Appendices to “Impact of Satellite Constellations on Optical Astronomy and Recommendations Toward Mitigations”

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Introduction

These appendices to the SATCON1 report, are the four papers written by the individual working groups over the 4–6 weeks preceding the SATCON1 workshop. The paper titles and working group member lists are given below.

Each of these four papers represents the combined input of the working group members. They include a wide range of detailed descriptions and, in places, individual opinions and survey responses. These do not necessarily reflect the consensus of the SOC expressed in the summary report.

Appendix A. Technical Report on Observations of Satellite Constellations
Allen, L., Abbott, T., Green, R., Haase, F., Heathcote, S., Krantz, H., Otarola, A., Pearce, E., Rawls, M., Storrie-Lombardi, L., Tregloan-Reed, J., & Tyson, T.

Appendix B. Technical Report on Simulations on Impacts of Satellite Constellations
Seitzer, P., Bassa, C., Galadi, D., Hainaut, O., Jah, M., Kuharski, D., McDowell, J., & Siminski, J.

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Appendix D. Technical Report on Metrics of Impacts of Satellite Constellations
Green, R.,, Allen, L., Barentine, J., Bauer, A., Greene, J., Hall, J., Heathcote, S., Krafton, K., Lowenthal, J., Puxley, P., Tyson, T., Walker, C., Williams, A.

Appendix A. Technical Report on Observations of Satellite Constellations

A. Summary and Recommendations

The Observations Working Group looked at observations to date of satellite constellations, what we have learned from those observations, and what is needed to ensure the success of future observations of satellite constellations. We summarize existing recent observations of Starlink satellites. The details of the observing methods and data processing are presented, along with what we have learned from these observations, e.g. about DarkSat (Starlink-1130). In both the immediate future and the long-term, there is a need for broad participation in coordinated efforts between researchers, observers, astrophotographers, and amateur astronomers to conduct observations and interpret the data. Through a comprehensive observing program, we can characterize the brightness of satellite constellations and test the efficacy of mitigation efforts.

Our findings are discussed in detail throughout this report, and lead to the following recommendations:

1. An immediate coordinated effort to observe satellite constellations now, for the purpose of satellite characterization and better understanding of the impact of the satellite constellations on science. These should include (but are not limited to)
    - Multiple measurements of satellite brightnesses, at a range of deployment stages and illumination angles in multiple filters.
    - Measurements of flare and glint behavior.
    - Measurements over satellite life cycles.

2. A comprehensive satellite constellation observing network be formed and sustained, to connect observers with telescopes, provide coordinated observing protocols and data analysis standards. Coordinate ongoing observations of satellite constellations and prepare for the next generation of LEOsats. The design and capabilities of this network should be forward-looking and be prepared for future satellite constellations.

While the Space Situational Awareness (SSA) community observes satellites, they are primarily concerned with tracking and orbit determination, rather than photometric measurements of satellite brightness.

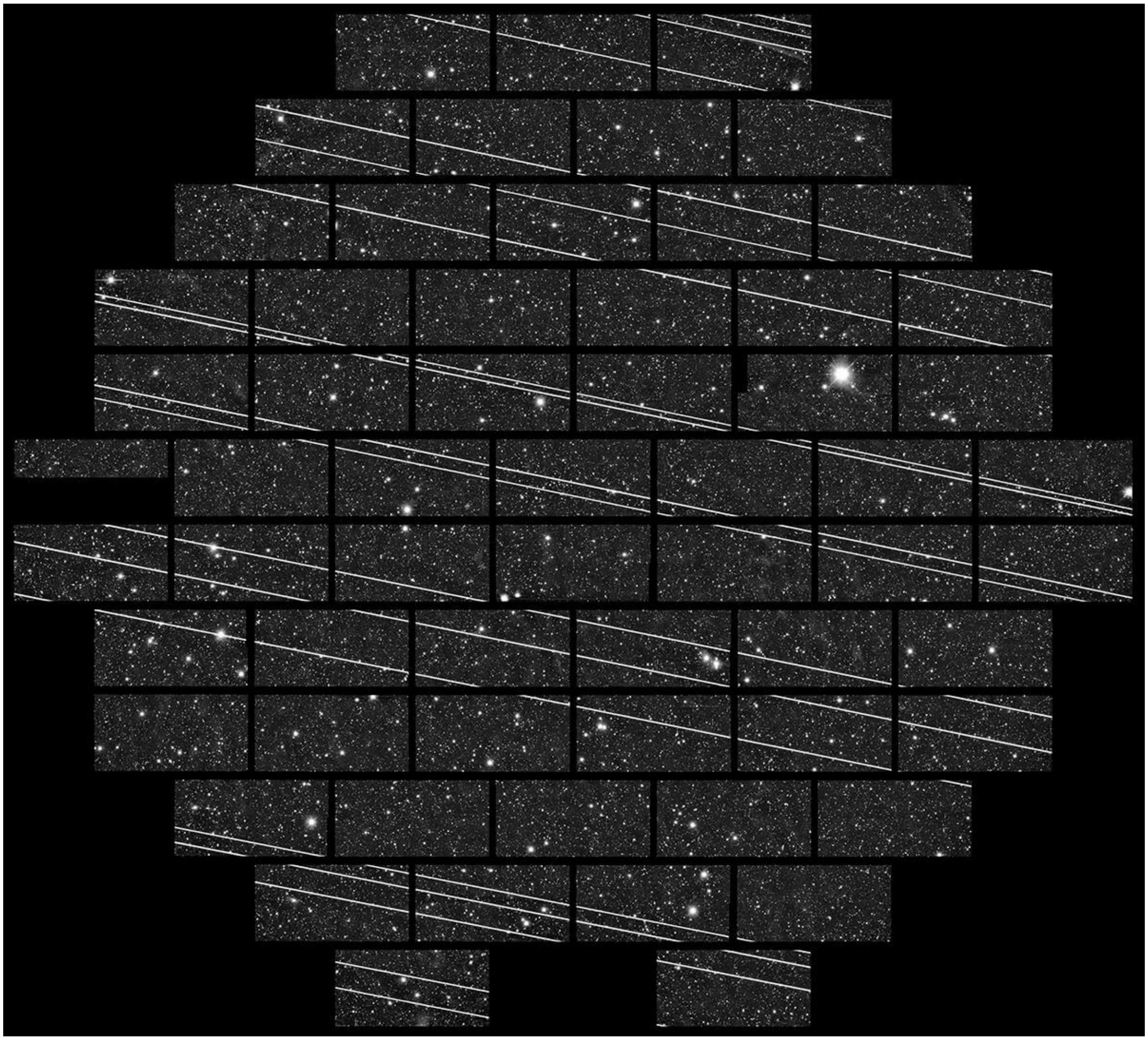

Figure A.1. A wide-field image (2.3 degrees across) from the Dark Energy Camera on the Víctor M. Blanco 4-m telescope at the Cerro Tololo InterAmerican Observatory, on 18 November 2019. Several Starlink satellites crossed the field of view. Image credit DECam DELVE Survey/CTIO/AURA/NSF.

B. Introduction

There are generally two reasons to observe satellites now and in the future: 1) to characterize the satellites and their behavior, and 2) to assess and understand their impacts on current and future science. While there is a growing awareness in astronomy of the need for these observations, to date they have been few and relatively uncoordinated. The primary finding of this report is that an organized, coordinated effort going forward is needed.

Satellite brightness is dynamic and highly dependent on numerous parameters. A single observation and photometric measurement is not sufficient to fully characterize the satellite's brightness. The same satellite may appear significantly brighter or dimmer at a different time or even to a different observer at the same time but different geographic locations.

To first order, a satellite can be considered as a simple uniform sphere with purely diffuse reflection. As the satellite's relative position to the observer changes the satellite's apparent brightness changes, e.g. increased range decreases brightness, reduced phase angle increases brightness. However, the reality is much more complicated. Satellites are not uniform spheres and have many surfaces with various levels of specularity. In addition to the relatively simple orbital geometry, we must consider satellite structure and attitude. In some cases minute changes in satellite orientation yield dramatic changes in apparent brightness. Thus, in order to characterize satellite brightness, we must measure the photometric brightness in a variety of geometries and orientations.

C. Observations Details

Technical Challenges

Making accurate photometric measurements of LEOsats includes a number of challenges:

- The lower altitude LEO satellites (i.e. <600km) are only observable for a short time (1-3 hours, depending on season) after sunset and before sunrise while they are still illuminated
- The satellites are fast-moving; ~0.5 degrees per second (varies with geometry)
- Need precise telescope control including pointing and timing

Planning and Predicting

Tracking satellites and predicting their positions is a mature science led by the US Space Command which maintains a catalog of objects in orbit and actively tracks over 17,000 objects. Satellite trajectories are published in a format called a Two Line Element set (TLE) which is a standardized set of two 70 character strings which include the orbital elements and time epoch needed to calculate the position of a satellite at any point in time. Due to uncertainty in the orbital propagation, the predictions from a given TLE become less accurate with increasing time from the original epoch.

TLEs generated by the US Space Command are publicly available on SpaceTrack.org. Other third-party publishers distribute the same TLEs and some from other sources. One source of note for Starlink TLEs is Celestrak, which coordinates with SpaceX through SpaceTrack to utilize first-party telemetry data to compute Supplemental TLEs.

There are numerous software tools and code libraries available to calculate a satellite ephemeris from a TLE. Some tools make approximations and are not as accurate as others. For many satellites these differences are minor and inconsequential; however, for LEOsats these errors are more prominent. The best software tools utilize the same SGP4 orbital models which are used to originally create the TLE. One such tool is a Python library called Skyfield (https://rhodesmill.org/skyfield/).

When directly overhead, Starlink satellites can move with an apparent angular velocity up to ~0.78 degrees per second when at their nominal 550 km orbit. Shortly after launch and during the orbit-raising phase the Starlink satellites can move much faster, up to 2 degrees per second. Successfully capturing an image of a Starlink satellite requires an accurate ephemeris calculator and precise timing. A timing or clock error of just one second may result in a missed observation for even wide-field imagers.

Observing Techniques

There are two possible techniques for imaging satellites. One technique is to drive the telescope to track the satellite. If well-tracked this method results in higher sensitivity for detecting the satellite and produces more data as the satellite can be imaged many times during the course of its flyover pass. If a high-speed camera is used it is possible to produce high-time-resolution data and record events like flares and glints.

Tracking on a fast-moving LEOsat is very difficult and requires a high-performance mount. Additionally, since the telescope is tracking the satellite, the background stars become trailed making relative photometry difficult to do accurately.

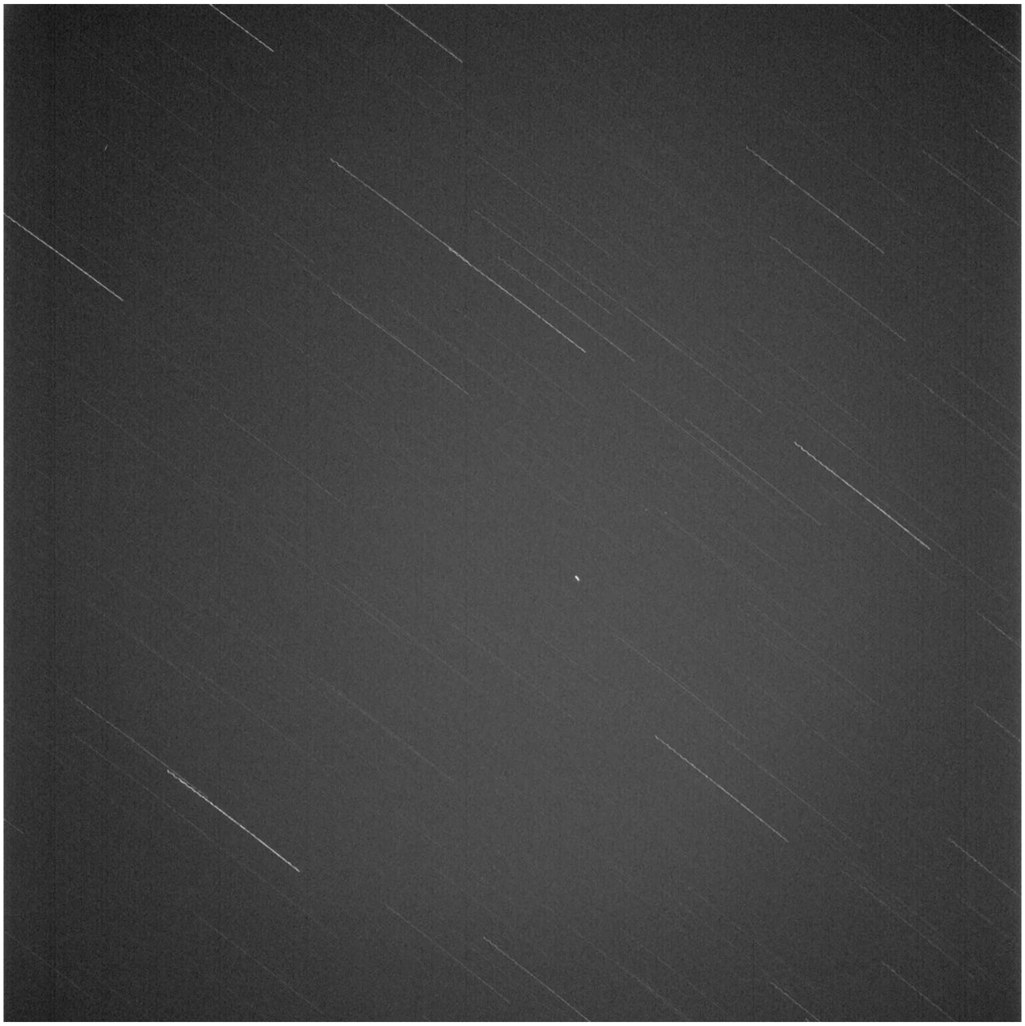

Figure A.2. Starlink-1130 being tracked by the Pomenis Observatory on 16 May 2020. The background stars are severely trailed and often overlap making relative photometry very difficult to do accurately.

The second option is called Wait and Catch. The telescope is pointed to where a satellite will be and tracks sidereally. Then the camera is triggered to catch the satellite as it flies through the FOV. This results in a trailed satellite and static background stars. For the most accurate and easiest to process data, the entire satellite trail should be visible within the image. If the entire trail is in the image frame, then the summed flux for the entire trail has the same exposure time as the background stars. If the entire trail is not in the image then the summed flux cannot be directly compared to the background stars. It is possible to compute the satellite's angular velocity from the orbital elements and determine the effective exposure time (e.g. Tregloan-Reed et al. 2020) though this method introduces a source of error which could be significant.

Fortuitously, a trailed satellite image contains very high resolution time-domain data albeit over a short duration of time. Even this short time is enough to capture some transient events like glints and flares, and possibly glean information about the satellite's orientation and reflectivity.

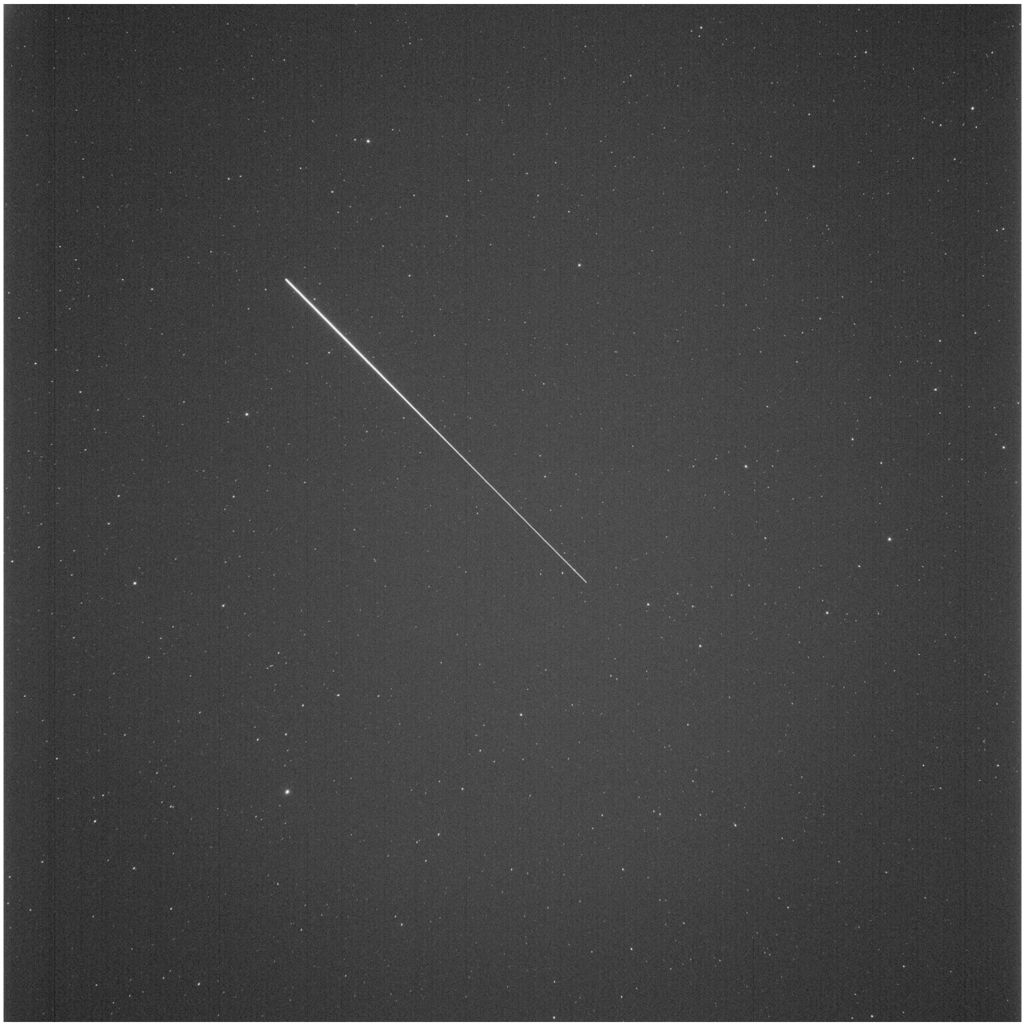

Figure A.3. Starlink-1352 exhibiting a flare event on 7 June 2020. Image by the Pomenis Observatory.

D. Observations to Date

This section details photometric measurements made of Starlink satellites by a few professional observers.

Pomenis Observatory (University of Arizona)

The Pomenis Observatory is a unique system that was developed specifically to perform synoptic surveys of Earth satellites such as Starlink. The 180 mm Takashi astrograph provides a 4.2 x 4.2 degree FOV on a 3056 x 3056 CCD imager with a 7-color filter wheel. The system is fully robotic and automated, allowing for remote operation and intelligent automated observing. The telescope is housed in a unique portable trailer-mounted enclosure allowing for relocation for different projects or observing programs. The Pomenis Observatory is most often located at the summit of Mt Lemmon near Tucson, AZ.

The wide FOV and robotic operation of Pomenis make it particularly capable of imaging fast-moving satellites like Starlink. Pomenis can image dozens of Starlink satellites every clear night, limited only by the overhead between targets, i.e. camera readout and slew time.

Planning Starlink observations with Pomenis utilizes a custom Python software program[1]. This program relies on the Skyfield code library for ephemeris calculation. The software downloads the newest Starlink TLEs from Celestrak and computes all the observable satellite passes for the forthcoming night. To be observable, a satellite pass must be above the horizon limit (20 deg) and be illuminated by sunlight, i.e. not in shadow. After determining all the observable passes, the software selects a subset of these to observe based on time availability and overhead needed between observations. The software outputs an ACP observing plan, a script which the Pomenis telescope uses to autonomously observe the satellites. The software is currently configured to image the satellites at the peak of their flyover pass.

Pomenis has observed Starlink satellites on a limited basis since February 2020 and began nightly observations in late May 2020. The entire system now runs autonomously including planning observations, recording images, and processing data. The current observations are 3-second exposures through the V filter.

On many nights it is possible to image every Starlink satellite that flies overhead including all members of a given satellite constellation train. Due to sensitivity and image processing limits, Pomenis struggles to capture meaningful data for Starlink satellites dimmer than 8th magnitude.

[1] This software package is currently available for download on Github. https://github.com/harryk333/StarlinkPassPredictor

Figure A.4. Starlink-1212 as imaged by the Pomenis Observatory on 23 May 2020.

Figure A.5. Starlink-1021 (top) and Starlink-1049 (bottom) as imaged by the Pomenis Observatory on 20 Feb 2020. Although these two satellites are at the same range and flying side-by-side, 1049 is significantly darker. This is likely due to differences in orientation at the time of observation and demonstrates how large an impact orientation has on the apparent brightness.

Ckoirama Observatory (Universidad de Antofagasta)

The Ckoirama observatory is located in Atacama Desert in northern Chile. It is owned and operated by the Centro de Astronomía (CITEVA), Universidad de Antofagasta, Chile. The observatory contains the Chakana 0.6m telescope, equipped with a FLI ProLine 16801 camera. The filter wheel contains three scientific filters: Sloan g' (475.4 nm), r' (620.4 nm), and i' (769.8 nm). The CCD covers a field of view of 32.4 × 32.4 arcminutes with a pixel scale of 0.47 arcsec pixel^{-1} (Char et al. 2016).

In early March 2020 the Chakana 0.6-m telescope was used to observe two Starlink LEOsats, Starlink-1113 and Starlink-1130 (DarkSat). The observations were performed on three nights, with a different filter on each night (see Figure A.6). The objective of the observations was to measure the reduction in reflective brightness of DarkSat as a function of wavelength.

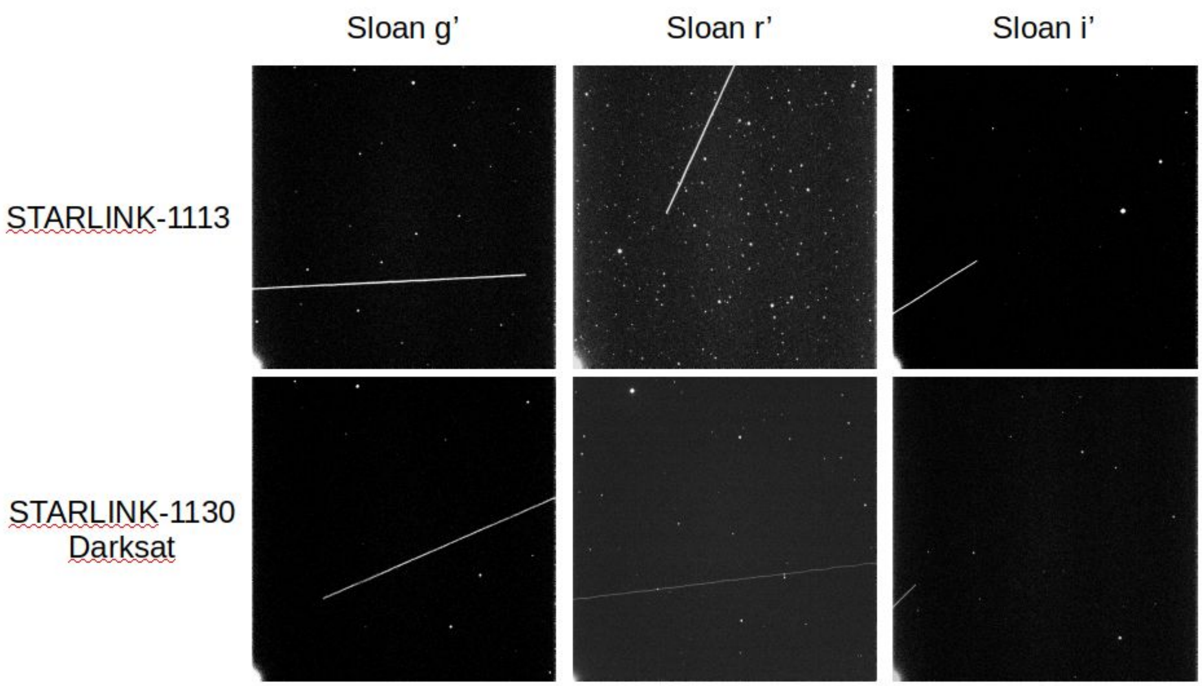

Figure A.6. *Starlink*-1113 and 1130 (DarkSat) observed from Ckoirama, Chile on 5 March 2020 (Sloan r'), 6 March 2020 (Sloan g') and 7 March 2020 (Sloan i'). Due to physical pointing restrictions at the Chakana telescope, it was only possible to just catch a small section of the satellite trails for the Sloan i' observations.

Prior to the Chakana observations a satellite telemetry code was developed to determine the ephemerides of the satellite and of the Sun, using the coordinates of the observatory. The telemetry code downloads the latest TLEs from Celestrak. The code is written in Python and makes use of the Pyorbital package from the PyTroll project.

VIRCam, VISTA 4m telescope (ESO paranal observatory)

VISTA (Visible and Infrared Survey Telescope for Astronomy) is a 4-m class telescope designed for wide-field surveys in the southern hemisphere. The telescope is situated at ESO's Cerro Paranal Observatory in Chile. The telescope is equipped with VIRCam (VISTA InfraRed CAMera). VIRCam has a 1.65-degree diameter field of view with a mean pixel scale of 0.339 arcseconds pixel^{-1}. The camera has five broad band filters Z, Y, J, H, and Ks along with three narrow band filters. Each ‘footprint’ consists of 16 images from the 16 CCD chips. A standard observation consists of five ‘footprints’, with a slight dither. This allows for objects which fall in the gaps between each chip to be observed at least once. Once the raw data have been collected they are processed by the calibration pipeline at Cambridge Astronomy Survey Unit (CASU).

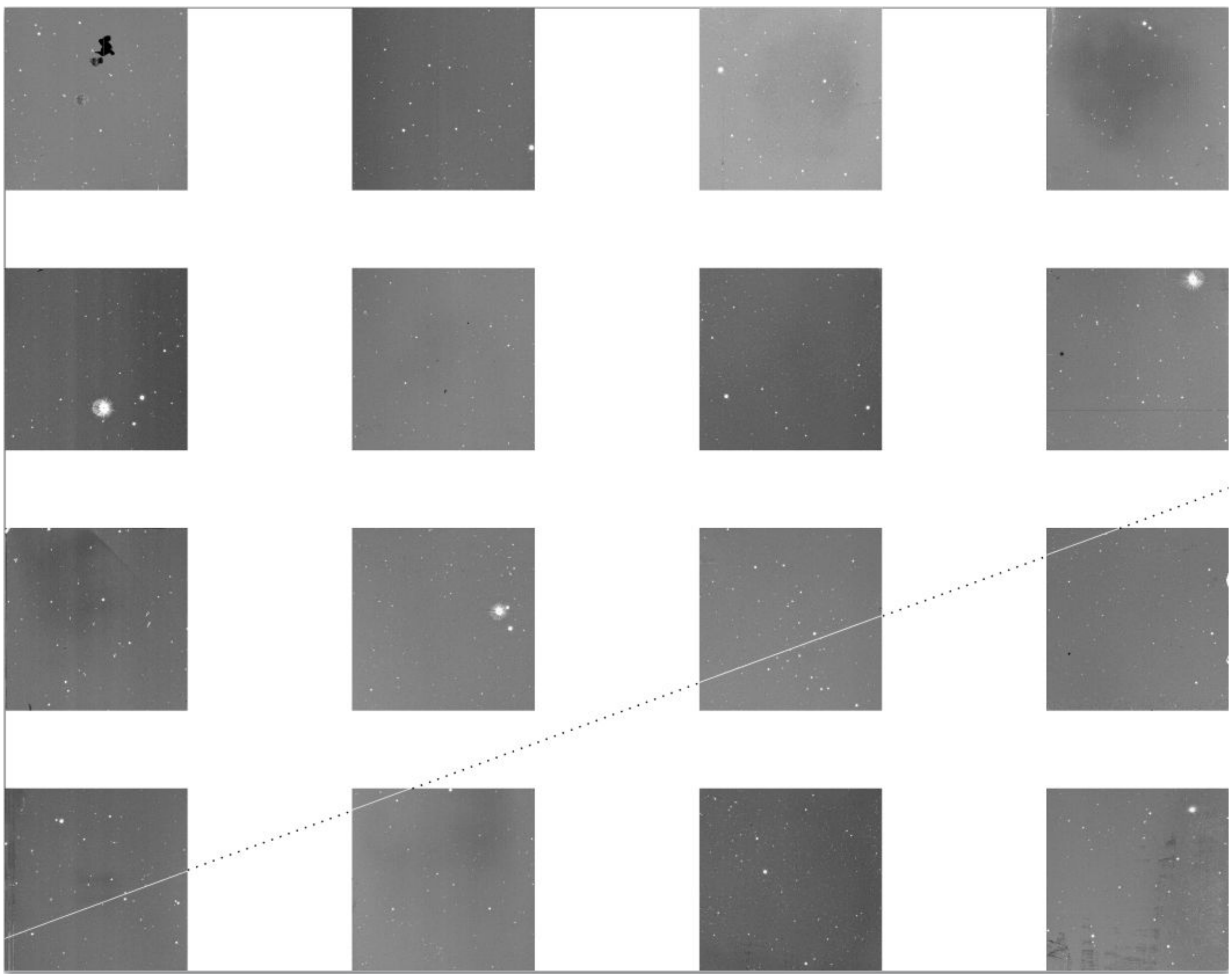

Figure A.7. NIR image of *DarkSat* taken using a J filter with VIRCam on the 4m VISTA telescope, ESO Cerro Paranal Observatory, Chile. The 16 CCD images (11.6 x 11.6 arcminutes) are arranged in geometric order and the gaps between the detectors are to scale. With the horizontal and vertical gaps between the detectors corresponding to 10.4 arcminutes and 4.9 arcminutes, respectively. The dotted line represents the satellite trail falling within the detector gaps.

On the evening (local time) of 5 March, VIRCam was used to observe both Starlink-1113 and Starlink-1130 (DarkSat) (see Figure A.7) in the NIR J-band (1250 nm), while on the evening (local time) of 7 March, both LEOsats were observed in the NIR Ks-band (2150 nm). The observations were in conjunction with the observations at the Ckoirama observatory, to obtain magnitude measurements of a standard Starlink LEOsat and DarkSat across a wide wavelength range, from the optical to NIR.

Víctor M. Blanco 4-meter Telescope DECam g-band (CTIO)

The Dark Energy Camera (DECam) is a 60-CCD wide-field visible imager on the Víctor M. Blanco 4-meter Telescope at Cerro Tololo Interamerican Observatory in Chile. It is one of two main precursor instruments used for verifying and validating the LSST Science Pipelines by Rubin Observatory Data Management. Tyson et al. 2020 (https://arxiv.org/abs/2006.12417) obtained about 30 minutes of observations of Director's Discretionary Time as part of the DECam Local Volume Exploration (DELVE) Survey on the night of 5–6 March 2020, about 1 hour after sunset. The five 120-second exposures in g-band were timed to image five Starlink satellites transit near zenith. All five Starlinks were launched in January 2020, and one of them is DarkSat (Starlink-1130). Using the LSST Science Pipelines, Tyson et al. (2020) reduced the data and measured airmass-corrected (zenith-extrapolated) stationary satellite magnitudes. They also report solar phase angle, stellar PSF, background surface brightness, average satellite trail profile FWHM, raw trail surface brightness, satellite angular speeds, exposure-time-corrected trail surface brightness (with satellite velocities computed assuming a 550 km circular orbit), stationary trail magnitude (before and after airmass correction), derived distance between the telescope and the satellite, and derived approximate size of the satellite. For more details on the analysis, please see Tyson et al. (2020), Section 6.

The main conclusion from this analysis is that DarkSat is 6.1 g mag AB at zenith while its four siblings are all around 5.1 g mag AB at zenith. (See Figure A.8.) In addition, the satellite trail is wider than the stellar PSF, because satellites at 550 km altitude are out of focus. The trail width is also a function of the telescope's primary mirror size, so the same Starlinks observed with Rubin Observatory's 8.4-m mirror would result in trails that are even wider.

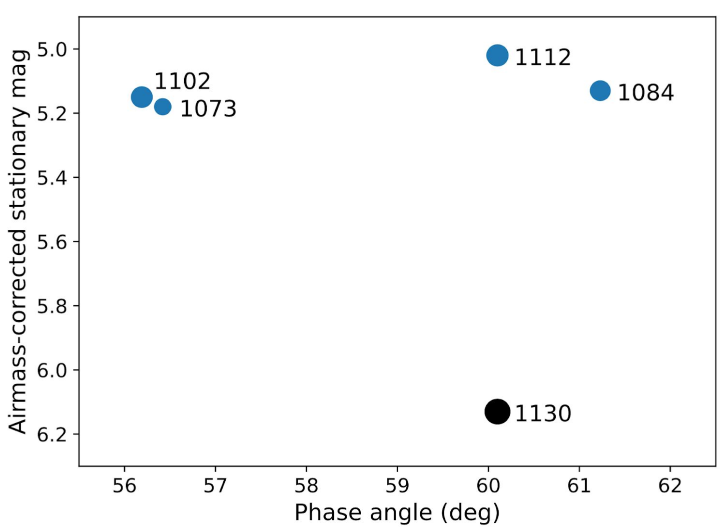

Figure A.8. Apparent stationary *g* band magnitude of five recent Starlink satellites in the "on station" main operational phase extrapolated to zenith as a function of solar phase angle. DarkSat (black) was measured to be 1 mag fainter than its four bright siblings launched in January 2020 (blue), which are in turn about 0.5 mag fainter than the older v0.9 Starlinks. Measurement errors are the symbol sizes. (Tyson et al. 2020)

E. Data Analysis and Results

Processing satellite images for photometric measurements presents a number of challenges. Depending on the observational method, either the satellite or the background stars will be trailed. Trailed sources complicate photometric processing and require either manual intervention or sophisticated algorithms to identify the trails. One complication with trailed sources is overlap between sources.

Pomenis Image Processing
The Pomenis images of Starlink satellites are autonomously processed with a custom Python software package. This software package utilizes many Astropy code libraries and algorithms to perform the image processing steps. The software performs a simple image calibration with bias subtraction, flat field correction, and background subtraction; due to the short exposure time (3 sec) dark current subtraction is not necessary. Sources in the image are detected with Photutils Image Segmentation algorithm.

