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THE FUTURE OF THE NIGHT SKY: LIGHT POLLUTION FROM SATELLITES

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Summary

The increase in pLEO (proliferated low Earth orbit) constellations set to launch over the next decade has fueled concern from the astronomy community, academia, and the general public over the light pollution visible in the night sky created by sunlight reflecting off these satellites. Like many aspects of large pLEO constellations, such as their effect on space traffic management efforts and potential increase in space debris, the overall impact of pLEO light pollution on astronomical observational equipment and research is still largely under-studied and merits objective analysis. Included in these "known unknowns" is the potential public impact of pLEO reflection of sunlight in addition to the larger light pollution problem from the ground, which has been shown to have adverse effects on astronomical research activities and stargazing. Although interference with astronomical observations from low Earth-orbiting satellites can, in principle, occur at the beginning and end of the night observation window during long winter nights, the effect is more pronounced and may last the whole night during short summer nights. Most telescopes are "overbooked," and any reduction in utility has an impact to operations. This paper presents an objective analysis of the increase of reflective satellites affecting astronomical observations and investments in astronomy and astronomical infrastructure worldwide.

Introduction

Commercial space companies, such as SpaceX, Telesat, OneWeb, and Amazon, have announced plans to launch large constellations of small satellites into low Earth orbit (LEO). The logic behind the large constellation architecture is to take advantage of advancements in automation and miniaturization achieved in the past two decades to quickly build and operate several thousand satellites. These "smallsats" are comparatively inexpensive, faster to produce, and can be more readily replaced and upgraded. Should they all make it to orbit, the proposed commercial large constellation satellites launched could total well over 17,000, distributed primarily between low and very low Earth orbits by the end of the 2020s[1] and could surpass 50,000 in the following decade.[2] The scale of these planned constellations is significantly large in comparison to the current satellite population in orbit.[*]

It's not only commercial companies eyeing the shift to large proliferated LEO (pLEO) constellation architectures (sometimes referred to colloquially as *mega-constellations*). For some national security missions, a constellation of multiple smallsats may

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[*] For comparison, fewer than 9,000 payloads have been put into orbit in the past 62 years.

be more elusive targets for an adversary to interfere with than traditional, exquisite satellites, which can sometimes reach the size of a school bus, take years (rather than weeks or months) to manufacture, and are orders of magnitude more expensive to produce. The Defense Advanced Research Projects Agency (DARPA) has been designing a LEO constellation program called Blackjack, which aims to develop and demonstrate the critical elements for a global high-speed network in LEO.[3] Blackjack will provide the Department of Defense (DOD) with "highly connected, resilient, and persistent coverage." DARPA and the DOD are also collaborating with the recently established Space Development Agency (SDA) to report to the House Armed Services Committee on the benefits of pLEO architectures, including how they could enhance overall system resilience, and making further recommendations for integrating such architectures into wider national security space strategy.

Despite the potential benefits from the proposed pLEO constellations and the recent public discussion, the aggregate effects of light pollution from such constellations remain underexamined in an objective way. If not carefully considered and mitigated at the design stage, optical reflective emissions of satellites may have a negative impact on astronomical research, undercutting investments made in astronomy by national governments, universities, and private foundations around the world. Astronomers can compensate for general light pollution by locating their telescopes in dark places, but they cannot site their telescopes to avoid satellites except for placing them in space themselves (like the future James-Webb Space Telescope). Stop-gap measures and temporary fixes already exist for when a single satellite passes through the field-of-view (FOV) of a telescope, but astronomers and telescope operators stress that a continued lack of high-level coordination on mitigation strategies will make satellite light pollution and radio frequency emissions an increasingly difficult problem to tackle as architectures shift toward large constellation models. The present concerns of the astronomy community and others over the contribution of reflectivity of pLEO constellations to overall light pollution are part of this larger, under-studied set of concerns that merit further interdisciplinary and objective research.

Satellites' Contribution to Light Pollution

The brightness of an object in space, such as a planet, a satellite, or a star as viewed in the night sky from Earth's surface is described as its *apparent* magnitude, with larger numbers indicating fainter objects. For astronomers with ground-based telescopes, brighter apparent magnitudes of satellites result in bright streaks of light across the exposures captured by their equipment (a satellite streak or track)—the same way a headlight from a car might appear as a streak of light across a long-exposure photograph taken by a camera at night. A similar effect is caused by airplane lights in the night sky. Depending on the apparent magnitude and the duration of the exposure, these satellite streaks in exposures are forcing astronomers to throw out some portions of their data at what they are warning could be an unsustainable rate.

