⁹⁸

The National Wilderness Preservation System now includes 803 Wilderness Areas protecting 450,691 square kilometers of federal lands. In 2020 the Boundary Waters Canoe Area Wilderness in Superior National Forest was designated as an International Dark Sky Sanctuary in recognition of its exceptional starry skies.⁹⁹

4.2.1.6 Recent National Monuments

In 2016 President Obama established National Monuments at Bears Ears in Utah, Katahdin Woods and Waters in Maine, and Castle Mountains in California/Nevada.¹⁰⁰ All three proclamations were issued under the authority of the Antiquities Act. They are noteworthy as they show how our understanding of "special landscapes that need protecting" now extends to the pristine dark night sky overhead.

⁹⁶ NPS, *Lightscape Management*, MANAGEMENT POLICIES 1, 57 (2006).

⁹⁷ Wilderness Act, 16 USC. § 1131-1136 (1964).

⁹⁸ *Id.* at § 1131(c).

⁹⁹ Kate Legner, *Superior's wilderness area world-recognized for its starry sky*, USDA FOREST SERVICE, <https://www.fs.usda.gov/features/superiors-wilderness-area-world-recognized-its-starry-night-sky> (Sept. 16, 2020).

¹⁰⁰ See Dana Varinsky, *Here's every piece of land Obama has put under protection during his presidency*, BUSINESS INSIDER (Dec. 30, 2016), <https://www.businessinsider.com/every-piece-of-land-obama-has-protected-2016-12>.

- The star-filled nights and natural quiet of the Bears Ears area transport visitors to an earlier eon. Against an absolutely black night sky, our galaxy and others more distant leap into view. As one of the most intact and least roaded areas in the contiguous United States, Bears Ears has that rare and arresting quality of deafening silence.
- The remoteness of the Castle Mountains area offers visitors the chance to experience the solitude of the desert and its increasingly rare natural soundscapes and dark night skies.
- Since the glaciers retreated 12,000 years ago, these waterways and associated resources — the scenery, geology, flora and fauna, night skies, and more — have attracted people to this area. Native Americans still cherish these resources.
- Katahdin Woods and Waters's daytime scenery is awe-inspiring, from the breadth of its mountain-studded landscape, to the channels of its free-flowing streams with their rapids, falls, and quiet water, to its vantages for viewing the Mount Katahdin massif, the “greatest mountain.” The area's night skies rival this experience, glittering with stars and planets and occasional displays of the aurora borealis, in this area of the country known for its dark sky.

4.2.2 Preventing New Sources of Interference with Astronomy (51 USC 50911)

Section 50911 of Article 51 of the US Code (51 USC 50911) prohibits “*the launch of a payload containing any material to be used for the purposes of obtrusive space advertising.*”¹⁰¹ In adopting this measure, which is discussed in the House of Representatives conference report on the NASA Authorization Act of 2000, the conferees indicate that they “*are seeking to preserve a view of the sky that humanity has enjoyed since the beginning of human existence. Moreover, this section will help prevent new sources of interference with astronomy.*”¹⁰²

The conferees note that obtrusive space advertising is defined as “*advertising in outer space that is capable of being recognized by a human being on the surface of the Earth without the aid of a telescope or other technological device,*”¹⁰³ i.e., that which is recognizable to the human eye.

4.3 Policy Rationales from Other US Laws to Protect Astronomy

4.3.1 Planetary Defense Efforts by the US and National Security

Planetary defense is considered a national security interest of the US. First, planetary defense may be understood as a national security interest purely on the basis that an asteroid plummeting toward Earth is nearly guaranteed to cause incredible and likely irreparable damage. Second, maintaining systems that identify exoatmospheric planetary threats like asteroids or other NEOs is an interest aligned with existing national security goals.

¹⁰¹ 51 USC. § 50911(a).

¹⁰² H.R. Rep. No. 106-843, at 35 (Conf. Rep.).

¹⁰³ *Id.*

Thus, light pollution which impairs the functionality of a telescope tasked with any aspect of planetary defense could impact national security. This concern is particularly broad given the multi-functional nature of most telescopes.

The consideration of national security interests requires balance. National security interests are supported by both satellite systems and astronomy. With respect to planetary defense in particular, the potential effect of light pollution on planetary defense telescopes is an important factor that must be taken into consideration. The very fact that light pollution may have an effect on planetary defense supports the need to include as a condition of licensing an obligation to reduce the impact of satellite constellations on astronomy to the greatest degree possible. Such conditions should be measured to take into account specific research with respect to the effects of light pollution on planetary defense telescopes.

The 2005 Authorization Act required NASA to enact the NEO Observation Program to locate, track, and characterize at least 90% of predicted NEOs of 140 meters or larger.¹⁰⁴

Planetary defense activities in the US are coordinated through the NASA Planetary Defense Coordination Office (PDCO), which works closely with the Jet Propulsion Lab's Center for Near Earth Object Studies and the Federal Emergency Management Agency (FEMA). The PDCO is also responsible for updating the AP.¹⁰⁵ The AP makes clear that NEOs are an issue addressed by multiple agencies:

*The Strategy and Action Plan builds on efforts by the National Aeronautics and Space Administration (NASA), Department of Homeland Security (DHS), and Department of Energy (DOE) to detect and characterize the NEO population and to prevent and respond to NEO impacts on Earth.*¹⁰⁶

The reasoning behind the vast number of agencies involved is succinctly explained by the AP:

*NEO impacts pose a significant and complex risk to both human life and critical infrastructure, and have the potential to cause substantial and possibly even unparalleled economic and environmental harm.*¹⁰⁷

Indeed, even the uncertainty of an impact could have major socio-economic consequences¹⁰⁸ beyond the scope of any single agency.

Recognizing the global implications of planetary defense, the AP elevates international cooperation to be one of its five goals:

Goal 4: Increase International Cooperation on NEO Preparation: Agencies will work to inform and develop international support for addressing global NEO impact risks.

¹⁰⁴ NASA Authorization Act of 2005, Pub. L. No. 109-155 § 321.

¹⁰⁵ Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects, *National Near-Earth Object Preparedness Strategy and Action Plan* (2018), available at <https://www.nasa.gov/sites/default/files/atoms/files/ostp-neo-strategy-action-plan-jun18.pdf>.

¹⁰⁶ *ibid.*

¹⁰⁷ *ibid.*

¹⁰⁸ Rudolf Albrecht, *Towards Plans for Mitigating Possible Socio-Economic Effects due to a Physical Impact of an Asteroid on Earth*, 7th IAA Planetary Defense Conference (Apr. 29, 2021).

*International engagement and cooperation will help the Nation to prepare more effectively for a potential NEO impact.*¹⁰⁹

which is aligned with US National Space Policy's guidelines, specifying that the Administrator of NASA shall:

*Develop options, in collaboration with other agencies, and international partners, for planetary defense actions both on Earth and in space to mitigate the potential effects of a predicted near Earth object impact or trajectory.*¹¹⁰

Among other things, PDCO:

- Provides early detection of potentially hazardous objects (PHOs) — the subset of NEOs whose orbits predict they will come within 5 million miles of Earth's orbit, and which are large enough (30 to 50 meters) to cause significant damage on Earth;
- Tracks and characterizes PHOs and issues warnings of the possible effects of potential impacts;
- Studies strategies and technologies for mitigating PHO impacts; and
- Plays a lead role in coordinating US government planning for response to an actual impact threat.¹¹¹

The PDCO is charged with warning the government, the media, and the public of any PHOs and disclosing their potential for impact. In the event that a PHO poses greater than a 1% threat over 50 years, the PDCO must notify the government.¹¹²

In June 2021 NASA approved the continued development of the NEO Surveyor, an infrared telescope designed to help "hunt" NEOs.

NASA's efforts to coordinate planetary defense strategies are primarily through the SMPAG and the IAWN, both of which international bodies were established in response to a 2013 UN COPUOS call for a recommendation to develop an international response to NEO threats.¹¹³ The Planetary Impact Emergency Response Working Group (PIERWG) was established in 2015 in partnership with FEMA to aid federal agencies in preparing for the possibility of future NEO collisions with Earth.¹¹⁴

¹⁰⁹ Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects, *National Near-Earth Object Preparedness Strategy and Action Plan* (2018), available at <https://www.nasa.gov/sites/default/files/atoms/files/ostp-neo-strategy-action-plan-jun18.pdf>.

¹¹⁰ US National Space Policy 2020, 24.

¹¹¹ Planetary Defense Coordination Office, NASA, <https://www.nasa.gov/planetarydefense/overview> (last accessed June 16, 2021).

¹¹² Planetary Defense Coordination Office, NASA, <https://www.nasa.gov/planetarydefense/overview> (last accessed June 16, 2021).

¹¹³ A/RES/68/75 (Dec. 11, 2013).

¹¹⁴ Planetary Impact Emergency Response Working Group (PIERWG) Charter, FEMA 1 (2015).

4.3.1.1 Telescopes Detect and Track NEOs

The Center for Near Earth Object Studies (CNEOS) computes the orbit paths of NEOs based on position data provided by the IAU's Minor Planet Center, the official repository of NEO observational data. The NEO Wide-field Infrared Survey Explorer (NEOWISE) spacecraft uses the Wide-field Infrared Survey Explorer telescope to survey NEOs. Wide-field telescopes are used to identify objects moving in the sky.

The Asteroid Terrestrial-impact Last Alert System (ATLAS) is an early-warning system funded by NASA and developed at the University of Hawai'i, comprising two telescopes on Mauna Loa and Haleakala. It is intended to provide one day's warning of a 30-kiloton (equivalent TNT) "town killer," one week's warning of a 5-megaton "city killer," and three week's warning of a 100-megaton "county killer."¹¹⁵

4.3.1.2 Telescopes Characterize NEOs

Follow-up telescopes are used to examine NEOs once identified to determine size, shape, orbit, etc. They include:

- Spacewatch
- Astronomical Research Institute
- Las Cumbres Observatory
- Magdalena Ridge Observatory
- Mission Accessible Near-Earth Objects Survey (MANOS)
- Infrared Telescope Facility (IRTF)
- NOIRLab large-aperture telescopes: Gemini, WIYN, Blanco, SOAR

4.3.1.3 Telescopes Integral to Early Detection

The AP identified the need to "[e]xercise, evaluate, and continually improve modeling and analysis capabilities."¹¹⁶ As such, NASA has participated in five tabletop exercises at Planetary Defense Conferences, in 2013, 2015, 2017, 2019, and 2021, and has additionally engaged in three joint exercises with FEMA, in 2013, 2014, and 2016.

Detailed in Annex II are the scenarios and findings of the most recent exercise, at the 2021 Planetary Defense Conference.

The CNEOS develops fictional impact scenarios to help identify the effectiveness of current planetary defense capabilities and to identify where they need to be improved. The 2021 Scenario was analyzed at the 7th International Academy of Astronautics (IAA) Planetary Defense Conference in April, hosted by UNOOSA and the European Space Agency (ESA).¹¹⁷

¹¹⁵ *Asteroid Terrestrial-impact Last Alert System, ATLAS*, <https://atlas.fallingstar.com/home.php> (last accessed Aug. 17, 2021).

¹¹⁶ Nat'l Sci. & Tech. Council Interagency Working Group for Detecting & Mitigating the Impact of Earth-bound and Near-Earth Objects, *National Near-Earth Object Preparedness Strategy and Action Plan* 1, 15 (June 2018).

¹¹⁷ See Annex II for an outline of the Conference activities.

Crucially, participants observed that had more sensitive detection systems been in place in 2014, the asteroid named 2021 PDC would have been detected seven years prior to potential impact rather than six months. This conclusion emphasizes the importance of precoveries in assessing impact probabilities.

4.4 Outer Space Treaty and US Law

The lineage of the principles under the OST in the US arguably began with the enactment of the National Aeronautics and Space Act of 1958 that stated “*it is the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all humankind.*”¹¹⁸ The Antarctic Treaty followed in 1959 with a similar purpose and, as will be demonstrated below, it served as the foundation for the OST.¹¹⁹

The United States of America has signed and ratified the OST and is therefore legally bound by its provisions. The US has also signed and ratified the following treaties concerning international space activities¹²⁰:

- Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (ARRA, 1968)¹²¹;
- Convention on International Liability for Damage Caused by Space Objects (LIAB, 1972)¹²²;
- Convention on Registration of Objects Launched into Outer Space (REG, 1975)¹²³.

4.4.1 Space Traffic Management

The US recognizes the need to protect the “space environment.” It is noteworthy that the US Government makes a distinction between the “space environment” and the “human environment” or “natural environment.”

Nevertheless, Space Policy Directive-3 which articulated the United States’ National Space Traffic Management Policy,¹²⁴ stressed the importance of the space environment:

Our society now depends on space technologies and space-based capabilities for communications, navigation, weather forecasting, and much more. Given the significance of space activities, the United States considers the continued unfettered

¹¹⁸ National Aeronautics and Space Act of 1958, P. L. No. 85-568, 72 Stat. 426-438, § 102.

¹¹⁹ Antarctic Treaty, 1.

¹²⁰ UNOOSA, Status of International Agreements Relating to Activities in Outer Space as at 1 January 2020, *available at* <https://www.unoosa.org/documents/pdf/spacelaw/treatystatus/TreatiesStatus-2020E.pdf>.

¹²¹ Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space, 19 December 1967, 672 U.N.T.S. 119, 19 UST 7570, TIAS No 6599, 7 ILM 151 (entered into force 3 December 1968).

¹²² Convention on International Liability for Damage Caused by Space Objects, 29 March 1972, 961 U.N.T.S. 187, 24 UST 2389, 10 ILM 965 (1971) (entered into force 1 September 1972).

¹²³ Convention on Registration of Objects Launched into Outer Space, 12 November 1974, 28 UST 695, 1023 U.N.T.S. 15 (entered into force 15 September 1976).

¹²⁴ National Space Traffic Management Policy, 83 Fed. Reg. 28969 (Jun. 21, 2018). This expanded upon the National Space Policy articulated in 2010 that committed to policies and guidelines that influenced space traffic through international cooperation and self-accountability.

*access to and freedom to operate in space of vital interest to advance the security, economic prosperity, and scientific knowledge of the Nation.*¹²⁵

The principles established in the National Space Traffic Management Policy include:

(a) Safety, stability, and operational sustainability are foundational to space activities, including commercial, civil, and national security activities. It is a shared interest and responsibility of all spacefaring nations to create the conditions for a safe, stable, and operationally sustainable space environment.

(b) Timely and actionable SSA data and STM services are essential to space activities. Consistent with national security constraints, basic US Government-derived SSA data and basic STM services should be available free of direct user fees.

(c) Orbital debris presents a growing threat to space operations. Debris mitigation guidelines, standards, and policies should be revised periodically, enforced domestically, and adopted internationally to mitigate the operational effects of orbital debris.

*(d) A STM framework consisting of best practices, technical guidelines, safety standards, behavioral norms, pre-launch risk assessments, and on-orbit collision avoidance services is essential to preserve the space operational environment.*¹²⁶

Generally, the first principle articulates a basis for protecting the space environment for all actors and persons reliant upon it. The second principle correlates with the recommendations of SATCON1 for timely telemetry and ephemeris data.¹²⁷ With respect to the latter two principles, the FCC recently promulgated regulations imposing obligations on space station operators with respect to space debris.¹²⁸ These regulations follow the efforts of the FAA and NOAA to update their regulations with respect to space operations.

This underscores that the FCC can pursue regulations that address perceived issues without invoking or relying on statutes like NEPA. Indeed, to the extent that relevant, data-driven standards are developed relating to astronomy mitigations (and benefits) from satellite constellations, the FCC can impose conditions as part of its license for a US authorized system.

However, this again raises challenges associated with operator “forum shopping,” since US license requirements are asymmetric, in that they do not apply to foreign-licensed systems. Without addressing this regulatory asymmetry, the likely result of additional conditions would be that operators will not license in the US, creating even less US oversight. This could, perhaps, be countered should the US be willing to

¹²⁵ *Id.*

¹²⁶ *Id.*

¹²⁷ SATCON1, C (Positional Accuracy), pp. 20-21; Recommendations 9 and 10, p. 22.

¹²⁸ “Report and Order and Further Notice of Proposed Rulemaking,” In the Matter of Mitigation of Orbital Debris in the New Space Age – IB Docket No. 18-313 (“18-313 Report and Order”) (April 24, 2020); see also Office of Safety and Mission Assurance, Process for Limiting Orbital Debris, NASA, <https://standards.nasa.gov/standard/nasa/nasa-std-871914>. Additional final regulations should be forthcoming in 2021.

assert Article IX “due regard” and “harmful interference” objections to the activities of other States or their nationals.¹²⁹

4.5 Radio Quiet Zones

RQZs are limited to specific geographies and allow the benefits of technology outside the zones. A brief summary is offered here to continue the discussion of how a balance may be struck between the critical services people can receive from satellite services and the impact of those services on astronomy.

The first RQZ, the US National Radio Quiet Zone (NRQZ) was established in 1958 and is administered jointly by the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia in conjunction with the FCC. The NRAO also represents the National Security Agency listening station in Sugar Grove, West Virginia. The NRQZ has an area of 13,100 square miles and a population of 600,000 people. That's comparatively large and well inhabited for a RQZ. Like other RQZs around the world the NRQZ is governed by laws in the national code.¹³⁰

Briefly put, the NRQZ imposes a requirement on the operation of all fixed licensed transmitters (but only those) to meet power level requirements as their emissions would be or are received at a reference point near the primary focus of the Green Bank Telescope (well above ground level). If they do not meet the power levels, the NRAO can protest to the FCC which generally upholds the NRAO's view. The vast majority of transmitters are well outside the area where they might interfere and are approved almost pro forma; a relative few must be adjusted to meet the rules and a very few wind up being rejected. The transmitters that are most likely to be allowed to operate with strong NRAO objections are those of government agencies like the US Department of Agriculture.

Transmitters that are not intended to operate at fixed locations inside the NRQZ, or in some cases at modestly changeable fixed locations within certain well-defined geographic areas of the NRQZ, are not affected. Transmitters on boats, planes, trains, or satellites are not governed by NRQZ rules per se. The FCC has ignored NRQZ rules in some rulings, for instance the so-called TV White Space Devices that provide broadband internet by operating in unused UHF TV channels. Potential interference from unintentional radiators like sawmills, gospel revivals and power lines is regulated by West Virginia state laws. The NRQZ rules are waived in cases of emergencies like floods when power transmission lines are loosely strung all over the site.

Worldwide, RQZs function somewhat like the US NRQZ, but with their own particular wrinkles. Not all regulate transmitters at all frequencies. One or two limit air traffic over the RQZ.¹³¹ RQZs have no regulatory recognition by the ITU Radiocommunications Sector (ITU-R), but rather a general awareness.

The uses and limitations of RQZs were discussed in the Radio Astronomy Working Group Report that can be found on the IAU website <https://iau.org/news/announcements/detail/ann21002/>.

¹²⁹ Outer Space Treaty, art. IX.

¹³⁰ 47 CFR 1.924(a); see also Paulette Woody, *National Radio Quiet Zone*, NRAO, <https://science.nrao.edu/facilities/gbt/interference-protection/nrqz> (last accessed Aug. 17, 2021).

¹³¹ The operation of the wider set of world RQZ is described by the ITU-R. ITU-R, *Characteristics of radio quiet zones*, RA.2259 (2012) (a new version will be published later this year).

5. Considerations Regarding Orbit as an Environment

5.1 The Outer Space Treaty and International Environmental Law

Article III of the OST¹³² prescribes that:

*States Parties to the Treaty shall carry on activities in the exploration and use of outer space, including the Moon and other celestial bodies, in accordance with international law, including the Charter of the United Nations, in the interest of maintaining international peace and security and promoting international co-operation and understanding.*¹³³

In the interest of understanding the specific applicability of international law provisions to the body of international space laws, we refer to the introductory section of the LTSG, which at Paragraph 7 states:

*In this regard, the guidelines also reiterate the principles contained in article III of the Outer Space Treaty that the activities of States in the exploration and use of outer space shall be carried out in accordance with international law, including the Charter of the United Nations. Accordingly, States should build on these principles when developing and conducting their national activities in outer space.*¹³⁴

Moreover, from the US perspective, the National Space Policy of the United States of America (9 December 2020), in its relevant portion, recognizes:

Preserving the Space Environment to Enhance the Long-term Sustainability of Space Activities Preserve the Space Environment.

To preserve the space environment for responsible, peaceful, and safe use, and with a focus on minimizing space debris the United States shall: Continue leading the development and adoption of international and industry standards and policies, such as the Guidelines for the Long-term Sustainability of Outer Space Activities and the Space

¹³² Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, 27 January 1967, 610 U.N.T.S. 205, (entered into force 10 October 1967) [Outer Space Treaty], Art III.

¹³³ Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, 27 January 1967, 610 U.N.T.S. 205, (entered into force 10 October 1967) [Outer Space Treaty], Art III.

¹³⁴ UN COPUOS Sustainability Guidelines, pp. 2, para. 7.

From a combined reading, it could be noted here that the LTSG and the provisions contained therein are intended/designed to expand the scope of Article III of the OST by inducting newer elements of consideration for national space legislations, policies, guidelines, etc. Thus, for the purpose of this report, we now turn to the enabling (applicable) provision(s) contained in the LTSG:

Guideline A.2

Consider a number of elements when developing, revising or amending, as necessary, national regulatory frameworks for outer space activities

...

2. In developing, revising or amending, as necessary, national regulatory frameworks, States and international intergovernmental organizations should:

...

(a) Consider the provisions of General Assembly resolution 68/74, on recommendations on national legislation relevant to the peaceful exploration and use of outer space;

...

(c) Address, to the extent practicable, risks to people, property, public health and the environment associated with the launch, in-orbit operation and re-entry of space objects;

...

(d) Promote regulations and policies that support the idea of minimizing the impacts of human activities on Earth as well as on the outer space environment. They are encouraged to plan their activities based on the Sustainable Development Goals, their main national requirements and international considerations for the sustainability of space and the Earth;

...

(g) Weigh the costs, benefits, disadvantages and risks of a range of alternatives and ensure that such measures have a clear purpose and are implementable and practicable in terms of the technical, legal and management capacities of the State imposing the regulation. Regulations should also be efficient in terms of limiting the cost for compliance (e.g., in terms of money, time or risk) compared with feasible alternatives;¹³⁶

In turn, the applicable provisions of General Assembly resolution 68/74 contain the following points for our additional consideration; it: (a) observes that appropriate action at the national level is needed in view of the increasing participation of non-governmental entities in space activities; (b) notes the need for consistency and predictability with regard to the authorization and supervision of space activities and the need for a practical regulatory system for the involvement of non-governmental entities to provide further incentives for enacting regulatory frameworks at the national level; and (c) recommends, *inter alia*, the following elements for consideration by States when enacting regulatory frameworks for national space activities: (i) scope of space activities targeted by national regulatory frameworks may include, amongst other things, operation and control of space objects in orbit, (ii) States might employ specific procedures for the licensing and/or for the authorization of different kinds of space activities, and (iii) the conditions for

¹³⁵ US National Space Policy 2020, 14..

¹³⁶ UN COPUOS Sustainability Guidelines, Guideline A.2, para. 2.

authorization should help to ascertain that space activities are carried out in a safe manner and to minimize risks to persons, the environment or property.¹³⁷

Here follows a more detailed description of the LTSG.

5.1.1 The Long-Term Sustainability Guidelines

The LTSG are a set of 21 voluntary guidelines grounded in the ideas, *inter alia*, that states remain committed to peaceful uses of outer space, pursue space use and exploration in sustainable ways, cooperate internationally to address natural and human-caused hazards, and develop national and international safety frameworks for space use and exploration.

The background text accompanying the LTSG makes clear that the guidelines were developed with the ongoing development of space in mind, including mega-constellations:

*The Earth's orbital space environment constitutes a finite resource that is being used by an increasing number of States, international intergovernmental organizations and non-governmental entities. The proliferation of space debris, the increasing complexity of space operations, the emergence of large constellations and the increased risks of collision and interference with the operation of space objects may affect the long-term sustainability of space activities. Addressing these developments and risks requires international cooperation by States and international intergovernmental organizations to avoid harm to the space environment and the safety of space operations.*¹³⁸

The background continues to note that the sustainable development of space is not something that can be achieved by the actions of any single State. Rather, it requires international cooperation, as the text explains:

*International cooperation is required to implement the guidelines effectively, to monitor their impact and effectiveness and to ensure that, as space activities evolve, they continue to reflect the most current state of knowledge of pertinent factors influencing the long-term sustainability of outer space activities, particularly with regard to the identification of factors that influence the nature and magnitude of risks associated with various aspects of space activities or that may give rise to potentially hazardous situations and developments in the space environment.*¹³⁹

As previously discussed, the development of mega-constellations and the prospects of the proliferation of space debris stand to impact space exploration by having adverse effects on astronomy, which is one of the foremost ways that humanity explores space. This is through direct interference with optical and radio observations, as well as indirect interference by potentially changing the sky brightness. The development of mega-constellations further has environmental impacts, including the potential for direct and indirect impacts on the climate and stratospheric ozone. The “*most current state of knowledge of pertinent factors*” influencing the development of space is changing rapidly along with our understanding of “*risks*”

¹³⁷ G.A. Res. 68/74, Recommendation on national legislation relevant to the peaceful exploration and use of outer space (Dec. 16, 2013).

