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Satellite Communications: An Objective Lunar Base and Beyond

The following chapter discusses the challenges and opportunities of utilising satellite telecommunications for space and Moon exploration. It also examines the critical role of communication satellite constellations in providing essential services for future space communications.

The paper comprehensively analyses the critical technical, economic and operational factors that affect the design and development of a lunar telecommunications system, as well as the security and defence risks and challenges.

In this scenario, various elements are highlighted that lead to the emergence of the need for multilateral cooperation between various actors, such as public and private, national and international, to promote the development of a sustainable, safe and advantageous lunar telecommunications system for everyone.

Satellite Constellations for Lunar Communications

Satellite constellations for communications are the backbone required by critical infrastructures to provide fundamental services on Earth. The other necessary parts are global navigation and Earth observation systems. A disruption of navigational and communication services would simultaneously affect transportation services, broadcasting services, the power grid and banking transactions, among others. Due to the increasing interest of New Space businesses in the cislunar[2] economy, it would not be premature to investigate the gap hindering

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[2] Volume within the Moon's orbit, or a sphere formed by rotating that orbit.

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the establishment of a secure and reliable satellite communication system orbiting the Moon rather than the Earth. This is especially true if the cislunar economy will soon enable the growth of lunar settlements and manned lunar missions.

The lunar economy[3] is a rapidly growing sector that offers opportunities for scientific, commercial and strategic development. In recent years, governments, space agencies and private companies have invested in the exploration and exploitation of the Moon's resources. These investments are expected to increase in the near future in view of possible human missions and greater international cooperation.

The most important artificial satellites are NASA's Lunar Reconnaissance Orbiter, which has been studying the lunar surface since 2009; China's Chang'e 5, which brought lunar samples to Earth in 2020; India's Chandrayaan 2; and Israel's Beresheet (Guruprasad et al. 2023).

The following governmental investments are among the most significant:

- The National Aeronautics and Space Administration (NASA)'s Artemis program aims to bring American astronauts to the lunar surface by 2027 (NASA 2022) and establish a sustainable presence by 2028. The programme also includes the construction of an orbital station around the Moon called Gateway, which will serve as support for lunar and Martian missions. The estimated cost of the programme is approximately USD 28 billion (Smith et al. 2020).
- China's Chang'e Project (or the Chinese Lunar Exploration Program) has already conducted five robotic missions to the Moon, including the first far-side moon landing in 2019 and in 2020 the first collection of lunar samples since 1976. The project has two more missions planned by 2024, with the goal being to build a research station on the lunar surface. The estimated cost of the programme is approximately USD 8 billion (Zuo et al. 2021).

[3] Lunar economy refers to all "economic activity associated with the production, use and exchange of lunar resources on the Moon's surface, in lunar orbit and on Earth" (Scatteia 2021).

In addition to private investment:

- The Lunar X Prize programme is an international competition sponsored by Google to encourage the development of private space technologies. USD 30 million will be awarded to the first team that lands a rover on the Moon, makes it travel at least 500 metres, and transmits images and data back to Earth. Thus far, while no team has managed to win the prize, some have announced a plan to launch their mission in the coming years (Smart 2018).

In fact, PwC estimated the interest and investment in the lunar economy to exceed €142 billion by 2040 (Scatteia 2021). The interest and investment are focused on the following three types of lunar activities: transportation, lunar data and in-situ resource utilisation (ISRU).

This article aims to provide a qualitative overview of the technological challenges faced by the satellite communication services that will support all lunar activities through the creation of a communication network to connect all stationary bases in situ and in orbit. The remainder of this paper is organised as follows: An introduction to the lunar economy and the future of the Lunar Gateway; the current scenario of the moon satellites; an overview of the future of lunar satellite system architecture as well as an overview of communication and possible challenges and risks as a result of the asset's criticality for security and defence. Lastly, the article identifies the need for cooperation in both the public and private sectors and in national and international environments.

THE LUNAR ECONOMY: NASA'S LUNAR GATEWAY

The first step to enabling the lunar economy is to establish a reliable and recurrent Earth–Moon transportation system. This step has been enabled by NASA's Artemis program, which is directly supported by its Lunar Gateway program. In particular, the Lunar Gateway program aims to develop a communication network around the Moon to support Artemis and beyond.

Lunar Gateway is an international project that aims to build a space station around the Moon to facilitate missions to the Moon and other planets. NASA is the leader of the programme, which also involves the space agencies of Canada, European countries and institutions, Japan and Russia. The space station will comprise various modules dedicated to housing different scientific, and logistical functions. The modules will be launched and connected between 2024 and 2030. Lunar Gateway aims to explore the Moon in a more in-depth and sustainable manner, experimenting with new technologies and paving the way for future explorations of Mars and beyond (Silva-Martinez et al. 2023).

