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Darkening Low-Earth Orbit Satellite Constellations: A Review

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ABSTRACT The proliferation of low-earth orbit (LEO) satellites and the LEO satellite internet will be a game-changer for the low-latency high-speed global internet. While this new generation of the satellite internet in conjunction with fifth generation network (5G) and sixth generation network (6G) enabled emerging technologies, such as precision farming and smart cities, it will bring new challenges, such as satellite collision, limited satellite lifespan, security concerns, and satellite brightness. This article discusses the satellite brightness caused by LEO constellations that potentially affect the ongoing astronomical studies. It reviews the underlying contributors to the satellite brightness as well as the state-of-the-art technologies proposed to mitigate this emerging challenge.

INDEX TERMS Low earth orbit satellites, satellite brightness, satellite internet, phased array antenna, brightness magnitude, satellite communication, SATCOM.

NOMENCLATURE

Abbreviation	Meaning
5G	5th Generation mobile network.
5G	5th Generation mobile network.
LEO	Low Earth Orbit.
MEO	Medium Earth Orbit.
GEO	Geosynchronous equatorial orbit.
GPS	Global positioning satellite.
O3b	Other 3 Billion.
SES	Société Européenne des Satellites.
NOIR Lab	National Optical Infrared Astronomy Research Laboratory.
m	Meters.
M	Magnitued.
ms	Millisecond.
Mbps	Megabits per second.
Gbps	Gigabits per second.
PSo	Particle swarm optimisations.

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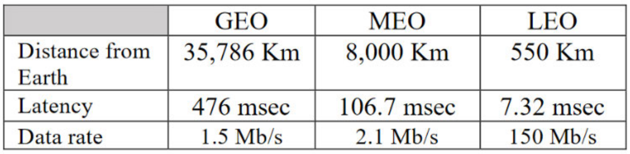
I. INTRODUCTION

In recent years, satellite internet has moved into the low earth orbit (LEO) arena, reducing latency, and increasing network speeds. Using several satellites in LEO, space players create constellations of internet satellites to cover the earth fully. SpaceX's Starlink network is the most developed of these with 1560 active satellites, as of 24 February 2022. Others include Telesat LEO, Amazon's Project Kuiper, Iridium NEXT, Globalstar and OrbComm [1].

A constellation of satellites in LEO comes with many benefits. Having a very high coverage percentage of the entire earth will help provide internet to remote areas to improve education and communication where traditional internet access is very limited and unreliable. Reduced latency will improve real-time communication speeds compared to traditional geosynchronous equatorial orbit (GEO) satellite internet. Running costs will be reduced due to the minimal ground-based infrastructure required as future satellites will be fitted with optical inter-satellite links for communication between the satellites without using ground stations, further increasing data transfer speed [2], [3]. Such

TABLE 1. Speeds from different orbital heights.



	GEO	MEO	LEO
Distance from Earth	35,786 Km	8,000 Km	550 Km
Latency	476 msec	106.7 msec	7.32 msec
Data rate	1.5 Mb/s	2.1 Mb/s	150 Mb/s

constellations will play an essential role in emergency communications in regional areas and oceans where conventional satellite communications and other terrestrial technologies are minimal [4], [5].

LEO satellite constellations can provide low latency, high bandwidth internet from an orbital height of 550 kilometers (km), significantly better than GEO internet satellites which are stationed in a 35,786 km orbit [6], [7] to stay constantly aligned with specific areas of the earth and have a much higher latency as well as lower bandwidth [8]. Table 1 shows a comparison of coverage and distance of GEO, medium earth orbit (MEO) and LEO Satellites.

Additionally, the LEO satellites can be de-orbited after they reach the end of life, another advantage over GEO technology. This helps in reducing the amount of space junk in orbit earth. Traditional GEO satellites are positioned into a graveyard orbit when they retire, which is more efficient than trying to deorbit it from its operating height [9]. Collision avoidance is an important aspect of LEO satellite constellations. The orbital space around earth is becoming increasingly busy with space junk, satellites, and other objects. Another major concern is that too many satellites may induce the Kessler effect, a cascading collision leading to a debris belt around the earth, limiting our capabilities to launch rockets into orbit and beyond [10], [11]. As stated in [12], there are over 120 conjunctions in a 30-day period that cross the threshold for the current collision avoidance regulations as well as 53 that cross the maneuver planning threshold that is used to control the current density of LEO space. For this reason, a collision-avoidance system has been implemented ont o the satellites to maneuver the satellite. Another key feature is to make de-orbiting the satellites part of the satellite mission. When they reach their end of life, they complete a de-orbit burn, eventually burning up in the Earth's atmosphere, further reducing the amount of space debris in orbit [13]–[15].

However, the LEO constellations require significantly more satellites to provide the same coverage amount compared to a GEO constellation as shown in Fig. 1, [6], [16].

This increases the number of objects in the orbit, and with it brings new challenges, such as orbital collusion, limited satellite lifespan, security concerns associated with tens of thousands of satellites, and satellite brightness. This review will systematically discuss the underlying factors of LEO satellite constellation brightness and the most recent technologies developed to mitigate this emerging challenge.

II. DEVELOPMENT OF LEO SATELLITES

Traditionally, internet satellites were in GEO, but in 2013 Société Européenne des Satellites (SES) launched four satellites, the start of its 'Other 3 Billion' (O3b) constellation into MEO to provide internet access to many countries around the world. The O3b constellation currently has 20 satellites in MEO, supporting many customers [17], [18]. In MEO, the satellites have a 100-120 millisecond (ms) latency, which is far better than GEO, but not as low as a LEO satellite constellation. Ob3 mPOWER is their newest satellite design, currently in production to increase bandwidth from 50 megabits per second (Mbps) to 1+ gigabits per second (Gbps) [19]. Since O3b's success in providing MEO satellite internet, LEO satellite constellations have been developed to compete with broadband and fiber internet on the ground as well as provide internet to rural areas without compromise.