¹³⁸ UN COPUOS Sustainability Guidelines, pp. 1, para. 1.

¹³⁹ *Id.* at pp. 4, para. 21.

associated with various aspects of space activities.”¹⁴⁰ In light of this, Guideline A.2 has several relevant paragraphs, as mentioned above.

Regarding A.2, 2(c), space launch and satellite re-entry activity may reach sufficient levels to require further study.¹⁴¹ Paragraph A.2, 2(d) has implications for light pollution (direct and diffuse), as it limits humanity’s ability to explore space. Together, these paragraphs, along with the risks discussed herein, suggest that EIAs should be conducted by States, through their national mechanisms, when granting licenses to mega-constellation companies and that the categorical exclusions (CEs) used by the FCC do not meet the US government’s (non-binding) commitments to the LTSG.

Paragraph A.2, 2(g) further suggests that the current use of CEs is inadequate:

*Weigh the costs, benefits, disadvantages and risks of a range of alternatives and ensure that such measures have a clear purpose and are implementable and practicable in terms of the technical, legal and management capacities of the State imposing the regulation. Regulations should also be efficient in terms of limiting the cost for compliance (e.g., in terms of money, time or risk) compared with feasible alternatives;*¹⁴²

An EIA would include a cost-benefit analysis and a risk assessment. These guidelines together are also consistent with the Rio Declaration on Environment and Development (the Rio Declaration) Principles 15, 16, and 17 (discussed in 5.1.7) through the promotion of identifying risks through EIAs and implementing “cost-effective” measures.

It may also be important to consider Guideline D.1, 2, and 4:

Promote and support research into and the development of ways to support sustainable exploration and use of outer space

(...)

2. In their conduct of space activities for the peaceful exploration and use of outer space, including celestial bodies, States and international intergovernmental organizations should take into account, with reference to the outcome document of the United Nations Conference on Sustainable Development (General Assembly resolution 66/288, annex), the social, economic and environmental dimensions of sustainable development on Earth.

*4. States and international intergovernmental organizations should consider appropriate safety measures to protect the Earth and the space environment from harmful contamination, taking advantage of existing measures, practices and guidelines that may apply to those activities, and developing new measures as appropriate.*¹⁴³

Paragraph D.1, 2 promotes States to include “social, economic, and environmental dimensions” into their “conduct of space activities”, with direct reference to the annex of resolution 66/288, which among other things reaffirms a commitment to the Rio Declaration. This guideline can thus be interpreted to include the

¹⁴⁰ *Id.* at pp. 4, para. 20.

¹⁴¹ *Id.* at Guideline A.2.

¹⁴² *Id.* at Guideline A.2, 2(g).

¹⁴³ *Id.* at Guideline D.1, 2, 4.

effects of light pollution on activities on Earth, as well as direct and indirect consequences of environmental changes.

Paragraph D.1, 4 may also be of interest, as it encourages States to consider “*appropriate safety measures to protect the Earth and the space environment from harmful contamination*”. Whether this implies protections for astronomy does depend on whether harmful contamination includes light pollution and the visible (and radio) alteration of the night sky.

From a cursory reading of the above, the following finer/subtle points emerge for consideration of the authors’ Study Report:

- § Apart from the environmental impact (on the “human environment”) of launch and re-entry of space objects, newer and increasingly well-defined risks associated with “in-orbit” operation of space activities is now becoming a vital element for consideration while assessing the overall impact of space activities in the outer space environment;
- § Regulations and policies regarding safe conduct of space activities may not only target the assessment of impact of such activities on the “human environment”, but also may include the outer space environment; and
- § Weigh the costs, benefits, disadvantages and risks of a range of alternatives and ensure that such measures have a clear purpose and are implementable and practicable.

5.1.2 Impact of On-Orbit Operations in Outer Space as Distinguished from the Environmental Impact of Launch and Re-entry of Launch Vehicles; Legal Policy and Support

At this juncture and for this part of the report, the authors, again, note with appreciation all actions (legislative, policy, directives, and implementation) of the US government in pursuance of its overall objective of the safe and sustainable use of outer space (please see the introduction to Section 5.1.1 above). The Working Group also wishes to reiterate its earlier concerns about the potential lacunae or “missing links” with respect to the urgent and immediate necessity of conducting due diligence or EIAs with respect to the “on-orbit” operations of commercial satellites of private constellations.

Principally drawing on our observations in Section 5.1.1., this section provides additional policy and legal support for the requirement to conduct due diligence based on international law, including well established and recognized principles of international environment law.

Please see again LTSG A.2 – Para 2 (a), (c), and (d) read with recommendations contained in UN General Assembly Resolution 68/74. In the LTSG, the use of the words “*in-orbit operation*” in Para 2(c) and the words “*minimizing the impacts of human activities on Earth as well as on the outer space environment*” in Para 2(d) are critical to the discussions above.

An authentic and conclusive UN Report by the Secretary General of the UN entitled *Gaps in international environmental law and environment-related instruments: towards a global pact for the environment*¹⁴⁴ was published on 30 November 2018 (hereinafter the SG Report) in response to General Assembly resolution 72/277 entitled *Towards a Global Pact for the Environment*, in which the General Assembly requested the Secretary General to submit, at its seventy-third session in 2018, a technical and evidence-based report that identifies and assesses possible gaps in international environmental law and environment-related instruments with a view to strengthening their implementation.

After a review and analysis of the corpus of international environmental law and environment-related instruments as well as the governance structure and implementation of international environmental law¹⁴⁵, it concludes the following on the prevention principle:

*Since it first appeared in the 1938 Trail Smelter arbitration, the prevention of transboundary harm has been framed as a principle in foundational instruments of international environmental law, United Nations instruments, regional instruments, texts drafted by civil society and the decisions of the International Court of Justice. This principle is intrinsic to a core preference in international law for preventing environmental harm rather than compensating for harm that has already occurred. The prevention principle is well established as a rule of customary international law, supported by relevant practice in many environmental treaties and major codification initiatives. In practice, this principle is also related to due diligence obligations, particularly the duty to undertake an environmental impact assessment prior to engaging in activities which pose a potential risk of transboundary harm.*¹⁴⁶

The SG Report also notes, in its preambular portion, that: (a) there is no single overarching normative framework that sets out what might be characterized as the rules and principles of general application in international environmental law ...; (b) international environmental law is piecemeal and reactive; (c) the structure of international environmental governance is characterized by institutional fragmentation and a heterogeneous set of actors.

Owing to the piecemeal nature of environmental law, even under the prevention principle, three different regimes appear to have emerged: (a) prevention of transboundary damage; (b) prevention of transboundary harm; and (c) prevention of transboundary environmental impact.

¹⁴⁴ Report of the Secretary General, *Gaps in international environmental law and environment-related instruments: towards a global pact for the environment*, U.N. Doc. A/73/419 (Nov. 30, 2018).

¹⁴⁵ *Id.* at 1. Although the primary purpose of this Report was to reveal gaps and deficiencies at multiple levels, this Report analyzes all relevant principles of international environmental law and confirms its findings on different levels based on an evidence based modality.

¹⁴⁶ *Id.* at 7. (emphasis added)

5.1.2.1 Prevention of Transboundary Damage

This specific principle pertains to transboundary damage and is essentially captured in certain foundational instruments of international environment law¹⁴⁷ and decisions of the International Court of Justice.¹⁴⁸

It requires the highest standard of care, and the corresponding obligation of due diligence, as there is State responsibility affixed with this principle. To state the exact principle:

*States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.*¹⁴⁹

The relevant US policy position/stance is reflected in the International Law Commission (ILC). As regards liability for transboundary damage, it is relevant to note that the US position (as captured by the Second Report of the International Law Commission¹⁵⁰) on the subject is as follows:

*The United States did not believe that “under customary international law, States are generally liable for significant transboundary harm caused by private entities acting on their territory or subject to their jurisdiction or control”. It added that, “from a policy point of view, a good argument exists that the best way to minimize such harm is to place liability on the person or entity that causes such harm, rather than on the State.”*¹⁵¹

However, in the domain of space activities, and given the nature of legal obligations contained in the space law treaties pertaining to state liability and responsibility, any potential liability has been drafted to be placed on States Parties (and not on its private entities); and thus, in cases of non-compliance, the US government may not be able to resort and defend this earlier position.

¹⁴⁷ See Declaration of the United Nations Conference on the Human Environment (Stockholm Declaration), Principle 21; Rio Declaration on Environment and Development, principle 2, June 13, 1992, 31 ILM 874 [hereinafter Rio Declaration]; World Charter for Nature (WCN), art. 21(d).

¹⁴⁸ Pulp Mills on the River Uruguay (Argentina v. Uruguay), Judgment, I.C.J. Reports 2010, pp. 14, para. 10 (The Court points out that the principle of prevention, as a customary rule, has its origins in the due diligence that is required of a State in its territory); (Corfu Channel (United Kingdom v. Albania), Merits, Judgment, I.C.J. Reports 1949, p. 22 (It is “every State’s obligation not to allow knowingly its territory to be used for acts contrary to the rights of other States”); Legality of the Threat or Use of Nuclear Weapons, Advisory Opinion, I.C.J. Reports 1996 (I), p. 242, para. 29 (A State is thus obliged to use all the means at its disposal in order to avoid activities which take place in its territory, or in any area under its jurisdiction, causing significant damage to the environment of another State. This Court has established that this obligation “is now part of the corpus of international law relating to the environment”).

¹⁴⁹ Rio Declaration, principle 2.

¹⁵⁰ International Law Commission, Second report on international liability for injurious consequences arising out of acts not prohibited by international law (prevention of transboundary damage from hazardous activities), pp. 17, U.N. Doc. A/CN.4/501 (May 5, 1999).

¹⁵¹ See U.N. Doc. A/CN.4/481, para. 24; see also, U.N. Doc. A/C.6/51/SR.39, at para. 31-33.

Please also see again, the SG Report and the excerpt quoted above which, in its relevant portions, states *“This principle is intrinsic to a core preference in international law for preventing environmental harm rather than compensating for harm that has already occurred.”*¹⁵²

5.1.2.2 Prevention of Transboundary Harm

The draft Articles on Prevention of transboundary harm from hazardous activities, as published by the International Law Association and as recommended by the UN General Assembly, through its Resolution 62/68 entitled *Consideration of prevention of transboundary harm from hazardous activities and allocation of loss in the case of such harm*,¹⁵³ contain the following considerations.

Article 2(a) states:

*Risk of causing significant transboundary harm includes risks taking the form of a high probability of causing significant transboundary harm and a low probability of causing disastrous transboundary harm.*¹⁵⁴

Given this definition, these articles offer a mid-way between (a) “transboundary damage” (for which there is State responsibility, or in certain cases, state liability, i.e., it requires the highest standard of care); and (b) “transboundary environmental impact” (for which the only obligation is of due diligence, potentially in the form of an EIA (see discussions in the next subsection) but it does not obligate a State to act on the due diligence of the EIA Report — it leaves it at the State’s discretion, i.e., the lowest standard of care is required).

Article 3 (Prevention) states:

*The State of origin shall take all appropriate measures to prevent significant transboundary harm or at any event to minimize the risk thereof.*¹⁵⁵

Article 5 (Implementation) states:

*States concerned shall take the necessary legislative, administrative or other action including the establishment of suitable monitoring mechanisms to implement the provisions of the present articles.*¹⁵⁶

¹⁵² Report of the Secretary General, Gaps in international environmental law and environment-related instruments: towards a global pact for the environment, U.N. Doc. A/73/419 (Nov. 30, 2018).

¹⁵³ G.A. Res. 62/68, Consideration of prevention of transboundary harm from hazardous activities and allocation of loss in the case of such harm (Dec. 6, 2007)

¹⁵⁴ <https://digitallibrary.un.org/record/613193?ln=en>

¹⁵⁵ <https://digitallibrary.un.org/record/613193?ln=en>

¹⁵⁶ <https://digitallibrary.un.org/record/613193?ln=en>

5.1.2.3 Prevention of Transboundary Environmental Impact

The essence of this is primarily captured in the Convention on Environmental Impact Assessment in a Transboundary Context (the Espoo Convention)¹⁵⁷. The US has signed but not ratified this Convention.

The prevention principle captured in this Convention requires the lowest standard of care, with a view to preventing, reducing and controlling significant adverse transboundary environmental impact from proposed activities (Article 2(1)), and recommends conducting an EIA prior to a proposed activity (Article 2(3)).

The Convention provides the following definitions:

“Proposed activity” means any activity or any major change to an activity subject to a decision of a competent authority in accordance with an applicable national procedure; and

“Transboundary impact” means any impact, not exclusively of a global nature, within an area under the jurisdiction of a Party caused by a proposed activity the physical origin of which is situated wholly or in part within the area under the jurisdiction of another Party.¹⁵⁸

Technicalities in the Convention: Certain activities stated in Appendix 1 are automatically deemed to cause significant transboundary impact. However, it is important to note here that the principles of this Convention are not only applicable to a “proposed activity” (as contained in Appendix 1), but is subject to all such “proposed activities” that may cause a significant transboundary environmental impact.

5.1.3 International Policy Analysis

The AAS, through its SATCON1 Report, states and affirms, with sufficient evidence and via a thorough scientific approach, that environmental impact/harm/damage (or, at the very least, environmental impact) is caused by light pollution resulting from the reflectivity of the satellites of mega-constellations.

Having discussed the three sub-categories under which the “prevention principle” has been applied in practice, the authors wish to note that the prevention principle per se is part and parcel of customary international law. The obligation to conduct due diligence is a natural and relevant outcome of this.

The authors commend the efforts of the US in pursuing EIAs of launch and re-entry of all space vehicles as well as of governmental and defense projects undertaken by NASA. The Working Group however, wishes to reiterate that there is a key missing link such that no due diligence is currently being conducted for the in-orbit operation of commercial satellites of private entities.

¹⁵⁷ Convention on Environmental Impact Assessment in a Transboundary Context, 1989 U.N.T.S. 309, Feb. 25, 1991 [hereinafter Espoo Convention] <https://unece.org/DAM/env/eia/documents/Espoo10years/english10years.pdf>.

¹⁵⁸ Convention on Environmental Impact Assessment in a Transboundary Context, 1989 U.N.T.S. 309, Feb. 25, 1991 [hereinafter Espoo Convention] <https://unece.org/DAM/env/eia/documents/Espoo10years/english10years.pdf>.

The Working Group wishes to draw attention to Article VIII of the OST¹⁵⁹ which postulates that space objects are within the jurisdiction and control of the State Party on whose registry it is carried. Thus, despite the fact that these satellites are operating in orbit, they continue to remain within the jurisdiction of the US. Any pollution (as is being alleged) generated by them would directly attract the customary international principle of the duty to undertake prevention and a corresponding obligation to conduct a due diligence at the very minimum.

If, in this regard, the US wishes to pursue a policy based or regulatory framework to fill the current gap, the authors request that it pay attention to the LTSG, which in Guideline A.2 states:

Consider a number of elements when developing, revising or amending, as necessary, national regulatory frameworks for outer space activities ... 2. In developing, revising or amending, as necessary, national regulatory frameworks, States and international intergovernmental organizations should:

...

*(h) Encourage advisory input from affected national entities during the process of developing regulatory frameworks governing space activities to avoid unintended consequences of regulation that might be more restrictive than necessary or that conflicts with other legal obligations;*¹⁶⁰

Affected national entities, in this instance, would include the concerns being raised by the AAS.

With the above in mind, the authors urge the US government to consider the following proposal, which may help to avoid any State responsibility or liability. Prevention should be a preferred policy because compensation in the case of harm often cannot restore the situation prevailing prior to the event or accident. Discharge of the duty of prevention or due diligence is all the more required as knowledge regarding the operation of hazardous activities, the materials used and the process of managing them and the risks involved is steadily growing. And thus, for the in-orbit operation phases of commercial satellites, due diligence may be conducted keeping in view the following tier-system or classification:

¹⁵⁹ Outer Space Treaty, art. VIII ("A State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body. Ownership of objects launched into outer space, including objects landed or constructed on a celestial body, and of their component parts, is not affected by their presence in outer space or on a celestial body or by their return to the Earth. Such objects or component parts found beyond the limits of the State Party to the Treaty on whose registry they are carried shall be returned to that State Party, which shall, upon request, furnish identifying data prior to their return.").

¹⁶⁰ UN COPUOS Sustainability Guidelines, Guideline A.2.

Table 1. **Prevention principle” and corresponding obligations**

Influence ¹⁶¹ of satellites	Application of principle	Standard of care required to be observed	Corresponding obligations	Additional remarks
Low	Prevention of transboundary <u>environmental impact</u>	A cumulative impact analysis of the total satellite population in orbit by all States is desirable.	Obligation to only conduct due diligence or EIA prior to the undertaking of a “proposed activity” or if there is a major change to any existing activity. Obligation to act on the EIA Report is left to the discretion of individual States.	Support: Espoo Convention; US has signed but not ratified this convention.
Medium	Prevention of transboundary <u>harm</u>	Includes risks taking the form of a high probability of causing significant transboundary harm and a low probability of causing disastrous transboundary harm	In addition to conduct of due diligence, States are asked to take the necessary legislative, administrative or other action including the establishment of suitable monitoring mechanisms.	Support: The draft Articles on Prevention of transboundary harm from hazardous activities, as published by the International Law Association and as recommended by the UN General Assembly, through its Resolution 62/68 entitled <i>Consideration of prevention of transboundary harm from hazardous activities and allocation of loss in the case of such harm</i> ¹⁶² Owing to the nature of space activities, the obligations would be very difficult to implement after an incident or activity. Thus, it may be prudent to combine this with a precautionary approach
High	Prevention of transboundary <u>damage</u>	Highest degree of care State	US position on this: <i>“The United States did not believe that under customary international law, States are</i>	Support: Foundational environmental treaties and conventions; ICJ cases, etc.

¹⁶¹ “Influence” generally refers to the cumulative effect of all satellites, with individual satellite characteristics also considered.

¹⁶² G.A. Res. 62/68, Consideration of prevention of transboundary harm from hazardous activities and allocation of loss in the case of such harm, Annex (Dec. 6, 2007)

		responsibility/ liability affixed for damage caused.	<i>generally liable for significant transboundary harm caused by private entities acting on their territory or subject to their jurisdiction or control". It added that, "from a policy point of view, a good argument exists that the best way to minimize such harm is to place liability on the person or entity that causes such harm, rather than on the State."</i> ¹⁶³	Please note that in the field of space activities, the US position would be automatically negated due to application of Article VI of the Outer Space Treaty
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The first column of the above table lists descriptors for the tier-system, addressing the effect that the satellite population has on the environment or other activities. In the present context, those activities are ground-based astronomy, including stargazing for cultural practices or night sky enjoyment. The authors purposefully do not define the technical thresholds for those categories, which should include a number of factors such as satellite numbers at different altitudes, the total on-orbit cross section of satellites, and the risk of proliferating debris. The descriptors are intended to have the following broad meanings:

- Low — Observing the sky is occasionally affected by the satellite population. There is only a minor disruption of activities. However, the growth of the satellite population could lead to a noticeable change in the sky. Conducting a cumulative impact analysis is desirable prior to approving additional satellites. SATCON1 astronomy impact category: "Negligible".
- Medium — Observing the sky is regularly affected by the satellite population. Some activities have large disruptions. Further growth could have severe impacts on sky use. SATCON1 astronomy impact category: "Significant but tolerable".
- High — Observing the sky is regularly and in at least some cases severely affected by the satellite population. Effects might include substantial data loss, major interference with stargazing, or inability to conduct some science programs. SATCON1 astronomy impact category: "Extreme".

It is the view of some members of the International Policy Subgroup that the current situation of on-orbit interference with astronomy and viewing the sky is between the Low and Medium categories above, with concern for a rapid transition to Medium. The members stress that carefully considered metrics needs to be developed to assess the current situation properly.

Moreover, recent trends, opinions of States, and related industry practices also show an increasing need to pay attention to EIAs for space activities during their operational phase in the "outer space environment" as distinguished from the impact of such activities only on the "human environment" on Earth.

¹⁶³ See U.N. Doc. A/CN.4/481, para. 24; see also, U.N. Doc. A/C.6/51/SR.39, at para. 31-33.

Thus, the new LTSG guidelines stress the words: minimizing the impacts of human activities on Earth *as well as on the outer space environment*. And thus, the authors urge the US to consider a holistic approach to the conduct of EIAs for in-orbit operations of commercial satellites with a view to ascertaining both (a) the impact on the human environment; and (b) the impact on the outer space environment. From a policy perspective, the procedure could be to ascertain all impacts of the in-orbit operation of commercial satellites, their rocket bodies, and their debris while they are in the orbital space. As the concerns of the AAS (as discussed in the preceding section) are concerns raised by “affected national entities”, their concerns would automatically find redressal if this policy approach is pursued.

Legal/policy support:

§ LTSG A.2 (2)(d) recommends promotion of regulations and policies that support the idea of minimizing the impacts of human activities on Earth as well as on the outer space environment;

§ UN General Assembly Resolution 68/74, noting the need to maintain the sustainable use of outer space, in particular by mitigating space debris, and to ensure the safety of space activities and minimize the potential harm to the [outer space] environment;

§ UN General Assembly Resolution 73/91 entitled *International cooperation in the peaceful use of outer space*, wherein the General Assembly expresses its deep concern “*about the fragility of the space environment and the challenges to the long-term sustainability of outer space activities, in particular the impact of space debris, which is an issue of concern to all nations*”;

§ To a certain extent, the US already considers aspects of the space environment, as contained in the Space Policy Directive – 3, wherein Section 2(a), (b) and Section 3 treats the “*space environment*” as a separate environment (albeit in the context of Space Situational Awareness (SSA) and STM activities).

§ NPR 8715.6B defines responsibilities and requirements to ensure that NASA and its partners, providers, and contractors consider the preservation of the near-Earth space environment and the space environment beyond Earth’s orbit.

5.1.4 Precautionary Principle

The precaution proposed to be considered by the US is (a) consider a Cumulative Impact Analysis of all satellites in orbit, and (b) consider enacting measures and policies deemed to be a tier above the current category as given in Table 1 above.

With respect to the precautionary principle (PP), which will be addressed further below, the SG Report¹⁶⁴ also notes:

12. This principle stipulates that States are required to adopt a precautionary approach when taking decisions or in regard to potential omissions which may harm the environment. Such a duty remains intact irrespective of the absence of scientific certainty as to the existence or extent of such risk. While the principle as formulated in Principle 15 of the Rio Declaration reflects other critical principles, such as the effective implementation of international environmental law, the legal basis of precaution as a principle is a matter of some controversy and debate. However, the exercise of

¹⁶⁴ Report of the Secretary General, Gaps in international environmental law and environment-related instruments: towards a global pact for the environment, U.N. Doc. A/73/419 (Nov. 30, 2018).

*precaution in this respect is expressed in other foundational instruments of international environmental law, regional instruments, texts drafted by civil society and rulings of the International Tribunal for the Law of the Sea.*¹⁶⁵

With respect to the application of this principle, although well-defined, the authors note that its implementation and state practice is not yet enough to categorize it as a customary principle of international law. The authors recognize that it would wholly be the prerogative of the US to consider and adopt this principle as regards the conduct of EIAs for in-orbit operations.

5.1.4.1 Preliminary Discussion

The PP is an approach that encourages preventative measures to be taken in the event that the full consequences of a hazardous activity are yet to be scientifically determined. Essentially, “...where there is the potential for serious or irreversible harm to the ecosystem or human health, anticipatory measures should be taken to prevent such harm; furthermore, uncertainty as to the likelihood or extent of the harm should not result in the postponement of cost-effective measures to avoid it.”¹⁶⁶ It is important to stress that the PP does motivate scientific inquiry into the potential consequences of hazardous activities. As a result, if scientific inquiry determines that an action initially prevented by the PP can be carried out safely with the implementation of proper measures, protections may be lifted, and the activity can move forward. However, as will be explored later in this section, there has been pushback from the US government in suggesting that the PP does not, in their view, promote a science-based approach; yet overlap between the US approach and the PP is present in that both seek to achieve the similar goal of exercising precaution and scientific investigation with regard to activities that present unknown hazards.

The PP was first incorporated into German law regulating air pollution in the 1970s as *Vorsorgeprinzip* — the translation of which is essentially the “foresight principle”.¹⁶⁷ Since the 1980s it has emerged as a widely cited concept in both international treaties and national legislation focusing on human health, safety, and the environment. However, the adoption of the PP varies in degree and interpretation, owing to the lack of a universal consensus on its definition.¹⁶⁸

Many international environmental instruments have included iterations of the PP in text to emphasize the precaution as a means of preserving human health and the environment. The Vienna Convention for the Protection of the Ozone layer (VCPOL)¹⁶⁹, adopted in 1985, was the first international treaty to explicitly emphasize the concept, with Article 2(1) of the Convention reading:

The Parties shall take appropriate measures in accordance with the provisions of this Convention and of those protocols in force to which they are party to protect human health and the

¹⁶⁵ *Id.* at 8.

