LIGHT POLLUTION FROM SATELLITES

Josef S. Koller, Roger C. Thompson, and Luc H. Riesbeck

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). As companies deploy more satellites in orbit in much larger numbers than in previous decades, this will become an issue in the next several years that requires leadership and decisionmaking by the U.S. administration—because there is currently no formal regulatory or licensing process addressing light pollution from space. The purpose of this paper is to provide an overview of an objective analysis performed by The Aerospace Corporation to inform leaders and decisionmakers on the issue.[1]

Background

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 achieve 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[2] and could surpass 50,000 in the following decade.[3] The scale of these planned constellations combined is more than twenty times the current satellite population in orbit.[*]

Despite the potential benefits from the proposed proliferated LEO (pLEO) constellations (sometimes referred to colloquially as mega-constellations) and the recent public discussion on this topic, 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 by placing them in space themselves (like the Hubble Space Telescope and the forthcoming 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. Astronomers and telescope operators, however, 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

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

concerns of the astronomy community and others over the contribution of reflectivity by 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.

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 from its dark side. Shortly after sunset, there is a period of twilight when the sky is still illuminated by the sun. Astronomical twilight ends 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 geosynchronous Earth orbit (GEO), generally lasts the entire night—although 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 for some, and satellite watching can be inspirational for 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, which turn out to be emanating from aircraft. 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 former's 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.[4]

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.[5] 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.

Modeling and Simulation of Optical Interference

To model the effects of satellite reflection of sunlight, Aerospace used the mathematical description of the optical assembly 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 modeled hypothetical constellations at 500 km and 1,200 km to illustrate the tradeoff between altitude and illumination. Specific simulations of proposed constellations are available upon request.

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. Our chosen observer location is Cerro Pachón, Chile, the site of the Rubin Observatory and the Large Synoptic Survey Telescope (LSST). We also included a constellation of 1,296 satellites at 50degrees inclination evenly distributed with 36 orbital planes and 36 satellites per plane in order to provide a sample of the fraction of satellites visible at certain times. We performed two simulations (summer vs. winter) to illustrate seasonal effects and the length of astronomical night.

For satellites orbiting at 500 km altitude (1,200 km in simulation 2) and during long winter nights, 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 (100 in simulation 2) illuminated. About 63 percent (80 percent) of the sky can contain 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.

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.

In summary, Aerospace’s simulations show that the number of illuminated satellites and the areas change throughout the night, leaving varying portions of the sky free from interference. It is technically feasible to predict the position of each illuminated satellite 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 some point.

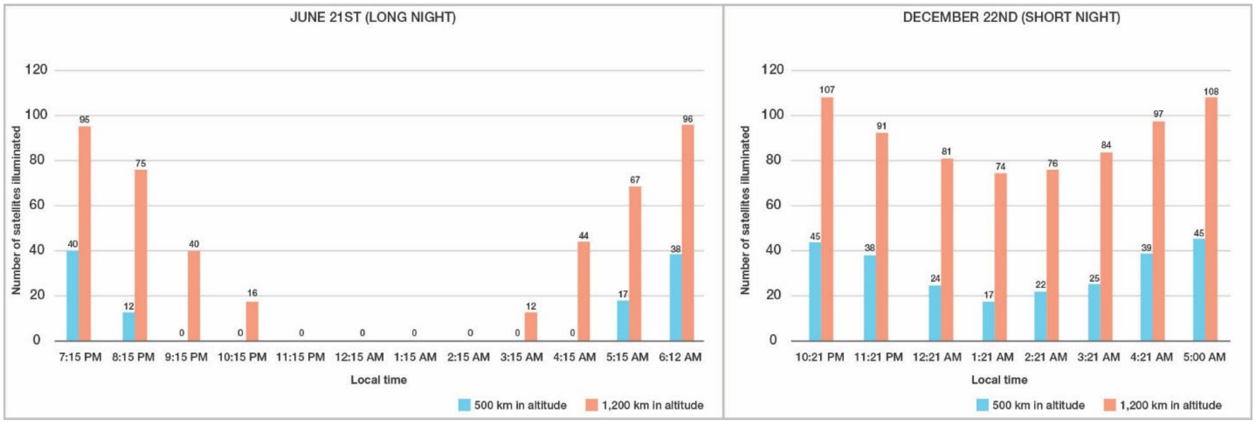

Figure 1: Summary of Tables 2 and 3 with number of satellites illuminated during a long winter night (June 21, left) and short summer night (December 22, right). Blue bars illustrate the number of satellites illuminated at 500 km, and orange bars show the number of satellites at 1,200 km altitude.