The first iteration of the Starlink satellite started as a standard MicroSat. During development, the two test satellites were named Tintin A and Tintin B. They were a box design measuring 1.1 meters (m) × 0.7 m × 0.7 m. The MicroSat consisted of a flight computer, power system, a control system, broadband and ground positioning satellite (GPS) antennas, and two solar panels. The satellites have a total mass of 400 kilograms (kg) each [20]. Tintin A and Tintin B, shown in Fig. 2, successfully communicated with ground stations, leading to the development of Starlink version 0.9. This satellite was an all-new design that consisted of a new flat-panel layout, allowing the satellites to be stacked vertically when loaded onto the launch vehicle. It uses a single solar panel, a new propulsion system using Hall Effect thrusters with Krypton fuel and a new collision-avoidance system. This new package reduced the weight of the satellite down to approximately 227 kg. On 15 May 2019, 60 of the new version 0.9 satellites were launched on a Falcon 9 rocket and reached an altitude of 550 km [21], [22]. The most current Starlink satellite in orbit as of this publishing date is v1.5. It uses two parabolic antennas and four phased array antennas in the Ku- and Ka-bands, as well as a star-tracker to help with attitude data and control while maintaining the single solar panel, Hall effect thrusters and the collision avoidance system from version 0.9. They weigh around 260 kg each [23]–[25]. OneWeb, another LEO constellation now operated by the British Government and Bharti Global, is working to extend its constellations with a plan to produce 648 satellites for its first-generation fleet for its initial constellation. Currently 394 satellites are successfully launched into LEO.

III. ONSET OF BRIGHTNESS

The presence of thousands of satellites orbiting the earth at a very low altitude causes the onset of streaks in the sky due to sun illumination known as satellite brightness.

The brightness of satellites can affect astronomers observing the night sky by creating streaks in the images, which can cause blown highlights in the astronomical images, which causes fainter objects not to be visible. If the satellite remains on any pixel for any length of time as it can saturate the pixel, creating artifacts and reducing the data captured [26]. Observatories with a wider field of view will be greatly affected due to observing a larger area of the night sky. Observatories with

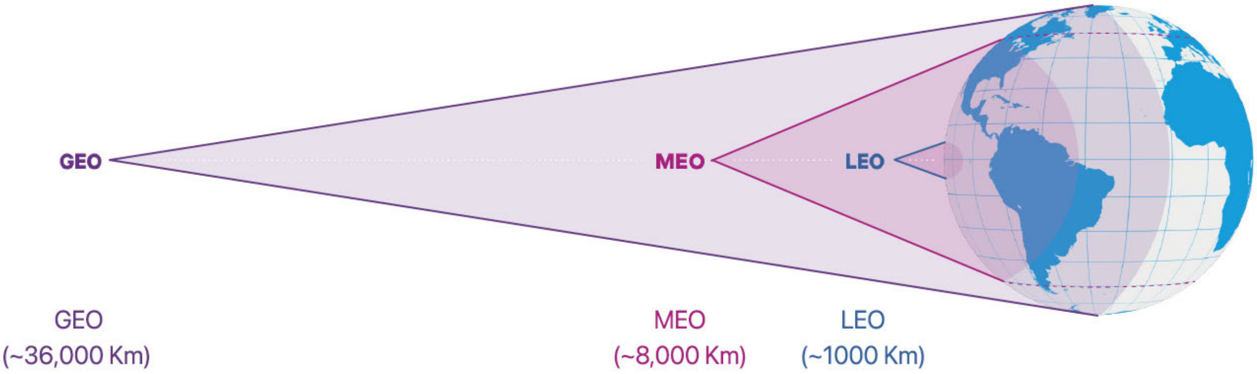


FIGURE 1. Comparison of coverage and distance of GEO, MEO and LEO satellites [6].

FIGURE 2. Tintin A & B pre-launch [20].

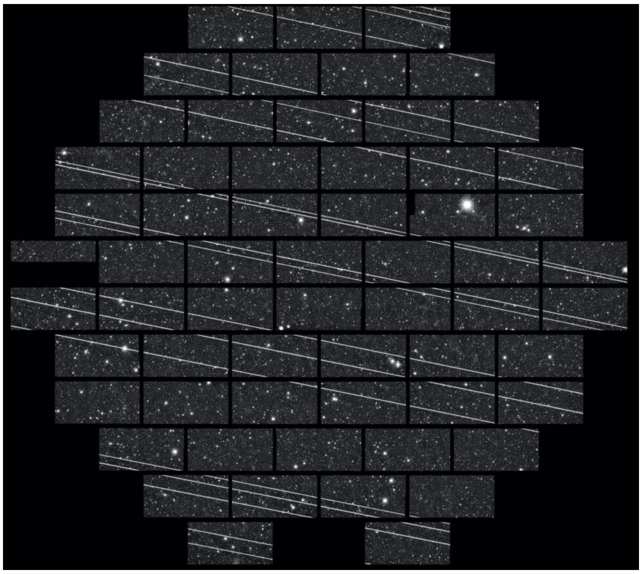


FIGURE 3. A wide-field image with satellite streaks [27].

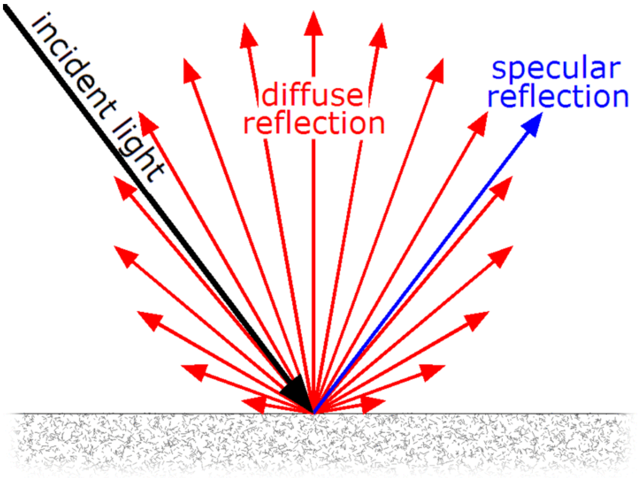


FIGURE 4. Diffused and specular reflections on a glossy surface [45].

a smaller field of view will be less affected, but the trails from LEO constellations can still affect their data. The reflections are at their worst during twilight hours when the satellites are in full view of the sun, yet the earth is still night. This is due to the height of the satellites in orbit. Most LEO satellites are around 550 km from the surface of the earth, resulting in a radial velocity of 7.6 km/s [26] which is slow enough to leave trails on the imaging sensors.