While the NASA programs aim to transport and host human crews, several concepts have been proposed for transporting cislunar cargo only. Current cislunar transportation systems are targeted at large-scale transportation of cargo with a mass of 2–8 tonnes, which includes logistics resupply services for Lunar Gateway, the transportation of modules for expanding the station, as well as lunar landers. Based on Gateway Logistics Services contracts, the potential market over 15 years is estimated to have a value of €398 million.

The aforementioned contracts are awarded by NASA to various space companies to provide logistics services to the Gateway orbital station, which will be positioned in lunar orbit (LO), between 3,000 and 70,000 km from the satellite according to a near-rectilinear halo orbit (ESA 2019), compared to the 408 km of the ISS. These services include the transport of payloads, equipment, materials and supplies for the Gateway and Artemis missions, which foresee the return of astronauts to the Moon by 2027. The contracts have a duration of 15 years and a total value of USD 7 billion. The companies selected by NASA are SpaceX, Sierra Nevada Corporation, Northrop Grumman and NanoRacks. Each company will use its spacecraft to make deliveries to the Gateway, which will serve as a staging and transit point for lunar and Martian exploration (Nakamura et al. 2023).

As an example, Moonport proposes a commercially viable cislunar transportation system based on a refuellable space tug. It will meet the conditions set out in NASA's Commercial Lunar Payload Services (CLPS) contracts, which focus on frequent large-scale cargo transportation within cislunar space.

CLPS contracts are a series of contracts awarded by NASA to various American companies for the transport of payloads to the lunar surface. These contracts have a term of 10 years (i.e. until November 2028) for a value of USD 2.6 billion (NASA 2019). The goals of CLPS are to exploit commercial capabilities to explore the Moon, test technologies, conduct scientific experiments and demonstrate the potential for future human missions. CLPS contracts require the selected companies to provide all services necessary for integrating, transporting and operating NASA payloads, including launch vehicles, lunar landers, surface systems and Earth re-entry vehicles. To date, eight missions have been awarded under the CLPS programme, which excludes one mission for which the contract was revoked after it was awarded and another for which the contract was cancelled after the company went bankrupt. The first commercial deliveries were scheduled for 2023 (Giordano et al. 2023).

Once cislunar transportation has been established, the second step will be to transport capabilities for the creation of lunar bases to support research and eventually tourism. Some concepts include versatile transportation systems that could act as carriers for human crew and cargo, whose structure could subsequently be repurposed as a lunar base. An example is SpaceX's horizontal Starship Human Landing System placed at the lunar south pole on the rim of the Shackleton crater. Interestingly, this is the same crater where the Chang'e 7 mission is scheduled to land.

Furthermore, several hotspots have been located on the Moon, which would require a solid communication system between lunar bases or between lunar bases and LO vehicles. For instance, the presence of ice at the Moon's south pole could provide water resources in situ for longer crew missions as well as the resources for producing hydrogen fuel for liquid rocket engines. Another potential hotspot is the Moon's far-side equatorial region, which could potentially host massive radio telescopes. However, the far side of the Moon implies radio silence with Earth as it (as well as large portions of the polar regions) has no direct line of sight to Earth. Even on the side of the Moon that faces Earth, hills and crater walls could block communications.

THE CURRENT SCENARIO

Lunar orbiting satellites are artificial devices that orbit around the Moon. They have various functions, such as data transmission, navigation, scientific exploration and surveillance. Some satellites have been launched by national or international space agencies, while others have been launched by private or commercial entities. Currently, there are approximately 50 satellites in LO, of which 20 are operational and 30 are deactivated or lost.

Regarding the precise number of satellites currently orbiting the moon, the number is relatively low if one considers only artificial satellites (i.e. those launched by man for scientific or technological purposes). However, if one also considers natural satellites, meaning the celestial bodies that orbit the Moon due to its gravitational pull, then the number is considerably higher. A cloud of dust called the lunar exosphere surrounds the moon, which contains thousands of microscopic particles. These particles are considered natural satellites because they follow a stable orbit around the Moon; however, their size and distance make observing and counting them difficult.

The first of the Moon's artificial satellites was launched in the 1960s during the space race between the United States and the Soviet Union. The first satellite to reach the Moon was the USSR's Luna 1 in 1959, but it did not enter orbit and continued into interplanetary space. The first satellite to enter LO was the USSR's Luna 10 in 1966, which transmitted data on the Moon's gravity and magnetic field. The first satellite to land on the Moon was the USSR's Luna 9 in 1966, which sent the first images of the lunar surface.

