Science summit for the G7 2026

S7 Academies joint statement

Large Satellite Constellations: Perspectives and Challenges

© Catalogued objects larger than 10 cm - NASA, 2022

Executive Summary

Large Satellite Constellations: Perspectives and Challenges

The rapid expansion of large satellite constellations, particularly in low Earth orbits (LEO), marks a turning point in humanity's relationship with near-Earth space. Propelled by the NewSpace era, characterised by private innovation, reusable launchers, and digital integration, tens of thousands of satellites are being deployed in LEO and medium-Earth orbits (MEO) to deliver global broadband access and real-time Earth observation. These advances promise transformative benefits for society, including universal Internet/communication coverage (there are about three billion people without coverage today), enhanced Internet/communication resilience, integration of communications and sensing, and, more generally, the potential for a space-based extension of the Internet.

Large constellations also pose unprecedented challenges and risks that need to be mitigated in the short term. (a) Reflected sunlight from satellites and radio emissions directed towards Earth are disrupting optical and radio astronomy. (b) The growing density of spacecraft is increasing the risk of collisions and debris generation, potentially rendering key orbital regions unusable. (c) The rising rate of rocket launches increases the risks of debris surviving re-entry and potentially causing injuries or damage to air traffic or on the ground. It also augments the injections of chemicals and particulates into the upper atmosphere, with consequences that are not well understood.

In view of the pace of evolution of the field, the promises of these constellations, and the nature of the risks, the S7 urges the G7 to:
(i) strengthen actions already under way, such as the definition and adoption of recommended practices, international standards, agreements between industry, space agencies and academic stakeholders;
(ii) create a governing body like the International Telecommunication Union, but with broader responsibilities covering not only frequency and orbit allocations, but also taking into account traffic management, orbital carrying capacity, environmental and astronomical impact;
(iii) based on (i) and (ii), let an international treaty emerge on these questions as a common framework for consolidating the advances brought and addressing the issues raised by these constellations.

The steps (i)-(iii) constitute the framework for the following seven recommendations:

1. Strengthen research, development and uncertainty quantification to take full advantage of the benefits of satellite constellations;
2. Improve space traffic management by enforcing de-orbiting and debris-mitigation standards and advance orbital carrying capacity assessment methods as a basis for licensing;
3. Protect astronomical observations from disruptive consequences through design innovation and regulation, and assure that Earth observation satellites will be able to pursue their mission with minimal interference;
4. Assess and minimize impact on atmospheric environment;
5. Implement new, more informed and fair allocation schemes for finite orbital and frequency resource management;
6. Extend to the future space-based Internet the principles of universality, transparency and equitable participation of the current terrestrial Internet;
7. Promote all actions already under way for addressing these issues and establish an intergovernmental panel providing policy makers with regular assessments of space sustainability.

The future of near-Earth space and its ability to serve humanity depend on the swift engagement of actions on the international level along these lines.

Statement

Large Satellite Constellations: Perspectives and Challenges

The acceleration of satellite deployments in the NewSpace era marks a radical transformation in global space activities. It is characterised by the growing role of private companies alongside governmental agencies, the development of disruptive business models, the design and exploitation of reusable launchers, new satellite platforms, and integration with digital networks and economy. NewSpace is defined by rapid innovation cycles, reduced launch costs, and ambitious large-scale projects. This statement is concerned with the rapid development of new low-Earth orbit (LEO, 350-2,000 km altitude) and to a lesser extent medium-Earth orbit (MEO, 2,000-25,000 km altitude) satellite constellations. The prospects for broadband communications are of about 80,000 satellites over the next 10 years, an already sizable number compared to the present situation, that would be notably exceeded by a recently announced project of orbit-based data centers with AI at an alarming scale of a million-satellite constellation.

Satellite constellations bring new opportunities and benefits for society and the economy, such as potential Internet access to the large fraction of unconnected people, but also raise significant risks for the Earth's environment, human safety and activities. These risks depend not only on the number and distribution of objects in space, but also on uncertainty in our ability to observe, estimate, and predict their states and interactions over time. The number of planned or operational satellites was several tens of thousands per constellation before the recent announcements of orbit-based data centers.

These trends in the use of space give rise to many opportunities in science and technology but also raise technical and operational difficulties and some major challenges in:

- Communications: broadband coverage, low latency, inter-satellite transmissions, cybersecurity, resilience, space-based Internet;
- Space Science and Technologies: constellation management, reusable launchers, miniaturised payloads, plasma thrusters for altitude and orbit control, collision avoidance, tracking, space debris, etc.;
- Astronomy: the negative impact of constellations on optical and radio observatories degrading observations and potentially preventing discoveries;
- Earth Environment: negative impact of the increasing frequency of launches and re-entries on upper-atmosphere chemistry, augmenting the density of satellites and debris in LEO/MEO, inducing hazards from debris surviving atmospheric re-entry.

These opportunities and challenges are analyzed below and followed by a set of recommendations.

Communications

Progress in space communications has enabled universal broadband coverage, offering an opportunity for connecting about three billion people without cellular and Internet access today, and opening prospects for a future space-based Internet. Current networks such as Starlink, One-Web, Amazon LEO, and China's Guowang, already comprise several thousand satellites, with many more announced for the near future. These satellites, deployed in LEO and MEO orbits, offer broadband coverage to ships, planes, and people in isolated areas, with reduced latency compared to geostationary (36,000 km) satellites that remain fixed relative to the Earth's surface. These networks are based on inter-satellite data relaying, on-board data processing, and in some cases host a combination of observation and communication functions. Although their global capacity (aggregate bit rate) is much lower than that of terrestrial networks, they will surpass the latter on long-distance end-to-end latency and resilience. Some early successful uses of on-board AI have been recently reported, as have the first quantum communications via quantum key distribution. The rapidly evolving state of the art prefigures a spatial Internet that will in the future complement and enrich the terrestrial Internet we know today. The benefits already brought by these constellations and the associated perspectives are therefore remarkable, but their development raises major issues. One of them is the limited amount of spectrum resources, a well-known problem within this context to which the general principles listed in the recommendations should prevail. Another is the technical feasibility (energy requirements, cooling, collision avoidance, space traffic management) of extremely large constellations meant for data centers that is lacking scientific backing at this stage.

Space Science and Technologies

Satellite constellations leverage multiple scientific and technological advances in this field, including on-board computing/data handling capabilities alongside supporting complex ground station operations. Injecting a large number of satellites into orbit is made possible by the notable cost reduction of access to space, the miniaturisation of spacecraft platforms allowing multiple payloads on a single launcher, the development of reusable rocket first stages, and innovative on-board plasma thrusters for spacecraft orbit control. New functionalities, namely broadband communications, Earth observation, global geopositioning, and time distribution lead to the development of a highly diversified range of new types of satellites and services.

