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Current Status and Development Trend of Satellite Laser Communication

Ning Li

Department of Navigational Technology, Merchant Marine College, Shanghai Maritime University, Shanghai, China

Email address:
15901917996@163.com

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Abstract: Satellite laser communication (SLC) is a technology that uses laser beams to transmit information between satellites and ground stations. SLC offers several advantages over traditional radio frequency (RF) communication, including higher data rates, lower power consumption, improved security, and longer communication distances. This paper introduces the latest research progress and development plan in the field of satellite laser communication in the United States, Europe, Japan and China, and summarizes the main parameters and indicators of domestic and foreign satellite laser communication demonstration projects. Meanwhile, based on the composition of satellite laser communication systems, this article provides a detailed analysis of the main technologies involved in satellite laser communication systems, such as Laser Transmitter, Laser Receiver, Adaptive Optics, Modulation Schemes, Pointing and Tracking. By studying the latest research progress and development plans of satellite laser communication, as well as analyzing the main technologies involved, the development trends of satellite laser communication in new laser technologies, standardization, commercialization, regulatory issues, cost effectiveness, and market demand have been summarized. It provides reference for promoting the application of satellite laser communication in maritime mobile communication, with the aim of achieving high-speed, more stable, and safer interconnection Between ships and shore, as well as between ships.

Keywords: Satellite Laser Communication, Pointing and Tracking, Development Trend, Main Technologies, Maritime Communication

1. Introduction

Maritime mobile satellite communication is an important component of maritime communication systems, providing satellite network communication services for maritime vessels. However, the current maritime mobile satellite communication system has problems such as low communication rate, narrow bandwidth, high cost, and low stability, which will seriously restrict the development of maritime economic activities and scientific research.

Satellite laser communication (SLC) is a technology that uses laser beams to transmit information between satellites and ground stations. SLC offers several advantages over traditional radio frequency (RF) communication, including higher data rates, lower power consumption, and improved security [1]. SLC has applications in a wide range of fields, including space exploration, earth observation, and telecommunications.

In SLC, a laser beam is generated by a laser transmitter on the satellite and directed towards a ground station. The laser beam carries the information signal, which is modulated onto the laser using various modulation schemes. The laser beam is received by a laser receiver at the ground station, which converts the optical signal into an electrical signal that can be processed and decoded.

SLC has several advantages over RF communication. Laser beams have a smaller beam width than RF waves, which allows for higher data rates and improved spatial resolution. Laser beams also experience less interference from atmospheric conditions, such as rain and fog, which reduces the loss of signal and improves the reliability of the communication link. Additionally, SLC offers improved security, as laser beams are more difficult to intercept or jam than RF waves.

SLC has applications in a wide range of fields, including space exploration, earth observation, and telecommunications.

SLC can be used to transmit high-resolution images and video from space-based instruments, such as telescopes and weather satellites. SLC can also be used to provide high-speed and secure communication for military and government applications, such as surveillance and reconnaissance. In the commercial sector, SLC can be used to provide high-speed internet access to remote areas and improve the efficiency of global supply chains.

SLC is a technology that uses laser beams to transmit information between satellites and ground stations. SLC offers several advantages over traditional RF communication, including higher data rates, lower power consumption, and improved security. SLC has applications in a wide range of fields and is an important technology for advancing space exploration, earth observation, and telecommunications.

2. Development Status

At present, the United States, Europe, and Japan are internationally leading in this field, conducting extensive theoretical and experimental work on various aspects of satellite laser communication, and achieving a series of research results [2-7]. The main research institutions include the National Aeronautics and Space Administration (NASA) of the United States, the Japan Aerospace Exploration Agency (JAXA), the National Institute of Information and Communication Technology (NICT) of Japan, the European Space Agency (ESA), and the German Aerospace Center (DLR), which have conducted a large number of inter satellite, satellite to ground Even the demonstration and verification experiments of satellite laser communication between the lunar orbit relay satellite and the ground station have achieved a series of significant results.