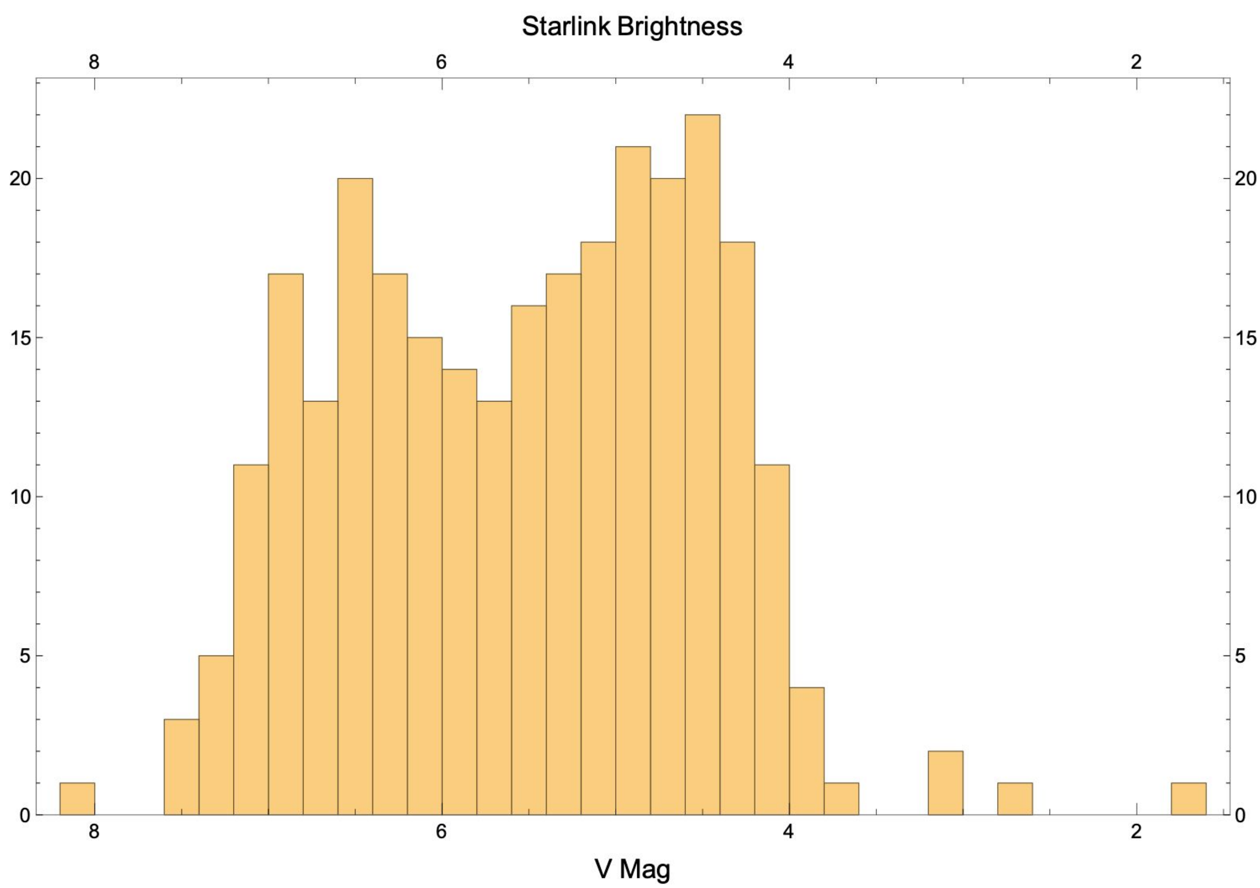

Figure A.9. A histogram of 281 visual magnitude measurements of Starlink satellites imaged by the Pomenis Observatory in late May and early June. The mean of all 281 measurements is 5.5 with a standard deviation of 1.0. This broad distribution of values demonstrates the varied brightness of Starlink satellites which depends on numerous geometric factors.

One challenge in autonomously processing the images is correctly identifying the target and encapsulating the entire trail. Fortunately, the trail inherently covers many more pixels than background stars and is easily differentiated via that measure. However in the event that more than one satellite trail is in the image, there is no easy way to determine which is the target and which is not. Additionally, if the target trail is very faint the source detection algorithm may not identify the trail as a single contiguous source or not detect the trail at all. These issues may be solved with more complex logic and algorithms but currently, if the software is uncertain which source is the target, it rejects the image.

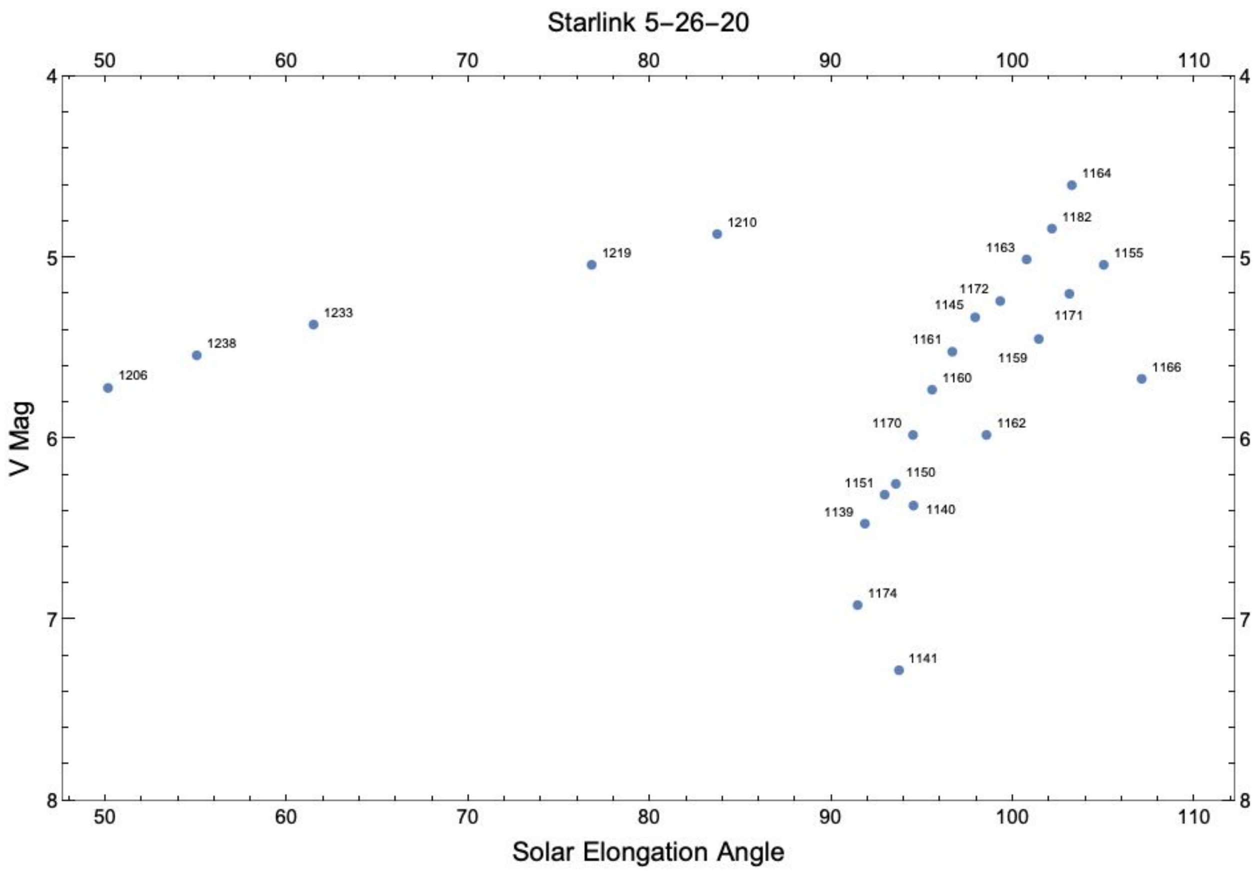

Figure A.10. The visual magnitudes of 25 Starlink satellites imaged by the Pomenis Observatory on the evening of 26 May 2020 (with no darkening or sun shading). Plotting the magnitude against the solar elongation angle shows the dependence of satellite brightness on elongation. Solar elongation angle is defined as the Sun ---> Observer ---> Target angle, with the Observer at the vertex. The maximum elongation angle is 180 degrees, when the target is directly opposite the Sun. It is important to understand that this is only one of many factors that must be untangled to characterize the satellite constellations. It should not be confused with the solar phase angle, which is the Sun ---> Target ---> Observer angle, with the Target at the vertex. The minimum phase angle is 0 degrees, when the target is directly opposite the Sun. [Krantz, private communication].

As part of source detection, the software sums the flux from the pixels which make up each source. After target determination, the software extracts the fifty brightest stars and queries astrometry.net for a plate solution. If a valid plate solution can not be found the image is rejected. Now with WCS information, SIMBAD is queried to identify the ten brightest stars and return reference magnitude values. If there are multiple catalog stars close together at a source's location, the stars' magnitudes are summed together. Then the zero magnitude flux is calculated for each reference star based on the reference magnitude and measured flux. Due to a number of factors the determined zero magnitude flux varies between stars. To autonomously guess the correct value, a rejection scheme is used to reject the stars whose calculated zero magnitude flux value is too far from the computed mode of the bunch. Then the mean is taken of the remaining values and used as the reference zero magnitude flux for calculating the target magnitude. Precisely measuring the systematic and statistical errors remains to be done and is non-trivial with the number of error sources and unique image processing. We estimate the current measurements are reliable to at least a 0.1 magnitude level.

Ckoirama and ESO VISTA Image Processing

The raw Chakana images are calibrated by bias subtraction and divided by flat-field. After this apertures were set around selected comparison stars, where the local sky-background was removed for each of the stars. The total integrated flux for each star was then calculated.

Due to the small field of view of the Chakana telescope, the satellite trails crossed the entire image. When examining the point spread function (PSF) of the satellite trails, it can be seen that there is a sharp cut-off between the trails and the sky-background (see Fig.1 *Tregloan-Reed et al. 2020, A&A, 637, L1).* This allows for two straight lines to be fitted along the edges of the trail and the total integrated flux of the trail to be determined. Because the satellite trails were not fully recorded then the estimated trail length for the exposure time was calculated using the angular velocity of the satellite for the given observation time. This then allowed for the estimated total flux of the trail to be calculated and compared to various fluxes of the comparison stars. This then gives the differential magnitude between the LEOsat and the comparison stars, which in turn gives the magnitude of the satellite, once the magnitudes of the comparison stars are determined from the literature (e.g. Two Micron All-Sky Survey, or 2MASS).

The field of view for the VISTA telescope covers a 1.65-degree diameter area of the sky; however, this field of view is made up of 16 different chips each with a field of view of 11.6 arcminutes. This meant that the satellite trail covered more than one chip in each observation. The raw images are then calibrated by the data reduction pipeline at CASU and the individual pawprints are made available. Each calibrated image is then analyzed using the same methodology as the Chakana images.

Ckoirama and VISTA Data analysis

Once the magnitudes of DarkSat and Starlink-1113 had been determined, they required normalizing to a standard range, solar and observer phase angles. This allows a direct comparison of the effectiveness of the DarkSat :darkening treatment: for each wavelength. We set the normalized position to be the local zenith (airmass = 1.0) of the observer. At this position the range to the satellite is equal to its orbital height (550km). The magnitude can be scaled by +5 log(r/550), where r is the range of the satellite at the time of the observation.

The solar phase angle (θ) can be computed from the sky positions (azimuth and elevation) of the satellite and Sun at the time of the observation. The telemetry code employed by Tregloan-Reed et al. (2020) automatically calculates the solar phase angle for both the satellite and local zenith for the time of the observation. The observer phase angle (φ) is defined as the angle between the observer and the unit normal of the Earth-facing surface of the satellite and is approximated by:

$$\phi = \arcsin\left(\frac{\eta}{H_{\mathrm{orb}}} \sin\alpha\right)$$

where η is the straight line distance between the observer and the satellite footprint (nadir), H_{orb} is the orbital height, and α is the elevation.

For a complex body like a LEOsat it is difficult to model the effects of the solar and observer phase angles. However, the effects can be approximated by using a Bidirectional Reflectance Distribution Function (BRDF). Without empirical measurements of the LEOsats BRDF, an estimated ratio of the solar phase attenuation between DarkSat and Starlink-1113 was done using a parameterized BRDF model from (*Minnaert, M. 1941, ApJ, 93, 403*).

$$R = \left(\frac{\cos\theta_{1130}\cos\phi_{1130}}{\cos\theta_{1113}\cos\phi_{1113}}\right)^{k-1}$$

where k is the Minnaert exponent and can simulate a dark surface by setting k = 0.5 (Stamnes, et al. 1999).

The resultant ratio of the solar phase attenuation is in agreement with the first-order approximation of the solar phase attenuation for a diffusing sphere, (1 + cos θ)/2 (Hainaut & Williams 2020).

The results (see Table 1) from normalizing the range and both solar and observer phase angles to local zenith indicate that the darkening treatment employed by Starlink has reduced the reflective brightness of DarkSat. The effectiveness of the darkening treatment though reduces with increasing wavelength and both DarkSat and Starlink-1113 show increases in reflective brightness with increasing wavelength.

Starlink	Sloan g' Magnitude (475.4 nm)	Sloan r' Magnitude (620.4 nm)	Sloan i' Magnitude (769.8 nm)	NIR J-band Magnitude (1250 nm)	NIR Ks-band Magnitude (2150 nm)
1113	5.33 ± 0.05	4.88 ± 0.05	4.41 ± 0.04	3.93 ± 0.01	3.62 ± 0.02
1130 (DarkSat)	6.10 ± 0.04	5.52 ± 0.07	4.94 ± 0.05	4.25 ± 0.01	3.87 ± 0.02

Table 1. Normalized magnitude measurements of Starlink-1113 and 1130 (DarkSat). Sloan g' (Tregloan-Reed et al. 2020). NIR, Sloan r' and Sloan i' (Tregloan-Reed, in preparation).

DECam image processing and satellite trail analysis
As described in Tyson et al. (2020), the LSST Science Pipelines were used to construct master biases, and master flats, and to perform standard image reduction steps (instrument signature removal, PSF measurement, background characterization and subtraction, and astrometric and photometric calibration with Gaia and Pan-STARRS, respectively). Once these calibrated exposures were available, the satellite trail brightness was measured in python using tools from Scipy, Astropy, and the LSST Science Pipelines. The steps are: load processed image data, select a single CCD with a suitably long trail, get Sun location and phase angle, rotate the image so the trail is horizontal, measure the raw trail brightness, account for the image exposure time, compute and account for the satellite angular speed, and finally estimate the distance to the satellite and derive its approximate size. This workflow is fully public and available at https://github.com/dirac-institute/starlink. The final results are given in Table 2 of Tyson et al. (2020). The same workflow was used to analyze a single image taken by Subaru's HSC which serendipitously included a satellite trail. (See Appendix C for details.)

Other satellite constellations will have similar impacts. For instance, OneWeb satellites are approximately V_{mag} = 8 in their 1200 km orbits. At that distance, they will have approximately 2x slower angular velocity and thus an impact similar to the 7th magnitude satellites at 550 km.

F. Lessons Learned

The Starlink satellites range in brightness by several magnitudes and depend on a multitude of factors. These include air mass, range, solar phase angle, line-of-sight angle, satellite orientation and wavelength.

The impacts of some of these factors, such as air mass and range, are easily understood, modeled, and predicted. The impacts of other parameters are more difficult to predict. All the parameters together are difficult to untangle.

Characterizing the brightness of a satellite constellation like Starlink cannot be done with a few measurements. Nor can mitigation efforts be properly tested with a few measurements on specific satellites. In order to fully characterize the satellites, many measurements are needed in all geometries. With many measurements, the impactful parameters can potentially be untangled yielding a better understanding of the satellite constellation as a whole and its impacts on science.

A particular Starlink satellite is typically only visible to a single observing site for a couple of nights every two weeks. This makes it impossible for a single observer to adequately characterize satellites due to geographic biases or effectively follow them during the orbit raising period which lasts 2-6 weeks.

G. Future Observations

1. Goals and Expectations

The ultimate goal is to characterize the brightness of LEOsat constellations, such as Starlink, and test the effectiveness of mitigation efforts to reduce their impact on astronomical observations.

Precisely measuring the brightness of a small number of satellites is not particularly useful due to the previously discussed variability in brightness and uncertainty in the multitude of determining factors. Observing many satellites in a wide variety of geometries and scenarios will be more effective at producing a statistical picture of the satellite brightness and unwinding the underlying factors.

A survey style observing program is likely the best path forward. Beyond observing as many satellites as possible, observing timings, geometries, and techniques should be informed by modeling and desires to test particular mitigation efforts.

Due to the limitations in visibility and observing geometry, having a network of observing sites spread out geographically will more rapidly fill in the statistical picture.

The tools for observing Starlink satellites are just as applicable to other satellites. While Starlink is the pressing need at the moment, observing programs should sample other LEOsats and upcoming satellite constellations such as OneWeb.

2. Plans and Possible Observation Coordination/Networks

Coordinating observations at multiple sites

There won’t be a huge benefit to coordinating observations versus each site independently planning their own. Exceptions would be focusing observations at different wavelengths on particular satellites like Visorsat, in order to characterize their effect on the acquisition of new astronomical datasets, or having particular observatories focus on imaging at certain phase angles, though typically observatories will be at the mercy of what satellites are visible to them. However, see “Software Tools” below.

Data Sharing

A data-sharing scheme would be ideal for compiling the most complete picture of the satellite constellation at a variety of geometries. This could be centralized or not.

Software Tools

Software for planning observations or processing images can be shared among observers or made entirely public. Some of these tools, like the observation planning, could be made into a web app which observers can use to easily determine which satellites will be visible at their site. One example that is already available is the ASTRIAGraph system[2] (Esteva et al. 2020), which combines information on satellite positions from a number of sources and provides a browser-based interface for users to search and visualize this information. An Application Programmable Interface (API) for the system is under development, in collaboration with the TOM Toolkit Project[3] (Street et al. 2018). TOMs, or Target and Observation Manager systems, are database-driven programs for planning and running astronomical observing programs, and the TOM Toolkit aims to make these systems easy for users to build and customize for their science. By collaborating with ASTRIAGraph, the Toolkit will provide user-side API query tools to interface with the ASTRIAGraph system and integrate visualizations of the resulting data such that users will be able to plan their observations to minimize interference from satellites.

Citizen Scientists

Involving citizen scientists could greatly increase the number and locations of telescopes. Amateur astrophotographers with high-end telescope systems should have little difficulty in imaging the Starlink satellites. The smaller, but wider FOV telescopes commonly used by amateurs are better suited to image LEOsats compared to large professional telescopes. The Pomenis telescope serves as a prime example of this. A citizen scientist program could be limited and informal in nature relying more on the abilities of the observers to utilize the software tools themselves. A widely open program could involve many more observers but would require robust, easier to use web-based tools for planning observations and submitting images for processing.

Archival and Serendipitous Observations

There are numerous automated survey telescopes around the world doing various types of research. Often these are small wide-field instruments that will undoubtedly image satellites accidentally. The same data pipelines and tools used for an intentional observing network should accommodate data from serendipitous observations.

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[2] http://astria.tacc.utexas.edu/AstriaGraph/

[3] https://lco.global/tomtoolkit/

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Appendix B. Technical Report on Simulations on Impacts of Satellite Constellations

A. Summary

Simulations of the visibility of various large satellite constellations have been done by six groups. Details can be found in the main section and in the technical appendix. We define visibility in a geometric sense as the satellite is above the horizon (or a given elevation) and in sunlight while the observatory is in darkness. These simulations can be used as a starting point for estimating the science impact on particular projects. All simulations agree on the following conclusions:

- The fraction of satellites that will be visible at any observatory at any one time is typically around 5%.
    - Higher altitude constellation shells will have a greater fraction visible (7-8%), lower altitude constellations a smaller fraction (4%).
    - Most of these satellites appear at low elevation over the horizon (typically 50% below 10deg).
- The number of satellites visible is a function of their orbital inclination, peaking at a latitude close to the inclination.
- Satellites enter the shadow of the Earth some time after sunset, and re-emerge some time before sunrise. While in the shadow, they are not visible.
    - Typically, about half the satellites visible are still illuminated at the end of the astronomical twilight. More for higher satellites (85% at 1200 km), less for lower satellites.
    - Higher altitude constellations (say at 1200 km) will be visible longer past astronomical twilight and into the darkest part of the night. Some satellites from higher altitude constellations can be visible all night long in summer.
    - For any constellation at 300 km and higher, there will be satellites visible past astronomical twilight at any time of year. How long depends on altitude and time of year.
- The constellation with the greatest impact for any observatory in terms of the number of satellites visible will be one at higher altitude and with an orbital inclination close to the latitude of the observatory.
- For some constellation architectures at 550 km and higher, the number of satellites visible between nautical twilight (Sun at -12 deg elevation) and astronomical twilight (Sun at -18 deg elevation) is only marginally smaller than the number visible at sunset. Significant falloff in the number visible does not occur until after astronomical twilight begins in some cases, particularly at elevations greater than 30 degrees. Yet this bright sky time is most important for Planetary Defense (Near-Earth Object surveys for killer

asteroids), comets close to perihelion, and multi-messenger astronomy (gravitational waves), just to mention some examples.

- The largest uncertainty in our simulations is the number of satellites being launched. Who is going to launch what, when, and where? Not all constellations have to submit public filings with the US Federal Communications Commission (FCC).

Besides computing the global number of satellites visible over a specific altitude, it is also necessary to determine the details of their distribution over the sky. This is a strong function of time and of the direction of observation, and these circumstances determine the possible effect on specific observations. This implies modeling the probability of finding satellites in specific directions (azimuth, elevation), as well as assessing their effects depending on apparent brightness and apparent angular speed. Different simulations and models have been developed that already allow us, for a given constellation, to predict the impact to any observatory using simulations. A model has been developed to extrapolate standard circumstances to arbitrary ones (field of view, integration time), through lookup tables. There are promising prospects to produce, in the near future, a software package based on analytic functions that may allow a realistic assessment of the impact to observations, including, for a given observatory, field of view and integration time: number of trails expected, apparent brightness, apparent angular speed and position angle of the trail.

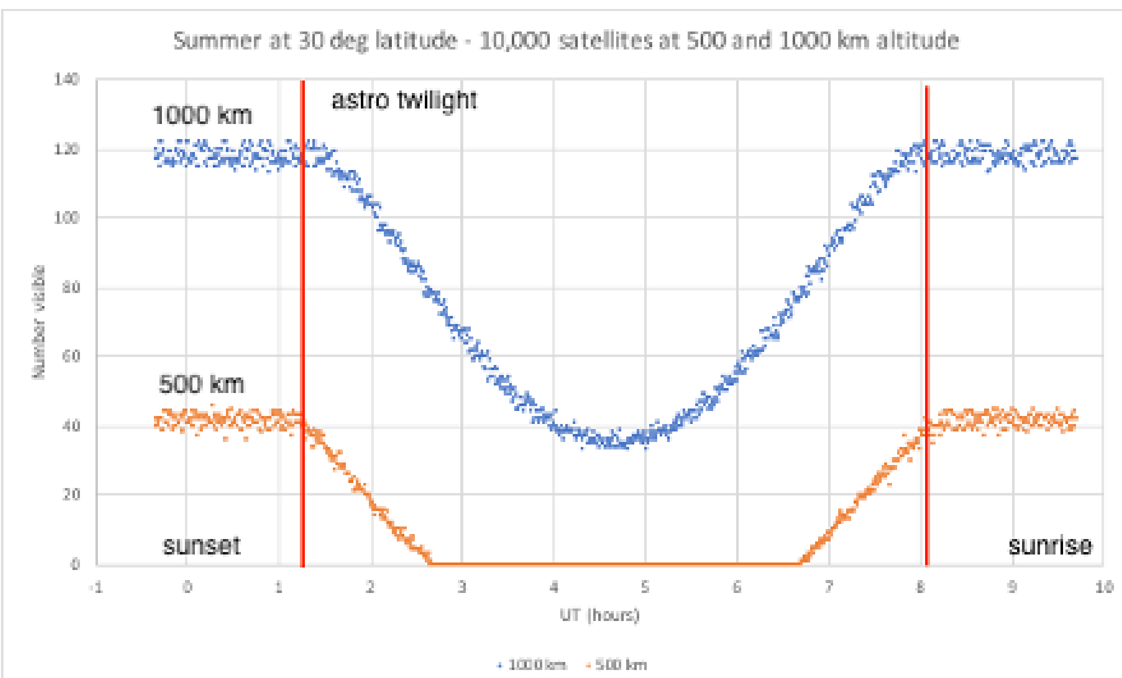


Figure B.1. Example of visibility of two identical constellations of 10,000 satellites each — one at 500 km altitude and the other at 1,000 km altitude. The plot runs from sunset at the left to sunrise at the right. The lower altitude constellation is not visible during the summer at an elevation of 30 deg (typical astronomical limit of airmass = 2 or less). But it may be visible closer to the horizon at high latitudes.

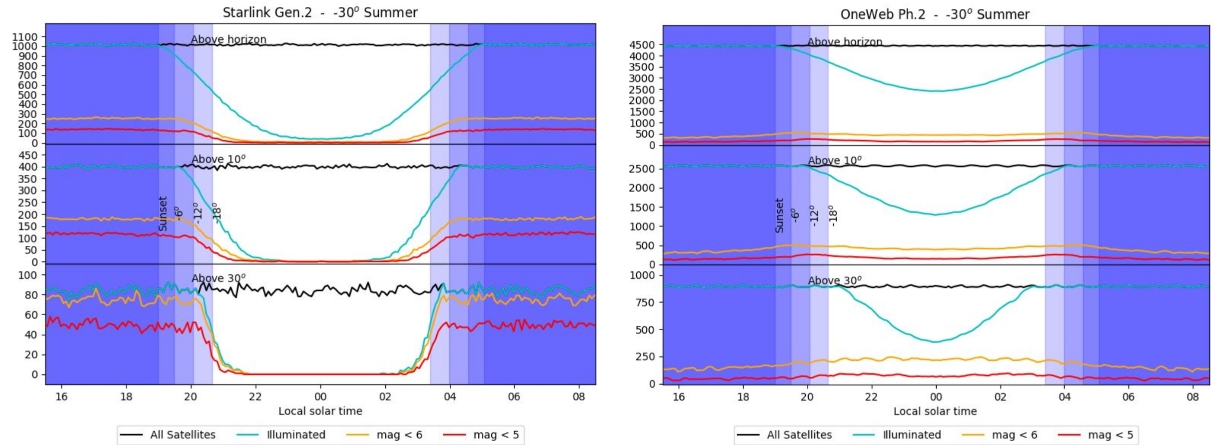


Figure B.2. Visibility of the proposed Starlink Generation 2 (left, 30 000 satellites mostly around 350km altitude) and OneWeb Phase 2 (right, 50 000 satellites at 1200km altitude), as seen from Rubin Observatory (30deg latitude S) at summer solstice. Top panels are for all satellites in sight, middle for satellites above 10deg elevation, and bottom, above 30deg of elevation (airmass = 2). The effect of altitude is striking: while all Starlink satellites drop in the shadow of the Earth soon after twilight, many OneWeb satellites remain illuminated during the whole night.

B. Recommendations for Future Work

- Simulate the impact on science of these constellations — how often will a specific observation be lost due to a satellite trail, for example.
- Simulate the other two phases of a constellation/satellite lifetime — initial mission phase and deorbit phase.
- High fidelity modeling of observed brightness including the defocus expected for satellites at small ranges.

C. Simulations Working Group Report

Optical and infrared astronomy will be seriously impacted by the launch of tens of thousands of new bright satellites being launched over the next decade. The purpose of the simulations working group was to quantify the challenge to observational astronomy by estimating the number of such satellites, when and where in the sky they would be visible, and how bright they could be.

According to detailed orbital plans filed with the US Federal Communications Commission (FCC), four of the largest proposed constellations with active filings under consideration are from SpaceX (Starlink), OneWeb, Amazon/Kuiper, and Telesat. If completed in full, the total of new satellites from these four constellations alone would be 82,751 satellites.

Constellation	Altitudes (km)	Inclinations (deg)	# of satellites
OneWeb	1200	40.0–87.9	47,844
SpaceX (Starlink)	328–614	30.0–148.0	30,000
Amazon/Kuiper	590–630	33.0–51.9	3,236
Telesat	1000–1325	37.4–99.5	1,671

Constellations may be managed and launched by way of the administrations of other nations, rather than the United States. All constellations would, however, be coordinated through the International Telecommunication Union (ITU) process. If a project does not want access to the domestic US market, then no filing would be made. Such projects will file with the International Telecommunications Union (ITU) for frequency coordination.

The AGI Corp has presented an animation of 107,000 proposed LEOsats to be launched before 2030. This includes all FCC and ITU filings, plus constellations described in press releases only. The animation is at https://www.youtube.com/watch?reload=9&v=oWB7ZySDHg8&feature=youtu.be

The four constellations in the above table account for more than 75% of the total of 107,000 LEOsats.

Launches have begun of the OneWeb and SpaceX constellations.

Every individual satellite and constellation has three distinct phases during its lifetime:

- Initial mission phase:
    - Launch.
    - On-orbit checkout.
    - Orbit raising to operational orbit.
- Operational phase where the satellite is at its operational altitude and attitude (orientation). The lifetime here could be 5 years or longer.
- Deorbit phase. To be in compliance with space/orbital debris rules, each satellite must be disposed of at the end of mission. The IADC/NASA/ESA guideline is 25 years, but most operators should strive to deorbit much quicker, hopefully within one year.

The simulations that have been done are all for the operational phase of various constellations. We recommend that future work simulations be performed for the initial mission phase and deorbit phase as well. The brightness of the satellites could be very different for all three phases.

In general, we would expect that phases 1 and 3 would be short-lived compared to the operational phase, and the number of satellites in these phases would be a fraction of the number in the operational phase. But this depends on a number of factors:

- OneWeb deployed its first 6 satellites into their final 1200 km orbit. But its next two launches are holding 68 satellites at 600 km, presumably waiting for their financial issues to be resolved.
- In order to deorbit within the 25-year guidelines, satellites at 1200 km must have an active deorbit system. If a satellite fails at 1200 km, then the deorbit time due to natural forces (atmospheric drag, for example) is centuries. A failed satellite could also tumble, resulting in bright flares. The natural deorbit time for a satellite at 600 km is less than 25 years, depending on solar activity and the satellite's drag coefficient.

We define the visibility of a satellite in a geometric sense: the satellite is in sunlight and there is a direct line of sight from the observatory to the satellite. Additional constraints may be imposed, such as above a certain elevation, typically 30 degrees corresponding to an airmass of 2, a usual limit for astronomers. But surveys for Planetary Defense (Near-Earth Objects (NEOs)), transient follow-up, and multi-messenger astronomy (gravitational wave follow-up) may work to a lower elevation limit of 20 degrees.

The factors determining visibility of an individual satellite are:

- Observatory:
  - Latitude.
  - Time of year.
  - Local time.
- Satellite:
  - Altitude.
  - Orbital inclination.
  - Time of year — how much of the orbit is in sunlight.
  - Local time (where the satellite is in its orbit).

The standard figure shows the number of satellites predicted to be visible during the night as a function of time: ranging from sunset to sunrise. Each figure has vertical lines marking the Sun's elevation in the evening and in the morning at three elevations:

- Sun at -6 deg elevation — civil twilight.
- Sun at -12 deg elevation — nautical twilight.
- Sun at -18 deg elevation — astronomical twilight.

In general, the sky is too bright to do anything until nautical twilight begins in the evening. The time between nautical twilight and astronomical twilight is useful for observations of bright objects, NEO surveys for killer asteroids, and multi-messenger astronomy (follow-up of transient events). The time between evening and morning astronomical twilight is the darkest part of the night and the most valuable time for observations of faint objects.

We present a range of simulations showing how the number visible during the night depends on the above. Emphasis is on Rubin Observatory (representative of the observatories in Chile), Maunakea, continental US, and continental Europe (for follow-up Rubin Observatory observations). Our conclusions in the Executive Summary are based on these simulations.

While the algorithms and methods used by different teams are different, the simulations all compute the position of the satellites around the Earth, evaluate which ones are illuminated by the Sun at the time of the observations, and computes the position of the satellites in the sky above the observatory considered.

Number of satellites in sight

The first key result is the total number of satellites in sight, i.e. above the horizon (or another elevation). While this number obviously scales with the number of satellites in the constellation, the altitude is a key factor. As illustrated in Fig. B.3, **2-4% of the satellites from a low-altitude constellation are above the horizon at any time**; that number rises to ~10% for constellations at higher altitudes. **About half of them are below 10 degrees of elevation, clustered around the horizon**. This is just a consequence of the geometry: a line-of-sight close to zenith probes only a small fraction of the constellation, while at low elevation, the line-of-sight peeks through a much thicker region of the constellation, as illustrated in Fig. B.4.