Magnitudes were created by ancient Greeks, are based on the response of the human eye, and are captured in a logarithmic equation where smaller numbers represent brighter sources, with each magnitude being a multiple of 2.512 times brighter or fainter, depending on whether the magnitude is smaller or larger. Using this scale, a magnitude 1 star is about 2.5 times brighter than a magnitude 2 star, 6.31 times brighter than a magnitude 3 star, 15.85 times brighter than a magnitude 4 star, and so on. For reference, the sun's apparent magnitude is –26.74, and the International Space Station (ISS) can reach –6. The Hubble Ultra-Deep Field detected objects as faint as +30 magnitude.[4]

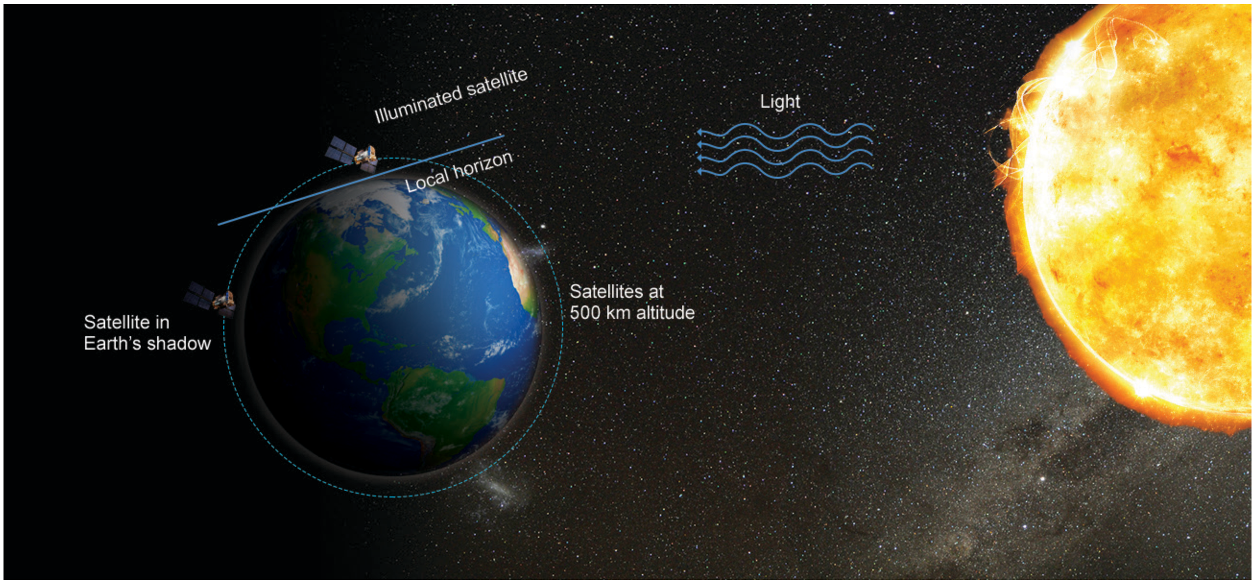

Figure 1: The period of illumination. *Interference with an astronomical image is possible* only *when a satellite is illuminated by the sun (outside of Earth's shadow)* and *the observatory is located in the dark. The diagram displays (roughly to scale) a satellite orbit at 500 km.*

The apparent magnitude of a satellite in space varies based on multiple factors such as the observer's position on the Earth's surface, the altitude and specific orbit of the spacecraft, and the angle between the sun, satellite, and observer in addition to the satellite's reflectivity. When viewed from the ground, satellite brightness can also vary by time of year as regions experience shorter periods of night during the local summer. On the Earth's surface, the *terminator* defines a moving line that separates the side of the Earth illuminated by the sun and its dark side (see Figure 1). Shortly after sunset, there is a period of twilight where the sky is still illuminated by the sun. Astronomical twilight begins when the center of the sun is 18° below the local horizon, which usually indicates the time at which astronomical observations can begin. The observation window ends when the sun again is 18° below the horizon prior to sunrise. Satellites, because of their altitude, can still be sunlit and visible to a telescope even when the location of the telescope is in "astronomical night" conditions. As the observer location rotates deeper into the night, satellites are in Earth's shadow and do not reflect sunlight. The interference period (satellites being illuminated) is longer for satellites at higher altitudes and, at geostationary Earth orbit (GEO), generally lasts the entire night—though, because they are so much farther away, they appear dimmer to the observer. Satellites at lower altitudes are brighter but have less impact because they move into Earth's shadow earlier than satellites at higher altitudes.

Orbiting spacecraft have generated optical interference for decades—most of them quite predictably. For example, the original Iridium constellation had predictable flares of specular reflection, visible to the naked eye, with a consistency that enabled them to be predicted down to the second. The timing of such flares has historically been tracked and published on the nonprofit Heavens Above website. Timing and observing them has become a hobby to some, and watching satellites with naked eye can be inspirational to children and the general public.

