REDUCING SATELLITE CONSTELLATION DISRUPTIONS ON PROFESSIONAL ASTRONOMY

PREPARED BY:

Asuka Bunthoambunlay
Master of Public Policy Candidate

PREPARED FOR:

UNIVERSITY of VIRGINIA

FRANK BATTEN SCHOOL of LEADERSHIP and PUBLIC POLICY

Table of Contents

Acronyms and Definitions

Acronyms

CFR: Code of Federal Regulations

ESA: European Space Agency

FAA: Federal Aviation Administration

GAO: Government Accountability Office

GEO: Geostationary orbit

GOCE: Gravity field and Ocean Circulation Explorer mission

HST: Hubble Space Telescope

IAU: International Astronomical Union

LEO: Low Earth orbit

MEO: Medium Earth orbit

NASA: National Aeronautics and Space Administration

SATCON1: Satellite Constellations 1 Workshop

UNOOSA: United Nations Office for Outer Space Affairs

Definitions

Dielectric mirror film is used on the second-gen Starlink satellites and is designed to scatter sunlight away from Earth, preventing satellite interference with ground-based astronomy.

Exposure time is the time span for which the telescope is exposed to the light to record or observe a celestial object. The exposure time is given in seconds.

Extraterrestrial is any object or being beyond planet Earth.

Megaconstellation or satellite constellation is a group of many satellites that work together for the purpose of delivering broadband Internet access.

Optical and near infrared astronomy are sub-disciplines of astronomy that focus on the observation and analysis of astronomical objects using visible and infrared radiation respectively. Optical and near-infrared astronomy are important because they allow us to observe celestial objects that are not easily visible in other wavelengths, such as cool bodies that emit little visible light but radiate in the infrared, and they provide insights into fundamental aspects of the universe, including the early history of stars and galaxies, the presence of interstellar dust, and the formation of planetary systems.

Acknowledgements, Honor Pledge, and Disclaimer

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Honor Pledge

"On my honor, I pledge that I have neither given nor received help on this assignment."

Disclaimer

The author conducted this study as part of the program of professional education at the Frank Batten School of Leadership and Public Policy, University of Virginia. This paper is submitted in partial fulfillment of the course requirements for the Master of Public Policy degree. The judgments and conclusions are solely those of the author, and are not necessarily endorsed by the Batten School, by the University of Virginia, or by any other agency.

Executive Summary

Everyday astronomers and scientific communities worldwide have their astronomy observations negatively affected by satellites due to light pollution caused by reflective material or light-emitted sources on the satellites, causing what is termed "Satellite Trails" or "Satellite Streaking". This report aims to identify satellite constellation disruptions on professional astronomy and find the most optimal mitigation strategy for satellite operators to reduce their negative impacts. Satellite deployments in Low Earth Orbit have experienced rapid growth numerically in the past few decades, with a more exponential increase in recent years, due to technological advances and leaps in space engineering allowing cheaper deployments of commercial satellites. With this boom in satellite deployments, policy and guidelines have failed to keep pace with newly discovered conflicts of interest. This write-up was created to assist NASA and other relevant space policy stakeholders with their decision making and considerations regarding satellite disruptions to astronomy.

Three main mitigation strategies[1] have come to the forefront of discussion as viable propositions to the satellite streaking issue:

M1: Optical darkening of satellites
M2: Deploying LEO satellites at a lower orbital altitude
M3: Optimizing observation schedules to avoid satellites.

These mitigation strategies are evaluated using four criteria: effectiveness, cost, feasibility, and equity considerations. I recommend mitigation strategy 1: optical darkening of satellites because of its proven effectiveness in reducing the satellite reflective brightness on ground-based astronomy, its relative low costs and availability to all satellite operators, its high administrative and political feasibility (there have been a lot of discussions within the legislative body on the topic of satellite disruptions), and its equity considerations for both parties affected: the astronomy community and the satellite operators. Moving forward, NASA will be at the forefront of actively advising and voicing the need for a regulatory body like the FAA to require the new batch of satellite operators to pursue some sort of darkening method starting in 2026.

None of the mitigation strategies mentioned above, including the darkening of satellites, can fully eliminate the large scale of disruptions on astronomical observations. However, I could not include a strategy of limiting the number of satellites in LEO or banning satellite launches without severely compromising the global connectivity benefits provided by these satellites. One simple fact is that thousands of satellites will continue to launch in the next ten years, and the best way to cope with that is to have a mitigation strategy that somewhat reduces the negative impacts while not compromising satellite works. While the method of darkening satellites is still at its early stage, satellite operators are committed to finding better ways and technology to make their commercial space operations less bright and less disruptive.

Ad Astra!

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[1] These mitigation strategies are for the satellite operators in the United States. Refer to the alternative section for more explanation.

Introduction

Imagine that you and two of your colleagues are early-career astronomers who recently just finished your PhD in astrophysics. Your group is tasked with a project to take optical and near-infrared observations of a galaxy at the Keck Observatory in Hawaii. This project is crucial in helping the team learn about other galaxies because they provide valuable insights into the fundamental processes regulating the formation of stars and the history of the universe, which is essential for understanding the origins of different types of atoms in our bodies and the world around us. Since the observation time is limited and the process of getting the telescope exposure time is competitive[2], your team is delighted to hear that you are granted 20-hour observation period at the observatory. You have allocated $5,000.00 USD (company budget) for this trip, which is a huge spending cost considering how small your organization is. Once your team arrives at the Keck Observatory, you start to work and expose the telescope to the target for 20 hours as intended. After 20 hours, your team combines the optical images in different wavelengths together (which took an additional 5-6 hours) and you quickly realize an alarming fact: the finished image has many satellite streaks on it (similar to figure 1). As an early-career astronomer, you can choose one of the three options: to start the project all over, to manually delete the trail from the image, or to abandon the project and return home. Since you cannot get more telescope time at the observatory, and you do not have the skills to delete the trail without affecting the actual composition of the galaxy in the image, you decide to return home with the ruined observation and data.

The general public will see the image in figure 1 and think that this is not a pressing issue. However, astronomers face this issue of satellite constellations interrupting their astronomical observations daily, and the problem will exacerbate as more satellites are being deployed into the soon-no-longer-dark sky. The Zwicky Transient Facility, a ground-based observatory in California, found 5,301 satellite streaks on observations from 2019 to 2021. The ratio of affected twilight images has risen steeply with the growth of the Starlink megaconstellation from only 0.5% in late 2019 to 20% in late 2021 (Pultarova, 2022). This report discusses the policy problem of the impact of satellite constellation on professional astronomy, client overview, problem background, its consequences, evidence on potential solutions to the problem, mitigation strategies to reduce the disruptions, criteria for evaluation, final recommendation, and steps for implementation. You will learn that this problem deserves a lot of immediate policy attention because the negative effects will multiply and become long-lasting without any intervention. It is important to note that this report aims to reduce disruptions to astronomers' day-to-day observations while also not compromising the global connectivity benefits offered by satellites in the low Earth orbit. All the mitigation strategies aim to find a middle ground that does not severely impact the works of astronomers/scientists and the American satellite operators.

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[2] Many astronomers submit their observation proposals months in advance to get observing time in big telescopes around the world.

Figure 1: Image of a galaxy with multiple satellite streaks (Kan, 2022)

Problem Statement

The rise in Low Earth Orbit satellite constellations poses a threat to the scientific community's ability to conduct astronomical research. These satellites interfere with professional astronomy observations by reflecting sunlight, resulting in bright streaks across images and complicating asteroid detection. If the proposed launch of over 100,000 LEOsats in the next decade goes unchecked, it could severely disrupt optical and near-infrared astronomy.

Public Policy Relevance

The problem of the rise in LEO satellite constellations is relevant to public policy due to its potential ability to disrupt optical and near-infrared astronomy, which is important to the public for several reasons. Optical and near-infrared astronomy is crucial for advancing our understanding of the universe, including the study of celestial bodies, the search for extraterrestrial life, and the monitoring of space for potential threats, such as asteroids. These scientific endeavors not only contribute to human knowledge but also have practical implications for Earth's safety and the future of space exploration. Therefore, the potential disruption of optical and near-infrared astronomy by the proliferation of LEO satellite constellations is a matter of public concern and warrants attention from policymakers to ensure the preservation of this vital scientific research (Venkatesan et al., 2020).

The impact of satellite constellations on astronomical research has led to discussions about developing technologies to darken satellites and implementing tools to help astronomers avoid or filter out light reflections or radio transmissions. Additionally, there are ongoing efforts to study and develop an international regulatory framework to control the impact of large LEO satellite constellations on astronomy and the night sky ("Large Constellations of Satellites: Mitigating Environmental and Other Effects," 2022). The Government Accountability Office (GAO) has also emphasized the need for research on darkening satellites and the limited resources for studying the potential effects of satellite constellations, highlighting the importance of addressing this issue from a policy perspective. Therefore, the problem of the rise in LEO satellite constellations is relevant to public policy as it requires the development of regulations, technologies, and international frameworks to preserve the integrity of astronomical research, which is important to the public for its scientific, practical, and safety implications. <u>It is also important to note that satellite constellations pose many issues to the public beyond just the scope of the problem mentioned, including environmental issues, orbital debris, and collisions.</u>

Client Overview

NASA's primary goal is to drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth. The impact of LEOsats on optical and near-infrared astronomy is a significant problem that NASA is actively addressing. For instance, the LEOsats can interfere with NASA's asteroid detection process (Waldek, 2022). NASA's role in addressing this problem is to work with other space agencies, governments, and private companies to develop and implement mitigation strategies that minimize the impact of LEOsats on astronomical observations. NASA is also investing in new technologies and techniques to improve the detection and tracking of LEOsats and their impact on astronomical observations. Addressing this problem is crucial because it has far-reaching implications for the future of astronomy and space exploration. By mitigating the impact of LEOsats on astronomical observations, the organization is helping to ensure that future generations can continue to explore and learn about the universe around us.