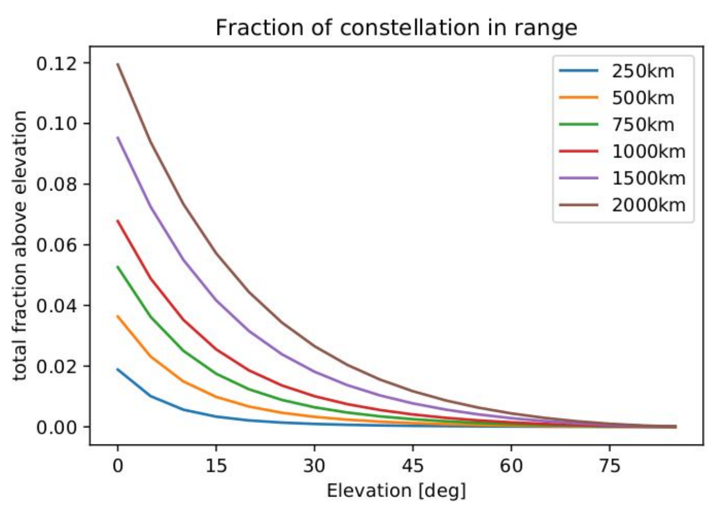


Figure B.3. Fraction of a constellation in sight above a given elevation on the horizon, for various satellite altitudes. (Hainaut & Williams 2020)

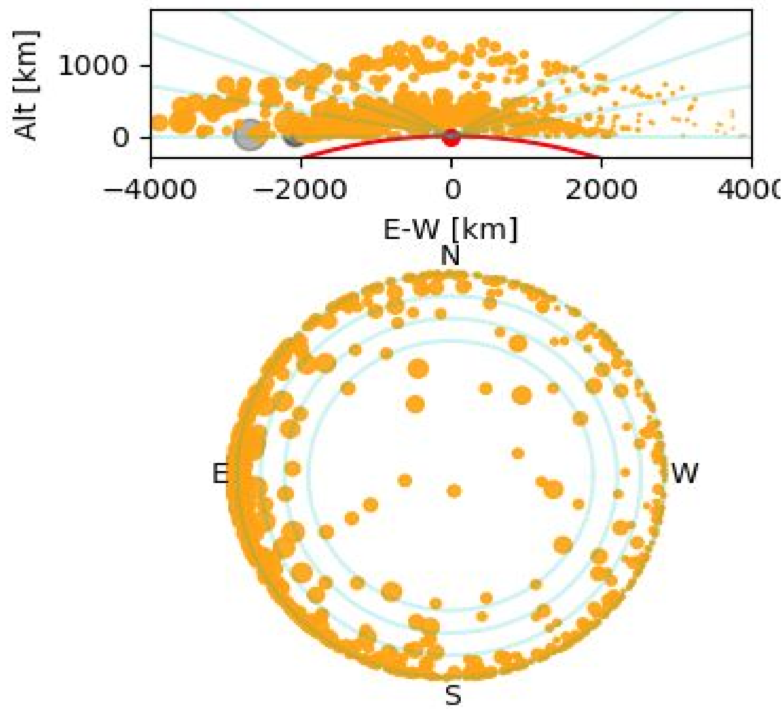


Figure B.4. Snapshot of a constellation, as seen in the sky (bottom) and from the side (top), illustrating that the satellites in sight cluster more densely along the horizon. (Points not to scale.) [Hainaut, private communications]

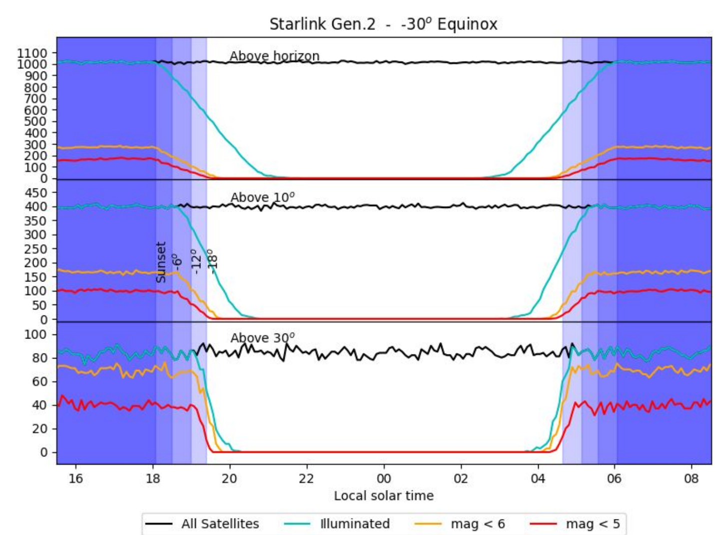


Figure B.5. Number of satellites above the horizon (top), above an elevation of 10 degrees on the horizon (middle), and above 30 degrees (airmass=2, bottom) as a function of the local time. Sunset and twilights are marked by blue shadings. The black curves count all satellites (including non-illuminated ones), the cyan curve the illuminated ones, and the red and orange curves those brighter than magnitude 5 and 6 (estimated using a simple model). [Hainaut, private communications]

Illuminated satellites
Only the illuminated satellites constitute a threat for observations in the visible and near-IR; satellites in the shadow of the Earth are invisible. As the Sun drops below the horizon after sunset, the Earth's shadow will engulf more and more of the satellites. How fast this happens is a function of the altitude of the satellite, of the latitude of the observatory, and of the season (i.e. declination of the Sun). Iterating over a full night, we show the evolution of the number of satellites for different configurations; an example is given in Fig. B.5.

Important characteristics of these curves are the steepness of the drop at twilight, and the duration of the period during which all satellites are all obscured. Steeper curves and a wider obscured period result in a smaller impact on astronomical observations. Figure B.6 compares the summer and winter curves for two constellations.

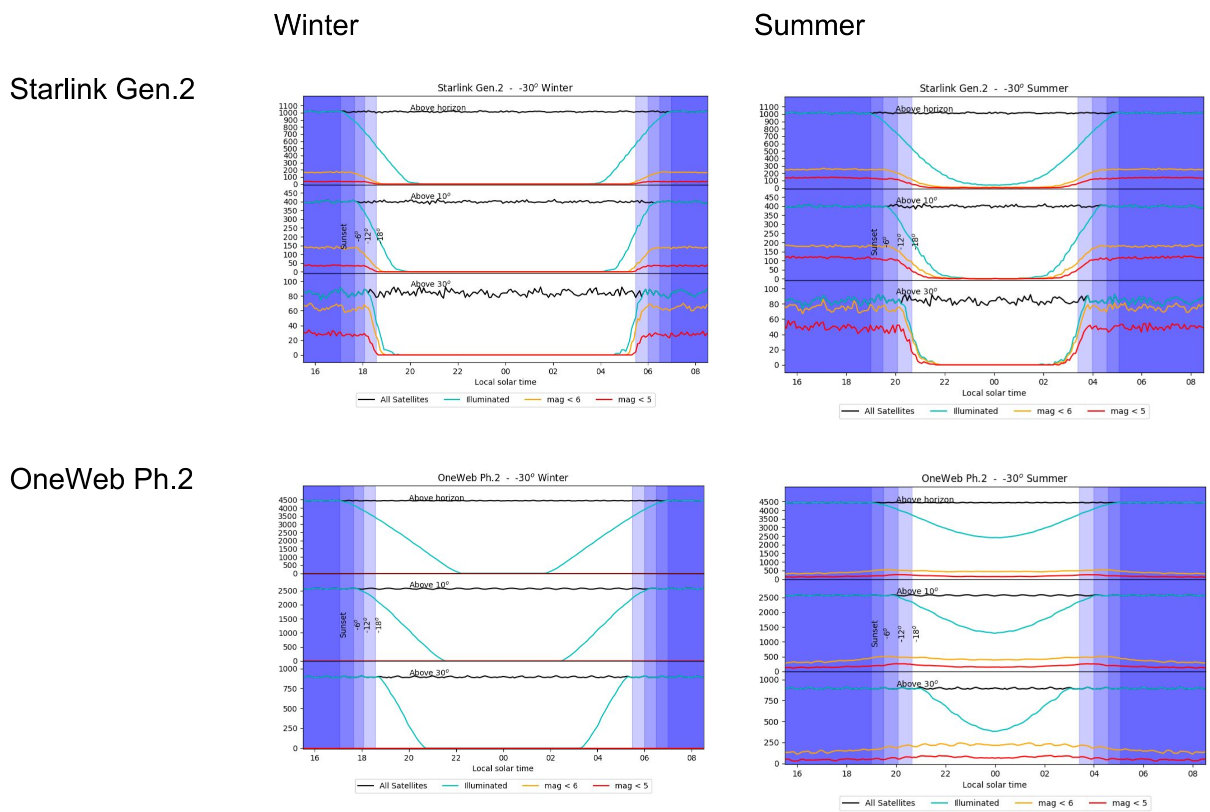


Figure B.6. Nightly count of satellites, as in Fig. B.5, for Rubin Observatory at summer and winter solstices, for the low-altitude Starlink Gen. 2 and OneWeb Ph.2 constellations (low and high altitude respectively). Note the **much steeper curves and wider obscured period for the low altitude satellites.** In particular, note that, for the **high-altitude constellation, a significant fraction of the satellites are visible and illuminated during the whole night.** [Hainaut, private communications]

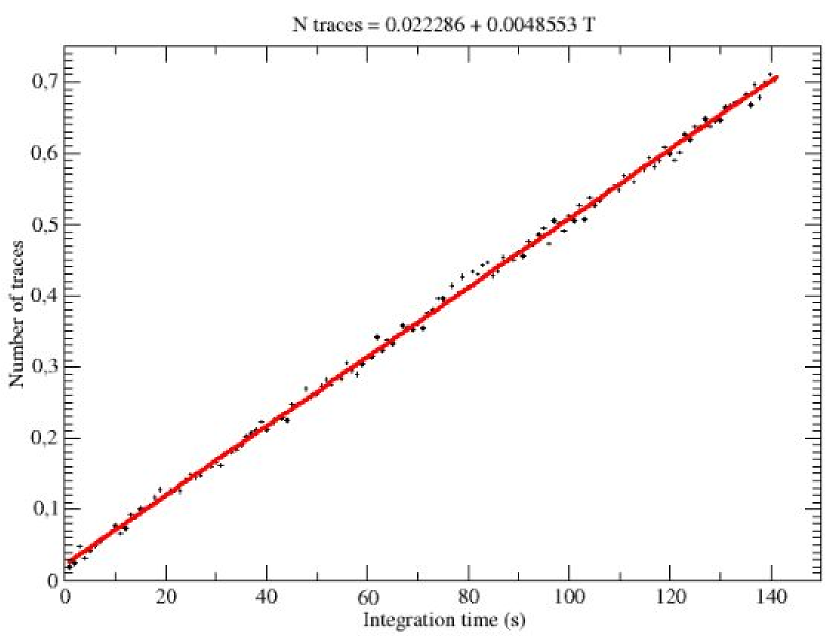
Effect on observations

Various methods are possible to evaluate how the visible satellites will affect the observations. The most straightforward — but computationally intensive — is to pick a point in the sky, run a satellite simulator, step through time for the duration of the exposure, check if a satellite is in the field of view of the instrument, and iterate to get good statistics. An alternative is to compute a map of the density of satellites (D_s) over the sky, and a map of trail density (D_t, number of satellites weighted by their apparent angular velocity). This can be done using a satellite simulator (with the advantage over the first option that it is done for the whole sky at once), or analytically (which is much faster).

The number of trails in an exposure is then given by

$$N = D_s * F^2 + D_t * F * t \quad \text{(Eq.1)}$$

where F is the diameter of the field of view, t the exposure time. Fig. B.7 compares the number of trails obtained using this relation with the number from a direct simulation.



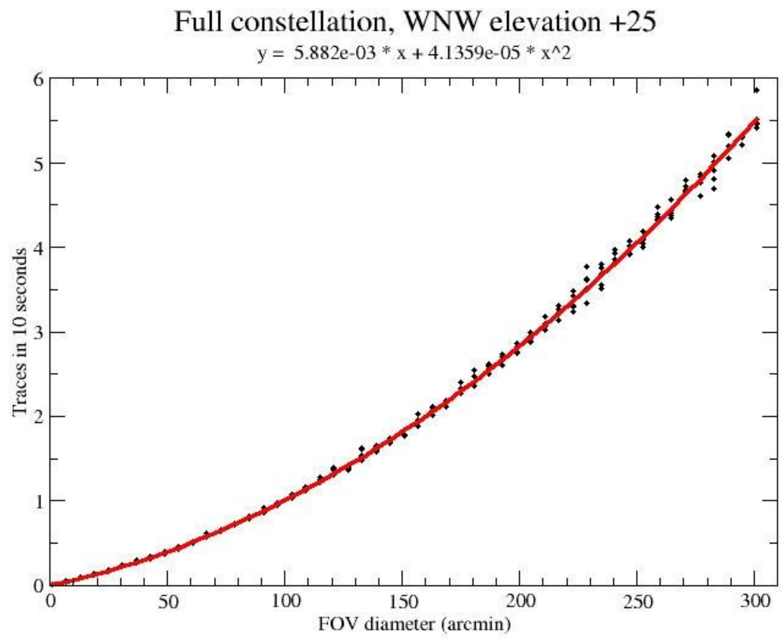


Figure B.7. Above: Count of the number of satellite trails affecting an exposure as a function of the exposure time, for a fixed FOV. Below: Count of the number of satellite trails affecting an exposure of fixed integration time, for increasing FOV. The dots represent a series of direct simulations of observations, while the lines reproduce fits that confirm the model of Eq. (1): linear trend with time (non-null intercept related to satellite density), parabolic trend with FOV (quadratic coefficient related to satellite density, linear coefficient related to trail density). [Galadi, private communications]

Using this formalism, maps can be generated for various times of night and times of year. These maps can be used to estimate the observation losses, or to guide the scheduling of the observations to minimize the interferences with satellites. Fig. B.8 shows an example for Rubin Observatory. The analytical solutions open the possibility of computing them in real-time, e.g. for the scheduling engine of queue observations.

Note the strong concentration of satellites in sunlight towards the south. At this time of year, the Sun is at its southernmost declination, and the shadow cone of the Earth points to the north. ***Observations of the Large Magellanic Cloud (LMC) (declination = -69 degrees) could always have satellite trails from constellations at 1200 km which are always in sunlight at this time of year.***

Detailed modeling of the number of satellites expected as a function of exposure time for a 1 square degree field shows this effect. [Galadi, private communications]

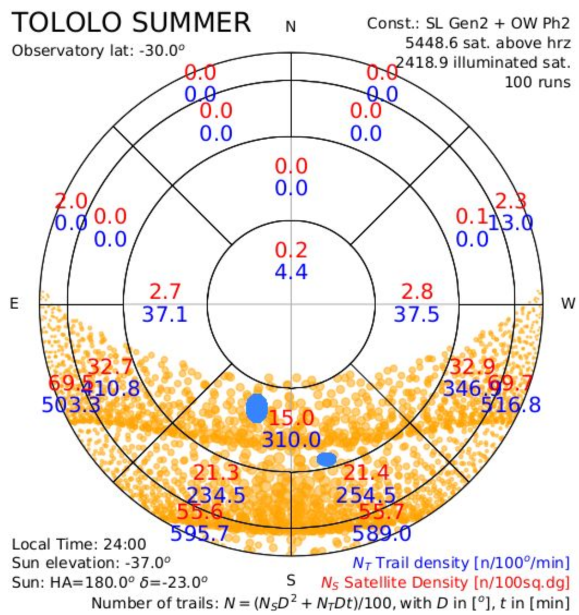


Figure B.8. Map of the satellite density (red, in satellite/100 sq.deg) and trail density (blue, in satellite/100 deg/min). The dots represent one realization of the constellation used to compute these values (here, the combined Starlink and OneWeb constellations). The map is for Rubin Observatory at midnight on summer solstice. The number of trails in an exposure is obtained from Eq.1. For instance, a 5min exposure with a 3x3 degree field of view in the Southern quadrant would expect N = (15* 3*3 + 310* 3 *5)/100 ~ 48 trails. The blue ovals mark the position of the two Magellanic Clouds, satellite galaxies of our own Milky Way galaxy.

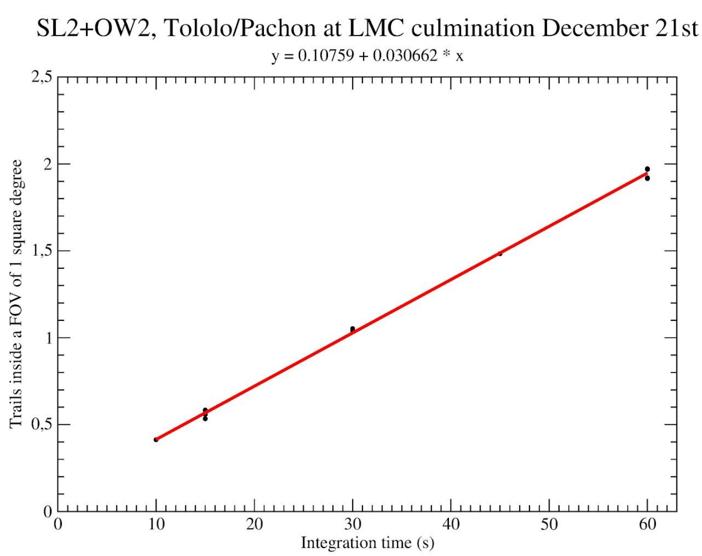


Figure B.9. Number of satellites expected as a function of exposure time in a 1 square degree field centered on the Large Magellanic Cloud in summer in Chile. Even for a short 30-second exposure at culmination (transit) there will always be one satellite trail, usually from a satellite in the 1200 km OneWeb constellation.

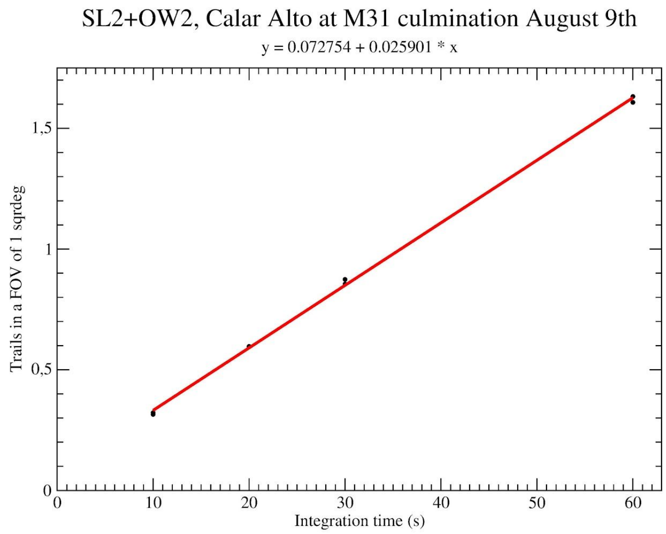


Figure B.10. Number of satellites expected as a function of exposure time in a 1 square degree field centered on the Andromeda Galaxy at Calar Alto in Spain (latitude also representative of continental US observatories). Even for a short 30-second exposure at culmination (transit) there will always be one satellite trail, usually from a satellite in the 1200 km OneWeb constellation.

The LMC is not the only such object or field of interest studied heavily by astronomers. Also in the south is the Galactic center (Sgr A) while in the north the Andromeda Galaxy (M31), the nearest large galaxy to our own Milky Way, is an object of intense interest. The declination is +41 degrees. Modeling shows that even short exposures are likely to have one satellite trail in it when the object transits (at culmination). Example for M31 is in Fig. B.10 above. [Galadi, private communications]

For longer exposures, say 300 seconds, which is typical of deep exposures to go faint, there will be eight (8) or more satellite trails.

Another example of fields of interest where long exposures are expected to go as faint as possible are the deep fields studied by the Hubble Space Telescope and other space-based observatories (Chandra X-ray) for example. Ground-based spectroscopy of objects in these fields is essential to understand the nature of sources. Here the exposure times could be one hour or more. These fields are distributed all over the sky.

Field	Constellation	RA (deg)	Dec (deg)
ELAIS ISO deep field	Phe	8.6	-43.6
CANDELS UDS	Cet	34.2	-5.1
Hubble UDF/CDFS	For	53.1	-27.8
Lockman Hole	UMa	162.7	57.2
Hubble Deep Field N/Chandra Deep Field N	UMa	189	62
Extended Groth Strip	Boo	214.4	52.5
Bootes Survey	Boo	216	34.0
Akari NEP Deep Field	Dra	269	66.4

Magnitude of the objects

While the brightness of a satellite is a critical element in determining the effect on observations, the previous simulations are not accounting for it: they are just counting satellite trails, independently of them being bright enough to saturate the detector, or too faint to be detected. Computing the magnitude of a satellite is not simple: they have a complex geometry, which is not fully characterized (at least by the astronomers). Furthermore, the reflected light has a diffuse component, but it can have a specular component too, causing glares and flares. The Observation Working Group describes how the parameters of the satellites can be measured.

Until better magnitude estimates are available, a simple (albeit extremely rough) estimate of the magnitude can be obtained modeling the satellite by a simple sphere, scaling the radius (and albedo) of the sphere to the few observations already available.

As the satellites are crossing the sky at very high apparent angular velocity, their light is trailed over the detectors. The effective exposure time t_E is therefore the time it takes the satellite to cross one resolution element of the system (eg the seeing disk for a telescope, or a pixel for very wide-angle systems), no matter what the actual exposure time *t* is. The peak brightness of the satellite trail will, therefore, be similar to that of a static object with a brightness t_E/t fainter, or, in magnitude:

$$M_{eff} = M + 2.5 \log(t_E/t) \quad \text{(Eq.2)}$$

For a telescope with a 1” seeing, the magnitude of a satellite observed close to Zenith drops by ~10 to 15 mag depending on the altitude of the satellite and the exposure time. For large telescopes, the drop in brightness will be even stronger because the satellite will be resolved and out of focus. The drop in brightness does not depend strongly on the zenithal distance, as the motion of the satellite is slower closer to the horizon.

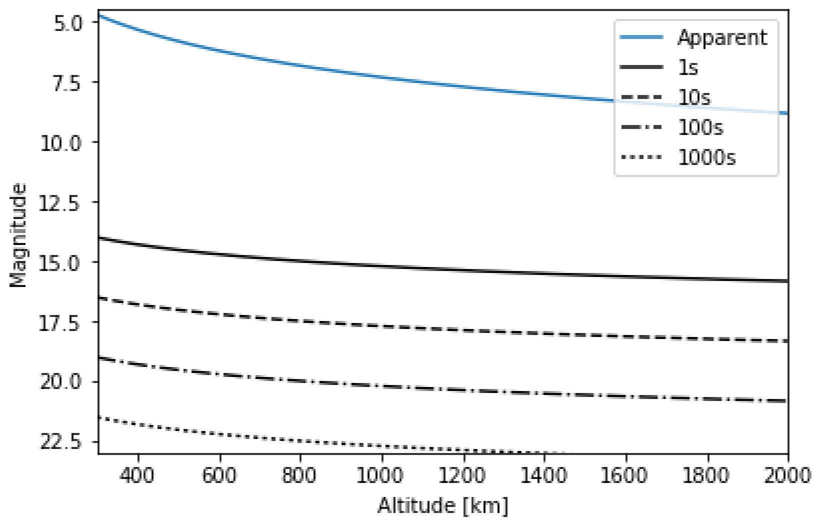


Figure B.11. Effective magnitude of a satellite trail (i.e. magnitude of a point source that would have the same peak surface brightness as the trail) as a function of the altitude of the satellite, observed close to zenith, for various exposure times. The blue line is the apparent magnitude of the satellite, here scaled to 5.5 at 550 km. [Hainaut, private communication; based on Hainaut & Williams 2020]

D. Simulations of Starlinks on orbit

A study of the brightness distribution of Starlinks now on orbit has been performed (by Kucharski & Jah, University of Texas at Austin).

The number of solar photons reflected off of the satellites towards a specific ground location depends mainly on the physical and optical properties of an orbiting object, the mutual geometric relationship between the Sun, satellite and the observer (e.g. on the ground) as well as the properties of what is between the satellite and the observer (e.g. the atmospheric layers through which the reflected light propagates). In order to estimate the number of solar photons reflected off of a space object and arriving at the ground telescope, a one-way optical link budget is modeled — this free-space link allows the reflected photons to arrive at the aperture of the ground observer. An experimental study of this concept was performed by Kucharski et al. (2019).

The spectral intensity profile of the solar irradiation at the satellite (exoatmospheric) is given by the ASTM G173-03 model. For now, applying a spherical approximation to the satellite shape (1 meter in diameter) and Lambertian Bidirectional Reflectance Distribution Function (BRDF), a fraction of diffusely reflected light off of a space object in the visible spectrum of 400–700 nm is predicted. The BRDF defines how the incident light is reflected, diffused or absorbed by the exposed surface elements. This includes modeling the directional intensity of reflection with respect to the incoming photon flux, surface orientation and the material properties of the illuminated facets.

The solar flux reflected towards the Earth propagates through the atmospheric layers where it attenuates due to absorption by ozone, water vapor, and carbon dioxide as well as being scattered by air molecules, water and dust particles. An observing telescope located within the reflection footprint can collect a portion of the photon flux which then propagates through the detection channel and can be focused on an imaging sensor.

Prediction of the satellites' passes within the theoretical line-of-sight of a specific ground location allows estimating their brightness and the number of reflected solar photons that "contaminate" the dark-sky. An example map of a "light pollution" caused by reflective space objects for Rubin Observatory (night of 20 June 2020) is presented on Fig. B.12: a) the reflected photon flux arriving at the site, b) the total number of photons collected by Rubin Observatory integrated over the field of view (3.5°) and the aperture area.

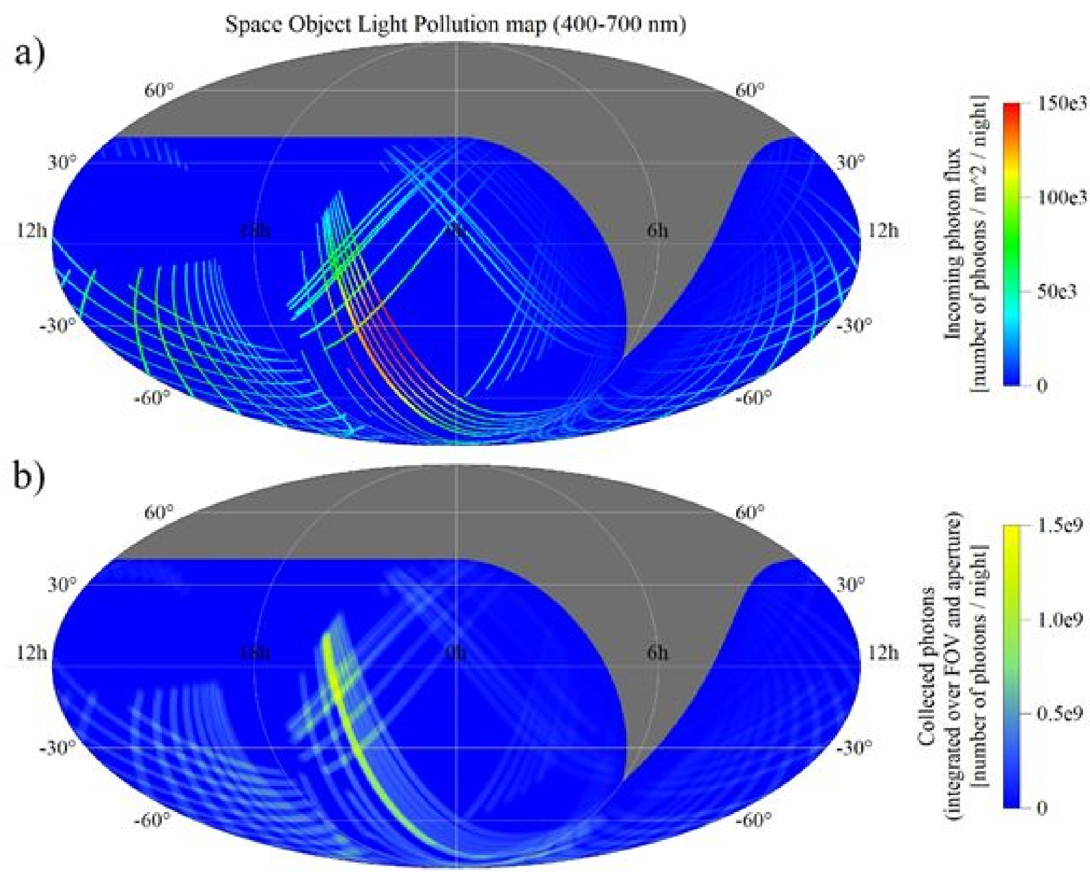


Figure B.12. Simulated light pollution generated by the Starlink satellites on 20 June 2020 as seen from Rubin Observatory mapped on the celestial sphere (RA/Dec in J2000): a) intensity of reflected flux arriving at the Rubin site, b) the number of photons collected by the Rubin aperture integrated over the telescope FOV. The gray area indicates part of the sky not observable due to the geographical latitude of the site and the horizontal elevation limit of 20°.

Using the Two-Line Element (TLE) data from the public catalog allowed predicting 109 Starlink passes visible from Rubin Observatory location on 20 June 2020 (nautical twilight; the minimum topocentric elevation of 20° is assumed). In Fig. B.12-a, the color-coded reflection flux expresses the cumulative number of solar photons arriving at the telescope per aperture unit area per night. The J2000 geocentric inertial reference frame is used to represent the simulated data points with the RA/Dec coordinates being the pointing direction of the ground telescope (i.e. topocentric line-of-sight represented in the geocentric inertial frame). The map indicates that the “light pollution” caused by the space objects is not uniformly distributed across the celestial sphere and there are regions of dark sky that could be selected for long exposure imaging during the particular night. Fig. B.12-b shows the satellite reflection flux integrated over the Simonyi Survey Telescope field of view and the aperture area (primary mirror); the most polluted parts of the sky are located where the bright passes cross or overlap.

The simulation algorithm will be further developed with the special emphasis put on the implementation of increasingly realistic satellite shape and BRDF models for the high-fidelity brightness analysis.

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Appendix B.1: Technical Appendix: Simulation Details

Simulations of the visibility of satellites were undertaken by six groups in the US and Europe:

- Jonathan McDowell (Center for Astrophysics)
- David Galadí (Icosaedro working group of the Spanish Astronomical Society SEA)
- Olivier Hainaut (European Southern Observatory)
- Patrick Seitzer (University of Michigan)
- Jan Siminski (European Space Agency Space Debris Office)
- Cees Bassa (ASTRON Netherlands Institute for Radio Astronomy)

To compare each group's results, a standard test constellation was defined for all groups to run: 10,000 satellites at 1000 km arranged in 100 satellites in each of 100 planes. The orbital inclination was 53 degrees.

For simulations of real constellations, the source of orbital elements was the public FCC filing for each constellation. In particular, the Schedule S provided the detailed orbital elements at a given epoch: altitude, number of planes, number of satellites in each plane, orbital inclination, Right Ascension of the Ascending Node (RAAN) of each plane, and the mean anomaly of each satellite in a plane.

Each group worked completely independently using different systems. There was no sharing of algorithms or software.

The remarkable agreement between all the groups gives us confidence that the results are correct, and that simulations from different groups can be used for different observatories and different times.

Details for each group:

McDowell: In all the proposed constellations the satellite orbits have sufficiently low eccentricity that it can be neglected; orbital planes are assumed to be equally spaced. Where satellite relative phases in the plane are provided I use those, otherwise I space satellites evenly in each plane but with a random phase offset from plane to plane. In the limit of large numbers of satellites, their space distribution is essentially time-independent so I make a single realization of this distribution. I treat the Earth as a perfect sphere. Then at a given observer latitude, longitude and epoch I calculate the Sun-Earth vector from the Jet Propulsion Laboratory Development Ephemeris (JPL DE405). Next, I find the observer elevation of each satellite and flag those satellites above a given elevation (usually zero or 30 degrees). For those satellites, I calculate the shadow cone half-angle (which depends on the satellite's height), and compare it with the Sun-satellite vector to determine whether the satellite is illuminated. (To high accuracy, the Sun-satellite vector is the same as the Sun-geocenter vector). For a fixed longitude, I iterate to get counts of total and illuminated satellites above the target elevation versus latitude in time steps of 5 * 10^{-4} days over a 24 hour period and in steps of 0.2-degree latitude. Finally, I filter the resulting dataset to get results for a given latitude band. (Note that I don't attempt to model the brightness of the satellites in this simulation.) More details of the approach are given in McDowell (2020, Ap.J. 892 L36). Below I show results showing the number of illuminated satellites above 30 deg elevation for a summer observer in Chile as a function of time of night (Fig. B.1.1).

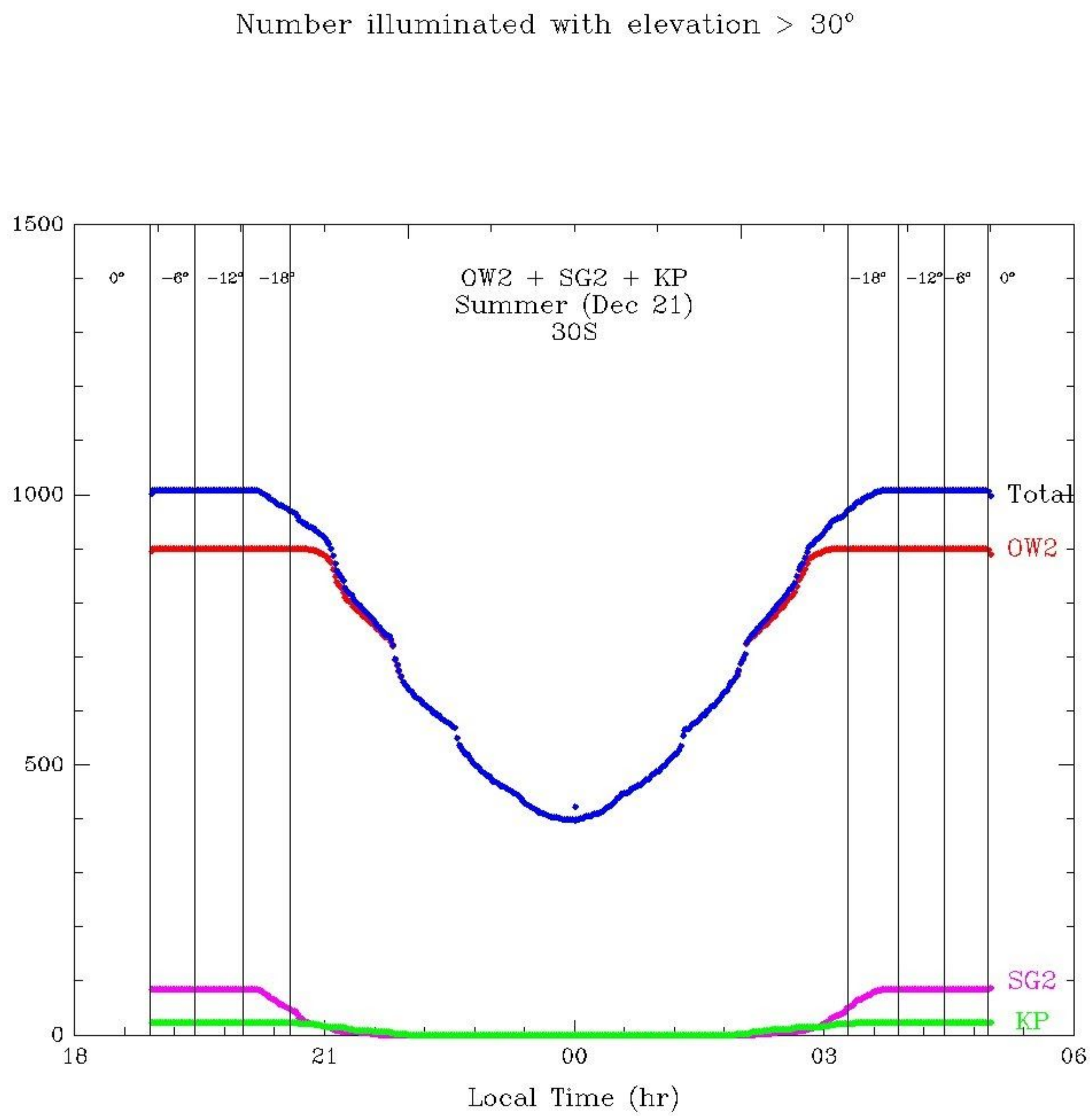

Figure B.1.1. The number of illuminated satellites above 30 deg elevation for a summer observer in Chile as a function of time of night.

