Impact of Satellite Constellations

on Optical Astronomy and Recommendations Toward Mitigations

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Cover image: In May 2019 SpaceX launched its first batch of 60 Starlink communication satellites, which surprised astronomers and laypeople with their appearance in the night sky. Astronomers have only now, a little over a year later, accumulated enough observations of constellation satellites like those being launched by SpaceX and OneWeb (seen in this artist's impression, not to scale) and run computer simulations of their likely impact to begin to understand the magnitude and complexity of the problem.
Credit: NOIRLab/NSF/AURA/P. Marenfeld

[EXECUTIVE SUMMARY]

Existing and planned large constellations of bright satellites in low-Earth orbit (LEOsats) will fundamentally change astronomical observing at optical and near-infrared (NIR) wavelengths. Nighttime images without the passage of a Sun-illuminated satellite will no longer be the norm. If the 100,000 or more LEOsats proposed by many companies and many governments are deployed, no combination of mitigations can fully avoid the impacts of the satellite trails on the science programs of current and planned ground-based optical-NIR astronomy facilities. Astronomers are just beginning to understand the full range of impacts on the discipline. Astrophotography, amateur astronomy, and the human experience of the stars and the Milky Way are already affected. This report is the outcome of the Satellite Constellations 1 (SATCON1) workshop held virtually on 29 June–2 July 2020. SATCON1, organized jointly by NSF's NOIRLab and AAS with funding from NSF, aimed to quantify better the impacts of LEOsat constellations at optical wavelengths and explore possible mitigations.

Recent technology developments for astronomical research — especially wide-field imaging on large optical telescopes — face significant challenges from the new ability in space and communication technologies to launch many thousands of LEOsats rapidly and economically. This troubling development went unnoticed by our community as recently as 2010, when *New Worlds, New Horizons* — the most recent National Academies' decadal survey of astronomy and astrophysics — was issued. In the last year, the sky has changed, with growing numbers of satellite trails contaminating astronomical images.

Many astronomical investigations collect data with the requirement of observing any part of the sky needed to achieve the research objective with uniform quality over the field of view. These include studies that are among the highest priorities in the discipline: stellar populations in the Milky Way and neighboring galaxies; searches for potentially hazardous near-Earth objects; identification of gravitational wave sources such as neutron star mergers; and wide-area searches for transiting exoplanets. At a minimum, a fraction of the area being imaged is lost to the trails or significantly reduced in S/N (signal-to-noise ratio). However, many of these areas of research also include a time-critical aspect and/or a rare, scientifically critical target. Such a missed target, even with low probability, will significantly diminish the scientific impact of the project. For example, if a near-Earth object is not recovered, its orbital parameters are lost. If the transit of a promising super-Earth exoplanet candidate is missed, the orbital timing may not be recovered. If the optical counterpart of a gravitational wave source is lost in the few percent of pixels in satellite trails, its rapid fading may preclude subsequent identification. Detailed simulations beyond the scope of this workshop are required to better quantify the potential scientific cost of losing uniform full area coverage in these cases.

Even more challenging simulations are required to understand the impact on very large samples (e.g., from Vera C. Rubin Observatory) that are limited not by small number statistics but rather by systematic uncertainties. One measure of precision cosmology, for example, is the gravitational weak lensing shear that elongates faint galaxy images, and more complex modeling is needed to understand the major impact these satellites will have on this field.

Initial visibility simulations have shown the significant negative impacts expected from two communications-focused LEOsat constellations, Starlink (launched by Space Exploration holdings, LLC [SpaceX]), and OneWeb. For SATCON1, simulations were performed of the visibility of LEOsats with 30,000 second-generation Starlink satellites below 614 km and ~48,000 OneWeb satellites at 1200 km, in accord with the FCC filings for these projects. 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 (~600 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

Figure 1: Starlink trails over Bryce Canyon. The image is a stack of multiple, consecutive exposures acquired over a period of about 30 minutes, an example of the impact of satellite constellations on multi-image astrophotography. Image credit, Spencer Camera and Photo

summer, with only a small reduction in the number visible compared to those in the twilight.

Mitigation of the most damaging impacts on scientific programs is now being actively explored by the professional astronomy community worldwide. These investigations have benefited from collaboration with SpaceX, the first operator to launch a substantial constellation of LEOsats (538 satellites over 9 launches as of July 2020). Changes are required at both ends: constellation operators and observatories. SpaceX has shown that operators can reduce reflected sunlight through satellite body orientation, Sun shielding, and surface darkening. A joint effort to obtain higher accuracy public data on predicted locations of individual satellites (or ephemerides) could enable some pointing avoidance and mid-exposure shuttering during satellite passage. Observatories will need to adopt more dynamic scheduling and observation management as the number of constellation satellites increases, though even these measures will be ineffective for many science programs.

SATCON1 was attended by over 250 astronomers and engineers from commercial operators (mainly from SpaceX since they are furthest along in their work on this issue), as well as other stakeholders, and reached a number of conclusions and recommendations for future work. The organizers hope that the collegiality and spirit of partnership between these two communities will expand to include other operators and observatories and continue to prove useful and productive. Our findings and recommendations should serve as guidelines for observatories and satellite operators alike to use going forward, even as we work toward a more detailed understanding of the impacts and mitigations.

Our findings and recommendations are listed below.

A. Findings

Finding 1

The projected surface density of bright satellites in constellations is greatest near the horizon and during twilight. For this reason, LEO constellations disproportionately impact science programs that require twilight observations, such as searches for near-Earth objects (NEOs), distant Solar System objects and optical counterparts of fleeting gravitational wave sources. Depending on constellation design, LEO satellites can also be visible deep into the night, broadening the impact to encompass all astronomical programs. We find that the worst-case constellation designs prove extremely impactful to the most severely affected science programs. For the less affected programs, the impact ranges from negligible to significant, requiring novel software and hardware efforts in an attempt to avoid satellites and remove trails from images.

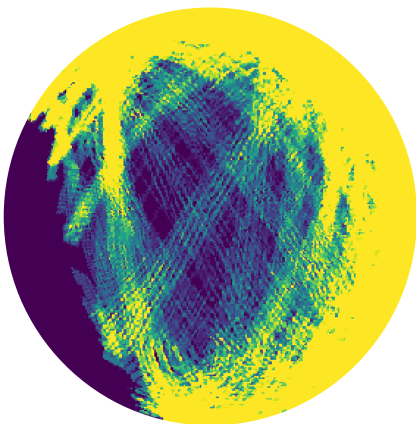

Figure 2: A simulated all-sky plot of trails of 47,708 illuminated LEOsats over a 10-minute time period as seen from Rubin Observatory in Chile with the altitude of the Sun at -18.4 degrees. Zenith is at the center, north is up and east is left. The trails are bunched due to populating the orbital planes. The trail-free region is caused by the Earth's shadow. Credit: P. Yoachim (U. Washington/ Rubin Observatory), private communication

We find two step-functions in impact based on the brightness of the satellites: naked-eye visibility and instrument sensor calibration range. If satellites are visible to the naked eye, the scope of impact expands to include non-professional, unaided-eye observers including amateur astronomers and astrophotographers, and possibly indigenous peoples and members of religions that observe the sky for calendar-keeping. Satellites whose apparent brightnesses are below unaided-eye visibility can have a much more severe impact on astronomical science if they are bright enough to cause non-correctable artifacts in the camera sensors. For fainter satellites, of course, the trail itself remains and must be dealt with. In the cases where it might be impossible to fully mask or remove trails, a bright enough satellite could induce systematic errors impacting some science investigations.