This has induced a need for new surveillance and tracking systems to maintain and update the ephemerides of satellites and catalogued debris, calculate collision probabilities, and to provide timely information to operators to implement avoidance measures. With the increasing number of constellations belonging to different countries, the growing satellite population and the additional debris it generates, LEO and MEO orbital management has become more complex. The number of manoeuvres required for avoiding collisions is already quite high (for example more than one hundred thousand in a single year of Starlink operation), and will increase further when and if larger- scale satellite constellation will be deployed. Collision avoidance maneuver rate and propellant expenditure should be treated as quantitative indicators of congestion and operational stress within an orbital shell. Information on satellite positions, brightness and demise data should be made publicly available so as to ensure that policy makers and public safety officials are able to make data-driven decisions.

Astronomy

The rapid expansion of constellations in recent years has an increasingly negative impact on optical and radio astronomy. In the optical domain, the reflection of sunlight by satellites produces streaks that contaminate telescopic images of the night sky. This has a significant impact on sky surveys with large-field-of-view instruments, in particular those searching for transient phenomena. Simulations show that with 48,000 satellites, up to 2,000 could be visible at twilight from the Atacama Desert in Chile (the home of ESO's Very Large and Extremely Large Telescopes and of the soon to be fully operational Vera Rubin wide-field telescope), with several hundred bright enough to be seen by the unaided human eye. For a million-satellite constellation, in the absence of substantial mitigations, about thousand satellites will be visible by human eye: the sky in the optical would be greatly altered. It is worth noting that even LEO space observatories begin to be affected by constellations. Radioastronomy is also disturbed, 24 hours a day, through interference from downlink transmissions and on-board electronics, threatening highly sensitive observations of radio sources and fundamental cosmological surveys. Some progress in mitigating this impact has already occurred thanks to local radio sanctuaries (requiring no signal transmission towards a terrestrial observatory when it is in sight). This procedure, which is voluntarily accepted by some operators, greatly reduces the impact on radio observatories. Unfortunately, even operators that adhere to this protocol do not fully mitigate their impact as unintended electromagnetic radiation emitted by satellite electronics at low frequencies produces additional disturbances for extremely sensitive radio astronomical observations. This situation may still dramatically degrade in a close future if million scale constellations are deployed.

Earth Environment and Chemistry

The major concerns in this domain are the proliferation of debris and the consequent enhanced spatial density of orbital shells together with the hazards on the ground created by falling debris. More than 28,000 objects larger than 10 cm are currently tracked, while there are hundreds of thousands of smaller fragments with no custody information. Last year's projections suggest the addition of up to 80,000 more satellites in LEO/MEO orbits within the next decade. This increases the risk of collisions with other active satellites, spacecrafts that have not been de-orbited at the end of their lives, and debris, and the complexity of automatic collision-avoidance systems should then be implemented in new LEO satellites, making them significantly more complex. For orbits at altitudes below 600 km, satellite removal on timescales of months to years (depending on altitude and solar activity) occurs due to atmospheric drag and will naturally remove debris from orbit and prevent their long-term accumulation. This cleaning is less effective at altitudes above 600 km because it takes much longer for objects to de-orbit from drag.

It is notable that some constellations (i.e., Starlink) build into their operational plans demise as a standard practice and replenishment through continual launches. In addition to responsible deorbiting of end-of-life satellites, there are new companies proposing active removal of defunct (non-operational) satellites and debris – although the feasibility and economics of such services remain to be assessed. The possible occurrence of cascading collisions (known as the Kessler syndrome) might render some LEO and MEO orbital regions unusable. In view of the accelerating pace of launches and the expanding number of large constellations, it is urgent to consider the orbital carrying capacity as a unifying concept for assessing sustainability in LEO and MEO. Orbital carrying capacity should be defined as a composite, consequence-based index describing the maximum sustainable operational load of an orbital region. It is reached when the coupled system of spacecraft, debris, operators, and tracking knowledge can no longer support safe and reliable operations with acceptable maneuver burden, collision risk and service continuity. Capacity saturation manifests through measurable indicators such as rapidly increasing avoidance maneuvers, conjunction alert overload, growing divergence between independent tracking catalogs and forecasts, restricted access to certain orbital shells for science or missions, and degradation of space-based services. Orbital carrying capacity therefore depends not only on object counts, but also on knowledge uncertainty. This will enable the identification of thresholds beyond which an orbital region can no longer reliably support safe, economically viable, and unimpeded operations. It could also provide a technical basis for more defensible licensing criteria, altitude-specific stewardship regimes, and active congestion management strategies.

The increase of launches also leads to greater depositions of chemicals in the atmosphere. This occurs during launch (black carbon and other combustion products) and in rocket stages and satellite re-entries (Lithium, Aluminum, Titanium). These chemicals accumulate in the mesosphere and stratosphere. Their impact on the upper atmospheric chemistry and more specifically on the ozone layer needs to be carefully assessed. Furthermore, satellite re-entries (currently exceeding several occurrences per day) increase the hazard to humans and infrastructures.

The S7 urges the G7 to consider the 7 recommendations below :

1. **To take full advantage of the benefits of satellite constellations** (Internet access to the large fraction of unconnected people on Earth, faster, more resilient, and more secure transmissions, new real-time Earth observation and monitoring capabilities, joint communication and sensing, edge computing, AI, and quantum communications...), **research and development on non-terrestrial networks should be strongly supported**.

These remarkable advances will only materialise and endure if the major negative impacts and risks listed in this document are collectively addressed. The next set of recommendations therefore pertains to these risks.

2. **Scientific evaluation of the orbital carrying capacity of LEO and MEO resources needs to be strengthened** to address the major risks induced by the rapidly increasing number of satellites. The rights to use and access orbital regions should be regulated in function of this capacity assessment, with an explicit recognition of our current incomplete knowledge on this matter. To prevent cascading collisions, it will be essential to make sure that satellites are de-orbited at the end of their lives and that tracking and collision-avoidance mechanisms are reinforced. It will be important to strengthen uncertainty quantification requirements in space traffic management, debris modeling, and constellation licensing.
3. Astronomy is and will be confronted to major the impact of current large satellite constellations on astronomical observations and taking into account plans for future constellations. **The impact of satellites should be reduced by innovative design. This should be implemented on a global scale through an international regulation protecting astronomy from disruptive consequences**. Remote sensing from space-based platforms in charge of Earth observation programs should also be protected.
4. The significant increase of rocket launches and the augmented number of satellite re-entries **require a quantitative evaluation of the upper atmosphere chemistry impact and its minimization**. Similarly, their impact on the Earth's global radiative balance and the increased risk of injuries or damages due to surviving components reaching the ground should be assessed.