¹⁶⁶ Theresa McClenaghan, *Precautionary Principle*, in # ENCYCLOPEDIA OF QUALITY OF LIFE AND WELL-BEING RESEARCH (ALEX MICHALOS ED., 2014). [NEED PIN CITE]

¹⁶⁷ Timothy O’Riordan and Andrew Jordan, *The Precautionary Principle in Contemporary Environmental Politics*, 4 ENVIRONMENTAL VALUES 191, 193 (1995).

¹⁶⁸ McClenaghan, *supra* note 157 at #.

¹⁶⁹ Vienna Convention for the Protection of the Ozone Layer, Mar. 22, 1985, 1513 U.N.T.S. 293 [hereinafter VCPOL].

*environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer.*¹⁷⁰

Article 2(b) of VCPOL again reiterates the PP:

*Adopt appropriate legislative or administrative measures and co-operate in harmonizing appropriate policies to control, limit, reduce or prevent human activities under their jurisdiction or control should it be found that these activities have or are likely to have adverse effects resulting from modification or likely modification of the ozone layer.*¹⁷¹

The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (the Montreal Protocol),¹⁷² which built on the obligations in VCPOL, further compelled states to take precautionary measures when dealing with substances that deplete the ozone layer. Although a comprehensive scientific understanding of ozone-depleting substances had not been established, the Montreal Protocol obligated states to phase out the use of certain chemicals and products and was ultimately successful in doing so — thereby allowing the ozone layer to recover.¹⁷³

The 1992 Earth Summit in Rio De Janeiro marked a significant rise in the inclusion of the PP within international legal instruments. The resulting documents included the Rio Declaration,¹⁷⁴ the United Nations Framework Convention on Climate Change (UNFCCC),¹⁷⁵ and the Convention on Biological Diversity (CBD),¹⁷⁶ all of which embody the PP. Principle 15 of the Rio Declaration is the most widely cited example of the PP in international legal instruments, offering a robust definition that includes the core attributes of the PP:

*Principle 15: In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.*¹⁷⁷

The UNFCCC, a monumental step in addressing global climate change that would later lead to the Kyoto protocol and the Paris Agreement, included a principle obligating states to prioritize human health in the case of scientific uncertainty in Article 3(3).

The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to

¹⁷⁰ Vienna Convention for the Protection of the Ozone Layer online Handbook, UNITED NATIONS ENVIRONMENT PROGRAMME OZONE SECRETARIAT, <https://ozone.unep.org/treaties/vienna-convention> (last accessed Aug. 21, 2021).

¹⁷¹ Vienna Convention for the Protection of the Ozone Layer, Mar. 22, 1985, 1513 U.N.T.S. 293.

¹⁷² Montreal Protocol on Substances that Deplete the Ozone Layer, 1522 U.N.T.S. 3, Sept. 16, 1987 [hereinafter Montreal Protocol]

¹⁷³ Guus Velders et. al., *The Importance of the Montreal Protocol in Protecting Climate*, 104 PNAS 4814 (2007).

¹⁷⁴ Rio Declaration on Environment and Development, June 13, 1992, 31 ILM 874.

¹⁷⁵ United Nations Framework Convention on Climate Change, May 9, 1992, 1771 U.N.T.S. 107.

¹⁷⁶ Convention on Biological Diversity, June 5, 1992, 1760 U.N.T.S. 79 [hereinafter UNFCCC].

¹⁷⁷ Rio Declaration, principle 15.

*deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost. To achieve this, such policies and measures should take into account different socio-economic contexts, be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors. Efforts to address climate change may be carried out cooperatively by interested Parties.*¹⁷⁸

Lastly, the CBD included a reference to the PP in its preamble:

*Noting also that where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimize such a threat.*¹⁷⁹

However, having said that, the authors wish to direct the attention of concerned policy-makers towards the positions stated in US policy documents:

§ National Space Policy of the United States of America (09 December 2020), page 5:

“Create a safe, stable, secure, and sustainable environment for space activities, in collaboration with industry and international partners, through the development and promotion of responsible behaviors ...”

§ National Space Policy of the United States of America (09 December 2020), page 15:

“Regularly assess existing guidelines for non-government activities in or beyond Earth orbit, and maintain a timely and responsive regulatory environment for licensing those activities, consistent with United States law and international obligations;”

§ Report No. IG-21-011, 27 January 2021: NASA's Efforts to Mitigate the Risks posed by orbital debris, Conclusion:

“Protecting the expanding space environment is critical since the services billions of people rely on daily such as weather forecasting, telecommunications, and global positioning systems require a stable space environment.”

5.1.5 Atmospheric Pollution and Relevant International Environmental Law

The effects of satellites on the environment cannot be considered in isolation. Rather, there are cumulative effects due to actions by multiple actors in various States. These effects can have a negative impact on the environment, human activities, and on all satellite operations. They also might not be recognized if a system of satellites is evaluated independently of other systems or, worse yet, only single satellites are considered. In the following discussion, the authors focus the discussion on two aspects of this cumulative effect problem as it pertains to mega-constellations, namely light pollution and atmospheric pollution, as the latter can affect ground-based astronomy in non-trivial ways. In regard to developing a regulatory framework addressing light pollution, governments might, for example, consider:

1. How bright is an individual satellite (which combines phase, albedo, and reflecting area)?

¹⁷⁸ UNFCCC, art. 3(3).

¹⁷⁹ Convention on Biological Diversity, June 5, 1992, 1760 U.N.T.S. 79.

2. How many satellites are there in a constellation?
3. What duration of the night are the satellites visible, for the time of year and latitude of the observer?
4. What is the diffuse brightness due to all material in orbit, for the time of year and latitude of the observer?

The brightness of an individual satellite may or may not be important. For example, the International Space Station can be brighter than Venus, but because it is a single object it is generally not a problem for stargazing or astronomical measurements. In contrast, the over 1600 Starlink satellites currently in orbit are notable for the combination of their brightness and their numbers. With the prospects of between ten and a hundred times more satellites of potentially comparable brightness, or brighter, the problem of light pollution is potentially significant for the amount of diffuse light. In this way, regulating, say, a single satellite's brightness might only address one part of the problem.

Air pollution provides another example on how cumulative effects can be overlooked by focusing on single satellites. The real effects might only be understood by considering the collective action of all operators over decade timescales, taking into account material placed into the upper atmosphere due to rocket launches as well as satellite re-entries. Information available to scientists and policy makers will be incomplete at first, even if potential issues are identifiable now. Again, there might not be a single metric that we can use to understand the full effects either, owing to secondary effects. For example, climate impacts could alter global atmospheric circulation, which in turn could alter weather patterns.

As described below, there are numerous instances of national and international law, as well as international guidelines, that are built on the concept of the PP. This is done to avoid activities that might cause serious or irreversible harm to people and the environment. Because it calls for action (or restraint) before a full understanding of a development can be made, it is sometimes viewed as an unscientific approach to development¹⁸⁰. However, making cautious policy decisions in the face of scientific uncertainty is not the same as making decisions based on conjecture. Indeed, the precautionary principle is rooted in the scientific process, as McClenaghan¹⁸¹ explains:

*Since there must be a basis on which to conclude that a threat of harm is serious and perhaps irreversible, the precautionary principle is truly science based. The more good science we have, the better our precautionary decision making can be. In other words, as more evidence is compiled, we might conclude that the harm in question either is not serious or irreversible or can be prevented through appropriate actions. Or we may conclude that there is less uncertainty or doubt about the potential harm that may be caused or alternatively that we cannot reasonably reduce the uncertainty and precaution must be maintained. (Once we have a great deal of certainty, we no longer need to apply the precautionary principle per se; our other decision-making criteria are relevant to determine what course of action is indicated).*¹⁸²

One way that there can be meaningful environmental assessment in the face of scientific uncertainty is to consider whether proposed or ongoing human activities will, directly or indirectly, introduce rates of

¹⁸⁰ McClenaghan, *supra* note 157, at #.

¹⁸¹ *Id.*

¹⁸² *Id.*

change in an environment that are comparable to or exceed natural rates or whether the development will introduce new damaging materials to an environment.

Current development of LEO has the potential to interfere with its future development, an antithesis to sustainable development.¹⁸³ This interference, as discussed above, includes the de facto exclusion of other actors from orbital slots, the increased conjunction assessment burden and corresponding maneuvers, and delays in launches.¹⁸⁴ Specific to astronomy, unsustainable practices in space may already be causing a change in the nighttime brightness of the sky due to light reflected off space debris.¹⁸⁵ These changes will not be noticeable at this time by stargazers, but may become measurable at dark sites when conducting any form of deep (long integration) imaging. Further proliferation of space debris and the widespread construction of mega-constellations is thus not just an operational concern for satellite activities, but a concern for the sky brightness. The overall effect will depend on the total reflecting area that is placed in orbit, including debris that will arise from any type of on-orbit fragmentation event from collisions, battery and fuel explosions, or meteoroid impacts. Understanding the scope of this problem requires evaluating the cumulative effects.

Another area of concern is the deposition of materials into the upper atmosphere well above natural rates. One example is the placement of soot, alumina, and ozone-depleting substances in the stratosphere by rockets.¹⁸⁶ Soot and alumina have climate implications by altering Earth's radiative balance, while alumina, chlorine, and radicals destroy ozone. Such ozone depletion has been measured directly in the wake of some rockets.¹⁸⁷ The rocket launches needed to support mega-constellations are a concern for altering Earth's climate and ozone layer. Note that CO₂ emission from rockets is of little to no concern at this time (although we should be mindful that this could change), and the evaluation of climate impacts based solely on CO₂ emissions misses the largest effects of rockets on Earth's atmosphere.

Along with direct climate and ozone implications, however, are secondary effects, such as changes to global atmospheric circulation and the formation of mesospheric clouds. The latter has direct implications for astronomical observations, and such mesospheric cloud cover is already thought to be influenced by space traffic.¹⁸⁸

Yet another area of concern is the deposition of material into the atmosphere due to satellite and rocket body reentries¹⁸⁹. Each day, meteoroids deliver 54 tons of material to Earth¹⁹⁰, most of which is deposited

¹⁸³ Report of the World Commission on Environment and Development: Our Common Future (1987).

¹⁸⁴e.g., The Future of Security in Space: A Thirty-Year US Strategy, 2021, C.G. Starling et al., Atlantic Council Strategy Paper Series,

<https://www.atlanticcouncil.org/content-series/atlantic-council-strategy-paper-series/the-future-of-security-in-space/>

¹⁸⁵ M. Kocifaj, et. al., *The proliferation of space objects is a rapidly increasing source of artificial night sky brightness*, 504 MNRAS, L40, L44 (2021).

¹⁸⁶ Martin Ross & James Vedda, *The Policy and Science of Rocket Emissions*, Aerospace Corp. (2018), available at https://aerospace.org/sites/default/files/2018-05/RocketEmissions_0.pdf.

¹⁸⁷ M.N. Ross et al, *Observation of stratospheric ozone depletion associated with Delta II rocket emissions*, 27 GEOPHYSICAL RESEARCH LETTERS 22209, 2209-2212 (2000).

¹⁸⁸ David E. Siskind et al., *Recent observations of high mass density polar mesospheric clouds: A link to space traffic*, 40 GEOPHYSICAL RESEARCH LETTERS 2813, 2813-2817 (2013).

¹⁸⁹ Aaron Boley & Michael Byers, *Satellite mega-constellations create risks in Low Earth Orbit, the atmosphere and on Earth*, 11 SCI. REP. 10641 (2021).

¹⁹⁰ Gerhard Drolshagen et al., *Mass accumulation of earth from interplanetary dust, meteoroids, asteroids and comet*, 143 PLANETARY SPACE & SCI. 21, 21-27 (2017).

in Earth's mesosphere. Satellite operations of large constellations are proposing system recycling approximately every five years. If one considers as an example the 42,000 satellites under consideration by the FCC for Starlink, the average satellite reentry from this constellation alone would be 23 satellites per day. For satellite masses of 260 kg (empty), this amounts to about 6 tonnes per day. At face value, one might see this human activity as having only a 10% effect compared with meteoroids. However, meteoroids and satellites have vastly different compositions. For example, satellites are mostly aluminum, while meteoroids are only about 1% aluminum by weight¹⁹¹. Thus, anthropogenic deposition of aluminum is poised to exceed that of meteoroids by a factor of ten. Other elements may also exhibit high levels of anthropogenic placement into the environment.

As seen with the rocket launch studies discussed above, high-altitude aluminum introduces multiple concerns, including albedo changes to Earth and ozone depletion as the material sinks into the stratosphere. The full composition of satellites may have further effects that cannot be identified until there is a registry of satellite composition by mass fraction (empty and wet). As an example, the sodium contained within meteoroids, which is only about 0.5% of their composition by weight, produces a sodium layer in the mesosphere. That layer leads to a component of "airglow", contributing to sky brightness in some observing bands.¹⁹²

5.1.6 The Rio Declaration

The Rio Declaration¹⁹³ consists of 27 principles adopted during the 1992 United Nations on Environment and Development, the so-called Earth Summit. While the Declaration is non-binding, it lays out several important ideas concerning the environment. All nations present at the Summit accepted the Declaration without change¹⁹⁴. The first principle emphasizes that the scope is centred on concerns for humanity:

*Human beings are at the centre of concerns for sustainable development. They are entitled to a healthy and productive life in harmony with nature.*¹⁹⁵

Principle 2 acknowledges the right of states to exploit their own resources, but also declares that states have a responsibility not to "cause damage to the environment of other States or of areas beyond the limits of national jurisdiction". In full,

*States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.*¹⁹⁶

¹⁹¹ Katharina Lodders, *Solar system abundances of the elements*, in PRINCIPLES AND PERSPECTIVES IN COSMOCHEMISTRY (Aruna Goswami and B. Eswar Reddy eds., 2008).

¹⁹² F. Patat, *UBVRI night sky brightness during sunspot maximum at ESO-Paranal*, 400 ASTRONOMY & ASTROPHYSICS 1183, 1183-1198 (2002).

¹⁹³ U.N. Doc. A/CONF.151/26 (Vol I) (Aug. 12, 1992).

¹⁹⁴ G.A. Res. 47/190 (Mar. 16, 1993).

¹⁹⁵ Rio principle 1

¹⁹⁶ Rio principle 2

Principle 3 goes on to define sustainable development, using language similar to that used in the Brundtland Report¹⁹⁷ and emphasizing that the development must be done in ways that do not prevent future generations from also developing an area:

*The right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations.*¹⁹⁸

Having defined sustainable development, the Declaration sees environmental protection as inseparable from the development process:

*In order to achieve sustainable development, environmental protection shall constitute an integral part of the development process and cannot be considered in isolation from it.*¹⁹⁹

While many of the principles contain text relevant to this discussion, it is important to highlight principle 15, which is a statement of the PP, namely:

*In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.*²⁰⁰

This principle highlights the situation we now face with the construction of satellite mega-constellations. Multiple risks have been identified, some of which are serious (as discussed above) and require further study. The lack of certainty must not be used to dismiss such concerns.

Principles 16 and 17 are also relevant. They are, in turn:

National authorities should endeavour to promote the internalization of environmental costs and the use of economic instruments, taking into account the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment

and

*Environmental impact assessment, as a national instrument, shall be undertaken for proposed activities that are likely to have a significant adverse impact on the environment and are subject to a decision of a competent national authority.*²⁰¹

Damage to the night sky, the atmosphere, and Earth's orbital environment through the use and occupation of satellites are examples of negative externalities that licensing States impose on the global population. As principle 16 explains, these externalities should be internalized and the "*polluter should, in principle, bear the cost of pollution*". Moreover, principle 17 gives States a responsibility to ensure that an

¹⁹⁷ Report of the World Commission on Environment and Development: Our Common Future (1987).

¹⁹⁸ Rio principle 3

¹⁹⁹ Rio principle 4

²⁰⁰ Rio principle 15

²⁰¹ Rio principles 16 and 17

environmental assessment is carried out for activities “*that are likely to have a significant impact on the environment*”. This must be read with principle 15 as well, again stressing that scientific uncertainty cannot be used as an argument to ignore potentially serious adverse effects.

The US joined over 170 other nations in adopting these non-binding principles. However, the US did note several reservations²⁰². Of the principles listed above, only principle 3 was offered an explicit note:

The United States does not, by joining consensus on the Rio Declaration, change its long-standing opposition to the so-called ‘right to development’. Development is not a right. On the contrary, development is a goal we all hold, which depends for its realization in large part on the promotion and protection of the human rights set out in the Universal Declaration of Human Rights.

*The United States understands and accepts the thrust of principle 3 to be that economic development goals and objectives must be pursued in such a way that the development and environmental needs of present and future generations are taken into account. The United States cannot agree to, and would disassociate itself from, any interpretation of principle 3 that accepts a ‘right to development’, or otherwise goes beyond that understanding.*²⁰³

Thus, while the US government rejected the idea that development is a right, it accepted the idea of sustainable development and that the needs of future generations must be “*taken into account*” when pursuing “*economic development goals and objectives*”.

Nonetheless, as emphasized above, the Rio Declaration is non-binding and its principles are open to interpretation by each State. To look at potentially relevant binding international law, we turn toward the 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP), the 1985 VCPOL, and the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer.

5.1.7 The Convention on Long-Range Transboundary Air Pollution

The preamble of LRTAP states that the parties agreed to the convention, including the United States,

*Considering the pertinent provisions of the Declaration of the United Nations Conference on the Human Environment, and in particular principle 21, which expresses the common conviction that States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility **to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction** [emphasis added],*

²⁰² Report of the United Nations Conference on Environment and Development, Rio de Janeiro (June 3-14 1992) (Vol. 2).

²⁰³ *Id.*

*Affirming their willingness to reinforce active international co-operation to develop appropriate national policies and by means of exchange of information, consultation, research and monitoring, the co-ordinate national action for combating air pollution including long-range transboundary air pollution.*²⁰⁴

In the Convention, the term “‘Air Pollution’ means the introduction by man, directly or indirectly, of substances or energy into the air resulting in deleterious effects of such a nature as to endanger human health, harm living resources and ecosystems and material property and impair or interfere with amenities and other legitimate uses of the environment, and ‘air pollutants’ shall be construed accordingly;”

As discussed above, the combination of rocket launches and satellite re-entries is a principal source of upper atmosphere air pollution and is expected to become more severe. The LRTAP continues under its “Fundamental Principles”:

Article 2: The Contracting Parties, taking due account of the facts and problems involved, are determined to protect man and his environment against air pollution and shall endeavour to limit and, as far as possible, gradually reduce and prevent air pollution including long-range transboundary air pollution.

*Article 3: The Contracting Parties, within the framework of the present Convention, shall by means of exchanges of information, consultation, research and monitoring, develop without undue delay policies and strategies which shall serve as a means of combating the discharge of air pollutants, taking into account efforts already made at national and international levels.*²⁰⁵

Together, these articles suggest that the US government should “develop without undue delay policies and strategies” that would address the cumulative atmospheric effects of the launch and re-entry of satellites operated by entities under its jurisdiction, as per Article VI of the OST. In understanding whether the US government considers the deposition of harmful substances into the upper atmosphere as “air pollution”, it should be noted that Title VI of the US Clean Air Act²⁰⁶ specifically addresses pollution in the context of stratospheric ozone protection, with reference to the VCPOL and the corresponding 1987 Montreal Protocol²⁰⁷.

5.1.7.1 The Vienna Convention on the Protection of the Ozone Layer and the Montreal Protocol

The preamble²⁰⁸ of the VCPOL affirms that states party to the treaty have a:

*responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.*²⁰⁹

²⁰⁴ Convention on Long-range Transboundary Air Pollution. Geneva, Nov. 13, 1989, 1302 U.N.T.S. 217.

²⁰⁵ Id.

²⁰⁶ Clean Air Act Title VI - Stratospheric Ozone Protection, 42 USC. § 7671 et. seq.

²⁰⁷ Montreal Protocol.

²⁰⁸ VCPOL, preamble.

²⁰⁹ Id.

Under the VCPOL, the US government has a general obligation:

- 1. The Parties shall take appropriate measures in accordance with the provisions of this Convention and of those protocols in force to which they are party to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer.*
- 2. To this end the Parties shall, in accordance with the means at their disposal and their capabilities:*
 - a. Co-operate by means of systematic observations, research and information exchange in order to better understand and assess the effects of human activities on the ozone layer and the effects on human health and the environment from modification of the ozone layer;*
 - b. Adopt appropriate legislative or administrative measures and co-operate in harmonizing appropriate policies to control, limit, reduce or prevent human activities under their jurisdiction or control should it be found that these activities have or are likely to have adverse effects resulting from modification or likely modification of the ozone layer...*²¹⁰

Given the potential of the construction and maintenance of satellite mega-constellations to contribute to ozone loss, appropriate measures may be required by all parties to the agreement to limit the impact of the cumulative effects of satellites on the atmosphere, including the ozone layer. We note that Section 11 of VCPOL focuses on dispute resolution, should there be a disagreement between parties to the agreement regarding the interpretation or application of the Convention. Thus, should parties find that some governments are approving the construction of mega-constellations without taking appropriate measures to limit adverse effects resulting from changes or likely changes to the ozone layer, then those governments may be subject to the execution of that dispute resolution.

This “Settlement of disputes” provision at Article 11 enables parties in significant disagreement regarding their VCPOL obligations to first mutually seek a resolution through negotiation (Article 11(1)) or mediation (Article 11(2)). This provision does, though, also contain at Article 11(3) a robust compulsory dispute settlement mechanism, involving either formal arbitration or submission of the dispute to the International Court of Justice for adjudication. Only five of the 197 States Parties (Andorra, Finland, the Netherlands, Norway and Sweden) have accepted this compulsory dispute settlement procedure,²¹¹ which accordingly is not applicable to the US.

The remaining 192 States Parties, including the US, are, however, alternatively subject to Article 11(4)-(5), where those parties not accepting the compulsory dispute settlement mechanism can instead be required to participate in a formal “conciliation commission” at the request of one party to a dispute under VCPOL. This is a final option should negotiation or mediation under Article 11(1)-(2) prove unsuccessful or inappropriate. Such a conciliation commission shall be composed of an equal number of members chosen by each party in dispute and a chair jointly selected by these appointed members. The power of the commission enables it to “*render a final and recommendatory award, which the parties shall consider in good faith.*” Article 11(4)-(5) accordingly offers a powerful, albeit very rarely used, diplomatic tool as it can be used to compel a party (such as the US) into a formalized dispute resolution process,

²¹⁰ VCPOL

²¹¹ *Id.*

where a final decision and award is publicly delivered by a commission of appointed experts, even though this decision and award is ultimately only recommendatory and non-enforceable. The mere existence of this conciliation commission as an obligatory institutional process within VCPOL can, however, positively influence the behavior of States Parties, via a wish to avoid the negative publicity and diplomatic fallout resulting from such a commission process being potentially initiated against it.

The Montreal Protocol is also of interest as it provides a forum for identifying new threats to the ozone layer's stability. Even secondary effects that can lead to ozone loss can be considered, as the United Nations Environment Programme Ozone Secretariat explains²¹²:

*The parties to the Protocol meet once a year to make decisions aimed at ensuring the successful implementation of the agreement. These include adjusting or amending the Protocol, which has been done six times since its creation. The most recent amendment, the Kigali Amendment, called for the phase-down of hydrofluorocarbons (HFCs) in 2016. These HFCs were used as replacements for a batch of ozone-depleting substances eliminated by the original Montreal Protocol. Although they do not deplete the ozone layer, they are known to be powerful greenhouse gases and, thus, contributors to climate change.*²¹³

While much of this is connected with atmospheric pollution rather than light pollution only, there may be considerable overlap in the steps necessary to limit both.

5.2 US and European Union Adoption of the Precautionary Principle in Domestic Legislation

Although the US rejects the Precautionary Principle (PP) as it is interpreted in international law and subsequent EU legislation, the US arguably operates with at least as much or, in some cases, more precaution than EU states regarding activities posing risks to human health and the environment.²¹⁴ For example, the Treaty on European Union: the environmental portion of the treaty includes the PP and has been adopted in the domestic legislation of many European countries:

*Community policy on the environment shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Community. It shall be based on the precautionary principle and on the principles that preventive action should be taken, that environmental damage should, as a priority, be rectified at the source and the polluter should pay. Environmental protection requirements must be integrated into the definition and implementation of other Community policies.*²¹⁵

Very little work has been done by the US government to implement the PP into domestic environmental law as it has been interpreted in international legal instruments. The US government rejects the idea that the PP — as it appears in international instruments — encourages science-based assessment in its

²¹² *Montreal Protocol on Substances that Deplete the Ozone Layer online Handbook*, UNITED NATIONS ENVIRONMENT PROGRAMME OZONE SECRETARIAT, <https://ozone.unep.org/treaties/montreal-protocol> (last accessed 26 June 2021).