Satellites below 600 km

LEOsat constellations below 600 km are visible for a few hours per night around astronomical twilight from observatories at middle latitudes, but they are in Earth's shadow and invisible for several hours per night around local solar midnight, with some satellites visible during the transitions. This visibility pattern causes these constellations to most heavily impact twilight observers (see the examples mentioned above). Since these orbits are closer to Earth, satellites at these altitudes will be brighter than the same satellites would be at higher orbital altitudes. The reduced range makes them more likely to exceed the unaided-eye brightness threshold if operators fail to design with this criterion in mind.

Satellites above 600 km

Satellites above 600 km are an even greater concern to astronomers because they include all the impacts mentioned above, but can also be illuminated all night long. Full-night illumination causes these high-altitude constellations to impact a larger set of astronomical programs.

Finding 2

Approaches to mitigate LEOsat impacts on optical-NIR astronomy fall into six main categories.

1. Launch fewer or no LEOsat constellations. This is the only option identified that can achieve zero impact.
2. Deploy satellites at orbital altitudes no higher than ~600 km.

3. Darken satellites by lowering their albedo, shading reflected sunlight, or some combination thereof.
4. Control each satellite's attitude in orbit so that it reflects less sunlight to Earth.
5. Remove or mask satellite trails and their effects in images.
6. Avoid satellite trails with the use of accurate ephemerides.

B. Recommendations

1. For Observatories

Recommendation 1
Support development of a software application available to the general astronomy community to identify, model, subtract, and mask satellite trails in images on the basis of user-supplied parameters.

Recommendation 2
Support development of a software application for observation planning available to the general astronomy community that predicts the time and projection of satellite transits through an image, given celestial position, time of night, exposure length, and field of view, based on the public database of ephemerides. Current simulation work provides a strong basis for the development of such an application.

Recommendation 3
Support selected detailed simulations of the effects on data analysis systematics and data reduction signal-to-noise impacts of masked trails on scientific programs affected by satellite constellations. Aggregation of results should identify any lower thresholds for the brightness or rate of occurrence of satellite trails that would significantly reduce their negative impact on the observations.

2. For Constellation Operators

Recommendation 4
LEOsat operators should perform adequate laboratory Bi-directional Reflectance Distribution Function (BRDF) measurements as part of their satellite design and development phase. This would be particularly effective when paired with a reflectance simulation analysis.

Recommendation 5
Reflected sunlight ideally should be 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.

Recommendation 6
Operators must make their best effor to avoid specular reflection (flares) in the direction of observatories. If such flares do occur, accurate timing information from ground-based observing will be required for avoidance.

Recommendation 7
Pointing avoidance by observatories is achieved most readily if the immediate post-launch satellite configuration is clumped as tightly as possible consistent with safety, affording rapid passage of the train through a given pointing area. Also, satellite attitudes should be adjusted to minimize reflected light on the ground track.

3. For Observatories and Operators in Collaboration

Recommendation 8
Support an immediate coordinated effort for optical observations of LEOsat constellation members, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations. Such observations require facilities spread over latitude and longitude to capture Sun-angle-dependent effects.
In the longer term, support a comprehensive satellite constellation observing network with uniform observing and data reduction protocols for feedback to operators and astronomical programs. Mature constellations will have the added complexity of deorbiting of the units and on-orbit aging, requiring ongoing monitoring.

Recommendation 9
Determine the cadence and quality of updated

positional information or processed telemetry, distribution, and predictive modeling required to achieve substantial improvement (by a factor of about 10) in publicly available cross-track positional determination.

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

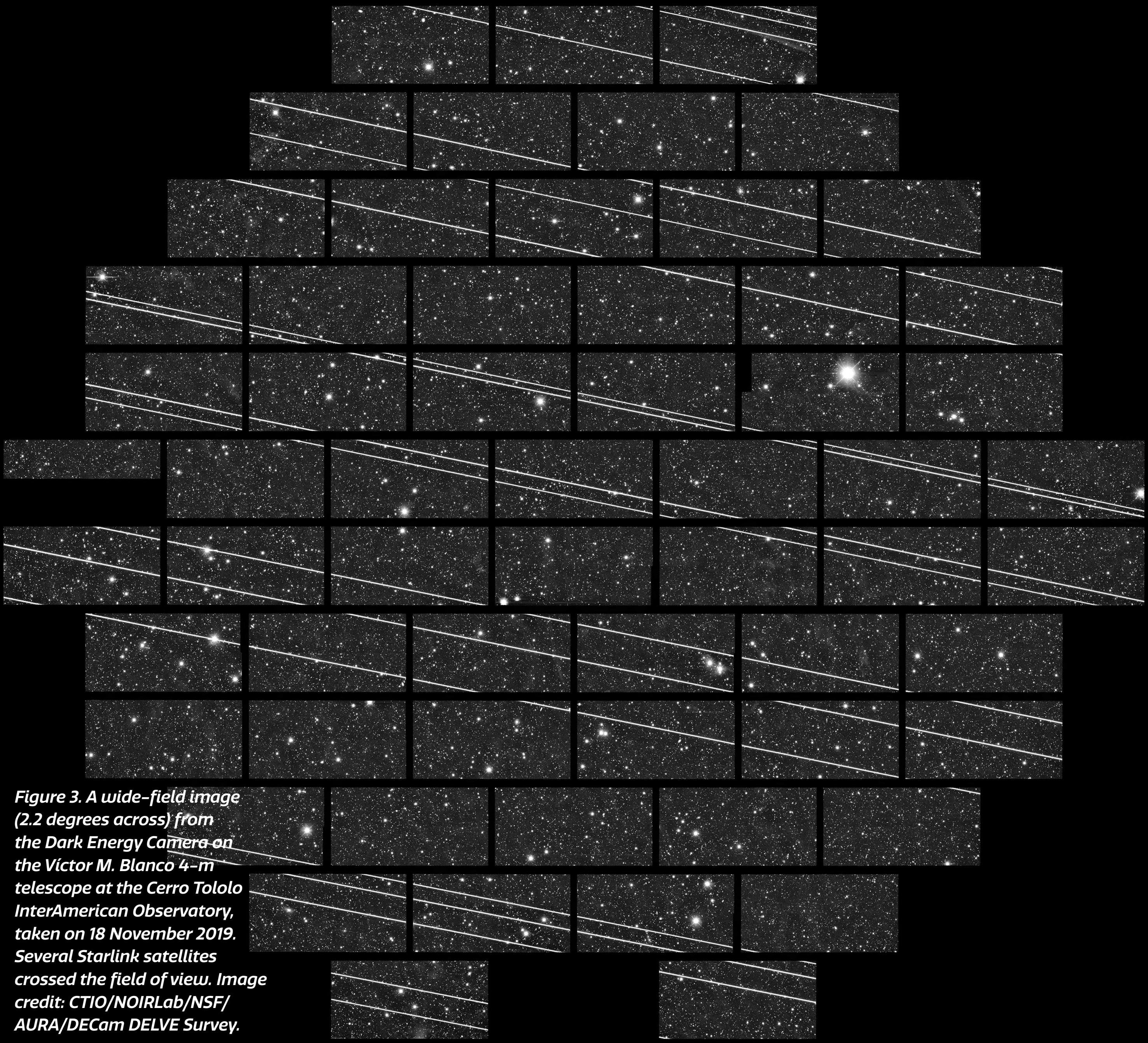

Figure 3. A wide-field image (2.2 degrees across) from the Dark Energy Camera on the Víctor M. Blanco 4-m telescope at the Cerro Tololo InterAmerican Observatory, taken on 18 November 2019. Several Starlink satellites crossed the field of view. Image credit: CTIO/NOIRLab/NSF/AURA/DECam DELVE Survey.