The final set of recommendations pertains to matters of principle:

5. Orbital and frequency resources are a common good of humanity and are fundamentally limited. **New, more informed, and fair allocation schemes are clearly needed in the short term**.
6. In the longer term, **the principles of universality, transparency and equitable participation of the current terrestrial Internet should be extended to the future space-based Internet** alluded to in this statement, which is compatible with a dual commercial and governmental use.
7. Actions already under way, such as the **definition and adoption of recommended practices, international standards, agreements between industry, space agencies and academic stakeholders** need to be promoted and strengthened. In order to ensure global sustainability, it is timely to establish (i) a permanent **governing body** like the International Telecommunication Union but with broader responsibilities covering not only frequency and orbit allocations but also taking into account traffic management considerations, environmental and astronomical impact; (ii) an **intergovernmental panel** focusing on these issues to provide policy makers with regular scientific assessments on the current state of knowledge and changes in the space environment. This framework should be used to let an **international treaty** emerge in order to consolidate the advances made and address the issues raised by these constellations.

Scientific background

Large Satellite Constellations: Perspectives and Challenges

1. Introduction

This document serves as a gateway between the Statement entitled "Large Satellite Constellations : Perspectives and Challenges" initiated in 2025 by the Academie des Sciences[1] and other related documents, in particular the 2024 report entitled "Large Satellite Constellations: Challenges and Impact"[2], on which the Statement in question is partly based. It also includes contributions from the seven academies, relies on a limited number of selected references and makes no attempt at being exhaustive.

The structure of the document is the following. Section 2 briefly describes the organization and functionalities of large satellite constellations, with a focus on those designed for broadband communications. Section 3 then complements the perspectives and challenges discussed in the Statement. It is organized in four subsections, one for each of the scientific and technological domains that are directly linked to or impacted by these constellations, *i.e.*, Space Science and Technologies, Communications, Astronomy, Earth Environment and Atmospheric Chemistry. Recent documents that deal with relevant issues are discussed in each of these subsections. Section 4 concludes the document by recalling the recommendations of the Statement.

2. Satellite Constellation-Based Communication Networks

Several large satellite constellations have been or are being designed to provide global broadband communications coverage and Earth observation, in addition to those already in use for geo-positioning. These constellations operate in different orbital regimes: LEO (Low Earth Orbit), which spans 350-2,000 km with ~100-minute orbital periods, ideal for broadband connectivity and Earth observation; MEO (Medium Earth Orbit) which ranges from 2,000-36,000 km, with orbital periods of a few hours, often used for navigation systems like Galileo; and GEO (Geostationary Orbit), at an altitude of 36,000 km in the equatorial plane, where satellites remain fixed relative to Earth. Such constellations are best described by Walker's Classification[18].

In its simplest version this classification features circular orbits, all with equal altitudes, satellites in the same orbit with a periodic arrangement, and a periodic arrangement of orbits.

There are two variants, the Walker Delta and the Walker Star. These, together with the organization of broadband access in the case with communications between satellites is depicted in Figure 1.

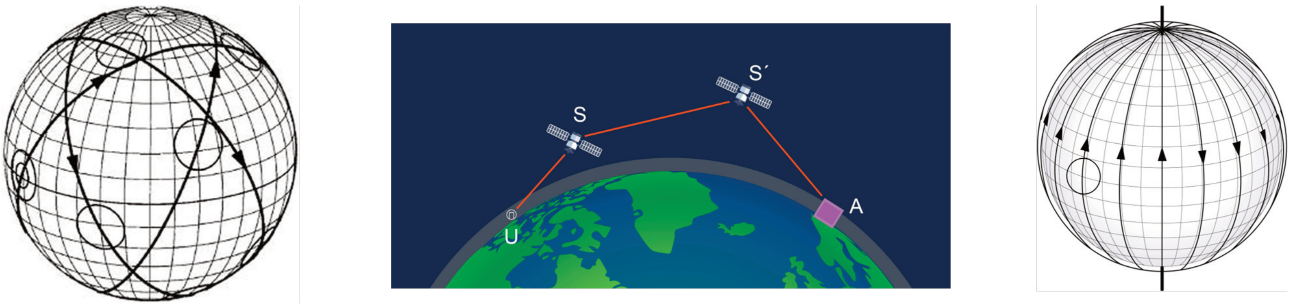

Figure 1: Left: Walker Delta, basis of Starlink and Galileo. all orbital planes have the same inclination; the ascending points are arranged periodically over 360o of the equator. Right: Walker Star, basis of Oneweb orbital inclinations are 90o (quasi-polar); ascending points are arranged periodically on 180o of the equator. Center: U: end user, S: satellite, A: anchor station. Examples of S-U and S-A links: Ku (10.7-14.5 GHz), Ka (17.3-30 GHz) and V (37-50.4 GHz) bands and 5G. Example of links between satellites: Laser.

Satellite constellations are transforming communications by providing high-speed, low-latency connectivity that extends broadband access to even the most remote regions. Prominent examples include SpaceX's Starlink, OneWeb, Amazon's Kuiper, and China's Guowang. Each of these operates or will operate thousands of satellites in LEO and MEO orbits. LEO satellites are particularly advantageous for communications because their proximity to the Earth reduces signal travel time, or latency, compared to satellites in higher orbits. While traditional geostationary satellites orbit at around 35,786 kilometers and experience latencies of about 500 milliseconds, LEO systems can achieve latencies of the order of a few tens of milliseconds, enabling near real-time applications.

These satellite networks transmit data using high-frequency radio bands, specifically the Ku, Ka, and V bands. These bands refer to ranges of the electromagnetic spectrum that are well-suited for high-speed data transfer. The Ku band operates roughly between 12 and 18 gigahertz (GHz), the Ka band between 26 and 40 GHz, and the V band between 40 and 75 GHz. Higher frequency bands can carry more data at faster speeds but require more precise signal alignment and are more sensitive to atmospheric conditions, such as rain or clouds.

Modern constellations often integrate laser intersatellite links, which use optical communication instead of radio waves to transmit data directly between satellites at the speed of light. This not only increases bandwidth but also reduces reliance on ground stations, enabling more resilient and flexible network architectures. Laser links from space to ground and ground to space begin to appear but require clear sky and methods to overcome effects of atmospheric turbulence. A demonstration of secure optical communication over several thousand kilometers through quantum key distribution has been demonstrated in China a few years ago[9].