NASA has been instrumental in assisting the development of reports to Congress and working with other regulatory bodies on mitigating negative impacts of satellite constellations. Recent example: 1) The United States Government Accountability Office (GAO) published the *Large Constellations of Satellites, Mitigation Environmental and Other Effects* in 2022 and it states that the disruption of astronomy is one of the top three concerns (the other two are increase in orbital debris and emissions into the upper atmosphere) stemming from satellites ("Large Constellations of Satellites: Mitigating Environmental and Other Effects," 2022). 2) The NASA Orbital Debris Program Office is in partnership with the US Department of Defense in tracking more than 500,000 objects in orbit with size larger than a marble and all US satellite operators are required to file detailed collision avoidance plans before launching (Venkatesan et al., 2020).

Problem Background

The increasing number of satellite constellations, particularly in LEO, has raised significant concerns within the astronomical community regarding their impact on optical and near-infrared astronomy. The visibility of these satellites, especially during dawn and dusk, has become a primary issue, affecting various facets of ground-based astronomical observations (Venkatesan et al., 2020). The size of the satellites, their apparent brightness, and the fraction of the night during which they are visible are key factors contributing to the problem (Background - CPS, 2024). The impact is substantial, with nearly every aspect of astronomy being affected, and the problem is expected to worsen with the planned launch of up to 100,000 LEO satellites by the end of the decade

(Venkatesan et al., 2020). Figure 2 below shows the results of a discrete simulation on telescope observations with different exposure times. You can see that as the exposure time of the telescope increases in seconds (x-axis), the number of disrupting satellite trails also rapidly increases on the y-axis (Bassa et al., 2022). This is especially concerning since more intricate observations require longer exposure time; thus they are more vulnerable to satellite trails.

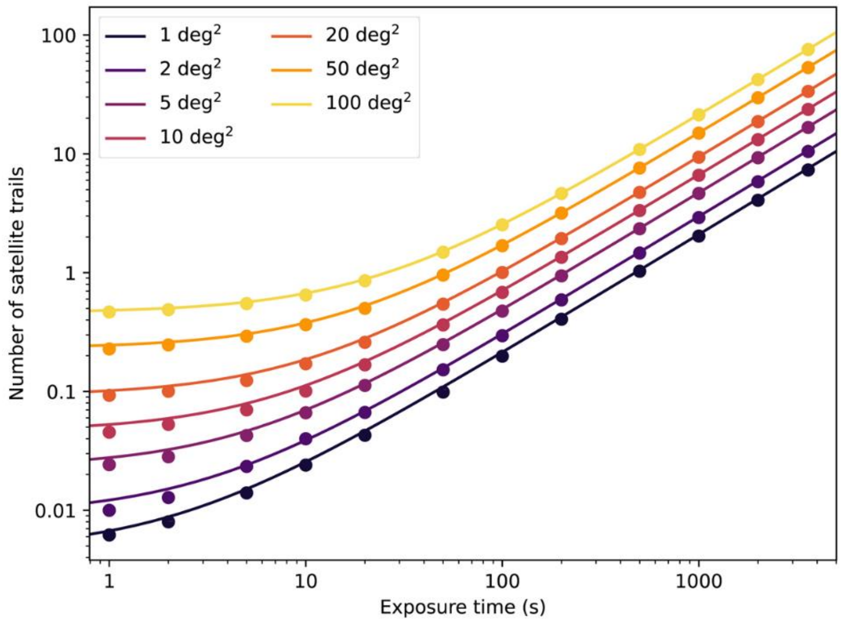


Figure 2: Simulation shows that as the exposure time of the telescope increases in seconds (x-axis), the number of disrupting satellite trails also rapidly increases on the y-axis (Bassa et al., 2022)

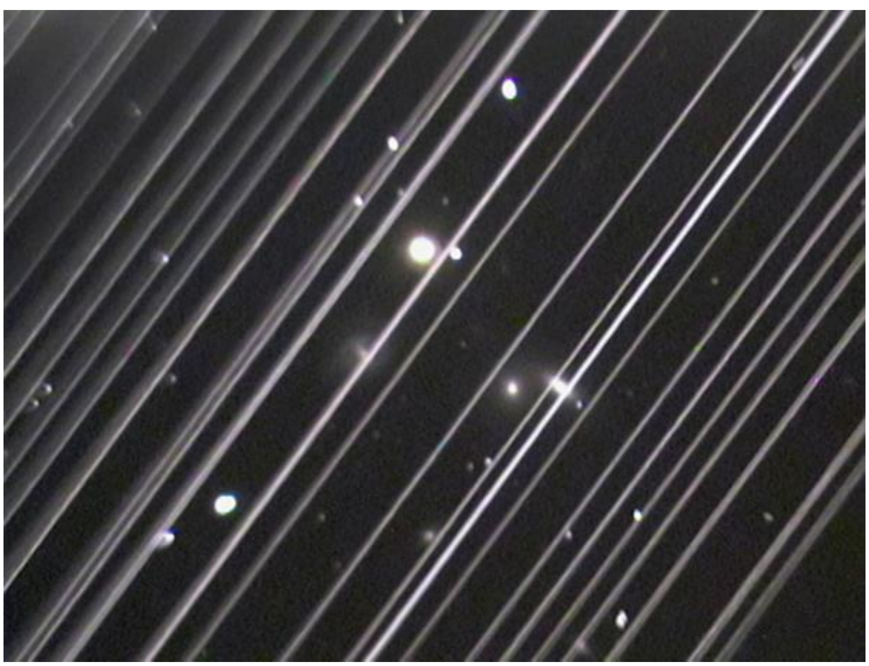


Figure 3: This image of the galaxy group NGC 5353/4 was taken with a telescope at Lowell Observatory in Flagstaff, Arizona, on 25 May 2019. The diagonal lines are trails of reflected light left

by more than 25 of the 60 Starlink satellites launched in May 2019, as they passed through the telescope's field of view (Background – CPS, 2023)

The history of the problem can be traced to the rapid increase in the number of satellites in the past few decades (see figure 4), particularly due to the deployment of megaconstellations for global broadband internet coverage. Astronomers were caught off guard by the lack of advance warning from the companies planning these constellations, leading to a scramble to mitigate the impact on their observations. The problem has not been solved due to the rapidly increasing number of satellite constellations being deployed each year, thus astronomers cannot completely eliminate the satellite streaks in their images and observations. While some mitigating options are available, such as darkening the satellites and calculating observational "avoidance zones" for astronomy, the fundamental issue remains unresolved as the number of satellites keeps going up (Venkatesan et al., 2020).

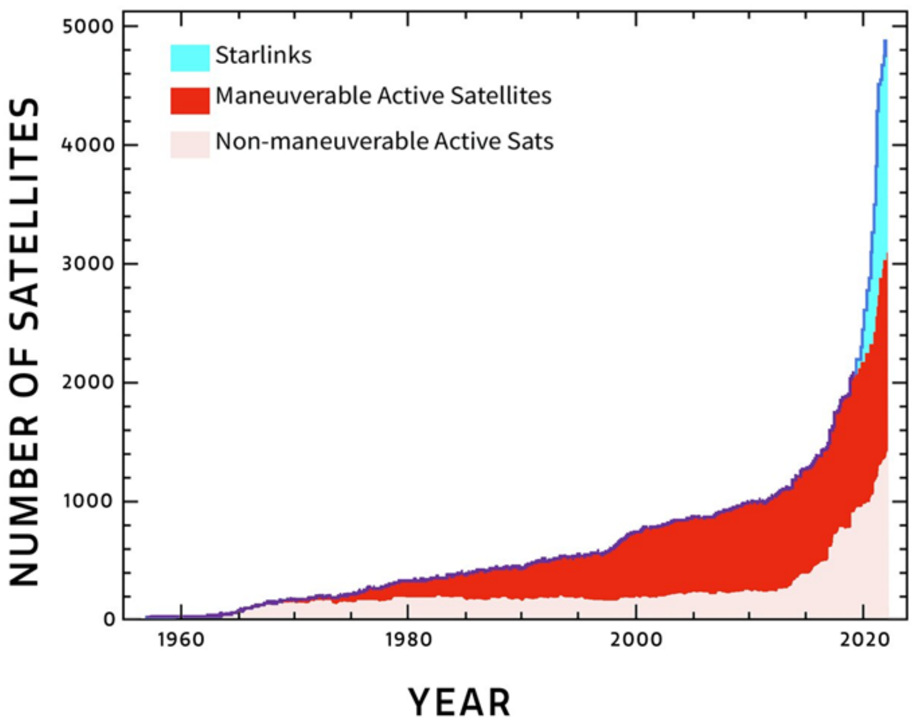


Figure 4: Plot of the number of satellites each year each year since 1957 (Background - CPS, 2024)

Astronomers are most concerned by the rapidly accelerating rate of satellites launching into space. In 1958, only ten objects were launched into space. According to the Index of Objects Launched into Outer Space, maintained by the United Nations Office for Outer Space Affairs (UNOOSA), 11,330 individual satellites were orbiting the Earth at the end of June 2023: a huge increase since the 1960s. Out of this huge number, only 68% of the orbiting objects are operational, the rest are junk (objects that ran out of fuel or are nonoperational) that are flying in LEO (Andy, 2023).

