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Large Satellite Constellations: Challenges and Impact

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ACADÉMIE
DES SCIENCES
INSTITUT DE FRANCE

Report of *Académie des Sciences*
**Large Satellite Constellations:
Challenges and Impact**

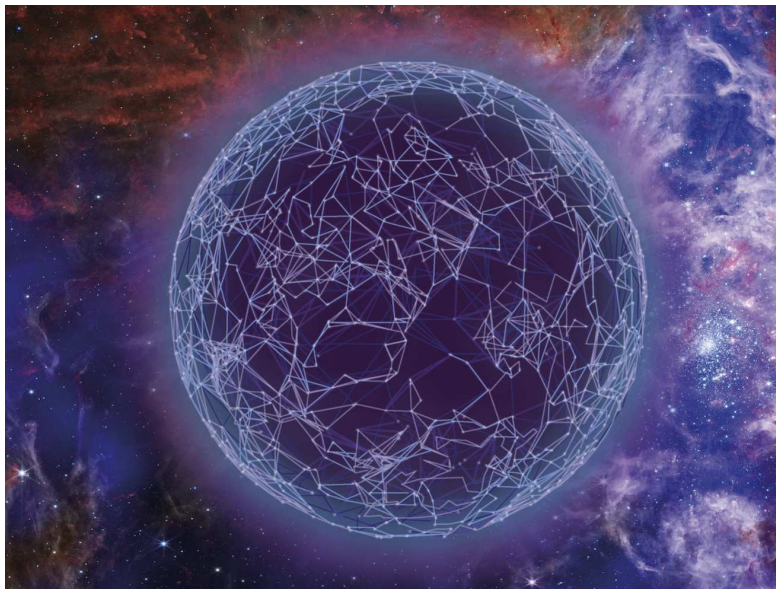
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Contents

1	Satellite constellations	6
1.1	Architecture	6
1.1.1	Orbits	6
1.1.2	Altitudes	6
1.1.3	The Walker classification	7
1.1.4	Anchoring stations	8
1.2	Satellites	8
1.2.1	Mass	8
1.2.2	Available electrical energy	8
1.2.3	Service life	9
1.2.4	Costs	9
1.3	Features	9
1.3.1	Telecommunications - broadband	10
1.3.2	Earth observation	15
1.3.3	Telecommunications - Internet of things	17
1.3.4	Geolocation	18
1.4	A few orders of magnitude	19
2	Research and development, scientific and technological prospects	20
2.1	Communication theory	20
2.1.1	Information and coding theory	20
2.1.2	Adaptive beam-forming and user antenna	21
2.2	Information technology	21
2.3	Propulsion	22
2.3.1	Situation of European launchers	22
2.3.2	Plasma propulsion	23
2.4	Outlook	24
3	Impact on astronomy	25
3.1	Impact on optical astronomy	26
3.1.1	The nature of impacts	26
3.1.2	Denoising by signal processing	30
3.2	Impact on radio astronomy	30
3.2.1	General description of the problem	30
3.2.2	Impact on data and calibration possibilities	32
3.2.3	Modalities to reduce the impact on radio observations	34
3.3	Actions underway	34
3.4	Prospects for astronomy	36

4	Environmental impact	37
4.1	Environmental impact components	37
4.2	The problem of space debris	38
4.3	Collision avoidance systems	39
4.4	The Kessler syndrome	40
4.5	Actions underway	40
5	Economic stakes	41
5.1	The NewSpace context	41
5.2	The situation in France and Europe	41
5.2.1	The budgets	41
5.2.2	The satellite industry	42
5.2.3	The launcher industry	42
5.2.4	The IRIS ² project	42
5.2.5	New entrants	42
5.3	Economic models	43
5.3.1	Broadband	43
5.3.2	Earth observation	45
6	Sovereignty issues	45
6.1	Sovereignty in telecommunications	46
6.2	European sovereignty	46
6.3	Military use	46
7	Regulation by international and national agencies	47
7.1	Involved institutions	48
7.2	The need for international regulations in this field	49
8	Conclusions	50
9	Recommendations	51
10	Appendix	53
10.1	Organization of work	53
10.2	Editorial secretariat	53
10.3	Authors	53
10.4	Other working group members	53
10.5	Hearings	54
10.6	Acronyms	54
10.7	Illustration credits	57

Abstract

The New Space Age (NewSpace) marks the advent of a new era in the use of space, characterized by the opening of space to new players, the use of new space technologies, new functionalities for satellites in orbit, and the development of satellite constellations, mainly in the fields of communications and Earth observation. These developments are underpinned by first-rate scientific and technological advances, as well as considerable public and private investment, in particular in the USA, China and, to a lesser extent, Europe. Fleets of small low- and medium-orbit satellites are replacing or complementing the large geostationary satellites that predominated in the previous period. Whereas space used to be reserved for a small number of states and major industrial groups, one is now witnessing the emergence of new space states, new industrial groups such as SpaceX or Amazon, and many start-ups. One also observes the emergence of companies with launching and satellite manufacturing capacities, which are also taking on the role of telecommunication operators and content producers.

The most visible result of the deployment of these new space networks is the ability to provide high-speed, low-latency Internet connections to any point on the globe. Combined with Earth observation capabilities, these new communications resources also enable real-time action to be taken in any region, including those with no equipment other than terminals. In addition, these space networks are remarkably resilient compared with terrestrial networks. Geostrategic and military considerations combine with rapidly evolving business models to explain the massive investments currently being made in this domain.

However, the lack of international regulation of the field is leading to a race to occupy orbits and frequencies, which has already had serious consequences for a whole range of scientific activities. These constellations have a potentially negative impact on astronomy in the visible and infrared optical domains, as well as on radio astronomy. They also raise a major problem in terms of space congestion, with an increase in the amounts of satellite debris resulting from launches or collisions between satellites, and the possibility of reaching a phase of chain reaction collisions. In addition, from an environmental point of view, the consequences of the proliferation of launches and uncontrolled re-entries into the atmosphere are equally worrying. What's more, this lack of regulation in the field also leads to a loss of sovereignty, since these new satellite communication networks do not comply with any of the rules that states impose on terrestrial communication networks operating on their territories. A sustainable, global solution must be found to these problems, before major and potentially irreversible damage is inflicted on the planet's environment, geostrategic balances, democracy, and science.

While the *Académie des Sciences* considers that France and Europe need to step up their scientific and industrial actions in this field in order to benefit from the remarkable advances of these new networks, and ultimately leverage the benefits of a resilient and secure communications network, the Académie also recommends working in parallel to strengthen regulation of the field with the aim of assuring sustainable access to orbital and frequency resources, as well as protection for negatively impacted fields, foremost among which are astronomy and the environment.

Introduction

In the general context of accelerated launches of low- and medium-orbit satellite constellations, this report aims to take stock of the opportunities opened by these new types of large networks, the issues they raise, and the negative impacts of their current and future developments. The report is divided into seven sections.

Section 1 describes the basic objects of these constellations, i.e. satellites and associated ground elements, as well as the main features of the networks of which they are elements in terms of organization and functionality. This section describes the direct high-speed links currently possible between ground terminals and moving satellites, the links between satellites in the same constellation, and the network architectures using these links, which today enable high-speed, low-latency space-based Internet access anywhere in the world. Satellite constellations open prospects beyond the telecommunication field, and are used for Earth observation, geolocation, links with fleets of vehicles (aircraft, ships, etc.), or for interaction with connected objects.

Section 2 describes the recent scientific and technological advances that have underpinned the development of these constellations and their new functionalities. It describes advances in telecommunications research (information theory, antenna beamforming and interference control, definition of dynamic routing protocols, broadband architectures, etc.). It also describes new ways of launching and propelling low- and medium-orbit satellites. The accelerating pace of deployment of orbiting objects raises many questions, not least those of overall sustainability in terms of space congestion and environmental impact on the one hand, and the consequences for astronomy on the other.

Section 3 addresses the negative impact of constellations on sky observation capabilities, in particular the effects of satellite trails on images in the optical domain. The impact of radio telecommunications and satellite onboard electronics noise on radio astronomy is also analyzed. This section also describes the initial measures taken to limit these impacts and explains why these measures are insufficient in the emerging context.

Section 4 focuses on the consequences of these deployments on the spatial environment and on the upper atmosphere. It lists the foreseeable consequences of the multiplication of debris from launches that are themselves satellites and the increased probability of collisions resulting from these operations. It also addresses the impact of launches and satellite ends of life on the upper atmosphere and on the Earth itself.

Economic, commercial and sovereignty issues are addressed in Section 5. In just a few years, the use of space has evolved at a sustained pace with the advent of NewSpace in the United States. This evolution has led to the emergence of many new projects led by private companies that very often benefit from government funding. This striking evolution is underpinned by new technical and economic models. For example, Starlink's supremacy is based on the development of new reusable launchers. The question of complementarity with terrestrial networks, which is central to the future of these constellations, is also discussed in this section.

Geopolitical issues and questions of sovereignty are dealt with in Section 6. The takeover of orbits and frequencies which is currently underway in the absence of global

regulation is leading to an offer of high-speed Internet services that de facto free themselves from the rules imposed by states on terrestrial networks. It also gives those who control these constellations new means of action in real time, anywhere on the globe.

Regulatory possibilities at the national and international levels complementary to those discussed in Subsections 3.3 and 4.5 are discussed in Section 7.

1 Satellite constellations

This section describes the constellations, by successively dealing with their architectures, the general characteristics of the satellites that make up the constellations, and their various functions. It is concluded with some general orders of magnitude.

1.1 Architecture

By constellation architecture, we mean the arrangement of orbits, the ordering of satellites in these orbits and the arrangement of ground stations, as well as the organization of all these elements into a network.

1.1.1 Orbits

The orbit of an Earth satellite lies in a plane that passes through the Earth center and is characterized by its inclination, which measures the angle formed by this plane with the equatorial plane, and by the ascending point of the orbit. This ascending point is marked by the angle, measured in the equatorial plane, between the point where the satellite crosses the equatorial plane from south to north and a given point on the equator. Circular orbits are defined by a single complementary parameter, the orbit altitude.

1.1.2 Altitudes

There are three groups of orbital altitudes:

- LEO or Low Earth Orbit, between 350 and 1000 km, with a period of about 100 minutes.
- MEO or Medium Earth Orbit, typically between 1,000 and 20,000 km, with a period of a few hours.
- GEO or geostationary, with an altitude of 36,000 km. In this case, the period is 24 hours, and the satellite remains stationary relative to the Earth.

It is worth noting that geostationary satellites provide poor coverage of the polar regions.

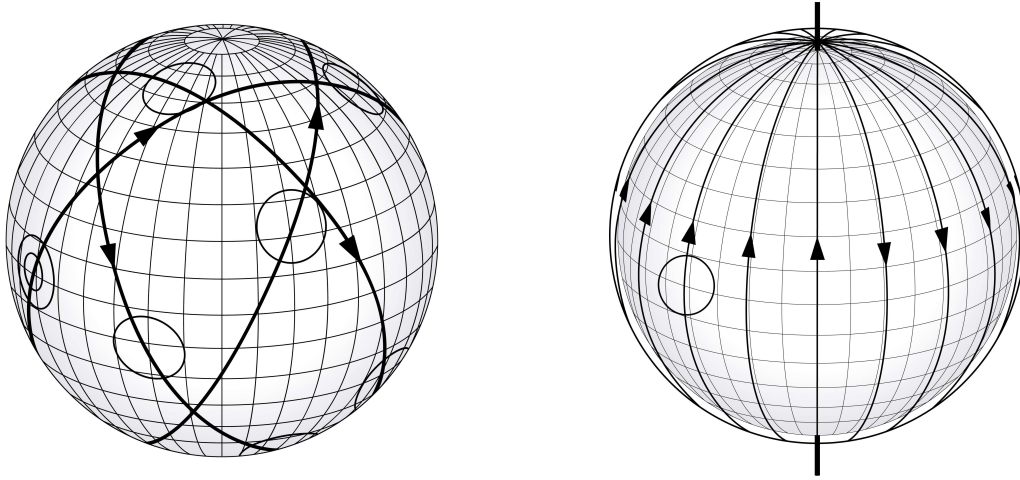


Figure 1: Left: Walker Delta (basis of Starlink and Galileo). Right: Walker Star (basis of OneWeb).

1.1.3 The Walker classification

Two frequently used satellite constellation classes, LEO or MEO, are the Walker delta and Walker star configurations. These two constellation classes are shown in Figure 1.

In a Walker delta constellation, all the orbital planes have the same inclination, the ascending points of these orbits are distributed periodically over the 360 degrees of the equator, the orbital altitudes are all the same, and the satellites on a given orbit are periodically distributed on this orbit.

A Walker delta constellation is characterized by a quadruplet noted $i : N/M/T$, with i the inclination of the orbital planes, N is the total number of satellites, M the total number of orbital planes and T the total number of satellites. The inclination parameter is used to only cover regions located at latitudes that do not exceed a certain threshold. So, for example, the Galileo navigation system is a Walker $56^\circ : 24/3/1$ constellation. This means that there are 24 satellites in 3 planes inclined at 56 degrees, distributed periodically over the 360 degrees of the equator. Note that in delta-type constellations, a given observation point may see both south-north and north-south oriented satellites pass at close range; in this case, the distance between two close satellites but with different orientations varies greatly.

Walker star constellations use orbits with inclinations close to 90 degrees (i.e. quasi-polar). The orbital planes are organized periodically on the equator, but on 180 degrees only, so that on the equator, the satellites are all ascending on the interval 0, 180 degrees and all descending on the complement. The Iridium constellation is a Walker star $86.4^\circ : 66/6/2$.

Many variants of these basic constellations are used, such as multi-altitude combinations, or star-delta, or LEO-MEO-GEO.

1.1.4 Anchoring stations

In most cases, the satellites in a constellation act as gateways between users and a terrestrial network/system (Internet, database, etc.). For the uplink, the data transmitted by the user is received by a satellite and sent back by this satellite to ground stations, also known as anchoring stations, connected to the terrestrial network/system in question. For downlink, the path is reversed: docking station, satellite, user.

For low-earth orbits, in the absence of communications between satellites, many anchoring stations are required if continuous coverage is to be achieved. The coverage area of a low-orbit satellite is reduced, and coverage of a user requires that the satellite to which it is attached also covers an anchoring station at all times. This latter constraint is lifted if there are direct communications between satellites, enabling information to be relayed from the satellite covering the user to a satellite covering an anchoring station. Satellite-to-satellite communications therefore make it possible to reduce the number of anchoring stations. It also reduces the number of satellites. However, these reductions are limited by geometry: each satellite must have another satellite or anchoring station in direct view. Any such reduction also leads to an increase in latency.

In the LEO and MEO cases, the anchoring stations are more complex than in the geostationary case since the antennas must be able to follow the satellites and switch from one to another.

1.2 Satellites

Satellite characteristics vary widely, in terms of mass, power level, cost and lifetime. It is important to note that satellites used since the 60s for geostationary orbits are distinct from those deployed in today's constellations in LEO or MEO orbits.

1.2.1 Mass

The mass of geostationary satellites exceeds several tons (3 tons for Eutelsat Konnect), while that of ICEYE's micro-observation satellites (see below) is of the order of 70 kg. For OneWeb, the order of magnitude is 150 kg per satellite, that of O3b's satellites is 700 kg, and Starlink is now moving towards heavier 2nd-generation satellites, weighing around 1500 kg.

1.2.2 Available electrical energy

Transmission and computing capacities depend on the electrical power available on board. Geostationary satellites have a power level of several kW. The power level of low-earth orbit satellites is lower, around 500 W for the first generation composing the OneWeb constellation. For the second generation, power is expected to be around 2 to 3 kW. More generally, on-board electrical power requirements will increase by a factor of 10. The growth in power corresponds to the increase in computing, data handling and signal processing requirements on board and is also associated with the objectives of software integration of non-terrestrial networks in the international cellular network

standards defined by 3GPP [15]. To obtain higher powers, m^2 of solar panels are needed, foldable and flexible. There is no limit to the surface area, apart from mass and folded volume. The power may be augmented by replacing silicon by gallium arsenide (GaAS) panels that are more efficient but also more expensive.

1.2.3 Service life

The lifetime of a geostationary satellite is between fifteen and twenty years. LEO and MEO satellites have shorter lifetimes. This is mainly due to the use of commercial components not designed for the space environment. The lifetime of OneWeb's second-generation satellites is expected to be 7 years.