I. INTRODUCTION

Figure 4: The Hubble Deep Field showed the value of observing the same patch of sky uninterrupted for days. Credit: Robert Williams and the Hubble Deep Field Team (STScI) and NASA/ESA

In 1995, the Hubble Space Telescope used its valuable observing time to do something seemingly frivolous: stare over ten days at a blank patch of sky. The target area was minuscule — just twice the apparent size of Venus in its crescent phase — but the resulting image, the Hubble Deep Field, revealed thousands of galaxies from the earliest history of the Universe. Subsequent deep field images revealed tens of thousands more galaxies in equally tiny patches of sky. Dark skies hold many secrets, and the flagship ground-based facilities of today are steadily revealing them. Vera C. Rubin Observatory, Astro2010's top recommendation for ground-based optical astronomy, will be online in the next decade. In upcoming decades a set of thirty-meter facilities will come online, expanding substantially our view to our origins. For numerous reasons of expense, maintenance, and instrumentation, these facilities cannot be operated from space. Ground-based astronomy is, and will remain, vital and relevant.

Reflected light from large constellations of LEOsats threatens the scientific viability of these current and future facilities. Constellations at high altitudes, such as the OneWeb constellation at 1200 km, present particularly serious challenges; they will be visible all night during summer and significant fractions of the night during winter, fall, and spring, and will have negative impacts on nearly all observational programs. The recommendations and mitigation strategies in the next section are based on work by and collaboration between astronomers and SpaceX, and no other stakeholders. Nevertheless, they are intended for a broad audience, and especially the satellite constellation industry as a whole. We welcome broader engagement on these issues.

SATCON1 was held virtually from 29 June to 2 July 2020, with over 250 attendees. It focused on the technical aspects of the impact of satellite constellations on optical astronomy; topics of policy and regulation were deferred to SATCON2, tentatively planned for spring 2021. The first two days of SATCON1 consisted of presentations by members of four working groups on topics from papers they had drafted in the preceding month. The remaining days involved revision of these papers.

In Section II of this report, we present our conclusions about the impact of LEOsat constellations on optical astronomy in nine critical use cases. In Section III, we present our recommended metrics and mitigation strategies.

II. IMPACT ASSESSMENT BY SELECTED OBSERVING GENRES AND SCIENCE CASES

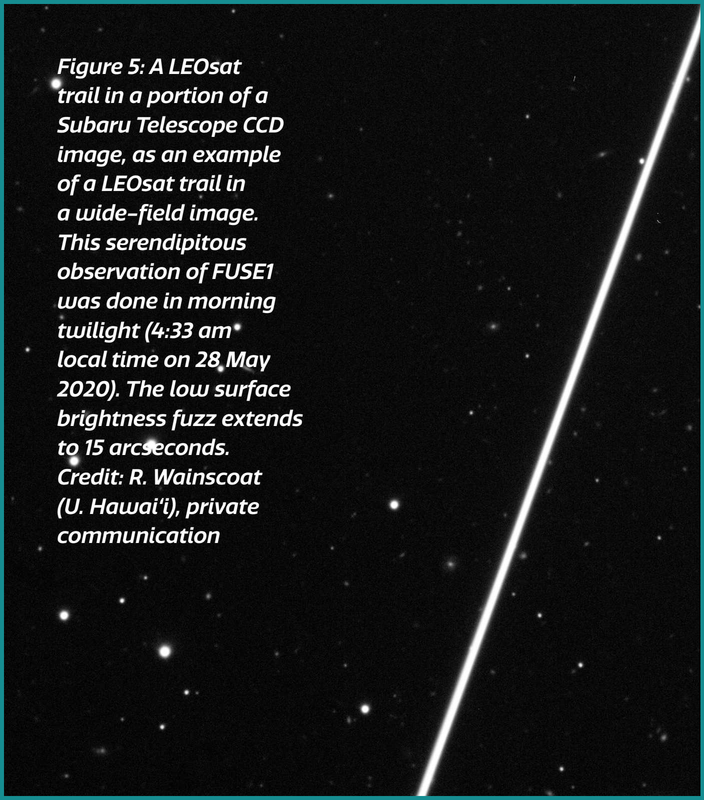

Figure 5: A LEOsat trail in a portion of a Subaru Telescope CCD image, as an example of a LEOsat trail in a wide-field image. This serendipitous observation of FUSE1 was done in morning twilight (4:33 am local time on 28 May 2020). The low surface brightness fuzz extends to 15 arcseconds. Credit: R. Wainscoat (U. Hawai'i), private communication

A. Introduction

To build a more nuanced and detailed view of the likely impacts of large constellations of LEOsats, we identified nine representative science cases and genres of sky observations potentially vulnerable to those impacts:

1. Rare transients, e.g. gravitational wave events, gamma-ray bursts, fast radio bursts.
2. Deep, wide, extragalactic imaging for, e.g., cosmology (dark matter, dark energy) via large numbers of weak lensing, galaxy morphology, and ultra-faint low surface brightness measurements.
3. Near-Earth objects (NEOs).
4. Deep multi-object spectroscopic surveys.
5. Deep wide-field near-infrared (NIR) imaging.
6. Imaging of large extended low surface brightness targets.
7. Exoplanet transits in wide-field surveys.
8. Discovery of new phenomena.
9. Citizen science, amateur astronomers, and stargazers worldwide.

Science and community leaders from many major observatories responded to requests for information in the context of a summary of the Simulations Working Group's models of the appearance of a constellation of 33,000 satellites at 600 km or below (Starlink scenario) and 47,844 satellites at 1200 km (OneWeb scenario). To assist the working group in developing a qualitative impression of the impacts of these constellations, some respondents agreed to categorize the impact through definitions provided in a simple rubric:

- **Negligible**: the program will be realized as originally planned essentially unchanged.
- **Significant but tolerable**: science goals will be somewhat compromised, additional time or resources being required to offset losses.
- **Extreme**: science goals cannot be realized.

Some respondents provided general statements, along with descriptions of relevant observatory performance. The sections below are taken from these responses, with some editing for clarity, narrative, and style.

B. Impacts on Scientific and Observational Programs

1. Rare Transients

Fast Transients
In the next decade, a "new sky" will open up: fast transients, an unexplored regime ripe for the discovery of the unexpected. Searches for optical or infrared counterparts to fast transients require a rapid response — often within 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 optical surveys include the Rubin Observatory Legacy Survey of Space and Time (LSST), the Zwicky Transient Facility (ZTF), and the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS). Sky surveys themselves and spectroscopic follow-up observations are separately impacted by satellite trails.

This is a burgeoning research area with many unknown events and physical phenomena; satellites can ruin detections of these events as well as spectroscopic follow-up and, as the events fade very rapidly, the ability to re-acquire the data is lost.

Optical Gravitational Wave Follow-Up
Simultaneous data from optical/IR observatories and other detectors, such as neutrinos or gravitational waves (GW), represent a unique multi-messenger science opportunity in the next decade. As frequently as once a week, the network of GW 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 images from large telescopes such as Rubin Observatory 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 to spectroscopic follow-up. Owing to the time-critical nature, some of this search will occur during twilight. Satellite trails interfere with algorithms developed to distinguish real transient events from false detections.