Since then, many other countries have launched satellites to the Moon for different purposes, such as geological exploration, topographic mapping, scientific research and preparation for future human missions. Countries that have sent satellites to the Moon include the United States, China, India, Japan and Israel, as well as European countries.

Artificial satellites that orbit the Moon serve to improve our knowledge of this celestial body, which has a large influence on life on Earth. Through satellites, the physical and chemical characteristics of the Moon can be studied along with its climate, environment, origin and evolution. Satellites also assist in the discovery of natural resources on the Moon and the evaluation of possibilities to exploit them in the future (Carlo–Salmieri 2021). In addition, these satellites have allowed important information to be obtained on the geology, topography, climate and resources of the Moon; new technologies to be tested; and future human missions to be prepared for.

CISLUNAR INFRASTRUCTURE

To create a lunar satellite system architecture, several technical, economic and operational aspects must be considered. First, the main technical factors include the choice of orbit; the type and number of satellites; communication, navigation and observation capabilities; and the launch, deployment and maintenance requirements. Second, the key economic factors include the cost of developing, manufacturing, launching and operating the system; sources of financing; and market opportunities. Third, the key operational factors include end-user needs and priorities, space regulations and policies, as well as security and sustainability challenges and risks. A lunar satellite system architecture must therefore be designed in a way that balances these aspects and guarantees the achievement of set objectives.

In this scenario, the core functionality for lunar and cislunar infrastructure would be enabled by a reliable real-time communication system in cislunar orbit. This would ensure that Security Operational Centres and the operation commands are alerted promptly when critical vulnerabilities are found. Crucially, such a system would not rely on a direct link to ground stations on Earth.

Cislunar infrastructures are infrastructures found in the space between the Earth and the Moon. Space stations, satellites, probes, vehicles and other elements can facilitate the exploration and exploitation of lunar resources as well as communication and cooperation between various space agencies. Cislunar infrastructure is considered crucial for the development of a permanent human presence on the Moon and for the preparation of missions to Mars and beyond (Fowler 2023).

Some examples of cislunar infrastructures are the Gateway, a lunar orbital station that will be built by NASA in collaboration with other international partners; the Lunar Orbital Platform-Gateway (LOP-G), a space station that will stably orbit the Moon to allow the transfer of payloads and astronauts between Earth and the lunar surface; and the Lunar Communication and Navigation Services (LCNS), a telecommunications and navigation system that will provide coverage and support for lunar operations.

The LOP-G space station is designed to host human and robotic crews as well as science and technology experiments. LOP-G is an integral part of NASA's Artemis program, which aims to establish a sustainable presence on the lunar surface and set the stage for future missions to Mars. Its telecommunications system is the Power and Propulsion Module (PPE) a solar-powered electric propulsion module developed by Maxar Technologies: it is specially developed for NASA: this module will be one of the main components of the Lunar Gateway and its launch is scheduled for May 2024, which will provide electrical power, communications and orbital manoeuvres; the habitation module (HALO) will provide living and working space for astronauts. The logistics module will transport supplies, equipment and spacecraft; and finally, the robotic arm (RA) will assist in extravehicular operations and docking. LOP-G will be able to support long-duration missions to the Moon as well as serve as a transit point for missions to Mars and other celestial bodies. Moreover, LOP-G will have an elliptical orbit with an apogee of approximately 70,000 km and a perigee of approximately 3,000 km, offering a unique view of the far side of the Moon (Freeman 2023).

The LCNS project aims to provide communication and navigation services for lunar missions. The project involves the development of a network of satellites in LO, which will transmit data, images, video and commands between lunar missions and control centres on Earth; ground stations; and spacecraft terminals. Space platforms are the systems that host spacecraft, such as capsules, landers, rovers and orbital stations. LCNS satellites are designed to be flexible, reliable and compatible with different space platforms. They are able to communicate with each other, with ground stations, and with spacecraft in orbit or on the lunar surface. The purpose of LCNS is to facilitate data, voice and video transmission between the Earth and the Moon; support lunar exploration operations; and contribute to scientific research. The LCNS project is an international collaboration between several space agencies, including NASA, the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA) and the China National Space Administration (CNSA) (Molli et al. 2023).

COMMUNICATIONS

Earth–Moon telecommunications occur between the Earth's surface and a satellite or probe in LO or on the lunar surface. These communications are critical for space missions that explore our natural satellites, both manned and unmanned (Carlo 2021). Earth–Moon telecommunications are based on systems of antennas, transmitters and receivers that operate at different electromagnetic frequencies, depending on the transmission needs and conditions. The main challenges of Earth–Moon telecommunications are distance, latency, interference, propagation and signal security.