Note that even in the middle of the night 400 satellites are high in the sky and illuminated, mainly due to the high-altitude OneWeb Phase2 constellation.

Galadí and Icosaedro group: the satellites are placed at their orbits (assumed circular) and their motion is solved the keplerian way. Keeping track of each object we derive statistics for a given latitude and time of the year. Also, pointing-oriented simulations are done, following the same process, to assess the impact on individual telescope pointings (azimuth and elevation, FOV and integration time have to be input).

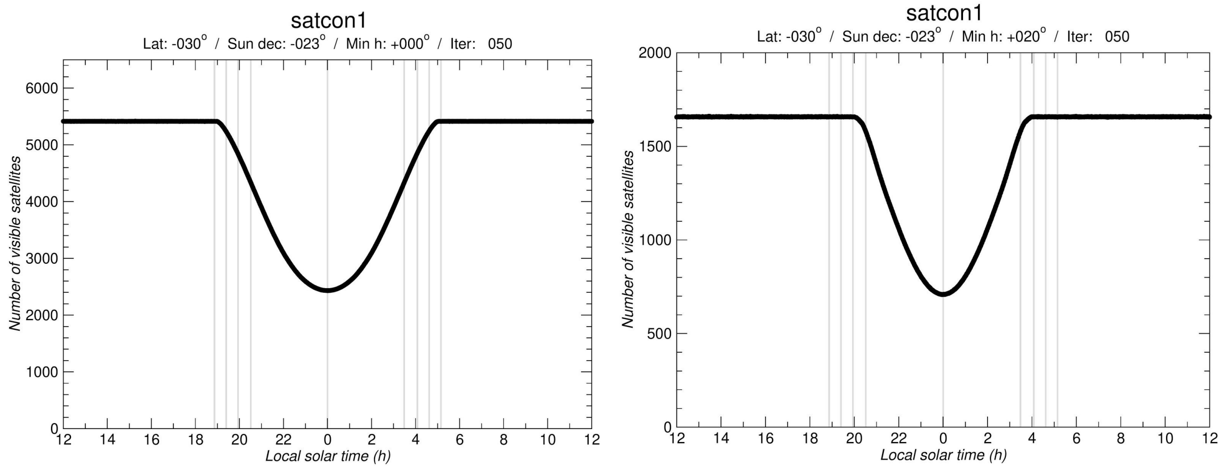

Figure B.1.2. Example of the results from D. Galadí and the Icosaedro group for latitude -30 deg, December solstice, counting satellites over the horizon (left) and above elevation 20º (right) for constellation profile Starlink 2 + One Web 2. Vertical lines indicate sunset, civil twilight, nautical twilight, astronomical twilight, midnight and the opposite sequence at dawn. The results reproduce other simulations to within a fraction of %.

Hainaut: a (sub) constellation is defined by the altitude *h* and the inclination *i* of the orbits (assumed circular), and by the numbers *n* of orbital planes and *N* total number of satellites. The initial positions of the *N/n* satellites in a plane are distributed at regular intervals on the circular orbit, with a random offset between the first one and the equator. The *n* orbital planes are also distributed regularly along the equator, with a random longitude offset for the first one. The position of the satellite along its orbit at the time of the simulated observation is set considering a uniform revolution with a velocity set by Kepler's law. The precession of the constellation is neglected, but the 24h Earth rotation is accounted for. For some simulations where the region of the sky considered is small, several realizations of the constellation are computed to get enough statistics (typically 10-100 realization, but in some cases up to 100 000).

The longitudes and latitudes of the satellites are converted into geocentric cartesian coordinates. Through a rotation so that the *z* axis points towards the sun, the satellites in the shadow of the Earth are identified (simplifying the shadow cone in a cylinder with $z<0$ and $\mathrm{sqrt}(x^2+y^2) < r\_earth$). With another rotation and a translation, the coordinates are converted to topocentric with *z* pointing toward the zenith of the observatory. The satellites above the horizon ($z > 0$) are selected, and the geometry of each satellite is computed (range, elevation, azimuth, airmass, etc).

The apparent magnitude of each satellite is estimated as $M = M_0 + 5 \log (Delta / 550 \text{ km}) + 2.5 \log ((\cos(alpha) + 1)/2)$ (adapted from Hainaut & Williams 2020), where $M_0 = 6$ is adjusted to match photometric measurements of Starlink satellites.

For each time step, the numbers of satellites in range, illuminated, brighter than a threshold magnitude are counted for satellites above the horizon and above 10 and 30 degrees in elevation. This is repeated for various observatories (at 0 degree latitude (Equator), -25 (Paranal), -30 (Rubin), +50 (Brussels)), and for various solar geometries (summer and winter solstice, and equinox).

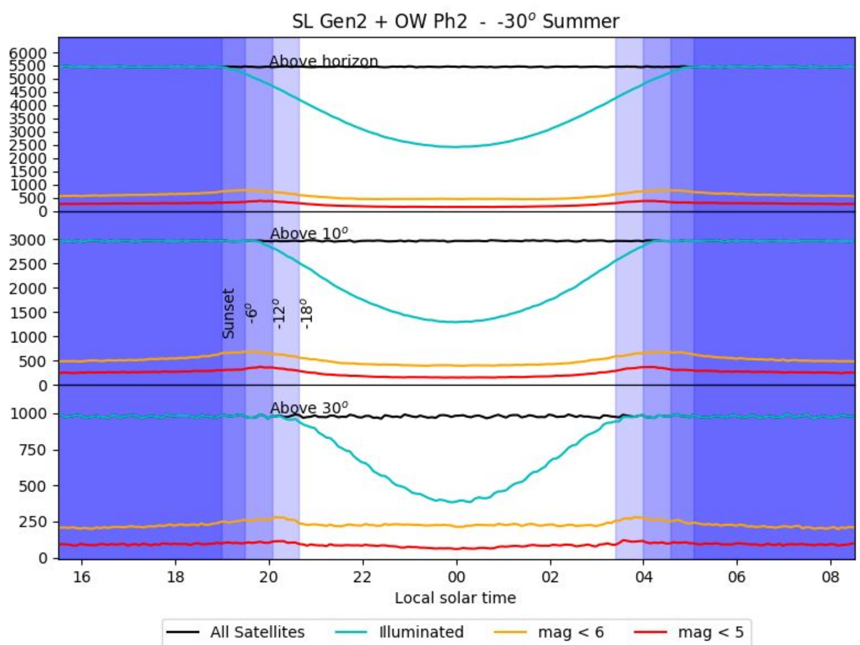

Figure B.1.3. Number of satellites above the horizon (top), above 10 degree elevation (middle) and 30 degree (bottom) as a function of the local time, for an observatory at 30 degree latitude South (eg Rubin Observatory) at summer solstice, for Starlink Generation 2 (30 000 satellites) and OneWeb Phase 2 (50 000 satellites). The cyan line (counting the illuminated satellites) of the bottom panel can be compared with the blue line in McDowell's plot above (which also includes 3000 Kuiper satellites). The red and orange lines show the number of satellites brighter than magnitude 5 and 6.

These simulations were performed for the test constellation and for a series of Starlink and OneWeb constellations. The following figure shows, as an example, the combined Starlink Generation 2 and OneWeb Phase 2 for Rubin Observatory. Other configurations are available at http://www.eso.org/~ohainaut/satellites/

Additionally, maps of the sky showing the satellite distribution are generated, together with various histograms and plots. An example is given below for Rubin Observatory at twilight.

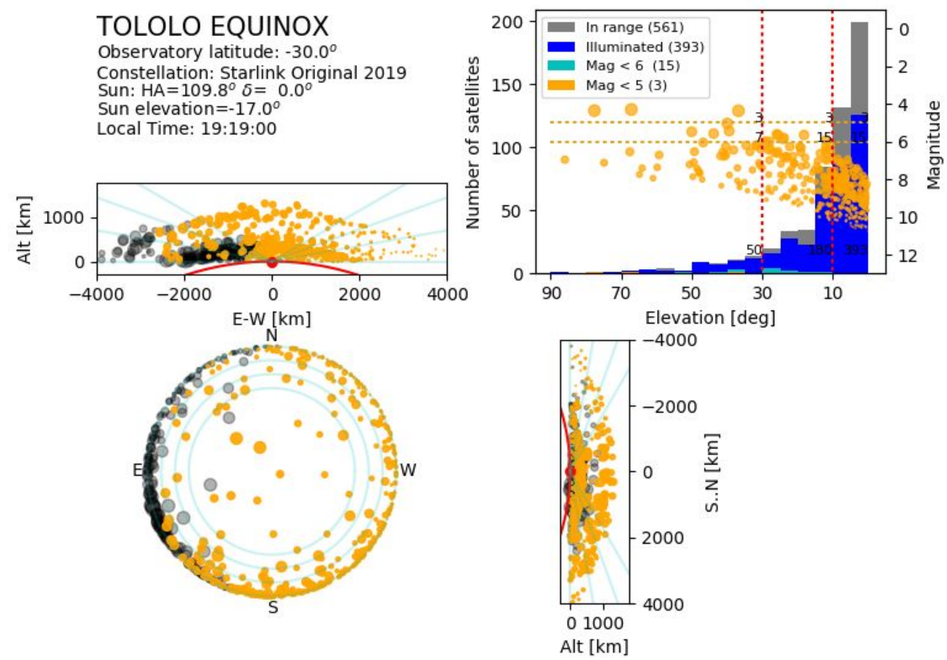

Figure B.1.4. Configuration of the Starlink (original configuration) over Rubin Observatory at twilight. Bottom left is a map of the sky, top-left and bottom-right are side views of the satellites. Orange dots mark illuminated satellites, black dots satellites in the shadow of the Earth. Top-right shows a histogram of the satellite elevations above the horizon (showing that ~half the satellites are below 10 degrees). The dots give the magnitude of the illuminated satellites as a function of elevation. The numbers in the plot are the count of satellites brighter and higher than the position of the number (eg, 7 satellites are brighter than magnitude 6 and higher than 30 degree elevation).

In order to simulate the effect of the satellites on observations, as well as to help mitigate it, density maps of the satellites are generated. The parameters needed to assess how many satellite trails could contaminate an exposure are the density of satellites (D_s, in satellites per sq.deg), and the density of trails (D_t, in trails per degree per minute) which is the density of satellites weighted by their apparent angular velocity. An example is given below. More details on this will be published in Hainaut, Galadi and Bassa (in preparation).

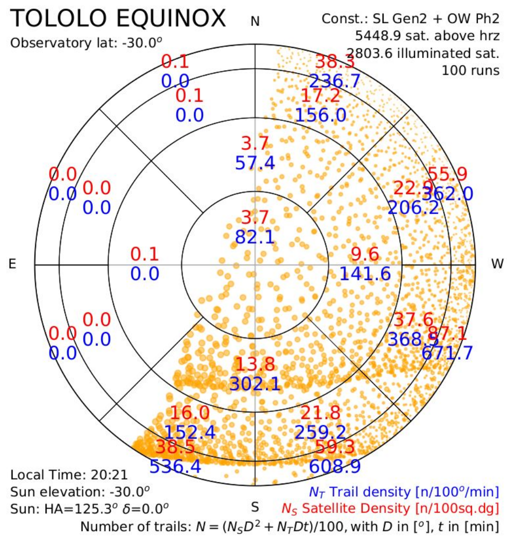

Figure B.1.5. An example of a satellite density map. The dots illustrate one of the realizations of the constellation used in the average densities. The red numbers give the density of satellites (D_s in N/100 sq.deg), and the blue numbers the density of trails (D_t in N/100 deg/min). The number of trails affecting an exposure can be estimated by $N = (D_s F^2 + D_t F t)/100$, where F is the size of the field of view [deg] and t the exposure time (min). As an example, a 1x1 degree observation with an exposure time of 1 minute at zenith would expect a 3.6 * 1 + 82.1 *1*1 = 82.1 % chance to be crossed by a satellite trail, or on average 0.82 trails per exposure.

Seitzer: For a given constellation, observatory and date, the satellites are placed at the initial conditions specified in the Schedule S at 1600 UTC for that date, The orbits are then propagated forward for 24 hours using the J4 propagator in the commercial software package Systems Tool KIt (STK). This propagator takes into account J2 and J4 terms of the oblateness of the Earth. The algorithm used by STK for eclipse timings is from the *Explanatory Explanation to the Astronomical Almanac.* No allowance for atmospheric drag was included. This should not be significant at these altitudes and for the maximum time span of 24 hours. Times of visibility are computed. Fig. B.1.6 shows the results for the 47,844 satellites in the proposed OneWeb constellation at 1200 km altitude, broken down by orbital inclination.

These 1200 km satellites are located towards the south (see above). There will be no “satellite dark time” for the LMC (noted above) from a 1200 km constellation.

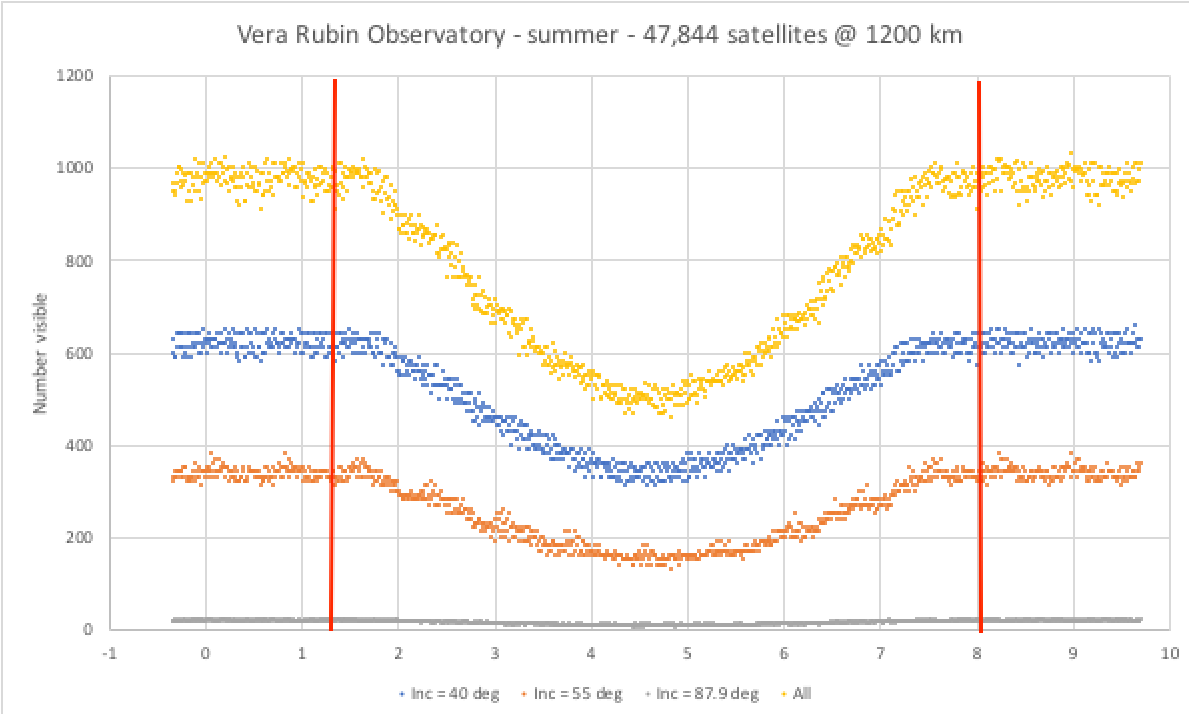

Figure B.1.6. Simulation of the proposed OneWeb constellation of 47,844 satellites at 1200 km altitude as seen from Rubin Observatory in the summer at an elevation of 30 degrees or more. The red lines are astronomical twilight. The constellation has three orbital inclinations: 40, 55, and 87.9 degrees. The numbers of satellites in the 40 and 55 degree sub-constellations are equal. The 40 degree inclination sub-constellation is the dominant source of satellites, being closest to the observatory latitude (-30 degrees).

Bassa: Numerical and analytical simulations have been performed. The numerical simulations model a constellation as a set of distinct orbital shells, with each shell defined by an orbital altitude and an inclination consisting of circular orbits. These simulations allow equal spacing of satellites within a plane, and equal spacing between orbital planes, as well as random spacing within orbital planes and between orbital planes. Satellite motion is modeled as purely Keplerian, neglecting drag, but including orbital precession due to the J2 term of the geopotential. Based on the simulated location of the satellites and the observer, the instantaneous density of satellites, their distances and angular velocities are obtained for each orbital shell. These simulations confirm that for a given orbital shell, the expected number of satellites N present in an exposure with a field of view of radius R_{FOV} and exposure time t_{exp} depends on the instantaneous satellite density ρ_{sat} and the angular velocity ω_{sat}, is given through $N = \rho_{sat} \pi R_{FOV}^2 + 2 \rho_{sat} \omega_{sat} R_{FOV} t_{exp}$, as highlighted in the Fig. B.1.7. This can be understood as the sum of the satellites which were located within the field of view of the exposure at the start of the exposure, and the number of satellites that move through the field of view during the exposure. As expected, large fields of view and longer exposures will contain more satellite trails.

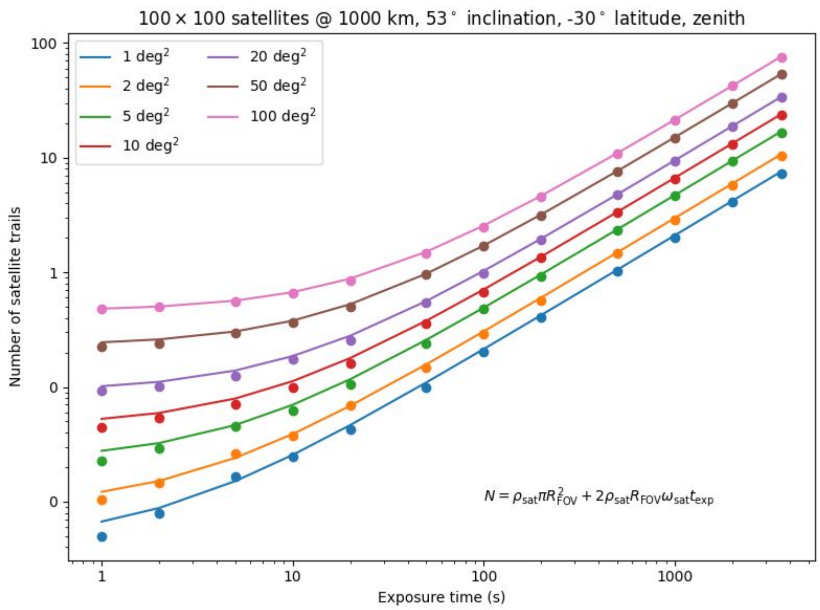

Figure B.1.7. The expected number of satellites N present in an exposure with a field of view of radius R_{FOV} and exposure time t_{exp} depends on the instantaneous satellite density ρ_{sat} and the angular velocity ω_{sat}, through $N = \rho_{sat} \pi R_{FOV}^2 + 2 \rho_{sat} \omega_{sat} R_{FOV} t_{exp}$. The dots denote results from numerical simulations, while the solid lines are predictions following the expression. These simulations are for the reference constellation of 100 orbital planes with 100 satellites each at 1000 km altitude and 53 deg inclination.

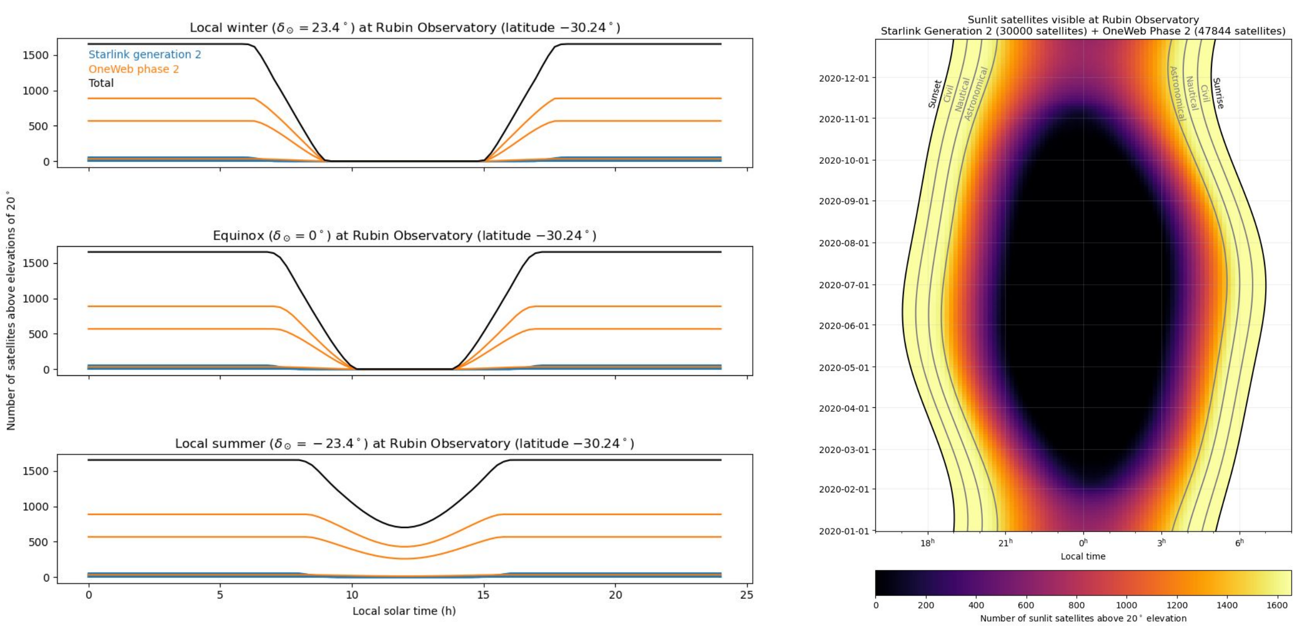

Figure B.1.8. Simulations of the number of sunlit satellites from the Starlink generation 2 (30,000 satellites in 8 orbital shells) and OneWeb phase 2 (47,844 satellites in 3 orbital shells) above 20 degree elevation from Rubin Observatory during local summer, winter and at the equinox (left) for different orbital shells, and the total number of sunlit satellites over the course of 2020 (right). During local summer, hundreds of satellites from these constellations will remain visible throughout the night.

The numerical simulations are time-consuming as they require position and velocity computations for tens of thousands of satellites and averaging over thousands of iterations. To alleviate this, analytical expressions have been derived for the probability density functions of a satellite in equatorial longitude, which is uniform, and latitude, which follows an arcsine distribution. Using these probability density functions, it no longer is required to simulate all satellites individually, but instead obtain average quantities for instantaneous satellite density, distance and angular velocities (speed and position angle). Also, apparent brightness is a deterministic function of pointing direction in this frame, and may be predicted on similar bases.

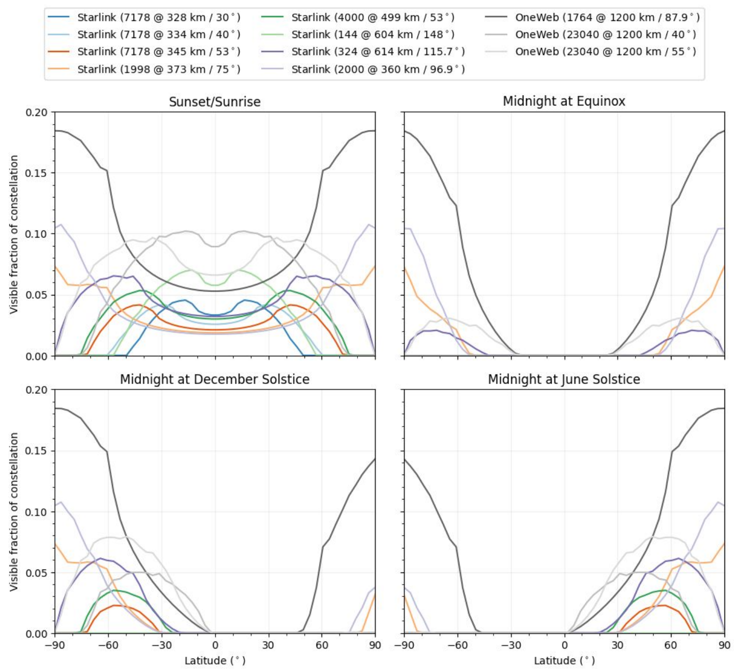

Figure B.1.9. The dependence on the latitude of the observer and time of year on the fraction of each orbital shell in the Starlink generation 2 and OneWeb phase 2 constellations. The fraction of satellites visible in an orbital shell increases with orbital altitude, and will peak at latitudes close to the orbital inclination of that shell.

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McDowell, J. 2020, Ap.J. 892, L36

Appendix C. Technical Report on Mitigations of Impacts of Satellite Constellations

A. Summary

We report on efforts to mitigate the effects of proposed low earth orbit satellite (LEOsat) constellations on optical astronomy research generally. Broadly speaking, mitigation options include fewer satellites, fainter satellites, lower-altitude satellites, smaller satellites, satellites visible in a smaller fraction of the nighttime, high-precision satellite attitude information, improved scheduling capabilities for observatories, improved image processing capabilities, and novel sensors for the future.

We list many of the optical observatories impacted, with estimates of the impact on their science programs and recommendations for further work. Large aperture facilities with large fields of view and broad science programs are the most impacted, in addition to telescope systems aiming for precision astrophysics (photometry, spectra, low S/N signal detection). The impact of bright LEOsat trails on telescope cameras and their sensors is an important issue because it can inform a target for satellite darkening efforts. We also discuss systematic effects due to LEOsat trails, time-critical observations, data analysis challenges, and plans for simulations of science impact under realistic LEOsat constellation scenarios.

B. The main recommendations of the Mitigations WG

- Darken satellites in all phases of the orbit, including launch, parking orbit, final orbit and decay.
- Darken satellites to >7th mag. Incorporate a corresponding <44 W/sr radiance in the satellite design process.
- Fewer satellites.
- Satellites on orbits as low as possible. No satellites at >>600 km. Satellites at 1200 km are particularly damaging.
- Increased public availability of high-accuracy orbital and location data.
- App for LEOsat position-time prediction for observers.
- Advanced algorithms for avoidance of bright satellites.
- Predictive model for satellite brightness vs orbit relative to observatory.
- Support for end-end simulations of broad science impact by the research community.

With tens of thousands of proposed LEOsats, we find that generally **no currently apparent combination of known mitigations can completely avoid the impacts of the satellite trails** on the science programs of the coming generation of optical astronomy facilities. These facilities are designed to probe the dark sky in new ways for dynamic events, very low amplitude and low S/N phenomena, and to reach unprecedented faintness. They were not designed and built to safeguard operations against the changes that constellations present to the observational space environment. A combination of efforts, including fewer and fainter LEOsats and other improved data and tools, will be required to realize their full scientific potential. For many programs of discovery opened by the next generation of astronomy facilities, this is far from guaranteed. Below we give several representative science cases where mitigation is particularly challenging.

C. Representative science cases

Fast transients with long exposure spectroscopic follow-up
In the next decade, a “new sky” will open up: faint transients. While there are a wide range of transient object programs planned, this is an unexplored regime ripe for the discovery of the unexpected. These discoveries in wide-fast-deep LSST surveying will be selectively followed up spectroscopically with large telescopes with long integration time. The sky survey itself and the spectroscopic follow-up are separately impacted by satellite trails.

Optical gravitational wave follow-up
This is a unique multi-messenger science opportunity in the next decade. As frequently as once per week it is expected that the network of gravitational wave detectors will detect events at very high S/N and within minutes will announce 90% likelihood areas on the sky. The first job is to detect any electromagnetic counterpart. This will be done by rapidly and repeatedly tiling this area with Rubin Obs. in multiple filters, in order to distinguish the object from thousands of regular transients detected during this tiling. Once detected, the candidate must be passed on for spectroscopic follow-up. Due to the time-critical nature, some of this search will occur during twilight. Satellite trails interfere with the real-bogus classifier.

Rapid contiguous monitoring of special sky areas
Like GW follow-up, several LSST science programs involve rapid contiguous monitoring of special fields. This precludes satellite avoidance strategies where one moves to an adjacent field. These special fields tend to be the same size as the field of view of the camera. One example is the Deep Drilling fields. These will be rapidly imaged in multiple filters in order to detect unusual events. Another example is the Large Magellanic Cloud, a nearby dwarf galaxy which is important for new transients and for probing the physics of dark matter.

Detection of potentially hazardous asteroids
NEO searches must be done in evening or morning twilight pointed into the twilight. This is where the density of LEOsats is highest. Pairs, triples, or quads of observations must be made within a short time in order to form a tracklet. The probability of parts of a LEOsat trail interfering with this is quite high.

Ultra deep sky survey
Low surface brightness surveying over the wide areas enables unprecedented probes of cosmology and galaxy evolution. Probes of the physics of dark matter and dark energy use billions of 26 magnitude galaxies for which the shape must be known to one part in 10,000. Systematic errors at low surface brightness remaining after masking satellite trails can lead to linear strings of correlated noise — causing weak gravitational lens shear bias. (Morganson et al. 2018)

D. Mitigation categories

1. Laboratory investigations of sensor response to bright LEOsat trails, understanding this via device physics and camera models, and exploration of sensor clocking mitigations

Some cameras for fast readout applications use CCDs which are segmented into multiple areas, each with its own output amplifier. These are clocked out simultaneously in order to minimize dead time between short exposures. This is most common in sky survey or high time resolution wide-field monitoring applications. The survey or monitoring efficiency is proportional to etendue (the product of aperture area and field of view), as is the data rate. Unfortunately, the rate of accidental satellite trails is also proportional to etendue (this is discussed below in Sections 5–7). Here we focus on mitigating electronic echos from bright satellite trails in the sensor and camera.

Rubin Observatory CCD studies (See also Tyson et al. 2020.)
Initial studies of satellite trails using Rubin Observatory's Legacy Survey of Space and Time (LSST) beam simulator in summer 2019 indicated the most serious effect of bright LEOsats on the CCD sensors might be the electronic crosstalk between the 16 segments of the CCDs, each of which has its own amplifiers and signal chains that are simultaneously sampled during readout. The electronic crosstalk on both types of LSSTCam sensors, e2v and ITL, has been measured to be smaller than a few parts in ten thousand with both positive and negative responses that are variable among segments and must be characterized for each CCD. Unfortunately, this crosstalk is unavoidable and has a multiplicative effect on the satellite trail, causing the bright linear satellite trails to have sixteen faint "echo" trails for every satellite trail in all affected CCDs.

The observed crosstalk trails are likely the combined effect of electronic crosstalk occurring at various stages of the readout electronics chain, both on- and off-chip. Preliminary measurements of the total electronic crosstalk response to illumination by bright spots at multiple different signal levels has shown that the crosstalk is nonlinear, i.e., the crosstalk response ("echo" trail region) is not strictly proportional to the bright stimulus (main trail region). Studies of the crosstalk induced by satellite trails of varying brightness indicate that this nonlinear crosstalk should be correctable via an algorithm in development. Additionally, studies to minimize the trail crosstalk (and thus impact of both satellites and bright stars) through modifications to the operating clocking & voltages of the CCD readout chain are underway. Besides slower read-out times (which negatively affect survey efficiency), possible modifications to the operation of our Application Specific Integrated Circuit, which amplifies and samples each segment's pixels sequentially, may have the potential to mitigate the effect of satellite trails on the LSST. A fainter satellite is a safer mitigation. Because of the errors in measuring crosstalk coefficients in operations this results in ~7th V_{mag} being "safe". A similar limit comes from residual systematics left after trying to mask the remaining bright trail itself (discussed below).

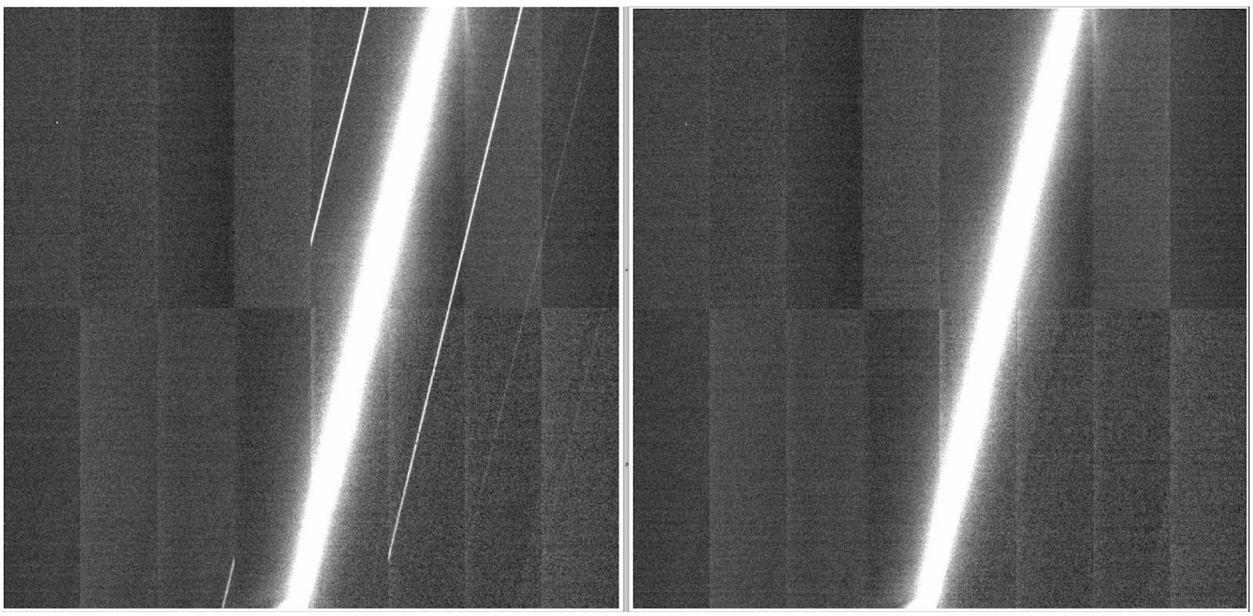

Figure C.1. Crosstalk: (*left*) a trail of brightness comparable to that expected from a LEOsat at 550 km generates parallel “ghost” trails due to electronic crosstalk in the sensor and electronics. These crosstalk effects are nonlinear and may be removed in LSSTCAM down to near the background noise level with a pixel processing algorithm, providing the satellite is fainter than about 7th magnitude (*right*).