Current Mitigation Efforts

Astronomers already employ methods to dampen the severity of ground-based light pollution in their observations. 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. However, particularly for short- and medium-duration exposures, streaks can still compromise some data beyond the point of use; still, 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, discarding those with streaks and averaging the rest. However, each exposure has an opportunity cost in the form of sensor read-out noise. This is why five separate 10-minute exposures are not equal to one 50-minute exposure; in the first instance, there are *five* samples of read noises to account for instead of only 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 exposures can have a substantial 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 challenge, 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.

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. Current proposals for large constellations have created even greater apprehension.

According to the National Conference of State Legislatures, at least 18 states have laws in place to reduce light pollution, which are mostly limited to outdoor lighting fixtures installed on the grounds of a state building or public roadway.[6] In 2015, the Environmental Protection Agency (EPA) administrator, Gina McCarthy, said that light pollution is "in our portfolio" and that the agency is "thinking about it." To date, EPA has no official regulation on light pollution.[7] 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.[8] It can be argued, however, that the time has come to address light pollution at the national level.

Table 1: Possible Mitigation Approaches	
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

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)[9] 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 then, SpaceX has continued to add sets of approximately 60 satellites with several launches and the numbers keep rising.[10] Directly following each launch, several videos of clearly visible "trains" of the spacecraft in preliminary orbits enroute 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.[11]

Though the brightness of the spacecrafts' reflection 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[12] 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 an early launch,[13] 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 good news is that multiple stakeholders involved in this issue are increasing their communication with each other. Notably, at a recent American Astronomical Society (AAS) conference, LSST Chief Scientist Dr. Tony Tyson remarked, "…we find that SpaceX is committed to solving this problem."

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 or 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 (such as orbital debris concerns) associated with pLEO constellations , no formal regulatory or licensing process currently exists for constellation operators to demonstrate their strategy for mitigating 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 optical 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 for nearly three decades to negotiate and form mutually agreed-upon mitigation guidelines preventing the widespread proliferation of orbital debris. 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.[14]

Groups like the 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.

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. This is an important issue and approach for the administration to foster and facilitate.

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About the Authors

Dr. Josef S. Koller is a senior systems director for The Aerospace Corporation's Center for Space Policy and Strategy, serving as an analyst and team leader on topics that cut across policy, technology, and economics. Prior to joining Aerospace, Koller served as a Senior Advisor to the Office of the Secretary of Defense for Space Policy, where he directly supported key national and international strategy efforts and provided technical advice and analysis on space-related U.S. government and DOD policy matters, including commercial remote sensing and space traffic management policy matters. Prior to that assignment, Koller managed and co-led over 40 scientists in the "Space Science and Applications Group" at Los Alamos National Laboratory. Koller also established and led the Los Alamos Space Weather Summer School to promote graduate student research. Koller has over 17 years of experience with global security and space physics programs. He has authored over 50 peer-reviewed scientific publications with 700+ citations. Koller has a Ph.D. in astrophysics from Rice University as well as master's degrees in physics and astronomy from the University of Innsbruck, Austria.

Dr. Roger C. Thompson a senior engineering specialist for The Aerospace Corporation's Mission Analysis and Operations Department. Thompson provides support for space situational awareness, collision avoidance, on-orbit breakup analysis and risk assessment, space debris issues, deorbit/reentry prediction, and orbital operations for many programs and space missions. He is one of the corporation's leading analysts in space traffic management and has represented Aerospace at high-level government and industry meetings where future space policy will be determined. Thompson has experience in uncertainty modeling, probability analysis, pointing and tracking systems, orbit and attitude dynamics, coverage analyses, optimal control systems, structural dynamics, and control of nonlinear systems. He also continues to support realtime launch and on-orbit collision risk assessment, orbit transfer and maneuver planning, orbital and trajectory modeling, and orbit determination. Thompson has a Ph.D. and a master's degree in engineering mechanics from Virginia Polytechnic Institute and State University as well as a bachelor's degree in engineering science and mechanics from North Carolina State University.

Luc H. Riesbeck is a recent graduate of the Space Policy Institute at George Washington University, researching space sustainability, orbital debris mitigation, and ethics in science and technology. A graduate of New York University Shanghai in 2018 with a bachelor's degree in social science with a minor in global China studies, Riesbeck recently served as a graduate intern at The Aerospace Corporation's Center for Space Policy and Strategy. They currently serve as a Space Policy Research Analyst at Astroscale U.S. In 2018, they were selected as a fellow in the Brooke Owens Fellowship's second annual class.

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