1.2.4 Costs

It costs around 300 M€ to design and manufacture a geostationary satellite. To this must be added around 100 M€ for launch and 100 M€ for construction of the ground segment (anchoring station). This defines an overall cost of around 500 M€ for a satellite with a lifespan of 15 to 20 years. With 3 geostationary satellites, one has global terrestrial coverage (excluding the poles, as already indicated). The cost of a low-orbit satellite is much more modest and this system can be considered as a consumable. For OneWeb, the order of magnitude of the cost of one satellite is 1 M€. The total expenditure was around €5 billion for the first generation of OneWeb and should be €3 billion for the second generation. It takes 3 years to produce these satellites. This means that a large constellation of this type requires a permanent financial flow of 1 billion €/year. For large constellations, however, the investment is much higher than for geostationary satellites. To this one has to add the cost of initial launches and renewals to maintain the constellation (from €10,000 to €20,000/kg, with lower values for SpaceX Falcon launches, which are of the order of €3,000/kg).

1.3 Features

Satellite constellations are used in a variety of applications, which can be divided into three broad categories:

1. Telecommunications, mainly broadband communications such as universal Internet access, but also low-speed communications for the Internet of Things. It is the broadband Internet access that drives the very large constellations currently in use or that are being planned, and that rely on tens of thousands of LEO or MEO satellites.
2. Earth observation (around 1,200 satellites): this function is highly diversified. It leads to the deployment of numerous constellations, each with a moderate number of satellites.
3. Geolocation and time distribution: this long-established field includes few constellations, each with a moderate number of MEO satellites.

The present report deals mainly with communications-type functions, while touching on other functions in less detail.

1.3.1 Telecommunications - broadband

This sub-section explains why very large constellations in low or medium orbit allow Internet coverage that is both universal (despite latitude constraints for certain configurations), without interruptions (for this, many satellites are needed in the LEO case), high throughput (under strong constraints on the number of users per satellite), with reduced latency (thanks to the use of low orbits) and with good spectral efficiency (thanks again to low orbits), resilient (or at least more resilient than terrestrial networks and more resilient too than the geostationary solution because more distributed).

Network components The network comprises three types of elements: terminals (telephones or laptop computers), anchoring stations, which form the terrestrial segment, and orbiting satellites. Terminals are equipped with antennas that enable direct communication with the satellites. Satellites communicate with terminals, possibly with other nearby satellites and with anchoring stations. Anchor stations are ground units that can be seen as the first points of access to the Internet and its databases. The function of the network is to interconnect each terminal with an anchor station at any given time, by means of a connection comprising at least one satellite and therefore at least two radio links (the one between the terminal and the satellite, and the one between the satellite and the anchor station).

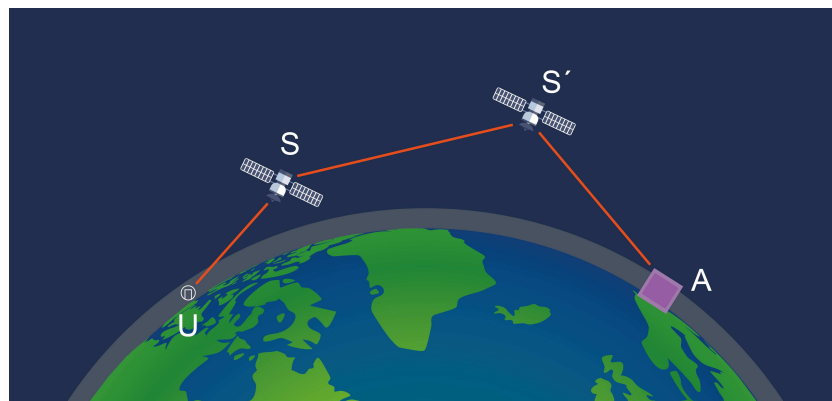


Figure 2: Network components (diagram not to scale): U: *end user*, S and S': *satellites*, A: *anchoring station*. Instances of S-U and S'-A links: *Ku-bands* (10,7-14,5 GHz), *Ka-bands* (17,3-30 GHz). Links between satellites: *Laser*.

Connectivity The connection between the final user and the Internet comprises a user-satellite link, then a series of inter-satellite links and a satellite-anchor station link.

This applies to both the uplink (data transfer from the user to the Internet) and the downlink (data transfer from the Internet to the user). If there are no connections between satellites, continuous coverage requires at least one satellite with the dual property of being in view of the user and of an anchor station, at all times and for all users. If there are several satellites with this property, a natural option is to always use the shortest paths (and correspondingly the shortest propagation delays), or the paths with the best data rates. For a given user, all this is very dynamic, especially in Walker delta constellations where the links in question must restructure rapidly as the satellites pass by. We note at this point that satisfying this double condition requires a high density of satellites and anchor stations.

The situation is different when satellites communicate with each other. In this case, at the cost of longer connection paths, i.e. with more inter-satellite links, it is possible to obtain broadband access in each region of the globe, on both uplink and downlink segments, without having to rely on anchor stations in that region. For example, for geostrategic reasons, the IRIS² constellation should be able to provide global projection, relying solely on anchor stations located in Europe.

Frequencies The information reaching the user is transported by carrier waves of different frequencies. In the simplest case (in the absence of satellite-to-satellite communications), this information departs from an anchor station, travels to the satellite, where it is retransmitted by the latter to finally reach the user's antenna.

Radio-frequency (RF) used for communications In the broadband context, current and many proposed satellite constellations use or will use the Ku (10.7-14.5 gigahertz [GHz]), Ka (17.3-30 GHz) and V (37-50.4 GHz) radio frequency bands for radio links between satellites and ground network elements. This is notably the case for Starlink. There are also plans to use 5G bands under agreements with terrestrial operators of 5G networks, which would open access to bands below 6 GHz as well as to the so-called millimeter bands of 5G.

Optical and THz communications Satellite-to-satellite communications, which must ensure much higher data rates, can be carried out by optical laser beams (with frequencies well above RF bands) analogous to those used in optical fibers. This option is used in the latest versions of the satellites in the Starlink constellation. Source and detector technologies are well developed in these optical bands, and because of the short optical wavelengths (in the micron range), it is possible to use small size optical systems (< 10cm) to establish large beams between satellites. Communications between anchor station and satellite can also be made optically, but in practice, optical transmission from ground to satellite is affected by atmospheric turbulence and clouds, requiring highly sophisticated adaptive optics to compensate for distortions. Companies like Cailabs, in France, offer telescopes with < 1 m aperture, to implement these principles and achieve data rates of over 10 Gbps.

Another alternative that is now being studied is the so-called THz range, which covers frequencies between 100GHz and 10THz. On the ground in a humid atmosphere, these frequency bands only allow communications over short distances (a few kilometers), due to the attenuation of THz waves by atmospheric water vapor (the use of THz is one of the avenues proposed for 6G). On the other hand, THz waves are not sensitive to atmospheric turbulence. In dry, high-altitude locations, this problem no longer arises. Submillimeter radio astronomy using these frequencies has demonstrated that with large-aperture radio telescopes, such as the Large Millimeter/submillimeter Array (ALMA) in the Chilean Andes, data rates of the order of Tbps can be achieved between the Earth and a satellite. By positioning anchor sites at altitude, operating in the THz range, one should be able to achieve high data rates in the ground/satellite link. This same frequency range can also be used for inter-satellite links. It should be noted, however, that THz wave sources and detectors have not yet reached the same level of maturity as optical components.

Antennas In the case of transmissions from geostationary satellites, the antennas on the ground are parabolic in shape to point in a fixed direction towards the satellite. The antennas of the anchoring station, which transmit towards the satellite, and those of the user have significantly different sizes. In the anchoring station, large dishes protected by a radome are used, whereas the user antennas that flourish on the buildings are much smaller. The cost of user antennas is correspondingly low. In LEO or MEO cases, ground antennas are more complex, as they have to follow the satellite on its track and switch from one satellite to another to maintain the connection. There are three types of antennas in LEO or MEO satellite constellations: station antennas, satellite antennas and user antennas.

Anchor station antennas handle high data rates, have large apertures, and are pointed at nearby satellites. Several dozen antennas under the radome are used to cover different sectors of the sky.

The antennas on board the satellites must be able to form several thousand simultaneous beams towards the different users. These are sophisticated antennas using multiple arrays of elements spread over surfaces of a few m^2 capable of adaptively directing beams towards a specific geographical area, in real time. Due to the laws of diffraction, these antennas are not perfect, and their side lobes illuminate areas larger than the desired ones.

As for users, they too need antennas capable of tracking moving satellites, and for this effect they exploit adaptive techniques as detailed below.

Capacity In the context of telecommunications, notions of capacity are used at various levels. One distinguishes the global capacity of a satellite, the global capacity of a constellation and the effective capacity of a radio link. The overall capacity of a telecommunications satellite is the sum of the data rates it offers on the downlink. As an example, Starlink's satellites are described as having a global capacity of 10 Gigabits/s. The overall capacity of a constellation is the sum of the capacities of its satellites.

The notion of the effective capacity (in the sense of the best possible throughput) of a radio link is defined by information theory (see Section 2.1.1). This capacity depends on the power of the received signal, as well as on the power of interference and thermal noise. The power of the signal received from (or by) the satellite is strongly dependent on its altitude; the spectral efficiency (throughput per Hertz of bandwidth) is therefore much better for LEO than for GEO satellites, for example. Interference from other satellites using the same frequency bands also plays a key role here. Their strength depends on the organization of the constellation as well as on the power dissipated in the secondary lobes. The effective capacity also depends on the rule for sharing the satellite's global resources between the users connected to it. The constellations currently being deployed are designed to offer to each user, under ideal conditions, effective speeds comparable to those of an optical fiber. Ideal conditions mean proximity to the connecting satellite, interference control and no sharing of radio resources between too many users.

It is useful to list a few orders of magnitude concerning the overall capacity of constellations. Today's constellations, taken as a whole, have a global capacity of 50 Terabits per second, spread across the entire planet. By way of comparison, the overall capacity of the French 5G network alone is around 300 Terabits per second, i.e. 6 times greater. The capacity of intercontinental cables of all types is three orders of magnitude greater than that of constellations. It is therefore impossible for constellation-based networks to replace, in the medium term, terrestrial networks in high-speed communications.

Latency Geostationary satellites have propagation delays of 500 milliseconds, which is too long for some applications. LEO satellites reduce this delay to 30 milliseconds. Latency control is essential in the context of applications with real-time constraints.

Resilience Networks based on LEO and MEO constellations have remarkable resilience properties: like networks based on geostationary satellites, they remain functional even in the event of degraded local situations, natural disasters, or the destruction of terrestrial infrastructure. The distributed, mobile, and reconfigurable nature of LEO and MEO constellations also makes their physical attack far more difficult than that of ground stations or geostationary satellites.

Universality Star constellations cover the entire Earth, including the polar regions. Delta constellations provide configurable latitude coverage. Constellations using low or medium-altitude orbits rely on high satellite densities and short distances between satellites to ensure uninterrupted service. As already explained, this seamless service is possible even in countries or regions where there is no 5G-type infrastructure or anchor stations, at least if the constellation allows inter-satellite communications.

Examples The very first constellations deployed for communications are as follows:

- Iridium, initially launched by Motorola, USA, this constellation comprises less than a hundred satellites configured in a star configuration. It is now used by the

US Department of Defense [18]. The satellite fleet has been renewed with new platforms developed by Thales Alenia Space (TAS). It comprises 66 satellites each weighing 860 kg injected at an altitude of 780 km in six orbital planes by Falcon 9 launchers between 2017 and 2019.

- Globalstar, initially launched by Qualcomm, USA in 1997, consists of 48 satellites placed in MEO configured in star orbits.

More recent constellations include:

- OneWeb, initially launched by the UK, comprising 624 satellites configured in a star configuration. OneWeb was more recently acquired by Eutelsat.
- O3b, initially launched in the USA by Greg Wyler (one of the pioneers of NewSpace) in 2007, currently comprises some 30 satellites produced by Thales Alenia Space in MEO (7,500 km) equatorial orbit. This constellation is now owned by SES.
- Starlink (Elon Musk, USA), is the largest of the constellations. It currently comprises 4,000 satellites in delta configuration, at altitudes of between 350 and 500 kilometers. It will have 8,000 satellites by 2024 and has an authorization for 42,000 satellites.

Here are just a few of the projects currently underway in the field of high-speed Internet access:

- Kuiper, Amazon's constellation in the USA, which will comprise 10,000 satellites organized in several delta-type configurations [12].
- IRIS2 a European Union project involving several hundred LEO and MEO satellites. This constellation is designed to provide a secure means of communication for the governments of European Union countries.
- Guowang, a Chinese satellite constellation expected to count 13,000 satellites, with a deployment schedule that is not yet clear at this date.

Starlink Starlink can be seen as the only constellation in operation that offers virtually universal broadband access to the Internet, with a business model that is in equilibrium¹. The foundations of this equilibrium are as follows. Starlink operates with low-cost satellites, using general public electronic components and technologies. The manufacturing methods adopted by this company are disruptive compared with the norm in the space field, and its satellites are launched virtually free of charge by Space-X. Starlink also relies on an efficient customer approach, with terminals marketed at reduced prices (€250) that are easy to install, and its subscriptions rates at around 50 €/month are relatively

¹The nature of this equilibrium is not so clear and for example, it does not seem to account for externalities corresponding to environmental costs.

close to those offered by terrestrial telecommunications operators. The antenna, which was initially bulky and comprised a dish on a tripod, now takes the form of an A5-format plate that is easily positioned and enables rapid connection to the constellation. Starlink’s target constellation is 42,000 satellites.

Additional features Constellation-based networks have functionalities that go far beyond universal broadband access. A dense constellation of LEO or MEO satellites, for example, can be used as a backhaul network (a backhaul network connects terrestrial base stations to the global Internet; the cost of deploying a terrestrial backhaul network is high). As already mentioned, constellations can also play a key role in boosting the resilience of terrestrial networks. Some edge computing functions could eventually be performed on the satellites themselves, to reduce latency. To all this, we need to add observation or radar detection functions that are not incompatible with communication functions. These networks will thus be able to combine communication functions with observation or detection functions.

1.3.2 Earth observation

Features The following civil observation functionalities are currently the most important: meteorology, agriculture, forestry, biodiversity, soil quality assessment, risk management, anomaly detection.

Observation is highly diversified and can be carried out at optical wavelengths (from ultraviolet to far infrared) and in the microwave electromagnetic range, in spectral or hyperspectral imaging modes, with synthetic aperture radars (SAR) in high-angle resolution imaging, with lidars and with gravimetric sensors. An important specificity of some observation and data collection missions is that they do not require permanent end user coverage by satellites. This explains why Earth observation satellite constellations are generally smaller than those aimed at universal coverage for Internet access. This fast-growing field is developing in new directions, such as the joint processing of requests by several different and complementary constellations, or the observation of the magnetosphere, cosmic particles, etc. The military implications of some of these issues give a geopolitical dimension to the sector.

Examples Small observation constellations cost tens of millions of euros, and their number is growing rapidly. Here are a few examples:

- Copernicus (microwave, radar) (EU) Copernicus is the name of an Earth observation program managed by the European Commission and implemented in partnership with ESA, member states and various European agencies, such as EUMETSAT (the European meteorological satellite organization) and Mercator Ocean. The aim of the program is to provide global, autonomous Earth observation capabilities. Copernicus follows on from the GMES (Global Monitoring for Environment and Security) program. This program is based on a family of Sentinel

1 to 6 satellites, equipped with synthetic aperture radars and high-resolution optical imaging systems, as well as means of detecting the composition of the Earth's atmosphere, CO₂ emissions monitoring, surface temperature measurement, radiometric microwave imaging and hyperspectral environmental imaging. The aim is to collect data that can help address maritime safety issues, monitor disasters (fires, floods, earthquakes...), anticipate harvests, improve environmental management, and identify the effects of climate change. Six priority missions (Copernicus Expansion Missions) are being considered in order to extend the current capabilities of the Copernicus space component, particularly regarding CO₂ measurement and hyperspectral imaging.