Other types of interference are continuously provided by airplane lights as well. Astronomers regularly find streaks of blinking lights in images throughout the night. Interference with star trackers on lower altitude satellites may be possible but is deemed unlikely due to the short exposure time and algorithms of these devices. Human navigators will also be able to quickly separate a LEO satellite from a star due to the fast movement across the night sky.

Streaks generated by large numbers of reflective satellites in LEO effectively create light pollution from space for astronomers attempting to observe dim stars in our own or distant galaxies. They make up a small and uncontrolled portion of the wider light pollution problem affecting astronomers. A 2016 American Association for the Advancement of Science (AAAS) study found that more than 80 percent of the world and more than 99 percent of U.S. and European populations live under light-polluted skies, and that the Milky Way is hidden from more than one-third of humanity.[5]

The low apparent magnitude (greater brightness) of satellite reflections in a telescope's FOV, which can be caused by both specular (direct, mirror-like reflections, which cause short flares or glints) and diffuse (indirect) reflection (which causes the longer streaks), degrades the quality of the exposures it captures. In extreme cases, they may even temporarily "blind" sensor pixels capturing the images. For astronomers, that interference can impede their ability to capture long-duration exposures of deep space. When interviewed, Johnathan McDowell, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics and staff member at the Chandra X-ray Observatory, said, "On a technical level, when an image is ruined, we throw out one, with the understanding that the next will be fine."

Most satellites need some form of surface coating to protect them from exposure to extremes of the space environment, including harmful radiation.[6] A satellite body's surfaces are characterized by its visible reflectivity or albedo (α) and its thermal infrared emissivity (ε).

Satellites often produce the largest signals (both visible or near-infrared reflected and thermal emitted signatures) because of the large surface area of solar arrays relative to the cross-sectional area of the body of the satellite. While the solar arrays of very small satellites do not typically have large surface areas, many glints and thermal signatures are dominated by the effects of reflected or emitted light from their arrays.

Many coatings applied to satellite bodies have high reflectivity to preclude the absorption of heat from the sun in the visible and near-infrared range, from approximately 0.4 microns (µm) to 2 µm. These same coatings generally have a high emissivity (meaning they radiate well in the thermal IR, between approximately 4 µm and 20 µm), so that they can radiate excess heat into space to control the temperature of the electronics. By contrast, solar arrays are designed to absorb the visible and near infrared photons from the sun, which has its peak brightness near 0.5 µm. About one-fourth to one-third of that energy is converted into electricity, while the rest of the energy goes to heat the arrays. The arrays are heated to around 390° Kelvin (contributing to their infrared signatures), and the emissivity of both the cover glass on the front of the satellite and the black coating on the back are designed to help radiate that heat into space before it can be conducted to the body of the spacecraft. Most exterior finishes provide the correct emissivity for thermal considerations or to insulate the interior. Any bare metal surfaces are generally treated so that they do not corrode in an orbital environment and change their emissivity. Multi-layer insulation (MLI) is less reflective and can also be used for this purpose.

Ultimately, some coatings applied to satellite bodies protect them but, unfortunately, can also generate the side effect of reflectivity of sunlight toward Earth. Streaks of diffuse reflection and unpredicted flares of specular reflection can affect some of the data astronomers collect.

In the past decade, as the price per kilogram of mass to launch to LEO has decreased, some satellites have been launched for the express purpose of reflecting sunlight down to Earth's surface, such as the art project HumanityStar in 2018. Launched by small launch developer, RocketLab, HumanityStar was a spherical reflective ball intended to serve as a visual reminder of humanity's "fragile place in the universe." Though the art installation de-orbited naturally several months later, the ease with which RocketLab was able to launch a highly reflective mirrored-surface object into orbit raised eyebrows among the astronomical community,[7] pointing to a lack of public sense of urgency surrounding optical interference.

Modeling and Simulation of Optical Interference

To model the effects of satellite reflection of sunlight, we used the mathematical description of the optical assembly[15] to determine the apparent magnitude of a satellite with respect to an observing ground site. The most influential parameters are the size, shape, and attitude of the spacecraft; the angle between the sun, satellite, and observer; and the reflection coefficients of the surfaces. All of these factors would need to be included in a detailed analysis to determine precise interference from a single object. Our purpose here is to define the periods when interference is possible without descending into the specifics of a particular satellite and orbit. To simplify the numerical results, we model hypothetical constellations at 500 km and 1,200 km to illustrate the tradeoff between altitude and illumination (see sidebar). Specific simulations of proposed constellations are available upon request.