3. Scientific Perspectives and Challenges

3.1. Space Science and Technologies

Satellite constellations leverage multiple scientific and technological advances in space science. Injecting a large number of satellites into orbit is made possible by the notable cost reduction of access to space, the miniaturisation of spacecraft platforms allowing the multiplication of payloads on a single launcher, the exploitation of reusable rocket first stages, innovative on-board plasma thrusters for spacecraft attitude and orbit control. New satellite functionalities, namely broadband communications, Earth observation, global positioning, and time distribution lead to the development of a highly diversified range of new types of satellites.

Figure 2 presents the spectacular growth of the number of satellites and of catalogued objects in Earth orbit over the last 25 years. Whereas the number of satellites above the 2,000 km altitude counts is only a few hundreds, the situation is vastly different at lower altitudes. The Space X Starlink mega constellation (around 500 km altitude) already encompasses more than 10,000 satellites with an authorization for 42,000. The OneWeb/Eutelsat company has deployed 640 satellites around 1,200 km. China SatNet is planning to launch about 13,000 LEO communication satellites. According to ESO, up to 100,000 LEO satellites could be launched into low-Earth orbit over the next decade. According to a 2025 estimate [4], this number could be of 560,000 satellites, but will be completed by the 1 million satellites project. Even if all these projects are not guaranteed to reach full completion, assuming that the plans of the two or three most advanced companies in this field are effectively carried out, a minimum of nearly 80,000 satellites could be present in 2035 at various altitudes between 328 and 1,325 km.

A crucial element in this respect is the satellite lifetime in orbit. Low altitude satellites (less than 500 km) experience the residual drag of the atmosphere, limiting their presence in orbit to a few years in the absence of residual propulsion systems. If a satellite becomes inoperable, it will fall down and burn into the upper atmosphere. On the contrary, above 1,000 km, the air drag becomes negligible, and a satellite will remain in orbit, if no de-orbiting action is taken, for more than a thousand years, considerably longer than the typical satellite operational lifetime of 7 to 10 years. On Figure 2, one should also note the broad peak around 800 kms, which contains a large fraction of catalogued long-lived Earth orbiting debris. This satellite and debris density is

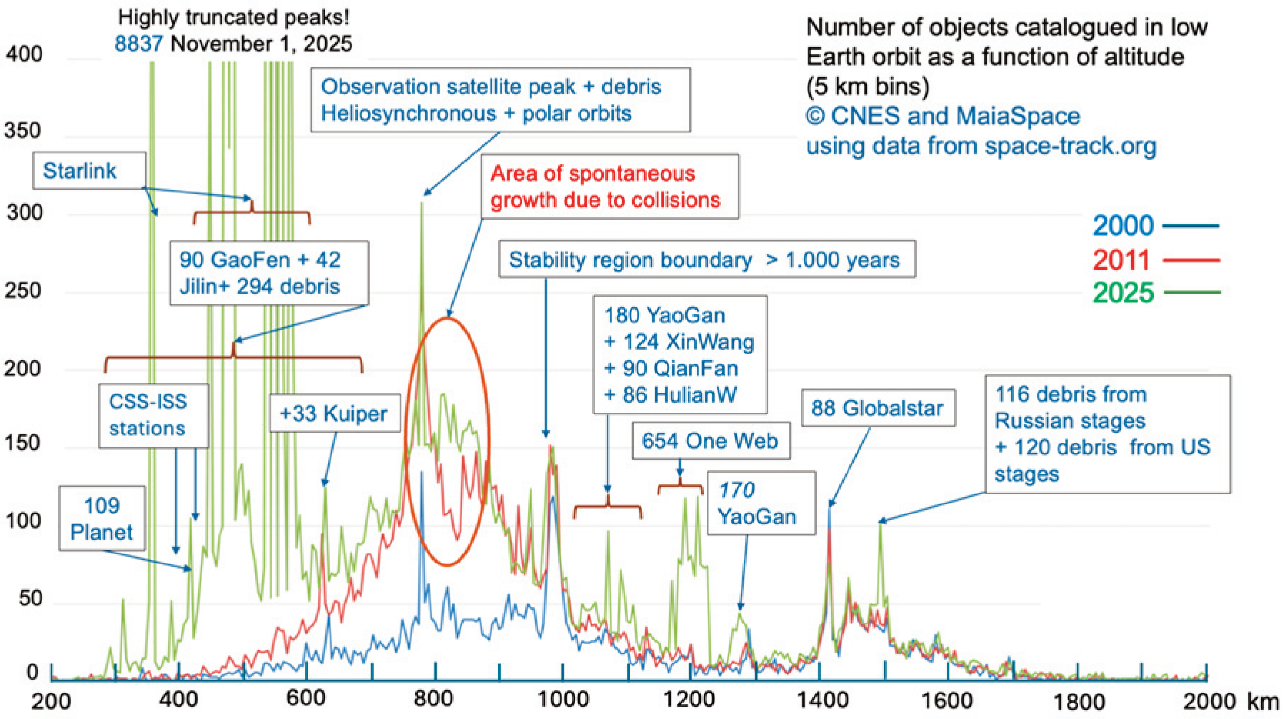

Figure 2 - Evolution over time of orbital population: number of LEO catalogued objects in function of altitude, based on space-track.org data. Courtesy of C. Bonnal[23].

clearly raising some important questions associated with collision avoidance, debris management and pollution of the upper atmosphere. In a recent communication, Starlink has already reported over 144,000 maneuvers between December 2024 and May 2025 for minimising the collision risk of their satellites. So far, no Star link satellite has experienced a collision but the probability for such an event is growing fast. With an increasing number of large constellations belonging to different operators in different countries, and a growing number of satellites and debris in each of these constellations, the orbital management of LEO and MEO becomes more complex. It is therefore clear that some sort of global platform linking operators will be needed to deal with collision avoidance issues.

Avoiding collision between satellites also bears a cost as it needs on-board energy and propulsion systems. Too frequent maneuvers will reduce the profitability of these large constellations. Collisions between two satellites have already taken place. In 2009, a collision between an active US satellite and a dead Russian satellite generated over 1000 trackable debris staying in orbit. As some of these debris may in turn collide with other satellites and produce even more debris, an avalanche phenomenon could take place, rendering space unusable in a process first identified as early as 1978 and designated as « Kessler's syndrome »[8]. Predicting when and under which conditions such a phenomenon will take place is a complex task. Considering the huge growth of the number of LEO satellites during the next decade, further research should be dedicated to this problem. New surveillance and tracking systems are also needed, to maintain and update the ephemeris of satellites and catalogued debris, calculate collision probabilities, and for timely information of operators to implement avoidance. Sustainable operation also requires international adherence to debris mitigation policies and satellite deorbiting. Reentry issues and chemical pollution of higher atmosphere are considered later on (Section 3.4).