- (Meteorological operational satellite) (EU), comprises 3 meteorological satellites placed in a sun-synchronous polar orbit at an altitude of 820 km, with equipment for measuring vertical temperature distribution, winds, and surface humidity over land. One of the instruments on board the METOP satellites, the IASI (Infrared atmospheric sounding interferometer) (3.7 - 15.5 μm), provides temperature measurements with an accuracy of 1°C and humidity measurements with an accuracy of 10% in every 1 km of atmosphere.
- CO3D (Optical constellation in 3 dimensions) (F) This constellation, deployed by CNES, comprises 4 Airbus Defense and Space 300 kg mini-satellites placed in sun-synchronous orbit at an altitude of around 500 km, designed to provide 3-dimensional images with an accuracy of the order of a meter in the vertical direction and half a meter in the other two directions.
- SCARBO (Space Carbon Observatory) (EU) A constellation of 25 small satellites equipped with miniaturized static spectrometers to monitor CO₂ and CH₄ emissions daily.
- ICEYE (Finland) A constellation designed for Earth observation and in particular natural disasters, featuring Synthetic Aperture Radar (SAR) satellites. This fleet of 31 satellites (the four most recently launched beginning November 2023) can provide rapid data access with high revisit rates and imaging capabilities at half-meter resolution, and a collection mode that enables rapid detection of changes on the ground. SAR imaging, using microwaves, gives access to usable information even in situations where the presence of clouds would preclude optical imaging.
- Unseenlabs (F) This constellation offers intelligence services based on innovative electromagnetic signal detection technology using a constellation of nanosatellites. The data collected can be used for maritime surveillance for French and international civilian and military customers (state bodies, private companies, institutions, non-governmental organizations, etc.). This constellation can be used to locate non-cooperating ships (so-called “dark ships”, which disable their automatic identification system or AIS) and thus combat illicit activities at sea: illegal fishing, pollution by degassing, piracy, circumvention of international sanctions, etc.

- Topex-Poseidon (CNES-NASA) and the Jason series. This constellation is made up of ocean altimetry satellites to improve the quantification of the rise in sea level resulting from the melting of glaciers and polar ice caps, and the expansion associated with the increase in mean ocean temperature. The rise in temperature accelerated after the start of the industrial era, and more markedly after 1930 constitutes a strong indication of its anthropogenic origin.

1.3.3 Telecommunications - Internet of things

Features LEO satellite constellations are also used to collect data from and distribute data to connected objects [30]. Communications of this kind are typically conveyed at low bitrates and under strong constraints in terms of energy expenditure by the objects. They are based on protocols differing from those used in broadband Internet. This field is also distinct from that of Earth observation in that it involves bidirectional transmissions between connected objects and satellites as they pass overhead. These constellations open new prospects in applications as diverse as health, surveillance, economic intelligence and logistics, all fields in which ground-based sensors collect data that need to be transferred, is not easily conveyed by standard means and can be conveniently transmitted through satellites links.

Examples Here are a few examples of projects in this area:

- KINEIS (F) is a constellation for satellite connectivity on the Internet of Things, comprising 25 intermediate-sized nanosatellites (mass 25 kg, power 15 W, electric propulsion) to be placed in sun-synchronous orbit at an altitude of 650 km. The satellites could then revisit a specific point in less than 15 minutes anywhere around the world. Kineis is based on the technology used in the Argos system, a positioning, data collection and acquisition service that has been in operation since 1987. Links will be provided in the UHF spread spectrum band. The project, supported by CNES, is being developed by Thales Alenia Space.
- ASTROCAST ASTROCAST (Switzerland) is a Swiss start-up based in Lausanne, supported by ESA and Airbus, which proposes to place 80 to 100 CubSat-type, 10cm in size, nanosatellites into orbit to offer object monitoring and geolocation services and communication with these objects. The objects are equipped with a miniaturized module (in partnership with Airbus, CEA-LETI and ESA) with very low power consumption compatible with the inexpensive L-band “patch” antennas that enable two-way communication with the constellation. Some twenty satellites are already in orbit at altitudes of around 500 km in a plane inclined at 97.4°.
- SWARM (USA) The start-up Swarm technologies operates a constellation of 72 to 120 very small picosatellites (11×11×3 cm³, 400 grams) placed in low-Earth orbit to provide low-cost, two-way IoT communication services.

1.3.4 Geolocation

Geolocation services are based on GNSS (Global Navigation Satellite System) satellites. This functionality is closely linked to UTC time distribution.

GPS GPS (“Global Positioning System”) is a constellation resulting from a project launched in 1973 under the aegis of the U.S. Department of Defense with an initial 24 satellites, put into orbit between 1989 and 1993 at an altitude of around 20,200 km, initially organized in 3 orbital planes. The constellation is now divided into 6 orbital planes comprising 4 satellites with an inclination of 55° . Each satellite completes 2 orbits per day, so that 6 of them are always in direct view of the globe. All satellites transmit on the L1 (1.57 GHz) and L2 (1.22 GHz) bands signals coded in spread spectrum and CDMA (Code Division Multiple Access), enabling geolocation by the receiving system. This service was made available to civilian applications in the early 90s.

Galileo (UE) Galileo (EU) is a satellite positioning system set up by the European Union from 2011 in the form of a delta constellation comprising 24 satellites. The last satellites are due to be placed in orbit in 2024. The satellites are positioned in three orbital planes with an inclination of 56° , at an average altitude of 23,200 km. The signals emitted by Galileo satellites in two frequency bands (1.16 - 1.21 GHz) and (1.56-1.59 GHz) can be used for geolocation with a horizontal accuracy of 4 m. It is worth noting that the performance of geolocation systems depends on the conditions in which the antenna receives the signals: satellite position, masking effect due to adjacent buildings, reflections of direct signals on neighboring infrastructures (multipath), etc. Thus, uncertainties are linked to each receiving station, and the issue is even more complex in the case of mobile antennas, which are confronted with changing situations. In definitive terms, instantaneous accuracy can be of the order of a meter or a few meters, depending on whether one considers multi-frequency or mono-frequency measurements. Galileo ensures the European Union’s autonomy from the services offered by the US GPS, the Russian GLONASS or the Chinese Beidou constellations.

Glonass (Russia) This constellation comprises 24 satellites on three orbital planes at an altitude of 19,100 km. The relatively steep inclination of the orbital planes (64.8°) enables coverage of the polar regions. Accuracy is of the order of a few meters.

Béidou (China) Beidou-1, operational since 2003, provided regional coverage (China and neighboring countries) via three GEO satellites. Beidou-3, which assures global coverage, became operational in 2020. It comprises a constellation of 27 MEO satellites, 5 GEO satellites and 3 satellites in inclined geosynchronous orbit.

New directions One of the new directions in this field is hyper-geolocation, which consists of modelling the errors of all GNSS satellites in real time, thanks to a network

ground stations that are precisely positioned. This information, once communicated to the user, enables him to correct his own measurements.

1.4 A few orders of magnitude

According to ESO, up to 100,000 LEO satellites could be launched into low-Earth orbit over the next decade. Assuming that the plans of the two most advanced companies in this field are effectively carried out, nearly 80,000 satellites could be present at various altitudes between 328 and 1,325 km. In 2022, G. Wyler, founder of OneWeb and O3b, created e-space, which plans to launch 100,000 to 300,000 micro-satellites into low-Earth orbit for communication and observation purposes.

It is not certain that these forecasts and projects will come to fruition. One current problem is that of production capacity for electronic components adapted to the space environment, which could meet the needs of all the constellation projects (IRIS², Starlink, OneWeb, Kuiper, etc.). It is not certain that the semi-conductor industry will be able to supply the components on time. One might think that demand will induce an increase in offer, but space-quality components that resist radiation take a long time to produce.

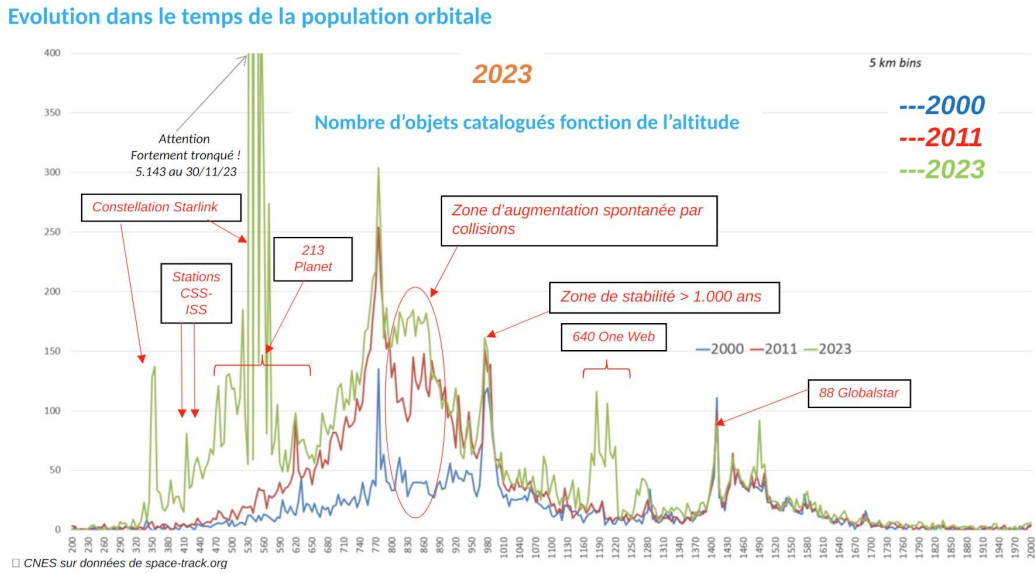


Figure 3: Evolution of the number of satellites in function of altitude.

2 Research and development, scientific and technological prospects

This section describes some of the areas of research and technological innovation that are enabling the current development of constellations, as well as the associated scientific perspectives.

2.1 Communication theory

2.1.1 Information and coding theory

Shannon Capacity The capacity of a radio link (e.g., the link between the user and the satellite to which he is attached) is given by Shannon’s information theory, which also tells us how the transmitted signal must be coded on a noisy transmission channel. In the simplest case (when interference is treated as noise), this capacity per Hertz of bandwidth is proportional to $\ln(1 + \text{SINR})$, where SINR is the signal-to-noise plus interference ratio. In the case of the downlink channel of a satellite-user link, the numerator of this ratio is the signal power received from the home satellite, and the denominator is the sum of the thermal noise power and the interference power (sum of the powers received from the other satellites in view). A similar formula applies to the uplink, where in this case, for a given user, the other users are those contributing to the interference perceived by the connecting satellite. The changing role of satellites also considers advances in multi-user information theory. In the current situation, on the uplink for example, the satellite is merely an intelligent reflector that transmits both the signal received from users and the noise to the anchor station. It may be far more efficient to proceed according to the “decode and retransmit” principle of information theory (from channel to relay) where the satellite decodes each of the signals and, once decoded, retransmits them to the anchor station. However, this requires satellites that are more intelligent, known as regenerative satellites, and therefore more calculations and more energy.

Sharing radio resources At any given time, a final user is usually attached to the nearest satellite (or the nearest in visibility to a docking station if there are no communications between the satellites). If there is more than one user attached to a satellite at any given time, access to the satellite is shared between these users over time, for example. In the simplest case, on the downlink channel, the instantaneous effective throughput of a user is therefore a function of both the capacity defined above and the number of users attached to the satellite at that instant.

Performance measures The global performance measures used are averages, in time or space, of these effective capacities or throughputs [28]. It is immediately apparent from the Walker delta example that these temporal averages are highly dependent on latitude. These indicators need to be corrected by considering interruptions at the times of end-to-end connection topology changes (between user and anchor station). As

already explained, one also uses as a performance indicator the sum of these effective flows over all the links in the network.

2.1.2 Adaptive beam-forming and user antenna

For LEO and MEO constellations, user antennas must enable real-time tracking of the fast-moving satellite(s) in orbit. A distinction is made between mechanical tracking antennas, semi-electronic antennas, and electronic antennas. Mechanical systems need to be able to switch between home satellites and are heavy (between 50 and 200 kg) and costly (at least 10,000 Euros). Semi-electronic systems are based on the motorization of a matrix array of antennas, each element of which has its own control system to change the signal phase. New-generation electronic antennas operate without motorization. They consist of an array of several hundred individual antennas (beamforming antennas), which are phase-controlled to perform a phase conjugation operation, with the aim of always pointing in the direction of a satellite. Starlink uses this solution, based on ST Microelectronics components, according to a “codesign” by Starlink and STM. This is one of the key features of their commercial success. Another promising solution, which consumes much less energy, consists of replacing these antenna arrays with a single antenna placed in front of a smart surface (metasurface) that acts as a deformable electromagnetic mirror, where the control circuit for each antenna element is limited to stop-and-go switching. Analogous to optical mirrors with phase conjugation, this type of device provides the equivalent of several parabolic antennas that can be oriented in real time. This is the solution proposed by Greenerwave, a French start-up.

2.2 Information technology

In large constellations, task planning and resource optimization are becoming extremely complex. These functions are handled by increasingly sophisticated control computing systems based on the achievements of 5G [1], artificial intelligence and distributed computing. Computing also plays a key role in the context of collision avoidance systems (see Section 4).

Resource scheduling The network operation is based on various tools from control theory, operational research and queuing theory, which enable the design of efficient algorithms for information flow scheduling, radio resource sharing, transmission power control, or spatial frequency reuse. The function of these algorithms is to share this overall transmission capacity between users present at a given time in the network, to maximize a certain collective metric, e.g., the sum of throughputs. Managing these resources when switching from one satellite to the next (handover) is particularly tricky in this context.

Virtualization Virtualization is the entirely software-based definition of network functions. This virtualization enables resources to be managed dynamically. This makes it possible to offer network slices specific to each use. Operators can thus easily create an

arbitrary number of secure, independent virtual networks from a single physical network, each dedicated to a group of users. The ability to remotely reconfigure after launch is essential in the satellite context.

Cybersecurity The cybersecurity of communications via low-orbit satellite constellations is still unsatisfactory, as demonstrated by the shutdown, an hour before the Russian invasion of Ukraine, of the VIASAT network used by the Ukrainian army. VIASAT is an American company marketing civil and military satellite telecommunications services, whose network was sabotaged by a forced update of terminals made possible by an intrusion into the operator’s administration network. The European NIS 2 directive aims to improve the security of satellite communications. Similar initiatives are also underway in the United States.

Massive data processing and artificial intelligence With the increasing number of Earth observation satellites, high-resolution images are becoming available in large numbers, and the volumes of data to be processed are becoming ever more massive. These data need to be stored, queried, and analyzed, an ensemble of operations which represent a considerable challenge for IT systems. This applies, for example, to geopolitical data (surveillance of borders or conflict zones) and those of an environmental nature (detection of greenhouse effect gas emissions). Both artificial intelligence and massive data analysis are essential for these tasks.

2.3 Propulsion

Putting satellites into orbit requires launchers with propulsion systems capable of delivering considerable levels of thrust (1,300 tons at lift-off for Ariane 5, 800 tons for Ariane 62 with 2 boosters and 1,500 tons for A64 with four boosters). These thrust levels can only be achieved by thermochemical means. Satellites also need on-board engines for altitude and orbit control. For a long time, on-board propulsion was provided by chemical engines fuelled by storable propellants. Today, a large proportion of vehicles use plasma thrusters. Development in this area is also of strategic importance. In the future, an increasing proportion (30-50%) of payloads will make use of electric propulsion systems.