The streaks of some LEO satellites, shown in Fig. 3 [27], are caused by the satellites being illuminated by the sun, and depending on the observational zenith angle, shown in Fig. 5, satellite altitude, and observing night, the brightness and number of streaks in the images can vary. Satellites are complex in design and shape, as there is no need for them to be aerodynamic. They consist of the body, which can vary in size and shape to house all the instruments in addition to a solar array or a singular solar panel. The solar panels and the antennas are known as two main reflection points on the LEO satellites, strongly contributing to satellites brightness. The solar array on most of LEO satellites is estimated size of 12 m × 3.2 m [28] that is large enough to reflect light.

The phased array antennas on most of LEO satellites are also a key point for reflections due to their reflective surface which helps reduce heat by reflecting the light

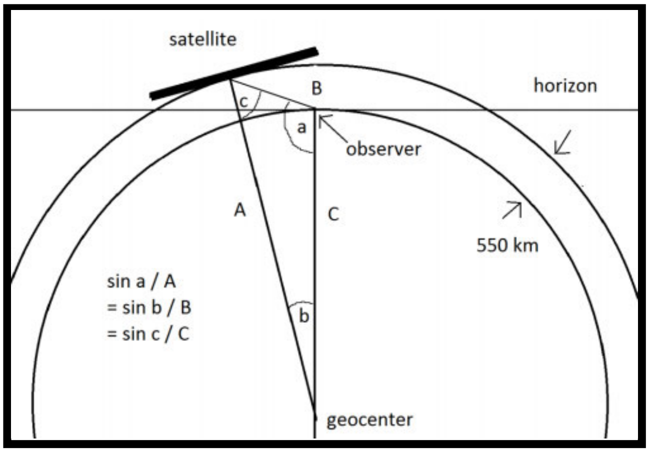


FIGURE 5. Observer aspect of the satellite [46].

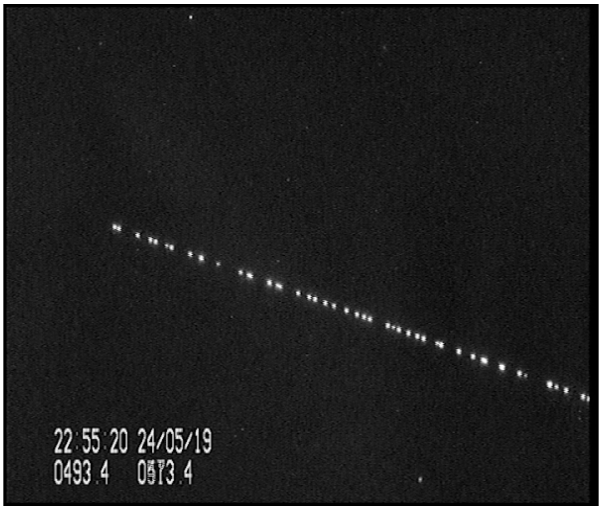


FIGURE 6. LEO satellites creating the "String of pearls" effect [48].

away. These antennas are essential to LEO satellites as they are responsible for providing internet communications on the V and Ku- bands, as well as connecting to the ground stations for tracking and system monitoring on the V and Ka- bands [23]. Apart from phase array technology, a new beam steering mechanism has recently been proposed based on near-field transformation, contributing to low-cost manufacturing [29]–[36]. This technique does not require expensive active phase shifters and can be implemented by all-dielectric substances [29]–[31], all-metal structures [32], [33], or hybrid materials [34]–[36]. Additionally, there are other antenna reconfiguring techniques that potentially can be adopted for such purposes [37]–[43].

Phased array antennas electronically steer the highly-directive beam of the antenna using several microwave phase shifters. The main beam can be oriented in any direction by fixing the arrangement of elements and changing the phase of each element accordingly. Despite their excellent performance, this class of antenna is susceptible to heat, where their radiation patterns, and particularly the antenna gain, are varied slightly as the heat increases. Because of this, reflective radiators are designed and placed on top of the antenna to minimize heat-driven variation in the antenna radiation patterns [44]. These radiators along with relatively large solar panels, reflect sunlight during sunrise and sunset as the satellites orbit the earth, producing both specular and diffused reflections [46].

As shown in Fig. 4, specular reflections occur when the incident rays are all aligned and reflect in the same direction as well as preserving the organization of the rays. This occurs on reflective and polished objects and means that the light is focused in one spot, rather than being scattered. Differently, diffused reflection occurs when the surface is un-even and the angle of the reflected rays are all different depending on what part of the surface is illuminated. If the surface has roughness, even at the molecular level, the light will be diffused due to the uneven surface [48]–[51]. Most LEO satellites have a square flat panel with flat radiators covering the phased array antennas. Both cause specular reflections back to the ground, making them appear as bright objects in the night sky as the sun reflects down to earth. This is because they are highly reflective to passively cool the satellite without the need for an additional cooling system [52]. Due to the orbital height of LEO constellations, the satellites are only visible around astronomical twilight and are not visible in the earth's shadow for local solar midnight [53]. The sun reflects off the satellites and solar panels and phased array antennas during sunrise and sunset as they orbit the earth, and this produces both specular and diffused reflections [46]. Due to this reflectiveness, satellites reflect sunlight back down to earth creating a "string of pearls when they are maneuvering to their operational orbit as seen in Fig. 6. This undesired streak effect on images as well as being visible to the naked eye [49], [54]. This side-effect only occurs immediately after they have been released from the second stage of the rocket and while the solar panels are in a low drag mode to reduce the effect the atmosphere has on the satellite. Over the course of 3 to 4 weeks as the satellites separate from each other and rise to their operational orbit the string of pearls effect slowly disappears.