3.2. Communications

LEO and MEO satellite constellations offer or will offer an unprecedented opportunity to provide phone and Internet access to the large fraction of unconnected people on Earth. To those already connected, they also provide or will provide faster, more resilient, and more secure communications, as well as new real-time Earth observation and monitoring capabilities. Currently these constellations mainly offer communications services; in the future, they will also allow joint communication and sensing, quantum cryptography, edge computing, and more.

Interplay between Constellation-based and Terrestrial Networks .The convergence of terrestrial mobile networks and satellite constellations is planned within the 6G framework. This concept envisions a hybrid network that merges cellular terrestrial infrastructure with LEO satellite networks to provide seamless connectivity anywhere on Earth. By combining terrestrial and orbital resources, this architecture will enhance resilience, which refers to the ability to maintain service under challenging conditions, such as natural disasters, warfare or infrastructure outages and will ensure real-time coverage and reliable communication in areas lacking terrestrial network coverage, such as polar regions, deserts, oceans, as well as so called white zones.

The Cybersecurity Challenge. As satellite communications expand, cybersecurity and system resilience become critical concerns. Cybersecurity refers to the protection of networks, devices, and data from unauthorized access, attacks, or disruption. Satellite systems are vulnerable to a variety of threats, including network intrusions, signal jamming, and malware attacks. A notable incident occurred in 2022, when the Viasat network intrusion disrupted satellite internet services, highlighting the potential vulnerabilities in global satellite communications. To address these risks, regulatory frameworks have emerged. For example, the European NIS2 Directive establishes security standards for information systems, including satellite networks, while similar initiatives in the United States aim to enforce robust protections and operational protocols for critical communications infrastructure. Strategic independence and secure communications are geopolitical priorities. The European Union's IRIS2 project, which is designed to provide encrypted communication services for governments, critical infrastructure, and public safety applications, exemplifies this approach.

Towards a Spatial Internet. An interesting longer-term perspective is that of moving some of the computing and storage functions to these constellations, following on from the idea of localizing edge computing in the satellites fleet. This reduces latency and can hence be useful in the context of real-time applications[6]. Along these lines, one can foresee the development of a spatial Internet which will combine a space-based routing infrastructure, on-board computing (particularly for signal processing and real-time services) and will combine communication and observation functions. However, the difficulties remain sizable. There are, on one hand, limitations defined by the average power that can be extracted per unit area of solar panels, and on the other hand, the problem of dissipating the heat produced by the calculators on board. First instances of this spatial Internet have been reported lately, like the use of embarked AI for on board treatment of data or the satellite-based distribution of quantum keys[9, 16].

3.3. Astronomy

The rapid growth of satellite constellations poses significant challenges to modern astronomy, both in the optical and radio domains. Optical astronomy is the study through observation of light emitted or reflected by celestial objects from the far UV to the far infrared[24], from close objects in the solar system to very distant stars and galaxies.

Large-scale observatories such as the European Southern Observatory Very Large Telescope (VLT) and the upcoming Extremely Large Telescope or the Vera Rubin Observatory, all in Chile, are particularly sensitive to artificial light sources. As thousands of satellites are launched into Low Earth Orbit (LEO), their reflective surfaces can catch sunlight during dawn and dusk, producing bright trails across the night sky. At the time of the report, expectations were that as many as 2,000 illuminated satellites could become visible simultaneously, leaving streaks in long-exposure images and contaminating deep-sky surveys.

Example of satellite streaks across the Orion nebula in December 2019 (credit : A. H. Abolfath). https://www.universetoday.com/161932/astronomers-have-figured-out-clever- tricks-to-reduce-the-impact-of-satellite- trails/.

This number will increase with the increasing number of satellite constellations. The streaks degrade the quality of astronomical data by adding noise and biases, some of which can be addressed by post-processing techniques but will damage a large fraction of the data even leading to the loss of time-varying phenomena. This will mostly affect wide-field observations but recent investigations show that spectroscopic observations will be affected as well, although with a much smaller probability of occurrence. In all cases, it is important that the visual magnitude of satellites be less than 7 as requested by the International Astronomical Union[19]. However, prospects are worse if one considers the total number of satellites of planned or in-project constellations with 96% of telescopes images being at threat with this scenario[4], including those originating from space telescopes.

Radio astronomy faces similar challenges from artificial signals, but because of a different process than for optical astronomy: radio observatories are affected by the emission of radio waves by satellite constellations. A big difference is that it is independent of the location of the Sun and therefore affects radio observatories 24 hours a day. Some bands are protected for radio astronomy by the International Telecommunication Union but this is insufficient for modern astronomy as sources are observed closer and closer to Big Bang. The detection bands are shifted by the Doppler effect due to the expansion of Universe to lower and lower frequencies which are not all protected. The overlap between the signals from the astronomical sources and the radio waves emitted by satellites is called radio-frequency interference (RFI) which causes extra noise and biases that can overwhelm the faint cosmic signals that astronomers seek to measure. Observatories such as the Institut de Radio Astronomie Millimétrique (IRAM) in France and Spain or the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile or the Square Kilometer Array (SKA), currently under construction in Australia and South Africa, although they are built in protected areas are or will be affected by these RFIs coming from the sky. The Low-Frequency Array (LOFAR) has even detected radio waves emitted by the electronics of satellites outside the classical ITU-approved Ku, Ka, and V bands. Although, as in the optical domain, signal processing will be used to soften the impact of constellations to reduce satellite-induced noise and biases from observational data, radio-quiet zones are required to protect observatories. The NSF and Starlink signed an agreement in 2023 to achieve this goal for USA radio observatories. It is a very good starting point that should be extended to observatories outside the USA and for other satellite operators. What is at stake is the ability for very sensitive modern observatories with strong survey and wide-field capabilities to operate as planned and at very high sensitivity.

More than ever, international collaboration is essential to address all these challenges. Organizations such as the International Astronomical Union (IAU) Centre for the Protection of the Dark and Quiet Sky (CPS) and the Committee on Radio Astronomy Frequencies (CRAF) advocate for policies that reduce the brightness and emissions of satellites. The astronomical community and some members of the satellite industry and operator communities work together at the CPS leading to first important results that help mitigating the impact of satellite constellations on astronomy (among solutions darker coatings for satellites to minimize reflected sunlight, design of smaller reflective surfaces, orbital altitudes below 550 kilometers to minimize the time of Sun reflection, radio quiet zones, etc.). The United Nations COPUOS (Committee on the Peaceful Uses of Outer Space) has agreed to point this matter on the agenda of its meetings for five years starting in 2024 which led to the creation of a Group of Friends[20] where the IAU and some observatories collaborate with diplomats and satellite industry and operators' representatives. This is going in the right direction and must be encouraged to share good practices and reach agreements between stakeholders with the aim to balance the benefits of satellite constellations, such as global communications and Earth observation, with the preservation of the night sky for scientific research.