First, to reduce the negative effects of distance, repeaters can be used in terrestrial or lunar orbit, which amplifies and retransmit the received signals. The use of repeaters in terrestrial or lunar orbit for satellite communications between the Moon and Earth offers several advantages to reduce the negative effects of distance. This includes the reduction of propagation delay, increase in signal power, better reliability of the connection, greater flexibility, energy efficiency and possibility of lunar exploration. The choice of using repeaters in Earth or lunar orbit depends on several factors, such as the distance between the Earth and the Moon, the frequency of the radio signal and the power available to transmit the signal. Generally, repeaters in Earth orbit are easier to install and maintain, but repeaters in lunar orbit offer better propagation delay reduction and higher link reliability.

Second, to reduce latency, communication protocols suitable for managing delays in data transmission can be used. Third, to reduce interference, signal coding, modulation and filtering techniques can be used, which increase the signals' robustness and quality. Fourth, to improve propagation, directional antennas can be used, which concentrate the signals towards the target. Lastly, to guarantee signal security, encryption, authentication and data protection systems can be used that prevent interception or manipulation by third parties (Mortensen–Withee 2023).

Noteworthily, the creation of satellite constellations for communications in LO would require a lower payload class. For instance, lunar relay spacecraft for satellite communications often belong to the CubeSats class. One example is the Argotec satellite concept, which has dimensions of $44 \times 40 \times 37$ cm^3 with solar panels and antennas stowed and a wet mass[4] of only 55 kg (Iess et al. 2023).

For lunar telecommunications, extremely demanding environmental challenges will be faced, requiring dedicated satellites. These satellites must be able to withstand the high radiation, temperature variations, and electromagnetic interference that characterise LO. The Van Allen belt does not offer any protection and the Moon does not have anything similar. Furthermore, they must be equipped with cutting-edge propulsion, navigation and communication systems to guarantee orbit stability and signal quality.

Moreover, the altitude at which they operate will depend on the type of orbit chosen and the operational needs. A low LO (LLO) offers the benefits of decreasing data transmission delay and improving image resolution, but it will require more satellites to cover the entire lunar surface. A high LO (LHO) will instead allow for greater coverage with fewer satellites, but it will imply greater delay and lower resolution. A possible solution could be to combine both types of orbits, thus creating an integrated network of lunar telecommunications satellites (Bhamidipati et al. 2023).

[4] Total mass including all propellants on board.

For lunar telecommunications, different types of satellites can be used depending on the needs and technical challenges. Some possible types of satellites that could be used are listed and described as follows:

- LLO satellites: These satellites orbit at a distance of a few hundred kilometres from the lunar surface and can provide direct and fast coverage between Earth and lunar bases. However, they have a limited useful life due to gravitational disturbances mainly caused by Earth and solar radiation. Therefore, they require a network of multiple satellites to ensure continuous communication.
- Medium LO satellites: These satellites orbit at a distance of a few thousand kilometres from the lunar surface and can provide wider and more stable coverage between Earth and lunar bases. While they have a longer useful life than LLO satellites (thanks to less exposure to radiation, less atmospheric resistance, a longer orbital period and a greater distance from Earth), they require greater power to transmit and receive and are more vulnerable to electromagnetic interference.
- Satellites in geostationary LO: These satellites orbit at a distance of approximately 60,000 km from the lunar surface and maintain a fixed position concerning the Moon. They can provide constant global coverage between Earth and Moon bases; however, they require highly advanced and expensive technology and are exposed to a high level of cosmic radiation.
- Satellites in Lagrangian orbit: These satellites orbit at one of the five points of gravitational balance between the Earth and the Moon, which are called Lagrangian points. They can provide reliable, long-distance communication between Earth and Moon bases; however, they require precise synchronisation and control and are subject to orbital variations due to disturbances from celestial bodies.

A critical choice when defining a concept of operations (ConOps) for satellite communications in a circular economy is the bandwidth of data to be transmitted. For lower bandwidth applications (e.g. text and voice messages), one satellite would be sufficient for collecting and aggregating data streams for relay elsewhere. For higher bandwidth applications (e.g. radio telescopes), an individual satellite is likely to reach its capacity with high data production.

Lunar satellite communications are a form of wireless telecommunications that use artificial satellites orbiting the Moon to transmit information between the Earth and the Moon or between different points on the lunar surface. Such communication entails the problem of signal latency, which refers to the time delay between sending and receiving data signals due to the distance between the transmitter and the receiver as well as the speed of light. Signal latency in lunar satellite communications limits the quality and efficiency of data transmissions between the Earth and the Moon. In the case of lunar satellite communications, the average distance between the transmitter and receiver is approximately 384,000 km; thus, the signal takes approximately 1.28 seconds to travel at the speed of light (300,000 km/s). Signal latency in lunar satellite communications can range from approximately 120 ms to 2.8 s depending on the relative position of the Earth and Moon. This delay can cause synchronisation problems, data loss, interference and signal degradation. It can also impact the performance and reliability of applications that require real-time communication or rapid response, such as navigation, remote control, or emergencies (Louca et al. 2023).