2. Development of pixel processing algorithms for suppression of these effects, validation via simulation and lab data, culminating in a goal for satellite brightness

Rubin Observatory algorithm studies

The majority of the effort in mitigating satellite trails in LSSTCAM sensors so far has been in the development of a nonlinear crosstalk measurement and correction algorithm. In typical instrument signature removal (ISR) pipelines, crosstalk correction occurs after bias correction, and involves multiplication of the bias-corrected stimulus (i.e., bright trail) frame by a predetermined coefficient and then subtracting it from the affected crosstalk frame. The coefficients are usually assumed to be constant, as the capacitive coupling between channels should be a linear function of the input stimulus. However, there appear to be multiple sources of crosstalk in LSST sensors and electronics which have varying contributions that cumulatively break the assumption of crosstalk linearity. Therefore, to correct for the multiplicative effect of satellite trails we must characterize and understand the sources of nonlinearity to correct for them. By simulating satellite trails on several LSST sensors and comparing them to bench-top electronic measurements, we have begun to characterize this nonlinearity and thereby develop a model of the nonlinearity which forms the crosstalk correction algorithm. However, residuals from imperfect correction are expected, and the understanding of their cumulative effect on LSST's precision astrophysics and cosmology is ongoing. We find that if a LEOsat at a range of 550 km is fainter than about 7th V_{mag}, this algorithm has enough dynamic range to suppress the "echo" crosstalk trails down to near the sky noise level (Tyson et al. 2020). 8th magnitude is a safer goal.

3. Measures to darken SpaceX Starlink LEOsats to meet this 7th mag brightness goal, including recent observations of DarkSat

For on-satellite mitigation efforts, we use the SpaceX Starlink program as a case study. While there are several other potential LEOsat mega-constellation operators, Starlink is the first one we can observe and the first opportunity astronomers (specifically Rubin Observatory scientists) have had to directly collaborate on mitigation efforts with a satellite operator.

For SpaceX Starlink satellites, scattered sunlight was identified as the primary source of observed brightness, and several approaches are being implemented to darken these satellites at various operational phases. Operators often deploy satellites in phases and assume different configurations during each phase. This is particularly true for LEOsat constellations that deploy in batches. This is due to the larger differences in atmospheric density in the lower regions of the atmosphere and the need to space groups of satellites apart.

We can generally group satellite mission phases into the following categories:

- **Insertion**: satellites are ejected from the delivery vehicle
- **Orbit raise**: satellites make their way to a target location (either their long-term orbit or a parking orbit)
- **Parking orbit**: satellites may be brought to an intermediate 'parking' orbit for precession or health checks. If a parking orbit is used, a second orbit raise will be required to put satellites on-station.
- **On-station**: the long-term position of the satellites, from where they will execute their mission.
- **Deorbit**: when satellites are decommissioned, they will be brought back to earth and either burn up on re-entry or crash-land on earth's surface.

Using our example of SpaceX's Starlink program, recent launches have looked like the following:

- **Insertion:** 60 satellites are inserted into an elliptic insertion orbit (*hours to days*)
- **Orbit-raise:** 20 satellites begin a roughly 1-month orbit raise directly to their on-station position and 40 satellites go to a parking orbit
- **Parking:** 40 Satellites remain safely clumped in the parking orbit while the planes precess above them (~ 1 month per plane hop). Of the 40 parked satellites, the first group of 20 requires a single plane hop and the second requires two hops. Once precession is complete, the satellites begin orbit raising (described above) to their on-station position.
- **On-station:** Once on station, the Starlink satellites begin serving Internet across the globe. The lifespan of the satellites is 5–7 years.
- **Deorbit:** Once decommissioned, starlinks will be actively deorbited. This process, which should roughly look like orbit raise in reverse, will end with the fully-demisable Starlink satellites burning up in the atmosphere.

When on-station in phase (iv), where Starlink satellites spend most of their estimated five to seven-year operational life, the satellite chassis is nadir pointing with the broadband antennas Earth-facing, and the solar array can actuate from an in-plane to a perpendicular position with respect to the chassis. The majority of light is either converted to power by the solar arrays, or reflected in a specular direction (typically away from Earth). What remains are diffuse and specular reflections off individual satellite surfaces. The phased array broadband antennas on the nadir-pointing side of the spacecraft were identified as a major source of scattered light. These surfaces were darkened on a test satellite launched in January 2020 (Starlink-1130, DarkSat). As a result, DarkSat was about 1 mag fainter than four bright siblings from the same launch, but still 0.9 magnitudes brighter than the 7th mag threshold.

Observations of DarkSat have shown a ~1 magnitude decrease in brightness (or 2.5x), as shown in Tyson et al. (2020). SpaceX has continued to test mitigation strategies to further reduce the brightness of future satellites. The next major trial was the launch of SpaceX's VisorSat (Starlink-1436) which features, among other mitigations, a deployable sun shield that blocks sunlight from reaching the main satellite body. The VisorSat test satellite was launched on 4 June 2020 and is currently in the orbit-raising phase to the parking orbit. Once there, observations can begin to evaluate the impact of the structural mitigation. Based on the results of this experiment, SpaceX plans to integrate sun visors into future Starlink spacecraft this summer.

In addition, SpaceX has used a detailed computer-aided design (CAD) model of the Starlink satellite and actual satellite surface materials evaluated for bi-directional reflectance distribution function (BRDF) to generate a stray light optical signature model. This optical signature model is in the process of validation against observed Starlink satellites, and will be integrated with the overall constellation model, for higher-fidelity brightness predictions. This will enable more accurate predictions of bright LEOsat trail appearance at any given time from any particular observatory's location.

4. Observation validation of these efforts, leading to further darkening experiments and some understanding of apparent brightness as a function of phase angle and other variables

Telescope observations of LEOsats

Satellite brightness has many degrees of freedom. These include phase angle, vehicle orientation (pitch, roll, yaw), and the orientation of all dynamic components on the vehicle (both actuated and non actuated). This trade space becomes very large when accounting for all possible surface treatments or structural additions. Due to the large size of the problem space and the slow cadence of data collection, we must combine observational data and optical modeling. The SpaceX plan is to use optical modeling to construct hypotheses that will guide experimentation and engineering efforts. Observations will be taken in parallel of both nominal and experimental satellites. These observations will further validate the aforementioned modeling efforts. The astronomical community is the ideal partner to collect these remote observations as this will help characterize both the satellites and optical instruments.

Laboratory measurements of LEOsats

As this working group's focus is forward-looking, it is important to consistently evaluate whether the approach here would be possible for operators at large. In the approach mentioned above, the remote observations are of satellites in orbit. However, not all operators will be capable of launching test vehicles and iterating design in the same fashion. It seems prudent to discuss how a similar approach could be used in which observational data is collected in ground-based facilities. A failure to think about this risks malformed incentives.

It is critical that satellite design includes optical reflectance considerations from the beginning. We recommend that new LEOsat operators undertake a suite of laboratory BRDF measurements as part of their satellite design and development phase. This would be particularly effective if paired with a reflectance simulation analysis.

5. Development of optimized observing scheduler algorithms that use satellite orbit information and science-driven schedule constraints. Simulations of observing efficiency

In theory, we could compute satellite positions ahead of time and schedule observations around them if these are feasible with the observing facility or observing program. This requires that LEOsat operators make location data publicly available (at high accuracy, both in space and time), which is not uniformly the commercial satellite industry’s practice. The required accuracy is approximately arcsecond in position and seconds in time.

While this may be a useful technique for some narrow-field ground-based optical telescopes, such as the large-aperture facilities that will be conducting spectroscopic follow-up of many of the most compelling LSST transient alerts, it presents a daunting task for Rubin Observatory, because of its wide field of view, and the fact that most twilight observations need to be taken in pairs separated by ~20 minutes. This is necessary so moving objects in the Solar System, such as near-Earth asteroids, can be identified. The high efficiency of the LSST scheduler comes from the ability to schedule observations of neighboring fields. For wide-field observatories like Rubin, avoiding satellites by pausing planned observations when a satellite is in the field-of-view is operationally inefficient. The dramatic impact this has can be seen in the simulation output below.

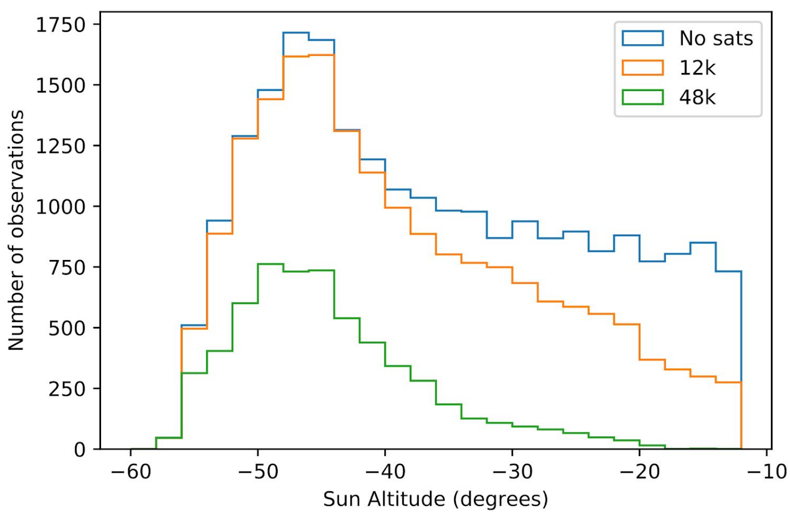

Figure C.2. The number of successful observations as a function of the Sun's altitude for LSST simulations employing an observation-delay satellite avoidance strategy. These attempts to avoid LEOsats rapidly become counterproductive as the number of LEOsats increases.

Exploration of scheduler algorithms which include the known non-uniform distribution of LEOsats on the sky (shown in the figure below) is needed. The feasibility of this is not assured, however, given the strong requirements of observing neighboring fields without delay.

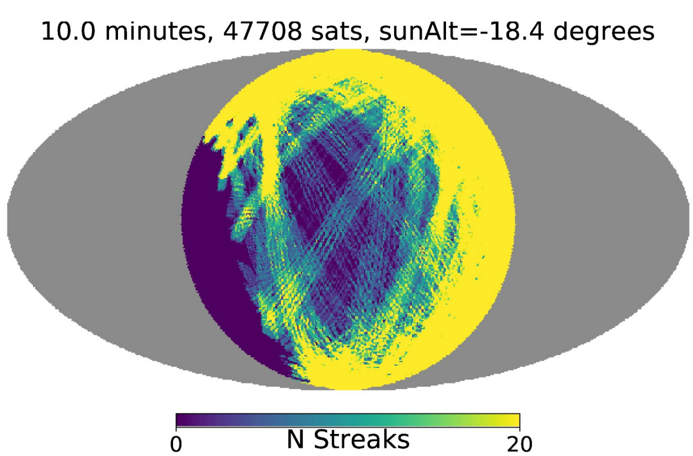

Figure C.3. An alt-az plot of trails of 47,708 illuminated LEOsats over a ten minute time period seen from Rubin Observatory. Zenith is at the center, North is up and East is left. The trails are bunched due to populating the orbital planes. The trail-free region is caused by Earth’s shadow.

A high priority would be an application that has a “server” mode, supplying relevant information in response to queries, and which also has a user-friendly interface (including apps for smartphones to support the enthusiast astronomer community). The service would allow an observer to access the satellite interference with a planned observation in real-time. This same app could also be used to schedule dodging. In addition, this functionality should allow for retroactive satellite position determination.

Some observatories, especially those with a very wide field, or using other observational constraints (such as staring at selected fields non-stop), have a much smaller opportunity to employ active avoidance strategies. For example, HATSouth observes the sky with 24 telescopes, each having a 4 x 4 degree field, tracking at a selected field until it sets, and then moving over to a new field for the rest of the night. Other projects, like Mascara, Evryscope, and HATPI observe the entire sky. Notably, HATPI uses 64 CCDs, each with a 13 x 13 degree field, to observe the sky above 30 degrees. It has no declination axis, only tracks in Right Ascension, and thus can not “dodge” satellites with a more sophisticated pointing algorithm.

For many wide-field astronomical surveys, avoidance through active scheduling is not a possible strategy for mitigating the impact of large satellite constellations.

Active shuttering

One possible way to avoid satellite trails is to close a shutter over a subset of camera pixels, provided good real-time satellite orbit information exists. This technique is called active shuttering and has been in development for some time. The most amenable camera would be a scientific CMOS (SCMOS), where individual pixels can be addressed. Unfortunately, current SCMOS sensors exhibit artifacts that exclude their use for most survey science programs where the noise needs to be uncorrelated. But there are some transient object surveys where they are becoming an attractive option.

Active shuttering of CCD cameras is also being done for small telescopes (StealthTransit) where the shutter is small and does not block the guider. For large focal planes, there are issues with this: the shutters are large and slow, and they often block the guide sensors. For LSSTCam the shutter takes 1-2 seconds to open and close, and the pointing of the telescope would be disturbed. It is simpler to split the short 30-second visit into two separate exposures.

Split exposures

Taking multiple exposures with LSSTCam during a 30-second visit to a field is a partial mitigation. When the nominal LSST visit time of 30 seconds is split into two back-to-back exposures of 15 seconds, as currently planned, the comparison of these exposures using difference imaging could be used to identify a satellite trail. The exposure with the satellite trail in it can be rejected, or the trail can be masked. This mitigation scenario would cost 8% of LSST observing time in order to accommodate the additional read-out time and shutter motion, assuming a negligible cost due to rejected pixels and that this two back-to-back exposure strategy would always be employed. There are specific science cases for 2x15 seconds.

However, it only partially mitigates some science (discovery of transients—the sample will be reduced, but cleaner). Static deep sky science relies on uniform depth, so the missing 15 seconds exposure would have to be obtained later in any case.

Self-shuttering cameras

A key potential science opportunity for a future survey would be to enhance the discovery potential for very short timescale phenomena while being minimally affected by LEOsats. Several aspects of the existing LSSTCam prevent fast exposures. The primary constraint is mechanical: a large mechanical shutter is required for the frame transfer read. The current LSSTCam electronics and data processing are designed around frame transfer CCDs. This is inherently a relatively slow process: even with parallel reads of the 16 segments of the LSSTCam 16 megapixel CCDs, the read noise rises for total read times less than 2 seconds, making exposures less than 10-20 seconds inefficient. CMOS cameras on the other hand can be designed differently, with fast electronics. Applied to a 2nd generation LSSTCam, the CMOS electronics and digital logic would reside next to each CMOS array, with only optical fibers exiting the dewar. The power requirements would be much smaller than the existing LSST camera.

While 3-4 micron pixel CMOS imagers have been developed for consumer applications, a new family of low noise high-QE scientific CMOS detectors, sCMOS, has recently been undergoing rapid development as well. The singular advantages of this type of detector are sub-second low noise read, and self shuttering so that the camera would not have to incorporate a faster shutter. These sensors feature kHz frame rates and support non-destructive read, enabling lower read noise on second timescales.

Scientific CMOS development is accelerating. Medical imaging applications are driving large format, and quantum computing applications are driving high QE and rapid read. There has been recent progress in back-illuminated sCMOS. Whether via mosaicing or larger individual sensors, it is likely that much larger sCMOS will be developed by 2030. Embedded signal processing is becoming more common, and by the end of the LSST survey, this new class of intelligent imager could emerge as an attractive choice for a follow-on mission. The costs of such a replacement are too uncertain at this stage to estimate, in light of the rapid state of technological development. However, it is likely that this would require an investment of at least ~$100M. It is worth mentioning that this would be a facility aimed specifically at short transient detection; none of the low surface brightness programs of LSST could be pursued.

6. Mitigations for LEOsats in parking orbit and orbit raise

At any one time, there should be a few hundred Starlink satellites (plus an unknown number of other LEOsats) in a lower temporary “parking” orbit (phase (iii)) around 380 km. Their presence and impact have been noticed by both astronomy enthusiasts and the professional astronomers, because they are bright, and they move in groups or “trains.” After about 4-8 weeks, their orbits are raised (phase (ii)) to the final orbits at an altitude of 550 km, where they spend most of their lives (5-7 years, phase (iv)).

The reason for the brightness in the parking orbit is two-fold: in addition to being closer, these are also usually configured for low drag, making them brighter. During this time, Starlink satellites are oriented with the solar array in-plane with the spacecraft chassis. In this orientation, satellite brightness is dominated by the white back surface of the solar array. Brightness during this orientation has been reported as dim as g_{mag} = 6 and as bright as g_{mag} = 1. For these early phases, two operational mitigations were developed and are currently being deployed to test satellites:

For parked satellites, SpaceX is changing the orientation of each solar array to prevent sunlight from reaching the back of the array. This has significantly reduced the brightness of parked satellites in phase (iii). (These parked satellites will be further dimmed in phase (iv) in their final orbits using the techniques that are currently being tested such as dark paint and Sun shades.)

For orbit raising satellites in phase (ii), SpaceX is rolling the satellite to reduce the projected area illuminated by the Sun.

Both of these operational techniques were tested in April 2020, and have now been deployed to all satellites in the constellation, including those launched prior to the implementation of this mitigation.

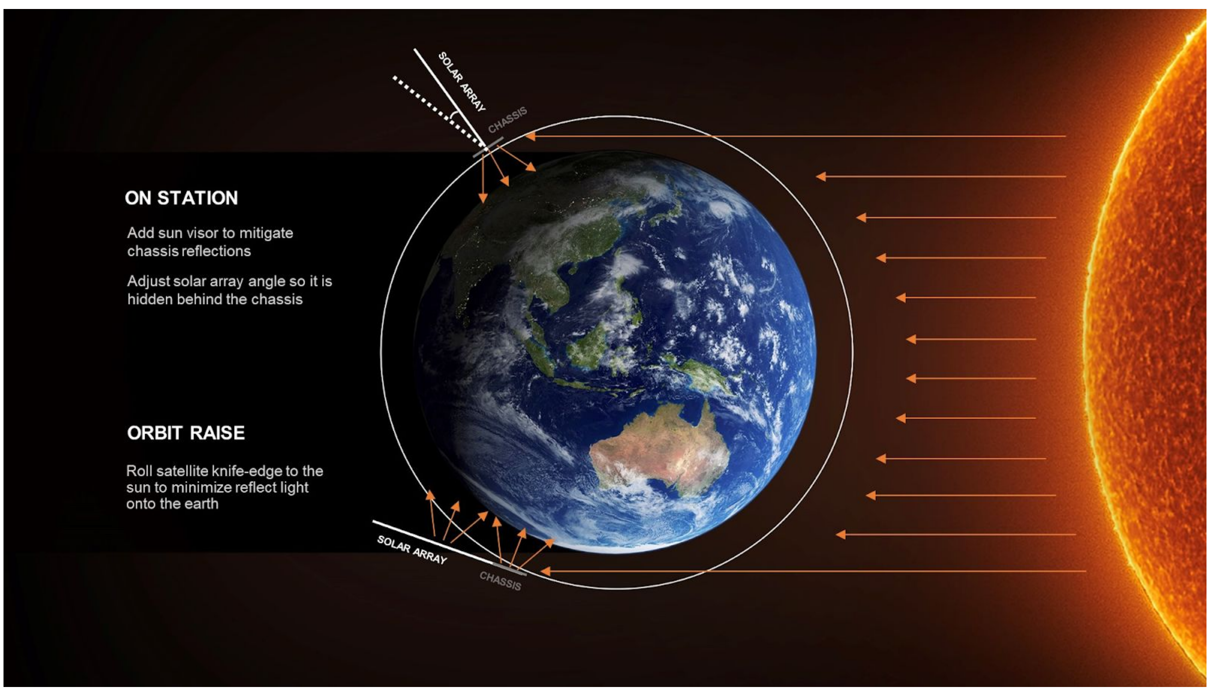

Figure C.4. Operational Mitigations: During orbit raise, satellites are rolled edge-on to the Sun to reduce the projected area illuminated by sunlight. On station, a Sun visor shades reflective nadir-facing chassis components.

Dodging efficiency
If the astronomy community has easy access to precision orbit information for LEOsats, then for certain facilities it may be possible to dodge 300 of them. For other facilities with very wide fields, rigorously pre-set observing programs (e.g., following a selected wide field), or no freedom to move on the sky, such dodging will not be possible (facilities can decide to lose all the observing time while these are visible). For observatory operations convenience, it may be better to have groups of 60 of these satellites highly clumped. This would minimize the number of sky windows to avoid. It is estimated that, with accurate orbit information provided publicly by constellation operators such as SpaceX, Rubin Observatory will be able to avoid as many as 300 known bright objects such as LEOsats in an optimized observation scheduler.

While these satellites will be clumped into single-digit groups, scheduling is also made more difficult in this category due to the format of publicly available satellite attitude information. Two-line-elements, which estimate the satellite as a projectile, account poorly for non-uniform acceleration. Orbit raising satellites are thrusting to change their orbits and parked satellites must burn more frequently due to the higher drag environment of the lower orbit. The frequent thrusting in both cases results in a higher TLE error during these stages of the satellites' lifetimes.

Flares
Until the recent operational mitigations, Starlink satellites in the parking orbit have been in the "openbook" configuration in which the solar array is placed in-plane with the chassis in order to minimize the drag on the vehicle. In this configuration, the diffuse, white backsheet of the solar array makes the satellites appear much brighter and have been reported at 1–2 mag, with rare flares as bright as –2 mag. Rolling the satellite bus to edge-on during parking and orbit raise will reduce the frequency of specular reflections off the array and bus. In the operational configuration, solar specular glints from the solar array should be directed away from observers. The majority of specular surfaces on the bus will be shaded by the visor. Remaining specular surfaces will be modeled by a full-satellite optical signature model, with the goal of reduction in frequency via future operational and design modifications.

Optical ghosts in the camera
Such bright flares, if they occur within several degrees of the camera FOV, can impact an exposure. Many optics used in astronomy produce ghost images due to multiple reflections internal to the camera and its optics. Notably, fast focus refractors produce a ghost that is centrally mirrored on to the optical axis.

7. Investigations of systematic effects due to LEOsat trails; and residual artifacts, time-critical observations, data analysis challenges, and plans for simulations of science impact under realistic constellation scenarios

Studying systematic effects of LEOsat trails on astronomical images is arguably the biggest item on our to-do list as a community, but full simulations of the science impact may take years, or will be learned as the impact happens. Because LEOsats can be slightly out of focus (for the largest telescopes), their trails have a “square” surface brightness profile with wings. This is good and bad: the peak brightness is lower, but the width of the trail is 30–100 arcseconds at surface brightnesses that the astronomy community cares about—implying possible systematic errors for some science applications—depending on how the Rubin Observatory LSST Project masks the trail and how the science community analyzes those data.

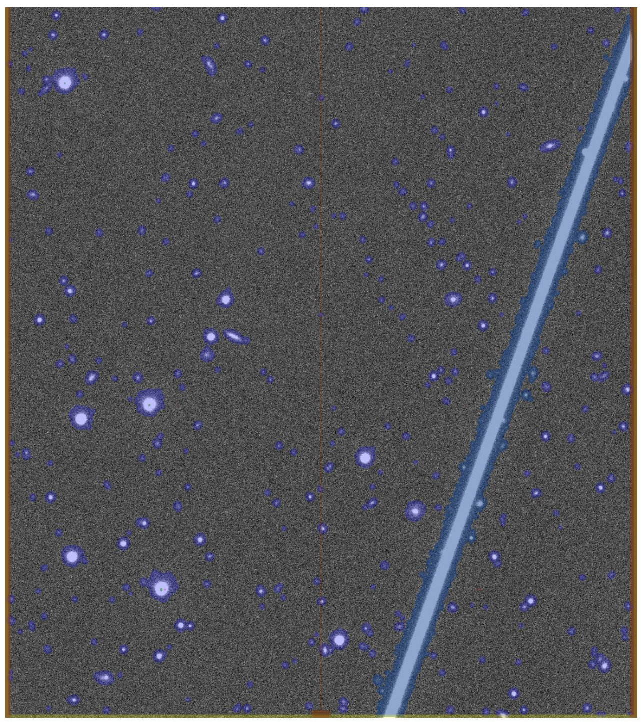

Figure C.5. A LEOsat trail in a portion of a single Subaru HSC CCD, as an example of a LEOsat trail in a wide-field image. This serendipitous observation of FUSE1 was in morning twilight (4:33 am local time on 28 May 2020) at a 55 degree zenith angle (airmass 1.77). The trail is slightly out of focus as expected for infinity focus of an 8 m mirror and a satellite at a range of 1200 km. The peak surface brightness is about 10,000 e/pix in the trail vs 70 e/pix sky noise in a 40-second r band exposure. Low surface brightness fuzz extends to 15 arcseconds. After processing and photometrically calibrating the image, this satellite would have a stationary (tracked) magnitude of $r = 4.2$ AB_{mag} if viewed at zenith.

To a given surface brightness, the power of an imaging survey to discover objects is proportional to etendue: the ability of a sky survey to cover the sky rapidly and deeply is proportional to the etendue. The survey data rate is also proportional to etendue. The high etendue of LSST enables it to revisit the same patch of sky 1000 times, forming a “data cube” containing information on position, flux, flux distribution, and time for every detected object — especially transient events — in that sky patch. The number of satellite trails in a single component exposure is proportional to the product of the size of the field of view, the exposure time, and the number of satellites. The data cube formed by the many revisits to a sky patch encapsulates all component satellite trails, or the residual systematics resulting from their approximate masking in the individual exposures. (Morganson et al 2018) Since the science from LSST will be largely limited by systematics, the correlations introduced by satellite trails (or their masks) can produce false signals in the time domain or at low surface brightness.

Even if the LEOsats are darkened sufficiently that the camera artifacts from the trail may be removed in pixel processing, the satellite trail itself remains. These satellite trails impact science in two separate discovery domains: time and space.

In the space domain, many science programs probe ultra-low surface brightness, usually for faint galaxies, but also for determining the sky level in each image for precision photometry. LEOsat trails exhibit broad low surface brightness wings, as shown below in Fig. C.6. They generally can cause a systematic error which is dependent on how the trail is masked. If masked at too high a brightness, then there will be two parallel lines of correlated noise at the mask edge — biasing weak gravitational lens cosmology.

In the time domain, variations in flux from the satellite as it passes through the camera field of view can occasionally be mistaken for a transient astronomical source — polluting the transient object detections and their statistics. This is shown below in Fig. C.7.

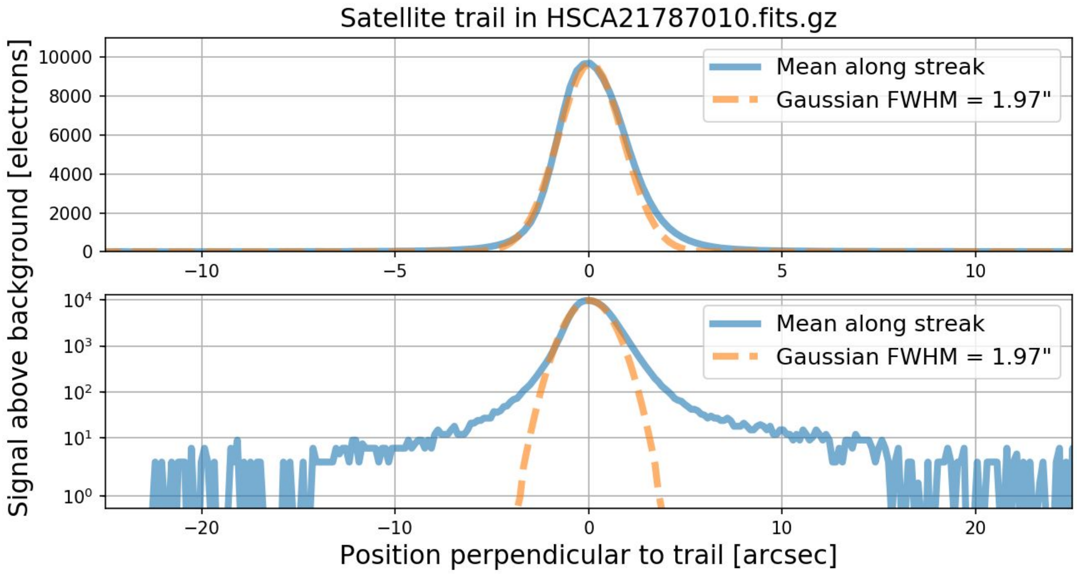

Figure C.6. Mean profile: The mean profile of the FUSE1 satellite trail, estimated as an average of 700 pixels (120 arcseconds) along the trail. Also shown is a Gaussian FWHM (notably larger than the PSF FWHM). Flux from the satellite is observed out to 15 arcseconds in this image, which will require masking without sufficient modeling of the trail.

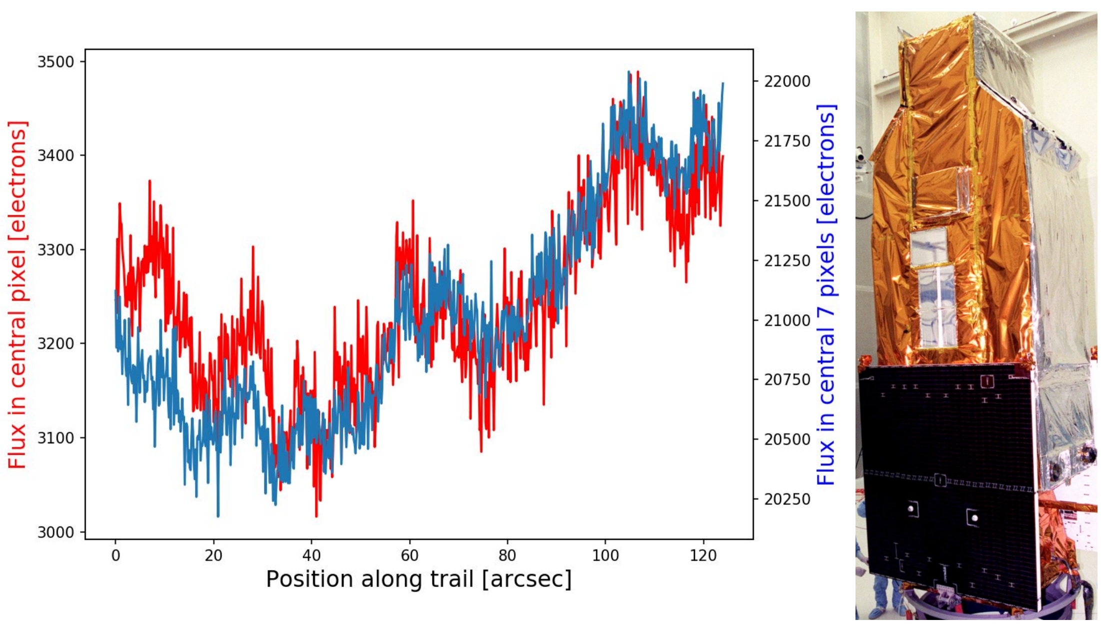

Figure C.7. Trail flux variation: (*left*) shows the flux measured along a portion of the trail in the central pixel (red) and the central seven pixels summed (blue). 10% variation in the per-pixel flux is seen along this trail. Large variations can be caused by changing reflections off the MLI blanket of the spacecraft (*right*).

E. Broad Impacts and Mitigation Strategies

Scientific investigations carried out by the large abundance of astronomy projects are very diverse, and thus the adverse effects of satellite trails are also diverse. Some projects try to measure the brightness of millions of stars to very high precision, using a large ensemble of comparison stars (e.g., looking for transiting exoplanets or small amplitude variable phenomena that reveal interesting physics). Other projects look for transient events that only happen once. Yet others are looking for faint and varying moving objects in the solar system: potentially hazardous near-Earth asteroids, comets, distant TNOs, and the occasional interstellar visitor such as ‘Oumuamua. At the other extreme, many instruments search for and characterize the faintest low surface brightness features in the Universe. Phenomena reach from near-Earth to cosmological distances, from right now back to the Big Bang. The scientific impact of trails of tens of thousands of LEOsats in images obtained by fast-deep-wide surveys of the sky like Rubin Observatory’s LSST in the next decade will limit discoveries.

The impact of mega-constellations also extends to planetary defense, and sometimes to literal impacts (https://www.nasa.gov/planetarydefense). Four small asteroids have been discovered before they impacted Earth: in 2008, 2014, 2018 and 2019. As the short interval between the most recent two imply, we are already getting more efficient at finding them. The advent of mega-constellations threatens our ability to identify and mitigate near-Earth object impact risks, as well as innumerable science investigations, just as new large-aperture, high-etendue facilities are nearing first light and are poised to address both goals. Time domain astronomy requires rapid follow-up observations coordinated through community brokers. The operators of mega-constellations should strongly consider participating in technical astronomy meetings such as SPIE’s Astronomical Telescopes and Instrumentation or Hot-wiring the Transient Universe (https://sites.northwestern.edu/hotwired6/program/). Mitigation strategies for LEO constellations will sometimes require trading off the needs of multiple astronomical facilities at the same time.

Not all astronomical facilities are telescopes. trails introduced into our data tonight will contaminate the holdings of astronomical archives indefinitely. Digital image archives reaching back decades are routinely and frequently searched, and holdings are repeatedly processed and reprocessed both manually and by automated pipelines. This will be true of the Legacy Survey of Space and Time archive. Even 19th-century photographic plates continue to be consulted for a diversity of purposes.

Astronomical observatories require efficient and reliable access to up-to-date ephemerides, e.g., Two Line Elements (TLE), for all satellites, including those not yet on station after launch, and for any constellations orphaned and adrift after the demise of their original operators. Ephemerides precise to arcseconds and a tenth of a second in time will sometimes be required. Operators should make an effort to announce maneuvers in advance. Archival cases require cradle-to-grave curation of the entire catalog of evolving satellite orbits.

F. Comparison of impact on various observatories and science

Below we list the various science programs on major research optical facilities that may be impacted by LEOsat trails, arranged roughly by etendue. This varies with the observatory and with instrumentation. Science impact is different for twilight observing and with LEOsats at 550 km and general observing all night with LEOsats at 1200 km. Below we list these impacted science programs by facility, and include where possible an estimate of the degree of impact and any suggested approaches to mitigation in science analysis, based on the facility etendue and LEOsat trail signal-to-noise ratio.