2.3.1 Situation of European launchers

After the end of the Ariane 5 launches, Europe’s space industry has entered a complex phase while awaiting for the first flight of Ariane 6. Pre-flight tests led to the successful operation on November 23, 2023, of the Vulcain 2.1 engine over a duration of 8 minutes, corresponding to that of a real flight. The upper stage engine was also tested in September 2023, indicating that a first flight can now be envisaged for 2024, some four years behind the original schedule, enabling Europe to regain launch capability. Beyond 2030, Ariane 6 will be replaced by ArianeNext, a reusable launcher. Current developments include the Prometheus cryogenic liquid propellant engine in the 100-ton thrust class. The aim is to replace the current Vulcain 2 engine with one that would allow a reduction of

production costs by a factor of 10. This engine will be powered by oxygen and methane, stored in cryogenic form. This combination of propellants will enable to achieve the 100 tons thrust level with a specific impulse of 360 seconds, a lower value than that of the Vulcain engine, whose I_{sp} is 434 s, for a thrust of 135 tons. The loss of performance in terms of specific impulse is offset by a simplification of cryogenics, as methane can be stored in liquid form at temperatures below -162°C , whereas -253°C is required to store hydrogen in liquid form. The density of methane is also much higher (420 kg/m^3 versus 70 kg/m^3 for liquid hydrogen), enabling a significant reduction in tank size. A single turbopump can also be used, whereas two are required for LOx/H₂ engines. The thrust of the Prometheus engine can be modulated between 30 and 110%, and it would be used on the main stage, in clusters of 7 to 9 units, and on the upper stage. This would enable the main stage to be reused, an important feature in the competition in this field, in which SpaceX has taken a significant lead. In this context, several programs are underway in Europe to develop reusability concepts:

- Callisto, a CNES project in partnership with JAXA (Japan's space agency) and DLR (Germany's space agency), is a demonstrator designed to carry out reduced-scale test flights (a 15 m rocket with a one-meter diameter and a reusable cryogenic engine) to control the return to Earth, validate and estimate refurbishment operations between two flights. The first flight is scheduled for 2024.
- Themis, a reusable first-stage demonstrator designed by ArianeWorks to prefigure the main stage of the future ArianeNext launcher. Measuring 30 m in height and 3.5 m in diameter, Themis will be powered by three Prometheus LOx/methane engines. Themis will build on the advances made on the experimental Callisto vehicle.

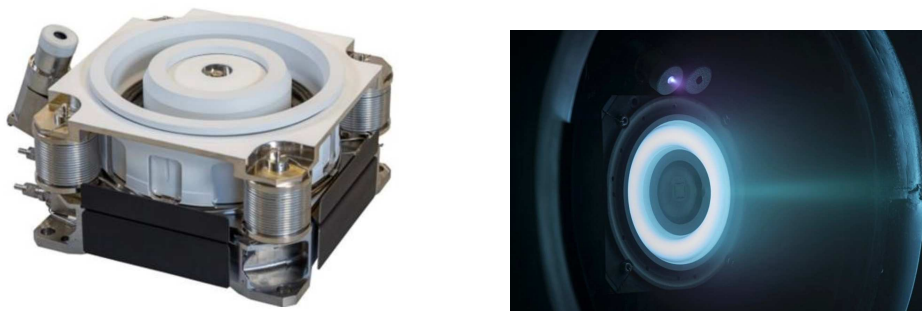


Figure 4: Left : plasma engine (Safran). Right : plasma engine PPS®1350-G in operation.

2.3.2 Plasma propulsion

Electric propulsion developments are relatively old, but their application to space is more recent. Telecommunications satellites use electric thrusters for maintenance in

geostationary orbit or any other type of orbit. Electric propulsion can also be used to station the satellite, replacing chemical propulsion. In this respect, it is interesting to compare these two options for this type of operation. On the one hand, one considers a typical apogee motor (the Mage 2) with a solid propellant mass of 500 kg and a thrust of 30 kN, and a plasma thruster produced by Safran (the PPS®1350) developing a much lower thrust of 0.1 N. The chemical engine will operate for 30 s, generating an impulse (the product of thrust and operating time) of around $9 \cdot 10^5$ Ns. The plasma thruster, on the other hand, will deliver thrust over a period of 4,000 hours, thus ensuring an impulse of $14 \cdot 10^5$ Ns greater than that generated by the chemical motor. This result is achieved by consuming 80 kg of xenon. The advantage in terms of mass is significant but is achieved at the cost of a 6-month increase in the time required for commissioning. Electric propulsion offers significant gains in terms of take-off mass. For satellites in geostationary orbit, with lifetimes of around 15 years, several hundred kilograms can be saved on an initial mass of around 3 tons. Electric propulsion can also be used to extend the life of low-orbit satellites, which are subject to the effects of the residual atmosphere and tend to progressively drop in altitude. There is currently a competition between two types of electric thruster architectures [21] that involves Grid Ionic Thrusters and Hall Effect Thrusters, also known as plasma thrusters. Both technologies use the same gas, xenon, which is injected into the motor body. Under the effect of an electron bombardment, this gas forms a partially ionized plasma. The ions are ejected at high speed (10 to 20 km/s) by an electric field established in the thruster. In ion engines, the electric field is formed by polarized grids. In Hall effect motors, a difference of potential is applied between a cathode and an anode in the presence of a magnetic field used to trap electrons at the thruster outlet, but that has little influence on the ions, which are ejected freely. The plasma thrusters developed by Safran and chosen by Airbus Defense and Space and Thales Alenia Space are simpler than their ionic competitors, chosen by Boeing for interplanetary missions. The range of plasma thrusters developed by Safran covers power ratings from 300 W to 5 kW. The most powerful thruster (PPS®5000), with a world-record service life of almost 20,000 hours, is designed to power geostationary communications satellites, ensuring their positioning and orbital control. Another PPS®X00 engine is designed to meet the needs of the smaller satellites used in constellations, ensuring orbital transfer, compensation of drag induced by residual atmosphere, and desorbiting at the end of life. These developments involve R&D efforts very often undertaken in partnership with CNRS laboratories, both by Safran and by start-ups such as Exotrail, which is developing miniature Hall effect motors for power ranges from 50 to 100W.

2.4 Outlook

Space Internet Several constellations already have satellite interconnection capabilities. Iridium’s satellites communicate in the Ka-band, and Starlink’s second-generation satellites communicate via laser optics. Another, more generic perspective is that of communications between constellations. The Space Based Adaptive Communications Node standard, which makes this possible, has just been proposed by DARPA. In the long

term, this will make it possible to build a new space Internet, a dynamic infrastructure comprising multi-orbital satellites (LEO, MEO and geostationary) and complementary to the core terrestrial Internet network. As already explained, the advantages of such a network as a complement to the terrestrial network are near-instantaneous projection capacity around the globe, independent of any changes or attacks that may occur on the terrestrial network; increased resilience for the global Internet network formed by the conjunction of the terrestrial and space networks; new capacities for joint observation and communication.

Software integration of terrestrial and satellite networks A second perspective, linked to the first, is the integration of satellites into 5G and 6G networks. This integration will require an overhaul of the organization of current satellite communications and will increase on-board energy consumption. However, it will ultimately have the advantage of complete compatibility with cellular network protocols, opening a host of new prospects.

Communications and computation in space Another longer-term perspective is that of moving some of the computing and storage power to these constellations, following on from the idea of localizing edge computing in the satellites fleet. This localization reduces latency and can be useful in the context of real-time applications [22]. 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. The difficulty remains sizable, however and 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.

3 Impact on astronomy

The launch of tens of thousands of satellites into low-Earth orbit is degrading access to the night sky and seriously handicapping ground-based astronomy. At the Cerro Paranal observatory in the Atacama Desert in northern Chile, site of the four 8 m telescopes that make up the Very Large Telescope (VLT) of the European Southern Observatory (ESO), many low-orbiting satellites are already visible from the observatory. Considering 19 constellations that will comprise up to 48,000 satellites over the next ten years, the number of satellites visible from Cerro Paranal at any given time can be estimated. Nearly 2,000 will be illuminated at the beginning or end of the night, 260 of which will have a brightness comparable to that of the faintest star visible to the naked eye, and nearly a hundred of which will be at least 30° above the horizon (simulations by Olivier Hainaut [10]). The consequences for the oldest of sciences concern both optical and radio astronomy, and will be dramatic if nothing is done, given the prospects for constellation development. It is worth noting that even low-orbit space observatories are beginning to be affected by constellations.

3.1 Impact on optical astronomy

The optical domain ranges from the ultraviolet to the mid-infrared. The main problem is the reflection of solar flux by satellites, particularly at sunrise and sunset, and for instruments with large fields of view. The growth in the number of debris circulating in low orbits will also pose a problem by the generation of an artificial background due to the reflection of sunlight at the beginning and end of night and that of the Moon by satellite debris in the upper atmosphere. Solar astronomy and the daytime observation of planets are not affected by this problem.

3.1.1 The nature of impacts

The direct consequences of the multiplication of constellations are as follows:

- the formation of light trails induced by the reflection of solar radiation from low-orbiting satellites towards the ground.
- increasing the brightness of the night sky by diffusion and reflection of moonlight by space debris.

The dominant effect is by far the first and is most pronounced at dusk and sunrise. The second effect is due to the increasing number of space debris. It is currently 6 to 7 orders of magnitude lower than the natural sky background. It could, however, no longer be negligible, and could even be significant in the event of the Kessler syndrome being triggered for a much larger population of satellites (see Subsection 4.4).

Satellite trails Astronomical observations generally take place from astronomical dusk to dawn when the Sun is at least 12° below the horizon. Observation is possible just before astronomical dusk or just after astronomical dawn for sufficiently bright objects, but not for the deepest sky, which largely motivates the realization of the largest telescopes. This astronomical observing time is also affected by bright natural sources, the most important of which is the Moon, which requires a distinction to be made between dark and bright (observing) time, with observations of the faintest luminous objects being made during dark time. The first impact of constellations is therefore to reduce the fraction of dark time.

LEO satellite constellations are visible at the beginning and at the end of the nights, around astronomical twilight since their trails are the reflection of sunlight by the satellites. The higher the satellites, the greater their impact. One Web’s satellites, at altitudes of 1,200 km, are visible for longer than those of Starlink, whose orbits are between 350 and 500 km.

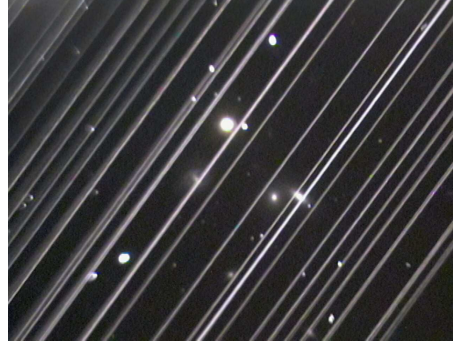


Figure 5 – Example of optical trails produced by 25 Starlink satellites in May 2019 on the NGC 5353/4 galaxy group.

The biggest impact: wide-field telescopes and the detection of transient sources Since the apparent motion of satellites is quick (0.4 degrees per second, i.e. about the diameter of the Moon per second for satellites at 500 km altitude), the impact of the trails is all the greater the larger the field of view of the instruments. This is the case for the instruments performing today, and especially in the decades to come, surveys in large fields. Among the main scientific objectives of these telescopes and instruments is the search for rare transient events, linked for example to the emission of gravitational waves, gamma-ray bursts, fast radio bursts, asteroids that could potentially be geocruisers, transits of exoplanets, and so on. The most ambitious programs also expect, by deploying observational resources that do not exist so far to make unexpected discoveries of new phenomena. The ability to observe transient and/or exceptional phenomena poses a particular problem, since the possibility of revisiting them is by definition zero and the loss consequently total. Other important objectives for wide-field telescopes are deep extragalactic imaging for, say, cosmology (dark matter and energy). These programs will be negatively impacted by trails due to constellations and perhaps also by the increasing brightness of the night sky, with a strong sensitivity to non-linearities resulting from bias subtraction, making these programs even more difficult.

Survey telescopes equipped with wide-field cameras already exist, such as VISTA in Paranal. The flagship telescope of this type is the Vera Rubin Observatory (VRO)², an

²The Vera Rubin Observatory is an 8.4-meter-diameter telescope with a very large instantaneous field of view, located on Cerro Pachón in Chile. Equipped with a 3.2 billion-pixel camera, it will observe from the ultraviolet to the near infrared. Its objective is to complete a survey, the Legacy Survey of Space and Time, over a ten-year period, during which it will cover the entire sky with a very wide-field camera in which France participated, and which will go into operation in 2024. With a field of view of around 10 square degrees, i.e. 40 times the surface of the Moon, this instrument is capable of scanning the entire visible sky every 3 or 4 days. This rapid rate of revisit of the entire sky observable from Chile will make it an extremely efficient instrument for the detection of transient sources such as supernovae or asteroids. The very long integration times over the ten years of operation will also make it possible to explore the cosmic web and characterize the dark matter in the Universe, matter whose existence has notably been established by Vera Rubin.

8.4 m telescope in Chile, equipped with a very wide-field camera, to the construction of which France contributed, which will go into operation in 2024. With a field of view of around 10 square degrees, i.e. 40 times the surface of the Moon, this instrument can scan the entire southern sky (18,000 square degrees) in just over three days, with a sensitivity reaching the visible magnitude³ of 24.

In at least ten years of planned operations, this means 825 visits to each part of the southern sky, ensuring both the detection of transient phenomena and an increase in sensitivity of almost 4 magnitudes compared with current surveys. Anticipated data losses for VRO are the highest just after sunset and just before dawn, the most favorable times for the detection of Near-Earth-Objects (NEO). The presence of satellite trails could therefore be systematic in VRO images for this field. In general, VRO estimates that 30% of the images taken will be contaminated by trails, with 42,000 satellites simulated for Starlink and almost all images for 400,000 satellites [23]. Other simulations [16] made with 26,000 satellites show similar results, from which we can deduce that more than 10% of the images will be affected, figures that rise to nearly 20% with this number of satellites for observations starting just before nautical twilight (Sun at 12° below the horizon). These figures are to be set against percentages of nights lost due to the weather: less than 20% of time lost at Maunakea, Hawaii (source: Japanese Subaru telescope), less than 12% of time lost at the VLT (April-September 2022), bearing in mind that these observatories are built on remote sites chosen for the transparency of the sky and the frequency of clear weather, as well as for their distance from man-made light sources, which represents a significant additional cost for these projects.

Impact on wide-field spectrographs The Vera Rubin Observatory is the first wide-field telescope of this generation. Others will follow; projects in the pipeline will use wide-field spectrographs with complementary capabilities. Losses are lower for spectrographs, but depend on resolution, with disturbances induced by the reflected solar spectrum. On the VLT, for example, the loss of data for the FORS spectrograph, one of the instruments currently in operation, is of the order of one percent at the beginning and end of the night, and less than 0.1% in the middle of the night in summer. It will be 0.7% for the HARMONI instrument of ESO's future Extremely Large Telescope (ELT) at the start of the night [2]. The loss will be much lower for the ELT than for VRO-type observatories, due to the much smaller field of view of very large telescopes.

Impact on space telescopes These losses do not affect only ground-based telescopes, as shown by a study published in Nature Astronomy [20], which shows that images taken by the Hubble Space Telescope, which operates at an altitude of 538 km, are affected by satellite trails whose presence increases over time. The percentage of contaminated images, currently 2.7%, could be multiplied by a factor of 10 with future constellations.

³The magnitude scale is a logarithmic scale that increases by 2.5 as brightness decreases by a factor of 10. An object 1,000 times less bright than another therefore has a magnitude 7.5 greater. The star Vega defines magnitude 0. The eye can detect objects up to magnitude 6, i.e. around 250 times less bright than Vega.

It is likely that in the future there will no longer be any telescopes in these low orbits, which present many disadvantages for observations.

Comparison with the brightness of the night sky The brightness of the sky is increased at the start and end of the night by light reflected and diffused by debris resulting from collisions between satellites and/or launch vehicle components. It also increases outside the new Moon due to lunar light diffused by debris. The brightness of the night sky has been estimated from a simplified model to obtain an order of magnitude of this artificial background per full Moon. The background is dimensioned by the statistically dominant 1 mm debris. It is 6 orders of magnitude smaller than the background emitted by the luminescence of the atmosphere through the excitation and de-excitation of chemical species, whose flux corresponds to around a magnitude of 22 per squared second of angle. It is also 7 orders of magnitude less than zodiacal light, which originates from the Sun's light reflected by small grains of interplanetary dust and has a visible magnitude of 20 per squared arcsecond of angle at high ecliptic latitudes. The artificial background produced by the debris is therefore very low for the moment, but if the number of debris were to increase faster than the number of satellites due to the Kessler syndrome, then its effect could no longer be negligible.