Specific sub-populations affected by this problem include the astronomical research community, which relies on ground-based optical and near-infrared observations for various scientific studies. The consequences of the problem are far-reaching, affecting not only scientific progress but also the cultural heritage of humanity, as the pristine appearance of the night sky is being compromised (Whitt, 2022). The costs of the problem are both tangible and intangible. Tangibly, the interference caused by satellite constellations in LEO results in visible streaks and trails across astronomical images, significantly compromising the quality and reliability of data collected by ground-based observatories. This interference hampers the ability of astronomers to study celestial objects and phenomena, affecting the accuracy and completeness of their observations. Additionally, the financial burden is incurred by research institutions and organizations investing in astronomical projects, as valuable observation time and resources are wasted when satellite streaks contaminate the data. Furthermore, the costs extend to potential technological solutions and modifications needed to mitigate the impact, such as darkening satellites, which may require significant research and development investments. Intangibly, the cultural and scientific heritage of humanity is at stake, as the night sky, a source of inspiration and knowledge for centuries, is eroded. The long-term consequences include the potential hindrance of scientific progress, limitations on astrophotography, and impacts on various aspects of human life that depend on natural light cycles (Background – CPS, 2023). Overall, the costs of satellite constellations on optical and near-infrared astronomy extend beyond the immediate financial implications to encompass broader societal and scientific repercussions.

Satellite Constellation Workshop and GAO Report

Satellite constellation 1 workshop (SATCON1) paved the way for more people to be aware of the impacts of satellite constellations on astronomy. Prior to the report produced by the first workshop in 2020, discussions surrounding the impacts of satellite constellations were unclear and unorganized. The workshop provided a space for all relevant stakeholders, including "astronomers, satellite operators, dark-sky advocates, policymakers, and other stakeholders and interested parties" to "work collectively towards effective solutions to mitigate those impacts and to publish them in a report which will be widely distributed". ("Satellite Constellations 1 Workshop Report | American Astronomical Society," 2023). This report quickly gained attention worldwide, and I have extensively studied each section of the report to inform my literature review in my project. The first workshop was the first time in history that astronomers accumulated enough data from observations of satellite constellations to run various simulations.

The first report offers two findings: the key problem and the key mitigation strategies. The first finding is that LEOsats have a disproportionate impact on scientific programs that rely on twilight observations. These programs include searches for Earth-threatening asteroids and comets, and outer and Solar System objects. The inability to detect asteroids and comets can have a severe consequence to humanity because certain regions need to be warned before a comet or an asteroid wave hit. These satellite constellations may significantly impact critical research programs conducted at the world's leading optical observatories. Additionally, depending on their altitude and brightness, these constellation satellites might also disrupt the serene nights enjoyed by amateur astronomers, astrophotographers, and other nature enthusiasts (see appendix A). The second finding is that based on the scientific simulations, below are some of the possible mitigation strategies (which I will elaborate more in the alternative section):

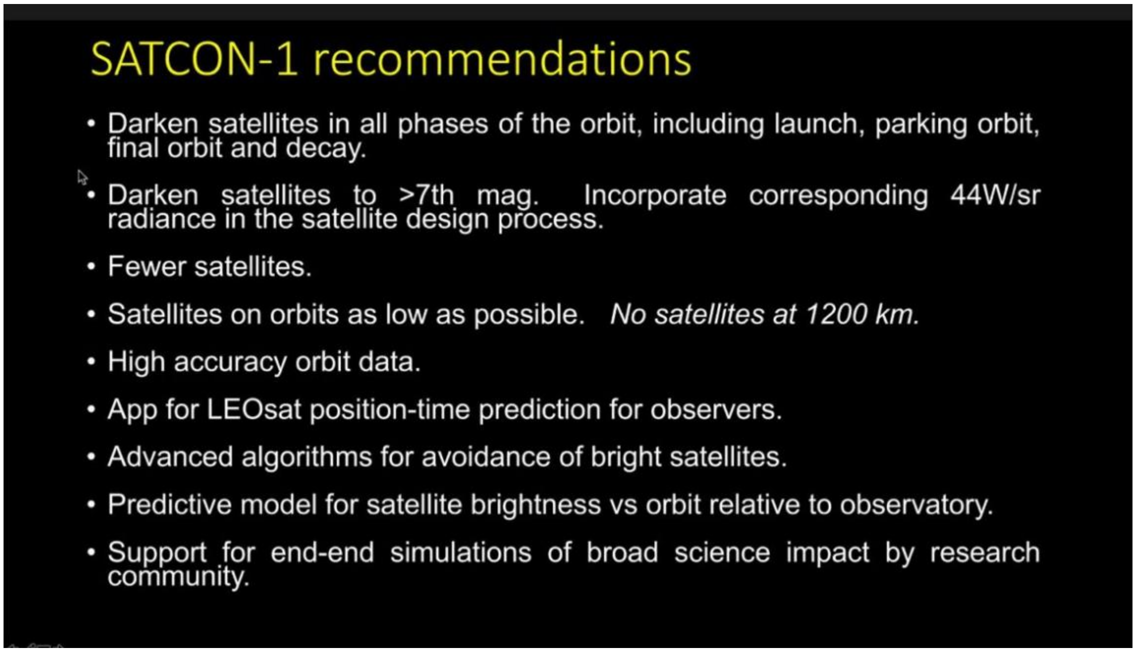
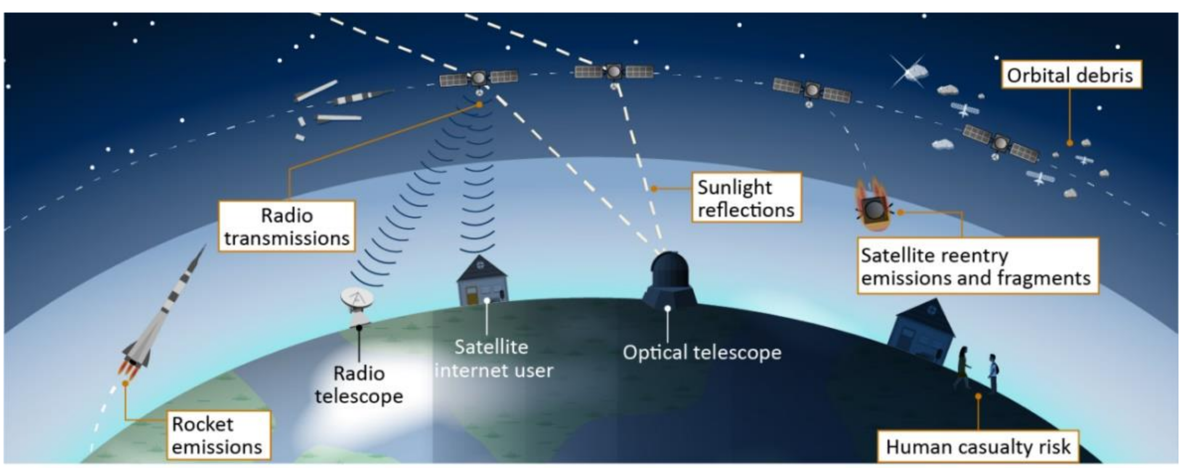


Figure 5: SATCON1 recommendations based on extensive simulations on satellite constellations (PSW Science, 2021)

Since the release of SATCON1, there have been numerous related reports, including SATCON2 and the GAO reports, urging policymakers to understand and address the problem in a timely manner. In 2022, two years after the release of SATCON1 report, GAO published an extensive report addressing three main concerns from satellite constellations:

1) A large buildup of orbital debris, causing collision risks and environmental concerns
2) Upper atmospheric concerns as satellites release unwanted chemicals back into the atmosphere
3) Disruption to astronomy (which is the primary concern in this APP) (Lis, 2022).



Source: GAO. | GAO-22-105166
Note: Image not to scale.

Figure 6: This image from the GAO report shows the main concerns posed by LEOsats. The report highlights sunlight reflections on optical telescopes as one of the main concerns (Lis, 2022).

Problem Consequences

To tie back to the little narrative story in the introduction, a series of papers published in the journal *Nature Astronomy* have warned that the increasing light pollution caused by megaconstellations threaten the future of many astronomers' profession (Collen, 2023). One paper from the journal measured for the first time how much a brighter night sky would scientifically and financially affect the work of a major observatory. The model suggested that for the Vera Rubin Observatory, a giant telescope currently under construction in Chile, the "darkest part of the night sky will become 7.5 percent brighter over the next decade" (Collen, 2023). This would reduce the number of stars the observatory is able to detect by 7.5 percent. Consequently, this would add nearly a year to the observatory's observing and surveying capabilities, costing around $21.8 million USD (Collen, 2023). Figure 4 shows a digital estimation showing objects orbiting Earth dating back to 2008, the number of satellites has significantly increased since then. Another cost of a brighter sky that is impossible to calculate is the "celestial events that humanity will never get to observe" and the loss of dark sky (Collen, 2023). Aparna Venkatesan, an astronomer at the University of San Francisco, and her co-authors said, "we must consider the impact of satellite constellations, and related future initiatives, on the essential human right to dark skies and on cultural sky traditions across all peoples" (Venkatesan et al., 2020). Thus, it is important to consider both the financial costs posed on astronomers and the immeasurable costs associated with the loss of the dark sky as a shared global common.