²¹³ *Id.*

²¹⁴ JOAKIM ZANDER, *THE APPLICATION OF THE PRECAUTIONARY PRINCIPLE IN PRACTICE: COMPARATIVE DIMENSIONS* 267-326 (2010).

²¹⁵ Treaty on European Union, art. 130r(2) Feb. 7, 1992 [hereinafter Maastricht Treaty].

determination of when an activity may result in serious harm to human health and the environment, and that such an approach stifles progress. A Statement by the US Chamber of Commerce highlights the obscure position that the US has adopted:

The regulatory implications of the precautionary principle are substantial. For instance, the precautionary principle holds that since the existence and extent of global warming and climate change are not known, one should assume the worst, and immediately restrict the use of carbon-based fuels. However the nature and extent of key environmental, health, and safety concerns require careful scientific and technical analysis. That is why the US Chamber has long supported the use of sound science, cost-benefit analysis, and risk assessment when assessing a particular regulatory issue.

²¹⁶

Alternatively, the US has adopted a precautionary approach which calls for science-based risk assessment and a cost-benefit analysis, but differs in that it aims to never prevent an activity from moving forward when the risks are not fully understood. Only if hard scientific evidence exemplifies that the activity is, or would be, detrimental to human health and/or the environment would the activity then be stopped. The US approach instead subjects riskier activity to more stringent regulatory scrutiny. As the US Chamber of Commerce states:

*The US Chamber of Commerce supports a science-based approach to risk management where risk is assessed based on scientifically sound and technically rigorous analysis. Under this approach, regulatory actions are justified where there are legitimate, scientifically ascertainable risks to human health, safety, or the environment. That is, the greater the risk, the greater the degree of regulatory scrutiny. This standard has served the nation well, and has led to astounding breakthroughs in the fields of science, health care, medicine, biotechnology, agriculture, and many other fields...*²¹⁷

Examples of the precautionary approach adopted in US environmental legislation are found in the following Acts.²¹⁸

- The Occupational Safety and Health Act of 1970²¹⁹
- The 1977 Clean Air Act²²⁰
- The 1975 Toxic Substances Act²²¹

²¹⁶ *Precautionary Principle*, US CHAMBER OF COMMERCE, <https://www.uschamber.com/precautionary-principle> (last accessed Jul 1, 2021).

²¹⁷ *Id.*

²¹⁸ For a full list of US Legislation and Executive Orders that contain a precautionary approach, see Zander, *supra* note 192, at xxx-xxxii.

²¹⁹ 29 USC. §651 *et seq.* (1970).

²²⁰ 42 USC. § ch. 85.

²²¹ Pub. L. No. 94-469 (Oct. 11, 1967).

5.3 US Environmental Law

5.3.1 NEPA

Any consideration by the US of modern regulation of the natural environment and the effects of human activity upon it must include a discussion of NEPA, enacted in 1970.²²² Through NEPA, the US articulated its national environmental policy:²²³

*to use all practicable means and measures to foster and promote the general welfare, create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans.*²²⁴

This declaration followed Congress's recognition of the "*profound impact of [hu]man's activity on the interrelations of all components of the natural environment.*"²²⁵ Congress further articulated the "*responsibility of the Federal Government to use all practicable means, consistent with other essential considerations of national policy, to improve and coordinate Federal plans, functions, programs and resources to the end to that the Nation may:*

- (1) fulfill the responsibilities of each generation as trustee of the environment for succeeding generations;*
- (2) assure for all Americans safe, healthful, productive, and esthetically and culturally pleasing surroundings;*
- (3) attain the widest range of beneficial uses of the environment without degradation, risk to health or safety, or other undesirable and unintended consequences;*
- (4) preserve important historic, cultural, and natural aspects of our national heritage, and maintain, wherever possible, an environment which supports diversity and variety of individual choice.*²²⁶

Within NEPA, Congress also created the CEQ to "*review and appraise the various programs and activities of the Federal Government in*" light of the national environmental policy.²²⁷ Indeed, NEPA sought "*to ensure Federal agencies consider the environmental impacts of their actions in the decision-making process.*"²²⁸ Subsequently, the CEQ promulgated regulations to establish parameters for agencies when they adopt their own NEPA implementing procedures in light of their own specific operations. In adopting their NEPA procedures, agencies must consult with the CEQ. When taking a major federal action (e.g., licensing), federal agencies must complete EISs for actions that will have a significant effect on the environment; when a proposed action may have a significant effect or "*when the significance of the*

²²² 42 USC. § 4321, *et seq.* (1970).

²²³ For this reason, any argument or discussion relating to the United States' environmental policy must begin with NEPA.

²²⁴ *Id.*; 40 C.F.R. § 1500.1 (1978).

²²⁵ 42 USC. § 4331 (1970).

²²⁶ *Id.* at § 4331(b).

²²⁷ 40 C.F.R. § 4344(3) (1978).

²²⁸ 40 C.F.R. § 1500.1 (1978).

effects is unknown,” the agency must prepare an environmental assessment.²²⁹ When actions do not have an effect on the environment either individually or cumulatively, the agency may categorically exclude the action from NEPA review (unless certain circumstances are present).²³⁰

Nevertheless, certain definitions within the US’s own national environmental policy are unclear. For example, an agreed definition on the limits of Earth’s environment within its broader regulatory regime remains somewhat elusive.

CEQ Implementing Regulations provide a definition for “human environment”:

§ 1508.14 Human environment.²³¹

*Human environment shall be interpreted comprehensively to include the natural and physical environment and the relationship of people with that environment. (See the definition of “effects” (§ 1508.8).) This means that economic or social effects are not intended by themselves to require preparation of an environmental impact statement. When an environmental impact statement is prepared and economic or social and natural or physical environmental effects are interrelated, then the environmental impact statement will discuss all of these effects on the human environment.*²³²

Despite the nomenclature “*human*” environment, the definition provided in the CEQ Implementing Regulations includes the entire “*natural and physical environment*” as well as the “*relationship of people with that environment*.”²³³

Some of the authors maintain that the absence of any limitations on the “*natural and physical environment*” suggests that the term includes Earth and its orbital environment. The debate then moves to the farthest extent of Earth’s environment — whether it includes the moon, and whether it even includes the greatest distances touched by human artifacts such as planetary probes.

The CEQ Implementing Regulations further define “effects” as:

§ 1508.8 Effects.

Effects include:

(a) *Direct effects, which are caused by the action and occur at the same time and place.*

(b) *Indirect effects, which are caused by the action and are later in time or farther removed in distance, but are still reasonably foreseeable. Indirect effects may include growth inducing effects and other effects related to induced changes in the pattern of land use, population density or growth rate, and related effects on air and water and other natural systems, including ecosystems.*

Effects and impacts as used in these regulations are synonymous. Effects includes ecological (such as the effects on natural resources and on the components, structures, and functioning of affected ecosystems), aesthetic, historic, cultural, economic, social, or

²²⁹ 40 C.F.R. § 1501.5 (1978).

²³⁰ *Id.*

²³¹ Although NEPA discussed “environment” and “natural environment,” the CEQ Implementing Regulations use the term “human environment” for the title of the definition.

²³² 40 CFR § 1508.14.

²³³ *Id.*

*health, whether direct, indirect, or cumulative. Effects may also include those resulting from actions which may have both beneficial and detrimental effects, even if on balance the agency believes that the effect will be beneficial.*²³⁴

While these implementing regulations contain some of the same terms as those in NEPA, they do not explicitly convey the same imperative and scope presumably intended under NEPA.²³⁵ This definitional discrepancy has arguably led to more limited interpretations of “environment” and “effects” by certain federal agencies.

Each of the federal agencies must ensure that its activities comply with NEPA and the CEQ Implementing Regulations; because NEPA is a federal obligation, licensees must comply with agency NEPA procedures if due diligence is delegated to them to ensure agency compliance.. With respect to commercial satellite operations within Earth’s orbital environment, two primary agencies whose actions trigger NEPA compliance include the FAA (e.g., permitting launch and re-entry of satellites) and the FCC (e.g., licensing satellite radio frequency operations).

5.3.2 FAA Interpretation

In adopting its NEPA procedures for its operations, the FAA has construed CEQ Implementing Regulations broadly. In 2015, the FAA updated and published its Order for Environmental Impacts: Policies and Procedures as Order 1050.1F (Order).²³⁶ In the 132-page Order, the FAA indicates several environmental impact categories that *may* be relevant to FAA actions under NEPA.

Not surprisingly, areas of potential applicable relevance identified by the FAA as environmental impact categories include: air quality; climate change; hazardous materials, solid waste, and pollution prevention; as well as historical, architectural, archeological, and cultural resources.²³⁷ With respect to satellites, the alumina introduced into the atmosphere clearly could invoke the first three categories listed. Light pollution could fall under pollution or the latter category of cultural resources.

Interestingly, the FAA also identifies visual effects, light emissions, and visual resources/visual character as a possible environmental impact category.²³⁸ Indeed, the FAA recognizes that light emissions can “affect the visual character of the area...including the importance, uniqueness, and aesthetic value of the affected visual resources.”²³⁹ With respect to light emissions, the factors to consider include:

[t]he degree to which the action would have the potential to . . . [c]reate annoyance or interfere with normal activities from light emissions; and . . . [a]ffect the visual character of

²³⁴ 40 CFR § 1508.8.

²³⁵ See discussion of NEPA *supra*.

²³⁶ US DEP’T. OF TRANSP., FED. AVIATION ADMIN., ORDER 1050.1F, ENVIRONMENTAL IMPACTS: POLICIES AND PROCEDURES (2015). FAA Order 1050.1D became effective December 1, 1983 and was cancelled on June 8, 2004. FAA Order 1050.1E became effective March 20, 2004, was amended March 20, 2006, and was cancelled on July 16, 2015. This Order mentions light emissions and visual impacts as an environmental impact category.

²³⁷ These all should be explored further.

²³⁸ FAA 1050.1F, at 4-1, 4-10.

²³⁹ FAA Order 1050.1F, at 4-10.

*the area due to the light emissions, including the importance, uniqueness, and aesthetic value of the affected visual resources.*²⁴⁰

With respect to visual resources/visual character, the FAA considers:

*[t]he extent the action would have the potential to: . . . [a]ffect the nature of the visual character of the area, including the importance, uniqueness, and aesthetic value of the affected visual resources; . . . [c]ontrast with the visual resources and/or visual character in the study area; and . . . [b]lock or obstruct the views of visual resources, including whether these resources would still be viewable from other locations.*²⁴¹

Of course, the FAA determined that certain light emissions and visual effects associated with aviation operations would fall within one or more categorical exclusions. For example, the FAA excludes certain lighting for operations and safety.²⁴² However, the analysis under this exclusion would still be subject to the assessment of “extraordinary circumstances.”²⁴³

At the same time, the FAA considers noise to be a significant environmental consideration. In fact, it represents that “[n]oise is often the predominant aviation environmental concern of the public.”²⁴⁴ Not surprisingly then, a number of statutes and regulations have been enacted and promulgated, respectively, related to noise and noise-compatible land-uses.²⁴⁵ With respect to the FAA, it established the Day Night Average Level metric for noise analysis in conjunction with decibel levels.²⁴⁶ The FAA also provides substantial guidance in preparing appropriate reports of such analyses for purposes of complying with NEPA.²⁴⁷ Depending on planned aircraft and land uses, different criterion levels and metrics may apply.²⁴⁸ For example (and perhaps most commonly), it delineates specific altitude ranges for noise analysis depending on arrival and departures at airports. It also recognizes that special sensitivities exist “with

²⁴⁰ FAA Order 1050.1F at 4-10 (Though, the “FAA has not established a significant threshold for Light Emissions.”).

²⁴¹ *Id.* (though, the “FAA has not established a significant threshold for Visual Resources/Visual Character.”).

²⁴² FAA Order 1050.1F at 5-8—5-9 (5-6.3 Categorical Exclusions for Equipment and Instrumentation);

²⁴³ *Id.*

²⁴⁴ 1050.1F Desk Reference (v2) (February 2020).

²⁴⁵ Airport and Airway Improvement Act of 1982, 49 USC § 47101 et seq. (authorizes funding for noise mitigation and noise compatibility planning and projects. Establishes requirements related to noise-compatible land use); Airport Noise and Capacity Act of 1990, 49 USC. §§ 47521-47534 § 106(g), 47523-47527 (establishes requirements regarding airport noise and access restrictions for Stage 2 and 3 aircraft); Aviation Safety and Noise Abatement Act of 1979, 49 USC. § 47501 et seq. (directs the FAA to establish a single system for measuring noise and determining the exposure of people to noise); Prohibition on Operating Certain Aircraft Weighing 75,000 Pounds or Less Not Complying with Stage 3 Noise Levels (Section 506 of the FAA Modernization and Reform Act of 2012), 49 USC. §§ 47534 (a person may not operate a civil subsonic jet airplane with a maximum weight of 75,000 pounds or less unless the aircraft complies with stage 3 noise levels); The Control and Abatement of Aircraft Noise and Sonic Boom Act of 1968, 49 USC. § 44715 (authorizes the FAA to prescribe standards for the measurement of aircraft noise and establish regulations to abate noise); The Noise Control Act of 1972, 42 USC. §§ 4901-4918 (amends the Control and Abatement of Aircraft Noise Sonic Boom Act of 1968 to add consideration of the protection of public health and welfare and to add the EPA to the rulemaking process for aircraft noise and sonic boom standards).

²⁴⁶ *Id.* at 11-2.

²⁴⁷ See generally 1050.1F Desk Reference (v2) (February 2020).

²⁴⁸ See generally 14 CFR § 36, *et seq.*

*respect to certain resources such as national parks.*²⁴⁹ The applicable decibel levels can further be applied depending on the size of the aircraft and the surrounding land use.

With respect to noise alone, the FAA provides numerous resources and tools to consider the applicable environmental impacts.²⁵⁰ The Desk Reference accompanying the Order includes 21 pages focused specifically on “*Noise and Noise-Compatible Land Use*.” Moreover, the FAA also licenses an Aviation Environmental Design Tool (AEDT) for aviation stakeholders that provides information on the specific environmental impacts of “*fuel consumption, emissions, noise, and air quality consequences*” and “*facilitates environmental review activities required under NEPA by consolidating the modeling of these environmental impacts in a single tool.*”²⁵¹

5.3.3 FCC Interpretation

In contrast to the FAA's and other agencies' NEPA procedures, the FCC's rules implementing NEPA at 47 CFR § 1.1307 construed the CEQ Implementing Regulations narrowly. Rather than identifying classes of actions that are categorically excluded, the FCC categorically excludes most of its actions but for those that fall within a limited set of circumstances, including facilities that affect historic resources or endangered species, or exceed Radio Frequency (RF) exposure limits. The relevant portions for satellites of Section 1.1307 focus on human exposure to RF from FCC-authorized facilities.²⁵² In explaining the scope of § 1.1307, the FCC stated:

*Based upon the Commission's experience, we have determined that the telecommunications industry does not generally raise environmental concerns. The comments filed in this proceeding support the Commission's determination. Thus, we have categorically excluded most Commission actions from environmental processing requirements.*²⁵³

It further stated that:

*The Commission has reduced to three general areas the types of actions that may have a significant environmental impact to include cases in which facilities: (1) will be located in sensitive areas (e.g. wildlife preserves); (2) will involve high intensity lighting in residential areas; and/or (3) will expose workers or the general public to levels of radiofrequency radiation which would exceed the applicable health and safety standards set forth in § 1.1307(b) of our rules.*²⁵⁴

²⁴⁹ 1050.1F Desk Reference (v2) (February 2020) at 11-1. This could very easily parallel the concerns of solar reflectivity affecting resources associated with dark sky areas.

²⁵⁰ *Airport Noise*, FAA, https://www.faa.gov/airports/environmental/airport_noise/ (last accessed Aug. 17, 2021).

²⁵¹ *Aviation Environmental Design Tool*, FAA, <https://aedt.faa.gov/> (last accessed Aug. 17, 2021).

²⁵² 47 C. F. R. § 1.1307 (1990).

²⁵³ *Environmental Rules in Response to New Regulations Issued by the Council on Environmental Quality*, 51 Fed. Reg. 14999 (Apr. 22, 1986) (to be codified at 41 C.F.R. pts. 1, 21, 63, 90, 94).

²⁵⁴ *Id.*

Despite the FCC's oversight and authorization of satellite operations, § 1.1307 makes no reference to satellites or the orbital space surrounding Earth in which the satellites will operate.²⁵⁵ And, the regulation has not been significantly amended since 1986.²⁵⁶

The FCC delegates the initial determination of whether a facility is categorically excluded to the applicant. Hence, FCC satellite license application forms inquire whether the facility would have a “*significant environmental impact*” as defined by 47 CFR §1.1307.²⁵⁷ Considering the FCC's interpretation of the CEQ regulations and the dearth of guidance to applicants on the due diligence required to answer this question, it should not be surprising that satellite license applicants have routinely indicated that their operations will not have a significant environmental impact under § 1.1307 so that no environmental assessment is required. It is worth noting that no-one seems to have raised potentially significant effects with the FCC with regard to any satellites authorized before 2020. However, it must also be noted that the satellite environment has changed significantly in the last year. Whereas in 2019 3600 satellites — both operational and defunct — were in orbit, that number has increased to 7500. This presents an ongoing and increasing challenge.

Based on the foregoing, some authors of this paper suggested that the FCC should be encouraged to interpret its NEPA obligations to include satellite operations above the Earth's surface²⁵⁸ and maintained that the FCC can implement this interpretation by amending § 1.1307²⁵⁹ to include:

- (c) Commission actions with respect to satellite operations may significantly affect the environment and thus require the preparation of EAs or may require further Commission environmental processing where:²⁶⁰
 - (1) Satellite operations may affect scientific investigations of space including, but not limited to, optical, radio, and infrared astronomy;
 - (2) Satellite operations may affect aesthetic or cultural use of the night sky; or,
 - (3) Satellites will contain elements or materials that could affect chemical composition of the atmosphere.

The proposed (c)(1) could be more explicit by adding that the visual effects of satellites would fall within its scope.

Additionally, some authors of this paper indicated that the FCC should provide satellite stakeholders with comprehensive and thorough resources to analyze the relevant environmental impacts. The resources

²⁵⁵ 47 C. F. R. § 1.1307 (1990).

²⁵⁶ *Id.*

²⁵⁷ Application for Satellite Space Station Authorizations, FCC 312 Main Form (November 15, 2016).

²⁵⁸ We do not need to assess whether the CEQ misinterpreted NEPA or the FCC misinterpreted CEQ regulations; CEQ approved FCC NEPA regulations. .

²⁵⁹ Further, the existing (c) would become (d), (d) would become (e), and (e) would become (f).

²⁶⁰ For reference, the language of 1.1307(a) states:

Commission actions with respect to the following types of facilities may significantly affect the environment and thus require the preparation of EAs by the applicant (see §§ 1.1308 and 1.1311) and may require further Commission environmental processing (see §§ 1.1314, 1.1315 and 1.1317):

provided by the FAA for aviation stakeholders can serve as an initial model. In particular, the FAA resources dedicated to assessing noise as an environmental concern should be quite instructive. Also, similar to the AEDT provided by the FAA and the NASA Debris Assessment Software, the FCC could develop and license software for satellite stakeholders to use in assessing satellite effects on astronomy in terms of radio, infrared, and optical interference. Many of these resources could be provided independent of any regulatory amendments.

Some authors of this paper pointed out that requiring EIAs or EISs for satellite licensing in the US could result in satellite operators abandoning the US licensing system. In counterpoint, access to the US market is likely to be viewed as attractive. It was suggested that the FCC already requires — as conditions placed on US licensees — protection for radio astronomy, for example, emphasizing that the application of NEPA is not a prerequisite to US government oversight of satellite systems. Indeed, the FCC has recognized the need to mitigate astronomy impacts in its most recent orders relating to constellations without invoking the NEPA requirement of preparing an EIA.²⁶¹

Moreover, some authors to this paper raised questions about how “*aesthetic or cultural use*” will be defined, what standards will be used and who arbitrates the applicability of those standards.

Finally, as for amending 47 C. F. R. § 1.1307 by adding the suggested point (c)(3), it was noted that this language is extremely overbroad without some defined limits, as all satellites contain such elements.

Potential conditions for licensing to mitigate the impact on astronomy for either FAA or FCC may be found in Annex III.

5.3.4 CEQ Clarification

Given the FCC’s narrow interpretation of CEQ Implementing Regulations, some authors of this paper suggested that the CEQ could also facilitate a broader interpretation by clarifying its own regulations. To begin with, it could amend (subject to comment) the title of the § 1508.14 definition from “*Natural environment*” to “Human environment.”²⁶² It also could amend (subject to comment) its regulations to clarify the scope of the environment and effect on it. Specifically, the CEQ could amend 40 CFR § 1508.14 to read:

§ 1508.14 Human environment.²⁶³

Human environment shall be interpreted comprehensively to include the natural and physical environment, **including Earth’s orbital space**, and the relationship of people with that environment. (See the definition of “effects” (§ 1508.8).) This means that economic or social effects are not intended by themselves to require preparation of an environmental impact statement. When an environmental impact statement is

²⁶¹ FCC Order 21-48, <https://docs.fcc.gov/public/attachments/FCC-21-48A1.pdf>.

²⁶² Within the International policy section, this report proposes an alternative that, rather than working with existing definitions, suggests adding a definition within the environmental regulatory regime expressly and specifically focused on the “outer space environment.” The international policy alternative does not necessarily conflict with the proposals to amend existing regulations and, in fact, could complement them. In any case, we collectively seek to provide as many options to for effectuating the same goal as possible.

²⁶³ The CEQ could also amend the title of the definition to be “natural environment” rather than “human environment,” however, the definition itself does include the “natural and physical environment.” 40 C. F. R. § 1508.14 (1978)

prepared and economic or social and natural or physical environmental effects are interrelated, then the environmental impact statement will discuss all of these effects on the human environment.

Some authors of this paper disagree with this proposed change as it was stated that it would have far reaching effects that would go well beyond the goal of this paper. The view was also expressed that it would fundamentally reset major areas of US policy and law, and likely result in a major degradation of US space capabilities while new regulatory structures were established to implement this language. The concern was raised that this change will upend US policy distinguishing between the Earth environment and the space environment with unpredictable consequences.

Some authors of this paper also suggested that the CEQ could amend § 1508.8 to read:

§ 1508.8 Effects include:

(a) Direct effects, which are caused by the action and occur at the same time and place.

(b) Indirect effects, which are caused by the action and are later in time or farther removed in distance, but are still reasonably foreseeable. Indirect effects may include growth inducing effects and other effects related to induced changes in the pattern of land use, population density or growth rate, and related effects on air and water and other natural systems, including ecosystems.

Effects and impacts as used in these regulations are synonymous. Effects includes ecological (such as the effects on natural resources and on the components, structures, and functioning of affected ecosystems), aesthetic, **astronomical (such as the effects on human enjoyment of the observable dark sky, optical astronomy, radio astronomy, and space debris)**, historic, cultural, economic, social, or health, whether direct, indirect, or cumulative. Effects may also include those resulting from actions which may have both beneficial and detrimental effects, even if on balance the agency believes that the effect will be beneficial.

It was indicated that these minor amendments would be consistent with the scope of NEPA and ensure that every agency properly includes more than the surface of Earth within the scope of its environmental jurisdiction.

However, concern was raised that the “effects on human enjoyment” is a highly subjective standard that would be easily abused.

5.4 Model from FCC Space Debris Regulations

Recently, the FCC implemented updated regulations focused on mitigating space debris. Notably, these efforts do not rely on NEPA or any other fundamental changes to US law.

This update to satellite regulations follows a general effort (concerted or separate) to update the space regulatory regime. For example, in 2020 NOAA published its final rules overhauling the licensing of

private remote sensing space systems.²⁶⁴ Similarly, the FAA implemented new launch and reentry regulations through its Office of Commercial Space Transportation.²⁶⁵ Consequently, regulations promulgated to mitigate adverse effects of satellites in Earth's orbit would be consistent with an overall objective to update the US space regulatory regime, again without the need to rely upon NEPA.

In doing so, the recent and current efforts of the FCC to adopt and implement regulations to mitigate orbital debris can provide a model through which to propose regulations relating to satellites and their interference in astronomy.

Some authors of this paper suggested that the recommendations from SATCON1 can be adopted into regulatory form as indicated in Annex II hereof.

Some authors of this paper indicated their opinion that this approach is flawed and requires additional consideration. These members suggested that this path incorrectly assumes the FCC has some expertise in which satellite technologies best mitigate reflectivity and can realistically assess whether an operator is using the best approach given its system. These members also noted that, assuming the FCC is even the best agency to make this assessment, a better approach may be to have the FCC check to see whether the satellites meet a data-derived standard prepared by experts, rather than a subjective assessment. The concern was raised that this approach is limited to current technology and would disincentivize the development of new technologies. Finally, some authors of this paper were concerned that this approach also fails to properly account for or balance against the critical services satellites can provide to people on the ground.