Rapid Contiguous Monitoring of Special Sky Areas
Like the 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 LSST Deep Drilling fields, which will be rapidly imaged for about one hour every night in multiple filters to detect unusual events. Another example is the Large Magellanic Cloud, a nearby dwarf galaxy important both for new transients and for probing the physics of dark matter.

2. Deep, Wide, Extragalactic Imaging

Low surface brightness imaging surveys over wide areas enable unprecedented probes of cosmology and galaxy evolution. Much of the science from the LSST will involve statistical analysis of trillions of photometric measurements of 20 billion objects. Measuring the physics of dark matter and dark energy requires billions of extremely faint (26th magnitude) galaxies for which the shape must be accurately known to one part in 10,000. Science discoveries from these measurements will be more affected by systematics than by sample size. This is a new paradigm.

One example is cosmology. The masked long satellite trails present a low surface brightness systematic error 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. Each satellite trail will have its own low surface brightness systematic error extending 30–60 arcseconds from the trail, depending on the satellite brightness. These residual errors and correlated linear noise features scale with trail brightness.

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 petabytes of images. They therefore will also rely on the LSST data management to do the required pixel processing and artifact removal. This work is algorithmically feasible for satellite trails that are fainter than magnitude 7–8, but it represents additional work beyond the original scope of the project. A key issue is systematic errors that will ultimately land in the alerts and catalogs released by the LSST for the scientific community; for those programs most affected, the sheer task of tackling these new systematic errors in the released data products is likely beyond the capability of many.

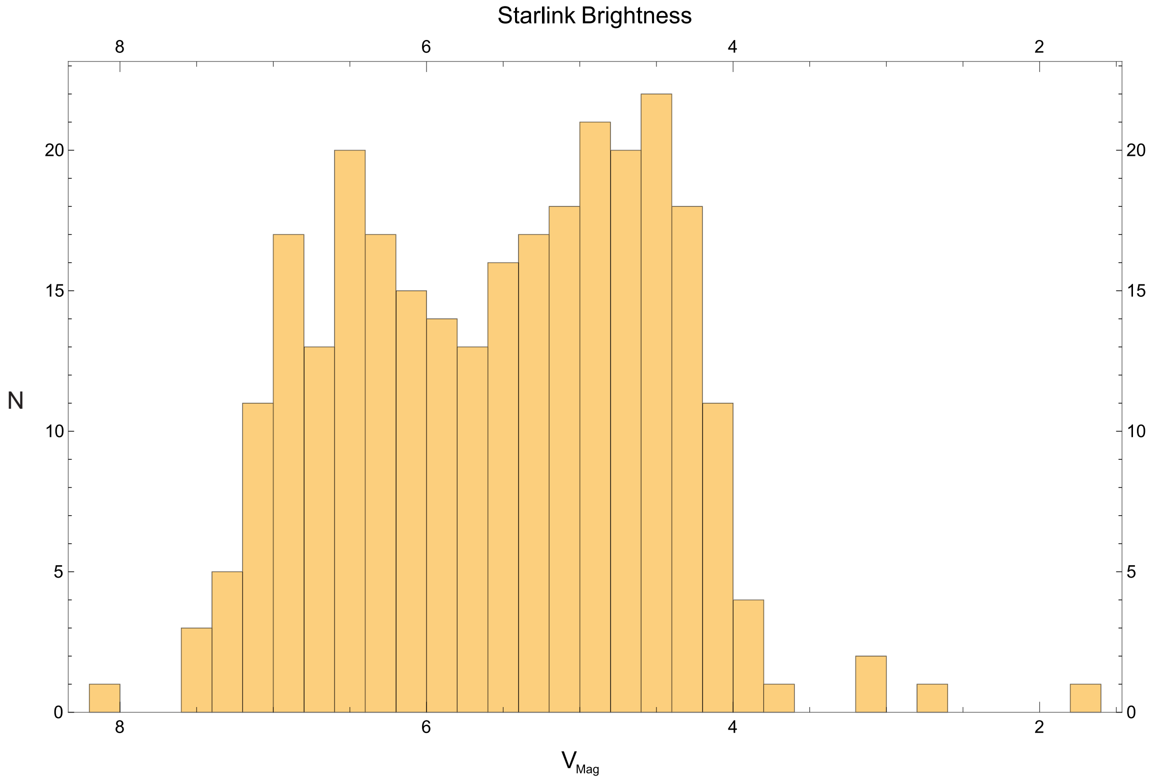

Figure 6: A histogram of 281 visual magnitude measurements of Starlink satellites imaged by the Pomenis Observatory in late May and early June 2020. The mean of all 281 measurements is V_{mag} = 5.5 with a standard deviation of 1.0. This broad distribution of values demonstrates the varied brightness of Starlink satellites which depends on numerous geometric factors. Credit: H. Krantz (U. Arizona), private communication

3. Near-Earth Objects (NEOs)

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, but the most direct motivation for discovering and characterizing NEOs is their potential to collide with the Earth and cause catastrophic damage to ecosystems and human civilization. Asteroids and comets have frequently impacted Earth in the past and will do so in the future, over long intervals with dramatic consequences, if not discovered and mitigated. NEO detection and characterization has a US congressional mandate and is also supported by the United Nations Office for Outer Space Affairs. These surveys operate in the twilight hours when their targets are visible but also when satellite interference is worst. Pairs, triples, or quads of observations must be made within a short time in order to form a moving object "tracklet," and the probability of a LEOsat trail interfering with this process is high.

LEOsats already cause loss of data to Pan-STARRS, the Catalina Sky Survey, and other NEO surveys, effectively wiping out a long trail in the focal plane. Trails also generate spurious artifacts that can confuse automated pipelines. Just after evening twilight and just before morning twilight are the only usable parts of the night for detecting NEOs at low solar elongation, a particularly rich area for NEO searches thanks to the line of sight along the orbit of Earth.

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" in the future. For the Catalina Sky Survey, one way of characterizing the impact is the fractional loss of pixel area from satellite trails; a rough estimate is that a satellite trail in every image will cost a few tenths of a percent in detection efficiency. This can be qualified as "negligible," but bright trails from satellites not yet on-station or that are brightly illuminated without mitigations may have more impact.

As currently understood, either the Starlink Generation 2 or the OneWeb scenario (of order 40,000 satellites) will significantly degrade twilight near-Sun observations, especially for the LSST, as implied by several presentations at the SATCON1 workshop. The satellite trail masking developed for the LSST pipeline processing is very promising, but it may also unintentionally remove trails originating from NEOs. The NEO Surveyor Mission (NEOSM) will observe the near-Sun region from L-1 and will not be impacted by LEOsats; however, NEOSM will be sensitive to larger, more distant NEOs, not the myriad close-approachers that must be observed from the ground. It is vital to model and simulate twilight observations, near-Sun or for illuminated satellites high in the sky, for all surveys.

4. Deep Multi-object Spectroscopic Surveys

Spectroscopic observations generally cover smaller fields of view than imaging programs. However, exposure times can be much longer for spectroscopy, e.g., 1800 sec or more vs. typically 300 sec or less for imaging. A bright satellite crossing near a long spectrograph slit, series of slitlets in a slit mask, or integral field unit (IFU) could ruin the entire exposure, as it is not known *a priori* which observations are contaminated, forcing a repeat exposure or possible loss of science opportunity.