3.4. Earth Environment and Chemistry

Today there are about 15,000 satellites in orbit, of which around 50% have been launched in the last five years. This number is expected to grow and reach a hundred thousand or more during the next decade. This leads in turn to an increase in the number of operational end of life satellite and upper-stage re-entries into the Earth atmosphere. The multiplication of launches (see Fig. 3) results in an increase in the amounts of debris in orbit. The growth in the use of space has a direct impact on the upper atmosphere as underlined in recent reports by JASON[7] and by the GAO (Government Accountability Office, the auditing body of the US Congress)[17] which highlight the environmental issues raised by the growing number of launches, the establishment of constellations, the growth in the amounts of debris on the one hand, and the re-entry of satellites and debris into the upper atmosphere on the other hand. Rocket launches release exhaust products into the stratosphere, the layer of the atmosphere located between 10 to 50 kilometers above the Earth's surface where the residence times of gaseous molecules and solid particles are large. The total quantities of water vapor and carbon dioxide from launches (259 launches in 2024, see Fig. 3 [15]) are notably lower than the sum of emissions from civil aviation flights[2,17] but are being partially emitted into higher atmospheric layers.

However, in addition to carbon dioxide and water vapor, rockets release chlorinated compounds and large amounts of solid particles including aluminum oxides, and soot particles designated as black carbon (BC). BC particles are formed by incomplete combustion in the fuel-rich reactive environments typically found in rocket engine thrust chambers, in proportions that are much higher than those generated by aircraft engine combustors, in which the oxidizer is in excess. This high fraction of BC from launchers and the multiplication of launches mean that soot particles have an impact that needs to be considered[10]. This is also the case for aluminum particles which, by reflecting incident solar radiation, have a cooling effect but can also absorb terrestrial radiation emitted towards space from the ground. As launcher emissions take place in the upper atmosphere and particularly above the tropopause, where molecules and particles residence times are significant, these chemicals and aerosols can accumulate over many years. This modifica-

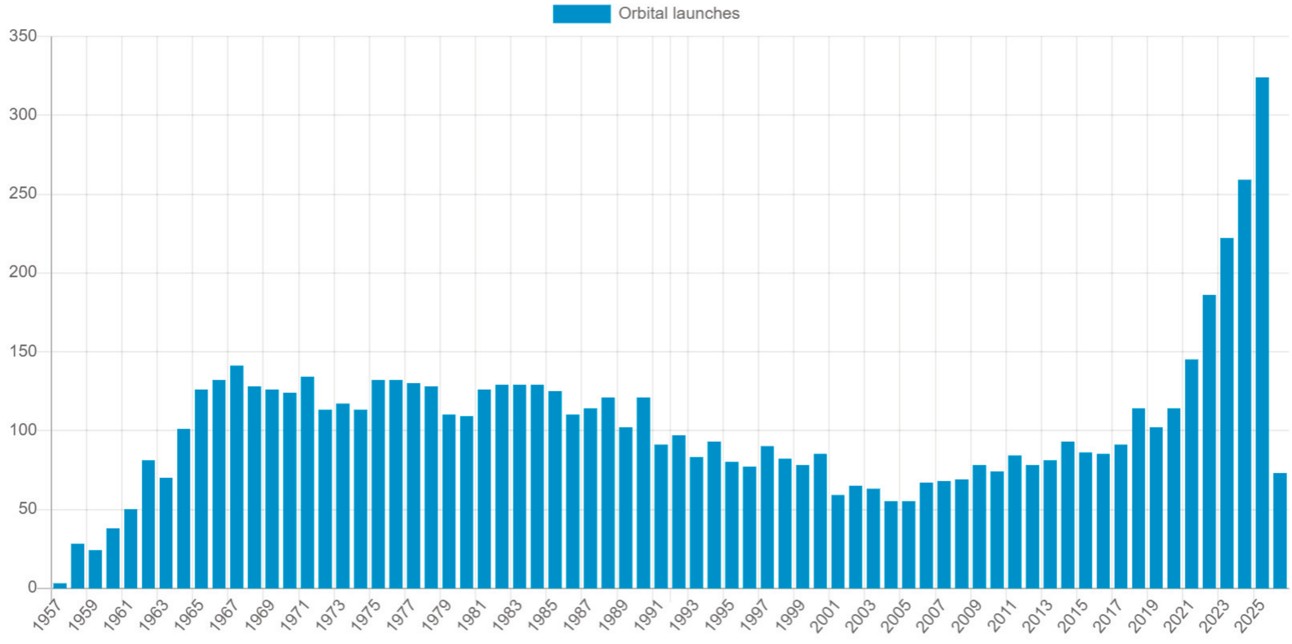

Figure 3 - Total number of rocket launches to reach Earth orbit[15]

tion of chemical composition could interact with the ozone layer, reducing ozone concentration by inducing chemical reactions or creating sites favoring the ozone decomposition reaction[11].

Another item that needs to be considered is that large satellite constellations can significantly interfere with passive microwave Earth observations. Because these observations rely on detecting extremely weak natural emissions from the Earth and its atmosphere, even small levels of additional human-made noise can degrade data quality for important Earth environmental observations[21].

3.4.1. Space Debris

Space debris correspond to any non-functional space object of human origin, including fragments in Earth orbit or re-entering the atmosphere. The proliferation of space debris is of particular concern. There are already in Earth orbit, ten thousand tons of debris, 28,000 objects over 10 centimeters in size, half a million marble-sized pieces of debris, one hundred million measuring about one millimeter. The United States Strategic Command (STRATCOM) maintains a catalogue of some 15,000 objects (over 10 cm in low Earth orbit and over 1 m in geostationary orbit). The debris originate from a variety of sources, including satellite destruction tests, satellite explosions and satellite collisions (like that of Iridium with Kosmos-2251 on February 10, 2009), all creating thousands of new pieces of space debris. With the densification of certain orbits, emergency maneuvers to avoid collisions are now commonly executed by constellation operators. This requires that satellites be equipped with operational propulsion systems, and that centralized Space Surveillance and Tracking systems be developed. The latter's functions are to maintain and update the satellite orbital locations and catalogued debris, calculate collision probabilities, and inform operators in good time so that they can implement avoidance measures. With the growing number of satellites and debris in low and medium Earth orbits (see Figure 4), space traffic management (STM) has become a highly complex task[3]. This last reference also contains a comprehensive review of the many dimensions of space traffic management and makes recommendations for promoting safe access to outer space, operations in outer space and return to Earth.