5.5 NASA and Planetary Protection

Planetary protection broadly encompasses the protection of Earth and other celestial bodies from cross-contamination.²⁶⁶ Its origins date back to the beginning of international space exploration and research in the 1950s.²⁶⁷ In fact, the International Council for Scientific Unions (now the International Science Council) issued a committee report in 1958 that contained a "Code of Conduct" for planetary protection and recommended that COSPAR²⁶⁸ address such matters. The international policy section of this document discusses COSPAR and other international components in more detail.

Within the US, NASA has implemented a PPP.²⁶⁹ The foundation for NASA's PPP arises from its interpretation of Article IX of the OST.²⁷⁰ To implement the policy, NASA established an Office of Planetary Protection within its Office of Safety and Mission Assurance. Some authors of this paper noted that

²⁶⁴ "Licensing of Private Remote Sensing Space Systems," 15 CFR § 690 (85 Federal Register 98, pp. 30790-30815) (published May 20, 2020, effective July 20, 2020).

²⁶⁵ "Streamlined Launch and Reentry License Requirements," 14 CFR 401, et seq. (85 Fed. Reg. 79566-79740) (published December 10, 2020, effective Mar. 10, 2021).

²⁶⁶ Planetary protection differs from planetary defense that focuses on protecting Earth from collision with space debris and celestial bodies.

²⁶⁷ Office of Safety and Mission Assurance, *Planetary Protection*, NASA, <https://sma.nasa.gov/sma-disciplines/planetary-protection> (last accessed Aug. 21, 2021).

²⁶⁸ COSPAR, <https://cosparhq.cnes.fr/> (last accessed Jun. 22, 2021).

²⁶⁹ There does not appear to be any specific regulation or statute directed to planetary protection by that term.

²⁷⁰ OFF. SAFETY & MISSION ASSURANCE, NAT'L AERONAUTICS AND SPACE ADMIN., NID 8715.128, PLANETARY PROTECTION CATEGORIZATION FOR ROBOTIC AND CREWED MISSIONS TO THE EARTH'S MOON (2020).

although focus is on “*the scientific study of chemical evolution and the origins of life in the solar system*,” an argument can be made that its broader philosophical basis “*promotes the responsible exploration of the solar system by implementing and developing efforts that protect the science, explored environments and Earth*.”²⁷¹

The implementation of this policy resulted in the publication of several documents. Most recently, these include Planetary Protection Categorization for Robotic and Crewed Missions to Earth’s Moon²⁷² and Biological Planetary Protection for Human Missions to Mars.²⁷³ Previously, NASA issued several iterations of 8020.7 Biological Contamination Control for Outbound and Inbound Planetary Spacecraft²⁷⁴ which cites principles from COSPAR as the foundation for PPP.²⁷⁵ Further, NASA’s Planetary Protection Provisions for Robotic Extraterrestrial Missions that became effective on 20 April 2011 will expire absent extension on 1 August 2021.²⁷⁶

It is argued by some authors of this paper that the focus on preventing contamination — i.e., protecting the environment — of celestial bodies under Article IX of the OST extends beyond the surface and orbits of Earth.²⁷⁷ Moreover, NASA’s implementation of Article IX’s planetary protection principles reflects this interpretation by the US. Consequently, Earth’s orbit and space activities therein clearly fall within the jurisdiction of Article IX and both its interpretation and implementation by the US. Combined with Article IX’s requirement that States Parties conduct activities in space “*with due regard to the corresponding interests of all other States Parties to the Treaty*” and potential remedies for instances where harmful interference in the activities of others may occur, these policies support regulation of satellite activity that adversely affects Earth’s environment and the activities of other actors in and related to space.²⁷⁸

That said, definitional hurdles were acknowledged. As has recently been stated:

Article IX is very broad in its terms and encompasses not just the concepts of due regard for, and the prevention of, harmful interference with activities of other states but also the inherent value in the preservation of natural celestial environments from harmful

²⁷¹ Office of Safety and Mission Assurance, *Planetary Protection*, NASA, <https://sma.nasa.gov/sma-disciplines/planetary-protection> (last accessed Aug. 21, 2021).

²⁷² The following interpretative language could be used elsewhere:

In this directive, all mandatory actions (i.e., requirements) are denoted by statements containing the term “shall.” The term “may” denotes a discretionary privilege or permission, “can” denotes statements of possibility or capability, “should” denotes a good practice and is recommended, but not required, “will” denotes expected outcome, and “are/is” denotes descriptive material.

OFF. SAFETY & MISSION ASSURANCE, NAT’L AERONAUTICS AND SPACE ADMIN., NID 8715.128, PLANETARY PROTECTION CATEGORIZATION FOR ROBOTIC AND CREWED MISSIONS TO THE EARTH’S MOON (2020) at 2.

²⁷³ OFF. SAFETY & MISSION ASSURANCE, NAT’L AERONAUTICS AND SPACE ADMIN., NID 8715.129, BIOLOGICAL PLANETARY PROTECTION FOR HUMAN MISSIONS TO MARS (2020).

²⁷⁴ OFF. SAFETY & MISSION ASSURANCE, NAT’L AERONAUTICS AND SPACE ADMIN., NPD 8020.7G, BIOLOGICAL CONTAMINATION CONTROL FOR OUTBOUND AND INBOUND PLANETARY SPACECRAFT (2020).

²⁷⁵ *Id.*; Comm. on Space Rsch. [COSPAR], *The COSPAR Panel on Planetary Protection Role, Structure, and Activities* (2019), available at COSPAR https://cosparhq.cnes.fr/assets/uploads/2019/07/PPP_SRT-Article_Role-Structure_Aug-2019.pdf.

²⁷⁶ OFF. SAFETY & MISSION ASSURANCE, NAT’L AERONAUTICS AND SPACE ADMIN., NPR 8020.12D, PLANETARY PROTECTION PROVISIONS FOR ROBOTIC EXTRATERRESTRIAL MISSIONS (2011).

²⁷⁷ Outer Space Treaty, art. 9.

²⁷⁸ See the discussion at Section III.B.3 above.

*contamination. Nevertheless, there is no international consensus on the definitions of “harmful contamination” or “interference.” Nor have the interests of other states that shall be given due regard been identified, other than avoidance of harmful contamination. However, the COSPAR PPP represents a consensus that, at a minimum, harmful contamination includes the introduction of biological matter from the Earth into at least certain celestial environments.*²⁷⁹

Based on the foregoing, some authors of this paper suggest that planetary protection can and should be used as a basis to support efforts to reduce the detrimental effects of satellite constellations on astronomy. Primarily, it was suggested that it should be presented as an example of how the international community and national actors implement obligations under the OST.²⁸⁰

Additionally, planetary protection furthers a general policy of protecting aspects of the space environment (albeit focused on contamination). And, on this point, it is argued by some members, planetary protection inherently demonstrates that our concept of environment and the regulation of human effects on the environment extends beyond the surface of Earth.²⁸¹ Consequently, the regulation of human activity on the natural environment above the surface of Earth and into its orbital environment remains consistent with existing US PPP.

5.6 FCC Categorical Exclusion

The FCC has implemented a Categorical Exclusion with respect to telecommunications activities but for those that fall into limited circumstances. It was pointed out that in *Foundation on Economic Trends v. Heckler* the court understood that federal agencies might attempt to avoid performing environmental reviews under NEPA by arguing that certain actions involving new technology have unknown environmental impacts, making them unreviewable.²⁸²

To combat this line of reasoning, the court pointed to the Council's requirement for an EIS when "*the possible effects on the human environment are highly uncertain or involve unique or unknown risks.*" The court concluded with an excerpt from the opinion of *Scientists' Institute for Public Information v. Atomic Energy Commission*,²⁸³ in which that court stated that it "*must reject any attempt by agencies to shirk their responsibilities under NEPA by labeling any and all discussion of future environmental effects as ‘crystal ball inquiry’.*"

²⁷⁹ Leslie Tennen, *The Role of COSPAR for Space Security and Planetary Protection*, Handbook of Space Security, (Jul. 3, 2020), <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7990663/>.

²⁸⁰ See the discussion at Section III.B.3 above.

²⁸¹ NASA actually refers to terrestrial missions as "*Earth-orbital*." 2020 Moon Directive, p. 2 P.2.c. Thus, we should be careful in using terrestrial to define merely that on the Earth's surface to avoid confusion on the terms. But, more importantly, NASA interprets Earth's terrestrial space as including its orbital space thereby lending support to the NEPA-CEQ-FCC interpretation of environment extending out this far. This should be further explored.

²⁸² 756 F.2d 143, 147 (D.C. Cir. 1985).

²⁸³ 481 F.2d 1079, 1092 (D.C. Cir. 1973).

6. Conclusions

6.1 Preliminary conclusions

This section is intended to be a very brief summary of the suggestions already made by the International and US Policy subgroups.

§ If the US wishes to adopt or amend/revise any legislative provisions concerning the conduct of EIAs for the in-orbit operation of commercial satellites, it should pay attention to the provisions contained in the LTSG, and specifically Guideline A.2 as indicated in Section 5.1.2.

§ The US may wish to consider the adoption of a due diligence mechanism (see Table 1 for details) for the in-orbit operation phases of large-scale commercial satellite constellations. In the event of transboundary impact/harm/damage (present as well as future), the US may not be able to take its previous views regarding the liability of a private entity/actor. This is due to the application of Article VI of the OST, where a State remains responsible for all its national space activities, and there is an obligation to continually supervise such activities.

§ The US government may wish to include the outer space environment as an additional domain for protection and conduct of environmental impact assessments. A similar approach has been followed internationally through the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD), 1977. Within the national policy section, this report proposes amending existing CEQ definitions to expressly include Earth's orbital space and specific astronomical effects. The Working Group members are of the view that the alternative(s) provided here in this section of the Report do not conflict with the one's provided in the national policy section, and in fact complement each other. In any case, we collectively seek to provide as many options for effectuating the same goal as possible.

§ The US may wish to adopt a precautionary approach owing to technical and policy considerations.

§ The US may wish to adopt a precautionary approach in the face of scientific uncertainty considering whether human activities proposed or underway will introduce, directly or indirectly, rates of change in an environment that are comparable or superior to natural ones or whether they will introduce new potentially harmful materials into an environment, such as the atmosphere.

To conclude the above considerations, this Working Group notes an important and relevant excerpt contained in the LTSG:

*20. International cooperation is required to implement the guidelines effectively, to monitor their impact and effectiveness, and to ensure that, as space activities evolve, they continue to reflect the most current state of knowledge of pertinent factors influencing the long-term sustainability of outer space activities, particularly with regard to the identification of factors that influence the nature and magnitude of risks associated with various aspects of space activities or that may give rise to potentially hazardous situations and developments in the space environment.*²⁸⁴

It also notes, with humility and concern, the following excerpt from the judgment of the International Court of Justice, in *Gabčíkovo-Nagymaros Project* (Hungary/Slovakia), Judgment, I.C.J. Reports 1997, p. 7, para. 140:

Throughout the ages, mankind has, for economic and other reasons, constantly interfered with nature. In the past, this was often done without consideration of the effects upon the environment. Owing to new scientific insights and to a growing awareness of the risks for mankind - for present and future generations - of pursuit of such interventions at an unconsidered and unabated pace, new norms and standards have been developed, set forth in a great number of instruments during the last two decades. Such new norms have to be taken into consideration, and such new standards given proper weight, not only when States contemplate new activities but also when continuing with activities begun in the past. This need to reconcile economic development with protection of the environment is aptly expressed in the concept of sustainable development.

6.2 Cultural Considerations

The Community Engagement Working Group is conducting extensive outreach with diverse communities, including indigenous peoples. Indigenous peoples in particular have sought recognition throughout history, yet throughout history their rights have been violated. Indeed, emerging bodies of work view current narratives of space exploration as parallel to the historic colonization that negatively impacts indigenous peoples, and how the commercial exploitation of space acts to further colonization.²⁸⁵

This section identifies some of the relevant International Frameworks that include human rights, culture, and the rights of indigenous peoples.

The first critical document is the United Nations Universal Declaration of Human Rights, adopted in 1948²⁸⁶. In 2007 UNDRIP was adopted by the General Assembly²⁸⁷. This was the culmination of work that had begun in earnest in 1985 when a working group was established.

Article 8:

1. Indigenous peoples and individuals have the right not to be subjected to forced assimilation or destruction of their culture.

²⁸⁴ UN COPUOS Sustainability Guidelines, pp. 4, para. 20.

²⁸⁵ Hilding Neilson & E.E. Ćirković, *Indigenous rights, peoples, and space exploration: A response to the Canadian Space Agency (CSA) Consulting Canadians on a framework for future space exploration activities* (2021) available at [arXiv:2104.07118](https://arxiv.org/abs/2104.07118)

²⁸⁶ G.A. Res. 217 A (III), Universal Declaration of Human Rights (Dec. 10, 1948).

²⁸⁷ G.A. Res. 61/295, United Nations Declaration on the Rights of Indigenous Peoples (Sept. 13, 2007).

- (a) Any action which has the aim or effect of depriving them of their integrity as distinct peoples, or of their cultural values or ethnic identities;*
- (b) Any action which has the aim or effect off dispossessing them of their lands, territories or resources;*

Article 18:

Indigenous peoples have the right to participate in decision-making in matters which would affect their rights, through representatives chosen by themselves in accordance with their own procedures, as well as to maintain and develop their own indigenous decision-making institutions.

Consultations to address the needs of indigenous communities also emerge as one of the most critical and important points of this Declaration, as stated in Article 19:

States shall consult and cooperate in good faith with the indigenous peoples concerned through their own representative institutions in order to obtain their free, prior and informed consent before adopting and implementing legislative or administrative measures that may affect them.

And Article 32(2) has:

States shall consult and cooperate in good faith with the indigenous peoples concerned through their own representative institutions in order to obtain their free and informed consent prior to the approval of any project affecting their lands or territories and other resources, particularly in connection with the development, utilization or exploitation of mineral, water or other resources.

In 2003 the UN Educational, Scientific and Cultural Organization (UNESCO) created an Astronomy and World Heritage Thematic Initiative as a means for states to evaluate and recognize this specific heritage. The guidelines start out²⁸⁸:

The sky, our common and universal heritage, forms an integral part of the total environment that is perceived by mankind. Including the interpretation of the sky as a theme in World Heritage is a logical step towards taking into consideration the relationship between mankind and its environment. This step is necessary for the recognition and safeguarding of cultural properties and of cultural or natural landscapes that transcribe the relationship between mankind and the sky.

In 2007 the participants of the International Conference in Defence of the Quality of the Night Sky, jointly with representatives of UNESCO, the UN World Tourism Organization, the IAU, and other international agencies, adopted the Starlight Declaration:

- a. An unpolluted night sky that allows the enjoyment and contemplation of the firmament should be considered an inalienable right equivalent to all other socio-cultural and*

²⁸⁸ Astronomy and World Heritage Thematic Initiative, UNESCO, <https://whc.unesco.org/en/astronomy/> (last accessed Aug. 21, 2021).

environmental rights. Hence the progressive degradation of the night sky must be regarded as a fundamental loss.

In a 2020 US Supreme Court ruling in *McGirt v Oklahoma*, Judge Gorsuch wrote that “... *the magnitude of a legal wrong is no reason to perpetuate it. ...*” He warns against arguments that the consequences will be:

*drastic precisely because they depart from . . . more than a century [of] settled understanding. ... In reaching our conclusion about what the law demands of us today, we do not pretend to foretell the future and we proceed well aware of the potential for cost and conflict around jurisdictional boundaries, especially ones that have gone unappreciated for so long. But it is unclear why pessimism should rule the day. ... As a result, many of the arguments before us today follow a sadly familiar pattern. Yes, promises were made, but the price of keeping them has become too great, so now we should just cast a blind eye. We reject that thinking.*²⁸⁹

6.3 Emerging Policy Gaps

6.3.1 The lack of considerations for light pollution due to on-orbit infrastructure

In these analyses, the Working Group sought to determine whether existing international or national laws and policies offer protections of the sky from human-made forms of interference, predominantly visible light. As discussed, the VCPOL, LRTAP, Rio Declaration, and LTSG provide mechanisms for addressing pollution of the atmosphere. The Working Group finds that this includes pollution by space launches and material reentries, with national mechanisms in place, even if inadequately executed, for conducting EIAs.

Protections of the orbital environment are less clear. For example, the US Space Policy Directive 3 issues guidelines for the STM of Earth orbit, but this is in the context of operational, security, and economic concerns, with appropriate standards still lacking in most ways. The LTSG go further, in this regard, to describe outer space as an environment that needs to be developed in a way that allows future generations to also develop space. In other words, the LTSG propose that space, including Earth orbit, is an environment worth preserving.

The concept of space as an environment is enshrined in Article IX of the OST, which is the basis of PPPs. Such policies seek to protect Earth from harmful contamination by extraterrestrial materials, as well as to protect environments beyond Earth from contamination by human exploration. Thus, there are environments beyond traditionally regarded human environments that are worth protecting (see further discussions in the US policy section analysis).

Moreover, according to Article IX of the OST, activities by a State Party to the Treaty that may cause “*potentially harmful interference with activities of other States Parties*” in their use or exploration of outer space have a duty to conduct international consultations. The Working Group takes the position that astronomy is a form, if not the oldest form, of space exploration. Thus, States Parties to the Treaty that place or have their entities place infrastructure into orbit that cause interference with ground-based

²⁸⁹ 140 S.Ct. 2452, 2480 (2020).

astronomy might not be meeting their commitments to Article IX of the OST without conducting international consultations. The Working Group found Article IX to be the piece of international law that is closest to providing protections of the night sky. However, invoking the OST may have limited effect, as there is not a clear internationally accepted meaning of “harm” in this context.

Ultimately, the Working Group finds that protections of the night sky from objects in orbit are lacking in national and international laws, representing a major policy gap. The US policy analysis section came to a similar conclusion. This gap has been able to persist because of a lack of need prior to entering an era of multiple, large-number satellite constellations. Concerns that range from preserving the night sky for future generations, to ensuring non-interference with space exploration by ground-based astronomy, to limiting the diffuse emission that could be produced by satellites and debris make it salient for national and international lawmakers to fill this gap. Such new policy can use Article IX of the OST as its foundation, similar to PPP, appropriately supported by the LTSG.

It may also be possible for the US government to make progress on this policy gap by

- (1) Broadening the concept of “human environment” to include, in the short term, Earth orbit and the Moon, and our interactions with them;
- (2) Expanding the definition of “effects” or “harm” to explicitly include interference with astronomy, wherever caused;
- (3) Considering outer space to be an additional domain for protection and requiring the conduct of due diligence and the completion of EIAs, with a view to assess the effects of on-orbit light pollution and other emerging issues that are specifically applicable to this new domain; or,
- (4) Developing new policies that address orbital light pollution.

We note that in the use of LEO and the regulation of Non-Geostationary Orbits (NGSOs) there are conflicting mandates, priorities, and review processes that need resolving. These include planetary defense, astronomical research, privatization of access to space, pursuit of broadband infrastructure and environmental protection. Mitigating the impacts on astronomical research and agency missions requires a whole-of-government approach.

6.4 The multiple actor problem

The US government, through national policies, could make major contributions toward addressing on-orbit light pollution and other environmental impacts, such as air pollution, resulting from the placement, use, maintenance, and decommissioning of orbital infrastructure, including large-number satellite constellations. The Working Group notes that the US is not the only launching state for so-called mega-constellations²⁹⁰, and thus progress toward reducing environmental impacts could be limited by other launching states should they not also require their entities to adopt emerging standards and best practices.

The Working Group is pleased that “*Canada, Japan and the United States therefore propose to inscribe a single-issue item on ‘General Exchange of Views regarding Satellite System Effects upon Terrestrial-Based Astronomy’ at the fifty-ninth session of the Scientific and Technical Subcommittee in 2022*”.²⁹¹ Although the proposal was not ultimately accepted by the Sub-Committee and moved forward,

²⁹⁰ Examples include OneWeb (UK) and StarNet/GW (China)

²⁹¹ U.N. Doc. A/AC.105/C.1/2021/CRP.24 (Apr. 27, 2021).

there is an evident interest in discussing such critical topics in a multilateral context. The Working Group encourages the US to engage, through multilateral fora, with all states seeking to place or who might seek to place large constellations into orbit. The Working Group further urges the US to seriously consider the output from SATCON2 and the 21 October 2021 IAU Dark and Quiet Skies workshop, as well as additional complementary reports submitted to other states,²⁹² in the proposed multilateral discussions at the fifty-ninth session of the UN COPUOS Scientific and Technical Subcommittee (STSC).

By taking a leadership position in implementing new policies for on-orbit environmental impacts, including light pollution, the US government can influence other State actors positively and engage them in an internationally constructive approach. To that end, the US government should support discussions of the interference of on-orbit infrastructure on astronomy, as well as other environmental impacts, in multilateral fora. This might include discussions within a subcommittee at UN COPUOS leading to a UN General Assembly resolution or through an ad hoc process. The Working Group notes the recent single-issue item A/AC.105/C.1/2021/CRP.24, which states

*1. At the current session of Scientific and Technical Subcommittee, the issue of the impact of new satellite constellations has been a topic for discussion. This discussion included a presentation of the results of an online workshop organized by the United Nations Office for Outer Space Affairs and Spain, jointly with the International Astronomical Union (IAU) on the topic of 'Dark and Quiet Skies for Science and Society', which took place on 5–9 October, 2020. This workshop was convened pursuant to the agreement reached by the Committee on the Peaceful Uses of Outer Space at its sixtieth session that the Office for Outer Space Affairs and IAU would jointly organize a workshop/conference on the general topic of light pollution. 1 Based on the results of this work, Chile, Ethiopia, Jordan, Slovakia, Spain and IAU submitted a series of recommendations in A/AC.105/C.1/2021/CRP.17. Although the delegations of Canada, Japan and the United States cannot support all recommendations presented in that conference room paper at this time, the fulsome consideration of this topic is supported.*²⁹³

²⁹² See e.g. Boley & Lawler, *supra* note 178.

²⁹³ U.N. Doc. A/AC.105/C.1/2021/CRP.24 (Apr. 27, 2021).

7. Industry Perspective

The Industry Subgroup used as its starting point the premise that satellite companies are predisposed toward good stewardship of space and operations that support space sustainability. Whether prompted by a commitment to space in general or a more pragmatic interest in protecting their investment in their various space-based interests, satellite companies have committed resources to improving space safety and innovated to improve reusability and reduce orbital debris. The Industry Subgroup considered the practicalities of the SATCON1 recommendations and mitigations from the perspective of a willing operator — whether analytical models could reliably predict the impact on astronomy from their spacecraft and systems, whether testing approaches prior to launch were available, affordable and accurate, how quickly observational feedback was needed to inject any alterations into ongoing plans, and whether operators could readily verify the relative success of any mitigations.

The Industry Subgroup concluded that satellite operators were more likely to adopt voluntary practices or mitigation tools if they engaged with astronomers early in their project cycle, before spacecraft designs were finalized and when modifications to architectures, spacecraft design or operations could be introduced at less cost or schedule impact. Further, the subgroup concluded that more work was required to ensure that analytical tools, test facilities and observational data are widely available to satellite operators, and are cost-effective, so that their adoption does not disrupt either budgets or schedule for their project.

The Industry Subgroup noted throughout that the work of analyzing the impact of diverse constellation architectures and spacecraft designs on the myriad astronomy scientific undertakings was still a relatively new practice, and that considerable ongoing work continues to analyze, test, innovate and observe the intersection of constellations and astronomical observation. With further inquiry and new case studies from new and diverse constellations, it seems likely that recommendations for operators will continue to emerge on the nature of satellite impact, innovations on additional mitigation approaches for both the satellite and astronomy operations, and the means to encourage voluntary steps that will allow both satellite development and astronomical discovery.

The scope of the Industry Subgroup was focused on the effects for ground-based optical astronomy primarily because this intersection has featured the most mature analysis to date and because the deployment of communications constellations has been rapid and on a large scale. Other individual spacecraft or constellations of satellites intended for other non-communications purposes, such as Earth imaging, weather, and asset tracking, among others, are being deployed and may also prove to impact optical astronomy activities, depending on their spacecraft design, altitude or operations. Similarly, SATCON1 and subsequent work with Dark & Quiet Skies have identified additional astronomy-related activities that may be affected by visibility from satellite constellations and merit review by the satellite industry when considering the impact from satellite constellations. Industry efforts to reduce harmful effects for astronomy could be better focused and potentially more effective with some characterization of the relative priorities of the astronomy activities identified.