Lunar satellite communications are a technological and scientific challenge that requires constant development and innovation to ensure optimal and reliable performance. To solve the latency problem, several strategies can be adopted, such as the following:

- Using satellites in LLO: This strategy reduces the distance and therefore the signal propagation time. However, it requires more power to transmit as well as greater pointing accuracy of the antennas.
- Using more efficient modulation and coding techniques: This increases the capacity and robustness of the communication channel. However, it requires greater device complexity and bandwidth.
- Using communication protocols suitable for high-latency conditions: Such protocols include error control, retransmission and data buffering mechanisms. However, this requires more memory and greater delay tolerance.

Moreover, some projects are currently in place or under development for solving the problem of signal latency. One of these projects is the Lunar Communications Relay and Navigation System (LCRNS), a system of three lunar geostationary satellites that will allow continuous, low-latency coverage of the lunar surface. The LCRNS was proposed by NASA in 2018 as part of its Artemis program for human exploration of the Moon (MURATA et al. 2022).

A cislunar satellite transmission system is a system that allows communication between the Earth and the Moon, or between two points on the lunar surface, using artificial satellites that orbit natural satellites. This type of system is useful for supporting human or robotic space missions that aim to explore the Moon as well as for transmitting scientific or commercial data.

A cislunar satellite relay system is composed of three main elements: a ground station on Earth, one or more cislunar satellites and a lunar station. The Earth station is the point of origin or destination of the signal, which can be modulated in different ways depending on the needs. The signal is sent to the nearest cislunar satellite, which receives it with a dish or slot antenna and retransmits it to the lunar station or another cislunar satellite. The lunar station is the end or starting point of the signal, which can be received by a lander, rover, astronaut, or other device on the lunar surface.

Noteworthily, a cislunar satellite transmission system faces several technical challenges, such as the aforementioned distance between the Earth and the Moon, electromagnetic interference, temperature variations, solar and cosmic radiation, reduced gravity and occultations caused by the movement of the Moon. To overcome these challenges, high frequencies (e.g. the S, X, or Ka bands), coding and error correction systems, resistant and lightweight materials, solar panels and batteries for power supply, thrusters for altitude and orbit control and thermal control systems (PASQUALE et al. 2022) can be employed.

When a cislunar relay is used, the communication distance is shorter, which means that a powerful terminal is not required to maintain a low-data-rate link[5]

[5] It is a type of data link that has limited data transmission capacity (a data rate of less than 100 kbps), often used for applications that send small amounts of data at regular intervals, such as IoT sensors, monitoring devices and security systems (RAZA et al. 2022).

with Earth. Direct communication to Earth would require some seconds in both directions. Furthermore, direct Moon–Earth communication requires a powerful communications terminal with a large antenna or a high-wattage amplifier.

The ultimate goal of lunar communications systems would be to establish 5G capabilities for the entire Moon. Moreover, 5G technologies should be further standardised for in-space and cislunar use wherever possible, thus enabling, for example, the installation of cell sites on the Moon to supplement the relay arrangement. This approach would allow devices to be connected to a lunar network, such as low-power Internet of Things sensors and autonomous vehicles (Kodheli et al. 2022).

Yet, how can this ultimate goal be achieved? Many researchers and engineers working on the Artemis project ask this question. Artemis is NASA's space programme for returning astronauts to the lunar surface by 2024 and building a permanent base there. 5G wireless communications technology offers very high data speeds, low latency and greater reliability than previous generations. Therefore, 5G could significantly improve scientific and logistical operations on the Moon, allowing astronauts to communicate with each other and with Earth, remotely control rovers and drones, transmit high-resolution data and images, and exploit artificial intelligence and cloud computing. However, building a 5G network on the Moon presents several technical and logistical challenges.

First, the Moon's extreme environmental conditions must be considered, such as high temperature variations, solar radiation, electrical dust storms and the lack of an atmosphere. These factors can negatively impact the performance and lifespan of the devices and infrastructure necessary for 5G. Second, the distance between the Moon and the Earth makes a real-time connection difficult to establish. Finally, the problem of resource scarcity on the Moon must be addressed, both in terms of energy and materials. Notably, 5G requires a large amount of energy to function, but the availability of solar energy on the Moon is limited as it depends on the Moon's position and the lunar cycle. Furthermore, transporting materials from Earth to the Moon has high economic and environmental costs.

