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.
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> **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 Interference[1] (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.

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[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 brightnesseses.
- 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.

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[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., ARCADE[4]). 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 trails[5]. 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

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[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 project[6] led by Sandor Kruk (European Space Agency). Other existing and future space telescopes in LEO will likely be impacted by satellites too.

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[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 observations[7] 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 Stacker[8]). 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

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[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 emcompasses 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 (AAVSO[9] 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,

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[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 CLEOsat[13]
- 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

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[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 Treaty[14] (1967),
- US Commercial Space Launch Competitiveness Act[15] (2015),
- National Environmental Policy Act[16] (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 Watcher[17], 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” course[18], as workshops before/during the AAS winter conference or other national conferences, or as fully fledged Carpentries-style modules like Foundations of Astronomical Data Science[19].

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[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 data[20]. 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.

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[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 format[21] 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 $\leqq$ 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.

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[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-derived[22] TLE accuracy to ~ 15 arcminutes.

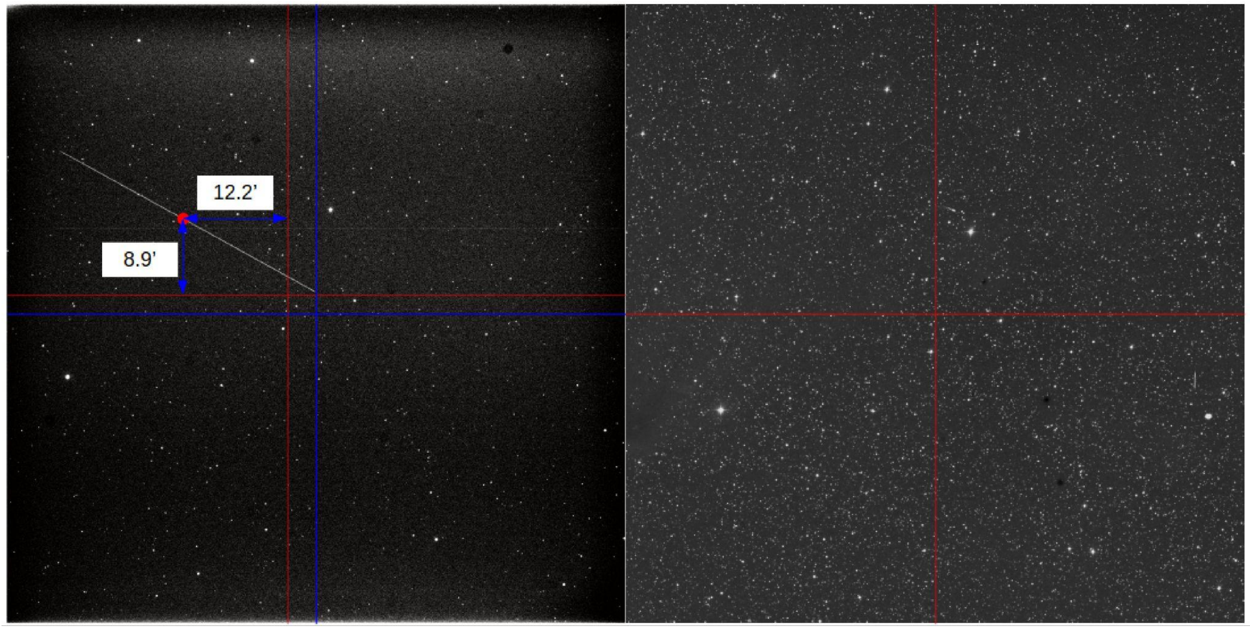

Figure 2. (Left) Observation of OneWeb-0210 obtained with the 0.6-meter telescope at Chungbuk National University Observatory, South Korea (courtesy of CLEOsat). The field of view is 72 x 72 arcminutes and the exposure time is two seconds. The image center is indicated by the blue crosshairs, while the 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 survey[23] 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

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[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.