Table 1: Examples of Highly Reflective Spacecraft

1990s	Russia announces a plan to light up Siberia at night to a "dusk-like" state through the use of space-based mirrors. A failed test in 1999 marked the end of the project.[8]
1990s to early 2000s	The original Iridium constellation generates regular, predictable flares, easily visible to the naked eye and tracked by the Heavens Above website.[9]
Mid-2010s	The completed ISS is visible, with predictable trajectory tracked via NASA's Spot the Station program and remains the third brightest object in the sky.[10]
2018	China announces a series of "artificial moon" reflective satellites to light the city of Chengdu after dark, to around one-fifth the brightness of streetlamps. If successful, it will be joined by three other "moons" by 2022.[11]
2018	New Zealand subsidiary of American startup company RocketLab launches the HumanityStar reflective "disco ball," raising light pollution concerns among the astronomy community. The object de-orbited[12] prematurely around two months after launch.[13]
2019	Russian startup company StartRocket proposes to investors an "orbital billboard" project to advertise in the night sky. PepsiCo's Russian arm becomes the company's first client but quickly backs out of the deal.[14]

Basic assumptions for the analysis are that the object is a sphere with a 1-meter radius and a diffuse reflection coefficient of 0.2. Having assumed that the object is a sphere, the attitude, orbit plane, and direction of motion are now inconsequential; all that matters is the orbit altitude and geometric relationship between the sun, satellite, and observer. However, there are constraints that limit the periods when interference can occur. We deployed hypothetical constellations (500 km, 1,200 km) each with 1296 satellites evenly distributed at 50 degrees inclination with 36 orbital planes and 36 satellites per plane. As the observatory, we chose the Large Synoptic Survey Telescope (LSST)[16] currently under construction in Cerro Pachón, Chile. In order to count toward possible interference, the observatory must be in astronomical night conditions (after the end of evening astronomical twilight and before the beginning of next morning astronomical twilight). The satellite must be above the horizon of the observer and must be in direct sunlight, and the observed apparent magnitude must be greater than 27 to be observable with the LSST.

To determine all possible geometries where the assumptions and constraints combine to create optical interference, we create a spherical grid at a specific altitude above the observer as shown in Figure 2. The grid shown is at an altitude of 500 km and the observer location is Cerro Pachón, Chile. We performed two simulations (summer vs. winter) to illustrate seasonal effects and the length of astronomical night.

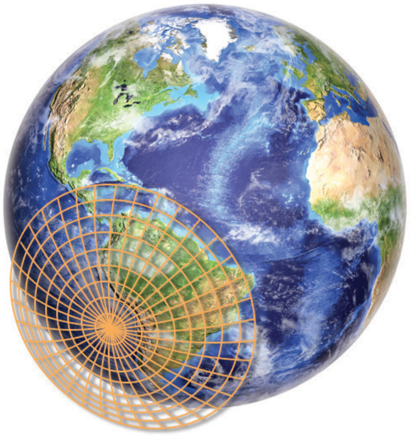

Figure 2: Interference grid of an orbit at 500 km altitude. *Satellites at that orbit will be visible to the ground site (here the LSST in Chile) if the satellites are illuminated by the sun.*

For satellites orbiting at 500 km (1,200 km in simulation 2) altitude and during long winter nights (Table 2), the results show that the observatory can have up to 4 hours (8 hours in simulation 2) of illuminated satellites in the night sky split almost evenly at each end of the night. The period of possible interference begins at the end of astronomical twilight (the first collection opportunity) with approximately 40 satellites (approximately 100 satellites) illuminated. About 63 percent (80 percent) of the sky can have illuminated satellites. At one hour into the night operations, approximately 28 percent (58 percent) of the sky can still receive solar reflections from passing satellites. Two hours (four hours) after astronomical twilight, the site has rotated into Earth’s shadow enough that both altitudes are no longer illuminated (see Figure 3).

During the short summer night, the illumination of both the 500 km and the 1,200 km shell never completely ends although the number of illuminated satellites drops significantly. Table 3 shows the number of satellites illuminated and the percentage of sky with possible interference for a short summer night on the southern hemisphere on December 22.

The sky views of the observatory for a long winter night (June 21) at the beginning (left) and one hour into the astronomical night (right) are shown in Figure 4, where the red region indicates the orbital shell with possible interference. Crosses in the figures denote a satellite location at a single instant in time at 500 km (1,200 km in Figure 5). The specific satellite locations are dynamic and will vary over time, and each satellite in the interference region will produce a streak in the telescope’s imagery if the telescope is pointed in that direction.