To overcome these challenges, researchers and engineers are studying several innovative and sustainable solutions, one of which is to use satellites in LO to create a 5G network that covers the entire lunar surface. The satellites could communicate with each other via lasers and provide connectivity to astronauts and vehicles on the Moon via radio waves. This solution would have the advantage of reducing the number of antennas and base stations required on the Moon, thus limiting the infrastructure's environmental impact and energy consumption. Another solution is to exploit the Moon's local resources to produce the materials required for 5G. For example, lunar regolith, the surface layer of dust and rock that covers the Moon, could be used to fabricate electronic components through 3D printing or other techniques. This solution would have the advantage of reducing dependence on Earth as well as transport costs (Raza et al. 2022).

In conclusion, establishing 5G capabilities for the entire Moon is an ambitious but feasible goal that requires international collaboration between various players in the space, telecommunications and industrial sectors. 5G may not only open new frontiers of scientific research and space exploration but also offer new economic and security opportunities.

PROJECTS

There are multiple ongoing projects, including a collaboration between NASA, Jet Propulsion Laboratory (JPL) and the Italian company Argotec proposes the realisation of relay satellites to support the bandwidth required for lunar and manned activities (Amoroso et al. 2022). The proposed Andromeda constellation is composed of 24 satellites, which are divided evenly among four different orbits. The relay network concept uses a class of stable orbits – so-called frozen orbits. Stable orbits make it easy to keep the satellites in their assigned orbits for a minimum of 5 years of operation. Each satellite is equipped with three different antennas to establish communications with Earth as well as the lunar surface. The K-band would be used for Earth-to-satellite connections since it has more bandwidth available compared with other bands used for space communications. Another reason is that for antennas of the same size, K-band frequencies have higher antenna gain; in other words, K-band antennas more efficiently convert the received signals into electrical power. However, the relay satellites would require an additional power margin to ensure that the link remains stable due to the weather sensitivity of K-band antennas. Currently, no standard protocol exists for communications between a relay satellite and a lunar user in the S- and K-bands. Standardisation, policy and regulations for lunar activities are crucial topics that must be developed in parallel.

ESA is also investigating the possibility of placing three or four satellites in highly eccentric orbits focused on the Moon's south pole through the Moonlight Initiative. The main goals would be to pinpoint geolocations on the surface of the Moon and to ensure high-speed data transmission back to Earth (Giordano et al. 2022).

Moreover, NASA's Space Communications and Navigation (SCaN) programme has developed the LunaNet architecture, a set of cooperating networks that provide interoperable communications and navigation services for users on and around the Moon. Briefly, each LunaNet Service Provider (LNSP) designs its own set of orbits. The Earth–Moon links would be dedicated to low-rate Telemetry, Tracking and Command (TT&C, X band) and high-rate mission data transmissions (Ka band), with the primary links being within cislunar systems. The baseline demand without human presence has been estimated as a data rate of 110 Mbps and a data volume of 600 GB/day. With the addition of Lunar Gateway at full capacity, the projections increase to 375 Mbps and 8.2 Tb/day, respectively. The increasing bandwidth demand due to human presence in lunar proximity would cause a congestion of RF bands, requiring optical communications to be tested and operational within this decade. Furthermore, optical capabilities would tighten avionics requirements for transferring the higher rate efficiently as well as increase pointing and stability requirements. The introduction of optical communication would also be required for future Mars activities (Giordano et al. 2023).

Other projects concern the development of new technologies and techniques for improving lunar satellite communications, such as the use of high-frequency radio waves, the use of lasers to transmit data at high speed, the adoption of adaptive and resilient network protocols, the creation of optical or radio intersatellite links, and deployment of wireless sensor networks on the lunar surface.

RISKS AND CHALLENGES

Lunar satellite telecommunications are also a critical asset for the security and defence of the moon installations. However, they are also exposed to various types of risks, including physical and cyber ones. To defend them, it is necessary to adopt a series of preventive and reactive measures that involve both technological and organisational aspects (Salmieri–Carlo 2021).

Generally, a broad understanding exists of the possible causes of disruption to the service of satellites in Earth orbit (EO), which vary from cyberattacks and space weather conditions to space debris and anti-satellite weapons. In principle, the same conditions apply to the LO, but with different severities and/or likelihoods of occurrence. For example, congested orbits like specific low EOs are absent in LO; thus, the likelihood of collisions with space debris is significantly reduced if one excludes meteorites from the equation. Furthermore, space weather events could have an even greater impact on cislunar systems. The Moon has neither a global intrinsic magnetic field – which causes direct charged particles to reach systems in LO and the lunar surface – nor a thick atmosphere – which enables the Earth's magnetosphere to directly impact the lunar surface for three to four days every month, even if the effect is very weak (Malinowska et al. 2023).