For the purposes of SATCON2, the Industry Subgroup did not discuss the following items:

- Radio astronomy. Although the emergence of large constellations is a concern to radio astronomy, there is no direct spectrum sharing in the most common frequency bands for the

largest constellations. Coordination and mitigation for out-of-band emissions from satellite constellations operating in frequency bands adjacent to radio astronomy frequency bands is addressed with the existing practice within the ITU and national spectrum regulation. Satellite issues of concern to radio astronomy are also being addressed in the Dark and Quiet Skies Workshops.

- Space safety topics like STM, satellite collision avoidance, end-of-life orbital disposal of satellites. While these aspects of constellation operations are of high interest to astronomers, they are well addressed in other fora.

7.1 Promoting Awareness and Industry Engagement with Astronomy

SATCON1 encouraged close collaboration between the satellite and astronomy communities and urged efforts to raise awareness across both communities at their intersections. Considerable work has been undertaken toward these dual goals of collaboration and awareness of the SATCON1 report and its findings.

Promoting SATCON1. Following the technical workshop from 29 June to 2 July 2020, the SATCON1 working groups produced and publicized the work in various fora. The SATCON1 white paper became available online in August 2020 and the AAS held a press conference on the report and launched a follow-up advocacy campaign to raise awareness on the issue generally. This included the AAS Public Policy Department (PPD) successfully advocating that NSF include the issue of satellite constellations in their authorization being drafted for the US. The report has since been published in the Bulletin of the AAS and NOIRLab also released a simultaneous announcement of the report. Dr. Tony Tyson of Vera C. Rubin Observatory and Dr Joel Parriott, Director of the AAS PPD, co-authored a companion article for *Science* magazine entitled Dark Skies and Bright Satellites. Members of the AAS group working on satellite constellations contributed to a *Nature Astronomy* paper on satellite constellations that was published on 6 November as part of a special edition on small satellites. Members of the AAS group working on satellite constellations contributed presentations at the Astronomical Society of the Pacific (ASP) meeting on satellite constellations in December 2020. The AAS PPD reached out to engineering societies to collaborate on raising awareness in January 2021.

Subsequent workshops. The AAS PPD also participated in the Dark and Quiet Skies Workshop in October 2020. The workshop was divided into working groups on the sub-disciplines of optical astronomy, radio astronomy, dark sky sites, light effects on the bio-environment, and the impact of satellite constellations on astronomy, both radio and optical. The AAS PPD joined the Recommendations group within the Satellite Constellations Working Group. Astronomers, operators, and space lawyers worked together to draft recommendations aimed toward international policy using the results in the report produced from the SATCON1 workshop. The SATCON2 workshop was announced and advertised by the AAS in May 2021. The AAS Committee on Astronomy and Public Policy and Committee on Light Pollution, Radio Interference, Space Debris co-hosted a town hall at the AAS 238 summer meeting on Astro2020 Advocacy, Satellite Constellations, and More! in June 2021.

US government outreach. To educate government decision makers on the findings of SATCON1, the AAS held an informational briefing with staff from Congressional offices and a meeting with the US communications regulatory authority, the FCC. The interagency Astronomy and Astrophysics Advisory

Committee also discussed the SATCON1 report at their meeting in September 2020. The AAS group working on satellite constellations presented information on satellite constellations to the National Academies' Board on Physics and Astronomy. The AAS PPD discussed options for authorizing NSF to address satellite constellations with Congressional staffers in April 2021. Following the November 2020 US Presidential elections, the AAS PPD met with the Biden transition team for NSF to discuss concerns about the threat that satellite constellations pose for ground-based observation. The AAS PPD also wrote letters to the incoming Biden-Harris transition team and included a section on the need to preserve our dark and quiet skies.

Satellite industry outreach. The AAS has also continued to engage directly with the satellite industry to broaden awareness of the potential impact of satellite visibility on astronomy, deepen technical dialogue with the astronomy community and encourage voluntary adoption of the recommendations developed in SATCON1. Voluntary collaboration is a particularly urgent aspect of protecting astronomical observation in the immediate and near term, while national and international decisionmakers become more educated about the issue and contemplate legal or regulatory requirements for satellite operators to consider astronomy in their design and deployment. Enlisting members of the satellite community is essential, given the number and pace of satellite constellations being planned, fielded and operated, contrasted with the expected lead time for any new requirements-based approach to be agreed upon, adopted and implemented by any given individual nation or internationally.

The AAS and the Satellite Industry Association (SIA), the leading US satellite trade organization, teamed up to host an October 2020 informational webinar on astronomers' concerns about satellite constellations and the technical recommendations of the SATCON1 Report. The AAS group working on satellite constellations hosted a special session at the AAS 237 winter meeting on Astronomy and Satellite Constellations with a panel that included astronomers, SpaceX, OneWeb and Amazon. The AAS group working on satellite constellations also continued to meet with SpaceX directly to discuss observations of VisorSat, the first of which had been launched around the time of SATCON1 with multiple subsequent spacecraft deployed.

The AAS and SIA plan to continue their partnership for informational webinars and the two associations plan to continue doing so in the future. The AAS also intends to contact other industry associations to help disseminate information across the space and satellite sector. The AAS and SIA will additionally try to partner with external organizations to organize events that will bring major international commercial satellite stakeholders to the table to further disseminate recommendations on satellite brightness and encourage the participation of international governments and regulators.

Public comments. The AAS also relied on the work of SATCON1 to become a more active participant in public consultations relating to satellite constellations and their impact on astronomy. In January 2021 the AAS PPD filed reply comments in the FCC docket considering a modification to allow SpaceX's Starlink constellation to fly lower, thanking Viasat for calling attention to the impacts of satellite constellations on astronomy and offering corrections to technical assumptions in Viasat's comments. The FCC quoted the AAS's comments about the benefits of lower altitudes in its Report and Order granting Starlink's modification, and included a condition that SpaceX consider impacts to astronomy as part of their deliberations, a landmark decision. The AAS PPD and the IAU's US National Committee joined forces to write a letter to the US Department of State urging them to endorse moving forward the Dark and Quiet Skies Conference Room Paper at the April meeting of the Long Term Space Sustainability sub-committee of COPUOS.

7.2 Future Plans and Next Steps

Rating system. The AAS is evaluating a rating system that can recognize companies who go to great lengths to mitigate the impacts of their satellite constellations on astronomical observations. To this end, the AAS have created a checklist for industry participants to use to measure mitigation strategies, with higher recognition standing given as satellite operators employ more of the identified mitigation steps. This is part of the AAS's approach of emphasizing a collaborative role with industry, while also pursuing an evidence-based advocacy strategy to ensure the various workshop report recommendations are implemented.

7.3 Identifying Key Satellite Characteristics that Affect Reflectivity

SATCON1 identified various operational, design and architecture mitigations for constellation operators to consider in mitigating their effect on astronomy. SATCON2 recommends identifying those key characteristics of a spacecraft or constellation that trigger heightened concern for ground-based optical astronomical observation.

The primary concern remains reflected sunlight from satellites. Using determinations from the Rubin Observatory system, an instantaneous brightness limit is defined for individual satellites. Satellites appearing brighter than this limit are expected to degrade substantially the data quality from astronomical observations. It is highly desirable to remain below that limit for all phases of a mission's lifetime. A key aspect of staying below these reflected brightness limits is avoiding bright glints from specular surfaces. Reliable attitude control is a crucial capability to limit periodic glints, in that an out-of-control or tumbling satellite is much more likely to generate glints and therefore less likely to remain within the brightness limits.

Beyond brightness, the Industry Subgroup discussed the value of creating a hierarchy of features that could aid new satellite operators in understanding whether and to what extent their proposed constellation is likely to impact ground-based optical astronomy, and to correlate their efforts at mitigation accordingly. Similarly, a construct to identify the constellation projects that create elevated concern will ensure that astronomy resources can be put to best use in analyzing and observing proposed satellite projects that are most likely to harm optical observation.

Recommendation. Building on SATCON1 and the primary concern of brightness, the Industry Subgroup recommends that astronomers continue to develop a hierarchy of additional characteristics of spacecraft, operations and/or altitude for satellites/constellation systems that would either indicate to owner/operators that they have a low/no concern from a reflection perspective, or that they have a high level of concern. These may include key characteristics that exclude/capture a constellation, such as Altitude, Number of satellites, Design of satellites, and the satellites' shape, surface or materials used. Astronomers should perform the same exercise on the recommendations that apply to them.

7.4 Establishing Criteria for Smaller Satellites

The Industry Subgroup also explored the possibility of recommending designs, materials and operations to limit impact on astronomy from cubesats and smaller satellites for remote sensing or Earth imaging. Commercial communications are being launched in larger numbers in the near term and typically weigh more than even the new generation of commercial remote sensing satellites, and should certainly remain the primary for technical work and stakeholder outreach. However, little technical work has been undertaken on the impact of cubesats and commercial remote sensing satellites, and deployments of both types of satellites are growing rapidly. Developing clear and early guidance would improve awareness and voluntary adoption of techniques among these additional types of satellites that could lessen the impact on astronomy.

Cubesats. The Industry Subgroup discussed the value of defining characteristics that could reasonably predict whether a cubesat would have higher or lower expected levels of brightness. The vast majority of cubesats right now are fainter than the desired cutoff and, as seen in the chart below, they are not yet a major contributor to bright sky objects. Most cubesats operate between 500 km and 700 km orbital altitude, with many at quickly decaying altitudes; it is unclear whether regulators like the FCC will impose regulations to limit their operating altitude.

Although only 200 cubesats are being launched per year, this number is expected to increase as space becomes ever more accessible and affordable. At current predicted deployment rates, cubesats are not expected to contribute substantially to overall light pollution for at least several generations of satellites. However, little study has been undertaken to date on those cubesats that are noticeably more visible and why the brighter ones are bright. Further study here could confirm which designs, materials and operational characteristics are less likely to be visible and add to the impact on astronomy.

The Industry Subgroup found it particularly important to provide recommendations for cubesats to voluntarily adopt, because the community proposing, designing and fielding cubesats may be more difficult to reach out to and to regulate. While there are commercial cubesat constellations, these satellites are largely faint. Many cubesats are academic or research-based and one-off projects, which have less access or ability to test or model their satellites in the same way as envisioned for the commercial industry. There may also be less willingness to impose stricter regulations on academic cubesats and chilling space research, as seen in the national and international resistance to regulating cubesats at an orbital debris level. Cubesats are also more likely to be outside of the jurisdiction of US FCC regulations, operating solely on approvals from their home country or launching state. In contrast, commercial satellites are often motivated to provide services in the US marketplace and therefore seek FCC licensing approval to win US market access. Very high-level best practices that are easily implementable, as well as any open source brightness modeling tools, will be critical to outreach and voluntary implementation across the diverse ranks of cubesat projects.

Commercial remote sensing. Satellites have been increasingly employed to detect and monitor the physical characteristics of an area by measuring its reflected and emitted radiation at a distance. Current and planned constellations envision hundreds of satellites weighing up to 30 kg and smaller constellations with dozens of satellites around 100 kg. Existing and planned commercial remote sensing constellations are distributed internationally, as shown in the picture below (SIA The community, with State of the Satellite Industry Report, 2021). Most remote sensing satellites will orbit in the 400–500 km range; many

do not feature propulsion, so will decay rapidly. Most of the commercial remote sensing satellites in the ~ 30–kg range are below the desired brightness threshold, but further consideration should be given to any new consideration for constellations of hundreds of satellites of this mass class. Heavier commercial remote sensing satellites are likely above the desired brightness threshold of 7th magnitude, but given the low total number of these larger satellites on-orbit, these may be best considered in their cumulative impact.

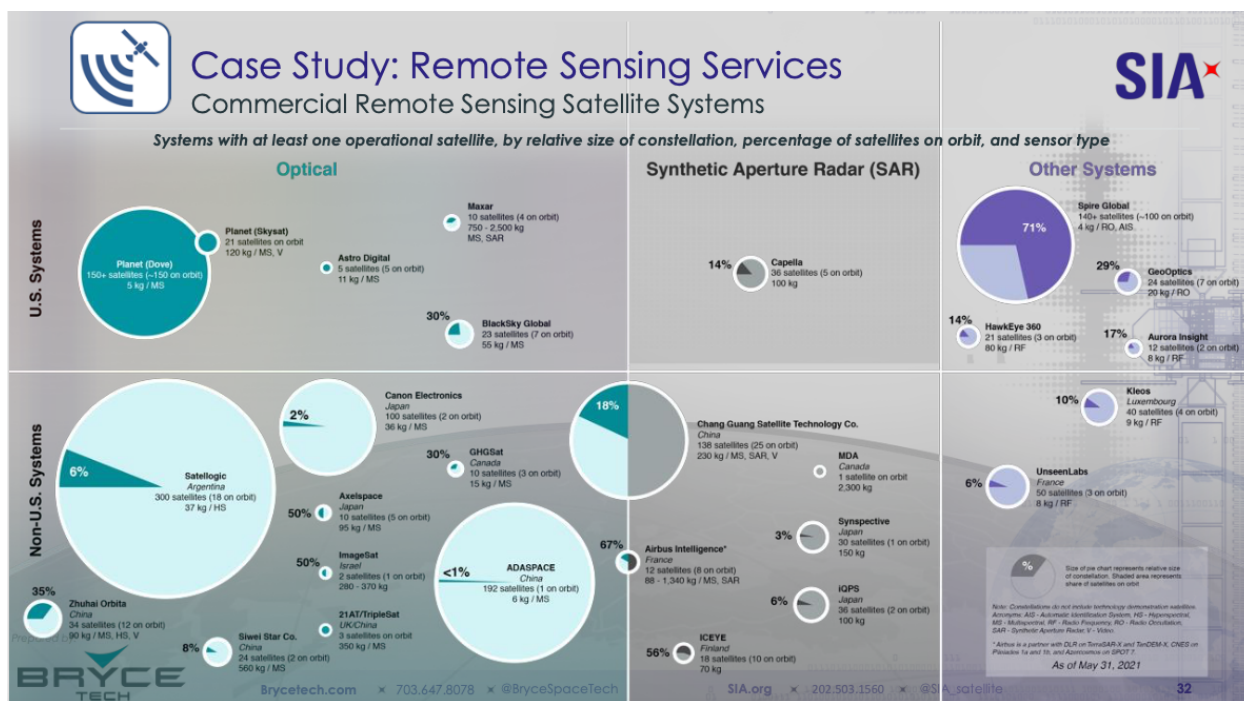


Figure 7.1. A case study for remote sensing services. (SIA)

The Industry Subgroup explored the usefulness of converting the kilogram-based definition that the FCC uses to define small satellites into a formulation scaling to surface area and reflectivity to evaluate altitude and numbers of satellites in constellations as a lower threshold. The first interpretation of this exploration, as depicted in Figure 7.1, is that there is a tail of the distribution of observed mean brightness at any mass that well exceeds the desired brightness limit. This suggests that all projects should be given guidance to minimize reflectivity. Additionally, there is a bigger fractional tail of maximum brightness, attributable to glints and flares off specular surfaces. This indicates that all satellite projects should be encouraged to minimize nadir-facing specular surfaces and maintain robust orbital attitude control.

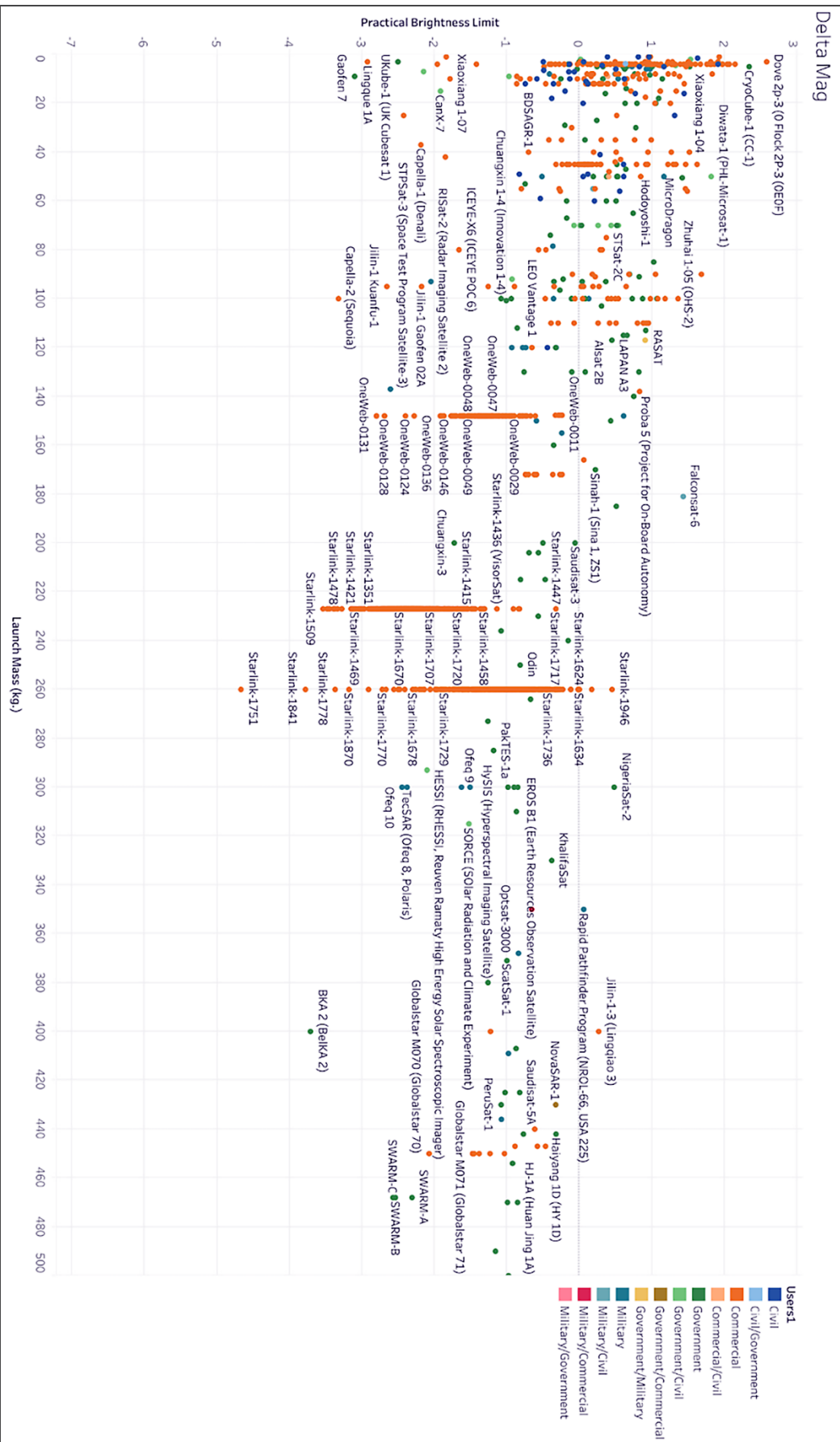


Figure 2 (preceding page). Brightness in reflected sunlight compared to satellite mass. The Y-axis is the difference in astronomical magnitudes between the brightness of the satellite as observed through a clear bandpass at its orbital height vs. the V magnitude limit as recommended in SATCON1 to stay below a data-damaging threshold. (Negative values are too bright.) The X-axis is the launch mass of each satellite. Magnitude data are from the Russian MMT database (<http://mmt9.ru/satellites/>) and the Union of Concerned Scientists Satellite database (<https://www.ucsusa.org/resources/satellite-database>). The easily readable interactive chart can be found at: <https://tabsoft.co/3ABZoqG>.

7.5 Collaboration Tools

7.5.1 IAU Centre

One important goal is to have a clear landing spot for continuing interaction of industry with the astronomical community. Given that each proposed satellite constellation to date features distinct spacecraft designs, orbital architecture and business model, the assessment of visibility, potential to disrupt optical observation and potential for effective mitigation approaches at pre-deployment phases are best assessed in a customized way, constellation by constellation. A centralized hub for communicating such evaluations would help reduce confusion and speed the process for assessing mitigation strategies. The IAU has taken the lead in establishing a Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference. The IAU call for proposals is at: <https://www.iau.org/news/announcements/detail/ann21039>. A successful centralized operation will require full time staff, and thus significant ongoing funding.

While the IAU is establishing a collaborative center intended to benefit astronomers and satellite operators alike from anywhere in the world, the AAS will remain a conduit for discussion, partnerships with US industry, and a major advocate for appropriate policies and oversight in the US and internationally. The AAS will work with the IAU on a strategy to help secure funding for the Centre. Once the IAU Centre is established, the AAS will act as an advocate for it and will continue communicating broadly with industry on behalf of the astronomical community, and guiding relevant spacecraft designers, manufacturers, and operators to the resources at the Centre and elsewhere (e.g., standards/testing capabilities at the National Institute of Standards and Technology (NIST) for US companies).

The IAU Centre will foster the development of tools and procedures that can mitigate the impact of satellite constellations on optical astronomy and will work with the space companies and industries to discuss and converge on mitigations. The overall situation has been thoroughly analyzed in the report of the online Workshop on Dark and Quiet Skies for Science and Society, which contains a number of recommendations for possible mitigation actions.

The focus is on mitigating optical interference from satellites and the goal is enabling the recommendations of the Dark and Quiet Skies Conference Room Paper. It is expected that the IAU Centre will be hosted by an existing institute or organization of excellence, or a partnership thereof, with proven experience in international cooperation.

The mission of the IAU Centre can be summarized as follows:

- Work together in partnership to coordinate the observation and measurement of the optical interference caused by satellite constellations.

- Establish contacts with the space companies and industries involved in the construction and deployment of LEO satellites and eventually with their national regulation authorities, in order to discuss and converge on relevant mitigation measures.
- Foster and coordinate the study and testing of hardware solutions aimed at reducing reflected sunlight by the satellites as well as thermal emissions from the satellite surfaces.
- Interface with space agencies in order to get access to accurate and up-to-date orbital parameters of all LEO satellites.
- Work together in partnership to coordinate the development of “smart” scheduling and/or detector operation software as well as specific artifact removal algorithms and distribute them.
- Provide suggestions for possible international regulations governing LEO satellites to the IAU Officers, in support of their pursuing the matter at the COPUOS level.
- Maintain regular contact on matters of common interest with the other IAU Offices.
- Create and maintain a dedicated set of web pages under iau.org for disseminating information about the protection of the dark sky from satellite interference.
- Organize thematic workshops (online and/or in person) as needed.
- Support the mitigation of interference caused by satellite constellations to radio astronomy as formulated in the Dark & Quiet Skies Workshop report and seek coordination of possible common actions with radio spectrum managers where appropriate.

The AAS will publish a checklist of mitigation strategies. This will be used to assess individual companies' efforts to mitigate impacts to astronomy. The more boxes a company can check, the higher their rating. The AAS will then issue an annual award for the highest rated companies, commending/ endorsing their efforts.

New companies can go to a new organization like the IAU Centre as a port of entry and start engaging.

7.5.2 Sharing Industry best practices and experiences

There are multiple advantages for industry to be enabled to share best practices while they develop effective techniques to mitigate the impact of satellites on ground-based observations.

- Many spacecraft designs and satellite constellation systems are highly customized and vary significantly in the nature of their mission (communications, imagery, tracking, Positioning Navigation and Timing (PNT)), space safety approach, and business approach.
- Still, it is instructive to share techniques tested and fielded across the satellite community to advance more rapidly an understanding of effective mitigation tools.
- Operational constellations and industry manufacturers are in a unique position and have the opportunity to introduce lessons learnt from previous experience into the design of future constellations.
- SpaceX's work with Starlink (the initial DarkSat demo in January 2020, and over 1200 VisorSats deployed in 2020–21, plus almost a year of experience employing post-launch orientation rolls) provides an early canon of mitigation techniques.
- OneWeb applied some changes to their Gen1 spacecraft design to mitigate the predicted satellite brightness in the design phase, but this was prior to the observation of the actual level of brightness on Gen1 satellites. OneWeb is working with astronomers now to verify the actual level of brightness and is considering painting certain on-board antennas with a dark coating, if needed. OneWeb expects to include further mitigations in their next-generation spacecraft design.

- **Recommendation.** Operators are recommended, as a first step, to share and publish their experience and lessons learnt across the community, in order to build understanding in mitigation design techniques and foster innovation in new concepts.
- SpaceX documentation/publication of mitigation efforts to date (DarkSat, VisorSat, Operational roll, early TLE provision, other)
<https://www.spacex.com/updates/starlink-update-04-28-2020/index.html>
- Collaborative paper with SpaceX / Vera Rubin Observatory discussing the impacts of different numbers of satellites, orbital characteristics, brightness magnitudes, etc. Includes data from DarkSat. <https://arxiv.org/pdf/2006.12417.pdf>
- Paper from National Astronomical Observatory of Japan, discussing DarkSat measurements: <https://iopscience.iop.org/article/10.3847/1538-4357/abc695>

Internationally, the Industry Subgroup noted the importance of engaging more actively with nations that have either licensed or directly invested in satellite constellations, but have not yet participated in the various US, European or international fora or technical discussions that focus on the intersection of constellations and astronomy. For example, China's Guowang satellite constellation of 13,000 broadband and 5G satellites has the potential to contribute substantially to light pollution, and early engagement with scientists and engineers from China will be critical to collaboration and adoption of best practices on mitigation.