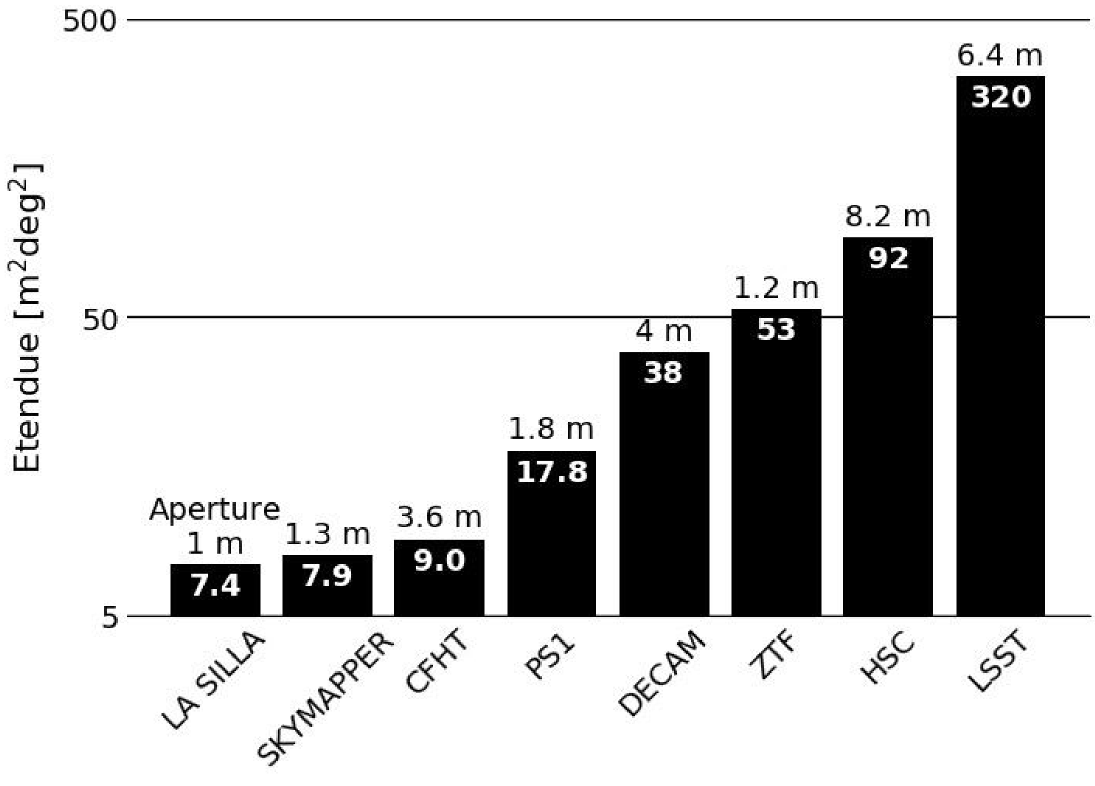

Figure C.8. Etendue of various public observatories on a log scale. To a given surface brightness, the rate of surveying the sky is proportional to etendue.

Rubin Observatory

Some Rubin Observatory LSST science is particularly sensitive to low-level systematic errors. Transient object science can be affected by the trails left by LEOsats, even with mitigations; the statistics of detections and non-detections will be biased. Additional impacts arise from the processing, detection, cataloging, and science analysis overheads due to any satellite trails. After crosstalk suppression, the satellite trails will remain at a very high signal-to-noise ratio, typically 100:1. It remains to be seen if it will be feasible to custom-model and subtract each trail to high precision. It is useful to compare the expected satellite trail brightness with the faint limits LSST is expected to reach. For example, a relatively faint 10,000 electron per pixel LEOsat trail would have a surface brightness about 1000 times greater than most galaxies in the LSST. By comparison, one of the faint galaxies in the "gold sample" of several billion galaxies has ~12 elecrons per pixel average surface brightness in a 30 seconds *g* band exposure (equivalent to 26.5 g_{mag} per sq.arcsec peak). To avoid obvious residuals, the process of satellite trail removal would have to achieve a surface brightness precision of one part in 10,000.

Given the tens of billions of stars and galaxies in the LSST database, sample statistics will not be the dominant source of error. Instead, systematic errors will dominate the science from LSST. One example is cosmology. The masked long trails present a low surface brightness systematic at the edge of the mask, generating a line of correlated noise — potentially producing a cosmic shear bias. Simulations are needed to assess the degree of science impact. The log surface brightness versus transverse distance plot above shows the problem: each satellite trail will have its own LSB systematic error extending from 30-60 arcseconds from the trail, depending on the satellite brightness. These residual errors and correlated linear noise features scale with trail brightness. This leads to a second justification for a ~7th magnitude LEOsat limit.

Rubin Observatory's LSST will uniquely open a new window onto our universe in the time domain: the discovery of the unexpected. Physics allows new classes of objects, and the LSST will probe the faint time domain for the first time. Unfortunately, tens of thousands of LEOsats can generate false signals.

Some observations cannot be easily rescheduled (for example, searches for transient phenomena in special announced directions in the sky, such as optical counterparts to gravitational wave triggers by LIGO and Virgo, gamma-rays bursts, neutrinos, etc). The gravitational wave 90% confidence areas must be covered multiple times by Rubin immediately after the alert, in order to identify the electromagnetic counterpart, so that follow-up spectroscopy can be obtained before the source fades. Dodging satellites during this rapid coverage is not an option.

Another example is the LSST "Deep Drilling" (DDF) fields. About 10% of the observing will be spent on repeated visits to a small number of fields which are comparable in size to the camera field of view. Every night (including some twilight time) one or more of these DDF fields will be readily covered in various filter bands for about 1 hour. These DDF observations are in specific well studied regions of the sky, and involve a rapid series of exposures without delay, and cannot be moved in response to satellites.

Observations in the evening directly after evening astronomical twilight, and in the morning, before morning astronomical twilight, are the only opportunities that astronomers have to search the sky for Near-Earth Objects (NEOs) at small solar elongation. These observations can only be acquired at the same time of night that LEOsats are illuminated. Many of the NEOs that can be seen in these directions seldom or never pass through opposition, and the NEO population with small aphelion is not well understood. NEOs with aphelion near 1 AU spend more time near Earth's orbit, and have higher potential danger of impact to Earth, so are of particular interest to discover and characterize. The satellites that may trail through these images will typically be ten million times as bright as the asteroids that we are trying to discover, and will wipe out long trails in each image, rendering any nearby pixels unusable. Asteroid detection typically requires a time spaced sequence of four images to find moving objects. Each of these four images may have different satellite trails in them, and asteroid discovery is compromised anywhere in the field where a satellite has passed in any of the four images. Although it may be possible to schedule around a smaller number of LEOsats that orbit in a grid system, it is clear that it is not going to be possible to avoid larger numbers of satellites.

Canada-France-Hawaii Telescope (CFHT)
The Canada-France-Hawaii is a 3.6m telescope located at the summit of Maunakea, Hawaii. It operates 5 instruments in queue mode; two wide-field cameras (MegaCam and WIRCam), one wide-field Fourier Transform Imaging Spectrograph (SITELLE) and two high-resolution fiber fed spectropolarimeters (ESPaDOnS and SPIRou). The effects of LEOsats on our two spectro-polarimeters should be minimal since they are fiber-fed by a few fibers covering a few arcsec^2 in the sky. However, the situation is more complicated with our three wide-field cameras. Our most affected instrument is MegaCam which covers an area of 1 square degree, and has an étendue of ~9 m^2/deg^2. Some science programs with this instrument are already starting to be affected. Our other two instruments, WIRCam and SITELLE, are likely to be more affected when the high altitude LEOsats are launched.

CFHT conducts a wide variety of scientific investigations with its three wide-field cameras. MegaCam is on the telescope about half the time and many important science programs will be affected by satellite trails. The instrument consists of 36 2048 x 4612 pixel CCDs (a total of 340 megapixels), covering a 1 x 1 square degree field-of-view with a resolution of 0.187 arcsecond per pixel to properly sample the 0.7 arcsecond median seeing offered by CFHT at Maunakea. The prime focus upper end, MegaPrime, includes an image stabilization unit and a guide/autofocus unit with two independent guide CCD detectors.

The instrument is an integral part of the recovery of Pan-STARRS discoveries of Near Earth Objects (NEOs) and Potentially Hazardous Asteroids (PHAs). The programs are part of NASA's Planetary Protection Program and these recoveries are essential for confirmation and accurate orbit determination. Observation of objects in twilight is an essential part of this program and can recover short elongation NEOs and PHAs located between the Sun and the Earth. The advent of a constellation of tens of thousands of satellites will have a significant impact on the capabilities of the program to recover Pan-STARRS discoveries. The LEOsats trails are orders of magnitude brighter than the sought after asteroids, comets or Interstellar Objects.

An example of the impact of satellite trails on MegaCam images comes from light curve observations of the first Interstellar Object, `Oumuamua discovered by Pan-STARRS and followed up with MegaCam in late 2017. During a sequence of 100 images with 180 second exposure time, three images were affected by LEOsats that passed through the chip (6.7 x 15 arc minutes) that contained `Oumuamua, and one of these satellites passed directly over `Oumuamua rendering the image unusable. Having a much larger number of satellites implies a much higher likelihood of data becoming unusable in long time-sequence image sequences like this. Such recovery attempts can potentially be rescheduled but the likelihood of target recovery goes down quickly with time. Also, it will be difficult to dodge LEOsats given the time-sensitive nature of the observations and the time-dependent error bars associated with the location of the potential recovery candidate.

There are also several observing programs that pursue very deep images using the low-surface brightness mode offered for MegaCam. Any image that contained a satellite trail would need to be discarded for this very deep work, and satellite trails would also need to be very carefully excluded from any flat-field images used to flatten data for this kind of science.

High Altitude LEOsats (HALs) will make things worse for the MegaCam programs cited above and will also affect other programs. Statistics on HALs visibility above Hawaii would be useful to estimate the impact on the instrument. HALs will also affect the operation of SITELLE, our Fourier Transform Imaging Spectrograph. The instrument mainly studies Galactic and Extragalactic HII regions, collecting over 4 million spectra on an 11 x 11 arcminute^2 field of view over windowed wavelengths ranging from 360 to 800 nm. The instrument records a cube of fringes produced by a Michealson interferometer using multiple exposures. A Fourier transform of this cube provides a wavelength cube that can be used for science. A satellite trail on one of the images of the raw fringe cube becomes a delta function when computing the Fourier transform of the fringe image. This operation superposes a sine wave on the whole spectrum of the pixels affected. This artifact is difficult to correct in software and our workaround is to redo the image. Ideally, image redos need to be contemporaneous with other data in the image cube — they can potentially be redone on another night but the changing atmospheric conditions from night to night make asynchronous re-observations much more risky. If the number of high altitude satellite trails becomes too high, we will have to develop a software solution that will require new resources for development. The amount of noise introduced by this correction will significantly affect the scientific capabilities of the instrument.

SUBARU HSC and PFS

The Subaru Telescope is an 8.2-meter telescope run by the National Astronomical Observatory of Japan on the summit of Mauna Kea in Hawaii. It hosts several instruments, of which two, the Hyper Suprime-Cam (HSC) and the Prime Focus Spectrograph (PFS), are the most sensitive to satellite contamination. HSC is an 870-megapixel prime focus optical imaging camera. The wide-field corrector delivers sharp images of 0.2 arcsec FWHM in the HSC-i band over the entire 1.5 degree diameter field of view. It will hold the world fastest survey speed until the Rubin Observatory LSST camera comes in two years. A five band wide-field campaign has been carried out to cover 1200 square degrees. The survey will continue to the end of 2021, followed by a recently approved 5000 square degree z-band survey. Prime Focus Spectrograph (PFS) is a fiber-fed spectrograph which shares the wide-field corrector with HSC. The multiplicity reaches up to 2500 and will become one of the most powerful spectrographs in a few years.

HSC is in many ways similar to Rubin Observatory; however, exposure times are typically longer, with many at 300 seconds, making it even more sensitive to satellite contamination. Indeed, satellite trails are already detected in a significant fraction of HSC images. The Subaru Strategic Program is the largest survey performed on HSC, currently using about 20% of the time on the Subaru Telescope, and includes NEO surveys. However, the survey includes some deep-drilling fields of the sky that are only visible at low elevation near twilight during certain periods of the year, meaning that they cannot be scheduled for times that will be less sensitive to satellites. Additionally, much of the observing time on HSC is used by astronomers who have been awarded a single night or half-night. Given these circumstances, they generally do not have the option to reschedule observations in order to avoid satellites.

The Prime Focus Spectrograph (PFS) is a fiber spectrograph that will soon begin observations. It has 2400 optical fibers that take simultaneous measurements of optical to infrared spectra over 1.3 square degrees. Assuming 40,000 satellites, this would mean that about 10 fibers would be affected during a typical 900-second exposure at twilight (-18 degrees) with up to around 40 fibers for the longest exposures. As described with VISTA 4MOST below, satellites may be difficult to detect in the data, leading to contaminated results.

DESI

The Dark Energy Spectroscopic Instrument (DESI) is a wide-field spectrograph on the Mayall 4-meter telescope at Kitt Peak National Observatory. With a 3.2-degree field of view and long exposures (10-20 minutes), it is not possible to "point between" satellite trails. However, DESI is blind to the light except when a trail intersects one of the 5000 optical fibers, each 1.5" on the sky. For constellations of 50,000 satellites, the trails affect roughly 0.5-1% of the fibers (if we neglect the wide satellite trail at low surface brightness), depending on constellation height. The impact depends on the brightness. Our estimate is that satellites brighter than about 7th magnitude substantially increase the Poisson noise in the spectrum; this cannot be mitigated in processing and essentially loses this object from the primary science application. With arcsecond-level prediction of trails an hour in advance, DESI could opt to avoid objects that would be impacted, i.e., we could choose other targets for individual fibers. Somewhat fainter satellites (down to about m=10) might still require some subtraction from the signal. For this, it would be best to detect the satellites with contemporary co-pointed imaging, so that our processing can determine which fibers were affected and with how much light. DESI already has a co-pointed sky monitor mounted on the truss; we are considering whether this could serve to supply the images. However, we note that a) this is a substantial software effort that risks duplication across observatories, and b) it implies that the sky monitor might need to be classified as essential equipment, which implies a stringent new requirement on up-time reliability.

DESI's fibers feed 10 three-arm spectrographs producing spectra that cover a wavelength range from 360-980 nm and have resolution of 2000-5500 depending on the wavelength. The DESI instrument is designed for a 14,000 sq. deg. multi-year survey of targets that trace the evolution of dark energy out to redshift 3.5 using the redshifts of luminous red galaxies, emission-line galaxies, and quasars. DESI complements imaging surveys such as the Rubin Observatory's LSST. DESI has completed its construction phase and will begin operations in 2021. LEOsats will impact DESI spectroscopy because of the large number of fibers, the width of each satellite tral, and especially the long integration times.

VISTA/4MOST

The 4.1m Visible and Infrared Survey Telescope for Astronomy (VISTA) located at ESO's Paranal Observatory will soon be fitted with 4MOST, a fiber-fed spectrograph to observe simultaneously 2400 objects in 4.1 square deg field-of-view. Considering ~80,000 satellites from the Starlink and OneWeb constellations, simulating the number of satellites crossing the instrument field of view and the average number of fibers affected by a satellite trail, up to 57 (2.3%) of the 4MOST fibers could be affected by a satellite during a 20min exposure at –18° twilight. While the contamination by low-altitude Starlink satellites stops as soon as the Sun drops below 24° below the horizon, the high altitude of the OneWeb satellites means the effect remains noticeable for various hours after and before the twilight, and during the whole night in summer. While these levels of losses are not negligible, the gigantic multiplexing factor of 4MOST allows it to deal with these losses, provided that the affected fibres are identified.

An illuminated satellite crossing the field-of-view of a 4MOST fiber will cause contamination at a level comparable to that of the science targets: both the satellites' effective magnitudes and the targets are in the mag 18-21 range. There will, therefore, be cases for which the on-the-fly data quality control will not identify the contamination (e.g. if the satellite is a few times fainter than the target), causing contaminated data to reach the science analysis, and/or precluding the ruined data to be re-acquired. To mitigate the impacts, it is important to be able to flag a-posteriori (within ~24 hours after the observations) which fibers were affected by a satellite. This implies having access to the positions of the satellites with a precision of ~1 arcseconds transverse to the trail (translating to a few meters at an altitude of 550 km), and with a timing accuracy of ~1sec. Additional *a priori* mitigation could limit the number of affected fibers: i) probabilistically, implying to have a generic description of the constellations (number of satellites, number of planes, inclination of the planes), and ii) specifically, implying having access to orbital elements enabling the 24-hour forecast of the apparent positions of the satellites at the arcminute level (transverse) and with a timing accuracy of ~1 minute.
Like other large observatories, some of the VISTA /4MOST science programs rely on LSST and are impacted by impacts on the LSST data.

Gemini Observatory

Gemini Observatory is an international partnership involving the USA, Canada, Brazil, Republic of Korea, Argentina, and Chile. It consists of twin 8.1-meter telescopes located on Mauna Kea in Hawaii and Cerro Pachon in Chile, thus providing access to targets over the entire sky. Gemini's queue-scheduled operations model and ability to switch rapidly among several instruments mounted on the telescope enable quick adaptation to changing observing conditions and efficient, multi-instrument target-of-opportunity observations. In particular, the geographical proximity of Gemini South to Rubin Observatory, so that they share the same immediate atmospheric conditions, and the availability of Gemini North for coordinated observations of equatorial targets for six hours after sunrise on Cerro Pachon, make Gemini a key part of the plans for spectroscopic follow-up of the most scientifically compelling transients discovered by the LSST.

Specifically designed for rapid and efficient follow up of LSST transients, the Spectrograph and Camera for Observations of Rapid Phenomena in the Infrared and Optical (SCORPIO), is an 8-channel imaging spectrograph currently in development for Gemini South. SCORPIO will simultaneously cover the range from 385 nm to 2.35 μm over a 4' field with eight independent arms that will allow exposure times to be set individually for each of the bandpasses in both imaging and spectroscopic modes. The throughput is optimized for spectroscopy of faint sources, while the negligible readout times of its detectors will enable short photometric exposures providing very high time resolution. SCORPIO is scheduled to be commissioned by the start of Rubin operations.

In addition, with new funding provided by the NSF, Gemini has undertaken major operations upgrades in preparation for the large number of transient alerts that will be produced by the LSST. These upgrades include the implementation of automatic triggering of observations of high-priority targets identified by transient alert brokers that monitor the public alert stream. As part of this, Gemini is developing dynamic queue scheduling software to optimize the planning and execution of all observations as new follow-up targets are triggered during the course of the night. The dynamic scheduler will incorporate information on current weather conditions, image quality and other constraints, program priority, and required turnaround time for meeting the science goals.

Of course, the most rapidly scheduled and efficiently executed follow-up observation may be ruined by an unfortunate coincidence of a satellite crossing the field during the exposure. The brightness of these satellites, even with greatly reduced reflectivity, would be sufficient to overwhelm the signal from any LSST transient target. The risk of this is low for any given exposure, but it increases for the most compelling transients that may be followed into twilight and/or until they are at low elevation. A prime example of this was the kilonova associated with GW170817, which was observed every possible night for nearly a month by Gemini South and other observatories, beginning in evening twilight and ending when the target was lost at high airmass. In the presence of 40,000 LEOs, the risk of losing a long exposure during the course of a multi-hour follow-up extending to low elevation is significant. Moreover, for satellites orbiting at 1200 km, for much of the year the risk remains significant throughout the night.

For the specific case of Gemini’s dedicated, automatically scheduled follow-up of high-priority faint transients discovered by Rubin, the most critical mitigation would be the availability of detailed and timely positional information for all LEOsats, with accuracy to arcsecond in position and seconds in time, as discussed in this report. This information could be incorporated into Gemini’s development of the dynamic scheduling software, and the worst coincidences could be avoided with optimized scheduling algorithms. Moreover, with the fast shutter and fast readout of SCORPIO and other Gemini instruments, it would then be possible to use active shuttering to avoid satellites trailing through the follow-up observations. To minimize time loss, the satellite location data must have high temporal accuracy.

SALT

The 9.6-m Southern African Large Telescope (SALT) is primarily used for optical long-slit and multi-object spectroscopy and narrow-field (~8 arcminutes) imaging. Over the next decade, near-infrared capability will be added, and ideas for multi-object spectroscopy over the much wider field of regard are under development. SALT is fully queue-scheduled and as the largest optical telescope in the southern hemisphere, it is an ideal instrument for follow-up of discoveries from the Rubin Observatory Legacy Survey of Space and Time (LSST). For time-domain astronomy, its geographic location in South Africa provides a unique time window when objects are not observable to telescopes at other locations. SALT has a 53 degree fixed elevation design such that only part of the sky is available at any time (objects at airmass ~1.3 at any azimuth are observable, typically for about one hour). LEOsats with lower elevation thus pose no concern. If paths of LEOsats could be well predicted (say ~one hour in advance) the dynamic queue scheduling for SALT could be modified to avoid taking observations that would be significantly impacted. This would not be feasible with tens of thousands of LEOsats.

VLT

ESO’s Very Large Telescope on Paranal, consisting of four 8.2-meter telescopes that can operate independently or combined, caters for a wide range of science cases, performing observations with a series of instruments. Like all ESO telescopes, it is accessible to astronomers from the whole world. Like other large observatories, some of the VLT science programs rely on LSST and are affected by impacts on the LSST data. The observations can be split in various categories, affected differently:

- **Imaging** (eg FORS2-imaging, HAWKI), with a moderate field of view (6 arcminutes for FORS2), with individual exposure times in the range of a minute or less (in particular in the IR) to a few minutes (for visible and narrow-band filters). Because of the moderate field of view and relatively short exposure times, this type of exposure is less likely to be crossed by a satellite trail. When it happens, the pixels under the trail are likely to be unrescuable, but the remainder of the field of view could still be usable, depending on the science case.

- **Spectroscopy** (eg UVES, XSHOOTER FORS2-spectro) is performed through a narrow slit (and up to ~30 slitlets in multi-object mode) a few arcsec to a few arcminutes long, with long exposure times (20 to 60 min). While the probability of a satellite crossing the field of view is small, the longer exposure times result in about the same level of contamination as for the imaging case. Because of the partial lack of spatial information in the spectra, the contamination by a satellite trail will appear as a spurious solar-type spectrum, which can be on top of that of the scientific target. Because of the fast motion of the satellites and the dispersion of the light by the spectrograph, the level of contamination will in some cases be fainter than the signal from the science target, which raises the prospect of the contamination being noticed only when analyzing the data. This implies that an a-posteriori way to determine whether a satellite crossed the field would be important.

- **Thermal IR and interferometry**: because of the small field of view (very small in case of interferometry) and short exposure times at that wavelength regime, the probability of an exposure being contaminated is small. In these modes, exposures are taken in series, so that the few contaminated exposures (if any) can be rejected with only a minor impact on the series.

Because the VLT is operated mostly in service mode (queued), most observations could be scheduled so to avoid the regions of the sky and part of the night that are most affected by satellites. Time-critical observations, transient observations, and a series of (near-) twilight observations (ranging from comets at low elongation to long-term monitoring covering the whole season from heliacal rise to setting) can not accommodate these constraints, and would be more affected.

Blanco DECam

Víctor M. Blanco 4-meter Telescope, Dark Energy Camera. Field of view 3 degrees^2, 0.263” per pixel resolution with 60 science CCDs that are known to exhibit crosstalk. Sensitivity is m ~ 23.5 mag (g-band) in 20 seconds, m ~ 26.5 magnitude (g-band) in an hour. Programs include deep galaxy surveys and transient surveys, including fast (seconds-to-hours duration) transients. Exposure times range from 20s to 900s.

- **Gravitational Wave electromagnetic counterpart searches** — CTIO DEcam is the main search telescope for LIGO/Virgo and future gravitational wave (GW) events, as they now reach well beyond 200 Mpc, causing the kilonova counterparts to require 4m-8m-class telescopes with wide-field imagers. The search areas are large tens to 1000s of degrees and DECam has the widest field of view of any 4-8-meter-class telescope. The events have durations of 1-4 days in the optical and the opportunity to image the large areas is typically only once, as it takes 1 or more nights to cover the needed area and access to telescope time is limited. Given the large area coverage needed, single exposures in g and z-band are the only viable observing strategy to provide a reference image and later detection image. Satellite trails eliminate the detection of any source in that filter. Missing one of two filter images (g and z) eliminates the ability to detect the source in the reference and detection image (both are needed).

- **Galaxy surveys** — Require very deep imaging consisting of long exposures and stacking those for the required depth. High redshift galaxies are 2-100 million times fainter (m ~ 23–27) than a V_{mag} = 7 satellite, however, the effect is diminished correspondingly for satellites moving at e.g., 0.5 deg/s. Satellites eliminate the use of the region of the frames for faint galaxy science extending > 60 pixels away from the satellite trail (i.e., 120-pixel diameter equivalent to ~30-arcsecond swath). Bright (m < 12) object reflections and ghosts can negatively impact, or prohibit the detection of faint galaxy detection in large regions of the field.
- **Fast transients** — Satellites passing near or over fast transients with short durations (seconds duration) can result in the complete loss of detection or adversely affect the measurements of the light curve evolution of events that are minutes-long or events that are little understood (and of high impact). Moreover, as the millisecond-to-second duration events are rare and little understood, glints from satellite reflections can appear as false transient candidates, contaminating the detections. Satellites would make understanding these events and their physics extremely difficult and could prevent any further progress in this burgeoning area of science. Finally, programs such as the DWF program coordinate ~30 other major telescopes at all wavelengths to observe simultaneously with CTIO DECam and to provide rapid follow up on 8m-class and space-based telescopes. Thus, as DECam (or Subaru HSC) are the deep optical telescope(s) in such programs, the negative impact cost from the satellites on the missed or negatively affected transients extends beyond the observations of the one telescope.
- **Very early transients** — Finally, very early detection of slower evolving events are rare and important, as they provide key observational insight into the physics of the explosions that cannot be gleaned otherwise. In addition, these events are very faint, as they are just beginning to explode and rise in brightness. A satellite near (e.g., within ~15 arcseconds) a very early detection can negate that event and rare opportunity, as typically 1-3 exposures are taken of areas on the sky each night. Having one frame lost results in no detection or a signal too faint to confirm and the lost opportunity to catch the event.

ELT

ESO's Extremely Large Telescope will cater to a variety of science cases, using various instruments. Their fields of view are small (arcsec), resulting in a low probability of encountering a satellite. However, the individual exposures will range from seconds to minutes, resulting in a non-negligible probability that an exposure will be affected (up to 1% at twilight for a 1h exposure). Because of the gigantic collecting area of the telescope, scientific data in exposures with a satellite will be overwhelmingly dominated by the light from the satellite. Furthermore, some of the ELT science programs will rely on LSST and are therefore indirectly impacted by impacts on the LSST data.

Keck (LRIS, DEIMOS, MOSFIRE) [FOBOS 20', KWFI 1 deg, proposed]
The W. M. Keck Observatory is a partnership between Caltech, The University of California, U. S. Community access via NASA, and other institutions. Keck operates two 10-meter segmented aperture telescopes on the summit of Mauna Kea in Hawaii, providing full coverage of northern declinations, and southern declinations down to approximately -40 degrees. A total of ten instruments are currently in use on Keck, with ~5 available at any given time, to facilitate rapid instrument switching for target of opportunity observations (e.g., supernova, rare bursting phenomena, and gravitational wave source follow up).

The field of view for Keck instrumentation ranges from tens of arcseconds for adaptive optics driven observations to up to ~20 arcminutes for natural seeing observations. Keck instrumentation performs imaging, polarimetry, and spectroscopy either with single or multiple slits, or with integral field systems. At the present time, the primary impact of LEO constellations is likely to be on deep (e..g, early Universe, galaxy, faint source) multi-object (~100-200 objects per mask) spectroscopy from the DEIMOS (FOV 16.7' x 5') and deep imaging and multi-object (~40 objects per mask) spectroscopy using LRIS having a 6' x 7.8' FOV. Integration times are typically 1800s, thus a satellite trail results in key data loss on long and costly exposures. Given the short time allocations per science program for this highly over-subscribed facility, many lost data cannot be re-attempted. In addition, some universities purchase the nights directly (>$100K USD per ~8 hr night), making 30 min exposures costly. In addition, MOSFIRE is a very sensitive Keck infrared instrument having a 6.1' x 6.1' FOV. As the exposure times are significantly shorter for MOSFIRE, mitigation is less important. Typical exposure time in the IR, tens of seconds to a few minutes.

In the future, Keck is considering wider field instrumentation for which LEO constellations would have a potentially large impact. The Keck Wide Field Imager (KWFI) is a UV-sensitive optical imager with a 1-degree field of view. KWFI would need mitigation strategies as it combines its large field of view and very high sensitivity toward bluer wavelengths. Transient and Deep imaging (to m ~ 29, i.e., more than half a billion times fainter than V_{mag} = 7 satellite) are key science drivers. The sensitivity of KWFI is ~3x that of Subaru HSC in the g-band, and typical exposure times are 300-900s and would incur similar/greater data loss. An additional concern is that satellites brighter than the V_{mag} = 7, as studied here, could potentially saturate the pixels. As a result, satellites would incur long-exposure data loss, but if reaching saturation, more significant data loss and correction complications from charge bleed. Finally, FOBOS, a planned wide-field multi-object spectrograph (20 arcmin diameter) will have a FOV much larger than DEIMOS, but will be blue-sensitive and acquire 1800 spectra per pointing, versus ~100-200 with DEIMOS.

Regarding mitigation, an all-sky monitor coupled with coordination via software could help mitigate impacts for all Mauna Kea observatories, particularly if the orbits are poorly known. Additionally, considerations should be given to a combination of all-sky monitoring + input orbits for better orbit definition. Observatories should strive to use mitigation techniques to augment metadata to improve data education and assist archival use for the world community.

AAT AAOmega+2dF

The AAT is a 3.9-meter telescope at Siding Spring Observatory in Australia and the AAOmega+2dF is a spectrograph with a 3 deg^2 (2-degree diameter) field of view and 392 fibers. Most science cases involve transient follow up from wide-field imaging surveys (e.g., the Dark Energy Survey (DES) via the OzDES program and aims to deliver for the Rubin Observatory), and deep galaxy spectroscopic surveys. So the science programs will be as impacted as the LSST data.

Maunakea Spectroscopic Explorer

The Maunakea Spectroscopic Explorer project will transform the CFHT 3.6-meter optical telescope into an 11 meter dedicated multi-object spectroscopic facility, with an ability to simultaneously observe more than four thousand objects simultaneously using a suite of spectrographs with a spectral resolution spanning 3,000 to 40,000. MSE is transforming and expanding the current CFHT partnership into one poised to tackle global themes in concert with the coming wide-field surveys such as LSST and the new Extremely Large Telescopes. The project completed Conceptual Design in 2018 and has recently entered the Preliminary Design Phase. A technically-paced schedule will see full science operations late in the 2020s, pending community consultations and important milestones, including the renewal of the Master Lease for the observatories on Maunakea. In concept, MSE is an 11-m-class version of 4MOST, with a field of view of 1.5 square degrees and 4200 fibers. We expect that, on average, at least 10 fibers would be affected per exposure due to LEOsats (the equivalent of a couple of hundred fibers per night).

This is likely an underestimate due to the wide satellite trails at the low fluxes that would impact our spectra. As a very large aperture facility, MSE will generally always target very faint sources, and so the signal from these satellites will dominate over the science target. Practically speaking, this will mean that the observation of those targets will be lost for science. It is intended that MSE observations will be able to be scheduled dynamically and automatically, to take best advantage of available sky conditions. Accurate knowledge of the anticipated paths of satellites may need to be incorporated into the scheduler in order to mitigate the otherwise significant number of lost observations. Finally, we note that even although MSE is a northern hemisphere facility, it can target more than half of the main LSST survey footprint, and so impacts of the satellites on LSST data will also impact MSE target selection.

PAN-STARRS

Pan-STARRS consists of two 1.8-meter telescopes near the summit of Haleakala. Each telescope has a 3.3-degree diameter field-of-view. Pan-STARRS presently spends 90% of its observing time searching the sky for Near-Earth Objects (NEOs — asteroids or comets that have perihelia less than 1.3 AUs). The main motivation for this is planetary defense — to find any objects that may hit Earth well in advance of the impact — so that efforts can be made to deflect the impact of larger objects, or to provide warnings for the impact of smaller objects.

All observations to discover Near-Earth objects require four images spaced over approximately 1 hour. Satellite trails will affect each of these four images, and regions in the sky affected in any of these component images will be ruined for NEO detection. So it is the product of trails in any of the four images that is damaged for science. Rough estimates suggest that 10–20% of the imaging area may be damaged, depending on the altitude of satellites and the number, but more detailed simulations will be required to properly assess the impact.

All-sky video monitors will not help, because there is no agility on scheduling once a one-hour sequence has been commenced, and the field of view is large. One mitigation would be to replace the cameras on each of the Pan-STARRS telescopes — approximate cost $6 million each. The existing cameras use orthogonal transfer arrays, which are not ideal for NEO searches. New cameras using modern larger CCDs could recover approximately the area of sky that will be lost due to satellites. The cost of two cameras (one for each telescope) is $12 million. Independent of the satellite threat, Pan-STARRS is planning to upgrade the cameras, and a proposal for funding has been submitted.

Another mitigation for the NEO search program would be to build another Pan-STARRS telescope. The approximate cost for a new Pan-STARRS telescope (including camera) is $20 million, plus additional cost for environmental assessment work ($1 million or more); there are suitable locations for two more Pan-STARRS telescopes on Haleakala. Adding another telescope produces additional operations cost. If satellite trails cause a loss of 20%, then three telescopes would produce 1.2 times as much sky coverage as two telescopes with no satellite trails (assuming 20% loss from satellite trails).

Stationary transients are also discovered from the NEO data stream, and this science will also be harmed by satellite trails, but to a lesser extent than NEO discovery, since only the individual trails in the component images will be lost, rather than the product of trails in the four-image sequence.

ZTF

The Zwicky Transient Facility (ZTF) is a new optical time-domain survey that uses the Palomar 48-inch Schmidt telescope to monitor the entire northern sky (Graham et al. 2019, PASP 131, 8001; Bellm et al. 2019, PASP 131, 8002). ZTF observing time is divided between several major programs, including the public surveys, which aim to observe the entire visible sky every three nights. The telescope is equipped with a custom-build wide-field camera that provides a 47 $degree^2$ field of view, which enables surveying the sky at a rate of 4,000 $degree^2$ per hour. Thus, a large fraction of science images taken during twilight may be affected by LEOsat trails.