Figure 7: a digital estimated visual of objects orbiting Earth in 2008 (Collen, 2023)

Evidence on Potential Solutions to the Problem

Similar to the study of artificial intelligence, the study of satellites is still limited and there is not much evidence to mitigate the satellite constellation disruptions on professional astronomy (just like how we lack policies on how to regulate AI). Nevertheless, as more members of the astronomy community recognize the threats that are posed by satellite constellations, there have been pressures to conduct certain mitigation strategies. The four strategies that are commonly known are: darkening the satellites, removing satellite trails from images, deploying satellites at lower orbital altitudes, and creating an observation scheduling tool to avoid satellites. None of these four options can completely eliminate the impacts of satellite constellations on optical and infrared astronomy, but they are proven to at least help mitigate the impacts. In this section, I will dive into only one strategy, manually removing satellite trails from images, because I will talk more extensively about the other three in the policy alternative/mitigation strategy section.

Removing Satellite Trails from Images

A highly successful and common mitigation strategy is removing satellite trails from images, which is an intervention by astronomers. Besides disrupting the works of ground-based telescopes, satellite constellations can affect the observations of space-based telescopes in LEO such as the iconic NASA/ESA Hubble Space Telescope (Kruk et al., 2023). Satellites are photobombing the HST's snapshots as much as every two to four hours, according to researchers at Baltimore's Space Telescope Science Institute (STScI) (Astronomers Are Reducing Satellite Interference in Hubble Images, 2023). It has been warned in the last three decades by scientists that "Artificial Earth satellites will cross the fields of view of operating HST science instruments with distressingly high brightnesses and frequencies" (Kruk et al., 2023). As they whirl around Earth, the satellites leave streaks across an image, like scratches on photographic film (see figure 8 below). Hubble is in a low Earth orbit and so many satellites in higher orbits sweep overhead. As the number of artificial satellites encircling Earth rises, sky contamination for all telescopes based on the ground or in Earth orbit becomes increasingly worse. One option that astronomers have done to mitigate this photobomb effect is to manually remove satellite trails from the observed image. Think of this option as people photoshopping or cropping unwanted marks on their images to improve the picture quality.

Space Telescope Science Institute (STSci) applied the new tool, based on the image analysis technique known as the Radon Transform, to identify satellite trails across Hubble's camera with the widest field of view, the Advanced Camera for Surveys (ACS). STSci developed a masking routine that identifies where the bad pixels are, the extent to which they affect the image, and then flags them. Scientists then can remove the bad pixels and recover the full, clean images without streaks. Previous efforts did not pick up the faint satellite trails, but new software is up to ten times more sensitive than prior software developed by STScI to detect satellite trials, and it identifies roughly twice as many trails as other studies (Astronomers Are Reducing Satellite Interference in Hubble Images, 2023). To remove the satellite streaks from images, astronomers have used various methods: image stacking, software tools, photoshop, and algorithms. Although astronomers located anywhere could come together to remove the streaks, one limitation is that as the number of satellites increases, new techniques and tools will need to develop and adapt constantly. This strategy is not considered as one of this report's policy alternatives because the process of eliminating satellite trails/streaks from images is time consuming, and it puts a huge burden on the astronomers (instead of the satellite operators) to put extra labor into removing the streaks. The process of removing the streaks is sometimes discouraged by professional astronomers because you risk accidentally removing some elements or compositions of the targeted celestial objects.

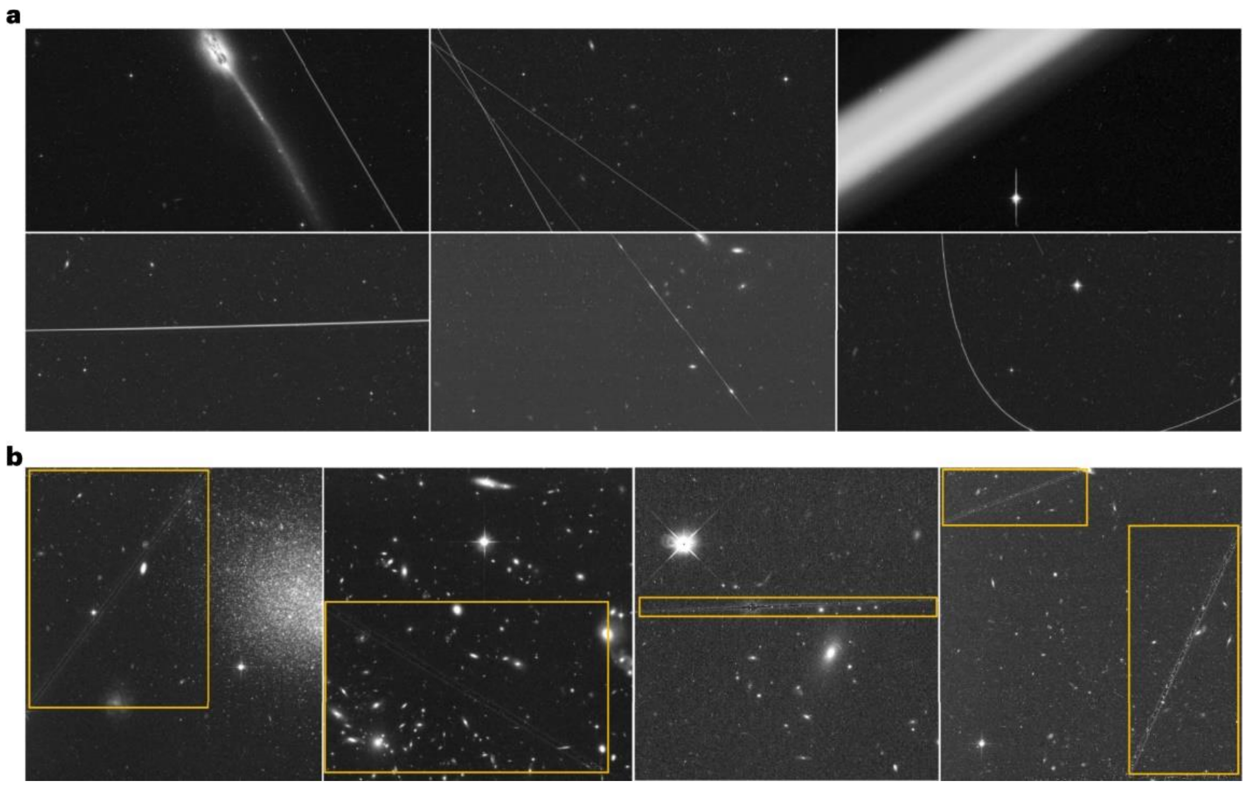


Figure 8: Examples of satellite trails in individual HST observation exposures (Kruk et al., 2023)

The biggest gap in learning about potential solutions to this problem is the lack of policy regulation and mitigation strategy in place. This problem of satellite disruption to professional astronomy has only gained a lot of attention the past five years after large satellite operators have started to deploy large megaconstellations into Earth's orbit. This report is considered being at an early stage at addressing this problem, as satellite operators and scientists are becoming more aware of the increasing scale of the disruption and finding more possible ways to mitigate the issue.

Policy Alternatives/Mitigation Strategies

For each alternative, I will dive into what the alternative entails, who has done it or will do it, and what incentives and specific policies will be in place. It is important to note that these alternatives will apply to the satellite operators and astronomy communities in the United States. While it is ideal that the recommended policy action will be followed by all satellite operators in the U.S. and beyond, there is currently no international body that can mandate such a large body of international operators. One benefit of focusing on the U.S. is the hope that other countries will follow its lead. For instance, the U.S. is considered the global leader in space by many countries including China. After placing the International Space Station (the ISS) into Earth's orbit and coordinating the Artemis missions to put more people on the moon, China is rapidly constructing its Tiangong Space

Station and announcing its five-year plan for moon exploration (David, 2021). In this case, the U.S. will take the lead in decreasing light pollution from the large satellite constellations, and other countries (including China) will soon follow. The second thing to note is that the ideal solutions (from the astronomer's perspective) is to set a size cap for large satellites or to decrease the number of satellites. I did not consider these alternatives in the report because the feasibility is too low. Satellite industry is booming and will continue to grow as time goes by (similar to artificial intelligence), thus we would impede this growing industry and the benefits that satellites have to offer if we restrict its numbers. As of now, the alternatives involve mitigating the negative impacts instead of completely eliminating them.

Mitigation Strategy 1: Darkening the Satellites – Satellite Operators' Intervention

There are two common options to darken the satellites: optical darkening and a sunshade to block the sunlight from hitting the reflective surfaces of the satellites. Mitigations have shown some success - optical darkening made one operator's satellites half as bright, according to a study looking at that operator's satellites actively in orbit - but may require additional technology development to meet desired standards set by astronomers (Large Constellations of Satellites: Mitigating Environmental and Other Effects, 2022). This method of darkening the satellites is a supply-side intervention, meaning that the satellite operators will take the lead in designing their satellites in a way that makes them darker and decreases light pollution. This option has already been done by space companies like SpaceX, and it is feasible and generalizable for other satellite operating companies to follow. As mentioned, although the success rate of decreasing the brightness is still limited, this option is one of the least complicated alternatives to address the problem.