These reflections can be mitigated by changing the orientation during the twilight hours where the satellite will be at its most reflective. During its orbital raising period, the satellite has the solar panel in a low drag mode, which increases the area that light can reflect from. The satellites are rotated so the solar panel is then in a "Knife edge" configuration, shown in Fig. 9, having the thin edge of the array facing the earth reducing the surface area that can reflect light during the orbital raising period, as shown in Fig. 7, and thus reducing the diffused reflections back down to earth [46].

Once the LEO satellite is in its operational orbit, the satellite's orientation will be changed during sunset and sunrise to minimize the reflections by positioning the satellite into the "Shark fin" orientation which will not reflect any light from

TABLE 2. Data from observatories on the satellite brightness magnitude after the application of low-albedo coating [59]–[62].

Date:	Starlink Magnitude	+/-	DarkSat Magnitude	+/-	difference	Observor
2020 Feb 26	4.5	± 0.2	5.7	± 0.3	1.2	R. Cole
2020 Mar 01	4.7	± 0.2	5.9	± 0.2	1.2	R. Cole
2020 Mar 06	6.59	± 0.05	7.46	± 0.04	0.87	J. Tregloan-Reed
2020 Mar 06	5.15	-	6.13	-	0.98	T. Boroson / J. A. Tyson
2020 Mar 06	5.18	-	-	-		T. Boroson / J. A. Tyson
2020 Mar 06	5.02	-	-	-		T. Boroson / J. A. Tyson
2020 Mar 06	5.13	-	-	-		T. Boroson / J. A. Tyson
2020 April 10	-	-	5.87	± 0.07		T. Horiuchi
2020 May 18	-	-	5.74	± 0.1		T. Horiuchi
2020 June 11	4.25	± 0.07	5.33	± 0.04	1.08	T. Horiuchi

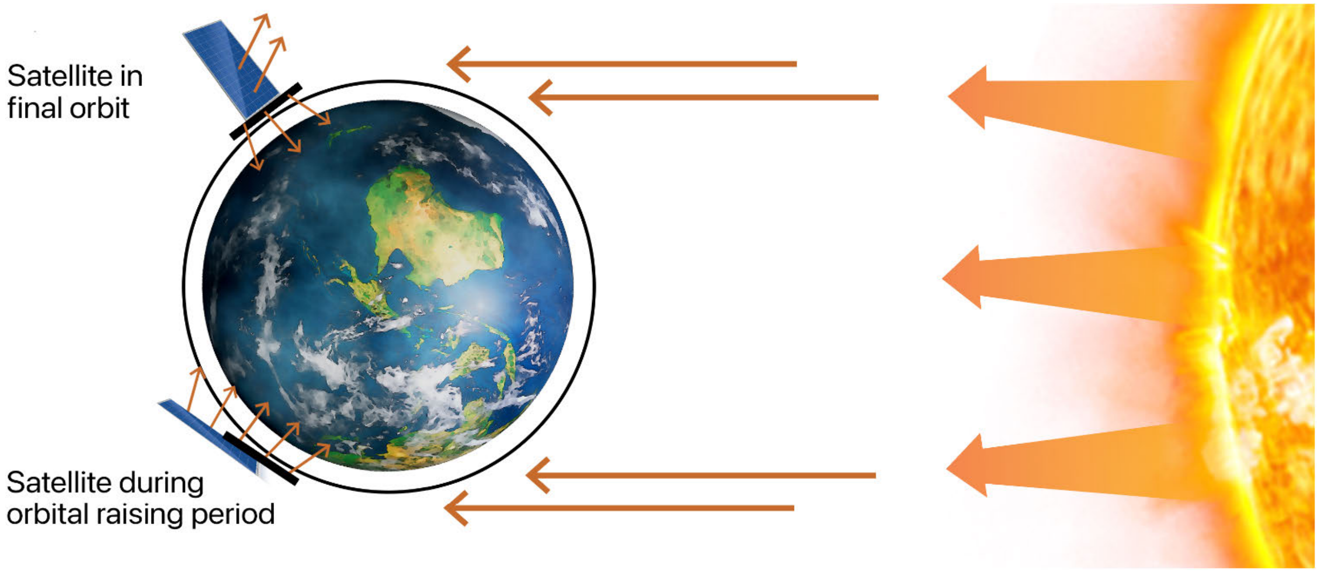


FIGURE 7. Angle of reflection during orbital raise and on station during twilight hours.

the solar array back down to earth, as shown in Fig. 8. This reduces the operational reflections to just the phased array antennas as the satellites make their way into the night.

IV. LOW-ALBEDO COATING

Low albedo coatings are used to absorb light on reflective surfaces and can be man-made or occur naturally in the world. While they greatly help reduce the solar reflectivity on objects, one downside is heat absorption. The surface reflects very little of the incoming light and heat, which in turn heats up the surface. Satellites are traditionally made to have a high albedo surface to reflect the heat away from them. This helps with cooling and keeps the weight of the satellite down as they do not need a cooling radiator to maintain a stable working temperature.

To mitigate the light reflectivity of LEO satellites, a low-albedo coating was proposed and applied to the LEO satellites. This coating is compatible with both the parabolic and phased array antennas used in the satellites, contributing to an overall satellite brightness reduction of 55% [46]. The satellites developed with the low-albedo coating were launched in March 2020 and placed in a low earth orbit to investigate the satellite brightness of the antenna system.

According to the several observations carried out over a time frame of 1 year, the satellite brightness has decreased, resulting in an increased apparent magnitude by more than one magnitude compared to the standard satellites in the same constellation, as summarized in Table 2 [59]–[62]. This table compares the apparent magnitudes of satellites with and without coating over 10 observations carried out in different times and different terrestrial locations by three observatory sites.