ZTF surveys the entire visible sky according to a pre-programmed schedule (Bellm et al. 2019, PASP 131, 8003) and, in principle, modifying the scheduler algorithm to avoid LEOsats to some extent may be possible. However, as the number of LEOsats is expected to rise, avoiding them will lead to significant losses of observing time and will eventually become impractical. In the current ZTF data reduction pipeline (Masci et al. 2019, PASP 131, 8003), bright satellite and aircraft trails are masked and the masked area is lost.

Several science programs may be impacted by LEOsat trails. In addition to the normal survey observations, ZTF performs "twilight" observations at dawn/dust to look for interior to the Earth asteroids and comets. Satellite/airplane trails may be mistaken with fast-moving near-Earth objects, but the ZTF collaboration uses a convolutional-neural-network, deep-learning classifier to identify fast-moving solar system objects and this algorithm is very efficient in rejecting satellite/aircraft trails (which make up the majority of all trail-like objects in the ZTF data; Duev et al. 2019, MNRAS 486, 4158).

LEOsats may also affect target-of-opportunity (ToO) observations of transient phenomena, such as gamma-ray bursts, neutrino counterparts, or gravitational wave triggers by LIGO and Virgo. These science programs are extremely time-sensitive and often require observations of large areas of the sky in a limited amount of time. Moreover, many ToO programs conducted by the ZTF collaboration use longer exposure times (300 s) than those in the regular survey (30 s), increasing the probability that a satellite enters the field of view. Another science area that may be potentially affected by LEOsat trails are searches for fast optical transients (on subsecond timescales), for example, optical counterparts to fast radio bursts.

ATLAS4

ATLAS was proposed as a replicable system that NASA could use to find dangerous asteroids, and optimization for the NASA mission opens synergistic opportunities for many other types of science. Predicting asteroid collisions with Earth places constraints on system capability, for example, warning of at least one day for a 1 Mton explosion requires all-sky monitoring at a sensitivity of m > 19. ATLAS consists of 0.5-meter diameter telescopes, each with 30 degree^2 field-of-view. One telescope is located on Haleakala, one on Mauna Loa, and two new telescopes are being constructed — one in Chile, and one in South Africa. Nearly every image would contain satellite trails. The impact likely will be larger than for Pan-STARRS due to the large field-of-view, and because pixels are larger, meaning that a larger percentage of pixels will be affected in each image. The main aim of ATLAS is the detection of Near-Earth Objects. Sequences of four time-spaced images are acquired. Trails in any one of the four images will affect the science in that part of the detector in all four images.

The only practical mitigation is to build more telescopes, which carries with it additional construction and operating cost. With such a large field-of-view, it is impractical to schedule around predicted satellite locations.

Catalina Sky Survey

Catalina Sky Survey (CSS) is the longest-running Near-Earth Object (NEO) survey and has discovered almost half of known NEOs, including more large Potentially Hazardous Asteroids (PHAs) than any other planetary defense survey. The broader science cases for CSS are similar to Pan-STARRS and ATLAS (http://nesssi.cacr.caltech.edu/DataRelease). Near-Sun observations in the early evening and late morning hours are especially valuable — when the interference from satellites in LEO will be largest.

CSS operates follow-up telescopes as well as our surveys using flexible queue scheduling. We will incur the loss of a similar fraction of our pixels/exposures as other wide-field, large-pixel surveys described here. Satellite trails, their optical artifacts, and electronic cross-talk introduce large numbers of false candidate moving objects that must be scrubbed by human eyeballs and/or machine-learning techniques. The question is: which pixels and images will be compromised (including archival precovery images)?

Mitigation for CSS operations will depend on predicting which queued exposures will be most affected, especially by multiple bright satellites in their initial trains, or by particularly inauspicious multiple satellite crossings. CSS has flexibility in reordering our queues, though similar scheduling concerns apply as for Las Cumbres Observatory. Given timely and accurate ephemerides and having predicted an exposure at risk, we may be able to substitute a different pointing. This will incur slewing overhead and introduce otherwise unnecessary complexity to our systems and procedures.

Images occur in multi-field multi-exposure sets covering between 50-200 square degrees four times in about 25 minutes. At some times of the night, every set will see multiple satellite trails. In the case of tens of thousands of LEOsats in the higher allocated orbits, every image could include trails. Reordering the queue may only spread the trails more evenly. An alternative would be to increase the number of repeat exposures of each field from 4 to 5 (or more) to compensate for clobbered pixels and exposures. This would incur at least a 25% penalty in time and efficiency of surveying, and ultimately can only be mitigated by commissioning additional telescopes in support of planetary defense.

Las Cumbres Observatory

Las Cumbres Observatory is a network of twenty-three robotically operated 0.4, 1, and 2-meter telescopes. The observatory operates as a single instrument, with the schedule dynamically updated every few minutes. The network was designed for transient event follow-up and characterization in multiple time-domain astronomy fields. Programs likely to be most impacted are observations of near-earth asteroids (NEOs) and comets, frequently only visible near twilight where the satellites would be brightest. This will also affect any sidereal targets with limited visibility near twilight. As discussed for ZTF above, LEOsats can affect observations of rare transient phenomena, such as gamma-ray bursts, neutrino counterparts, or gravitational wave triggers by LIGO and Virgo. Some supernova observations can only be taken within hours of the explosion. Observations of transient microlensing anomalies, which can reveal the presence of exoplanets but typically last only hours, are similarly impacted, as are programs studying stellar flares and accretion outbursts. These programs are extremely time-sensitive and often require observations of large areas of the sky in a limited amount of time. The time sensitivity associated with unique or rare events also often means following unique targets in morning or evening twilight.

Calibration relies on sky flats (the domes do not have internal flat-fielding capability), which must be done in morning and evening twilight. Since each telescope has 21 filters, there is not enough time during twilight to flat-field each filter each night, so that a flat-field sequence takes several nights. Flat fields contaminated by trails will degrade flat-fielding and image processing efficiency.

Satellite trails could also derail robotic target acquisition procedures, requiring additional software changes to make them more robust. The observatory could, at the expense of considerable effort, research revised scheduling algorithms that seek to actively avoid or minimize satellites passing through the field of view, but this may still result in some programs becoming unschedulable, and a decrease in the efficiency of the entire network.

All-sky monitors

HATPI

The HATPI facility is looking at the entire visible sky above 30 degrees, observing it at high cadence (every 30 seconds), useful resolution (23 arcseconds per pixel), and very high photometric precision (reaching close to 1 part in a thousand, i.e. 1 mmag, at 30 second cadence). HATPI is located at Las Campanas, Chile, and is using 64 back illuminated CCDs and 64 fast focus special lenses on a common mount. The mount can track in Right Ascension, and after an hour it is rewound to the starting position. Due to the large field and the special instrument, no “dodging” of satellites is possible. The dual-channel readout of CCDs has a cross-talk, which has been reduced by collaborating with the manufacturer (but is still present, and can not be further removed). Saturation of stars is around r_{mag} = 8, and the 5-sigma detection threshold at new Moon is at r~16.4. The key science goals are i) transiting extrasolar planets (down to Neptune-sized objects at long periods), ii) transient events (novae, supernovae, gamma-ray bursts, gravitational wave events), iii) fast-moving objects (Near-Earth Asteroids, meteor streams).

All of these are adversely impacted by LEOsat trails. The high precision photometry is not only impacted by a trail crossing through a star, or near a star, but also by affecting the comparison stars for deriving the highest possible precision. We developed the widely used Trend Filtering Algorithm (TFA; Kovacs, 2005, MNRAS), which is part of the tool-set for achieving very high photometric precision. As stars across the field are impacted by trails at different times and to a different extent, the TFA will break down. Obviously, transient events that happen under the trail of a satellite are not only impacted, but are not recoverable. The trail may be confused by shooting star trails, leading to confusion in the detection of streams. Our only option is “intelligent” loss of data, whereby we are aware of the satellite trail, and mask out that region. Of course, this requires significant development, which is beyond our resources. Some other facilities run in a similar way, but are somewhat less affected, because either having less sensitive detectors, or smaller lenses (Evryscope, FlyEye).

Figure C.9. A wide-field astrophotograph taken by Clarence Spencer, showing the trails of multiple SpaceX satellites.

HATNet and HATSouth

These telescope systems are located in Arizona (HATNet), Hawaii, Chile–Namibia–Australia (HATSouth). HATnet employs 6 wide-field telescopes, each with a 10 x 10 degree field, while HATSouth uses 24 telescopes, each with 4.2 x 4.2 degrees of fields. These two projects, combined, have discovered 140 extrasolar planets, many of them being the first of their kind. The observing algorithm is fairly simple; a single wide field is followed until it sets below the 25-degree horizon, at which point the telescope slews to another pre-selected field, and observes it the rest of the night. All stars in the wide-field (100,000 or more) are measured at a 3 or 4-minute cadence, the brightest ones at 3 mmag photometric precision. Slewing away is not an efficient option, as sparse observations on random other fields (with no actual satellite crossing) is a simple loss of planet detection efficiency. A number of other facilities operate with similar principles, such as WASP (UK-led), NGTS, and others.

G. List of optical observatories impacted by LEOsat trails and some related parameters

Table of parameters for observatories/cameras observing in twilight
Including estimated peak LEOsat trail brightness in electrons/pixel based on an angular velocity of 0.5 degree/s and apparent (*if tracked*) satellite of $V_{mag} = 7$. So, for example, the exposure time on a 1 arcsecond pixel is 0.6 milliseconds, independent of the camera exposure time.

Observatory/ instrument	**Camera type & FOV [deg^2]**	**Typical exposure [sec]**	**Cadence #exp per night**	**Twilight Phase**	**V band rms sky noise [e/pix[4]]**	**V_{mag} = 7 LEOsat Trail [e/pix]**	**etendue [sq. m sq. deg]**
Rubin	CCD 9.6	15, 30	900	-12 deg	80	7000	320
Subaru HSC	CCD 1.77	60-300	150	-12 deg	100-200	9000	92
DECam	CCD 3	30-120	200	-15 deg	44	2600	38
Pan-STARRS1	CCD 7.5	45	600	-12 deg	17	1700	20
Pan-STARRS2	CCD 7.5	45	600	-12 deg	17	1700	20
CFHT Mega Cam	CCD 0.904	300	200	-12 deg	15	347	9
MaunaKea Spectroscopic Explorer	3200 fibers 1.5	300-1200	20-80	-12 deg	15	20,000	150
VISTA 4MOST spectro	2400 fibers 4	3x1200	7	-12 deg	5	100	48
ATLAS ATLAS4	CCD 29 116	30 30	900 3600	-13 deg	35	790	4.3 17

[4] On an image taken with the typical exposure time indicated in Column 3

ZTF	CCD 47	30	900	-12 deg	12	700	53
HATNet	10.4 x 10.4 x 6	180	160	-11 deg	17	120	5.09
HATSouth	4 x 4 x 24 inst.	180	160	-11 deg	12	165	13.3
HATPI	13 x 13 x 64	30	900	-11 deg	30	1183	87
Evryscope	16510	120	250	-20 deg	11	31	48.2
SPECULOOS Paranal	CCD nIR 0.042	60	450	-15 deg	78	79	0.79
TRAPPIST La Silla	0.3	30	800	-15 deg	41	160	0.34
ESA FLYEYE La Silla	CCD 34	40	450	-12 deg	80	5600	35.2
ASAS[5]	CCD 800	180	160	-11 deg	60	120	6.78
ASAS-SN	CCD 400	90	6000[6]	-12 deg	40	160	6.2
Gemini SCORPIO	8-channel CCD 0.005	120	250	-12 deg	50	6500	0.2
VLT FORS	CCD 0.01	300	100	-12 deg	90	7500	0.7
CSS-1.5m (G96)	CCD 5	30	800	-12 deg	70	400	9
CSS-0.7m (703)	CCD 19	30	800	-12 deg	120	800	7
LCO 2.0m	CCD 0.028 x 2	10-600	50- 200, up to 600+	-12 deg	40-150	~560	0.34 for 2 units
LCO 1.0m	CCD 0.19 x 10	10-600	200-1200	-12 deg	20-90	~300	5.9 for 10 units
LCO 0.4m	CCD 0.23 x 10	10-600	100-800	-12 deg	8-30	~60	1.17 for 10 units

[5] 4 telescope at Campanas, another 4 at Maui
[6] 20 cameras in the network. 300 exposures per night per camera.

H. Impact on large spectroscopic facilities

Large spectroscopic facilities can be more impacted than originally thought. The large collecting area of the primary combined with long integration times is certainly a prescription for trouble. It was thought that the small filling factor of the fibers or slits in the focal plane would make the likelihood of a collision with a satellite trail negligible. However, this was based on assuming that the satellite trail was a few arcsec wide. The science impact would be if one of these trails went through one of the thousands of slits or fibers, it would be discovered only in data analysis — obviously unrecoverable. Because of the assumed arcsecond scale trail width it was thought to be a rare occurrence.

In fact, LEOsats leave a much wider trail at the surface brightness which could impact such long spectroscopic integrations on faint objects. The plot below shows the LEOsat trail width for a typical 4.5 V_{mag} satellite at 550 km seen at 40 degrees zenith angle in 6 different wavelength bands, as a function of telescope aperture. By far the largest contributor is the wide wings of the PSF in typical turbulent air corresponding to 0.7 arcseconds FWHM seeing. The seeing profile is modeled with the von Karman turbulence theory. Since the mean separation between fibers or slits instrumenting a 0.2–1 degree focal plane is comparable to this trail width, the probability of pollution of one or more spectrum is actually quite high on the next-generation large spectroscopic facilities in the scenario of tens of thousands of LEOsats. Due to the long exposure times there is no mitigation.

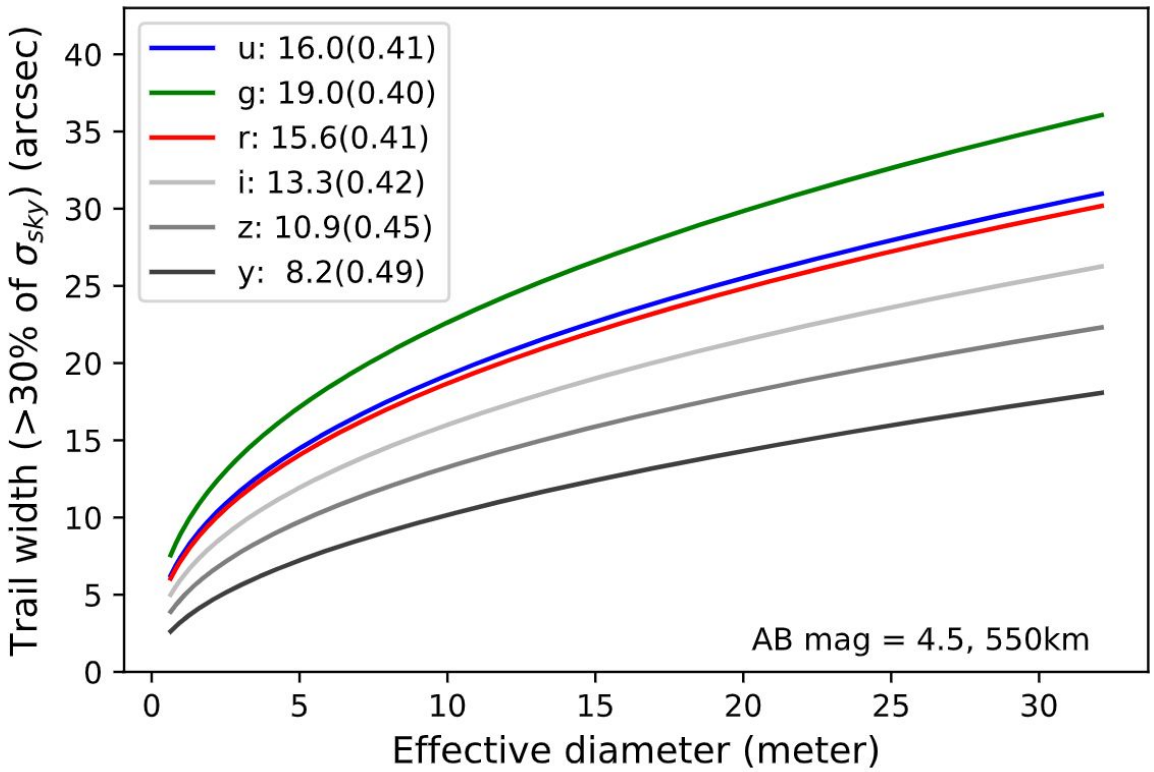

Figure C.10. LEOsat trail width for a 4.5 V_{mag} satellite vs telescope aperture. Most long exposure spectra would be polluted by even lower surface brightness trails than 30% of sky noise. At 1% sky noise, the trail widths approach 60 arcseconds.

References

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Appendix D. Technical Report on Metrics of Impacts of Satellite Constellations

A. Summary

The existing and planned constellations of communications and low-latency (minimal transmission delay) satellites in low-Earth orbit (LEO) fundamentally change the way astronomers can plan and execute observations. The condition that a given area on the nighttime sky can be observed without the passage of a Sun-illuminated satellite will no longer routinely obtain. With tens of thousands of LEOsats, **no combination of mitigations can avoid the impacts of the satellite trails** on the science programs of the coming generation of optical astronomy facilities. Constellations orbiting at 1200 km can be visible all night, and will have negative consequences for nearly all observational programs.

The purpose of this section is to provide some actionable metrics for the impacts and mitigation of those impacts from satellite constellations on astronomical observations. These metrics are motivated by the material provided in the other sections of this report, and represent a distillation of current understanding of that material. This section contains recommendations for development of common tools for observation planning and data processing, as well as for further simulations and studies to quantify the impact on key scientific programs. It also provides an evaluation of the impact to non-scientific observations of the night sky. Although the recommendations and mitigation strategies for constellation operators are based on the positive interactions of the astronomical community with SpaceX, they are intended for the industry as a whole. The astronomy community would welcome broader positive engagement on these issues.

B. Performance Metrics

1. Visibility

Six groups performed simulations of representative LEO constellations, from which preliminary conclusions about the impact on astronomical observations could be drawn. For all orbital heights, the visibility of sunlit satellites remains roughly constant between sunset and astronomical twilight (Sun 18 degrees below the horizon). The key difference between lower (~500 km) and higher (~1200 km) orbits is the visibility in the dark of night between astronomical twilights. Higher altitude constellations can be visible all night long during summer, with only a small reduction in the number visible compared to those in twilight. Scientific investigations requiring imaging with uniform S/N of complex regions over large fields of view will need multiple additional exposures to compensate for masked satellite trails, where such image combination is possible at all. With currently planned constellations at 1200 km, companion galaxies such as the Large Magellanic Clouds or the Andromeda Galaxy will have a trail superposed every 30 seconds.

Finding: *With state-of-the-art masking techniques for satellite trails and current understanding of systematics and losses induced by the requirement for such masking, the impact of higher altitude LEOsat constellations ranges from costly additional exposure time per area (at the 10-20% level or higher) to the complete loss of ability to study certain astrophysical problems. The impact becomes increasingly strong with increasing altitude above ~600 km and increasing numbers of constellation satellites.*

Operator Mitigation: Design constellations for lower operational orbits, preferably below 600 km, with the minimum number of units needed for bandwidth and coverage requirements.

2. Reflected Sunlight

Operational Orbit:

The most common impact on astronomical observations will be the trails of reflected sunlight imposed onto the focal surfaces of telescopes and instruments by the passage of satellites through the field of view during an exposure. The most thoroughly studied instance of that effect is for the Rubin Observatory wide-field detector array. Through laboratory simulations, Rubin Observatory staff identified the surface brightness upper limit within a satellite track required to allow calibration and removal of low-level cross-talk, which would otherwise affect many lines of pixels parallel to the track. That limit is well below detector charge saturation. Maintaining surface brightness within that upper limit confines the loss of usable pixels on the detector to the log rectangular area of the primary trail. In order to use these data, one must mask the trail with a pixel mask out to a width where the brightness of the trail exceeds some fraction of the sky background noise.

Rubin Observatory was motivated to undertake these measurements and simulations by the initial launches of the SpaceX Starlink constellation in mid-2019. They worked collaboratively with SpaceX to determine the apparent brightness of a Starlink unit corresponding to the calibratable surface brightness limit and to find mitigations for spacecraft illumination at the nominal orbital height of 550 km to bring the reflections within that limit. The limit was determined to be $V_{mag} = 7$, leading to the following metric:

Requirement for operational orbit: *Reflected sunlight 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_{mag} *+2.5 × log(*r_{orbit} */ 550 km), equivalent to 44 × (550 km /* r_{orbit}*) watts/steradian.*

The recorded image for the Rubin Observatory and other large-aperture telescopes of similar focal length is resolved in angle because a satellite subtending ~⅓ arcsecond is well out of focus compared to infinity at a distance of 550 km. For those constellations planned at altitudes of ~1200 km, the surface brightness projected onto a pixel in the track is dimmed in comparison to that at 550 km by $\sim 1/r^2$, but the footprint of the out-of-focus image is contracted, leading to a concentration of light proportional to $\sim r^2$. The recorded surface brightness therefore depends only on the dwell time from the orbital motion, proportional to ~r, with a constant recorded limit requiring reduced effective reflection by 1/r. It is shown that addressing the issue for the telescope with the greatest etendue, that of the Rubin Observatory, is likely to put most other facilities into a similar or better performance regime with respect to imaged satellite trails.

Operator MItigations:

- Surface darkening
- Sun shielding
- Possible attitude control consistent with power constraints to reduce effective reflectance

SpaceX Visorsat is the latest experiment attempting to reach the needed limit, employing all three mitigation approaches.

Observatories' Immediate Mitigation Options:

- Image post-processing to identify and mask affected pixels in track with additional noise > threshold over sky noise.
- With precise ephemerides of entire constellation suites, close shutters for the seconds around the predicted passage. Option available to those instruments and programs for which shutter close and open does not compromise image quality or cause unacceptable delays for target/guide star reacquisition.

Observatories' Longer-term Mitigation Options:

- New instruments designed for mid-exposure shuttering.
- Exploration of CMOS detectors for pixel shuttering.

Recommendation: *Support for development of an application available to the general astronomy community to identify and mask satellite trails in images on the basis of user-supplied parameters.*

Recommendation: *Support for selected detailed simulations of the effects on data analysis systematics and data reduction S/N impacts of masked trails on key scientific programs of the mid to late 2020s. The former is particularly relevant to very large (billion object LSST) samples* *that are not limited by Poisson statistics; the latter to any problem with the expectation of 100% areal coverage with uniform S/N limits. Other specific issues that could benefit from simulations include exposure of spectroscopic fibers to reflected sunlight at low levels and multiple sequence infrared exposures with processing currently not set up to accommodate detection or removal of trails in individual frames. 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.*

Recommendation: *New LEOsat operators perform adequate laboratory BRDF measurements as part of their satellite design and development phase. This would be particularly effective when paired with a reflectance simulation analysis.*

Flares

Flares are specular reflections off of designed facets of the spacecraft. They can be many times brighter than the surface brightness limit above, leading to uncalibratable cross-talk or saturation. A usable astronomical exposure is incompatible with flare illumination. The expectation is that flares will be rare events.

Operator Mitigations:

- Potential to adjust attitude to avoid flares projecting along the ground track.

Collaborative Mitigations:

- Sufficiently accurate ephemerides of the flares themselves for pointing avoidance.

Glints

Any fine texture on the reflecting surface of the satellite, such as multi-layer insulation, will provide rapidly varying reflectivity, possibly on msec timescales. The noise produced in a track by glints will greatly exceed the photon statistical noise, although the total reflected sunlight could still be below the recommended limit. Although it might be possible to recover some measurable area along the low-intensity skirts of the (out-of-focus) point spread function under such a track, it would be more computationally expensive than a mask, essentially the equivalent of removing the background in a dispersed spectrum.

Impact

On the basis of future simulations of impact on a range of scientific programs, it may be possible to determine a threshold for a reduced upper limit on effective reflectivity that provides a significant recovery of lost imaging area and/or lost total exposures. For example, a constellation like Starlink at 550 km impacts scientific programs because of its visibility in twilight; constellations planned for 1200 km will be visible all night, and will impact all nighttime programs.

Goal for operational orbit: *Reflected sunlight slowly varying with orbital phase as recorded by high etendue, large-aperture ground-based telescopes to be fainter than 7.0* V_{mag} *+2.5 × log(*r_{orbit}

/ 550 km), equivalent to 44 × (550 km / r_{orbit}) watts/steradian. End-to-end scientific simulations to provide the basis for fainter threshold and actual quantitative values.

3. Post-launch Parking, Boosting, and De-Orbiting Stages

These mission stages can cause sunlight reflection much stronger than that in the operating orbit. For the small fraction of constellation units with uncontrolled de-orbit, facet flares can be much more frequent. Even with a build-out of tens of thousands of constellation units, the number of satellites in these mission phases is expected to number in the hundreds at any given time.

Observatories' Mitigation:

- Pointing avoidance when possible.

Collaborative MItigation:

- Ephemerides as accurate as possible, publicly available.

Operators' Mitigation:

- Best efforts for attitude control of units within power constraints to minimize effective reflectivity in the direction of ground-based observatories.

For all the issues including determining reflectance as a function of solar elongation, slowly varying body reflectance with orbital phase, glints and flares, a campaign of optical/IR ground-based measurements will provide the needed data. Confirmation of the efficacy of mitigation techniques is also essential through follow-up observations. Such observations would complement those of existing Space Situational Awareness (SSA) arrays, which tend to concentrate on positions for refining orbits rather than on the brightness of reflected sunlight.

Recommendations: *Support for 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 for 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 units and on-orbit aging, requiring ongoing monitoring.*

4. Positional Accuracy

All impacted observational programs will rely on sufficiently high-quality information for pointing avoidance and/or identification after the fact in the recorded image. Pre-scheduling of observations of critical fields that can be adjusted slightly in time can use the information for planning. Time-critical observations, including long exposures of transient phenomena like gravitational wave sources may have the option of closing the shutter during the passage of the satellite, provided the system doesn't lose target lock.

Current expectations for quasi-ballistic mission phase (on-station operations): *For a given position on the sky and given start and end times for an exposure, the ephemerides of all units of a constellation shall be specified in a public database to sufficient accuracy that the transit of any unit across the field during the exposure interval 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.*

Current expectations for phases with frequent thruster firings or reduced control, such as parking, orbit raise, and deorbiting: *For a given position on the sky and given start and end times for an exposure, the ephemerides of all units of a constellation shall be specified in a public database to sufficient accuracy that the transit of any unit across the field during the exposure interval can be predicted within 12 hours in advance of the observation to an accuracy of 10 seconds in time and the position of the track to 12 arcminutes in the cross-track direction and 12 arcminutes in position angle.*

Collaboration action item: *Determine the update cadence and quality of publicly available positional information or processed telemetry, distribution, and predictive modeling required to achieve substantial improvement (~10x) in cross-track positional determination.*

Recommendation: *Support development of an application available to the general astronomy community for observation planning 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 such development.*

Recommendation: *A new standard format be used for ephemerides beyond TLEs in order to include covariances and other useful information. The application above should be compatible with that format and include the appropriate errors.*

Recommendation: *Immediate post-launch configuration enables pointing avoidance most readily if the units are as tightly clumped as possible consistent with safety, affording rapid passage of the whole train through a given pointing area.*

C. Scientific and Cultural Impact

We have summarized above our best understanding of the quantifiable impacts of large constellations of LEOsats on a large range of astronomical research projects and facilities. We have attempted to derive quantitative metrics for reflected sunlight and positional accuracy that astronomers, satellite operators, regulators, and decision-makers may use in their efforts to control and minimize those impacts.

Depending on the number of satellites, their apparent brightness, and their orbital parameters, many astronomical research programs will be impacted severely enough to render them unfeasible.

Various LEOsat constellations could also be bright and numerous enough to alter irrevocably the visual appearance of the night sky to the general public, casual observers, amateur astronomers, astrophotographers, and indigenous and traditional peoples who depend on the stars for religious or navigation purposes.

In this section, we aim to capture and convey the scale of the opportunity cost in lost science programs and natural heritage of the night sky, and to identify additional criteria for mitigating impacts of satellite constellations.

The AAS survey of major observatories (Dec. 2019) produced an overview of the anticipated impacts to research astronomy of large constellations of LEOsats. However, the survey was asking observatories to respond only to the specific scenario of 1584 satellites at 550km and then what if that spatial density of these satellites increased by one order of magnitude.

A common theme of the community responses for wide-field imaging is the loss of the area of the satellite trails. For example, the Zwicky Transient Facility (ZTF) estimates losing 0.2% of their image area per trail, while ATLAS estimates a total loss of a few percent in twilight. Neither has those trails saturated in imaging of current Starlink units. Instruments with large pixels on the sky and dynamic range of their detectors more limited than those on the Rubin Observatory may encounter saturation of trails that satisfy the LSSTCAM limits. Many of the respondents defined ‘tolerable impact’ as trail removal with only a moderate increase in the noise level along the track. The range of responses based on initial estimates puts the actual reflected sunlight value at 9th to 10th magnitudes for 550 km to recover measurable sky area under the track.

There are classes of programs for which a satellite crossing means a loss of the full exposure. Examples include imaging of extended objects, such as nearby galaxies or Galactic nebulae, for which a uniform signal-to-noise (S/N) ratio of detection across the image is essential to the program; or exposures on an instrument for which target acquisition is time-consuming and target lock would be lost if the shutter were closed mid-exposure.

A common concern is the loss of critical, long-exposure data, particularly for time-critical observations like multi-messenger sources with positions not known long in advance, because of a rare satellite crossing of a small-field instrument that cannot be intermittently shuttered. A possible metric here is the probability of exposure loss vs. rarity of the event.

A questionnaire was sent to selected programs in early July. It asked the investigators to rate the impact of simulated satellite trails for the second-generation SpaceX Starlink constellation with 33,000 satellites at 600 km or below and OneWeb with 47,844 satellites at 1200 km. The questionnaire requested responses to the following questions:

1. Title/name of science case/genre on which you are reporting (e.g. “Search for NEOs in twilight”):
2. Please give a brief summary (1-3 sentences) of the main science case/genre, pitched towards a general scientific audience.
3. Please assess briefly (1-2 paragraphs) the impact you anticipate to the science case or genre under each of the two scenarios above. What are the losses you anticipate to your data (measured in pixels, frames, time, detector persistence, or any other unit)? What are the losses you anticipate to science results? Please share as much detail as possible about any assumptions or thresholds you use. Please use the following categories if possible:
    a. **Negligible**: science goals will be realized with the original plan essentially unchanged
    b. **Significant but tolerable**: science goals will be somewhat compromised, additional time or resources required to offset losses
    c. **Fatal**: science goals cannot be realized
4. Given a satellite predictor tool, do you have the capability to control the shutter mid-frame to avoid satellite trails? How would that change your assessment of losses to data and to science?
5. Please describe synergies expected in the next 5 years between your program and other facilities e.g. Rubin/LSST that may be seriously impacted by LEOsats.
6. What metrics or questions did we not suggest that you think would be appropriate for assessing the impact of LEOsats on your science case? Please provide answers to your own question(s) and be quantitative if possible. If you’re willing to share your calculations leading to any of the conclusions you state, that would also be very helpful.

Here we summarize by sub-field the expected losses to science and provide some representative assessments by science project leaders and observatory directors worldwide of impacts to their observatory or program’s operations. It is clear that the community is just beginning to grapple with the question of the impact of tens of thousands of LEOSats, leading to diversity in assessment of impact, even for related scientific topics.

Fast transients (e.g., gamma ray bursts, fast radio bursts, gravitational wave transients, high-redshift supernovae)

Searches for OIR counterparts to fast transients generally require extremely rapid response — often a few minutes or less — to triggers from space- or ground-based gamma-ray, optical, or radio surveys. Follow-up observing networks can include dozens of ground-based telescopes. Major surveys include the Rubin Observatory LSST, Zwicky Transient Facility, and PanSTARRS.

> “This is a burgeoning research area with many unknown events and physical phenomena. We coordinate over 60 major facilities to work simultaneously and in rapid-response mode to detect and follow up fast transients (millisecond-to-hours duration). Satellites can ruin detections of these events and, as the events fade very rapidly, the ability to acquire the rare data is lost forever. Moreover, hundreds of thousands of dollars of telescope time is proposed for, awarded, and coordinated, thus the impact on cost is very large.” (Jeff Cooke, Swinburne U.)

> “High redshift supernovae … events are very faint and are acquired during classically scheduled telescope time on the largest optical telescopes in the world (Keck, Subaru, VLT, Gemini, SALT, LBT, etc.). They require hours of exposure time to achieve a signal-to-noise ratio of a few.... The time on these large telescopes is very competitive and satellites can ruin long exposures and the data is lost forever, as well as the telescope time, which is purchased at ~$100,000 per night, or about $4 a second.” (Jeff Cooke, Swinburne U.)

> “Time-critical observations of transient phenomena will be irretrievably lost, and long exposure spatial observations of the most distant galaxies (imaging or IFU) will also be irretrievably lost. Exploratory imaging searching for high-z galaxy candidates may also be impacted. This is critical science for 8-10m class telescopes, but is also key science for the ELTs. The financial impact of satellite constellations will be even more significant for ELTs in these science areas.” (Lisa Kewley, Australia National University)

> “It's unlikely that the albedo could be reduced enough from magnitude 5 to reduce the loss enough. The surface brightness of the trail (assume 1 arcsecond width) would need to be reduced to > 22 magnitude /arcseconds^2 or fainter.” (Richard Wainscoat, PanSTARRS)

Wide-field/All-sky surveys

Wide-field large-aperture surveys are especially vulnerable to satellite trails: their wide fields of view mean images are more likely to be crossed by satellites, and their large light-collecting area means the trails left by those satellites are more likely to saturate the detector, causing irretrievable loss of information. These include some of the most scientifically successful facilities around the world and some of the top-ranked projects recommended by the 2010 Decadal Survey of Astronomy and Astrophysics (“New Worlds, New Horizons”, NAS), such as the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST).