7.6 Mitigation Goals

The SATCON1 and Dark & Quiet Skies efforts set targets for the reduction of the visible brightness of the satellites as seen from the ground, by both naked-eye observers of the night sky and ground-based optical telescopes. Reach the fainter of these in all phases of a constellation:

- Naked eye visibility: $V = 7.0$ mag (Broad-band visible light filter, centered on 550 nm).
- Or
- $V = 7.0 + 2.5 \log_{10} (r_{\text{orbit}}/550 \text{ km})$, equivalent to $44 \times (550/r_{\text{orbit}})$ watts steradian⁻¹, where r_{orbit} is the altitude of the satellite orbit in km.

If met, that brightness limit would render constellations effectively invisible to the unaided eye once in orbit, addressing the naked eye observation concerns, including potential cultural impact.

The reference goals following, based on the SATCON1 recommendations, have been articulated by the International Dark-Sky Association for constellations at <https://www.darksky.org/satellite-megaconstellations-and-the-night-sky/>. Corresponding consideration should be given to minimize apparent brightness during mission phases of orbit-raise and de-orbit as much as practicable, to address the same visual concerns.

IDA's **five principles** to preserve the quiet enjoyment of the night sky and protect the general public from the impacts of mega-constellations:

1. **Stewardship** of the night sky is a shared responsibility that requires participation and consultation with all stakeholders.
2. The **cumulative impact on night sky brightness** attributed to satellites does not exceed 10 percent above natural background levels.
3. **Maintained satellite brightness** is below the threshold for detection by the unaided eye.

4. **Satellite visibility** is an unusual occurrence.
5. **Launch schedules and orbital parameters** are publicly available in advance.

Provided glints and flares are avoided, meeting the limit defined above would reduce the impact to below the threshold defined in SATCON1 for wide-field, large aperture telescopes, such as Rubin Observatory.

7.7 Open Issues from Industry Discussants

1. Should there be different targets based on different wavelengths? Some relevant information is contained in the analysis of the impact on Rubin Observatory by Tyson et al. (2020, *Astronomical Journal*, 160, 226). These limits depend on the sensitivity of the Rubin Observatory system, including filters and detector. For the limits for calibratable cross-talk corresponding to $V = 7$ mag at 550 km, in the LSST bandpass system, the other band limits are $u \sim 5.5$ mag; $r \sim 7$ mag; $i \sim 6.5$ mag; $z \sim 6.8$ mag; and $y \sim 6.5$ mag. Note that these are not equivalent to a wavelength-independent reflection of the solar spectrum. Visual reference for filter bandpasses are found at <https://www.lsst.org/scientists/keynumbers>.
2. Note that other potential impacts exist, but are not currently prioritized on account of their level of development being too low to provide actionable guidance to satellite owner/operators.
3. Interference with infrared observations (this issue is discussed in the NSF JASON report https://www.nsf.gov/news/special_reports/jasonreportconstellations/).
4. Interference with low-solar-elongation observations for near-Earth asteroid searches, with potential impacts on planetary defense (see US and International Policy Group Papers for policy considerations).
5. Interference with high-cadence occultation surveys due to unlit satellites passing in front of stars and momentarily blocking light.
6. Interference with high-cadence time domain astronomy through optical flashes of otherwise low-brightness satellites and debris.
7. Aggregate effect vs an individual effect.

7.8 Aggregate Impact

Discussion was held of an eventual cumulative effect of visibility that could create an overall lighter night sky, reducing ability to make observations. This concern is developed in a peer-reviewed publication based on numerical modeling, by Kocifaj et al. (2021, *MNRAS Lett*, 504, L40). Using plausible assumptions, they show that scattered sunlight from all current LEO satellites and space debris may already have brightened the diffuse natural sky glow by 10%. Measurements to test for this change in absolute level on a large angular scale are challenging and have yet to be made or examined in archival data.

A parallel exists in spectrum rules for Non-Geostationary Systems by establishing both individual limits of power (Equivalent Power Flux Density or EPFD) for each individual constellation, but also an aggregate EPFD limit to protect higher-orbiting geostationary satellites operating in the same frequency band. This is conceptually interesting, but an arbitrary number of assumed systems (3.5) and no practical testing of this undermine its value as a template for brightness.

Regarding the aggregate-effect vs the individual-effect, there is not sufficient evidence or study of this problem to characterize it properly or recommend an arbitrary number that, unsupported by any empirical

testing, would undermine its value and meaning. However, the modeling formalism is now in place, and can be subjected to variation of assumptions and parameters as well as observational validation. Although further simulations are needed for impacts on data analysis for specific investigations, it is generally true that streaks from individual satellites impact finite areas of images, while increased diffuse sky glow requires increased exposure time for all images.

7.9 Impact Metric

In reviewing the recommendations for satellite operators made in SATCON1 and subsequent papers, the Industry Subgroup noted certain internal tensions among the recommendations, with some that are mutually exclusive and others setting up trade-offs on their relative impact to astronomy from a preferred system architecture or spacecraft design. For example, SATCON1 sets a clear priority on constellations flying at lower altitudes, in order to reduce the time that the spacecraft are moving across the field of view of the observer on the ground. Another SATCON1 recommendation prefers reducing the overall number of satellites even though, in general, constellations operating at lower altitudes require more spacecraft to yield comparable geographic coverage and throughput. Similar tensions have been identified in the recommendation to darken satellite services to reduce reflection, which may in turn elevate the thermal footprint so as to cause disturbances for infrared astronomical observations.

Spacecraft design changes and satellite system mitigations all tend to feature some sort of trade-off in performance, reliability or attitude control, or spectral efficiency or data rates. Well-intentioned satellite operators will need further guidance from astronomers on how to weigh these trade-offs and avert the potential for unintended consequences on other fields of astronomy. We note that the SatHub discussed elsewhere in the SATCON2 exercise may be a productive venue to evaluate the relative tradeoffs for a given constellation between internally-conflicted technology or mitigation solutions.

Similarly, not all mitigations will have the same usefulness across the astronomy community, and the satellite industry would benefit from deeper insights into the relative impacts and priorities, and which astronomy activities merit concentrated efforts to address. This sort of “impact metric” could consider which mitigations would yield the widest possible benefit across the astronomy field, as well as those more specialized activities that have limited alternative workarounds available to date.

For example, it has been useful for the satellite community to have as a target the general agreement from the astronomy community that reaching a brightness of 7 magnitude is of the highest priority, because meeting this target would relieve concerns both about naked-eye visibility and loss of the night sky for unaided observation, and also appears to provide the minimum mitigation needed for most professional optical telescopes. It is less clear, however, what astronomers would characterize as the next highest priority target to achieve. Further delineation of the remaining astronomical targets within a subtler hierarchy could better guide industry in its ongoing assessment of mitigations.

Beyond the types of telescopes and astronomical observations, industry research and experimentation could be better applied with further astronomy community guidance as to which of the various concerns and/or stakeholder groups would have the largest or most beneficial impact if solved. While the majority of study to date has focused on Rubin Observatory as a wide-field observatory most impacted by constellations, there are relatively few such wide-field telescopes to date, and it is unclear how many (if any) other observatories are affected as non-linearly. Other mitigations may be of use to the large inventory of narrow-field telescopes.

Industry R&D efforts can be focused on most impactful problems if guided with the development of an impact metric to depict the relative effect of satellite visibility on various astronomy fields, and not just the types of telescopes or observations, but also their frequency or proliferation. While this may be a problematic value judgement for the astronomy community to adopt broadly, it could be considered on a constellation-by-constellation basis as part of the SatHub concept discussed elsewhere in the SATCON2 workshop.

7.10 Mitigation Approaches

While other aspects of SATCON2 evaluate approaches that would compel satellite constellation operators to consider and address their effect on astronomy through regulatory or legal means, the Industry Subgroup focused on the resources and recommendations that could be reasonably adopted by those satellite owner/operators that are committed to voluntarily limiting their impact on astronomy. The Industry Subgroup's focus was to inform and enable satellite operators and manufacturers of the tools and techniques they can voluntarily employ to minimize their potential impact on astronomy. This section explores the resources available to, or necessary for, satellite stakeholders to voluntarily assess and, if necessary, mitigate the visibility of proposed satellites as seen from the ground.

An initial list of recommended performance metrics and mitigation techniques was provided in the AAS document from SATCON1, *Impact of Satellite Constellations on Optical Astronomy and Recommendations toward Mitigations*, while the effectiveness of these techniques is being evaluated and discussed elsewhere in the current work of SATCON2.

Many of the initial mitigation techniques rested on SpaceX's pioneering work with Starlink, including the initial DarkSat demonstration satellite launched in January 2020 and the initial test VisorSat from May 2020 and subsequent production-version VisorSat models. With over 1000 VisorSats deployed in 2020–21 and over a year of experience employing post-launch orientation rolls for Starlink, there is a reasonably rich early canon to consider these initial mitigation techniques.

OneWeb also has applied some changes to their Gen1 spacecraft design to mitigate the predicted satellite brightness in the design phase. However, these were undertaken prior to the observation of the actual level of brightness of Gen1 satellites in orbit. OneWeb has commenced work with astronomers to verify the observed level of brightness and persistence in view, and is considering painting certain on-board antennas for its remaining Gen-1 satellites with a dark coating, if needed. OneWeb expects to include further mitigations in their next-generation spacecraft design.

With the recent proliferation of constellations, and with extensive analytical work and collaborative commitment from the astronomy and industry communities, a critical opportunity presents itself now for visibility to be taken into account in the early stages of project development, spacecraft design and constellation architecture.

Operational constellations and industry manufacturers are in a unique position to introduce lessons learned from previous experience to improve the design of future constellations and eventual upgrades to those constellations now being deployed. It will be instructive to share techniques tested and fielded across the satellite community to more rapidly advance this nascent field of engineering and analysis. To the extent possible, satellite operators are encouraged to share and publish their experience and lessons

learned across the community, in order to build understanding of effective mitigation design techniques and foster innovation in new concepts.

Not all mitigation techniques will be satisfactorily effective, nor will each technique suit each proposed constellation. Whereas satellite systems in decades past tended to be produced by a small number of spacecraft manufacturing companies, today's small satellites and constellations come from a far more diffuse source of manufacturers and their designs are highly customized. Further, constellations and small satellites vary significantly by the nature of their business approach or mission, whether for broadband communications, Earth imagery, tracking, or navigation. The most suitable, cost-effective and available mitigation techniques will certainly depend on the specific spacecraft design and orbital characteristics.

7.11 Pre-Launch Analytical Resources

The challenge of accurately predicting the visibility of a spacecraft prior to launch is a novel one for spacecraft designers, and one not previously a part of the routine test and design practice of the commercial satellite industry. However, pre-launch modeling and testing are arguably the least disruptive and most effective ways to prevent inadvertently pronounced visibility that is harmful to astronomy.

The most effective time to avert harmful brightness is in the design phase of the spacecraft and when the constellation architecture is still in development. It is expected that many satellite constellation operators, particularly those who commission the design and production of satellites from a third-party manufacturer will be limited in their ability to halt production lines mid-stream for modifications to mitigate visibility, and will potentially be deterred by the prospect of added costs from retooling designs and disrupting production lines as well as cascading project delays and eventual time to market effects.

Ideally, modeling and testing for impacts to astronomy would become routine for satellite constellations, and all satellite operators would interject into the design phase a step to model their spacecraft to accurately predict the likely visibility well before designs are set and any test articles are fabricated. Further, prior to deployment, any demonstration satellites ideally would be subjected to ground testing, as well as the kind of systematic observation measurements of brightness once launched as is contemplated elsewhere in SATCON2.

While testing for reflection and albedo during the development stage is a worthwhile goal, these are relatively new engineering protocols. Given the newer nature of this consideration, additional experience and development are needed to allow for a mature capability to the point where willing satellite operators can readily access reliable and cost effective testing tools.

Material level optical property testing should be considered in the design cycle of the spacecraft. It is feasible to conduct ground optical testing for specific material samples using the limited existing databases which provide optical properties for various materials. However, these databases do not appear to be comprehensive in nature. This potentially useful predictive tool requires further exploration of appropriate testing parameters to obtain accurate material properties for a more complete range of materials commonplace in spacecraft manufacturing.

Traditional optical modeling remains quite complex and challenging to implement, given the lack of experience and background in using these capabilities in this way. Further analysis on approaches and

capabilities should be developed in order to simplify the problem and enable operators to incorporate this potential preventative step into their design cycle.

Modelling by using Bi-directional Reflectance Distribution Function (BRDF) testing in the laboratory is a promising step in the development phase to forecast the expected brightness level. BRDF testing could be introduced through a process similar to the Thermal Balance and Vibrations test used to correlate thermal and finite element models of a satellite during the environmental test campaign. The Industry Subgroup inquiry concluded that full satellite-level optical property testing is not currently feasible, given the limited facilities and complication with this type of integrated test. In order to reach a point where such testing is accessible, cost-effective and ultimately routine for satellite operators, further inquiry will be required to refine and mature the analytical techniques needed to predict brightness levels reliably, and also to evaluate the technical requirements and expected costs of BRDF test set-ups.

7.12 Post-Launch Mitigation Techniques and Analytical Resources

7.12.1 Transparent Location Data after Deployment

As noted in both SATCON1 and discussed in SATCON2, astronomers seek more readily available, more extensive information on satellite positions in order to permit many telescopes to apply scheduling tools to avoid the impact of constellations on observation images. The owner/operators are encouraged to provide and make publicly available high-accuracy data on the predicted locations of individual satellites (or ephemerides). In general, satellite operators are willing to share accurate, timely orbit position information in whatever format the government and industry eventually agree on, noting that access to these data needs to be reasonably controlled. This drive coincides with a broader desire within the space and satellite community to improve collision avoidance and enhance space safety by collecting and sharing more detailed and readily accessible ephemerides and covariance data, as well as early assignment of two-line element identifiers (TLEs). Sharing of such information is still uneven across various satellite owners, with several governments encouraging more transparency and new data sharing tools.

To a certain extent, the requirements of astronomers exceed the level of detail being considered for space safety purposes, such as proposals to utilize a new standard format for ephemerides beyond TLEs to include covariances and other useful information. The Industry Subgroup noted that there are limitations within the existing system to capturing ephemeris data at more frequent intervals and with finer specificity. At this time, the current system is not set up to share this level of data, although there is great interest in the US and internationally in upgrading capabilities to permit improved information collection and sharing. The Observations Working Group of SATCON2 is considering these.

To incentivize further refinement of the systems now in place, the Industry Subgroup noted that it would be helpful to understand just how widely such information could be used for astronomy, including what representation of telescopes could or would reasonably employ scheduling. It is unclear how many observatories have available software or are inclined to employ scheduling techniques for avoidance should such data be made available. If it is clear that the higher frequency interval of data or its specificity would be of high potential use to widespread telescopes, this could elevate the priority and prompt new resources to work on the enhancement of data systems for the unique requirements of astronomy.

7.12.2 End of Life Deorbit

The US government's ODMSP were updated in 2019 to accommodate the changing near-Earth space environment. As the preamble explains: *“While the original ODMSP adequately protected the space environment at the time, the [US government] recognizes that it is in the interest of all nations to minimize new debris and mitigate effects of existing debris. This fact, along with increasing numbers of space missions, highlights the need to update the ODMSP and to establish standards that can inform development of international practices”*.²⁹⁴

Of particular importance, the new ODMSP state that “[t]he new standard practices established in the update include the preferred disposal options for immediate removal of structures from the near-Earth space environment.” Specifically, standard 4-1(a) lists the preferred options as follows: *Direct reentry or heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit at the end of mission into (1) a reentry trajectory or (2) a heliocentric, Earth-escape orbit. These are the preferred disposal options. (...)*

Standard 4-2(b) lists a second option, which is restating the well-known 25-year rule: *Atmospheric reentry: Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to as short as practicable but no more than 25 years after completion of mission. If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit. (...)*

While these standards are written with space environmental stability in mind, they have implications for astronomy.

Satellites deorbiting as part of their EOL, a requirement for space safety, present several complications for astronomy. For mature constellations that require the continuous replacement and EOL maneuvers of satellites, the deorbiting satellites could lead to a non-negligible addition to the bright satellite population. This is expected to be more acute for long deorbiting timescales, even when adhering to the 25-year rule. Moreover, satellites that are passively deorbiting are expected to tumble, which will cause variations in satellite brightness, with the possibility of bright transients. Such variations have the potential to cause significantly greater data loss than those under active control meeting the recommended brightness limit. On-orbit aging of satellites, whether active or defunct, could further lead to changes in satellite brightness or variability.

For these reasons, satellite operators should deorbit their satellites as soon as practicable upon satellites reaching their end of mission, consistent with ODMSP 4-1(a).

Adherence to ODSMP 4-1(a) presumes spacecraft of concern will feature propulsion capabilities adequate to accelerate natural deorbiting. Other methods exist to decrease the natural deorbiting timescale, such as drag enhancement (e.g., drag sails). Such devices necessarily increase the cross

²⁹⁴ United States Government. Orbital Debris Mitigation Standard Practices. November (2019). https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf

section of the satellite, which has the potential to substantially increase its brightness or variability, even for small satellites.

For this reason, satellite operators who use drag enhancement technology should, in addition to the considerations presented in ODMSP 4-1(b), demonstrate that the use of such technology adheres to best practices for astronomical impact reduction.

In particular, because many small satellites do not have propulsion, such systems may require ongoing evaluation and monitoring to understand correlations, if present, between the likelihood of a satellite having an astronomical impact and its satellite type, deorbiting method and characteristics, and altitude.

7.13 Ongoing Mitigation Iteration

The Industry Subgroup noted throughout its discussions that it is a relatively new field of technical work to analyze the impact of diverse constellation architectures and spacecraft designs on the myriad astronomy scientific undertakings. This intersection between satellite constellations and astronomy is prompting a new field of engineering that is cycling rapidly with iteration in new mitigation approaches. While not all techniques are destined to prove effective, this is a dynamic area of inquiry that is rapidly deepening understanding of how to lessen the impact of satellite constellations on astronomy.

For the satellite industry, it is nascent engineering work to conceive, test and field mitigation techniques to reduce visibility on communications satellites operating in LEOs. To date, only SpaceX's experimentation on the Starlink DarkSat test satellite and considerable deployments of the now ubiquitous VisorSat design and operational roll techniques have been well studied to date. With growing participation from OneWeb, Amazon Kuiper and Telesat's Lightspeed, and work to engage spacecraft manufacturers and proponents of new constellations from other countries, there is further voluntary work toward innovations in spacecraft designs and operational adjustments with astronomy in mind. Ongoing work by SpaceX and now other systems will yield new iterative mitigation approaches that may better suit different types of spacecraft and varying constellation designs. This diversity of approach should be encouraged, as new iterations will benefit both new constellations that are currently in the planning phase and future generations of spacecraft to upgrade existing constellations.

The considerable efforts of the astronomy community to analyze and observe the intersection of constellations and astronomical observation are also providing new and valuable insights to the efficacy of early mitigations and prompting concepts for alternate mitigation approaches.

Recommendation. Because the technical and practical inquiry into mitigation techniques is still at an early stage, the Industry Subgroup endorses an outcome-driven focus for any mitigation recommendations and guidelines, rather than overly prescriptive language that stipulates a specific technology or technique. The community should continue its work to establish data-driven, well-defined standards and requirements based on continued research, modeling, and analytical efforts, and promote meeting these desired performance-based outcomes. With such dynamism and iteration in mitigation techniques and ongoing work to evaluate their effectiveness, recommendations should incentivize further innovation and leave room for variations in mitigation approaches that may be suitable for different types of constellations and operators.

Annex I – State Lighting Regulations

Table 2. State Lighting Regulations

State	Statute	Summary ²⁹⁵
Arizona	Ariz. Rev. Stat. Ann. §§49-1101 <i>et seq.</i> (2020)	<p>Outdoor light fixtures must be fully or partially shielded.</p> <ul style="list-style-type: none"> Exempt are: <ul style="list-style-type: none"> Incandescent fixtures of 150 watts or less or other light sources of 70 watts or less; Emergency and construction lights; Airport lighting. Nonconforming light fixtures are allowed as long as they are extinguished by automatic shutoff between midnight and sunrise. <p>Towns, cities, and municipalities may have more stringent regulation.</p>
Arkansas	<p>Ark. Stat. Ann. §§8-14-101 <i>et seq.</i> (2019)</p> <p>Short Title: Shielded Outdoor Lighting Act</p>	<p>Stated purpose: conserve energy and preserve environment.</p> <p>Outdoor lighting fixtures installed using public funds must be shielded <i>unless</i> a municipality determines doing so would be cost prohibitive.</p> <ul style="list-style-type: none"> Analysis must include cost of fixtures and projected energy cost of operation. <p>Electric public utilities must offer a shielded lighting option to customers.</p>
Colorado	Colo. Rev. Stat. §§24-82-901 <i>et seq.</i> (2018)	<p>Any new outdoor lighting fixture installed after 1 July 2002 by or on behalf of the state must meet the following requirements:</p> <ul style="list-style-type: none"> Fixtures with a greater output than 3200 lumens must be full cutoff luminaires. Fixtures only emit as much light as is necessary for the intended purpose. For roadway lighting, it must be shown that the intended purpose <i>could not</i> be achieved by other means (ie., reflective markers, warning signs, etc.) Environmental/energy costs and glare reduction measures must be considered. <p>Subject to exemptions/exceptions.</p>
Connecticut	Conn. Gen. Stat. §13a-110a (2019)	<p>State funds may not be used to install or replace a permanent outdoor light fixture on a roadway unless:</p> <ul style="list-style-type: none"> It is designed to maximize energy efficiency and minimize light pollution/glare/trespass; It only emits as much light as is necessary for its intended purpose;

²⁹⁵ Luminaire and lighting fixture are used interchangeably. Some statutes define these elements individually, some do not. Generally, a luminaire refers to the lighting unit itself and the lighting fixture refers to any fixed or moveable equipment used to install the luminaire (ie., a streetlight pole).