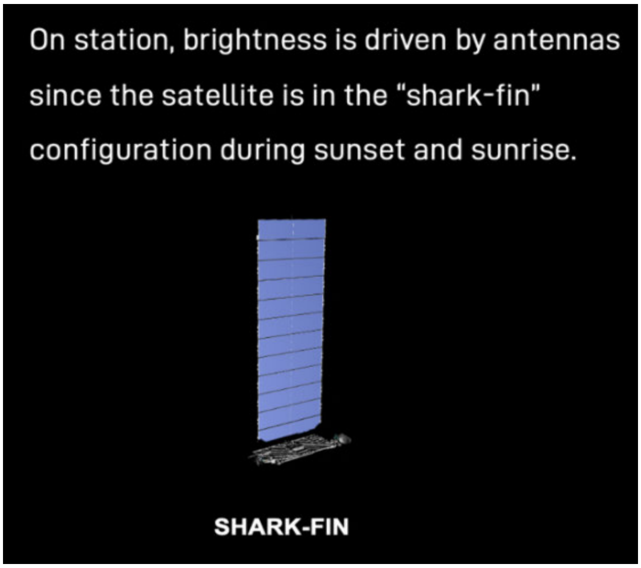


FIGURE 8. A satellite in the shark-fin orientation once in operational orbit [46].

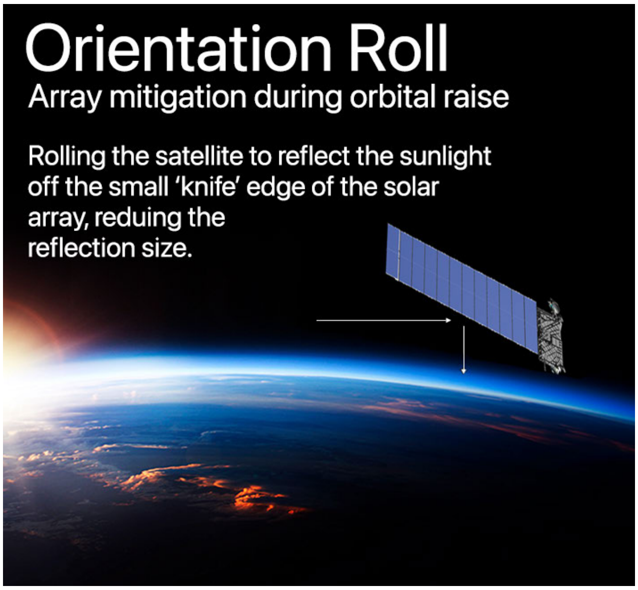


FIGURE 9. A satellite in "Low drag knife edge" orientation [46].

Apparent magnitude is a measure of brightness of different objects (stars, satellites, etc.) observed from Earth, where the brighter the object is, the apparent magnitude of it is lower, shown in Fig. 10 [55], [56].

$$M_x = -2.5 \log_{10}\left(\frac{F_x}{F_{x,0}}\right)$$

$$M_1 - M_2 = -2.5 \log_{10}\left(\frac{L1}{L2}\right)$$

Each magnitude (M) increase implies a decrease in brightness by a factor of $\sqrt[5]{100} \approx 2.512$ also known as Pogson's Ratio [55]–[58].

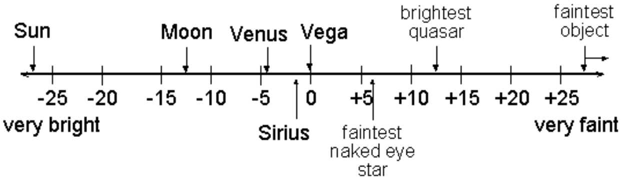


FIGURE 10. Apparent brightness's of some objects in the magnitude system [63].

Although observations show that the coating reduced the brightness albeit to varying degrees, the brightness of the satellites still could interfere with astronomical observations. The images captured by Tregloan-Reed and Horiuchi in Fig. 11 show streaks from satellites with coating, although darker, are still persistent in astronomical imaging [59]–[62].

The results also show that the 55% reduction of reflectivity [46], [60] varies in different locations. This could be due to many factors such as the distance from the satellite, the angle of the satellite in relation to the sun and different altitudes of the satellites [61].

While there is some improvement in darkening LEO satellites through low-Albedo coating, the technology used in coating antenna systems increases the antenna's heat absorption on the satellites, contributing to a short life span of the electronic components, such as phase shifters in the antennas system.

More importantly, the phased array technology, responsible for providing steerable, highly directive radiation patterns, is highly susceptible to heat and the antenna gain drops as temperature increases. This means that the satellite terminal antennas on the ground may not receive the signals transmitted by LEO satellites, posing a serious barrier to providing low latency, high bandwidth satellite internet promised by such new constellations. Additionally, overheating the antenna system creates interference in infrared observations as the satellites will be visible due to their higher temperature. The heating problem associated with low-albedo coating makes this class of satellites less appealing. The low albedo coating has little to no advantage compared to the foam visor, with additional weight being applied as well as extra heat absorption from the coating on the antennas.

V. SPECIALIZED FOAM VISOR

Foam visors have been used in many applications all over the world to block light and reduce surface reflections. They can be made from many different materials but when they are used with satellites, they need to be designed to allow radio waves to pass through without degrading the signal or blocking it all together as well as being light weight, as every gram counts when launching a group of satellites into LEO. Being radio transparent is one of the biggest challenges as the design of current and future constellations require high speed connections with minimal data loss and interruptions, as they are intended to be a consumer-based internet connection,