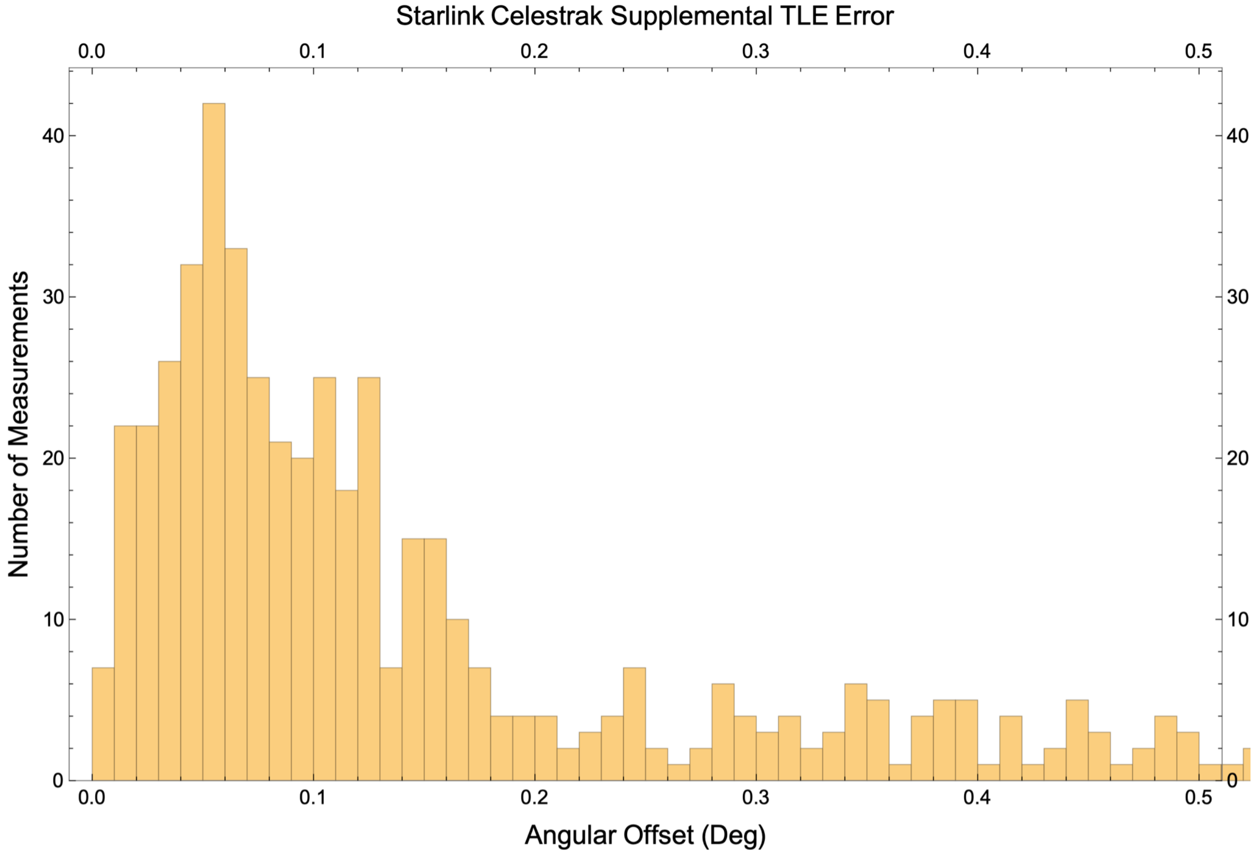

Figure 3. This histogram shows the error in satellite position measured from 567 observations made by Pomenis (University of Arizona) in the northern summer and fall of 2020. The angular offset is the difference between the expected satellite position as calculated from the most timely TLE and the satellite's 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-2[24], 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.

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[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., OrbDetPy[25] 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.

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[25] https://github.com/ut-astria/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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