> “[B]y the time (2027 in mid-LSST survey) the full Starlink constellation of 42,000 is in place at orbits from 320-550 km. Initial scheduler simulations of dodging for that density of satellites show that at astronomical twilight only half of the number of available observations would be completed.” (Tony Tyson, Rubin Observatory)

By mid-decade, a representative wide-field near-IR camera will be WFCAM on the UKIRT 4-meter telescope on Maunakea. Can LEOsat trails be appropriately handled on those images?

> “While it is certainly the case that the default pipeline stacking, which includes k-sigma clipping, will remove short "obvious" satellite trails, LEOSats generally leave longer lower surface brightness tracks. These are much harder to get rid of cleanly. If it became a serious problem with a two order of magnitude increase in numbers, it would almost certainly require some bespoke software to attempt to use their characteristic longer track signatures to locate more directly the pixels they influence.” (Mike Irwin, Cambridge)

If the near-IR trail is simply reflected sunlight, the WFCAM impact is as follows:

> “A single pointing of WFCAM is 0.2 square degrees for all four cameras combined, which gives a chance for 0.1 trail for a typical 10-sec exposure in J [broad band centered at 1.25 μm] in one of the four cameras. If we assume that we do 10-s exposures all night, we may take about 2100 images. So, in about 210 exposures, we may have a trail in one of the four cameras.
>
> Using Solar colors, SDSS g_{mag} = 7, will be about UKIDSS J_{mag} = 5.49, which is way above our saturation magnitude in J if we try to track at the rate of the satellite. However, at a speed of 0.5 degrees/seconds, the centroid will spend about 0.00022 ms on the 0.4” pixel of WFCAM if it crosses the pixel along any of the sides (slightly higher depending on the angle). This will be like a 14.6 magnitude star crossing the array (will be fainter when we degrade the PSF for seeing and focus). This will not leave any noticeable latency, but a long trail will be seen in the images, and will have an effect in crowded fields or when we try to detect very faint objects (if we are unlucky).” (Watson Varricatt, UKIRT Observatory)

Deep long-exposure spectroscopy

Spectroscopic observations generally cover smaller fields of view than imaging programs. However, exposure times can be much longer for spectroscopy, e.g. 1800 seconds or more vs. typically 300 seconds or less for imaging. A bright satellite crossing a spectrograph long slit, series of slitlets in a slit mask, or integral field unit (IFU) could ruin the entire exposure, forcing a repeat exposure or possible loss of science opportunity.

Large statistical surveys (e.g., weak lensing, Dark Energy)

As wide-field or all-sky surveys become more common including on large telescopes, the number of objects targeted increases to the point where the uncertainties in the distributions of measured parameters (e.g. galaxy shape, size, brightness, orientation) are dominated not by Poisson sampling noise but by systematic uncertainties. Some of those systematics can be seriously affected by bright satellite trails, including in ways that are not yet recognized. This could jeopardize the ability of such surveys to meet their primary science goals, such as measuring and understanding the nature of Dark Energy by quantifying the distortion of images of distant galaxies due to weak gravitational lensing.

> "[M]ost of LSST science derives from the statistical analysis of trillions of photometric measurements of 20 billion objects. The science discoveries will thus be more affected by systematics than sample size. This is a new paradigm. Residual image artifacts can create systematics which affect the science discovery space to varying degrees. Virtually the entire astronomical community will rely on the released LSST data products (transient alerts and static deep sky catalogs) rather than processing the hundreds of PB of images. Thus they will rely on the LSST data management to do the required pixel processing and artifact removal. The issue is systematics that may print through to the catalogs and alerts. The science collaborations would need to characterize them. For those programs most affected, the sheer task of tackling these new systematics in the released data products is likely beyond the capability of many in the astronomical community." (Tony Tyson, Rubin Observatory)

OIR followup of gravitational wave triggers from LIGO, VIRGO

Arguably the most spectacular and profound science result of the last 50 years is the detection in 2016 of gravitational waves by the Laser Interferometry Gravitational Wave Observatory (LIGO) and its European partner, VIRGO. The window to multi-messenger astronomy — messages gathered via both electromagnetic radiation and gravitational waves — is now open. This powerful combination of techniques provides crucial information on extreme events such as the mergers of black hole pairs and neutron star pairs in distant galaxies. LIGO and VIRGO events trigger rapid response followup by OIR telescopes around the world. Because the events often have short OIR lifetimes — days to minutes — there is often only one chance for OIR telescopes to observe them before they fade from view. Thus an ill-timed satellite trail could potentially prevent the discovery of a rare and important find.

> "The Gravitational wave Optical Transient Observer (GOTO) is a project that performs a high-cadence survey of the optical sky down to ~20 magnitudes, by making use of an extensive array of wide-field telescopes (up to 32). Satellites can't be avoided in projects like this that survey the visible sky all the time, and survey observations are scheduled during the whole night, including twilight. With an instantaneous sky coverage of 80 square degrees, it is not feasible to schedule the observation around an increasing number of contaminating satellites. Some fraction of the data is compromised, depending on the brightness of the object. With typical exposures of 60 s, the satellites would fully trail across CCD images, which span several square degrees across. Since the main science goal involves fast-evolving transients, many observations are time-critical and cannot simply be rescheduled at a later time." (Danny Steeghs, Gravitational wave Optical Transient Observer)

Large-scale Surveys for exoplanet transits

- **Impact Assessment — HATNet + HATSouth and transiting planets**

Metrics WG Questionnaire Response from Gaspar Bakos, Princeton:

1. Project/genre: search for Transiting Exoplanets with HATNet (HN) and HATSouth (HS).

2. Brief description: The HATNet telescopes are sensitive, wide-field (10.4 degrees x 10.4 degrees) optical instruments, staring at selected fields in the night sky, taking images every 3 minutes. There are 6 HAT telescopes (4 currently operational), installed in Arizona and Hawaii. The HATSouth telescopes, altogether 24, run in a similar way, but they are in the Southern hemisphere, distributed at 3 continents. HATNet and HATSouth specialize in very high precision relative photometry, so we can confidently detect the shallow transits of extrasolar planets in front of their host stars. These transits range from 2-3% for the largest planets to one part in a thousand for the most exciting exoplanets, such as hot Saturns, Neptunes and super Earths. HATNet and HATSouth have been operating for over a decade, and have discovered over 140 transiting exoplanets. Many of these exoplanets were first of their kind, and greatly helped both the theoretical investigations of exoplanets and the planning of present and future space missions. The specialty of the HAT projects is very high precision, very low systematic-noise, long-term photometry of millions of stars.

3. Impacts of LEOsats (and other space-born light pollution):
   a. Stars that fall under the trajectories of the visible satellites will have added noise.
   b. Stars that fall next to the trajectories of satellites, will have their background sky measurements distorted, and thus will have skewed photometry.
   c. The overall photometric precision will suffer due to the comparison stars being compromised as per points 1 and 2 above.
   d. The overall trend removal process (called TFA) will suffer due to added incoherent systematic noise in the light curves.

With the simulations presented (approx 80,000 satellites), HATNet would have 67 satellites crossings per frame (180s), 6x67 for all 6 telescopes, blocking out around 10% of the pixels. HATSouth would have 51 satellites crossing per frame (180s), 6 x 51 crossings for the network, blocking 7.4% of the pixels. The equivalent magnitude of a SpaceX satellite in the r = 3 pix aperture of HN is r ~ 17, the same number is r ~ 18.2 for HS (this takes into account the 1 degree/second angular speed of the satellite). HN measures stars in the range of r~[8,14], while HS in r~[9,15]. This means that for our sources the relative contribution of a Visorsat in the r=3 pix aperture for a 14^{th} mag source is about DeltaMag ~ 3 (HN) to 4 (HS), corresponding to a flux dilution of ~6.3%. As a reminder, we are looking for signals with a total amplitude of 0.1 to 1%. The most affected targets will be the M dwarf stars; the later the M dwarf (at fixed distance), the larger the relative effect. I think we will completely lose our ability to detect super-Earth planets around M dwarf stars that are being crossed by satellites. For a 12th magnitude star and a hot Jupiter with a 1% transit, the flux dilution (noise) due to SpaceX satellites will be similar to the signal due to the planet itself. The transit lasts for hours, and a single crossing by a satellite affects 3 minutes, so the impact will depend on the number of satellite crossings during a planetary transit. Nevertheless, as a rough first estimate, our ability to detect hot Jupiters will be compromised for stars fainter than 12. For a V_{mag} = 9.5 star, the crossing of a SpaceX satellite will cause a signal with the amplitude equivalent to the transit of a Super-Earth, consequently, our ability to detect such planets for stars V_{mag} > 9.5 is compromised; the fainter the host star, the larger the effect.

I'd say this falls in the "very significant, but tolerable with large amounts of antidepressants" in your classification.

4. Given a satellite predictor tool, do you have the capability to control the shutter mid-frame to avoid satellite trails? How would that change your assessment of losses to data and to science?

No, we can not control the shutters in mid-frame. Our data acquisition is very complex. While the shutter is open for 180 seconds, we are "dithering" around the telescope on a prescribed pattern to achieve a slight widening of the stellar profiles.

5. Please describe synergies expected in the next 5 years between your program and other facilities e.g. Rubin/LSST that may be seriously impacted by LEOsats.

All the HAT surveys nicely complement LSST in magnitude range, coverage and cadence. While LSST covers the visible Southern sky every ~3 days, with saturation around 14, the HAT projects cover the Southern sky in the magnitude range of 8–14 (HN), 9–15 (HS), 8–15 (HATPI). They do "deep drilling" on selected fields with 3 minute cadence. HATPI will cover the entire visible Southern sky every 30 seconds, simultaneously. Together these projects (say HATPI and LSST) would provide a multi-year, high precision and accuracy all sky variability for every visible source between magnitudes 8 and 24 (? the low end of the LSST photometry).

6. What metrics or questions did we not suggest that you think would be appropriate for assessing the impact of LEOsats on your science case? Please provide answers to your own question(s) and be quantitative if possible. If you're willing to share your calculations leading to any of the conclusions you state, that would also be very helpful.
    a. Financial loss per year, including person-hours spent on avoidance, data management, scheduling, fraction of site fees, facility operating costs (time

and pixels lost due to satellites, pro-rated). Losing 10% of my pixels in ~2 (dusk) + 2 (dawn) hours is a major loss. Through the way it affects the data, it is more than a 5% loss (an average dark night counted as 8 hours). The extra trouble in looking for polluted transients or shallow exoplanet transit features will be prohibitive. My vague estimate is that our loss is at least 25% of all investments and running costs.

b. Research time lost per year (instead of indulging in astrophysics; what fraction of our time are we spending on satellite mitigation). // My impression is that > 100 people in the astronomical community are losing at least 10% of their time (per year) dealing with satellites. This is 0.1 x $100,000 x 100 ~ $1 million/year (with a very rough ballpark figure for annual income). I think this is a very conservative under-estimate, as I spent more time on these satellites, and I know others who spent almost all their time on this. I think that just the time of the astronomical community diverted into satellite mitigation is on the order of $5 million/year.

c. Trivial metrics: fraction of pixels, time, targets lost for the given science case.

7. An inherent problem with science that its financial value is hard to estimate. How much does a habitable super-Earth worth? How much does it worth to discover alien life on an exoplanet? What is the price-tag for detecting an optical afterglow of two colliding black holes, with a potential of fundamental changes to physics? How much does a rare flare of a star worth, which was just devouring of its planet? These questions are fundamental to humanity, and define our meaning on this planet. The overarching goal of humanity should be understanding our place and existence in the cosmos, and co-existing with nature. I know these are big words, and may sound ridiculous for the cynical, but I truly think this is our mission, and in fact, our only way to survive. There is no associated dollar value, as it is above and beyond the noise of stocks, bonds, insurance policies. Providing world-wide Internet should not violate these fundamental principles, and not compromise on the discovery of nature. Finally, what is the value of discovering a near-earth asteroid that is on a collision course with the Earth? How can we possibly compromise on this.

- **Impact Assessment — HATPI transiting planets, all-sky variability and transients.**

Metrics WG Questionnaire Response from Gaspar Bakos, Princeton:

1. Project/genre: All-sky variability with HATPI, including the search for transiting exoplanets and transient sources.

2. Brief description: HATPI is a unique, very high sensitivity optical sky survey that will image the entire visible sky (above 30 degrees) every 30 seconds from Chile, using 64 back-illuminated CCDs and 64 large aperture, short-focus lenses. HATPI is

tracking the sky for one hour, while performing close to 120 exposures (per camera), after which it “rewinds” to the East, and starts tracking again. Photometry is carried out for sources down to r ~ 15. The 5-sigma detection threshold is r ~ 16.5 (@30s). The specialty of HATPI is that it images the entire sky all the time, it is very sensitive, and it provides very high precision photometry. HATPI will gather far more high precision data points, for far more stars (> 33 million), than has been done by any transit survey to date .

3. Impacts of LEOsats (and other space-born light pollution):
   a. Stars that fall *under* the trajectories of the visible satellites will have added noise, spoiling the very high precision photometry.
   b. Stars that fall *next* to the trajectories of satellites will have their background sky measurements distorted, and thus will have skewed photometry. The impact is slightly smaller than that of #1.
   c. The overall photometric precision will suffer due to the comparison stars being compromised as per points 1 and 2 above.
   d. The overall trend removal process (called TFA) will suffer due to added incoherent systematic noise in the light curves.

With the simulations presented (approx 80,000 satellites), HATPI would have 29 satellites crossings per frame (@30s), 64 x 29 = 1856 such crossings for the entire field of view every 30 seconds. The satellite trails would block out around 8.4% of the pixels. The equivalent magnitude of a SpaceX satellite in the r = 3 pix aperture is r ~ 14.2 (this takes into account the 1 degree/second angular speed of the satellite). The Oneweb satellites are 1 mag fainter (0.4 x the flux), but move half the speed, which two effects roughly cancel out when we calculate the equivalent magnitude in a fix aperture. HATPI measures stars down to r~15. This means that for our sources the relative contribution of a Visorsat in the r=3 pix aperture can be very significant, even dominant. For an r=14.2 mag source, the flux dilution by a satellite is 100%. Flux dilutions are as follows: r=8 (0.0033), r=9 (0.008), r=10 (0.02) or 2%, r=11 (0.052), r=12 (0.13), r=13 (0.33), r=14 (0.83), r=15 (2.08). In other words, an r=10 source will have a 2% change in its flux due to a satellite crossing, while a faint, r=15 mag source will have a 200% change in its flux. <u>A key science goal of HATPI is looking for transiting extrasolar planets.</u> The system was designed to be compatible and competitive with the Transiting Exoplanet Survey Satellite (TESS), and to offer synergies with TESS while both are operational, but to run well past TESS. HATPI will more than double the yield of TESS for transiting exoplanets with periods longer than 50 days and orbiting stars V <12. At least 600 planets not found by TESS will be recovered by HATPI. Discovering and characterizing exoplanets is seriously compromised by the satellite crossings. As an example, HATPI can detect a super-Earth crossing an 8^{th} magnitude star, causing a 3 mmag transit. However, a single satellite crossing has the effect of 3 mmag. HATPI could easily detect transiting hot Jupiters around V=12 stars, which have a signal depth of 1%, but a single satellite crossing will cause a 13x larger signal.

Another key science goal of HATPI is all sky variability at very high precision. Simulations show that HATPI will discover hundreds of thousands of new variable stars, including for example 100,000 eclipsing binaries (up to very long orbital periods). All sky variability has *not* been explored at the milli-magnitude level, at short time-scales (~minutes), and at very long timescales (years, a decade). Satellite crossings will compromise variability studies for the low amplitude and short time-scale phenomena. For example, understanding the rate of flares for solar type stars is of fundamental interest (including for our own habitability), but the flares are rare, short-lived, and small in amplitude. This science may be lost due to satellites. Similarly, flares of M dwarf stars are essential for understanding habitability around the most common stars in the Universe. A satellite crossing around a 14^{th} magnitude M dwarf causes a flux increase of 100% with HATPI, and the added noise can greatly confuse flare detection algorithms. Variability of stars at the 1 minute timescale is largely unknown, other than e.g. the flickering of accreting stars. Novae and supernovae are also known to exhibit very rapid and very small amplitude variations, which studies will be compromised by satellite crossings.

A third, very important key science goal of HATPI is to look for transients. Our 5-sigma detection threshold of 16.6 (@ 30s) and 18.2 (@ 1 hour), and the simultaneous all sky coverage together permit the detection of a large number of transients. Transients are typically not repeating; we have one shot. They can include exotic phenomena, such as the optical afterglow of LIGO gravitational lens events, light from merging black holes, planets swallowed by their host stars. Satellite crossings will cause great confusion. Even by applying a virtual mask on ~8.4% of our pixels, the frames will be further affected by glints and dual channel readout cross-talks. Looking up the positions and crossings for 80,000 satellites and applying relevant masks on the images will cause a delay, whereas in transient science, the goal is an immediate and high confidence trigger of large telescopes. Every second matters. The confusion will also cause large telescope resources to burn time on misinterpreted satellite crossings.

Altogether, I'd say this falls in the "**very significant, barely tolerable**" in your classification.

4. Given a satellite predictor tool, do you have the capability to control the shutter mid-frame to avoid satellite trails? How would that change your assessment of losses to data and to science?

No, we can not control the shutters in mid-frame. First, this is technically not enabled by the cameras. Second, even during the 30s integration, all individual lenses and cameras are moved to perform microtracking. Coordinating this with a ~13 to 26 second satellite crossing does not work. Finally, doing this for 64 individual lenses and cameras is beyond our control system; exposures are done simultaneously.

5. Please describe synergies expected in the next 5 years between your program and other facilities e.g. Rubin/LSST that may be seriously impacted by LEOsats.

HATPI will cover the entire visible Southern sky every 30 seconds, providing photometry for everything down to r = 15. It is a perfect complementary project to LSST. Together these projects (HATPI and LSST) would provide a multi-year, high precision and high accuracy all sky variability for every visible source down to r~24. (HATPI saturates at 8, but we are working on doing photometry for bleeding stars, as bright as r~5).

6. What metrics or questions did we not suggest that you think would be appropriate for assessing the impact of LEOsats on your science case? Please provide answers to your own question(s) and be quantitative if possible. If you're willing to share your calculations leading to any of the conclusions you state, that would also be very helpful.
    a. Financial loss per year, including initial investment (HATPI is $3 million), person-hours spent on avoidance, data management, scheduling, fraction of site fees, facility operating costs (time and pixels lost due to satellites, pro-rated). Losing 8.4% of our pixels in ~2 (dusk) + 2 (dawn) hours is a major loss (about 4.1% overall; an average dark night counted as 8 hours). Through the way it affects the data, it is far more than a 4.1% loss. Through its very high sensitivity, large pixels, and all sky coverage, HATPI is especially impacted, more than HATNet and HATSouth. Some of the key science cases are likely lost.
    b. As noted for HATNet and HATSouth — research time lost per year (instead of pursuing astrophysics; the fraction of our time are we spending on satellite mitigation). See my comments for HATNet and HATSouth.
    c. Trivial metrics: fraction of pixels, time, targets lost for the given science case.
    d. Public outreach. As an example, for the HATPI all sky mosaic, we planned on displaying this as a movie in major US planetariums. Visitors would see the real sky, as of a couple of nights before, as if they were standing in the Atacama Desert, and as if they had a visual limiting magnitude of 10. This beauty of the cosmos will be spoiled by 1856 satellites trailing across, each at g=7 to 8 in some of the grandest hours of night, which is dusk and dawn (and the hours following/preceding). Given our visual sensitivity to moving objects, the "experience" will be dominated by looking at the swarm of moving man-made objects broadcasting Internet.

Near-Earth asteroids and comets

Since the 1980s, numerous projects worldwide have been devoted to scanning the skies for near-Earth asteroids and comets. These are interesting scientifically for the clues they give to the formation and evolution of the solar system, as well as from a global safety perspective for their potential to collide with the Earth and cause catastrophic damage to ecosystems and human civilization. These surveys operate throughout the night, but also in twilight hours, when near-sun targets are visible but also when satellite interference is the worst. It is noted that NEO searches are mainly supported by the NASA Planetary Defense Office; the following are informed opinions of individual scientists.

> "LEO satellites already cause loss of data to Pan-STARRS, effectively wiping out a 3 degree long trail in the focal plane. More satellites will only make it worse. The part of the night right after evening twilight and right before morning twilight is the only part of the night that we can search for Near-Earth Objects at low solar elongation. This is a particularly rich area for the NEO search because we are looking along the orbit of Earth." (Richard Wainscoat, PanSTARRS)

Rob Seaman, Catalina Sky Survey:

> Asteroids and comets have frequently struck the Earth in the past and will do so in the future, over long intervals with very dramatic consequences if not discovered and mitigated. We were asked to rate impacts to science, and in the case of NEOs to planetary defense, due to anticipated mega-constellations, in the three categories of "negligible", "significant", and "fatal". The full build-out of the mega-constellations cannot be categorized as having "negligible" impact on planetary defense, since any single foreground artificial satellite might compromise the discovery of an asteroid-impactor, delaying mitigation (for instance, timely launch of a kinetic redirection mission). The large numbers of satellites in a mega-constellation increase such risks. Numerous Sci-fi B movies have depicted less likely scenarios of large meteor / asteroid impacts. Arguably these could fall in the "**fatal**" category in the rubric.
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> That said, for the NEO community the risks are perhaps best expressed as a tax — an unfunded mandate — imposed on NEO survey and follow-up operations. Per the rubric, the risks to our community will be generally "**significant**". Whether they are tolerable or intolerable or somewhere in between may depend on the specific survey project. My comments below will mostly contrast impacts to Catalina Sky Survey and LSST operations.
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> Either the Starlink2 or the OneWeb scenario will significantly degrade twilight near-sun observations, perhaps fatally for LSST as implied by several presentations at the SATCON1 workshop. The LSST scheduler will not point near-Sun (meaning far west early in the evening or far east in the late pre-dawn hours) if there will be a significant likelihood of LEOsat trails. The detrailing options for the LSST pipeline processing were very interesting, but these will also tend to remove trails originating from NEOs. Catalina and other ongoing NEO surveys will be similarly impacted but may not have the same cross-talk or focus trade-offs as LSST. The NEO Surveyor Mission will cover the near-Sun region from L-1 and will be unimpacted by LEOsats, however NEOSM will be sensitive to larger, more distant NEOs, not the more frequent small close-approachers. It

would be useful to model / simulate twilight observations, near-sun or for illuminated satellites high in the sky for all surveys together.

The OneWeb scenario will additionally degrade NEO discovery and follow-up all night long and from all ground-based observatories. (There are few NEO sites at very high latitudes.) For LSST it would be useful to model/simulate the detrailing techniques against trails or simply elongated PSFs of moving objects.

We were asked that if *given a satellite predictor tool, does Catalina Sky Survey have the capability to control the shutter mid-frame to avoid satellite trails? How would that change your assessment of losses to data and to science?* The answer is yes, but CSS survey exposures are 30 seconds with 3.5-second readouts. CSS follow-up exposures are typically shorter than this, but can also be longer. Shuttering takes 0.6s to both open and close for our survey cameras. Our follow-up shutters are tens of milliseconds. But since objects are moving we will likely never close a shutter mid-exposure for this purpose. If / when trails become numerous enough to endanger a significant fraction of our interleaved multi-exposure field visits (scheduled as sets of about ten fields, repeated four times), we would likely modify our queue manager to schedule around predicted traversals of a field. Precision satellite ephemerides, with or without an accompanying predictor tool, would be critically important in such a case.

And we were asked to *describe synergies expected in the next 5 years between your program and other facilities e.g. Rubin/LSST that may be seriously impacted by LEOsats.* The NEO community has long been among the best examples of multi-observatory scheduling in astronomy. All NEO discoveries, including unique objects like the interstellar asteroid ‘Oumuamua, rare objects like the mini-moons 2020 CD3 and 2006 RH120, less rare than one finds comfortable impactors 2008 TC3, 2014 AA, 2018 LA, 2019 MO — all NEO discoveries are community efforts that often interleave multiple survey detections as well as numerous targeted follow-up. The value of new facilities like Rubin’s LSST or of NEOSM is in danger of being throttled by mega-constellations either on the survey or follow-up side. In addition to being a survey engine, Rubin will be a wonderful follow-up engine for discoveries from NEOSM or the ongoing ground-based northern surveys. Twilight near-Sun is precisely where NEOSM will need ground-based optical follow-up to deliver albedos for their new discoveries.

Eric Christensen, Catalina Sky Survey:

Satellite mega-constellations [probably do not] represent an existential threat to NEO surveys, at least for programs like CSS that have a single goal of moving object detection and operate in a truly NEO-optimized way: four exposures evenly spaced over <1 hour, in the same filter, without strict requirements on photometry.

As for metrics: we could reasonably estimate the impact of satellite constellations on our efficiency by counting pixels that would be lit up by a satellite — essentially treating satellite trails as gaps that get carved in our detector. It's fairly straightforward to estimate how a 98% fill factor mosaic compares to a 100% fill factor mosaic when used in a NEO-friendly cadence, for example.

There may be a tipping point where active avoidance or fancy processing techniques pay off, but even with ~100x more satellites I'm not sure we'd reach that point. Consider a worst-case where every survey image contains a satellite that fully crosses the image — 5 binned pixels wide, running diagonally from corner to corner. That's 37,000 pixels out of 27.9 million, or about 0.13% of the detector. The fill factor drops from 100% to 99.87%. If the detection criteria were a strict 4 out of 4, then raise 99.87% to the fourth power and your detection efficiency becomes 99.48%. Relaxing to 3 out of 4 allows you to recover some of that, preferentially for brighter objects.

Our detection efficiency doesn't start at 100%, but a rough estimate is that a satellite trail in every image will cost a few tenths of a percent in detection efficiency. I'd qualify this as "**negligible**", nowhere near "significant" or "fatal".

Our follow-up use case is also more forgiving than most — since we use short exposures, all we'd have to do is drop out any images that have a trail going directly over the object. Satellites could be present in the images but if they don't cross the precise position of the object, they don't cost anything. For the worst-case survey example of a trail crossing every survey image, scale by the FoV of a follow-up telescope (say 1/20th the FoV of a survey telescope) to estimate one satellite per 20 images. For a 2K detector, 14,500 pixels out of 4.2 million get carved out, or 3.5%. An average of 2 images per 40-image stack will contain a trail, but only 1 out of about 30 satellite-affected images will touch the object of interest. I think this boils down to 1 or 2 images per night might have to be rejected due to a coincidental passage of a satellite over a targeted NEO — which is unlikely to make the difference between detection and non-detection in a 10-image stack. I think the worst-case scenario of a trail in every survey image, or in every 20th follow-up image, is only relevant if satellites are visible all night long to 1-2 meter class telescopes. If they're visible only near twilight, then scale the overall impact to detection efficiency down by a factor of 5-10 x.

Distant Solar System objects

"[W]e are in the process of dedicating our smaller telescopes to transient discovery and monitoring. We also have an active imaging survey to look for distant solar system objects. Bright moving satellites could impact the real-time analysis of these surveys, although we might be able to mitigate this by avoiding certain areas on the sky around sunset/sunrise." (John Mulcahey, Carnegie Observatory)

Discovering the unexpected

> "[D]ue to its unprecedented etendue LSST opens the prospect of discovering the unexpected. This very likely will occur in the time domain — precisely the discovery space most at risk from artifacts arising from tens of thousands of LEO Sats." (Tony Tyson, Rubin Observatory)
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> "Astronomy is still driven by discovery." (New Worlds, New Horizons, 2010 Decadal Survey of Astronomy and Astrophysics)

Concerns of the non-professional astronomy community and adjacent night-sky stakeholders

John Barentine, International Dark-Sky Association:

This group of users of the night sky is impacted in ways that are as meaningful and significant as their professional counterparts. In addition to the scientific value of the night sky, there is cultural and social value that is difficult, if not impossible, to quantify in dollars. However, some of the same mitigation approaches that allay concerns of the professional astronomy community may well serve the interests of the non-professional user community.

Ensuring that satellite visibility is unusual (relatively speaking) and that the time-averaged brightness of satellites is held below the threshold of naked-eye visibility is not a sufficient criterion to satisfy the needs of this constituency, but it is a start. Glints are less of a concern, especially if they are predictable; the amateur community found Iridium flares, for example, to be more exciting than annoying. Glints also ruin far fewer pixels than long continuous trails.

Wide-field astrophotographers suffer the same problem as high-AΩ telescopes, albeit with considerably smaller apertures. A significant fraction of night photography is now done with wide-angle lenses that capture wide swaths of the sky. Also, most images are also created with relatively long shutter speeds ranging from 15-30 seconds for static cameras to many minutes on tracking mounts. Taken together, these two characteristics mean that visible satellite and airplane trails are already a nuisance in night photography. The current reality is that most night photography images will have a small satellite or airplane trail visible within them somewhere. And yet many night photography image opportunities are difficult or impossible to replicate, so asking photographers to just "try again" isn't a particularly realistic solution.

Individual satellite and airplane trails can be removed from single images through editing. While time-consuming, the process is fairly straightforward and can be done with minimal disturbance to the image. The prospect of removing multiple satellite trails from single images, however, is daunting. Satellite removal in photographic time-lapses is problematic because any alterations to local areas of individual images become noticeable when a sequence of images is animated.

The local adjustments will be slightly different for each image, and these minor differences become evident when the sequence is animated. Currently no post-processing tool exists to adequately address this issue.

Modern DSLR and mirrorless cameras with full-frame sensors equipped with a wide-angle lens can routinely capture images containing objects as faint as magnitudes +9 to +10. When using a DSLR with a fast telephoto lens on a tracking device under dark and transparent skies, it is possible to capture images of objects as faint as magnitudes +15 to +16. This ability to capture otherwise-invisible night sky subjects is one of the features that makes night photography so compelling. Furthermore, “astro-modified” cameras whose IR-blocking filters have been removed are sensitive to any near-IR emissions or reflections from satellites.

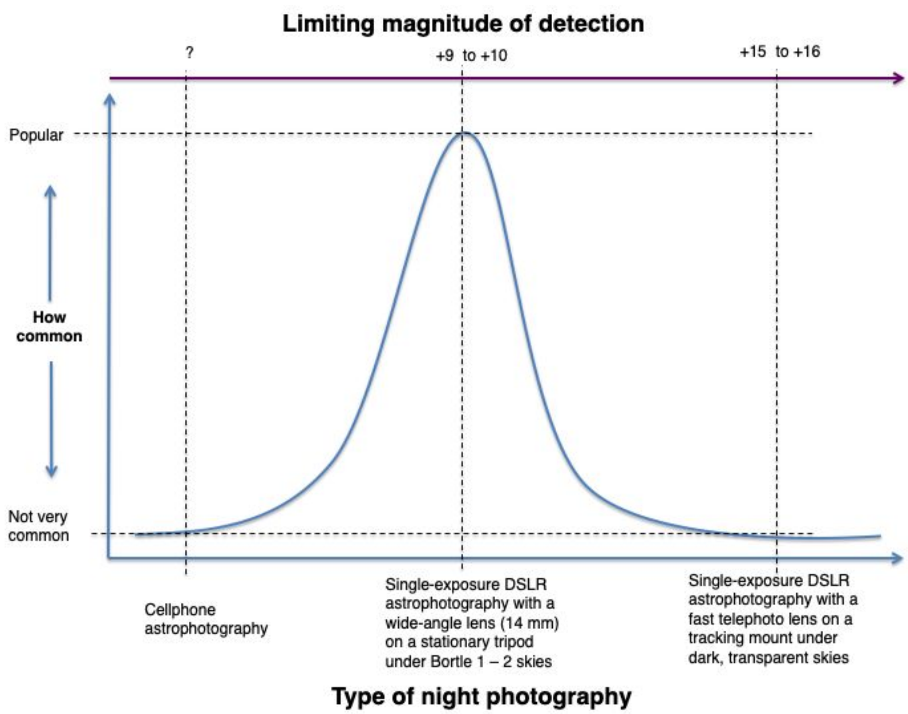

Figure D.1. Frequency of types of astrophotography, expressed as distribution of exposure fraction with limiting magnitude.

For casual stargazers and people whose cultural and religious practices involve use of the night sky, a maintained brightness threshold at the limit of naked-eye detection for the majority of observers is sufficient. We recommend no brighter than visual magnitude +7 to be on the safe side, even though people with unusual visual acuity may see fainter, and the faint limit might be helped by atmospheric scintillation. This will of course not account for glints, although presumably that is a problem limited largely to twilight.

For the questionnaire rating (John Barentine, IDA and Mike Shaw, astrophotography):

Unaided-eye visual observers
A maintained visual magnitude of +7 or fainter obviates the problem for observers of the night sky who use no optical aid. But the problem should not be considered “solved”. SpaceX says there will be ~300 Starlinks either on their way up or down at any given time, and that number will increase as more operators start launching. These objects may be brighter than magnitude 7 even though they will be mostly noticeable during twilight. It depends somewhat on whether the DarkSat/VisorSat/orientation-roll combination brings them *quickly* to maintain +7 mag after launch. Still, relative to the existing population of objects in LEO, Starlink alone may roughly double the number of moving objects detectable by the unaided eye around twilight. We rate this impact as **negligible to annoying**.

Telescopically-aided visual observers
These observers are already impacted by the presence of satellites and other orbital objects well below the naked-eye visibility threshold. Given typical angular speeds and generally small fields of view, the distractions caused by moving objects are brief in duration, although bright, unexpected objects moving through telescopic fields of view can be startling. We rate this impact as **negligible to annoying**.

Mobile-phone astrophotographers
Given capabilities in the current generation of mobile devices, which tend to have small and relatively noisy sensors, these devices are unlikely to record trails from objects at magnitude +7 or fainter. These devices may be sensitive to bright objects near twilight, and to glints/flares later at night, but we expect the overall effect to be small. We rate this impact as **negligible to annoying**.

Narrow-field astrophotographers
These photographers use long-focus lenses or telescopes and tracking mounts to achieve sufficient exposure times, so they stare at smaller fields of view than visual observers or mobile-phone/wide-field photographers albeit for longer times. Assuming the availability of a reliable satellite pass prediction tool, these photographers are better able to avoid exposing while satellites are present. We rate this impact as **significant but (potentially) tolerable**.

Wide-field astrophotographers
These photographers capture views with fields of view comparable to mobile phone cameras but with significantly larger sensors and greater light-gathering power. They also achieve considerably fainter limiting magnitudes even in relatively short exposures. Given an average of two satellite trails per square degree per 60-second exposures near the horizon, as indicated by simulations, 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. We rate this impact as **fatal**.