Table 2: Beginning (7:15:00 PM) and End (6:12:00 AM) of Astronomical Twilight on June 21 at Cerro Pachón

June 21 (long night)	500 km		1,200 km	
Local Time	% FOV with Possible Interference	Number of Satellites Illuminated	% FOV with Possible Interference	Number of Satellites Illuminated
7:15:00 PM	63.4	40	79.6	95
8:15:00 PM	28.1	12	57.9	75
9:15:00 PM	0.52	0	34.1	40
10:15:00 PM	0	0	11	16
11:15:00 PM	0	0	0	0
12:15:00 AM	0	0	0	0
1:15:00 AM	0	0	0	0
2:15:00 AM	0	0	0	0
3:15:00 AM	0	0	12.1	12
4:15:00 AM	1.18	0	35.2	44
5:15:00 AM	29.8	17	59.1	67
6:12:00 AM	63.5	38	79.4	96

Table 3: Beginning (10:21:00 PM) and End (5:00:00 AM) of Astronomical Twilights on December 22 at Cerro Pachón

December 22 (short night)	500 km		1,200 km	
Local Time	% FOV with Possible Interference	Number of Satellites Illuminated	% FOV with Possible Interference	Number of Satellites Illuminated
10:21:00 PM	63.3	45	79.4	107
11:21:00 PM	38.6	38	64.9	91
12:21:00 AM	21.3	24	53.5	81
1:21:00 AM	13.4	17	47.7	74
2:21:00 AM	15	22	48.9	76
3:21:00 AM	26	25	56.8	84
4:21:00 AM	46.2	39	69.5	97
5:00:00 AM	63.3	45	79.4	108

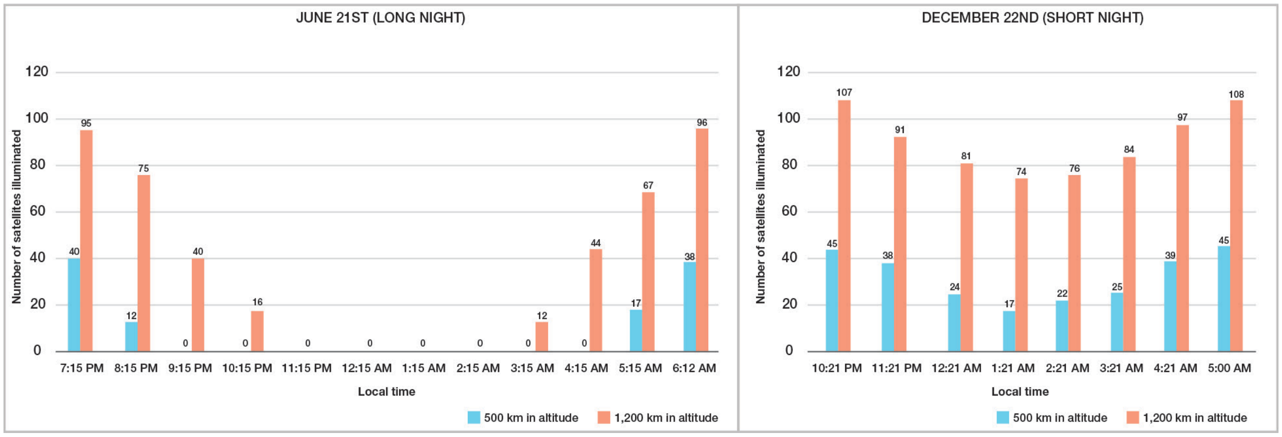

Figure 3: Summary of Tables 2 and 3 with number of satellites illuminated during a long winter night (June 21, left) and short summer night (December 22, right). *Blue bars illustrate the number of satellites illuminated at 500 km, and orange bars show the number of satellites at 1,200 km altitude.*

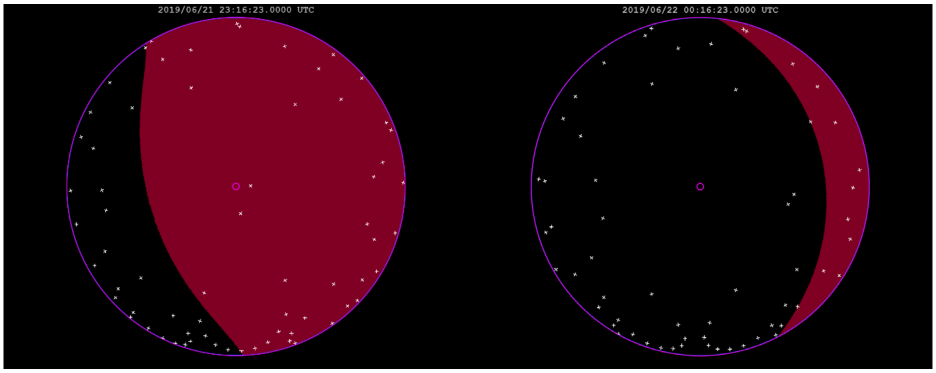

Figure 4: Sky view of illuminated satellites at 500 km altitude on June 21. *The red area shows the part of the orbital shell with satellites still illuminated by the sun as the night progresses. Satellites (crosses) in that part of the sky will reflect the sun. Satellites in the black part of the sky will be dark. The small circle in the center shows the dimension of the FOV of 1.75 degrees half-cone angle (Large Synoptic Survey Telescope). The left figure is based on a simulation at the end of astronomical twilight and the right figure is one hour after astronomical twilight with significantly less of the orbital shell with illuminated satellites in the sky.*