Additional challenges related to satellite constellations in LO are linked to the complexity and longevity of space systems, which require frequent updates or patches. Harsh space environments, which are characterised by radiation and microgravity, will impact the performance and durability of security systems. Last but not least, maintenance in LO would be more complicated than in EO. In both cases, once a satellite is deployed, physical maintenance becomes challenging and hazardous.

To prevent physical risks, it is advisable to design satellites with resistant and shielded materials, equip them with control and manoeuvre systems, constantly monitor their orbit and state of health, and plan for possible replacements or repairs (Cetin et al. 2023).

Moreover, among the cyber risks are cyberattacks aimed at intercepting, altering, or blocking satellite communications, or at damaging or destroying the satellites themselves. To prevent these attacks, it is necessary to adopt robust and up-to-date security protocols, encrypt transmitted and received data, protect infrastructures on the ground and in space from physical or logical intrusions, and develop capabilities for detecting and combating cyber threats (Marsili et al. 2023).

To create the cyber architecture of a lunar satellite system, it is necessary to follow some fundamental steps. First, the objectives and functionality of the system must be defined, taking user needs and environmental challenges into consideration. Second, the communication network between the satellites and Earth must be designed, with the most suitable methods, frequencies and protocols selected. Third, software and security systems must be developed to ensure the operation, control and data protection of the system.

Furthermore, to create a lunar satellite system cyber architecture, it is necessary to consider several aspects, including security, resilience, scalability and interoperability. First, security concerns the protection of data and communications from cyberattacks, which could compromise the functionality and integrity of the system. Second, resilience refers to the system's ability to resist and recover from adverse events, such as failures, interference, or sabotage. Third, scalability implies the possibility of adapting the system to operational needs and available resources, both in terms of the number of satellites and performance. Lastly, interoperability means the ability to communicate and cooperate with other satellite systems, both terrestrial and space-based.

Additionally, cyber threats can be of a technical, human, or environmental nature. Technical threats exploit vulnerabilities in software, protocols, or networks to alter or interrupt the functioning of the system; human threats come from malicious agents, such as hackers, crackers, or terrorists, who attempt to access, manipulate, or destroy the system; and environmental threats depend on external factors, such as solar radiation, space debris, or atmospheric conditions, which can affect the quality and reliability of communications (Sawik 2023). To address the aforementioned threats, it is necessary to adopt a series of physical and digital systems that guarantee the protection, monitoring and control of the lunar satellite system. Among the physical systems are encryption devices, sensors, transmitters and receivers, which allow data to be encrypted, transmitted, and received in a secure and robust manner. Among the digital systems are antivirus software, firewalls, intrusion detection and prevention systems, authentication and authorisation protocols, which allow cyberattacks to be identified, blocked and countered.

NEED FOR COOPERATION

For an effective defence of lunar satellite telecommunications, cooperation between the various actors involved – both public and private as well as national and international – is essential. Here, Europe is a prime example of cooperation with many projects, such as the Copernicus Programme for Earth observation, the GOVSATCOM programme for government communications, and the Quantum project for secure communications based on quantum mechanics (Carlo 2021). These initiatives aim not only to strengthen European space capabilities for security and defence but also to promote shared space governance and a culture of responsibility among space users (Prest–Bonifazi 2023).

The creation of a lunar satellite telecommunications system involves several regulatory and political challenges – both international and national. At the international level, it is necessary to define a legal framework that regulates the access to, use of, and management of cislunar space and its resources in accordance with the principles of space law and international law. At the national level, it is necessary to harmonise national regulations that relate to the licencing, frequencies, safety and liability of space activities, considering the interests and needs of the various actors involved, such as space agencies, private companies, scientific organisations, and civil society. These challenges require multilateral cooperation and dialogue between various stakeholders to promote the development of a lunar satellite telecommunications system that is sustainable, safe and beneficial to all (Keles 2023).

Next, this section examines the initiatives that have been taken to address the regulations and policies for establishing a lunar satellite telecommunications system. A lunar satellite telecommunications system is undoubtedly an ambitious project that requires various actors to collaborate, including space agencies, governments, companies and international organisations. To realise such a system, regulatory and political challenges in terms of security, sovereignty, accountability, resource sharing and cooperation must be addressed. Some steps that have been taken in this regard are described as follows:

- The Artemis Accords: This international agreement is promoted by the United States to establish principles and rules for the exploration and peaceful use of the Moon, Mars, asteroids and other celestial bodies. The treaty is named after the Artemis program, which aims to land the first woman and first black man on the lunar surface. It was signed by 36 countries, including Italy, on 13 October 2020 (U.S. Department of State 2023). The Artemis Accords builds on the 1967 Outer Space Treaty, which prohibits the militarisation of space and recognises that space exploration is in the common interest of humanity. The treaty also requires space activities to be conducted transparently, responsibly, and in compliance with international law and safety standards. Furthermore, it stipulates that participating countries must share scientific information and data obtained from their missions, protect the historical and cultural heritage of space, preserve the space environment and prevent the creation of space debris. The Artemis Treaty has been welcomed by many countries that see space exploration as an opportunity for scientific, technological and economic development. However, the treaty has also attracted some criticism from other countries, such as Russia and China, who see it as an attempt to impose a unilateral vision and exclude other actors from exploiting space resources. Some experts have also raised doubts about the treaty's compatibility with the principle of the nonappropriation of space enshrined in the Outer Space Treaty (Renshaw 2023).