There are several large spectroscopic facilities nearing operation or in advanced planning that are all vulnerable to LEOsat trails. The Dark Energy Spectroscopic Instrument (DESI) is a wide-field spectrograph on the Nicholas U. Mayall 4-m telescope at Kitt Peak National Observatory. With an 8 square degree field of view and long exposures (10–20 minutes), it is not possible to "point between" satellite trails. DESI has completed its construction phase and will begin operations in 2021. LEOsats will impact DESI spectroscopy because of the large number of fibers in the focal plane (5000), the width of each satellite trail, and especially the long integration times. The far larger Maunakea Spectroscopic Explorer (MSE) project could transform the Canada-France-Hawaiʻi (CFHT) 3.6-m optical telescope into an 11-meter dedicated multi-object spectroscopic facility, with the ability to observe more than four thousand objects simultaneously using a suite of spectrographs with a variety of spectral resolutions. With its large aperture, MSE will generally always target very faint sources, and so the signal from LEOsats will dominate over the science target. Practically speaking, this means that the observation of those targets will be precluded.

LEOsats also leave a much wider trail than the effective size of low surface brightness objects, which will impact the necessarily long integration times for these faint objects. The largest contributor to this effective faint object size is the wide wings of the point-spread function (PSF) in typical turbulent air corresponding to good sky conditions (0.7 arcseconds FWHM seeing). Since the mean separation between fibers or slits in a 0.2–1.0-degree focal plane is comparable to LEOsat trail width, the probability of a LEOsat trail polluting one or more spectra is high with tens of thousands of LEOsats. Owing to the long exposure times, there is no mitigation for the next generation of large spectroscopic facilities where control of mid-exposure shuttering is not possible.

These levels of impacted spectrograph fibers are significant, and the science impact generally will not be discovered until after the observations. At low contaminating flux levels, on-the-fly data quality control will not identify the contamination (e.g., if the satellite is a few times fainter than the target). As a result, contaminated data will impact the science analysis and it may no longer be possible to re-acquire ruined data. To mitigate the impacts, it is important to be able to promptly flag (within ~24 hours after the observations) which fibers were affected by a satellite. This implies developing the ability to access the positions of the satellites with a precision comparable to a fiber diameter, and with a timing accuracy of ~1 second.

5. Deep Wide-field NIR Imaging

Wide-field large-aperture surveys are especially vulnerable to satellite trails; WFCAM, a wide-field near-IR camera at the 4-m United Kingdom Infra-Red Telescope (UKIRT) on Maunakea, is an appropriate example. It is almost impossible to determine if LEOsat trails can be handled in its images; the default pipeline stacking will remove short obvious satellite trails, but LEOsats generally leave longer and lower surface brightness tracks, and these are much harder to get rid of cleanly. Custom software would be required to attempt to use the characteristic LEOsat longer track signatures to locate more directly the pixels they influence.

6. Imaging of Large Extended Low Surface Brightness Targets

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 (V_{mag} ~ 23–27) than a V_{mag} = 7 satellite moving at 0.5 degrees/s, which has a surface brightness of V_{mag} ~ 16 after correcting for exposure time. Satellites prevent the use for faint galaxy science of the region of the frames extending up to 60 or more pixels away from their trails (i.e., 120-pixel diameter, equivalent to ~30 arcseconds swath). Bright (V_{mag} < 12) image artifacts can make it difficult or impossible to detect faint galaxies in large regions of the field. This argument is generally true for extended regions of low surface brightness, or for any imaging program with the expectation of uniform signal-to-noise ratio (S/N) over 100% of the areal coverage.

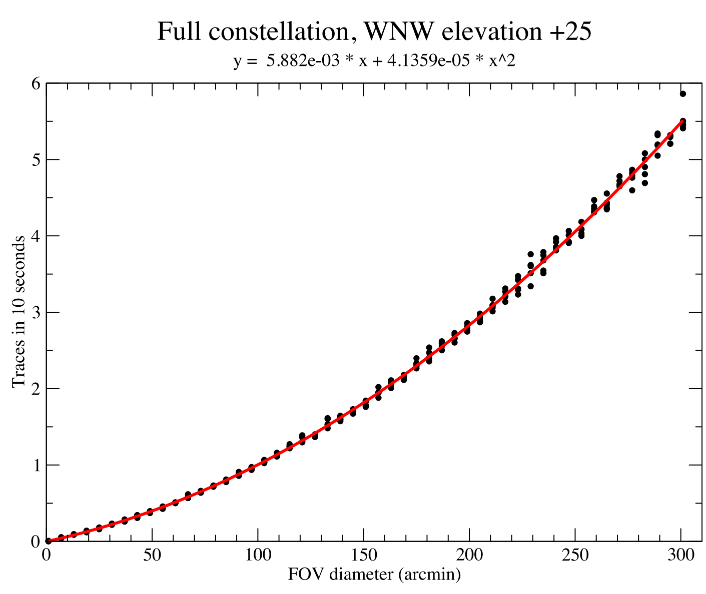

Figure 7: Count of the number of satellite trails affecting a 10-second exposure for increasing field of view (FOV). The dots represent a series of direct simulations of observations, while the line shows a model fit. Credit: Galadi, private communications

7. Exoplanet Transits in Wide-field Surveys

LEOsat constellations will impact exoplanet surveys. Stars that fall near satellite trails will suffer from skewed and less precise photometry, as well as added noise. Exoplanet detection will be impossible for stars that fall directly under a trail. Some of the most severely affected targets will be the M dwarfs, since cooler stars (at a fixed distance) will suffer larger relative effects. With the full constellations deployed, it will be impossible to detect super-Earth planets around M dwarf stars crossed by satellites.

An example of impacted facilities is the Hungarian-made Automated Telescope Network (HATNet) telescopes, which are sensitive, wide-field (10.4 degree x 10.4 degree) optical instruments, staring at selected fields and taking images every 3 minutes. They make high precision, low-noise relative photometry to detect the shallow transits of extrasolar planets in front of their host stars. The amplitudes of transits range from 2–3% for the largest planets to 0.1% for targets such as hot Saturns, Neptunes and super-Earths. All-sky variability has not been explored at the milli-magnitude level, at short timescales (~minutes), and at very long timescales (years, a decade), and satellite crossings will compromise variability studies for these low-amplitude and short-timescale phenomena.

8. Discovery of New Phenomena

Arguably the most exciting and important science to come out of current and planned astronomical facilities will be the discoveries of types of objects and phenomena not yet observed nor predicted by theorists. New technology has always led to such surprise discoveries (e.g., moons of Jupiter discovered with the new telescope by Galileo, pulsars discovered with radio telescope by Jocelyn Bell, stellar activity revolutionized with Kepler exoplanet space telescope), and almost certainly the coming decade of new facilities will likewise produce unpredicted and profound surprises. Those discoveries have the potential to revolutionize our understanding of every field from exobiology to cosmology.

“Astronomy is still driven by discovery.”

(New Worlds, New Horizons — 2010 Decadal Survey of Astronomy and Astrophysics)

For example, thanks to its unprecedented etendue (the product of a telescope's effective light-collecting area in square meters and its field of view in square degrees), Rubin Observatory opens the prospect of discovering the unexpected, especially in the time domain. It is precisely this discovery space that is most at risk from artifacts arising from tens of thousands of LEOsats.

It is impossible to calculate the risk or the impact of losing such opportunities to discover the unexpected without knowing what we're missing. But some phenomena will surely go undiscovered as a result of significant interference from LEOsats.

9. Citizen Science, Amateur Astronomers, and Stargazers Worldwide

This group of users of the night sky is impacted in numerous ways. In addition to the scientific value of the night sky, there is cultural and social value that is difficult, if not impossible, to quantify.