3.4.2. Re-entries and Atmospheric Chemistry

Satellite and debris re-entries, whether intentional, such as controlled deorbiting, naturally occurring or accidental—also produce a variety of chemical compounds and particulate matter that accumulate in the upper atmosphere. During reentry,

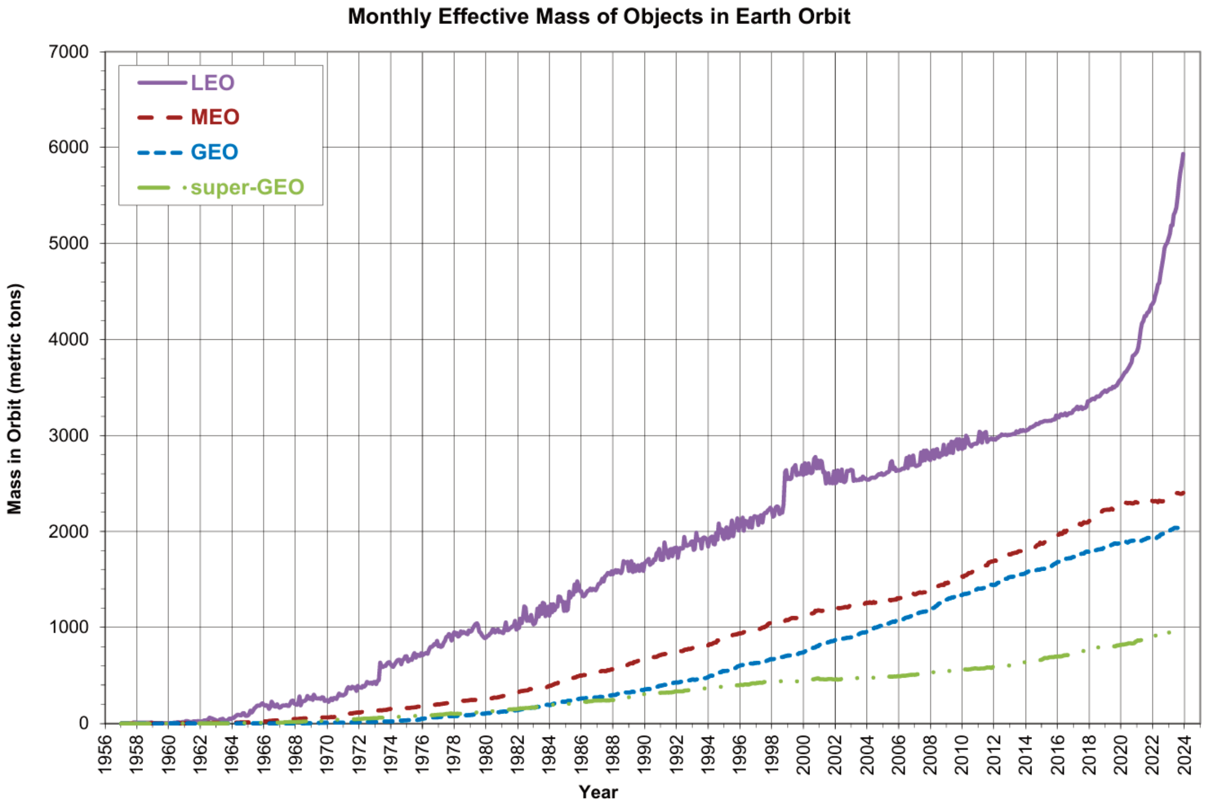

Figure 4: Monthly effective mass of objects in Earth orbit showing the fast growth associated with LEO and MEO constellation [12]

satellite and launcher upper stages are subjected to extreme heating, high temperature oxidation releasing metallic oxides of aluminum, lithium, silicon and other metals that are present in the spacecraft structures and components. These particulates accumulate in the upper atmosphere and are transported mainly into the polar winter stratosphere where they have already been observed[22]. Studies indicate that between 10 to 40 percent of these materials can survive atmospheric entry, eventually reaching the lower atmosphere or even the Earth's surface, contributing to trace metal deposition in soils and water systems and potentially harming populations in case of uncontrolled atmospheric entry. For the year 2022, there were about 2400 objects re-entering the atmosphere with a total mass of 340 t. It is interesting to compare this figure with that of the mass of meteorites that enter the Earth's atmosphere, which is estimated to be of the order of 15,000 to 20,000 t per year. The mass re-entering the atmosphere was only 1.7% of the naturally incoming mass[14].

However, the current rate of launches is augmenting the mass in orbit, see Fig. 4, essentially in LEO, at a much faster pace which now reaches about 1600 t/yr[12], a figure that would be doubled or more in the near future if planned constellations are effectively deployed. Then, in a few years from now, one may expect to see a rate of mass re-entry that will be larger than 3200 t/yr and its percentage with respect to the natural flux of material (16%) will be non-negligible. Some estimates of about 8000 t/yr of re-entry mass[5,14] would even bring this percentage to about 40% of the flux of material that naturally enters the Earth atmosphere.

4. Concluding remarks

This brief document serves as a scientific background to the statement on large satellite constellations. It specifically considers constellations aimed at providing global access, high speed low latency connectivity to the internet. It also considers issues raised by these constellations including their impact on astronomy, rapid densification of orbits, re-entry of end of life satellites and debris, enhanced deposition of chemicals in the upper atmosphere. Like the statement, it gathers contributions from the working group formed by the delegates of the seven academies.

Acronyms

ALMA : Atacama Large Millimeter/submillimeter Array
CPS : Centre for the Protection of the Dark and Quiet Sky
COPUOS : Committee on the Peaceful Uses of Outer Space
CRAF : Committee on Radio Astronomy Frequencies
ELT : Extremely Large Telescope
ESO : European Southern Observatory
GAO : Government Accountability Office
GEO : Geostationary Earth Orbit
IAU : International Astronomical Union
IRAM : Institut de Radioastronomie Millimétrique
IRIS^2 : Infrastructure for Resilience, Interconnectivity and Security by Satellite
ITU : International Telecommunication Union
JASON : JASON advisory group
LOFAR : Low Frequency Array
NSF : National Science Foundation
RFI : Radio Frequency Interference
SKA : Square Kilometre Array
STM : Space Traffic Management
STRATCOM : United States Strategic Command
VLT : Very Large Telescope

References

[1] Academie des sciences, "Large Satellite Constellations: Challenges and Impact", S7 Statement communicated to the G7 Academies, 2026.

[2] Baccelli, F., Candel, S., Perrin, G., Puget, J.-L., Large Satellite Constellations: Challenges and Impact. Académie des sciences. https://doi.org/10.62686/3, 2024.