SpaceX, an aerospace company, has been at the forefront of implementing this strategy. The two reasons that motivated SpaceX to darken its satellites are for publicity and scientific purposes. Since large-scale Starlink satellite launches started in May 2019, astronomers have expressed great concerns that those satellites appear far brighter than expected. They were particularly concerned with SpaceX's plan to launch 12,000 or more satellites in the next several years (Foust, 2020). In response to the public backlash and scientific concern, SpaceX launched a prototype Starlink satellite known as DarkSat, which features a black anti-reflective coating. This coating is designed to reduce the amount of sunlight that the satellite reflects to Earth, thereby reducing its visibility from the ground (Zhang, 2020). Regarding its effectiveness, the DarkSat prototype was observed from the ground and found to be half as bright as a standard Starlink satellite. While this is a significant improvement, it still falls short of what astronomers say is needed. The brightness of satellites is a concern because it can interfere with astronomical observations, outshining celestial objects and leaving streaks across images captured by telescopes. Despite these efforts, SpaceX's dark satellites are still considered too bright for astronomers. The company continues to explore additional mitigation measures, such as controlling the orientation of satellites to reflect less sunlight to Earth and installing sunshades to block sunlight from hitting reflective surfaces (Petersen, 2023). While darkening satellites can help reduce their impact on astronomy, it is important to note that this strategy alone cannot completely eliminate the problem.

Space X recently covers the bottom of its second-generation satellites with dielectric mirror film (see figure 9) that is 10 times better at reducing observed brightness than the first-generation film. SpaceX encourages all satellite operators to use this film, and it will sell this product on the Starlink website so that other operators may use it to reduce the brightness effects of their own constellations (SpaceX, 2022). The same second-generation satellites have also been built with a "Low Reflectivity Black" paint across the hardware's angled surfaces (Michael Kan, 2023). Satellite operators are encouraged to combine the black paint with the new mirror film due to the low associated costs.

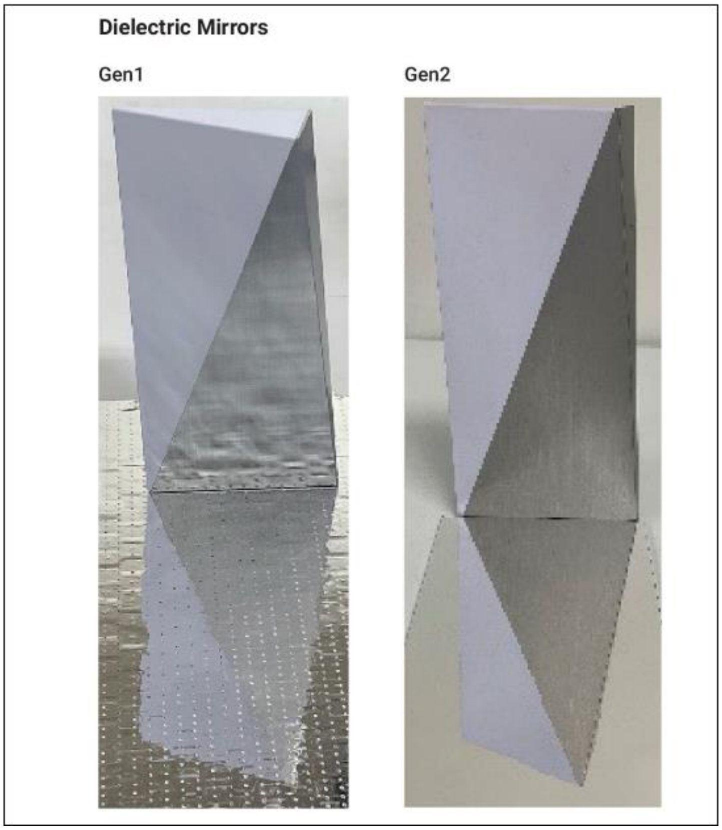


Figure 9: the second-generation dielectric mirror film reduces observed brightness by ten times compared to the first-generation film (SpaceX, 2022)

Darkening satellites is one step closer to mitigating the light pollution effect on professional astronomy, big satellite operators are more incentivized to pursue this route due to the environmental responsibility and public perception. By actively participating in efforts to reduce light pollution and space debris, satellite operators demonstrate their commitment to environmental stewardship. Public awareness of these initiatives can enhance the operator's reputation and foster positive public relations (PR) and reputation, which can lead to increased trust and support. However, PR alone is not enough for more satellite operating companies to buy in, that is where the legislative piece comes in. The FAA will have to set a regulatory rule that each new satellite in its design phase must have some sort of darkening component in it: it can be either installing a sunshade or optical darkening before deploying into LEO (see implementation for more information on FAA's authority and rights).

Mitigation Strategy 2: Deploying LEO Satellites at a Lower Orbital Altitude

This alternative recommends satellite operators like Starlink to deploy their satellite at a lower altitude, starting from the new batch in 2026. One finding from the Satellite Constellation workshop is to deploy LEO satellites at lower orbital altitudes ~ about 600 kilometers (km) above the Earth surface. Satellites below 600 km are visible a few hours per night. Satellites above 600 km pose greater concerns to astronomers because they can illuminate all night long (Satellite Constellations 1 Workshop Report | American Astronomical Society, 2023). Full-night illumination causes these high-altitude constellations to impact a larger set of astronomical programs. The United Nations Office of Outer Space Affairs recently published a report that supports deploying LEO satellites on orbits as low as possible due to three main reasons. First, LEOsats at a higher orbital altitude may be illuminated all night long, rather than just in evening and morning twilight, causing more disruptions to optical astronomy. Second, a higher-altitude LEOsat is visible above the horizon for longer than a lower-altitude one. Third, higher-altitude LEOsats have slower angular velocities and appear more "in focus" to telescopes on the ground. The result is a brighter satellite trail in the image (Walker et al., 2022). To support this point, scientists made a simulation that compares communications-focused LEOsat constellations, Starlink (launched below 614 km), and OneWeb (launched at 1,200 km). Higher altitude constellations (OneWeb) can be visible all night long during summer, proven to cause more disruption than the lower altitude constellations, Starlink (ConstanceWalker et al., 2020). The population of large artificial satellites in orbits below 600 km is undergoing rapid change and is now dominated by the Starlink system (McDowell, 2020). This could be a limitation because the lower LEO will become increasingly congested as time goes by.

This mitigation strategy also places the financial and operational burden on the suppliers – satellite operators – to manipulate their placing and the orientation of satellites. The idea is that better placement of the satellites will decrease the light pollution effects on ground-based telescope imaging. These findings are reliable and valid because the Satellite Constellations 1 (SATCON1) workshop was hosted by the National Science Foundation's NOIRLab and the American Astronomical Society. The workshop also created simulations to show the impacts between deploying the satellites below and above the 600 km range. The study shows that the impacts on astronomical observations are mitigated if satellites stay below 600 km.

In the past five years, satellite operators have been more incentivized to deploy their LEOsats at a lower orbital altitude. The two main reasons are improved observations and national security. Satellites in very low Earth orbit (VLEO), flying at altitudes commonly between 250 to 350 kilometers, are twice as close to the ground compared to legacy LEO satellites. This proximity allows them to observe ground activity with greater detail and precision, making them valuable for military and intelligence operations (Wise, 2024). For example, during the Ukraine conflict, satellite imagery played a crucial role in monitoring troop movements and revealing Russia's intentions. The U.S. government purchased commercial satellite imagery to provide real-time information to the public and Ukraine (Wise, 2024). Even in non-national security related satellite operations, many satellite companies benefit from having satellites at a lower orbit that can produce clear imaging and communications. The European Space Agency's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission, operational from 2009 to 2013, mapped Earth's gravity while orbiting at an altitude of about 255 km (Wise, 2024). For the regulatory piece, I recommend the FAA to add additional fees if the satellite operators aim to place their large satellite constellations at a higher orbit above 600 km. Another thing to note is that some satellite operators still prefer higher orbits in some settings, thus this mitigation strategy cannot be implemented smoothly without backlashes from those actors. Let us dive into the OneWeb example that was mentioned earlier. OneWeb's satellites are positioned at an operational altitude of 1,200 kilometers (km), which is over double the altitude of Starlink satellites. The higher LEO orbit allows each OneWeb satellite to cover a larger service area on the ground. This means that fewer satellites are needed to achieve global coverage. The larger coverage area per satellite helps achieve this goal efficiently (Wise, 2021). This higher altitude deployment also comes with its costs: latency trade-off. Thus, satellite operators can still benefit from stronger signals and faster speed if they deploy satellites below 600 km orbital altitudes.

Mitigation Strategy 3: Optimizing Observation Schedules to Avoid Satellites – Astronomers' Intervention

Given a known distribution of LEOsats on the sky, an advanced telescope scheduling algorithm may have potential to more effectively avoid them: the development of AI algorithm and a scheduling tool should be pursued (Satellite Constellations 1 Workshop Report | American Astronomical Society, 2023). The International Astronomical Union (IAU) debuts a website including tools to help telescope operators predict satellite locations so that they can point their instruments elsewhere (Witze, 2022). The new tool is called Astrosat and it will project satellite orbits onto a coordinate system for a given observer location and time and field of view. This enables observers to mitigate the effects of satellite trails through their images by avoiding observation for the duration of the transit (Osborn et al., 2021). Astrosat also provides some analysis on the apparent brightness of the largest of the constellations, Starlink, as seen by a typical observatory and as seen with the naked eye. It is important to note that although telescope project managers are rewriting scheduling programs to avoid the new satellite swarms, that task will grow impossible as the number of spacecrafts in low-Earth orbit keeps rising (Boyle, 2023). This mitigation effort hopes to create a new tool starting in 2025 that shows accurate satellite scheduling and is utilized by all astronomers and satellite operators.