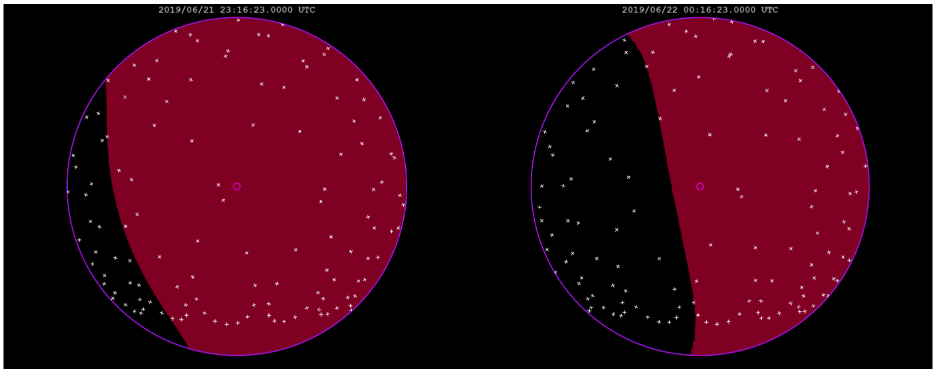

Figure 5: Same as previous figure, showing an orbital shell at 1,200 km altitude also on June 21. *Due to the higher altitude, satellites are much longer illuminated by the sun.*

This analysis shows regions of possible interference from satellite reflections and where orbital shells can have illuminated satellites based on hypothetical constellations at 500 km and 1,200 km. Astronomical telescopes generally have a very small FOV (small magenta circle in the center of Figures 4 and 5) and most are unable to point to all possible regions of their visible sky. This can be due to telescope mount limits or to avoid atmospheric turbulence when pointing close to the horizon. In practice, optical and infrared observations are generally taken at air masses[†] of less than 1.5 (elevation angle greater than 42°) and rarely at air masses greater than 2 (elevation angle less than 30°). Even though more illuminated satellites will appear close to the horizon, most telescopes will not make observations at that angle.

In summary, our simulations show that the number of illuminated satellite and the areas vary throughout the night, leaving varying portions of the sky free from interference. It is technically feasible to predict each position of illuminated satellites and implement the information into astronomical scheduling and optimization routines. However, doing so may lead to an overall reduction in time available to the observatory and may also become impractical at one point.

Current Mitigation Efforts

Astronomers already employ methods to dampen the severity of *ground-based* light pollution in their observations. For example, most amateur telescopes can be fitted with light-pollution reduction (LPR) filters, which are able to block discrete wavelengths, such as those from sodium and mercury street lamps and from atmospheric "airglow," a faint emission of light generated in Earth's upper atmosphere. While these filters can be useful for amateur and hobbyist stargazers, the filters also block the light emitted from stars at those wavelengths—resulting in no improvement in contrast when observing some stars, star clusters, and galaxies. Unfortunately, LPR filters are not effective against satellite flares or streaks; flares are reflected "broadband" light, following the solar spectrum, while the filters are designed for only a very narrow band.

Astronomers must therefore rely on other mitigation strategies to decrease optical interference from satellites. Many algorithms can stitch together multiple exposures taken over specific intervals and digitally combine them to "erase" current levels of satellite streaks. Particularly for short- and medium-duration exposures, though streaks can still compromise some data beyond the point of use, this "stitching" (sometimes called a "track-and-stack" approach) has proved useful as a stop-gap measure to retain as much raw data as possible from each night of measurements.

Mitigating the effects of satellite streaks gets tougher when applied to larger telescope systems, which are sensitive enough to see fainter satellite streaks. Researchers using these systems take multiple exposures of a section of the night sky and median-filter them, throwing out those with streaks and averaging the rest. But each exposure has an opportunity cost in the form of read noise. This is why five separate 10-minute exposures are not equal to one 50-minute exposure; in the first instance, you have five samples of read noises to account for instead of one. Also, reading out an image takes time, adding to the overhead and allocation of observation time requirement. When planning the logistics of operating large telescopes, it becomes a question of balancing this "cost" in read noises. This illustrates why satellite streaks during long-duration

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[†] Air mass indicates the ratio of absolute air masses at oblique angles relative to that at zenith. By definition, the relative air mass at the zenith is 1. Air mass increases as the angle between the look-angle and the zenith increases being highest at the horizon.

exposures can have an impact on data collection efforts; while it may be possible, it could also become impractical to carefully time one hundred 1-minute exposures in between periods of interference. To add to the problem, bright satellites can cause saturation in some pixels, with charge spilling over and "blooming" into the rest of the image. However, using the "track-and-stack" approach on a pixel-by-pixel basis could be an alternative.