Severe impact potential

- Though we know of no plans to deploy a large unaided-eye-visible satellite constellation, there is no technical or legal barrier to building one. Such a constellation would have a very extreme impact on unaided-eye visual observers around the world.
- Given an average of two satellite trails per square degree per 60-second exposure near the horizon, as indicated by simulations, wide-field astrophotography would be severely impacted by the fully-deployed Starlink Generation 2 and OneWeb constellations.

Moderate impact potential

- Based on current deployment strategies, we expect there to be hundreds of satellites on their way up or down at any given time. These may be brighter than magnitude 7 even though they will be mostly noticeable during twilight. It depends somewhat on whether operator mitigations bring 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 space-based moving objects detectable by the unaided eye around twilight.
- The night sky has been a cultural resource since our earliest ancestors, with its significance ranging from practical benefits (e.g., tracking seasonal changes) to religious practices. With sufficient numbers of bright satellites, these stakeholders could be impacted as well and should be included in deliberations as LEOsat deployment continues.

Minor impact potential

- Casual observers using telescopes are already impacted by the presence of satellites and other orbital objects below the naked-eye visibility threshold. These distractions are brief, although bright, unexpected objects moving through telescope fields of view can be startling.
- A similar impact applies to mobile-phone astrophotographers, as these devices tend to have small and relatively noisy sensors 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.
- Narrow-field astrophotographers observe smaller fields of view than visual observers or mobile-phone/wide-field photographers. However, they do so 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.

C. Summary

The impacts of large constellations of LEOsats on astronomical research programs and the human experience of the night sky are estimated to range from negligible to extreme, depending on factors including the scientific or other goals of the observation, the etendue of the facility, the observing strategy and ability to avoid satellites, and the ability to mask or remove satellite trails in data. The impact also depends strongly on the number of satellites, the orbital altitude of the satellites, the apparent brightness and attitude of the satellites, and the accuracy of their positional ephemerides. Most astronomical researchers and institutions are only now, a little over a year after the first tranche of 60 Starlink satellites were launched, coming to appreciate fully the magnitude and complexity of the problem.

III. PERFORMANCE METRICS AND RECOMMENDATIONS FOR CHARACTERIZATION AND MITIGATION

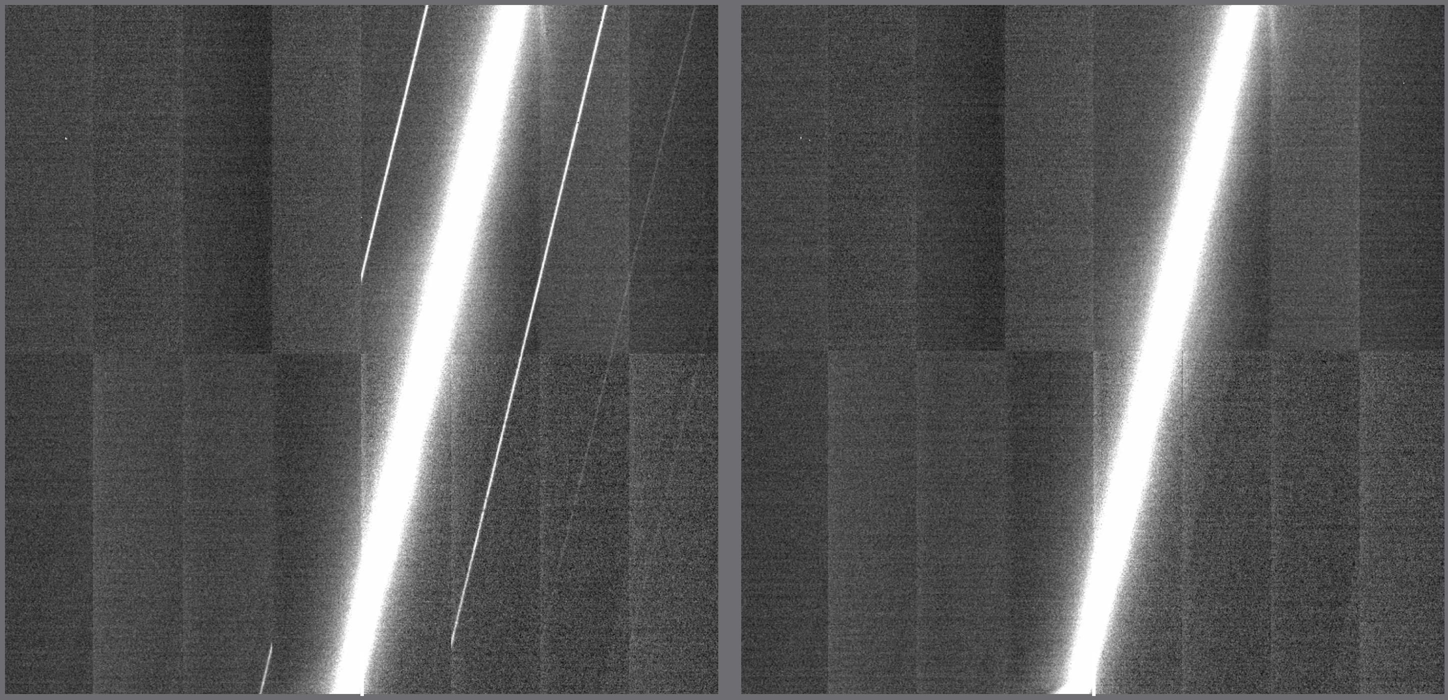

Figure 8. Simulation of a trail from a LEOsat at 550 km in Rubin Observatory's Legacy Survey of Space and Time (LSST). The most serious effect of bright LEOsats on the CCD sensors might be the electronic crosstalk (left) between the 16 segments of the CCDs, each of which has its own amplifiers and signal chains that are simultaneously sampled during readout. 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). Credit: T. Tyson UC Davis/Rubin Observatory, private communication

A. Visibility

Six groups performed simulations of representative LEOsat constellations, from which we draw preliminary conclusions about the impact on astronomical observations. 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 (~600 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. The passage of a LEOsat through the field of view produces a bright trail; in that area the information from the night sky is lost. (The area must be identified and eliminated from analysis; that process is called masking.) Scientific investigations requiring imaging with uniform signal-to-noise (S/N) of complex regions over large fields of view will need multiple additional exposures to compensate for masked satellite trails, assuming 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. Figures demonstrating these effects are shown on the next two pages.

1. 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 grows with increasing altitude above ~600 km and increasing numbers of constellation satellites. Future simulations of impact on a range of scientific programs may allow the determination of a threshold for a reduced upper limit on effective reflectivity that provides a significant recovery of lost imaging area and/or lost total exposures.

2. Mitigation

For satellite operators:
Design constellations for operational orbits below 600 km with the minimum number of units needed for bandwidth and coverage requirements.