Reduced sensitivity and access time to astronomical sources Optical astronomical observatories are used to considering the constraints of time (observability of a source), sky brightness (phases of the Moon) and sky transparency when scheduling observations. A constraint on source height is added to this for observations requiring correction for atmospheric turbulence (observation at the diffraction limit of the telescope with a resolution better than seeing⁴). This constraint on source height is to minimize atmospheric thickness by minimizing the amplitude of light-wave phase fluctuations caused by atmospheric turbulence. Taken together, these constraints already lead to a limitation in access time to astronomical sources. Excluding the presence of constellation light trails, whether by programming observations based on precise satellite ephemerides, or in real time by closing a shutter, or a posteriori by data processing, is a further limitation on observation time and therefore on the sensitivity of astronomical instruments. Given the cost of building these large observatories (just under 1.5 billion euros for the ELT) and that of a night of observation (around 1€/s for an 8-10 m class telescope), the longer operating time needed to achieve the same result (which sometimes even becomes out of reach in the case of transient phenomena) as well as the additional work involved in data processing will lead to an economic loss in addition to the scientific losses. Additional costs may also be incurred for imaging instruments for satellite detection if ephemerides are not sufficiently accurate.

⁴Seeing is the limit of angular resolution imposed by atmospheric turbulence in the absence of correction. It is of the order of a second of angle at astronomical sites, and reaches a few tenths of a second of angle at the best sites.

Impacted Domains Astronomical studies in the optical domain that could be durably affected by the multiplication of satellite constellations are rare transient events, deep extragalactic imaging, asteroids (potentially NEOs), faint extended objects in the visible, exoplanet transits, discoveries of new phenomena. This non-exhaustive list covers both wide-field and narrow-field observations, as well as recurrent and exceptional observations. As mentioned above, the ability to observe transient or exceptional phenomena is thus diminished, without the possibility of compensating for it by revisiting. In addition to this, one should consider the impact on amateur astronomy and citizen science, combining professional work and public participation.

3.1.2 Denoising by signal processing

In the case of astronomical observations, the additional signals in the measurements are both a source of additional noise (trail photon noise, spatial and temporal signal fluctuations) and a source of additional bias (detector saturation, non-linear detector response when operating close to saturation). It is conceivable that some of these biases can be removed after modelling, but it is highly probable that not all biases can be eliminated from the data, thus generating a purely human-induced degradation of the data. Further signal-processing techniques may make it possible to reduce the impact of trails on astronomical data, but it is certain that this will not solve 100% of the problems affecting the data, some of which will be lost.

3.2 Impact on radio astronomy

Radio is defined here as the range from low frequencies to 50 MHz and extending to THz. This sub-section shows how the prospect of permanent pollution from the multiplication of constellations is detrimental to radio astronomy. The notion of local radio sanctuary (which consists in not transmitting signals towards terrestrial radio observatories and in stopping transmissions in certain channels when a radio observatory is in sight), which is accepted by some operators, greatly reduces the flux on stations, but does not eliminate it. Given the width of the primary and secondary lobes of satellite and radio telescope antennas, satellites are in practice seen by radio telescopes over most of the celestial vault. Furthermore, satellite electronics can emit at low frequencies and therefore constitute sources of noise, even when they are not emitting telecommunication signals, according to LOFAR's observations of Starlink. Protecting observations in intercontinental interferometric mode (such as those that enabled the Event Horizon Telescope to obtain direct images of the super-massive black holes M87* and Sagittarius A*) could require coordinated actions at different points in the constellations.

3.2.1 General description of the problem

Nature of disturbance Millimeter and submillimeter observatories work at frequencies ranging, for example, from 71 to 276 GHz (i.e. wavelengths from 1.09 to 4.23 mm)

for NOEMA at IRAM and from 35 to 950 GHz (0.3 - 8.6 mm) for ALMA. The low-frequency range for the Square Kilometer Array, for example, extends from 50 MHz to 15.4 GHz (i.e. wavelengths from 1.95 cm to 6 m), with the aim of extending to 24 GHz (1.25 cm). It can be estimated that current millimeter observatories represent an investment of around 2.5-3 billion euros, and that future programs will also represent an investment of this order. As far as low-frequency telescopes are concerned, the construction of the SKA represents an investment of around 2 billion euros. Some of these telescopes will carry out wide-field surveys, or even specialize in this type of survey, as in the case of the CMB-S4 millimeter project for measuring the polarization of the cosmological background (the B modes generated by primordial gravitational waves), whose signal is extremely weak. Comparable effects to those in the optical domain are therefore to be feared. However, radio observatories are not polluted by the reflection of sunlight by the satellites but by the radio emission from satellites, whether intentional for telecommunications or the result of radio emissions from on-board electronics. These emissions are therefore independent of the diurnal cycle and affect observations at any time of the day or night, since radio observations can be made at night as well as during the day, except for observations in sub-millimeter bands that are highly sensitive to air humidity, so there is no lesser sensitivity for radio observatories depending on the time of observation.

Insufficiency of radio protection Some radio observatories are built in sanctuaries which, along with their surroundings, are subject to a strict regime of protection against human radio emissions. Despite this, radio observations are hampered by these emissions, which are now the main source of interference to radio data, ahead of satellite interference. However, the existence of satellite radio sources and their growth prospects are a major potential hindrance. For the very large radio interferometer currently under construction, the Square Kilometer Array (SKA)⁵, radio sanctuaries have been established in the Karoo desert in South Africa (medium frequencies) and in the Murchison desert in Australia (low frequencies). Satellite transmissions in the 10.7-12.7 GHz frequency band encroach on a sub-band (Mid Band 5b 8-15 GHz) of the 7 bands selected for SKA. This will result in a loss of sensitivity in the frequency range used by the constellations, with astronomical observations taking at least longer. The scientific impact will be most significant for studies of molecular and atomic spectral lines at these frequencies.

Ground-based telecommunications or those based on constellations are not the only sources of interference, since the band between 70 and 116 GHz is used by military or

⁵The Square Kilometer Array is the largest radio observatory currently under construction. The final objective is to reach a collecting surface of 1 km². It comprises two interferometric arrays located in the southern hemisphere: one in Australia, in the Murchison Desert, for the low-frequency part (SKA-LOW, 50 - 350 MHz), the other in South Africa, in the Karoo Desert, for the medium-frequency part (SKA-MID, 350 MHz - 15 GHz). The project has been designed by an international consortium to investigate key scientific questions ranging from the birth of the Universe to the origins of life. For example, it will be able to detect the birth of the first stars within the first galaxies, marking the end of the dark ages of the Universe a few hundred million years after the Big Bang.

civilian radars (e.g. car radars), which have an impact on IRAM. It should also be noted that constellations and ground telecommunications are also sources of indirect interference. The 22 GHz frequency is used in the millimeter range for water vapor radiometry for wave phase calibration. Only a very small band is protected, whereas the flanks are needed to achieve very good sensitivity for estimating the amount of water vapour. The preservation of radio bands for astronomy was quickly perceived as a necessity as early as the 1970s, under the aegis of the ITU, which set up the Radio Astronomy Service. But this protection was based on the sharing of bands around wavelengths of interest to astronomy, given by atomic and molecular transitions. Since then, radio astronomy has made enormous progress in terms of sensitivity. As a result of the expansion of the Universe, the line located at 21 cm in the hyperfine structure of hydrogen is detected in the local Universe at 21 cm (1,420 MHz), but also at much longer wavelengths closer to the Big Bang, shifting this line from GHz to MHz as we go back in time. Another example concerns the progress made in studying the interstellar medium, with the identification of lines and bands unsuspected or even unknown in the Universe, such as the diffuse lines of the interstellar medium or those of aromatic polycyclic hydrocarbons, the study of which requires access to vast spectral ranges (particularly for the identification of specific molecules) that are no longer limited to the bands defined in the 1970s. The idea that studies would be limited to small spectral windows around a few specific lines is therefore outdated, making the existence of radio sanctuaries, where astronomers have access to a large proportion of radio frequencies, more necessary. Elsewhere, the spectrum ranges outside protected bands are almost totally occupied today due to the explosion in the exploitation of radio bands for telecommunications. This continued pressure on radio spectrum exploitation increases the likelihood of leakage to adjacent or nearby protected radio astronomy spectral bands.

3.2.2 Impact on data and calibration possibilities

A cell phone transmitting from the Moon produces a signal of 63 Jy (the Jansky (Jy) is a unit used in radio astronomy to measure the energy flux of radio signals, 1 Jy corresponding to $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$) and the energy flux of a telecommunication satellite is of the order of several million Jansky, where SKA's sensitivity is measured in micro-Jansky. This could lead to detector saturation and, at the very least, induced non-linear effects that are extremely difficult to calibrate. As an example, the state of the art in signal rejection for measuring the cosmological background microwave in the millimeter range is 10^{10} for the Planck mission, whereas here a rejection of 10^{12} is required, i.e., 100 times better. But this nonlinearity is greatly weakened if the satellites do not point into the area to be protected. Simulations of Starlink Phase 2 were carried out by SKAO to determine the probability of a satellite to within 1° from a source during an observation [7]. This probability, which reaches a maximum of 6% in certain areas of the sky, will increase with the multiplication of constellations and the number of satellites per constellation.

Impact on protected bands For example, the protected bands for radio astronomy at 10.6-10.7 GHz, which are just adjacent to those used for constellation downlink signals between 10.7 and 12.7 GHz, may no longer be usable as the number of satellites increases, due to harmonic contamination of telecommunications signals. To avoid this, some constellation operators accept not to use the channel between 10.6 and 10.7 GHz, and to make do with the other half of the band. The current sensitivity of low-frequency interferometers is not yet necessarily limited by these pollutions, and processing techniques are efficient for the time being [27]. This is the case, for example, for the detection of the reionization epoch signal with LOFAR with 500 hours of exposure [14]. But the additional subtraction of constellation signals will be costly in terms of observation time at the price of a loss in efficiency and therefore in final sensitivity. It should be noted that radio interferometers benefit from an advantage over radio telescopes used individually in that they measure spatially correlated signals and therefore naturally reject uncorrelated signals emitted by independent satellites. More problematic still, it has recently been shown, thanks to measurements made at low frequencies, between 110 and 180 MHz, by the LOFAR observatory, that radio emissions from electronics on board Starlink satellites, in addition to those used for telecommunications, are also to be taken into account in the constellation radio pollution balance [6]. The highest emissions measured exceeded the ITU ceiling by a factor of 10 [32], while the lowest emissions detected were already above the ceiling. Research - by the authors of [6] - is underway to develop better models and statistics for these emissions. To this could be added the potential problem of reflections of terrestrial radio signals by satellites.

Consequences of radio emissions The direct consequence of constellation radio emissions on observatories in this wavelength range is therefore the photon noise associated with man-made electromagnetic signals, as well as biases due to imperfect signal subtraction or detection non-linearities. While in the present situation the dominant sources remain ground-based telecommunications disturbances, and in some cases the astrophysical foregrounds themselves, the increase in radio emissions from space will lead to new difficulties as these biases will become dominant with the increase of the sensitivity of astronomical observations. As for the photon noise of radio pollution, which is a fundamental noise, it cannot be removed and the only solution to compensate for it is therefore to increase the integration time. The effects of bias could be estimated by measuring and modelling satellite radio emissions. But this would require fully-fledged instruments with observations made in parallel with astronomical observations, as their subtraction may be imperfect. At present, there are no plans to attempt such corrections. This would potentially have a significant cost on top of that of the observatories and their instruments, which the scientific communities will have difficulty in financing. This would require additional resources, which would reduce those needed for scientific instrumentation. It should also be noted that these signatures are difficult to calibrate over not easily repeatable integration times of hundreds of hours. In this context, for example for SKA, it will be difficult to achieve some of the scientific objectives that call for the part of the spectrum that is under threat, part of band 5b for SKA MID and

perhaps also a band of frequencies for SKA LOW. The problem is different depending on whether the constellations are in low or geostationary orbit. For the latter, signal unmixing techniques have been perfected, whereas for low-orbit satellites interference patterns change rapidly. Future generations of observatories like SKA that operate in phased array mode cannot retain all their raw data for post-processing due to the high data rates (several terabytes per second for SKA), making data calibration for rapidly changing bias sources even more difficult if not impossible at this stage.

3.2.3 Modalities to reduce the impact on radio observations

Single-site observations The simplest way to reduce the impact of constellations on radio observations would be to stop transmitting in the vicinity of observatories, or at least to ensure that they never point towards protected areas. Because of the emission in secondary lobes (or even higher order lobes, given the sensitivity of modern observatories), an avoidance angle of the order of 10° or more is essential for this overfly switch-off technique to be efficient. As far as the emissions of on-board electronics are concerned, discussions with operators and regulators are taking place to try to mitigate these emissions in future satellite series. In the same vein, inter-satellite communications could be a problem for the same reasons if done by radio. As in the optical field, correcting bias and scheduling observations, in the offending bands will be easier if the real-time positions of the satellites are known in advance or at least a posteriori. Regulators and satellite operators should therefore take into account the harmful impact of constellations on radio astronomy, and agree to produce or follow a set of rules currently being drawn up (see Section 7).

Intercontinental observatories The special feature of radio observatories is that they can be used in intercontinental interferometric mode to obtain the highest possible fine resolution on Earth at the wavelengths used. This is how, for example, the Event Horizon Telescope obtained the first resolved image of a black hole, M87*, by recombining data from 8 millimetric radio observatories spread over several continents and observing at 1.3 mm wavelength (230 GHz). In this type of observation, the source is necessarily low on the horizon for at least one of the observatories. Some observatories can benefit from a transmission interruption because they are located below the satellites. This is not the case for those observing almost at the horizon. A priori, they do not receive beams from these satellites, which are too low for them on the horizon. But, depending on the observation frequency, these antennas can collect the emission of the on-board electronics of these satellites or reflected radar signals. Spatially coherent signal detection should help to filter biases, provided they are out of saturation range. Constellations are therefore a potentially an additional source of limitations for radio observatories.

3.3 Actions underway

In the optical domain The astronomical community, through the International Astronomical Union (IAU), has launched several initiatives as early as the first Starlink

satellites were launched in 2019. Work carried out by several groups bringing together 150 astronomers and experts from industry and space policy led to the organization of the SATCON 1 workshop and the Dark & Quiet Skies 1 conference, which identified the problems and drew up initial recommendations for reducing the impact of the constellations. SATCON 2 and Dark & Quiet Skies 2 continued this work to identify how to implement the recommendations. The aim of these constructive recommendations is to make the public, politicians and industry understand the risks posed by constellations to astronomy. This approach has opened channels of discussion with industry, with the aim of minimizing impact by optimizing satellite design. These conferences were also an opportunity for the astronomical community to define common actions for taking constellations into account in the design of astronomical observatories, and define collective impact measurement campaigns and common software tools to mitigate the consequences of constellations. These actions paved the way for the creation on April 1, 2022, of the IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (CPS), led by NOIRLab for the optical domain and SKAO for the radio domain. The CPS is an operational structure without walls that embodies the will of astronomers to react and fight to inform about the harmful impacts of constellations on astronomical research. Through the IAU and its SPC, astronomers have been able to bring the need to preserve the astronomical heavens into the discussions of COPUOS, the UN Committee for the Pacific Use of Outer Space. In addition to raising awareness, these steps have led to the establishment of a dialogue with manufacturers, first and foremost Starlink, which has already led to upgrades of their satellites to reduce their reflectivity (second generation Starlink satellites have magnitudes lower than 7 [24]). These solutions have also been published for use by other manufacturers and operators [11]. It is also worth noting that manufacturers participate directly in the SPC, with the Industry & Technology working group co-chaired by an Amazon executive. These initiatives enable governments to understand the impact of constellations on astronomical research. Astronomers would ideally like COPUOS to discuss the establishment of international rules or at least guidelines that take astronomy into account and lead states to regulate constellations to minimize their impact. The 1967 UN space treaty defined the responsibility of states, but does not directly bind industry, nor does it include any provisions for the protection of observations.

In the radio domain The IAU’s SPC is a novelty for optical astronomy. On the other hand, there are international regulatory bodies for radio frequencies. The radio spectrum is governed internationally by the ITU for ground and space, which also regulates geostationary orbits for telecommunications. The ITU, however, plays no role in the use of low orbits, and does not recognize radio quiet zones at international level. European radio astronomers have joined forces to defend their interests within the European Science Foundation’s Committee on Radio Astronomy Frequencies (CRAF). CRAF is an observer on the CEPT (European Conference of Postal and Telecommunications Administrations), which includes the ECC (Electronic Communication Committee). At national level, radio astronomy is represented by the MESR, which has a seat on the

National Agency for Frequencies (ANFR). Decisions taken at different international levels are to be applied by the agencies within the framework of the national laws to which they are subject. As far as observatories are concerned, SKAO is present at the ITU and CRAF, for example. On the space side, COPUOS is the appropriate body at the UN, where SKAO is also an observer along with the IAU, ESO and the European Astronomical Society (EAS), and as such participates in the work of the STSC (Scientific and Technical SubCommittee).