For this mitigation strategy to work, NASA will take the lead in the development and dissemination of this new technology. There are already many satellite tracking systems including Astrosat and Space-Track.org, but I hope to have one centralized system within NASA itself, which is ultimately funded by the federal government (SAIC admin@space-track.org, 2024). The FAA will need to require all new satellites to be reported in the tracking system.

Criteria

The impact of LEOsats on optical and near-infrared astronomy is a significant problem that NASA is actively addressing. For instance, the LEOsats can interfere with NASA's asteroid detection process. NASA's role in addressing this problem is to work with other space agencies, governments, and private companies to develop and implement mitigation strategies that minimize the impact of LEOsats on astronomical observations. NASA is also investing in new technologies and techniques to improve the detection and tracking of LEOsats and their impact on astronomical observations Addressing this problem is crucial because it has far-reaching implications for the future of astronomy and space exploration. By mitigating the impact of LEOsats on astronomical observations, the organization is helping to ensure that future generations can continue to explore and learn about the universe around us.

Stemming from this, NASA values the effectiveness of the recommendation, cost, feasibility, and equity.

1. Effectiveness:
   This criterion is the core of assessing each alternative. Effectiveness highlights how each alternative (independent variable) can reduce the disruption of astronomy observations (dependent variable). The outcome that I am interested in measuring is the reduction in the disruption to optical and infrared astronomy, and each alternative will have different ways to measure that. For example, I will assess how much the current method of darkening the satellite reduces satellite visibility in the low Earth orbit (in percentages). For each mitigating strategy, scientists have come up with calculations and data to back up their argument as to why each strategy is effective, thus I intend to use those calculations to showcase effectiveness. One example is SpaceX's initial effort at mitigating the spacecraft's impact. It involved launching a prototype Starlink satellite known as DarkSat that features a black antireflective coating. Recent ground-based observations of DarkSat in orbit found it half as bright as a standard Starlink satellite—a significant reduction of about 50% in the overall light pollution (Zhang, 2020). I will also take into account that this will only apply to satellite operators in the United States.
2. Cost:
   Since NASA is publicly funded, the organization itself cares about minimizing costs. I will assess each criterion based on how much direct and indirect cost each mitigation strategy will sum up to be. To operationalize this, I will dive into costs that include: the immediate cost of enacting the programming, labor cost, and all other administrative costs. For example, I will look into how much SpaceX spent on darkening each satellite constellation. If I cannot find any immediate data, I will investigate how much it costs to build the outer coating system for each satellite constellation. For mitigation strategy 3, I will look into how much it costs to create a scheduling tool and how much it costs to maintain the system in the long run.
3. Feasibility:
   NASA cares deeply on whether a recommended path will operate smoothly or not (without significant pushbacks and backlash). The alternatives will be assessed on their feasibility of implementation and enforcement. This criterion accounts for aspects of political feasibility, but primarily focuses on whether the alternative will be efficiently implemented in the current regulatory and administrative climate.
4. Equity:
   Finally, I will rank equity in terms of how much burden will be placed on the satellite operators or the astronomy community. While large satellites negatively impact professional astronomy, it is inequitable to hinder these satellites' mission of enhancing global communication. For example, NASA seeks to ensure that it recommends a mitigating strategy that would not benefit one group while severely hurting another. I will rank equity based on how equitable the alternative is to the burdened party. For example, I will look at how equitable it is to let astronomers carry the burden of building a whole scheduling system

on their own. Equity is hard to measure, but I might measure the hours and labor that the scientists spend monitoring the tool like Astrosat.

Alternatives Evaluated

There were about 2,000 LEO satellite constellations in 2020. I project that the scope of the problem will rise dramatically in the next decade. By 2030, there will be over 100,000 LEO satellite constellations due to the launch of planned satellite constellations (Venkatesan et al., 2020). The scope of the problem in this case will increase 50 times within ten years.

Mitigation strategy 1: Optical Darkening of Satellites

Effectiveness:

Recent observations using a telescope in Chile found that DarkSat was about 55% dimmer (0.88 magnitudes) than an ordinary Starlink satellite without darkening treatments (Foust, 2020). Since the 4th of June 2020, Starlink satellites have been equipped with a type of "sunshade", that reduces the amount of sunlight reflected to Earth, hence the name "VisorSat" (Gisiger, 2021). The VisorSat reduces brightness by about 70% (Gisiger, 2021) However, satellite companies are exploring ways to reduce reflectivity further. Future Starlink missions will utilize more of the "sunshade" – which works like a patio umbrella from the satellite (Foust, 2020). Thus, the assumption is that this method will get more effective over time. Currently, the U.S. owns and operates about 67 percent of the LEO satellites. I rank the overall effectiveness as 55% to 70% which means it reduces 55 to 70% of the disruption to professional astronomy. However, since only the American operators will adopt this strategy, the effectiveness will drop to the 37% to 47% range.

Cost:

There are no fundamental additional costs to this method, largely due to its implementation at the design phase. Satellite engineers who are creating the new satellites will simply have to change the outer coating of the satellites. Estimating costs for space launch vehicles is rarely straightforward. In many cases, space launches are arranged through private or classified contracts. SpaceX charges $61.2 million to launch a telecommunications satellite to orbit, which results in $4,653 per kilogram of satellite (SpaceX – Lowering the Cost of Access to Space - Technology and Operations Management, 2015). Since the technology to darken the satellites already exists, my main assumption here is that it does not add a lot of burden for engineers to mass produce mirror films or paint a darker coat for all future satellites. This assumption is further supported by engineers and astrophysicists that I talked to, including Jonathan McDowell. SpaceX also talks about its commitment and plans to share its dielectric mirror film at a low cost to all other satellite operators (SpaceX, 2022). Since the mirror film is a small component of the overall satellite design, I assume a cost less than 5 million USD for each satellite to use this darkening method (the price is subjected to change based on how large a satellite is). Note that SpaceX has not disclosed any pricing information on how much a film would cost. I rank the cost as low for this alternative.

Feasibility:

I rank this alternative high on feasibility for three main reasons. First, there has been an overwhelmingly high push from the scientists, specifically the crucial astronomy stakeholders from

The National Science Foundation's NOIRLab and the AAS, to pursue darkening the satellites as a mitigation strategy (Satellite Constellations 1 Workshop Report | American Astronomical Society, 2023). Second, as mentioned, satellite operators like SpaceX have been (to a degree) successful in mitigating some of the light reflectivity impacts from their satellites and are planning to improve their darkening technology. Third, the impact of satellites on public policy has recently gained a lot of (bipartisan) attention in the legislative arena. For instance, the U.S. Senate Committee on Commerce, Science, and Transportation regularly holds hearings on space sustainability with representatives from relevant stakeholders including National Aeronautics and Space Administration, Federal Aviation Administration, National Oceanic and Atmospheric Administration, and Department of Defense (Government Promotion of Safety and Innovation in the New Space Economy, 2023).

Equity:

I rank equity high for this alternative due to two factors: satellite operators do not receive a fundamentally high burden in terms of cost. Most satellites are mass-produced, and adding a darkening element into the design phase can become the new norm (Arevalo, 2020). Second, this alternative does not disrupt satellite operators' work in global connectivity. They can still deploy their satellites as planned, and the only change involved is in the design, not their work (Petersen, 2023).

Mitigation Strategy 2: Deploying LEO Satellites at a Lower Orbital Altitude

Effectiveness:

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. Satellites above 600 km are an even greater concern to astronomers because they can be illuminated all night long. Full-night illumination causes these high-altitude constellations to impact a larger set of astronomical programs (ConstanceWalker et al., 2020). I rate this effectiveness 70% since the satellites are still visible for a few hours per night and can still disrupt professional astronomy during this visibility transition. However, since only 67% of the satellite operators (counting those in the U.S. only) adopt this strategy, the effectiveness now ranks 47%.

Cost:

One caveat about shifting to a lower orbital altitude is that the closer you are orbiting to the Earth's surface, the more satellites you need to put up (compared to being further up, which covers more surface area). My assumption is that LEOsat operators who used to put satellites up at a > 600 km range will have to double or triple their satellite capacities (see appendix C). On average, a standard satellite costs $100-$300 million to construct and deliver into orbit (Pow, 2023). Adding a few satellites per mission means that the costs can double or triple. For this reason, I rank this criterion high for deploying satellites at a < 600 km orbital range.

Feasibility:

As mentioned, there has been a recent shift to deploy satellites at a lower orbital altitude due to national security and clear observation benefits (Wise, 2024). However, due to the administrative costs mentioned in the cost criterion, there will be a lot of pushbacks from satellite operators who have benefitted from stationing the satellites above 600 km. There are also additional technical challenges: satellites must be designed to operate effectively at lower altitude and satellites in low orbits are more susceptible to collisions with space debris due to congestion. There are also some regulatory challenges. The FAA in the United States and other national regulatory bodies play a crucial role in licensing and regulating satellite operations. Implementing altitude restrictions requires updating existing regulations or creating new ones. This involves legal processes, stakeholder consultations, and public input, which can get contested fast. One example was during the Federal Communications Commission (FCC) Guidance on Orbital Debris Mitigation plan in early 2024. The FCC aims to hold operators accountable for complying with orbital debris policies and reinforcing space sustainability (Jewett, 2024). Notably, Commissioner Nathan Simington expressed the view that the same orbital debris rules should apply to both U.S.-licensed providers and market access licensees authorized in other countries. He highlighted the potential disadvantage faced by U.S.-licensed providers due to more rigorous regulations compared to non-U.S.-licensed space stations (Jewett, 2024). Thus, one factor to consider is that if the FAA mandates the orbital restrictions within the U.S., other countries might not follow our lead and continue to benefit from operating satellites at a higher altitude. I rank feasibility low for this alternative.