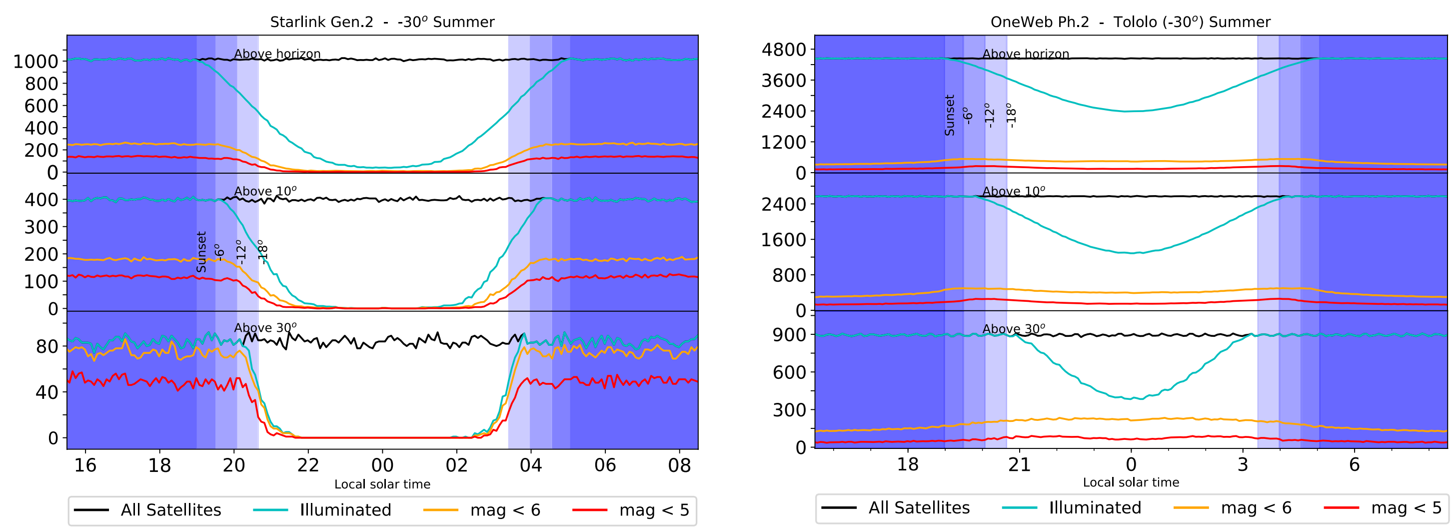

Figure 9. These figures show the visibility of the proposed Starlink Generation 2 (left, 30,000 satellites mostly around 350 km altitude) and OneWeb Phase 2 (right, 50,000 satellites at 1200 km altitude), as seen from Vera C. Rubin Observatory (30 deg latitude S) at summer solstice. Within both figures, the top panels are for all satellites in sight, middle for satellites above 10 deg elevation, and bottom, above 30 deg 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. Credit: O. Hainaut (ESO), private communication

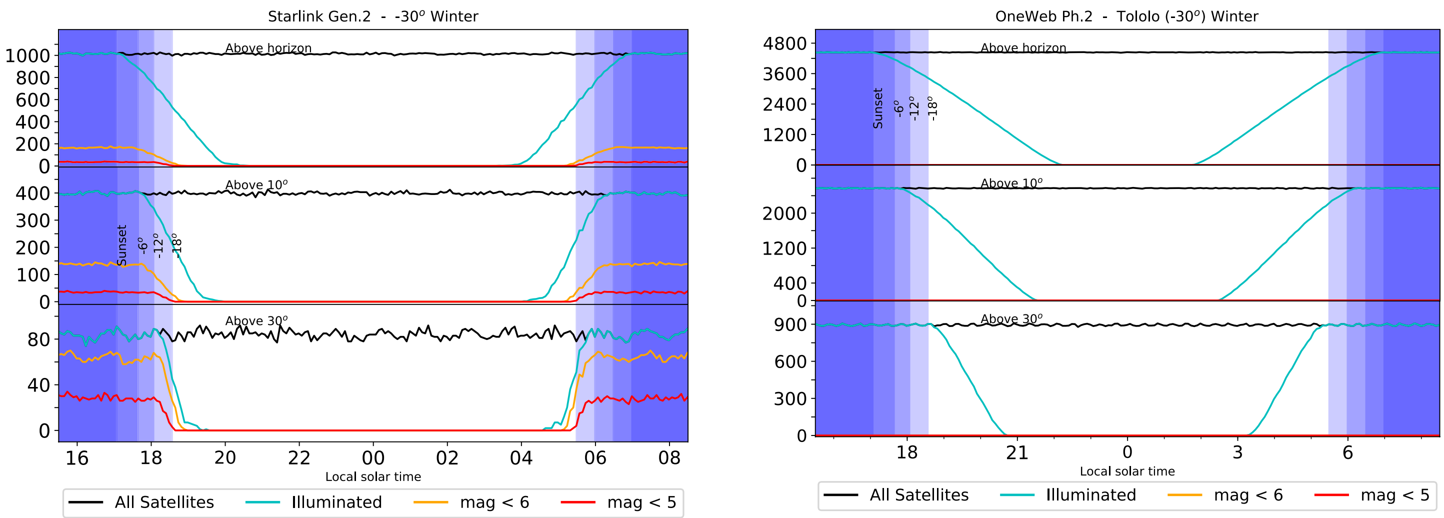

Figure 10. These are the same figures as on the previous page, except shown for winter solstice at Rubin Observatory. Again, note the much larger obscured period and much steeper curves for the lower-altitude Starlink satellites as compared to the OneWeb constellation. Credit: O. Hainaut (ESO), private communication

B. Reflected Sunlight

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

These mission stages can cause sunlight reflection much stronger than that in the operating orbit. Even with a build-out of tens of thousands of constellation units, the number of satellites in these mission phases is expected to be in the hundreds at any given time. However, the higher the orbit, the longer the deorbit phase (up to centuries from 1200 km).

2. On-station

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 crosstalk, 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 area of the primary track, requiring masking where the brightness of the trail exceeds a 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. Satellites fainter than V_{mag} = 7 were found to be necessary, leading to the following metric:

Reflected sunlight should be slowly varying with orbital phase as recorded by high etendue (effective area × field of view) and for large-aperture ground-based telescopes should be fainter than $7.0\ V_{mag} + 2.5 \times \log(r_{orbit} / 550\ \text{km})$*, equivalent to* $44 \times (550\ \text{km} / r_{orbit})$ *watts/steradian.*

The recorded image for Rubin Observatory and other large-aperture telescopes of similar focal length is resolved in angle because a satellite subtending ~0.33 arcsecond is well out of focus at a distance of 550 km compared to infinity. For constellations at the higher ~1200 km altitude, the surface brightness is lower because the satellite is further away (proportional to 1 / distance^2), but the footprint of the more in-focus image is smaller (leading to a concentration of light proportional to distance^2). Meanwhile, the observed angular velocity across the sky scales as distance$^{-1.5}$. The recorded surface brightness therefore depends only on the dwell time from the orbital motion, proportional to distance, with a constant recorded limit requiring reduced effective reflection by 1/distance. Taken together, a full simulation of these effects leads to the conclusion that satellites at 1200 km must be fainter than V_{mag} = 8 to compare with the effects of V_{mag} = 7 satellites at 550 km. Unfortunately, satellites at 1200 km can be visible all night long. Addressing this issue for the telescope with the greatest etendue, that of Rubin Observatory, is likely to put most other facilities into a similar or better performance regime with respect to satellite trails.

SpaceX has conducted a series of development efforts exploring possible mitigation strategies. VisorSat is the latest experiment attempting to reach the minimum requirement, employing a combination of these mitigation approaches.

3. Flares and Glints

Flares are specular reflections off designed facets of the spacecraft. They can be many times brighter than the surface brightness limit above, leading to uncalibratable crosstalk or saturation. The illumination by a flare makes an astronomical image unusable. The expectation is that flares will be rare events.

Any fine texture on the reflecting surface of the satellite, such as multi-layer insulation, will provide rapidly varying reflectivity known as glints, possibly on millisecond 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.