It is still unknown how such algorithms would retain their efficacy, as the number and frequency of satellite constellation flares and streaks increases. "From my perspective," McDowell disclosed, "much of the discussion from the commercial side gives me the impression they don't understand how precise astronomy is. It doesn't take much scattered light to ruin an exposure. . . . The point is, the uncertainty is high. And that's a problem."

As skies have grown more polluted with a variety of light sources, state and local governments, as well as grassroots organizations, have started to push back. The International Dark Sky Association (IDSA), for instance, is a nonprofit organization advocating for the preservation of the night sky and providing guidance and education to regulators on how to mitigate light pollution from terrestrial sources. For example, IDSA is working with the public, city planners, legislators, lighting manufacturers, parks, and protected areas to provide and implement smart lighting choices. Astronomers have voiced growing concern as early as the late 1990s, when the first satellite constellations were initially proposed. Proposals for large constellations have created even greater apprehension.

Many cities worldwide have heeded the concerns of groups like the IDSA, incorporating localized efforts to combat ground-based light pollution into their urban planning processes, such as new designs for street lamps that produce less light pollution and are more energy efficient.[4] Ground-based light pollution is especially prominent in densely populated cities, where nighttime lights contribute to the creation of "skyglow," or scattered light in the atmosphere at night. For astronomical equipment and to the human eye, skyglow greatly reduces the contrast between stars and galaxies and the sky itself, making it harder to see fainter objects such as galaxies and nebulae, even with powerful telescopes. Even before exposures are taken, astronomers rely on the periods just after sunset to calibrate their equipment's settings to accurately capture light from astronomical objects in space. For this reason, the locations of wide-field, multi-million-dollar telescope projects designed for long-exposure imaging of deep space are chosen with extreme care, usually at high-elevation and comparatively remote sites.

According to the National Conference of State Legislatures, at least 18 states have laws in place to reduce light pollution but are mostly limited to outdoor lighting fixtures installed on the grounds of a state building or public roadway.[17] In 2015, the Environmental Protection Agency (EPA) administrator, Gina McCarthy, said that light pollution is "in our portfolio" and that the agency is

Table 4: Possible Mitigation Approaches

Summary of Currently Known Mitigation Approaches with Varying Degrees of Feasibility

Astronomers	Satellite Operators
♦ Optimize observation schedules to avoid satellites ♦ Apply "stitching" and median-filter algorithms	♦ Apply special coating or paint to lower reflectivity ♦ Modify orbit placement and satellite orientation

"thinking about it." To date, EPA has no official regulation on light pollution.[18] A recent article highlighted that the EPA has provided the Federal Communications Commission (FCC) with a categorical exclusion since 1986, arguing that such activities do not impact the environment and thus do not require a review.[19] It can be argued, however, that the time has come to address light pollution at the national level.

Local approaches in areas with large astronomical infrastructure can also take the form of laws and regulations that mitigate the effects of ground-based light pollution and radio interference with certain telescopes. These local mitigation efforts have been particularly effective for protecting radio astronomy. West Virginia, for example, is home to the Green Bank Telescope, the world's largest fully steerable radio telescope, and has strictly enforced a "Radio Astronomy Zoning Act." The act prohibits the operation of weak and strong electrical equipment such as microwave ovens and even Wi-Fi routers within two- and ten-mile radii of any radio astronomy facility, respectively, "if such operation causes interference with reception by said radio astronomy."[20] Other radio quiet zone laws restricting radio transmissions within certain areas can be found internationally as well, such as the areas surrounding the Itapetinga Radio Observatory in Brazil and the Murchison Radio-astronomy Observatory in Australia.

Astronomers, however, have found that much of the diligence, investment, and preparation to shield equipment from ground-based light pollution is being undercut by a lack of regulatory coordination around mitigating satellite light pollution and reflections from above. This is of particular concern for wide-field telescopes taking long exposures. "A substantial increase in number of satellites in LEO will certainly change the operations of major ground-based telescopes," confirmed McDowell. Facilities, such as the Large Synoptic Survey Telescope (LSST)[21] currently under construction in Cerro Pachón, Chile, and the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), located at the Haleakala Observatory in Hawaii, perform observations that will help scientists better understand deep space, the nature of dark matter, and how the Milky Way was formed. However, the telescopes also search for undiscovered near-Earth objects (NEOs). The LSST alone will be able to detect between 60 percent and 90 percent of all potentially hazardous asteroids (PHAs) larger than 140 meters in diameter, serving a key warning function for planetary defense against potential impact threats.