[3] Bonnal, C., McKnight, D., Jorgenson, C., Masson-Zwaan, T., IAF – IISL – IAA initiative on space traffic management: Synthesis report on IAF technical committee TC 26 on space traffic management. Acta Astronautica 232, 706–720. https://doi.org/10.1016/j.actaastro.2025.03.024, 2025.

[4] Borlaff, A.S., Marcum, P.M., Howell, S.B., Satellite megaconstellations will threaten space-based astronomy. Nature 648, 51–57. https://doi.org/10.1038/s41586-025-09759-5, 2025.

[5] Glassmeier, K.-H., Schulz, L., Mitchell, A., Murphy, D., 2, Concerning Mega-constellations, Space Waste, and our Atmosphere. Presented at the 45th COSPAR Scientific Assembly, p. 2585, https://ui.adsabs.harvard.edu/abs/2024cosp...45.2585G/abstract, 2024.

[6] Handley, M., Using ground relays for low-latency wide-area routing in megaconstellations, Proceedings of the 18th ACM Workshop on Hot Topics in Networks., ACM Workshop on Hot Topics in Networks, ACM, Princeton NJ USA, pp. 125–132. https://doi.org/10.1145/3365609.3365859, 2019.

[7] JASON, The Impacts of Large Constellations of Satellites (Technical Report No. JSR-20-2H). The MITRE Corporation. https://nsf-gov-resources.nsf.gov/files/JSR-20-2H_The_Impacts_of_Large_Constellations_of_Satellites_508.pdf?VersionId=B6k0jpAipAxYm9liFTyH4TnN1YZKTFvT, 2021.

[8] Kessler, D.J., Cour-Palais, B.G., Collision frequency of artificial satellites: The creation of a debris belt. J. Geophys. Res. 83, 2637–2646. https://doi.org/10.1029/JA083iA06p02637,1978.

[9] Liao, S.-K., Cai, W.-Q., Liu, W.-Y. et al. Satellite-to-ground quantum key distribution. Nature 549, 43–47. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/JA083iA06p02637, 2017.

[10] Maloney, C.M., Portmann, R.W., Ross, M.N., Rosenlof, K.H., Investigating the Potential Atmospheric Accumulation and Radiative Impact of the Coming Increase in Satellite Reentry Frequency. JGR Atmospheres 130, e2024JD042442. https://doi.org/10.1029/2024JD042442, 2025.

[11] Maloney, C.M., Portmann, R.W., Ross, M.N., Rosenlof, K.H., The Climate and Ozone Impacts of Black Carbon Emissions From Global Rocket Launches. JGR Atmospheres 127, e2021JD036373. https://doi.org/10.1029/2021JD036373, 2022.

[12] NASA, Orbital Debris Quarterly News Volume 28.https://ntrs.nasa.gov/api/citations/20240004032/downloads/ODQN%2028-2_final.pdf, 2024.

[13] Russell, L., China's Adaspace orbits first 12 AI-cloud satellites of 2,800-strong constellation. Data Center Dynamics., https://www.datacenterdynamics.com/en/news/chinas-adaspace-orbits-first-12-ai-cloud-satellites-of-2800-strong-constellation/#:~:text=At%2012%3A12%20on%20May%2014%2C%20Chengdu%20Guoxing%20Aerospace,launch%20vehicle%20at%20the%20Jiuquan%20Satellite%20Launch%20Center, 2025.

[14] Schulz, L., Glassmeier, K.-H., On the anthropogenic and natural injection of matter into Earth's atmosphere, Advances in Space Research, 3, 67, pp. 1002-1025, https://doi.org/10.1016/j.asr.2020.10.036, 2021.

[15] Space Stats Online, Orbital launches by year, https://spacestatsonline.com/launches/, n.d.

[16] Swayne, M., China Establishes Quantum-Secure Communication Links With South Africa. The Quantum Insider, https://thequantuminsider.com/2025/03/14/china-established-quantum-secure-communication-links-with-south-africa/, 2025.

[17] United States Government Accountability Office, Large constellations of satellites, Mitigating environmental and other effects (No. GAO-22-105166). https://www.gao.gov/assets/730/723162.pdf, 202

[18] Walker, J.G., Satellite constellations, Journal of the British Interplanetary Society, 37, 559-571, https://ui.adsabs.harvard.edu/abs/1984JBIS...37..559W, 1984.

[19] IAU Centre for the Protection of the Dark, Quiet Sky from Satellite Constellation Interference (CPS), Józsa, G. I. G., Williams, A., Green, R., Marsh, I., Antoniadis, J., Barbosa, D., et al., Call to Protect the Dark and Quiet Sky from Harmful Interference by Satellite Constellations, arXiv preprint. https://doi.org/10.48550/arXiv.2412.08244, 2024.

[20] IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS), Group of Friends of the Dark and Quiet Sky, https://cps.iau.org/group-of-friends/, 2026.

[21] Onrubia, R., Oliva, R., Duncan, D., Bormann, N., Barbosa, J., Nestoras, I., Jordão, A., Jorge, F., Challot, J., Soldo, Y., Systematic Assessment of the RFI Environment in Passive Microwave Bands for Earth Observation from 6 to 200 GHz, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-4838, 2025.

[22] Murphy, D. M. et al., Metals from spacecraft reentry in stratospheric aerosol particles, Proceedings of the National Academy of Sciences of the United States of America, 120(43), 2023. https://doi.org/10.1073/pnas.2313374120, 2023.

References

[23] M. Stevenson, D. McKnight, H. Lewis, C. Kunstadter, R. Bathia. Identifying the Statistically-Most-Concerning Conjunctions in LEO, Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS) 2021.

[24] DIN 5031-9 Physics of radiation in the field of optics and illuminating engineering; definitions in the field of luminescence. https://www.physicsnorm.com/DIN/141234648/DIN-5031-5, 1982.

[25] International Telecommunication Union (ITU): Investment in Space Infrastructure and Sustainable Satellite Systems, ITU Publications, https://www.itu.int/dms_pub/itu-s/opb/gen/s-gen-invest.con-2025-pdf-e.pdf, 2025.

Signatures

Mamoru Mitsuishi

Mamoru MITSUISHI

JAPAN
Science Council of Japan

Roberto Antonelli

Roberto ANTONELLI

ITALY
Accademia Nazionale dei Lincei

Françoise BAYLIS

CANADA
Royal Society of Canada

Françoise COMBES

FRANCE
Académie des sciences

Marcia McNutt

Marcia McNUTT

UNITED STATES
National Academy of Sciences

Paul Nurse

Paul NURSE

UNITED KINGDOM
The Royal Society

Rockenbach

Bettina ROCKENBACH

GERMANY
German National Academy of Sciences Leopoldina