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.

4. Mitigation

For satellite operators:

- Surface darkening.
- Sun shielding.
- Avoiding the use of non-rigid specular materials on the nadir face of the satellites to reduce false transients.
- Potentially adjusting attitude to avoid flares projecting onto major ground-based observatory sites.
- Best efforts for attitude control of satellites within communications and power constraints to minimize effective reflectivity and ensure predictable nadir-facing specular surfaces in direction of ground-based observatories.

For observatories, near-term:

- Image post-processing to identify, model, subtract, and mask affected pixels associated with the satellite trail.
- With precise ephemerides of entire constellation suites, and for those facilities where it may be practical, close shutters for the seconds around predicted passage.
- Pointing avoidance when possible.

For observatories, decadal-scale:

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

Collaborative:

- Sufficiently accurate ephemerides of the flares themselves for pointing avoidance.
- Publicly available ephemerides as accurate as possible.

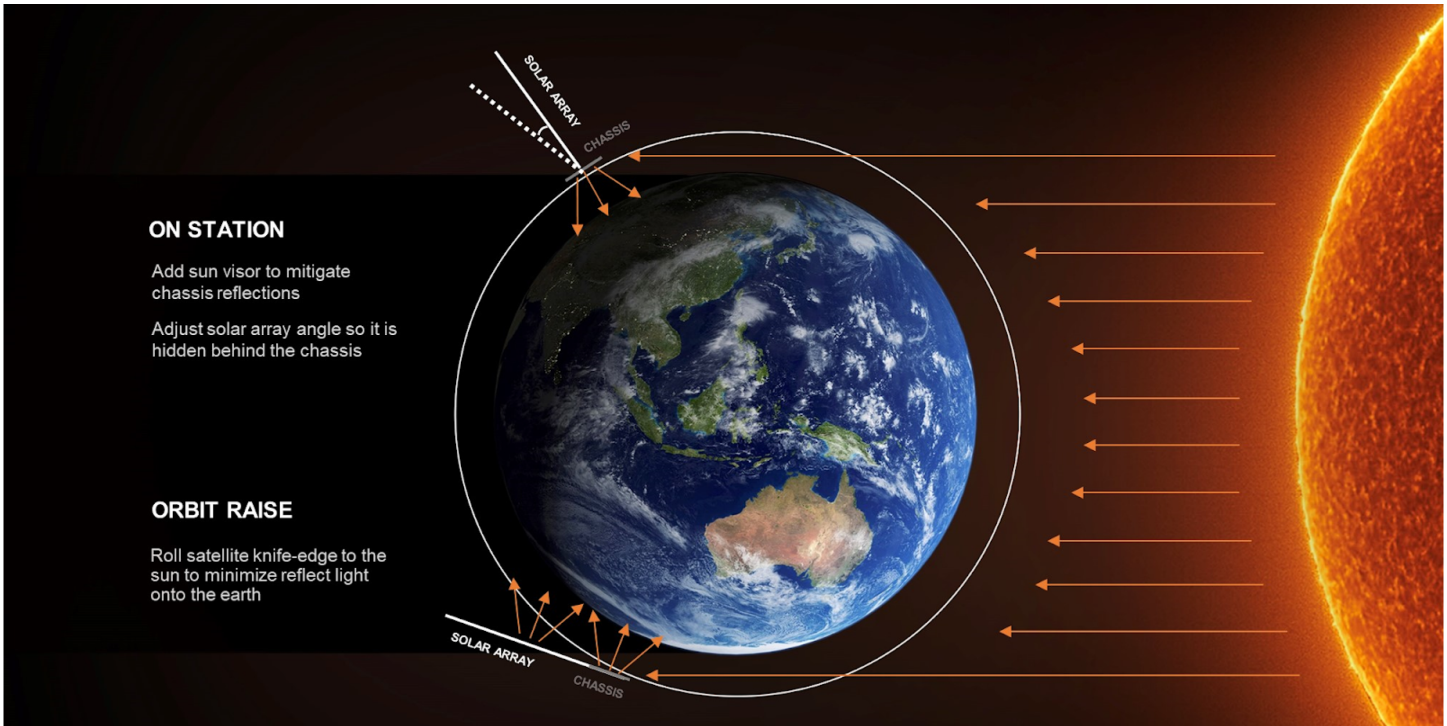

***Figure 11:** As an example of operational mitigation, during orbit raise, Starlink satellites are rolled edge-on to the Sun to reduce the projected area illuminated by sunlight. On-station, a Sun-visor shades bright nadir-facing chassis components. Credit: SpaceX*

C. 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. The following expectations and recommendations are based on what is currently achievable. The need for significant improvement will require astronomers to develop more dynamic observation scheduling and operators to share their more frequently updated positions as input to improved predictions of orbital elements.

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

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. In this case, we require 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. We must also know the position of the track to within 12 arcminutes in the cross-track direction and 12 arcminutes in position angle.

2. On-station

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.

3. Mitigation

Collaborative:
Determine the update cadence of publicly available positional information or processed telemetry, distribution, and predictive modeling required to achieve substantial improvement, which we require to be a minimum of a factor of 10, in cross-track positional determination.

D. Recommendations

1. For Observatories

Recommendation 1
Support development of a software application available to the general astronomy community to identify, model, subtract, and mask satellite trails in images on the basis of user-supplied parameters.

Recommendation 2
Support development of a software application for observation planning available to the general astronomy community that predicts the time and projection of satellite transits through an image, given celestial position, time of night, exposure length, and field of view, based on the public database of ephemerides. Current simulation work provides a strong basis for the development of such an application.

Recommendation 3
Support selected detailed simulations of the effects on data analysis systematics and data reduction signal-to-noise impacts of masked trails on scientific programs affected by satellite constellations. Aggregation of results should identify any lower thresholds for the brightness or rate of occurrence of satellite trails that would significantly reduce their negative impact on the observations.

2. For Constellation Operators

Recommendation 4
LEOsat operators should perform adequate laboratory Bi-directional Reflectance Distribution Function (BRDF) measurements as part of their satellite design and development phase. This would be particularly effective when paired with a reflectance simulation analysis.

Recommendation 5
Reflected sunlight ideally should be 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 Vmag +2.5 × log(rorbit / 550 km), equivalent to 44 × (550 km / rorbit) watts/steradian.

Recommendation 6
Operators must make their best effort to avoid specular reflection (flares) in the direction of observatories. If such flares do occur, accurate timing information from ground-based observing will be required for avoidance.

Recommendation 7
Pointing avoidance by observatories is achieved most readily if the immediate post-launch satellite configuration is clumped as tightly as possible consistent with safety, affording rapid passage of the train through a given pointing area. Also, satellite attitudes should be adjusted to minimize reflected light on the ground track.

3. For Observatories and Operators in Collaboration

Recommendation 8
Support an immediate coordinated effort for optical observations of LEOsat constellation members, to characterize both slowly and rapidly varying reflectivity and the effectiveness of experimental mitigations. Such observations require facilities spread over latitude and longitude to capture Sun-angle-dependent effects. In the longer term, support a comprehensive satellite constellation observing network with uniform observing and data reduction protocols for feedback to operators and astronomical programs. Mature constellations will have the added complexity of deorbiting of the units and on-orbit aging, requiring ongoing monitoring.

Recommendation 9
Determine the cadence and quality of updated positional information or processed telemetry, distribution, and predictive modeling required to achieve substantial improvement (by a factor of about 10) in publicly available cross-track positional determination.

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

Acknowledgments

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