Equity:

I rank equity low for this alternative because there is a large burden being placed on the satellite operators. A regulatory mandate would place an economic burden on the satellite operators while also jeopardizing their work. Many satellite operators choose to place their satellites at a higher orbit for several reasons. Higher LEO orbits experience less atmospheric drag, resulting in longer orbital lifetimes. Satellites can remain operational for extended periods. Satellites in higher LEO cover a larger area of Earth’s surface during each orbit. This broader coverage is advantageous for global monitoring and communication.

Mitigation Strategy 3: Optimizing Observation Schedules to Avoid Satellites

Effectiveness:

I rank effectiveness medium or 50%, because although this technological tool will allow astronomers to avoid observations during current peak satellite passing hours, this is not a long-term effective approach because the light pollution is expected to worsen (by 50 times) as companies plan to send thousands more satellites into space (Patel, 2023). Since only satellite operators in the U.S. will report their deployment activities, the effectiveness now stands at 33.5%. In a few years, once the number of orbiting satellites reaches about 65,000, they’ll make up about one in 10 lights one can see in the night sky, either with telescopes or the naked eye (Skibba, 2022). Soon, there will be no portion of the dark sky that does not have satellite trail passing through.

Cost:

LeoLabs, a space situational awareness company, unveiled a small satellite tracking service called LeoTrack. As of February, 2024, LeoLabs Raises $29M to Deliver Enhanced AI-powered Insights for Space Operations (Dargan, 2024). A similar tool would cost about the same price range to start up and maintain - $30M to $50 M. Let us compare that to the overall agency budget: NASA's 2024 budget is $24.9 billion, but only 4.9% of the overall budget goes to technology (see appendix D). Bearing in mind the many other technological programs that exist within the agency, I rank the cost medium for this mitigation strategy.

Feasibility:

I rank feasibility high because there are already many algorithms available to track satellites (for exam: space-track.org and LeoLabs). Since there are already many congressional hearings on the impacts of satellite constellations, the federal government is likely to pass funding for the tracking tool.

Equity:

I rank equity low because this alternative does not mitigate the scientific disruption that the satellite constellation imposes on the astronomy community. As mentioned, the astronomy and scientific community will continue to be negatively affected as the number of satellites increases (Skibba, 2022).

Outcome Matrix (all weighted equally)

Criteria	M1: Darkening the Satellites	M2: Deploying LEO satellites at a lower orbital altitude	M3: Optimizing observation schedules to avoid satellites
Effectiveness	**37 to 47%**	47%	33.5%
Cost	**Low**	High	Medium
Feasibility	**High**	Low	High
Equity	**High**	Low	Low

Recommendation

Upon analyzing the outcome matrix, I strongly advocate for the implementation of the first mitigation strategy: darkening the satellites. This approach holds great promise in mitigating the adverse effects of large LEOsat systems on professional astronomy. Satellite operators are actively exploring innovative methods to enhance the darkening process. Furthermore, the associated cost burden remains minimal, primarily due to incorporating mass changes during the design phase of new satellites. Importantly, both feasibility and equity factors align favorably with this strategic approach. The obvious tradeoff is that the effectiveness is still heavily limited due to 1) the darkening strategy does not fully remove the light pollution effect and 2) only the satellite operators in the U.S. will adopt this strategy, which adds an additional burden compared to those operating in other countries. I hope that this is one of the many other strategies that will be proposed in future workshops (similar to SATCON1) that can extend to other countries as well.

Implementation

For the implementation part, I will provide a detailed plan with three parts to consider: stakeholders involved, necessary steps, and perspectives from the stakeholders.

Part 1: Who are the stakeholders?

NASA as an advisor: NASA has been instrumental in assisting the development of reports to Congress on the negative impacts of satellite constellations. A recent example: the United States Government Accountability Office (GAO) published the Large Constellations of Satellites, Mitigation Environmental and Other Effects in 2022 and it states that the disruption of astronomy is one of the top three concerns (the other two are increase in orbital debris and emissions into the upper atmosphere) stemming from satellites (United States Government Accountability Office, 2022). In regarding to darkening the satellite policy, NASA will not take a direct regulatory approach, but instead it will advise and guide a regulatory body like the FAA to set the regulatory rule. Even with the rising commercial companies, NASA is still considered the leading space and aerospace agency, thus it has a lot of leverage in persuading the FAA to pursue a certain course of action. For example, NASA regularly joins the FAA during the congressional hearing on space sustainability and often advises on what course of actions the government should pursue for space sustainability purposes (Government Promotion of Safety and Innovation in the New Space Economy, 2023).

FAA as the regulatory body: the stakeholder that has the most regulatory and administrative influence in this endeavor is the FAA. The FAA is the primary agency that issues satellite licenses for launch, re-entry, launch operator, and experimental permits. According to the Code of Federal Regulations (CFR), its title 14 says that "The FAA's regulations on commercial spaceflight cover the "authorization and supervision" of any U.S. organization or citizen conducting space endeavors. It requires commercial missions to receive a license to launch (and re-enter), and it also requires licenses for commercial spaceports" (Space Foundation, 2021). The FAA already has extensive criteria and requirements for launching satellites. For example, two important checklists for all U.S. satellite operators are Orbital Debris Assessment Plan (ODAP) and Debris Removal. Per ODAP, Operators licensed to perform launches with a planned altitude greater than 150 kilometers must submit an Orbital Debris Assessment Plan prior to each operation. The FAA also requires that any debris fragments greater than 5 millimeters in size must be removed from highly used regions within 25 years (Mitigation Methods for Launch Vehicle Upper Stages on the Creation of Orbital Debris, 2023).

Satellite operators in the U.S. as the affected party: the obvious scenario here is that the satellite operators in the U.S. will have some sort of darkening strategies that will decrease the light polluting effect by at least half. The hope is that as time passes, these industries will figure out more effective ways to not produce bright streaks in the dark sky.

Astronomy community: scientific communities will continue to host workshops like the SATCON1 to find more ways to reduce the negative effects of satellite constellations on professional astronomy. The darkening method is not 100% effective, thus a combination of strategies in the future will likely be more sustainable.

Part 2: What are the next steps?

Step 1: NASA will voice this mitigation strategy in future congressional hearings, with the support of the scientific community.
Step 2: The FAA will adopt this new guideline in the Fall of 2024
Step 3: Rolling phase – satellite operators that are building the new batch of satellites starting in 2025 will start to incorporate darkening method in their design.
Step 4: By mid-2025, large satellite operators will launch satellites with the darkening method.
Step 5: By the end of 2025, smaller satellite operators and those that have limited resources will fully incorporate the darkening method.
Step 6: By the start of 2026, every satellite operator in the U.S. will mass produce satellites with some sort of darkening method.

Part 3: What are the perspectives of the various stakeholder groups?

By reading various reports including the GAO and the SATCON1, NASA, FAA, and the various astronomy communities would be supportive on this policy recommendation specifically because they support space sustainability actions. Any additional regulation will be negatively viewed by the affected party – satellite operators – at first. However, NASA will have to recommend the FAA to put less constraints on satellite operating companies that do not have a lot of resources. It was easier for a large organization like SpaceX to test out various darkening methods and roll out many satellites with those methods, but many smaller commercial satellite companies will need additional time. That is why I gave some grace period (in part 2) for smaller satellite operators to fully incorporate this recommendation.

Conclusion

The growing proliferation of satellites in Low Earth Orbit has significantly impacted professional astronomy, leading to the phenomenon known as "Satellite Trails" or "Satellite Streaking." As astronomers worldwide grapple with light pollution caused by reflective materials and emitted light from these satellites, finding effective mitigation strategies becomes paramount.

This report examines three primary mitigation approaches:

1. Optical Darkening of Satellites (M1): This strategy, which involves modifying satellite surfaces to reduce their reflective brightness, has demonstrated effectiveness. By minimizing the impact on ground-based astronomy, it offers a practical solution accessible to all satellite operators. Moreover, its relatively low implementation costs and high feasibility make it an attractive choice.

2. Lower Orbital Altitude Deployment (M2**)**: While deploying satellites at lower orbital altitudes could mitigate satellite trail effects, it presents challenges related to costs and feasibility. The feasibility and cost-effectiveness of this approach warrant further investigation.

3. Optimized Observation Schedules (M3): Adjusting observation times to avoid satellite interference is another viable option. However, this approach requires coordination across global observatories and may not be sustainable in the long run when the sky is no longer clear of satellites passing.

The evaluation criteria, effectiveness, cost, feasibility, and equity, favor M1: Optical Darkening of Satellites. Notably, this strategy aligns with administrative and political feasibility, as evidenced by ongoing legislative discussions. Furthermore, it ensures equity for both astronomers and satellite operators, striking a balance between scientific progress and commercial interests.