First results These initial actions have already had a positive effect through dialogue with SpaceX, OneWeb or Amazon-Kuiper. For example, the NSF and SpaceX have signed an agreement limiting the brightness of satellites to magnitude 7 to make them invisible to the naked eye and avoid saturating VRO detectors [4]. SpaceX has also pledged to respect standard protection measures for radio astronomy. But this is a modest first step, as the reduced brightness level still leads to the anticipated contamination of 30% of VRO data for 42,000 satellites. All these actions depend on the goodwill of companies in an unregulated market where strategic and economic considerations are strong. The launch of the BlueWalker III satellite in 2022 is just the kind of event we can expect in the future. This prototype features an antenna with a surface area of 64 m² that reflects sunlight with a brightness that makes it the sixth brightest source in the sky, with a visible magnitude of 0.4, on a par with Procyon [26]. The IAU, via the SPC, reacted to the satellite's launch with a press release [17]. The proliferation of this type of satellite would of course be catastrophic for astronomy.

3.4 Prospects for astronomy

The future is therefore far from under control, with the multiplication of strategic and commercial partners and constellations. While few constellations have been launched to date, the most important being Starlink, the situation is already critical for the next generation of optical observatories. The impact on the detection of transient sources, for example, could be very damaging. The dialogue initiated by the international astronomical community should be pursued, but support from the public authorities is necessary if we are to avoid major investments seeing their scientific impact reduced, as this dialogue is subject to the vagaries of international diplomacy and economic competition. We can, however, pin some hopes on a declaration by the United Nations made during its 61st session (Vienna, January 29-February 9, 2024) and recently adopted by delegations representing 102 countries within the COPUOS framework. The COPUOS scientific and technical subcommittee has agreed to add an item to the agenda for the next five years in order to discuss emerging issues and challenges for astronomy related to large satellite constellations.

4 Environmental impact

There are today about 14,000 satellites in orbit, of which around 35% have been launched in the last three years. The number of satellites placed in orbit per year, which was relatively stable between 1975 and 2013 at around 75 to 100, became 300 in 2019, rising to over 1,000 in 2020, 1,600 in 2021 and 2,250 in 2022. The number of launches also increased, but to a lesser extent. In 2012, there were around 75 orbital launches. By 2023, the number will be around 200, with each launch very often corresponding to the placing into orbit of several satellites. The number of satellites in orbit is expected to reach a hundred thousand during the next decade. The growth in the number of satellites in orbit is leading to an increase in the number of operational end of life for these satellites, and a multiplication of returns to Earth. It is also leading to an increase in the number of debris, which could reach a worrying super critical phase. In addition, this growth in the use of space has an impact on the upper atmosphere and the environment that is insufficiently considered at present. A recent report by the GAO (Government Accountability Office, the auditing body of the US Congress) [13] highlights the environmental dangers resulting from the multiplication of launches, the establishment of constellations on the one hand, and the re-entry of satellites into the upper atmosphere on the other.

4.1 Environmental impact components

This sub-section successively reviews the impact of launches, in-orbit propulsion, and atmospheric re-entry of end-of life satellites. It also addresses the issue of space debris, collision avoidance and the possible multiplication of debris through the Kessler syndrome.

Impact of launches Launches are accompanied by emissions that depend on the type of engine and the propellant couple powering the engines. The oxygen/hydrogen pair, used on the main stage and second stage of Ariane 5 launchers (Vulcain and HM7B cryogenic engines) and Ariane 6 (Vulcain and Vinci cryogenic engines), mainly produces water vapor. However, the P230 solid boosters (EAPs) fitted on Ariane 5 and the P120s fitted in groups of two or four on Ariane 6 (A62 and A64) also emit aluminum particles and chlorinated products. The latter, and hydrochloric acid, have a major impact on the launch pad area and are also involved in the chemical evolution of the upper atmosphere [5]. SpaceX Falcon launchers, the Starship heavy launcher and, more generally, all launchers using an oxygen/kerosene or oxygen/methane pair emit carbon dioxide, water vapor, unburned hydrocarbons, and soot particles. These particles, often referred to as “black carbon” (BC), are emitted in large quantities by LOx/kerosene engines due to incomplete combustion in a fuel-rich environment. BC particle emissions are therefore much higher in proportion than those generated by aircraft engines, in which the oxidizer is largely in excess [31]. Emissions from each launcher are of the order of a thousand tons, around 1,400 t for each Falcon 9 rocket. The hundred or so launches of Space X’s Falcon rockets during 2023 led to the emission of around 140 ktons,

and the quantities of water vapour and carbon dioxide from these launches remain much lower than the sum of emissions from transatlantic civil aviation flights. However, the high proportion of BC in the gases produced by rocket engines, measured per unit mass of fuel, is much higher than corresponding to civil aircraft. According to [31], the ratio is of the order of 10^4 . This high proportion of BC from launchers and the multiplication of launches mean that soot particles have an impact that deserves to be considered [31]. 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 molecule and particle residence times are significant, and aerosols can accumulate over many years, this modification of chemical composition could interact with the ozone layer, reducing ozone concentration by creating sites favoring the ozone decomposition reaction [25], changing the radiative balance and changing the temperature distribution. There are uncertainties about these effects due to lack of data, as measurements are difficult when the volume fractions involved are quite small. As the quantities of fuel used by launchers are relatively small compared with those used in civil aviation or automotive transport, this issue has generally received less attention.

In-orbit propulsion In the field of on-board propulsion, advances have been made with the implementation of plasma propulsion to replace engines using storable propellants such as hydrazine and nitrogen tetroxide. However, plasma propulsion uses rare gases such as xenon, which leads to problems of availability and the need to find alternative solutions. The resource problem could lead to the use of alternative propellants such as argon or solid-state iodine.

Uncontrolled atmospheric re-entry This problem is predominantly linked to the re-entry of constellation satellites. For the year 2022, there were about 2,400 objects re-entering the atmosphere with a total mass of 340 t and an equivalent surface area of $3,500 \text{ m}^2$ [8], p.44. It is interesting to compare this figure with that of the mass of meteorites that enter the Earth's atmosphere each year, which is thought to be of the order of 15,000 to 20,000 t per year. The risks associated with uncontrolled atmospheric re-entry are well known: first there is random fragmentation of the satellite between 90 and 60 km due to dynamic pressure, then partial melting between 70 and 50 km due to heat flux. These objects burn up in the atmosphere, but not completely: between 10% and 40% of the mass survives re-entry and impacts the earth's surface. This applies to the electric motor, batteries, and flywheels. The rest vaporizes in the upper atmosphere. A significant proportion of the mass therefore reaches the Earth's surface, where its fall can cause destruction and loss of life.

4.2 The problem of space debris

Space debris is 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 [3].

Already in Earth orbit

- Ten thousand tons of debris.
- 28,000 objects over 10 centimeters. 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);
- Half a million marble-sized pieces of debris.
- One hundred million measuring about one millimeter.

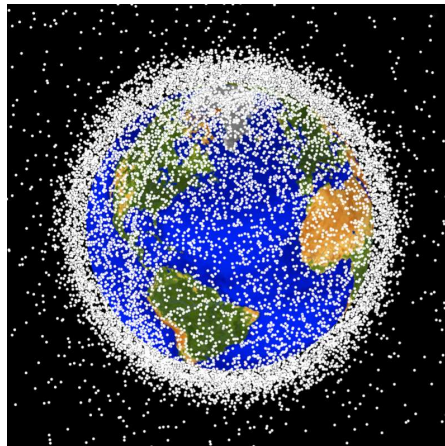


Figure 6 – Catalogued objects larger than 10 cm - NASA, 2022.

The effect of gravitational diffusion combines with the diffusion associated with collisions to generate a quasi-isotropic distribution of debris.

The debris originate from a variety of sources, including:

- Satellite destruction tests by certain countries (USA, Russia, China); the destruction of a satellite by explosion creates thousands of new pieces of space debris.
- Satellite collisions (a remarkable example of this is the collision between Iridium 33 and Kosmos-2251 on February 10, 2009). The impact energy is very high, due to the relative velocity (which can reach 15 km/s).

Aluminum debris with a radius of 1 mm have an energy of 1 kJ, equivalent to a bowling ball at 100 km/h. Debris with a radius of 1 cm have an energy of 1 MJ, equivalent to a car travelling at 130 km/h. A piece of debris 10 cm in radius has an energy of 1 GJ, equivalent to 40 kg of TNT.

At this stage, 97% of the current debris originates from the following three countries: USA, Russia, and China. With the number of launches increasing by 27% between 2021 and 2022, this situation can only worsen, and there is a risk of an uncontrolled proliferation of debris.

4.3 Collision avoidance systems

With the proliferation of satellites and space debris, emergency maneuvers to avoid collisions are essential. This requires that satellites be equipped with suitable propulsion systems, and that centralized Space Surveillance and Tracking systems be developed. The latter's functions are to maintain and update the ephemeris of satellites and catalogued debris, calculate collision probabilities, and inform operators in good time so that

they can implement avoidance measures. The growing number of satellites and debris in low and medium Earth orbits makes this a highly complex task. Artificial intelligence could enable more efficient collision avoidance operations

4.4 The Kessler syndrome

As early as 1978, Nasa consultant Donald J. Kessler envisaged the possibility of a process, known today as the “Kessler Syndrome”, whereby the increasing number of satellites and debris in orbit could lead to a multiplication of collisions and even a chain reaction with an exponential increase in the amount of debris. The region most directly concerned is that between 300 and 1,100 km above sea level. Several factors could contribute to the onset of this syndrome:

1. The uncontrolled launch of too many new satellites (if this syndrome is considered, the indirect costs of these uncontrolled launches could be huge),
2. The growing use of anti-satellite weapons, which generate large quantities of debris,
3. The difficulty of predicting collisions and implementing collision avoidance procedures. Various simulations have been carried out to determine the satellite and debris densities that lead to this chain reaction. The latter, which is stochastic in nature, has not been extensively investigated and is poorly understood.

4.5 Actions underway

Debris It is imperative that the debris problem be addressed based on the following principles:

- Ban on anti-satellite operations,
- Controlling the generation of debris, by managing the end of life of satellites,
- Implement collision avoidance through ephemeris maintenance and mandatory satellite motorization.

At this stage, this issue is only the subject of a discussion forum between agencies, with the development of best practices, but there are no legal constraints or penalties. However, the ISO/DTS6434 standard brings together norms based on the above principles. The USA is also planning to introduce binding rules, notably on desorbiting processes and orbit protection. Europe and France are forerunners in this field, thanks to the French Space Law. Every satellite must be able to be de-orbited at the end of its life. A fundamental issue in this context is the organization of space monitoring and surveillance.

Space activities and the environment The analysis of in this section highlights the need for more in-depth consideration of the impact of space activities on the environment. On the launch side, one notes that the quantities of propellants used are small compared with the quantities of kerosene consumed by aviation, but it was also indicated that the proportions of BC aerosols are much higher than those found in the gases originating from aircraft engines (the estimated factor is 10^4 between the two). Actions of the same nature as those described above would be desirable in the field of pollution generated by satellite launches and re-entries into the atmosphere. This requires both collecting data and using this data to build models and thus estimate the effects of emissions, particularly those associated with soot and aluminum particle aerosols, on the upper atmosphere in terms of chemical evolution and warming.

5 Economic stakes

Economic issues need to be addressed in a context of emergence of new spatial states, new industrial players such as SpaceX and Amazon, and, more generally at a stage of intense development of NewSpace in the United States and increased R&D budgets in Europe. All this is leading to the deployment of a web of new start-up entrants to complement the major projects. This section describes this new context before reviewing the business models for the various constellation functionalities. These economic models are not easily separable from the competition for orbit and frequency occupancy and, more generally, from the sovereignty issues that are the subject of the following section.

5.1 The NewSpace context

Before the advent of NewSpace, space was de facto reserved for the military and states. Satellites whose mission was neither scientific nor military were mainly used for TV and radio channels broadcasting. This type of service offered by geostationary satellites is declining for television but remains on the rise for radio channels (digital radio). NewSpace appears to be the major inflection point in relation to this situation. In this context, one is witnessing the creation of a new industrial fabric aimed at the softwerization of space, with giants like Starlink, start-ups and SME (small and medium-sized enterprises) in large numbers (12,000 companies, mainly in the United States, thanks to substantial state financial support provided, the action of the National Space Council and the engagement of several thousand investors). The United States accounts for 84% of government investment in global NewSpace with as one objective the capturing of the largest market share in the communications sector.

5.2 The situation in France and Europe

5.2.1 The budgets

At the European Space Agency Ministerial Conference held in Paris on November 22 and 23, 2022, ESA member states decided on a total European investment of €17 B. France

has targeted two priorities under this subscription: strengthening European autonomy in the space sector, particularly in terms of access to space, telecommunications, and the competitiveness of the European space sector, and improving knowledge of climate change. France remains Europe's biggest contributor to space.⁶ In terms of launchers, France is providing support for Ariane 6 (€523 M), the continuation of the Themis reusable first-stage demonstrator (€50 M) and the Prometheus engine (€156 M). Defined on December 7, 2021, the space component of the France 2030 investment plan was endowed with €1.5 B, with the priorities of catching up in key areas such as reusable launchers or constellations and investing in new uses.

5.2.2 The satellite industry

Several major European groups, such as Airbus, Thales Alenia Space and OHB, set the standard.

5.2.3 The launcher industry

Europe has considerable expertise in launchers, and the Ariane launcher has been a success story. Replacement of Ariane 5 is currently underway, and the first flight of Ariane 6 should take place before the end of 2024. However, Ariane 6 does not allow reuse, which is now routinely practiced by SpaceX and has led to a reduction in launch costs. As mentioned above, several current projects aim to equip European launchers with reusability capabilities, with the development of the 100-ton thrust Prometheus engine, which could replace the Vulcain on Ariane Next. Dozens of start-ups in Europe are working on the niche of smaller launchers for on-demand replacement of small satellites.

5.2.4 The IRIS² project

The project (Infrastructure for Resilience, Interconnectivity and Security by Satellite) project is designed to provide a means of communication for governments, businesses, and citizens of the European Union (see also the end of Subsection 1.3.1).

5.2.5 New entrants

New European entrants are launching fleets of small or nano satellites, with development costs far lower than those of geostationary satellites⁷.

Here are just a few examples:

- U SPACE: A French start-up based in Toulouse, supported by CNES, DGA and BPI, which develops CubeSats, aims to move upmarket in constellations and offers services to maintain space systems in operational condition.

⁶France devotes €3 billion/year over 3 years to space, which is the largest European budget.

⁷It should be noted that while LEO satellite development costs are lower than those of geostationary satellites, the lifetimes of the former are shorter than those of the latter.

- **AEROSPACE LAB:** A company backed by Belgium, whose high-speed satellite manufacturing plants are aiming to produce two satellites a day, using technologies from the automotive sector.
- **ASTROCAST:** This Swiss start-up, already described above, offers monitoring, geolocation, and object communication services, and already has some twenty micro-satellites in low Earth orbit.
- **CONSTELLATION TECHNOLOGIES:** the ESA-incubated start-up described above, which aims to launch a broadband constellation operating in the 5G millimeter bands, in synergy with terrestrial operators.

5.3 Economic models

5.3.1 Broadband

A key question in the field of constellations is the economic viability of their offer of universal broadband coverage. Initial constellations, which perhaps didn't really offer broadband and required large antennas that offered little compatible with mobility, all failed from an economic point of view before reorienting themselves towards "professional" applications. The economic failures of Globalstar or Iridium can be partly explained by the fact that these networks required the implementation of dedicated, heavy, and expensive terminals. The potential of satellite communications could have been different if this lock had been lifted and if consumer smartphones had been able to take on the role of connection terminals. Even for large constellations, satellite link Internet coverage service cannot compete with that offered in areas well covered by terrestrial networks, particularly when 5G is deployed. Constellations can, however, complement terrestrial networks for coverage of white areas and that of landlocked territories (a good example is French Guyana) where the cost of deploying optical fiber is very high, and coverage by constellations is economically justified. However, the market associated with white zone coverage remains small because the number of users is not large (if it were otherwise, coverage would be provided by the 5G network). What's more, most white areas are economically disadvantaged and therefore cannot be major sources of revenue for satellite network operators.