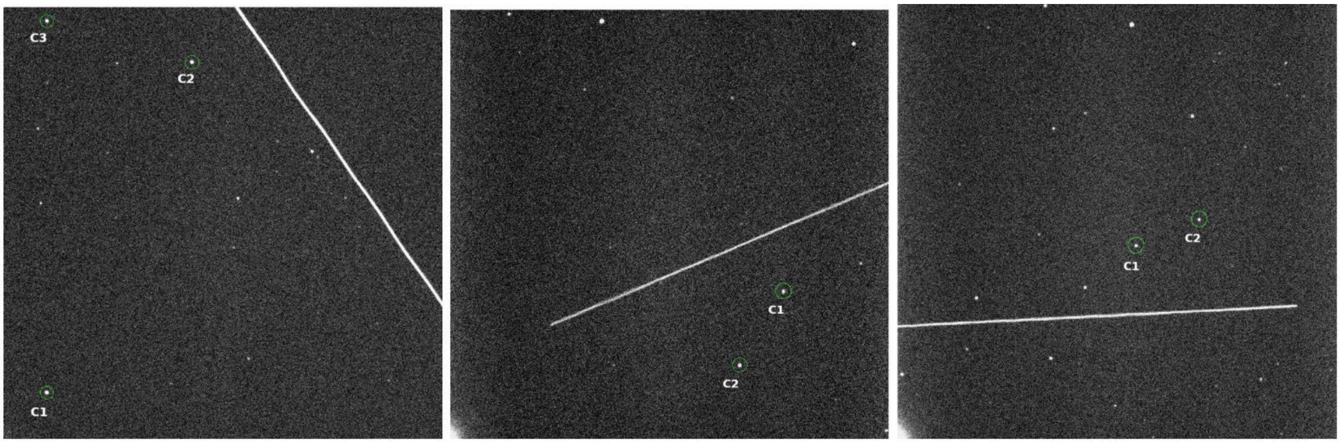


FIGURE 11. Left satellite with coating: 2020/02/08. middle satellite with coating 2020/03/06. right STARLINK-1113: 2020/03/06 [60].

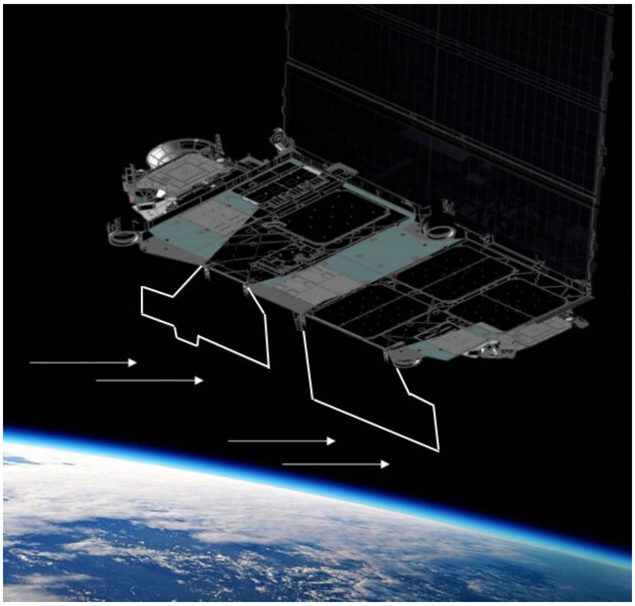


FIGURE 12. Satellites with visor deployed covering the phased array antennas [40].

so the foam visor has to be transparent to radio waves over a vast frequency range.

There are many companies producing polyurethane foams that are transparent to radio frequencies that would be ideal for keeping a satellites reflective components shaded without compromising the antennas on the satellite.

In order to block the sun hitting the phased array antenna systems, that are widely used in the LEO satellites, a special foam visor was recently proposed to cover the antennas [46]. It has been designed to maximise the shade on the antennas while keeping weight down, which is why they are the shapes as seen in Fig. 12, outlined in white. At the time of publishing, no detailed information has been released on what type of foam was used to form this visor used in the trial.

Such specialized visor foam allows radio frequencies to pass through while reducing the heat absorbed by the LEO satellites equipped with this technology, resulting in 1.29 magnitudes darker than other LEO satellites in the same constellation with a mean magnitude of 5.92, 5.8, 5.9 and 6.0 [59]–[61]. It was observed that while the visor foam blocked most of the light, there were still some minor bright spots due to potential gaps in the panel sections, which allow sunlight to reach the rear side and the edges of the satellite still being illuminated by the sun [67].

Unlike low-albedo coating technology, the visors will also stop the antennas from heating up and provide more protection to the antenna system. Based on the limited information released, visors are slightly darker than LEO satellites with the low-albedo coating, while there is more room for improvements in the design and implementation of the visor such as removing all gaps in the panel as well as expanding it past the edges to fully cover the underside of the satellite reducing all possible chances of sunlight hitting the reflective surfaces. The only downside to increasing the surface area of the foam visor is the added weight, which in terms of satellites and rocket launches, every gram needs to be accounted for, that is why the visors has a particular shape to block the most reflective components.

The foam visor has more advantages over the low albedo coating, being able to cover more than just the antennas which reduces the overall reflections as well as reduces the heat absorbed by the antenna covers. Despite both these changes to the original satellite, neither are enough to darken the satellites to an acceptable level for astronomical explorations world wide.

VI. FUTURE IMPROVEMENTS

A new solution for darkening LEO constellations is being tested in which the sun is in-plane with the solar panel, reducing the area of reflection and flairs from the satellite body during the raising period. There are some challenges associated with this approach, including light reduction on the solar panels, which would reduce the operating power, reduction in antenna contact time, as the antenna facing earth for a shorter period of time, and satellite lifespan reduction due to higher fuel consumption [46], [68]. Along with the satellite orientation is to place the satellites closer to their final orbit on launch reducing the time spent in their raising period to reach the operational orbital height, reducing the amount of time in their most reflective position. The challenge with this is that it would be more expensive to raise the second stage of the rocket up higher by using the first stage for longer [69].

A report by C Walker at National Optical-Infrared Astronomy Research Laboratory (NOIR Lab) in 2020 suggests developing a software application to identify, model and mask the satellite trails to predict the satellite interference in astronomy imaging [53].

For example, an artifact detection and masking algorithm was proposed in [70] which relies on 1- a dataset containing several visits to the same part of the sky, 2- detailed modeling of the position variable point spread function (PSF) on single epoch images, 3- the production of PSF homogenized artifact-less images, 4- the image's model fitting catalogs, 5- the construction of position variable PSF convolved simulated images utilizing PSF models and the model fitting catalogs. Such methods can be adapted to detect objects that leave streaks using an algorithm to remove these streaks and artifacts. Using multiple images and interpolation to create an image that has no artifacts, this method can be applied to any survey that images the same section of the sky multiple times. This could be implemented and developed further to work with specific observatories to reduce the impact of brightness as more satellites enter orbit [71]. There are other algorithms that can be used alongside this method to improve the tracking and detection rate covering more potential objects that could leave streaks and artifacts in the imaging [62], [72], [73].