– The Lunar Communications Architecture Working Group (LCAWG): This working group is composed of experts from different space agencies, industries, universities and nongovernmental organisations. They collaborate to identify the needs, challenges and opportunities for effective and reliable communication between the Earth and the Moon and aim to define the technical and operational standards for lunar communications. The LCAWG is responsible for defining and developing a communications network for lunar missions. It aims to create a shared vision and roadmap for the lunar communications architecture based on the principles of interoperability, standardisation, modularity and sustainability. The group meets periodically to discuss progress, best practices and recommendations for the future of lunar communication (Muff et al. 2023).
– Participation in the Moon Village Association (MVA): The MVA is a nongovernmental organisation that promotes international cooperation for the development of a sustainable human presence on the Moon. This includes the creation of a lunar telecommunications network for a permanent community there. The MVA is based on the 'Moon Village' concept proposed by the ESA in 2015, which involves a series of lunar activities and projects by various actors, both public and private, for scientific, commercial, or exploratory purposes. It refers to a vision of a sustainable, long-term human presence on the Moon, based on cooperation between different partners and sectors. This is not a specific project or a precise location but rather a general idea that encourages the development of lunar activities and infrastructure for various purposes,

such as scientific research, exploration, resource exploitation, tourism and culture. The MVA aims to facilitate dialogue and collaboration between stakeholders, to provide information and advice on the opportunities and challenges posed by the human presence on the Moon, and to support public education and awareness of the importance of the Moon for the future of humanity (Kansra 2023).

– In addition to these, there are also various private consultations with national and international regulatory authorities. This is necessary for obtaining the necessary authorisations for the launch and operation of lunar satellites, considering current regulations regarding frequencies, orbits, interference and space debris. Said authorisations are governed by a series of international and national regulations that aim to ensure the safety, sustainability and responsibility of space activities. At an international level, the main references are the 1967 Outer Space Treaty, the 1975 Convention on the Registration of Objects Launched into Outer Space and the 2007 United Nations Guidelines for the Reduction of Space Debris. Nationally, each state that intends to launch a lunar satellite system or put one into orbit must obtain a licence from its regulatory body, which may be the country's national space agency, its Ministry of Defence, or another competent body. The licence establishes the technical, legal, and financial conditions and requirements that the applicant must satisfy to conduct the operation. Additionally, the applicant must provide detailed information on the satellite system, launch vehicle, intended orbit, mission objectives, and measures taken to prevent or mitigate the generation of space debris. Depending on the complexity and sensitivity of the mission, the authorisation process can take several months or even years (Lee 2023).

CONCLUSIONS

Satellite telecommunications play a crucial role in the exploration and utilisation of the Moon. Since satellite technology constantly evolves, new advancements can enhance lunar communication capabilities. By utilising satellite constellations, we can establish a resilient and flexible infrastructure for lunar communications. However, the distance between the Earth and the Moon causes significant propagation delays, and the harsh lunar environment can damage satellites. Additionally, lunar communication technologies are still in the development stage. To address these issues, humanity is developing new technologies to reduce propagation delays and designing satellites that can withstand the lunar environment. This effort requires significant public investment in research and development of advanced lunar communication technologies.

This paper analyses the role of satellite constellations for communications as the backbone of critical infrastructure to provide fundamental services for the future of space communication. Satellite communications are fundamental to realising the presence of man on the Moon and beyond, as they allow data, images, audio and video to be transmitted between the Earth and other celestial bodies. Without satellite communications, it would not be possible to coordinate space missions, monitor the health of astronauts, receive scientific and technical information from experiments and spacecraft, and share the discoveries and excitement of exploration with the public. Satellite communications require a complex network of ground stations, artificial satellites, interplanetary probes and orbital relays, which must be synchronised and protected from interference and obstacles. It is, therefore, necessary to develop a strategic plan for lunar telecommunications and promote international cooperation for space and Moon exploration. Satellite communications pose technological, logistical, political and mental challenges, but they are also an indispensable resource for expanding the frontiers of knowledge and human adventure in space.

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