Starlink's business model At this point, it is worth considering the case of Starlink. This network currently brings together one to two million customers, corresponding to a turnover of the order of one billion dollars, which is relatively modest but allows us to break even or come close to breaking even financially. It should be noted that the use of the Starship rocket for satellite orbiting could further reduce launch costs. For Elon Musk, founder of Starlink and SpaceX, what sets Starlink apart from other constellations would be the following assets:

- Reduced and controlled launch costs thanks to the choice of launcher reuse,

- Starlink’s ability to act as a provider of global real-time Internet access for Tesla automobiles,
- Starlink satellites that rely on the use of consumer electronics technologies and a difference in manufacturing and human resources management methods compared to those that prevailed until recently in the space industry, leading to a reduction in costs,
- An evolution towards heavier (1,500 kg) 2nd generation satellites that communicate with each other by laser.

The routine reuse of launchers is effective as a competitive advantage. The second point could also be an asset, and it is interesting to note the potential interest of German automotive manufacturers in investing in constellations for this very reason. It is not certain that Starlink will ever become the source of profit to finance the Mars conquest project. However, to achieve this, SpaceX’s new bet is the Starship, with a take-off mass of 6,500 to 7,000 tons and 33 Raptor engines running on liquid oxygen and methane. Engine operation would be managed by artificial intelligence to avoid the collective phenomena that can occur in configurations that use a large set of propulsion systems. The launcher’s structure is made of steel, a heavier but more resistant material than light alloys. Thrust can be adjusted by changing the number of engines. This vehicle could reduce launch costs by a factor of 20.

However, the first two tests were not entirely successful. The first Starship launch, on April 20, 2023, ended in an explosion a few minutes after lift-off, as the stages failed to separate. Three and then six first-stage engines failed. The second launch (November 18, 2023) also ended in an explosion, but after separation of the second stage. SpaceX relies on failures to correct Starship, as these tests reveal many implementation problems for this giant launcher. Extensive damage to the launch pad after the first launch led to corrective measures, including the injection of water showers at liftoff. However, the impact on the launch pad environment remains significant.

Elon Musk is considered by some to be at the helm of the world’s leading space power, and if Starship achieves its objectives, it will usher in a new revolution in constellation launch cost reduction.

Potential interactions of constellations with 5G/6G cellular networks One of the business models envisaged is that of agreements between terrestrial and constellation operators enabling the latter to use 5G frequencies. The 3GPP (Third Generation Partnership Project), which is responsible for developing technical specifications for cell phone networks, will shortly be proposing a standard for a 5G chipset⁸ with non-terrestrial communication functionality. Interactions between terrestrial networks and low- and medium-orbit satellite networks will be fully standardized in the context of 6G. This opens new perspectives that are currently being studied (offloading, backhauling).

⁸A chipset is a group of integrated circuits that can be used to perform a single function, in this case communication with a 5G network. Chipsets are manufactured and marketed as a whole.

For example, Constellations Technologies, an ESA-incubated start-up, is banking on the use of 5G's millimeter bands. A key issue here is that of terminal antennas. It is worth noting the existence of projects with the potential for direct interaction between the satellite and a standard phone, such as BlueWalker 3, a prototype satellite from AST SpaceMobile featuring a 60-square-meter antenna to establish a direct connection with cell phones via standard frequencies. BlueWalker 3, which will be placed in orbit in 2022, prefigures commercial satellites known as "BlueBirds". Apple and Samsung will also be marketing smartphones that enable direct Internet coverage via satellites networks for certain applications. Apple offers a satellite SMS service in its new generations of smartphones.

Competition and return on investment in the broadband sector In the competition between constellations for broadband communications, "the winner takes all", and it will be difficult to compete with Starlink. No other company has the competitive advantage of low launch costs. Starlink follows a monopoly model like that exploited by Microsoft, whose operating system for personal computers has become indispensable.

Even if new broadband markets are developing today, such as services for transport companies (sea and air) or those based on using the same frequency bands as terrestrial networks and gaining access to their markets, it is difficult to see what could enable competitors to offset investments that are estimated in billions of euros and make profit.

5.3.2 Earth observation

The question of economic models is less central in the field of Earth observation than it is for broadband communication, since a significant proportion of these observations are essentially scientific in nature. Data collection in some of the fields listed in Subsection 1.3.2 does, however, lead to the launch of constellations based on classic business models for commercializing these data, or even responding to data orders. As the associated constellations are small (since continuity of coverage is not needed), they require far less investment than broadband constellations. This opens new prospects for this type of activity.

6 Sovereignty issues

Beyond the commercial offer of universal broadband, the quest for sovereignty could be the main reason for deploying satellite constellations in LEO and MEO orbits. The advantages of these constellations are as follows:

- Their resilience, a corollary of the deployment of a very large number of reconfigurable satellites. One can destroy one of them, but it's difficult to attack all of them,
- Their coverage of the polar regions (at least for star configurations). This coverage is not well provided by geostationary satellites,

- Their low latency, which can play a central role in applications where transmission times are critical,
- Their universal coverage, giving access to continuous observation of events around the world and to new means of action,
- The absence of binding regulations and the resulting flexibility in implementation.

6.1 Sovereignty in telecommunications

Constellation-based communication networks de facto free themselves from all the rules that are imposed by States on terrestrial network operators operating on their soil:

- A low-earth-orbit satellite operator can deploy broadband communications services in a country without going through the country's regulatory authorities, whereas 5G and 6G network frequencies are controlled by these authorities. For the time being, however, this form of competition does not jeopardize terrestrial operators of 5G networks, for the reasons already mentioned (satellite services are currently only competitive in white zones).
- Current constellations do not comply with the sovereignty rules that apply to terrestrial 5G networks. For example, the rule that the core network must be hosted in France does not apply. In this respect, it should be noted that Starlink's core network is hosted in the USA by Amazon Web Services, which means that it is not possible to control the confidentiality of communications between users of this network.

The deployment of these networks in their current forms (Starlink, Amazon) can therefore only be seen as a direct loss of sovereignty for states in this sector.

6.2 European sovereignty

France strongly supports the European IRIS² project. This constellation is seen as a necessity for France's independence and access to a secure, resilient communication network. European industry has the skills to develop such a project. A consortium with Thales and Airbus will respond to the European Commission's call for offer to launch a sovereign European constellation with both commercial and defense functions. States that master these secure, universal communication systems, independent of local conditions, will have a major geopolitical advantage. The other priority for Europe is to retrieve a reliable launcher enabling independent access to space for missions of all kinds.

6.3 Military use

Military use of constellations In the military field, Earth observation and secure communications play a key role in both peacetime and wartime. These two functions are

currently carried out by means of specific and dual constellations. The global coverage of constellations is of major interest for military applications. For example, Starlink's activities are heavily subsidized by the US Department of Defense (DoD). The example of Starlink's use in Ukraine illustrates the ability of constellations of this type to provide high-speed coverage and means of action, including operational ones, in countries in crisis or war situations. In this context, the speed of overflight and of obtaining images and data on the country concerned is of prime importance. So is the ability to rapidly revisit a certain region, 24 hours a day, to detect anomalies or conduct operations in any theater, which is not possible with geostationary satellites or conventional constellations with a small number of satellites. The fact that armies can buy data from private operators offering global services for operational needs is also a new development that is both a source of resilience and dependency. This dependence is reduced, however, if the number of independent private constellations is large. Eventually, very dense constellations of low-orbit satellites may also enable better coordination of various types of weapon systems for collaborative combat, which requires low latencies and continuous coverage of the operating terrain.

Physical and cyber-attacks on constellations In today's context, with the proliferation of players in the space sector (and the presence of countries that were previously absent, such as North Korea), space is more than ever a place of conflict, where questions of satellite security and on-board system cybersecurity must be considered. Several countries are studying ways of neutralizing a constellation, notably through cyber-attacks, jamming methods, or even by satellite destruction. Missile strikes on low-orbit satellites are examples of physical attacks with far-reaching consequences for the debris issue. In the case of constellations, cyberattacks are the most promising, as the spatially distributed nature of the constellation makes physical attacks far more difficult than for terrestrial infrastructures. As already mentioned, a space-based Internet network is considerably more resilient than the current system of cables and autonomous domains. The cyber-attack on the VIASAT satellite communications network that was used by the Ukrainian military just before the outbreak of war is a recent illustration of the fact that such a well-executed attack could in principle interrupt the communications functions of constellations made up of thousands of satellites. Since the safety of constellations is essential for military applications, the possibility of laser links between the satellites in a constellation is of interest for reinforcing them since they are neither interceptable nor interferable from the ground or from satellites, unlike radio communications.

7 Regulation by international and national agencies

Access to and use of space are regulated in the United States. The same is true in France, which also defines the regulations for Europe, since it is the nationality of the launch site - Kourou - that determines the applicable law, particularly about the management of space debris. By way of example, the rules governing the fragmentation of rocket stages exist in France and the United States, but not in China. International rules on access to

geostationary orbits are long-standing. The organization in charge of this access is the ITU. On the other hand, there is very little international regulation today in the field of LEO and MEO constellations, and the major space powers (China, USA, Russia) are free to act as they wish.

7.1 Involved institutions

The institutions involved at national and international levels are as follows:

ITU The International Telecommunication Union (ITU), which brings together 70 countries, is responsible for non-terrestrial operators. The ITU satisfactorily manages geostationary orbits. In the LEO and MEO domains, it also allocates orbits and Ka and Ku frequency bands. The principle is first come, first served. This practice leads to a de facto occupation of space in these frequency bands by the operators quickest to apply. The only constraint is to effectively use the acquired right. If the satellites are not installed in the allocated orbits, the right is lost.

3GPP The 3rd Generation Partnership Project has been integrating satellite standards as part of 5G since 2017 and aims for full integration of terrestrial and satellite networks in the 6G standards. The prevalence of 3GPP standards in the field of smartphones should, in time, lead to a form of international standardization in the field for everything to do with software. In the long term, therefore, satellites will certainly have standardized interfaces based on 3GPP standards, at least for constellations aiming for direct access to 5G or 6G smartphones.

Regulatory agencies in the United States The U.S. regulatory agencies concerned with the development of satellite communications networks or involved in licensing are as follows:

- **FCC:** the Federal Communications and Information Commission works with the ITU.
- **NTIA:** the National Telecommunications and Information Administration (NTIA, US federal government) is involved in licensing the use of licensed radio frequencies.
- **NOAA:** National Ocean and Atmospheric Administration.
- **FAA:** the Federal Aviation Administration.

EUSPA EUSPA (“European Union Agency for the Space Programme”) is responsible for:

- Satellite navigation services through the Galileo constellation,
- Earth observation services based on satellites and data collected by Copernicus,

- Secure satellite communications and services with the future IRIS² constellation,
- And soon, front desk services for EuSST (the European surveillance and tracking service).

7.2 The need for international regulations in this field

The organizations listed above provide only partial and fragmented coverage of the issues raised by constellations.

As already mentioned, access to low- and medium-Earth orbits is essentially free: any entity, state or private, wishing to launch a constellation can do so, without having to comply with any regulations. Wavelengths and orbits are allocated on a “first come, first served” basis by the ITU, leading to a race to occupy the resources in question without any consideration of negative impacts. International bodies with partial jurisdiction over certain aspects of constellation implementation and operation have so far issued only non-binding recommendations. For example, the issue of debris is the subject of an international standard published in January 2024 (see Subsection 4.5), which can be seen as a quality label to be adopted by willing states and industry. While it is recommended that anti-satellite weapons be banned, no authority is empowered to sanction any violation in this area. However, the risks induced by debris are sufficiently obvious and incurred by all stakeholders, so that interest drives them to respect certain precautions. The problem of the impact on astronomy is taken care of at the scientific level within the framework of organizations like the IAF to identify the nature of the problems and develop good practices, but likewise without binding force. The problem posed by the planned deployment of constellations must be considered as a whole, in all its dimensions: a global approach to the impact of constellations should replace the current fragmentation. A sustainable, global solution must be found to the problem, before major, irreversible damage is inflicted on the planet’s environment, geostrategic balances, democracy, and science.

Without waiting for an international agreement to be reached and a law covering all aspects involved to be enacted, which will take several years, it is a matter of the utmost urgency that any new deployment of LEO and MEO constellations should comply with the imperative of reversibility. This mainly implies that the satellites ends of life should be programmable, so that their re-entry into the atmosphere be in conformity with strict rules designed to reduce risks and nuisances.

The question then is how to impose rules of good conduct on players in the field, designed firstly to ensure the reversibility of future deployments for the period ahead, and secondly to establish a code of ethics based on a balance of coordination that everyone has an interest in respecting. A first step would be to set up an international liaison committee between civil and military academies and research organizations, tasked with proposing a code of good conduct, together with measures to motivate stakeholders to respect the code. This kind of mechanism as part of the soft law of international law might draw on experience gained in other fields. Consider, for example, the processes that led to the Antarctic Treaty, which predates the emergence of the notion of soft

law, or that which gave rise to the International Atomic Energy Agency, as well as the still imperfect attempts to impose intangible limits on genetic engineering, as possible options given the conjunction of civil, military, economic and environmental aspects, .

8 Conclusions

In just a few years, the space industry has entered a new phase known as *NewSpace*, characterized by easier access to space, an abundance of projects, more and more small satellites being put into orbit, and the development of constellations comprising very large numbers of satellites with most of these developments exploiting low and medium-altitude orbits for the possibilities they offer in the fields of telecommunications, geolocation, and Earth observation. Among these applications, communications for universal broadband access to the Internet is also the one that raises most questions, as its generalization to many users will require large number of satellites to be placed in orbit. The constellation that currently provides this high-speed access, Starlink, already comprises over 5,000 satellites, and there are plans to add several tens of thousands more. The figures foreseen by competing networks that are not yet operational are also of the same order, and the launches planned over the next few years could lead to around a hundred thousand satellites being put into orbit. This accelerated development is linked to economic and geostrategic prospects in the telecommunication field, and to a variety of other applications, foremost among which are those relating to Earth observation. For telecommunications, the major advantage of satellite networks lies in their resilience and their ability to provide access to any point on the globe with a minimum of terrestrial infrastructure - the anchor stations that connect the satellites to the Internet. When satellites are communicating with each other, these anchor stations can be located at great distances from users. This is an important advantage, as it enables coverage of isolated regions and connections even under degraded conditions following natural disasters or disruptions by war. Recent events, such as the war in Ukraine, have demonstrated the value of combining satellite communications, satellite observations and geolocation to communicate and act even when terrestrial infrastructures are damaged. However, the present report also indicates that the use of space in the low- and medium-earth orbit (LEO) domain is currently carried out in an insufficiently regulated framework, in which competition is engaged to occupy orbits and frequency bands. This lack of international regulation has many negative aspects. In the field of telecommunications, these constellations lead to a loss of sovereignty on the part of states in the management of communications originating in their territories, since the anchoring stations and the core network of a constellation can be located anywhere, and the rules governing the protection of data and the use of frequencies are no longer those of the regions or states that are covered. In the space sector, the increase in the number of launches has an environmental cost that is still not well understood and accounted for. Furthermore, the proliferation of satellites is leading to worrying problems of space densification, and orbital congestion caused by the presence of satellites and debris from their launch or from collisions. In the field of astronomy, all satellite constellations and those to come

will have a strong negative impact in the optical and infrared domains, which is analyzed in this report if nothing is done to correct the effects. The impact on radio astronomy is also very worrying, due to interference from communications and from the electronics on board the satellites, whose continuous operation makes it difficult to preserve quiet zones in the environment of radio observatories. This report also describes some of the initiatives currently being taken to address these negative impact issues and to develop best practices in this area.

9 Recommendations

1. **Observation:** The rapid development of satellite constellations has been driven by industrial innovations which have reduced the cost of satellites and launches, and by advances in scientific research into communications theory, computer science, and electromagnetism.

Recommendation: It is important to support French and European research and innovation in a variety of fields, including information theory, radio access, optical links between satellites, antenna design, improved thrusters, tracking systems for collision avoidance and, more generally, the design of sustainable architectures for these space networks.

2. **Observation:** Large satellite constellations open a wide range of new prospects for communications and observation. Composed of many satellites, they have resilience properties that are superior to those of terrestrial networks and open possibilities for establishing connections to the Internet in regions where terrestrial infrastructures would be hard to deploy.