Another method for brightness mitigation is to develop software that plans and predicts the time and projection of the satellites' transit over the observatory so they can take images of the night sky when there are no satellites in transit in their desired area of the night sky for the duration of the exposure [53], [74]. This seems more promising as observatories can then see when they will have clear skies overhead to image the night sky. In addition to knowing when they have clear skies, it also depends on what type of imaging the observatory is performing and the required time to take the image. If a minimum timeframe for the exposure can be identified, the orbital spacing can be defined to ensure that there is a minimum window of time between each satellite passing through these selected orbital zones. However, having a minimum operating window would prevent longer exposures occurring without interference from these constellations.

Interruption of the observations can be another approach to brightness mitigation. If observations are required in the same region of the sky where the satellites are illuminated the exact time they cross the field of view, this can be computed, and the shutter can be closed during that time while the satellite passes over and then reopened to continue capturing data and won't appear in the final image. However, this approach is not practical for all observatories. For example, there would be too many interruptions for a large field of view telescope, due to the large area of the night sky it is imaging, more satellites would cross this zone, causing it to close its shutter more frequently, which in turn reduces its exposure time, reducing the amount of data collected in each image, making this approach less effective [47]. There are other measures such as satellite number minimization based on particle swarm optimizations (PSO) as reported in [16]. More information on the implementation of a PSO algorithm can be found in [75], [76]. Apart from PSO, other nature-based algorithms such as grey wolf optimization [77]–[79], ant colony optimization [80], [81], artificial neural networks [82]–[89], and genetic algorithms [90] can be adopted for the same purpose.

In summary, operators need to do their best to avoid specular reflections in the direction of observatories [48]. This is critical particularly for the observatories with larger field of view and can be implemented by adjusting the satellites to reduce specular reflections while transiting over observational areas. However, it will cost the satellite fuel every time it passes over to rotate the satellite to an angle to reduce the reflections and then return to its normal position, further reducing the satellite's lifespan.

Every day, more and more satellites are being put into LEO, as such, observation times will slowly decrease as the sky fills up with bright satellites. At this current time, there is little to no information on the reduction of observable time due to these satellites and it being a new emerging technology.

VII. CONCLUSION

One of the critical emerging challenges associated with the LEO satellite constellations is the unwanted brightness of these constellations visible from earth in the night sky. Such brightness interferes with astronomical viewing in many ways, potentially disrupting the observatories' function. The urgency for the LEO constellations brightness rectification was understood recently, and several technologies have been proposed and tested to mitigate this issue.

The future improvements have some promising methods that will also need improvement over time as new methods and technology are created to help with this new problem. Adjusting the satellite to have the satellite in-plane with the sun would be the easiest method to help reduce the reflectivity of the solar panel. The downside to this is that this uses up more fuel than normal [46], reducing the satellite lifespan and reducing the time the solar panel will be in direct sunlight and will change the orientation of the antenna, reducing the contact area with the ground stations.

Masking the trails, satellite planning, and imaging interruption will make moving the satellites to be in-plane with the sun unnecessary.

These two methods will help imaging directly, reducing the streaks and artifacts in both scenarios. The downside to masking the trails, is there will be more images required to cover the viewing area, making sure the combined images have no overlap of streaks that can be removed [53]. As well as this, these methods could lose valuable scientific data from losing data due to streak removal, or not being able to operate at specific times due to satellites flying overhead [74]. Satellite planning will dictate when the observatories can view the night sky and they might miss key events due to the satellites blocking the view. A way to mitigate this is to plan and work with the constellation companies to create a gap in the constellation for these events [74].

Interruption of the imaging process will be more viable for small field of view observatories as there will be less satellites crossing its viewing area compared to wide field of view observatories. As with the other two methods, there is a potential to lose data when interrupting the imaging and would lose more data compared to the other methods above as well as taking longer from all these interruptions and additional processing.

Apart from all modifications proposed or implemented on the satellite's configuration, mathematical modeling highly tailored for each major observatory to predict the brightness caused by each LEO constellation is another promising avenue to rectify this existing challenge.

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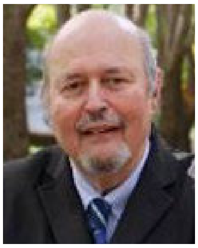
KARU P. ESSELLE (Fellow, IEEE) received the B.Sc. degree (Hons.) in electronic and telecommunication engineering from the University of Moratuwa, Sri Lanka, and the M.A.Sc. and Ph.D. degrees with near-perfect GPA in electrical engineering from the University of Ottawa, Canada.

Previously, he was the Director of the WiMed Research Centre and an Associate Dean—Higher Degree Research (HDR) of the Division of Information and Communication Sciences and directed the Centre for Collaboration in Electromagnetic and Antenna Engineering, Macquarie University, Sydney. He has also served as a member of the Dean's Advisory Council and the Division Executive and as the Head of the Department several times. He is currently a Director of Innovations for Humanity Pty, Ltd., the Distinguished Professor in electromagnetic and antenna engineering at the University of Technology Sydney, and a Visiting Professor at Macquarie University. According to the Special Report on Research published by *The Australian* national newspaper, he is the 2019 National Research Field Leader in Australia in both microelectronics and electromagnetisms fields. He has authored over 600 research publications and his papers have been cited ~12,000 times. In 2021, his publications received over 1,400 citations. His H-index is 52 and i-10 is 204. He is in the world's top 100,000 most-cited scientists list by Mendeley Data. Since 2002, his research team has been involved with research grants, contracts, and Ph.D. scholarships worth over 21 million dollars, including 15 Australian Research Council grants, without counting the 245 million-dollar SmartSat Corporative Research Centre, which started in 2019. His research has been supported by many national and international organizations including Australian Research Council, Intel, U.S. Air Force, Cisco Systems, Hewlett-Packard, Australian Department of Defence, Australian Department of industry, NSW Chief Scientist & Engineer Office, and German and Indian governments. He has provided expert assistance to more than a dozen companies including Intel, Hewlett Packard Laboratory (USA), Cisco Systems (USA), Audacy (USA), Cochlear, Optus, ResMed, and Katherine-Werke (Germany). His team designed the high-gain antenna system for the world's first entirely Ka-band CubeSat made by Audacy, USA, and launched to space by SpaceX in December 2018. This is believed to be the first Australian-designed high-gain antenna system launched to space, since CSIRO-designed antennas in Australia's own FedSat launched in 2002.