The proposed implementation plan outlines a comprehensive approach to addressing the issue of light pollution from satellite constellations through the implementation of satellite darkening methods. The plan identifies the key stakeholders involved, including NASA as an advisory body, the FAA as the regulatory authority, satellite operators as the affected parties, and the astronomy community as a scientific voice. The plan consists of six steps, beginning with NASA voicing this mitigation strategy in congressional hearings, followed by the FAA adopting new guidelines in Fall 2024. Subsequently, a rolling phase will be implemented, with larger satellite operators incorporating darkening methods by mid-2025, and smaller operators following suit by the end of 2025. The goal is for all the U.S. satellite operators to mass-produce darkened satellites by the start of 2026.

While NASA, the FAA, and the astronomy community are likely to support this policy recommendation, satellite operators may initially view additional regulations negatively. However, the plan acknowledges the need for flexibility and a grace period for smaller operators with limited resources to fully incorporate the darkening methods. This implementation plan strikes a balance between addressing the concerns of light pollution and space sustainability while considering the practical limitations and challenges faced by various stakeholders. It represents a collaborative effort to mitigate the negative impacts of satellite constellations on astronomical observations and paves the way for a more sustainable space environment.

"We are a way for the universe to know itself" – Astronomer Carl Sagan.

Appendix

Appendix A: More Visual Examples of Satellite Trails

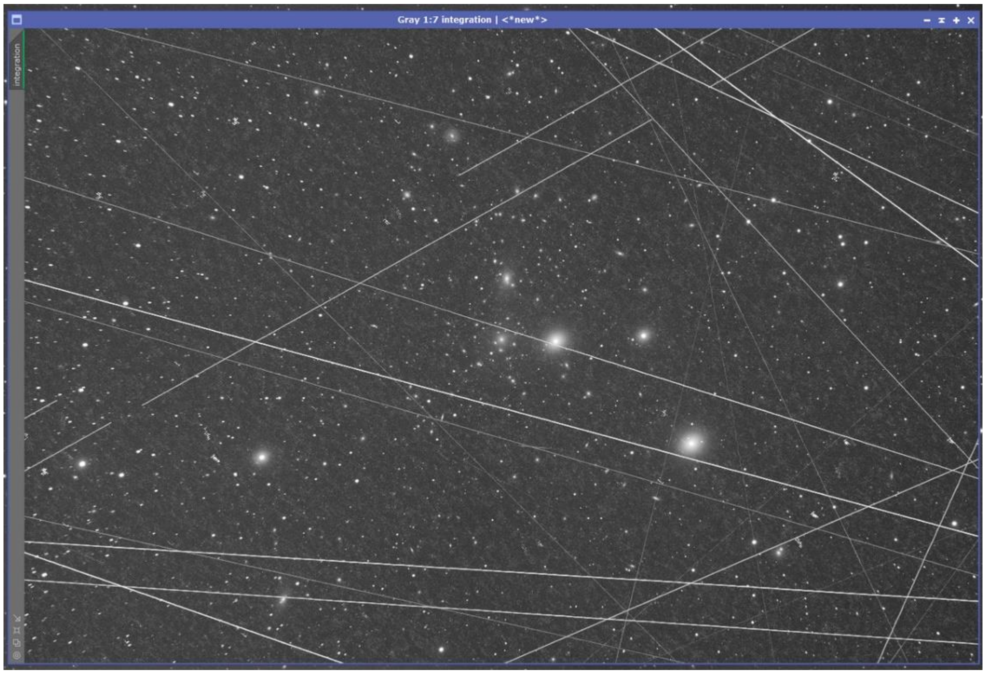


Image 1: A stack of astronomy images with 120 seconds of exposure time (SlimPaling, 2020)

Image 2: SpaceX Starlink satellites over Essex (Ingram, 2020)

Image 3: "This long exposure photo of the sky above Gunnison National Park in Colorado shows the movement of light—coming from both natural and artificial sources. The thousands of satellites in orbit around the earth can shine millions of times brighter than objects farther away in space, getting in the way of astronomic observations" (Ward, 2023)

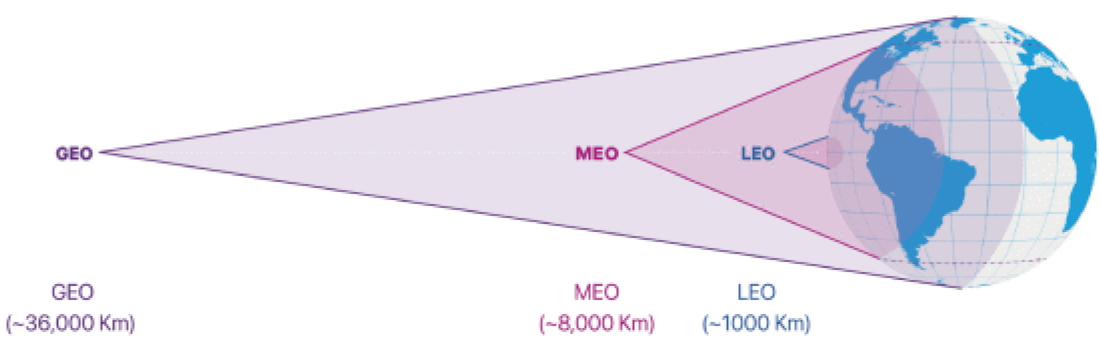
Image 4: Satellite trails were visible in almost every single photo from over 3 hours of shooting in Western Australia. The astrographer "decided to put the satellite trails together into a single image to show how polluted the night sky is becoming" (Gold, 2022)

Lastly, this video provides a glimpse into how people can easily see the megaconstellation in the dark sky without using a telescope. This "train" of satellites photobombed the National Geographic filming of the night life in California's Pinnacles National Park (Ward, 2023).

Appendix B: Cost Categorization for the Evaluative Criteria

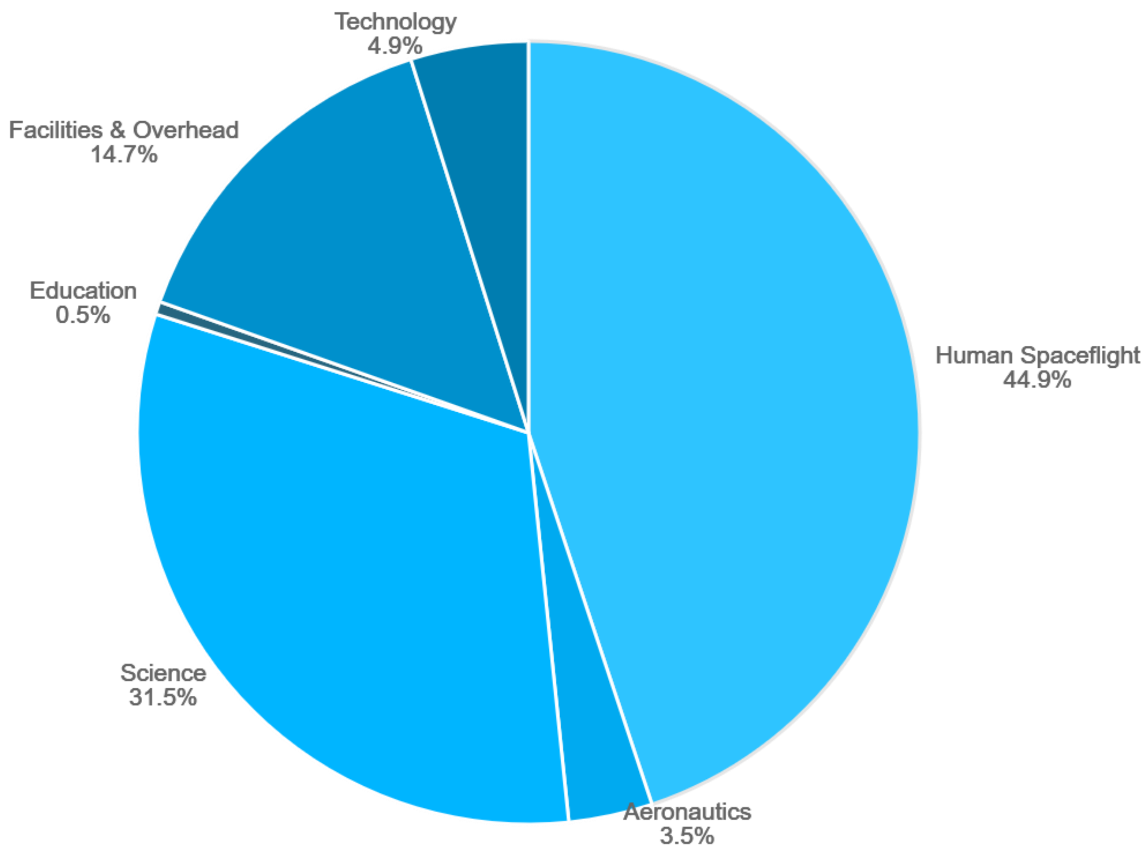
Low Costs	**Medium Costs**	**High Costs**
< 5 million USD	$30 million - $50 million USD	>$100 million USD

Appendix C: Different Earth Orbits



The LEO satellite constellations require significantly more satellites to provide the same coverage amount compared to the MEO and GEO. This explains the congestion and the rapid increase in the deployment of satellites in LEO ("Darkening Low-Earth Orbit Satellite Constellations: A Review," 2022).

Appendix D: NASA Budget Breakdown



Above is the breakdown of NASA's budget by major programs (Planetary Society, 2024).

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