Recommendation: The Académie considers that France and Europe must commit to developing a constellation to provide secure Internet connections, cover geostrategic needs, ensure European sovereignty in this field, and enable economically controlled commercial exploitation that is not totally dependent on private or state interests outside Europe.

3. **Observation:** Access to low-cost launches is a key condition for the implementation of constellations comprising a large number of satellites.

Recommendation: The efforts undertaken to equip Europe with a reusable launcher as well as the demonstrator programs developed at this goal deserve to be supported over the long term, so that Europe will eventually be possible to carry out launches with reuse of the first stages.

4. **Observation:** The future impact on astronomy of the development of low- and medium-orbit satellite constellations, without any real international regulation, is

particularly worrying. These constellations will have an impact on observations in both the optical domain, due to the trails generated by the passage of large numbers of satellites reflecting sunlight, and in the radio domain, which will potentially be strongly impacted by the electromagnetic interference associated with radio communications and by the emission of on-board electronics.

Recommendation: The Académie recommends that actions already underway be continued, and that new initiatives be launched to ensure that the negative impact of constellations on astronomical observations is considered, and that resources are put in place to ensure that this impact is minimal and controllable and does not call into question ground-based observation capabilities.

5. **Observation:** One of the major challenges for the future is to ensure sustainable access to orbital and frequency resources, allowing one to benefit from the remarkable possibilities offered by low- and medium-orbit constellations in terms of Internet connectivity, Earth observations and new applications, while at the same time protecting space and the environment. The multiplication of launches has led to an increase in pollution and in the number of objects in orbit, both satellites and debris. Space congestion is already necessitating more and more evasive maneuvers, and may eventually render certain orbits unusable, or even lead to chain collisions.

Recommendation: The Académie considers that the problem of the densification of space should be addressed as a matter of high priority, through the shaping of standards of good practice designed to preserve the space and terrestrial environments, and that specifically consider launches and the organization of the end of life of satellites. It recommends pursuing all actions that could lead to the adoption of these standards by all stakeholders. It also recommends that France and Europe establish an independent space surveillance capability to ensure the safety of satellite fleets.

10 Appendix

10.1 Organization of work

An interdisciplinary working group on satellite constellations was set up within the Académie des sciences in February 2023, was set up gathering members from different disciplines including physics (Catherine Bréchnac, Mathias Fink), sciences of the universe (Catherine Cesarsky, Hervé Le Treut, Guy Perrin, Jean-Loup Puget) and mechanical and computer sciences (Serge Abiteboul, François Baccelli and Sébastien Candel), as well as a member of the Académie des sciences morales et politiques (Daniel Andler). François Baccelli and Jean-Loup Puget co-chaired this group.

10.2 Editorial secretariat

- Juliette Rochet, Director of Comités, avis et rapports department of the Académie des sciences.
- Florent Gozo, Assistant to the Director of Comités, avis et rapports department of the Académie des sciences.
- Oksana Pischko, illustrations.

10.3 Authors

- François Baccelli, INRIA and Télécom-Paris, member of the Académie des Sciences
- Sébastien Candel, Centrale Supélec, member of the Académie des Sciences
- Guy Perrin, Observatoire de Paris, member of the Académie des Sciences
- Jean-Loup Puget, CNRS, member of the Académie des Sciences

10.4 Other working group members

- Serge Abiteboul, INRIA, member of the Académie des Sciences
- Daniel Andler, Sorbonne University, member of the Académie des sciences morales et politiques
- Catherine Bréchnac, CNRS, member of the Académie des Sciences
- Catherine Cesarsky, CEA, member of the Académie des Sciences
- Mathias Fink, ESPCI, member of the Académie des Sciences
- Hervé Le Treut, Sorbonne University, member of the Académie des Sciences

10.5 Hearings

The report is based on the following hearings organized in 2023

1. Maria Guta, Telecommunications Systems Division, ESA/ESTEC (Netherlands).
2. Jean-Yves Le Gall, former Chairman of CNES.
3. Philippe Baptiste, President of CNES.
4. Gilles Bergametti, CNRS, Chairman of the CNES Scientific Programs Committee.
5. Éric Lagadec, assistant astronomer at the Observatoire de la Côte d’Azur (optical astronomy).
6. Jean-Jacques Juillet, former Director of Countries Programs Coordination, Thales Alenia Space.
7. Carole Vachet, Deputy Director for Space, Electronics and Software (DGE).
8. Chiara Ferrari, astronomer at the Observatoire de la Côte d’Azur (low-frequency radio). Karl Schuster, Director of IRAM (Institut de radio astronomie millimétrique).
9. Estelle Malavolti, teacher-researcher at ENAC in Toulouse, researcher at TSE.
10. Jean Bolot, Director of Research, Orange.
11. Bernard Rosier, Orbital Systems Program Director (ONERA).
12. Renaud Labelle, Deputy Director Expertise (ANSSI).
13. Arnaud De Rosnay, Head of Spacecraft and Systems Engineering (Airbus).
14. Geoffroy Lerosey, CEO/CSO of Greenerwave.
15. Piero Benvenuti, Director of CPS (UAI).
16. General Philippe Adam, Space Commander.
17. Christophe Bonnal, senior space debris expert (CNES).

10.6 Acronyms

3GPP 3rd Generation Partnership Project Global Mobile Telecommunications Standardization Cooperation.

5G 5th generation mobile network standard **6G** 6th generation cell phone network standard **AFP** Agence France-Presse.

ALMA Atacama Large Millimeter/Submillimeter Array (Chile).

ANFR National Frequencies Agency.

ANSSI French national agency for information systems security.

Ka-band Kurz-above band - Frequency band between the K-band and the Q-band, i.e. between 26.5 and 40 GHz.

Ku-band Kurz-unten band - Microwave frequency range from 12 gigahertz (GHz) to 18 GHz.

BPI Public Investment Bank.

CDMA Code Division Multiple Access.

CEO Chief Executive Officer.

CEPT European Conference of Postal and Telecommunications Administrations.

CMB-S4 Cosmic Microwave Background Stage 4.

CNES Center national d'études spatiales CO3D 3-dimensional optical constellation.

COPUOS Committee on the Peaceful Uses of Outer Space - Comité des utilisations pacifiques de l'espace extra-atmosphérique.

CPS Center for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference.

CRAF Committee On Radio Astronomy Frequencies - Comité des fréquences de radioastronomie.

CSO Chief Scientific Officer.

DARPA Defense Advanced Research Projects Agency.

DGA Directorate General of Armaments of the French Ministry of the Armed Forces.

DGE Direction Générale des Entreprises of the French Ministry of the Economy and Finances.

DLR Deutsches Zentrum für Luftund Raumfahrt - German Space Agency.

DoD Department of Defense.

ECC Electronic Communication Committee.

ELT European Extremely Large Telescope.

ENAC National School of Civil Aviation.

ESA European Space Agency - Agence spatiale européenne.

ESO European Southern Observatory - Observatoire Européen Austral.

ESTEC European Space Research and Technology - Centre Centre européen de recherche et de technologie spatiales.

EUSPA European Union Agency for the Space Programme.

FAA Federal Aviation Administration - Government agency responsible for regulating and controlling civil aviation in the United States of America.

FCC Federal Communications Commission of the United States of America.

FORS FOcal Reducer and low dispersion Spectrograph Spectro - Imagers for the European Southern Observatory's Very Large Telescope.

GAO Government Accountability Office - The audit, evaluation and investigation agency of the Congress of the United States of America responsible for auditing the public accounts of the budget.

GEO Geostationary Orbit.

GNSS Global Navigation Satellite System.

GPS Global Positioning System.

HARMONI High Angular Resolution Monolithic Optical and Near infrared Integral

field - The HARMONI spectrograph.
IAU International Astronomical Union - Union Astronomique Internationale (UAI).
IoT Internet of Things.
IRAM Institute for Millimetric Radio Astronomy.
IRIS Infrastructure for Resilience, Interconnectivity and Security by Satellite.
Isae-SupAéro Institut supérieur de l'aéronautique et de l'espace.
Isp Specific impulse.
ITU International Telecommunication Union - Union internationale des télécommunications (ITU).
JAXA Japan Aerospace Exploration.
LEO Low Earth Orbit.
LH2 Liquid dihydrogen.
LOFAR LOw Frequency Array - European radio interferometer.
LOX Liquid oxygen.
M87* Messier 87, supergiant elliptical galaxy.
MEO Medium Earth Orbit.
MESR French Ministry of Higher Education and Research.
MetOp Meteorological Operational satellite.
MIMO Multiple Input, Multiple Output.
NIS Network and Information Security - European Union Directive on the protection of computer networks and information.
NOAA National Ocean and Atmospheric Administration.
NOEMA Northern Extended Millimeter Array - Astronomical Observatory of the Institute for Millimeter Radio Astronomy.
NOIR Lab National Optical-Infrared Astronomy Research Laboratory.
NSF National Science Foundation of the Government of the United States of America.
NTIA National Telecommunications and Information Administration.
O3B Other 3 billion - Telecommunications satellite operator.
OCA French Riviera Observatory.
OHB Orbitale Hochtechnologie Bremen.
ONERA Office national d'études et de recherches aérospatiales.
UN United Nations.
PC Personal Computer - Ordinateur personnel.
R& D Research & Development.
SAR Synthetic-aperture radar **SATCON** Satellite Constellations **SCARBO** Space Carbon Observatory.
SINR Signal-to-interference-plus-noise ratio.
SKA Square Kilometer Array, the world's largest radio telescope.
SME Small and Medium-sized Enterprises.
SMS Short message service.
SES Société Européenne des Satellites.
SpaceX Space Exploration Technologies Corporation.
STM Franco-Italian multinational that designs, manufactures and markets electronic

chips (or ST Micro-electronics).

StratCom United States Strategic Command.

STSC Scientific and Technical SubCommittee - Sous-comité scientifique et technique.

THEMIS Time History of Events and Macroscale Interactions during Substorms.

EU European Union.

UHF Ultra high frequency.

UTC Universal Time Coordinated.

VISTA Visible and Infrared Survey Telescope for Astronomy - A telescope from the European Southern Observatory.

VLT Very Large Telescope.

VRO Vera Rubin Observatory - Observatoire Vera Rubin.

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References

- [1] Académie des sciences. Rapport sur la 5G et les réseaux de communications mobiles (2021).
- [2] C.G. Bassa, O.R. Hainaut & D. Galadí-Enríquez, “Analytical simulations of the effect of satellite constellations on optical and near-infrared observations”, *Astronomy & Astrophysics*, 657, A75 (2022).
- [3] G. Brachet “Les enjeux d’un développement durable des activités spatiales” *Géoeconomie* 2012/2 (n° 61), pages 95 à 106, <https://www.cairn.info/revue-geoeconomie-2012-2-page-95.html> (2012).
- [4] <https://cps.iau.org/news/nsf-and-spacex-sign-agreement-to-mitigate-impact-of-starlink-satellites-on-ground-based-astronomy/>
- [5] J.A. Dallas, S. Raval, J.P. Alvarez Gaitan, S. Saydam and A.G. Dempster, “The environmental impact of emissions from space launches: a comprehensive review”, *Journal of Cleaner Production*, 255, 120209 (2020).

- [6] F. Di Vruno et al., “Unintended electromagnetic radiation from Starlink satellites detected with LOFAR between 110 and 188 MHz”, *Astronomy & Astrophysics* 676, A75 (2023).
- [7] F. Di Vruno, personal communication.
- [8] ESA’s Annual space environment report, September 12, 2023.
- [9] <https://www.esa.int/SpaceSafety/SpaceDebris/Spacedebrisbythenumbers>
- [10] <https://www.eso.org/~{}ohainaut/satellites/index.html>
- [11] F. Fankhauser, J.A. Tyson & J. Askari, ”Satellite Optical Brightness”, *The Astronomical Journal*, 166, 59 (2023).
- [12] Federal Communications Commission, “Kuiper systems, LLC application for authority to deploy and operate a Ka-band non-geostationary satellite orbit system,” no. SAT-LOA-20190704-00057, Jul 30, <https://www.fcc.gov/document/fcc-authorizes-kuiper-satellite-constellation>, (2020).
- [13] GAO (United States Government Accountability Office) “Large constellations of satellites, Mitigating environmental and other effects”. GAO-22-105166 (2022).
- [14] B. K. Gehlot et al., “Transient RFI environment of LOFAR-LBA at 72-75 MHz: Impact on ultra-widefield AARTFAAC Cosmic Explorer observations of the redshifted 21-cm signal”, à paraître dans *Astronomy & Astrophysics*, ArXiv :2311.03023 (2023).
- [15] A. Guidotti, A. Vanelli-Coralli, M. Conti, S. Andrenacci, S. Chatzinotas, N. Maturo, B. Evans, A. Awoseyila, A. Ugolini, T. Foggi, L. Gaudio, N. Alagha, and S. Cioni, “Architectures and key technical challenges for 5G systems incorporating satellites,” *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 2624–2639, (2019).
- [16] O.R. Hainaut & A.P. Williams, “Impact of satellite constellations on astronomical observations with ESO telescopes in the visible and infrared domains”, *Astronomy & Astrophysics* 636, A121, (2020).
- [17] <https://www.iau.org/news/pressreleases/detail/iau2211/>
- [18] Iridium Communications, Inc, “History of Iridium,” <https://www.iridiummuseum.com/timeline/> [Online].
- [19] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. Mendoza Montoya, J. C. Merlano Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, Lei Lei, Thang X. Vu , and G. Goussetis. “Satellite Communications in the New Space Era: A Survey and Future Challenges”, *IEEE Communications Surveys & Tutorials*, Vol. 23, pp. 70-109 (2021).

- [20] S. Kruk, P. García-Martín, M. Popescu, B. Aussel, S. Dillmann, M.E.Perks, T. Lund, B. Merín, R. Thomson, S. Karadag, M.J. McCaughrean, “The impact of satellite trails on Hubble Space Telescope observations”, *Nature Astronomy*, 7, 262–268, 2023.
- [21] I. Levchenko, S. Xu, S. Mazouffre, D. Lev, D. Pedrini, D. Goebel, L. Garrigues, F. Taccogna, and K. Bazaka, “Perspectives, frontiers, and new horizons for plasma-based space electric propulsion”, *Physics of plasmas*, 27, 020601 (2020).
- [22] S. Liu, Z. Gao, Y. Wu, D. W. Kwan Ng, X. Gao, K.-K. Wong, S. Chatzinotas, and B. Ottersten, “LEO satellite constellations for 5G and beyond: How will they reshape vertical domains?” *IEEE Commun. Mag.*, vol. 59, no. 7, pp. 30–36, (2021).
- [23] <https://www.lsst.org/content/lsst-statement-regarding-increased-deployment-satellite-constellations>
- [24] A. Mallama, ”The newest and largest starlink satellites are also the faintest”, *Sky & Telescope*, (2023).
- [25] C. Malaoney, R.W. Portmann, M.N. Ross, K.H. Rosenlof, “The climate and ozone impacts of black carbon emissions from global rocket launches”, *JGR Atmospheres*, 127, e2021JD036373 (2021).
- [26] S. Nandakumar et al., “The high optical brightness of the BlueWalker 3 satellite”, *Nature*, 623, 938-941 (2023).
- [27] A. R. Offringa, F. Mertens & L. V. E. Koopmans, “The impact of interference excision on 21-cm epoch of reionization power spectrum analyses”, *Monthly Notices of the Royal Astronomical Society*, 484, 2866 (2019).
- [28] N. Okati, T. Riihonen, D. Korpi, I. Angervuori, and R. Wichman, “Downlink coverage and rate analysis of low earth orbit satellite constellations using stochastic geometry,” *IEEE Trans. Commun.*, vol. 68, no. 8, pp. 5120–5134, (2020).
- [29] <https://orbitaldebris.jsc.nasa.gov/faq/>
- [30] Z. Qu, G. Zhang, H. Cao, and J. Xie, “LEO satellite constellation for Internet of Things,” *IEEE Access*, vol. 5, pp. 18 391–18 401, (2017).
- [31] M.N. Ross and P.M. Sheaffer. ”Radiative forcing caused by rocket engine emissions”, *Earth’s Future*, 2, 177-196 (2014).
- [32] Recommendation UIT-R RA.769-2 sur les “Critères de protection applicables aux mesures en radioastronomie”.