A "Wake-Up Call"

In May 2019, the commercial space company, SpaceX, launched the first 60 satellites belonging to its Starlink LEO constellation, which will eventually have 1,584 satellites orbiting at a 550 km altitude. Since November 2019, SpaceX added an additional four launches with 60 satellites each (as of early March 2020). Directly following the launch, several videos of clearly visible "trains" of the spacecraft in preliminary orbits en route to their final orbital positions and orientations were uploaded to social media, and confused local citizens even filed numerous reports of UFOs in the areas where the satellite trains were visible.[22] Though the brightness of the reflection of the spacecraft at the time they were observed (within the few days following launch) are not representative of their brightness once in their final positions, the videos[23] nevertheless contributed to renewed discourse on the effect of space commercialization on astronomical research and society more generally.

The International Astronomical Union, the world's largest international association of local and regional chapters of professional astronomers, issued a statement following the launch,[24] depicting a photo of a telescope's FOV obstructed by light streaks from Starlink satellites. The picture was taken early on as the satellites made their way into their final orbits, noting in the image caption that the density of satellites is significantly higher in the early days after launch and that the satellite brightness would diminish as they reach their final orbital altitude. The statement urged constellation "designers and deployers as well as policy-makers to work with the astronomical community in a concerted effort to analyze and understand the impact of satellite constellations."

The National Radio Astronomy Observatory (NRAO) issued its own statement following the launch,[25] remarking that SpaceX officials had been diligent in their consideration of interference with radio astronomy while planning how Starlink would operate—in accordance with domestic and international regulations regarding harmful satellite radio interference. NRAO noted that it had been working directly with SpaceX to "jointly analyze and minimize any potential impacts from its proposed Starlink system," and that their discussions had resulted in "valuable guidelines that could be considered by other such systems as well." In addition, SpaceX treated one satellite of the January 2020 batch with a special coating, lowering its brightness in response to reports from the public and the astronomical community.[26]

Overall, the brightness of any satellite (whether it is in a constellation or not) and the duration of its optical interference with astronomical observation is a function of the altitude of the satellite. The magnitude of the reflected signal (usually sunlight) will amount to 1 divided by the square of the distance of the satellite—so, as the altitude is raised, the brightness will become smaller. This underscores why LEO constellations at different altitudes pose risks of interference to astronomical observation: the amount of possible interference time is reduced at lower altitudes, but satellites are generally brighter.

Looking Ahead

Despite the preparation and investments already made to mitigate ground-based light pollution for wide-field and long-exposure telescopes, the impact of light pollution of satellite constellations is currently not given consideration at the federal and international level.

Thanks to institutions like the International Telecommunications Union (ITU), radio astronomers are equipped with both policy protections in the form of regulation and a forum to challenge any harmful interference with their observations. For instance, many satellites broadcasting signals must redirect or cease such signals when passing over radio astronomy facilities. However, as of today, researchers in optical astronomy have no such recourse; unlike other risks and hazards associated with pLEO constellations, such as orbital debris concerns, no formal regulatory or licensing process currently exists for constellation operators to demonstrate their strategy for mitigation of the adverse impacts of reflectivity in their license applications.

An organized avenue for coordinated discussion on guidelines and mitigation strategies among stakeholders is needed to address the wider concerns of the astronomy community. Other aspects of managing the risks of pLEO constellations are already discussed at interagency, national, and international fora, such as the Inter-Agency Space Debris Coordination Committee (IADC), which has worked to negotiate and form mutually agreed-upon mitigation guidelines preventing the widespread proliferation of orbital debris for nearly three decades. The IADC is tasked with "consideration of space sustainability effects from deploying large constellations of satellites" at the federal level, but satellite light pollution is outside the scope of IADC.[27]

Groups like the American Astronomical Society (AAS) and the International Astronomical Union (IAU) already act as representatives of the larger astronomy community working to express optical interference concerns to regulators. Other, more collaborative avenues may prove more appropriate; to ensure allied and multi-national coordination, for example, regulators could look to successful models that resulted in progress for other space sustainability issues, such as within the United Nations working group on the "Long-Term Sustainability of Space."

Conclusion

From a U.S. policy perspective, pLEO constellations—both governmental and commercial—will provide novel services and benefits to their users. As more satellites are launched, and industry players continue to develop norms of operation in LEO, astronomers will want a larger role to play in wider constellation management and space safety coordination considerations. Operators of such constellations face an opportunity to get ahead of the issue by working with stakeholders to consider strategies for mitigation of optical reflectivity and albedo reduction. Regulators, astronomers, and industry should be in communication about their respective operational needs to explore options for building optical interference mitigation into existing constellation licensing application processes. Multiple stakeholders involved in this issue are increasing their communication among each other. Notably, at a recent AAS conference, LSST Chief Scientist Dr. Tony Tyson remarked, ". . . we find that SpaceX is committed to solving this problem." In the years to come, information-sharing and cooperation could help facilitate the creation of industry best practices and standards to ensure the long-term sustainability of both ground-based astronomy and LEO constellations.

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