Dr. Esselle is a fellow of the Royal Society of New South Wales and Engineers Australia. His awards include Excellence Award—the most prestigious—2021 Australian Defence Industry Awards, the 2021 Academic of the Year Award, Finalist for 2021 Australian National Eureka Prize for Outstanding Mentor of Young Researchers, Runner-Up to the same prize in 2020, the 2019 Motohisa Kanda Award (from IEEE USA) for the most cited paper in IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY in the past five years, the 2021 IEEE Region 10 (Asia–Pacific) Outstanding Volunteer Award, the 2020 IEEE NSW Outstanding Volunteer Award, the 2019 Macquarie University Research Excellence Award for Innovative Technologies, the 2019 ARC Discovery International Award, the 2017 Excellence in Research Award from the Faculty of Science and Engineering, the 2017 Engineering Excellence Award for Best Innovation, the 2017 Highly Commended Research Excellence Award from Macquarie University, the 2017 Certificate of Recognition from IEEE Region 10, the 2016 and 2012 Engineering Excellence Awards for Best Published Paper from IESL NSW Chapter, the 2011 Outstanding Branch Counsellor Award from IEEE headquarters (USA), the 2009 Vice Chancellor's Award for Excellence in Higher Degree Research Supervision, and the 2004 Innovation Award for best invention disclosure. His mentees have been awarded many fellowships, awards, and prizes for their research achievements. Fifty-five international experts who examined the theses of his Ph.D. graduates ranked them in the top 5% or 10%. Two of his students were awarded Ph.D. with the highest honor at Macquarie University—the Vice Chancellor's Commendation, and one received University Medal for Master of Research. From 2018 to 2020, he chaired the prestigious Distinguished Lecturer Program Committee of the IEEE Antennas and Propagation (AP) Society—the premier global learned society dedicated for antennas and propagation—which has close to 10,000 members worldwide. After two stages in the selection process, he was also selected by this society as one of two candidates in the ballot for the 2019 President of the Society. Only three people from Asia or Pacific apparently have received this honor in the 68-year history of this society. He is one of the three Distinguished Lecturers (DL) selected by the society in 2016. He is the only Australian to chair the AP DL Program ever, the only Australian AP DL in almost two decades, and second Australian AP DL ever (after UTS Distinguished Visiting Professor Trevor Bird). He has served the IEEE AP Society Administrative Committee in several elected or ex-officio positions 2015–2020. He is a Track Chair of IEEE AP-S 2021 Singapore and AP-S 2020 Montreal, Technical Program Committee Co-Chair of ISAP 2015, APMC 2011 and TENCON 2013, and the Publicity Chair of ICEAA/IEEE APWC 2016, IWAT 2014, and APMC 2000. He is also the Chair of the Board of management of Australian Antenna Measurement Facility, and was the elected Chair of both IEEE New South Wales (NSW) and IEEE NSW AP/MTT Chapter, in 2016 and 2017. He is in the College of Expert Reviewers of the European Science Foundation (2019–2022) and he has been invited to serve as an international expert/research grant assessor by several other research funding bodies as well, including the European Research Council and funding agencies in Norway, Belgium, the Netherlands, Canada, Finland, Hong Kong, Georgia, South Africa, and Chile. He has been invited by the Vice-Chancellors of Australian and overseas universities to assess applications for promotion to professorial levels. He has also been invited to assess grant applications submitted to Australia's most prestigious schemes such as Australian Federation Fellowships and Australian Laureate Fellowships. In addition to the large number of invited conference speeches he has given, he has been an invited plenary/extended/keynote speaker of several IEEE and other conferences and workshops including GSENN2022, Copenhagen, Denmark; EuCAP 2020 Copenhagen, Denmark; EEEMEET 2022, Dubai; URSI'19, Seville, Spain; and 23rd ICECOM 2019, Dubrovnik, Croatia. He has served or is serving as an Associate Editor of IEEE TRANSACTIONS ON ANTENNAS PROPAGATION, *IEEE Antennas and Propagation Magazine*, and IEEE ACCESS. His research activities are posted in the web at http://web.science.mq.edu.au/~esselle/ and https://www.uts.edu.au/staff/karu.esselle.



SAM REISENFELD (Life Member, IEEE) received the B.S. degree in information engineering from the University of Illinois, in 1969, and the M.S. and Ph.D. degrees in communication systems engineering from UCLA, in 1972 and 1979, respectively.

From 1969 until 1988, he was a Space Communication System Engineer at the Hughes Air-Craft Company, Space and Communications Group, El Segundo, CA, USA. From 1988 until 2009, he was an Associate Professor of telecommunications engineering at the University of Technology Sydney, Australia. From 1988 until 1992, he was a Researcher in satellite communication technology at the Overseas Telecommunications Commission, Sydney. He was the Organizer of the IEEE GLOBECOM'98, Sydney. From 1997 until 2005, he was the Research Leader for Ka-band satellite technology at the Australian Cooperative Research Center for Satellite Systems. In 2009, he joined the School of Engineering at Macquarie University, where he currently is an Associate Professor of telecommunications engineering. His research interests include satellite communication systems, cognitive radio networks, digital signal processing, software defined radio, frequency estimation, direction of arrival estimation, and artificial intelligence.

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