		<ul style="list-style-type: none"> Any fixture with a greater output than 1800 lumens is a full cutoff luminaire; and It can be shown that the intended purpose <i>could not</i> be achieved by other means (ie., reflective markers, warning signs, etc.)
	Conn. Gen. Stat. §4b-16 (2019)	<p>State funds may not be used to install or replace a permanent outdoor light fixture on the grounds of any state building unless:</p> <ul style="list-style-type: none"> It is designed to maximize energy efficiency and minimize light pollution/glare/trespass; It only emits as much light as is necessary for its intended purpose; and Any fixtures with a greater output than 1800 lumens is a full cutoff luminaire.
Delaware	Del. Code Ann. Tit. 7, §§7101a <i>et seq.</i> (2021)	<p>State funds may not be used to install or replace a permanent outdoor light fixture unless:</p> <ul style="list-style-type: none"> It is designed to maximize energy efficiency and minimize light pollution/glare/trespass; It only emits as much light as is necessary for its intended purpose; and Any fixture with a greater output than 1800 lumens is a full cutoff luminaire. <p>For roadway lighting, it must be shown that the intended purpose <i>could not</i> be achieved by other means (ie., reflective markers, warning signs, etc.).</p>
Florida	Fla. Stat. §161.163 (2020)	Model lighting ordinance to guide municipalities in enacting policies to protect sea turtles when hatching.
Hawai'i	HRS § 201-8.5 (2019)	<p>Establishes standards for outdoor lighting:</p> <ul style="list-style-type: none"> Outdoor lighting emitting more than 3000 lumens must be fully shielded. Where lighting is not required to be shielded, it still must meet criteria outlined.
	2017 Haw. Sess. Law, Act 185	<p>Establishes a Dark Skies Protection Advisory Committee, comprised of 13 members to evaluate issues relating to light pollution reduction, energy conservation, value associated with dark night skies, protection of endangered species and astronomical efforts, etc.</p> <p>In December 2020 the Committee provided a report to the legislature identifying several issues for further exploration including the replacement of streetlights in Maui with LED lights. However, the Committee stated that it was not yet prepared to produce a full report.</p>
Maine	Maine Stat. 5 § 1769 <i>et. seq.</i> (2011)	State funds may not be used to install or replace a permanent outdoor light fixture unless:

		<ul style="list-style-type: none"> Any fixtures with a greater output than 1800 lumens is a full cutoff luminaire; It only emits as much light as is necessary for its intended purpose; and Consideration is given to minimizing glare and light trespass. <p>Exceptions/exemptions may apply.</p>
Maryland	Md. State Finance & Procurement Code Ann. §14-412 (2018)	<p>State funds may not be used to install or replace a permanent outdoor light fixture unless:</p> <ul style="list-style-type: none"> It is designed to maximize energy efficiency and minimize light pollution/glare/trespass; It only emits as much light as is necessary for its intended purpose; and Any fixture with a greater output than 1800 lumens is a restricted uplight luminaire.
Michigan	Mich. Comp. Laws § 324.75101 <i>et. seq.</i> (2021)	Designates specific areas as dark sky preserves and limits the installation of lighting in these areas unless required for safety or the reasonable use and enjoyment of the preserve. When lighting is installed it must be fully shielded and directed downward.
Minnesota	Minn. Stat. §16B.328 (2020)	<p>Instructs the commissioner of administration to develop a model ordinance governing outdoor lighting with the intent of reducing light pollution. The model ordinance is intended to be utilized by cities, counties, and towns.</p> <p>Prohibits the use of state funds to install or replace an outdoor lighting fixture unless:</p> <ul style="list-style-type: none"> It is designed to maximize energy efficiency and minimize light pollution/glare/trespass; It only emits as much light as is necessary for its intended purpose; and Any fixture with a greater output than 1800 lumens is a full cutoff luminaire. <p>For roadway lighting, it must be shown that the intended purpose <i>could not</i> be achieved by other means (ie., reflective markers, warning signs, etc.).</p>
New Hampshire	N.H. Rev. Stat. Ann. §§9-E:1 <i>et seq.</i> (2020)	<p>State funds may not be used to install or replace a permanent outdoor light fixture unless:</p> <ul style="list-style-type: none"> It is designed to maximize energy efficiency and minimize light pollution/glare/trespass; It only emits as much light as is recommended for the intended purpose as outlined by the IES or FHA; and Any fixture with a greater output than 1800 lumens is a fully shielded fixture. <p>Encourages municipalities to enact local ordinances to conserve energy, minimize light pollution, and preserve dark skies.</p>

New Mexico	N.M. Stat. Ann. §§74-12-1 <i>et seq.</i> Short Title: Night Sky Protection Act	All outdoor lighting fixtures must be shielded except incandescent fixtures of 150 watts or less or other sources of 70 watts or less. No outdoor recreational facilities may use lighting after 11:00pm with fines for violation.
New York	N.Y. Public Buildings Law §143	<p>State funds may not be used to install or replace a permanent outdoor light fixture or to pay for the operating cost of such fixtures unless:</p> <ul style="list-style-type: none"> • For roadway or parking lot lighting, the fixture is fully shielded; • For building-mounted fixtures, the fixture is fully shielded if it is greater than 3000 lumens • Façade lighting is shielded; and • For ornamental roadway lighting, the fixture is not greater than 700 lumens above the horizontal plane. <p>Exemptions:</p> <ul style="list-style-type: none"> • Temporary emergency lighting • Lighting for athletic playing areas (however, fixtures must minimize upward lighting and glare as much as possible) • If a safety or security arises, as determined by the state • For replacement of a previous outdoor fixture • Lighting for tunnels and underpasses • If the cost of implementing compliant fixtures is prohibitive
Oregon	Or. Rev. Stat. §455.573 (2019)	<p>Public buildings constructed on or after 1 January 2010 or that have fixtures installed or replaced must use shielded lighting fixtures to the greatest extent possible.</p> <p>Municipalities may require more stringent regulations, and may also waive the above requirement if the building is of a historic nature or for other reasons.</p>
Rhode Island	R.I. Gen. Laws §§42-136-1 <i>et seq.</i> (2020) Short Title: Outdoor Lighting Control Act	<p>Mandates new or replacement permanent outdoor lighting fixtures by or for a state agency to meet the following requirements:</p> <ul style="list-style-type: none"> • Must consider maximizing energy efficiency and minimizing light pollution. • New or replacement fixture permits no more than 2% of the total lumens in the zone of 90–180 degrees if the total output is more than 3200 lumens. • Only emits as much light as is necessary for its intended purpose. <p>For roadway lighting, it must be shown that the intended purpose <i>could not</i> be achieved by other means (ie., reflective markers, warning signs, etc.).</p>
Texas	Tex. Local Government Code §§240.031 <i>et seq.</i> (2019)	Instructs commissioners court of a county located within 57 miles of a major astronomical observatory at the McDonald Observatory to adopt orders regulating the installation and use of outdoor lighting.

		<p>Permits commissioners of court within 5 miles of a major astronomical observatory at the George or Stephen F. Austin State Observatory to adopt orders regulating the installation and use of outdoor lighting at the request of the director of the observatories.</p> <p>Permits commissioners of court to adopt orders regulating the installation and use of outdoor lighting at the request of a military installation, base, or camp commanding officer.</p>
	<p>Tex. Health and Safety Code §§425.001 <i>et seq.</i> (2020)</p>	<p>Prohibits the use of state funds to install or replace an outdoor lighting fixture unless:</p> <ul style="list-style-type: none"> • It is designed to maximize energy efficiency and minimize light pollution/glare/trespass; • It only emits as much light as is necessary for its intended purpose; and • Any fixture with a greater output than 1800 lumens is a full cutoff luminaire. <p>For roadway lighting, it must be shown that the intended purpose <i>could not</i> be achieved by other means (ie., reflective markers, warning signs, etc.)</p>
Virginia	<p>Va. Code §2.2-1111 (2016)</p>	<p>Requires that the state only procure shielded outdoor light fixtures and provides waivers for this requirement if the Division determines there is a bona fide reason to do so.</p>
Wyoming	<p>Wyo. Stat. §37-16-202</p>	<p>Mandates that electric utilities offer tariffs for utility-provided outdoor lighting that provide an option for customers to choose a lighting fixture designed to minimize illuminating unintended areas and maintain dark skies.</p>
District of Columbia	<p>D.C. Code Ann. §§8-1776.01 <i>et seq.</i> (2019)</p>	<p>The Smart Lighting Study Act of 2009 instructed the Department of Energy and Environment to submit a report recommending strategies and standards for optimal lighting methods, taking into account public safety, energy efficiency, cost efficiency, effects on environmental health, and aesthetics. This must include an analysis of IDA and IES standards.</p>
Puerto Rico	<p>P.R. Code §§8031 <i>et seq.</i> (2019)</p> <p>Short Title: Program for the Control and Prevention of Light Pollution)</p>	<p>The Environmental Quality Board will approve regulations.</p> <p>Regulates light fixtures installed on private properties:</p> <ul style="list-style-type: none"> • Colored and decorative lights must have automatic on/off switches. • Lighting systems used for security or to light walkways must use low-pressure sodium emission sources. • Certain lighting systems must be turned off between 11pm and dawn. <p>Makes 1 August Light Pollution Awareness Day</p>

Annex II — 2021 Planetary Defense Conference Hypothetical Asteroid Impact Scenario

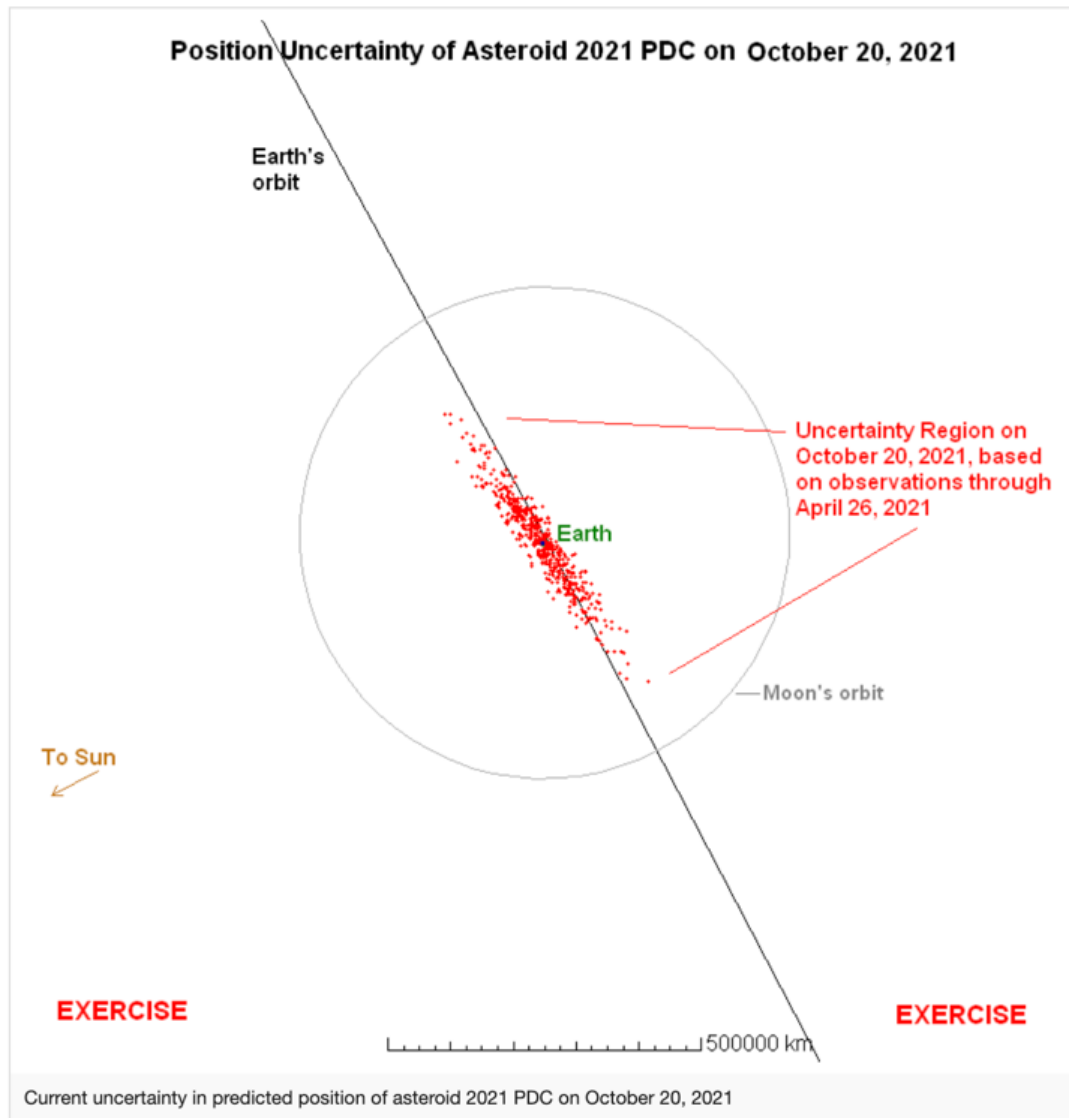


Figure All.1. Input to Multi-agency exercise for potential asteroid impact.

- Asteroid 2021 PDC is discovered by Pan-STARRS and named by the Minor Planet Center on 19 April 2021.
- 20 April 2021: JPL's Sentry impact monitoring system and ESA's CLOMON system identify potential impact dates.

- Both systems predict possible impact on 20 October 2021 — a short time frame but low probability (1 in 2500).
- Pre-Conference Details
 - Size of 2021 PDC is uncertain: estimated to be ~ 120 meters but could be anywhere between 35 and 700 meters.
 - 2021 PDC continues to approach Earth for 3 weeks but wouldn't be detected on radar until October when it became much closer to impact.
 - As of 26 April — the date of the conference — the probability of impact has reached 5%.
- Over the course of 3 days, participants assessed the data and drafted a briefing detailing the mission options.²⁹⁶
 - Day 1 (Setting: 26 April 2021)
 - Day 2 (Setting: 2 May 2021)
 - Newly processed data from Pan-STARRS collected in 2014 shows that 2021 PDC could have been identified up to 7 years earlier. Using these data, astronomers determine that there is 100% certainty that 2021 PDC will make impact in either Europe or north Africa.
 - Day 3 (Setting: 30 June 2021)
 - Shrink impact zone to Czech Republic, Austria, Slovenia, and Croatia.
 - Size remains uncertain but NASA NEOWISE satellite narrows parameters to 35–500 meters.
 - Day 4 (Setting: 14 October 2021)
 - Identified likely location of impact as Czech Republic near Germany/Austria border, ~ 300 km.
 - 2021 PDC is close enough that Goldstone System Radar can detect it and determine its size and characteristics.
 - 2021 PDC is smaller than expected, lessening the region of impact.
 - Commence discussions on evacuation of region.

²⁹⁶ https://cneos.jpl.nasa.gov/pd/cs/pdc21/pdc21_day2_briefing2.pdf

Annex III – SATCON1 “Regulations”

The following are suggested conditions of licensing for launch and/or operations of a satellite constellation to mitigate the impacts on astronomy.

47 CFR--PART 25

§25.114 Applications for space station authorizations.

(d) The following information in narrative form shall be contained in each application, except space station applications filed pursuant to § 25.122 or § 25.123:

* * * * *

(19) A description of the design and operational strategies that will be used to mitigate interference with Earth surface-based optical and radio observation of space, including the following information:

(i) A statement detailing the manner in which the space station operator has assessed and limited the amount of reflected sunlight occurring during normal operations, with reflected sunlight ideally slowly varying with orbital phase as recorded by high etendue (effective area \times field of view), large-aperture ground-based telescopes to be fainter than $7.0 V_{\text{mag}} + 2.5 \times \log(r_{\text{orbit}} / 550 \text{ km})$, equivalent to $44 \times (550 \text{ km} / r_{\text{orbit}})$ watts/steradian.

(A) The statement must include the extent to which the satellite operator considered:

- (1) Satellite darkening;
- (2) Sun shielding; and,
- (3) Avoiding non-rigid specular materials on the nadir face of the satellites to reduce false transients.²⁹⁷

(B) Where applicable, this statement must include a reflected sunlight mitigation disclosure for any separate deployment devices, distinct from the space station launch vehicle, that may become a source of reflected sunlight;²⁹⁸

(ii) A statement that the space station operator has assessed and limited the probability that the space station(s) will become a source of specular reflection (flares) in the direction of observatories. Space station operators must make their best effort to avoid such flares. However, if such flares will occur, accurate timing information from ground-based observing must be required to enable observatories an opportunity for planned avoidance. The statement must indicate whether this probability for an individual

²⁹⁷ SATCON1 4.

²⁹⁸ SATCON1 Recommendation 5.

space station is 0.01 (1 in 100) or less, and indicate the means by which such calculation has been obtained;²⁹⁹

(iii) A statement detailing the manner in which the space station operator has assessed and limited reflected light on the ground track by adjusting space station attitudes. The statement should indicate when and how the space station operator has the capability to adjust its space station attitudes.³⁰⁰

(iv) A statement that the space station operator has assessed and planned satellite proximity configuration to facilitate pointing avoidance by observatories, with the understanding that this can be most readily achieved if the immediate post-launch satellite formation is configured as tightly as possible consistent with safety and orbital debris mitigation requirements such that the orbit raise affords rapid passage of the train through a given pointing area;³⁰¹

(v) A statement detailing the manner in which the space station operator shall ensure observatories obtain the information needed for pointing avoidance, with specific reference to the provision of updated positional information or processed telemetry;

(vi) A statement whether the satellite operator has engaged in any efforts to support coordinated efforts for optical observations of constellation space stations in LEO, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations.³⁰²

(vii) A statement whether the satellite operator has engaged in any efforts to support a comprehensive satellite constellation observing network with uniform observing and data reduction protocols for feedback to operators and astronomical programs.³⁰³

(viii) For operators of space station constellations, a statement that the space station operator has assessed the ability to limit the number of space stations to the minimum number of units needed for bandwidth and coverage requirements and maintain their operational orbits below 600km to mitigate adverse effects on Earth surface-based optical and radio observation of space. Where the space station operator has not implemented such limits on units or orbit altitude, the space station operator shall explain in sufficient detail the calculations and needs that support such decision.

(ix) For operators of space station constellations, a statement that the space station operator has implemented measures to ensure ongoing provision of ephemerides information for all constellation space stations in a public database to sufficient accuracy.

²⁹⁹ SATCON1 Recommendation 6.

³⁰⁰ *Id.*

³⁰¹ SATCON1 Recommendation 7.

³⁰² SATCON1 Recommendation 8.

³⁰³ *Id.*

(A) For purpose of this requirement, sufficient accuracy shall mean information that enables the transit of any unit across the field during the exposure interval to be predicted:

(1) To be predicted within 12 hours in advance of the observation, to an accuracy of 10 seconds in time, as well as the position of the track to within 12 arcminutes in the cross-track direction and 12 arcminutes in position angle;³⁰⁴ and,

(2) For a given position on the sky and given start and end times for an exposure, can be predicted within 12 hours in advance of the observation to an accuracy of 2 seconds in time and the position of the track to 6 arcminutes in the cross-track direction and 6 arcminutes in position angle.³⁰⁵

(x) For operators of space stations in LEO orbit, a statement that the space station operator has performed adequate laboratory Bi-directional Reflectance Distribution Function (BRDF) measurements and a reflectance simulation analysis as part of the satellite design and development phase.³⁰⁶

(xii) For non-US-licensed space stations, the requirement to describe the design and operational strategies to minimize Earth surface-based optical and radio observation of space can be satisfied by demonstrating that mitigation plans for the space station(s) for which US market access is requested are subject to direct and effective regulatory oversight by the national licensing authority.

§25.122 Applications for streamlined small space station authorization.

* * * * *

(c) Applicants filing for authorization under the streamlined procedure described in this section must include with their applications certifications that the following criteria will be met for all space stations to be operated under the license:

* * * * *

(15) The space station(s) will operate only in non-geostationary orbit;

(i) A statement detailing the manner in which the space station operator has assessed and limited the amount of reflected sunlight occurring during normal operations, with reflected sunlight ideally slowly varying with orbital phase as recorded by high etendue (effective area × field of view), large-aperture ground-based telescopes to be fainter than $7.0 V_{\text{mag}} + 2.5 \times \log(r_{\text{orbit}} / 550 \text{ km})$, equivalent to $44 \times (550 \text{ km} / r_{\text{orbit}})$ watts/steradian.

(A) The statement must include the extent to which the satellite operator considered:

- (1) Satellite darkening;
- (2) Sun shielding; and,

³⁰⁴ SATCON1, C.1.

³⁰⁵ Id.

³⁰⁶ SATCON1 Recommendation 4.

(3) Avoiding non-rigid specular materials on the nadir face of the satellites to reduce false transients.³⁰⁷

(B) Where applicable, this statement must include a reflected sunlight mitigation disclosure for any separate deployment devices, distinct from the space station launch vehicle, that may become a source of reflected sunlight;³⁰⁸

(ii) A statement that the space station operator has assessed and limited the probability that the space station(s) will become a source of specular reflection (flares) in the direction of observatories. Space station operators must make their best effort to avoid such flares. However, if such flares will occur, accurate timing information from ground-based observing must be required to enable observatories an opportunity for planned avoidance. The statement must indicate whether this probability for an individual space station is 0.01 (1 in 100) or less, and indicate the means by which such calculation has been obtained;³⁰⁹

(iii) A statement detailing the manner in which the space station operator has assessed and limited reflected light on the ground track by adjusting space station attitudes. The statement should indicate when and how the space station operator has the capability to adjust its space station attitudes.³¹⁰

(iv) A statement that the space station operator has assessed and planned satellite proximity configuration to facilitate pointing avoidance by observatories, with the understanding that this can be most readily achieved if the immediate post-launch satellite formation is configured as tightly as possible consistent with safety and orbital debris mitigation requirements such that the orbit raise affords rapid passage of the train through a given pointing area;³¹¹

(v) A statement detailing the manner in which the space station operator shall ensure observatories obtain the information needed for pointing avoidance, with specific reference to the provision of updated positional information or processed telemetry;

(vi) A statement whether the satellite operator has engaged in any efforts to support coordinated efforts for optical observations of constellation space stations in LEO, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations.³¹²

(vii) A statement whether the satellite operator has engaged in any efforts to support a comprehensive satellite constellation observing network with uniform observing and data reduction protocols for feedback to operators and astronomical programs.³¹³

³⁰⁷ SATCON1 4.

³⁰⁸ SATCON1 Recommendation 5.

³⁰⁹ SATCON1 Recommendation 6.

³¹⁰ *Id.*

³¹¹ SATCON1 Recommendation 7.

³¹² SATCON1 Recommendation 8.

³¹³ *Id.*

(x) A statement that the space station operator has performed adequate laboratory Bi-directional Reflectance Distribution Function (BRDF) measurements and a reflectance simulation analysis as part of the satellite design and development phase.³¹⁴

³¹⁴ SATCON1 Recommendation 4.

Acronyms & Abbreviations

Acronym/abbreviation	Meaning	First appears on page
OBSERVATIONS chapter		
AO	adaptive optics	27
BRDF	Bidirectional Reflectance Distribution Function	20
COPUOS	(UN) Committee on the Peaceful Uses of Outer Space	18
D&QS Report	Dark & Quiet Skies Report	3
EIRP	effective isotropic radiated power	20
FCC	Federal Communications Commission	18
IAU	International Astronomical Union	3
ITU	International Telecommunications Union	18
LEO	low-Earth orbit	1
LEOsat	LEO satellite	1
NIR	near-infrared	2
OEM	orbit ephemeris message	19
OMM	Orbit Mean-elements Message	24
STK	Systems Tool Kit	26
TLE	two-line element	2
WCS	World Coordinate System	9
ALGORITHMS chapter		
18SPCS	US Space Force 18th Space Control Sqn.	20
API	applications programming interface	13
BRDF	bidirectional reflectance distribution function	17
CADC	Canadian Astronomy Data Centrer	12
ESA	European Space Agency	12
GNSS	Global Navigation Satellite System	22
GPU	Graphics Processing UNit	17

ICRS	International Celestial Reference System	6
ILRS	International Laser Ranging Service	20
ITC	International Telecommunications Corporation	22
IVOA	International Virtual Observatory Alliance	5
JSON	software protocol	17
LEO	low-Earth orbit	3
TAP	Table Access Protocol	17
TLE	two-line element	19
WCS	World Coordinate System	6
ITRF	International Terrestrial Reference Frame	20
CCSDS	Consultative Committee for Space Data Systems	22
COMMUNITY ENGAGEMENT chapter		
AAS	American Astronomical Society	6
AAVSO	American Association of Variable Star Observers	21
IPS	International Planetarium Society	40
LEO	low-Earth orbit	2
LIPS	Live Interactive Planetarium Symposium	39
NEPA	National Environmental Policy Act	5
OST	Outer Space Treaty	5
UNOOSA	UN Office of Outer Space Affairs	43
FCC	Federal Communications Commission	44
IAU	International Astronomical Union	6
EO	Earth Observation	47
POLICY Chapter		
AAS	American Astronomical Society	5
AP	National NEO Preparedness Strategy and Action Plan	28
ATLAS	Asteroid Terrestrial-impact Last Alert System	41
BRDF	Bi-directional Reflectance Distribution Function	102
CBD	Convention on Biological Diversity	60
CE	Categorical Exclusion	48
CEQ	Council on Environmental Quality	8
CNEOS	Center for Near Earth Object Studies	41

COPUOS	(UN) Committee on the Peaceful Uses of Outer Space	4
COSPAR	Committee On Space Research	29
CSLA	Commercial Space Launch Act	23
EIA	Environmental Impact Assessment	48
EOL	end of life	10
EPFD	Equivalent Power Flux Density	99
FAA	Federal Aviation Administration	7
FCC	Federal Communications Commission	7
FEMA	Federal Emergency Management Agency	39
GSO	geostationary orbit	25
IAA	International Academy of Astronautics	42
IAU	International Astronomical Union	9
IAWN	International Asteroid Warning Network	27
IDA	International Dark Sky Association	31
IES	Illuminating Engineering Society	31
IRTF	Infrared Telescope Facility	41
ITU	International Telecommunications Union	25
LEO	low-Earth orbit	12
LRTAP	Convention on Long-Range Transboundary Air Pollution	66
LTSG	Guidelines for the Long-Term Sustainability of Outer Space Activities	7
MANOS	Mission Accessible Near-Earth Objects Survey	41
MLO	Model Lighting Ordinance	31
NASA	National Aeronautics and Space Administration	23
NEO	near-Earth object	27
NEOWISE	NEO Wide-field Infrared Survey Explorer	41
NEPA	National Environmental Policy Act	7
NOAA	National Oceanic & Atmospheric Administration	7
NPS	National Park Service	36
NRAO	National Radio Astronomy Observatory	44
NRQZ	US National Radio Quiet Zone	44
NSF	National Science Foundation	11
ODMSP	Orbital Debris Mitigation Standard Practices	10
OST	Outer Space Treaty	4
PDCO	[NASA] Planetary Defense Coordination Office	39
PIERWG	Planetary Impact Emergency Response Working Group	40

PP	precautionary principle	58
PPD	(AAS) Public Policy Department	90
PPP	planetary protection policy	3
RQZ	Radio Quiet Zone	7
SIA	Satellite Industry Association	91
SMPAG	Space Mission Planning Advisory Group	27
SPD	Space Policy Directive	21
STM	space traffic management	7
TLE	two-line element	103
UN	United Nations	4
UNDRIP	UN Declaration on the Rights of Indigenous Peoples	8
UNESCO	United Nations Educational, Scientific and Cultural Organization	85
UNFCCC	UN Framework Convention on Climate Change	60
UNOOSA	UN Office of Outer Space Affairs	27
US NSPP	National Strategy for Planetary Protection	30
VCPOL	Vienna Convention for the Protection of the Ozone Layer	59