2.1. America

The United States is the first country to study satellite laser communication. Its main research institutions include the National Aeronautics and Space Administration (NASA), Goddard Space Center (GSFC), National Defense Space Force, Jet Propulsion Laboratory (JPL), MIT Lincoln Laboratory [8] and other government research institutions, as well as Northrop Grumman, Ball Aerospace and other commercial research institutions.

LCRD (Laser Communications Relay Demonstration) is a space laser communication relay demonstration and verification project conducted by NASA, aiming to verify high-speed optical communication links and network technologies in space. On December 7, 2021, the LCRD space payload was launched aboard the US Department of Defense's space test satellite STPSat-6 to conduct a bidirectional laser communication test between space and ground stations.

ILLUMA-T (Integrated LCRD Low Earth Orbit User Modem and Amplifier Terminal) is a low-cost low Earth orbit integrated terminal developed by NASA and the first in orbit test user after the end to end laser relay service of LCRD is fully operational. It is expected to be launched to the International Space Station in 2023, with the purpose of establishing a two-way communication link between GEO-LEO and completing the space networking of the space station LCRD ground station. The terminal will receive high-resolution data from the space station and transmit the data to the LCRD space payload, which will be sent to the ground station.

The DSOC (Deep Space Optical Communications) project is carried out by NASA JPL, with the main tasks of developing deep space optical transceivers and ground stations with a working wavelength of 1550nm. The goal of DSOC is to improve space communication performance and efficiency by 10 to 100 times without increasing the volume, weight, power, and spectrum burden of space terminals. The project underwent validation testing from 2018 to 2019, and it is expected that the DSOC space payload will be launched with the satellite Psyche in 2022. The launch has now been postponed, and it is expected to operate in working orbit by 2026.

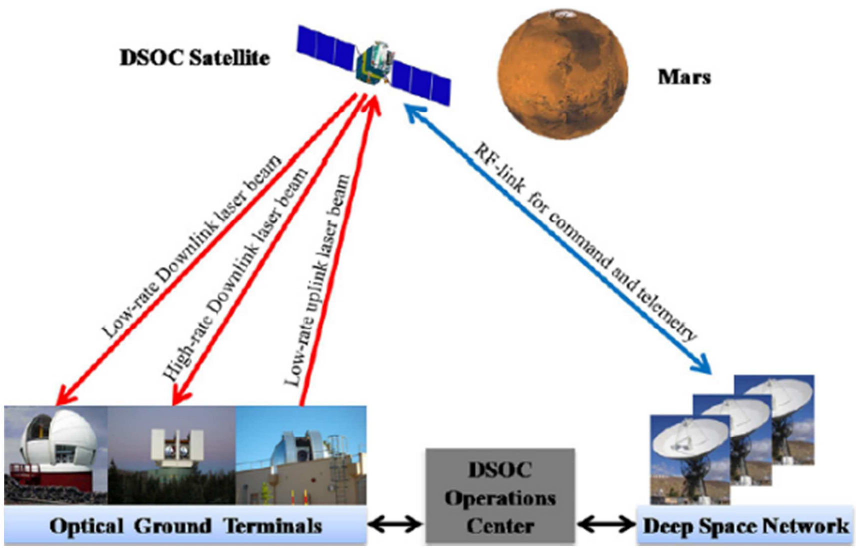

Figure 1. *Deep Space Optical Communications (DSOC).*

In 2023, NASA plans to launch the Artemis II manned spacecraft to orbit the moon. The O2O (Orion Artemis II Optical Communication System) will achieve 4K real-time ultra high definition video transmission and enhanced scientific data transmission between Artemis II and Earth, making this mission one of the first to use laser communication technology for manned spaceflight.

2.2. Europe

In 1977, Europe began researching satellite laser communication. The government agencies involved in the research mainly include the European Space Agency (ESA), the German Aerospace Center (DLR), and commercial institutions include Oerlikon Contraves, Marconi, and others.

In 1989, the European Space Agency (ESA) began the SILEX (Semiconductor Inter satellite Laser Communications Experiment) research program [9, 10]. The SILEX system is designed with two satellite laser communication payloads, which were launched in 1998 and 2001 on low orbit satellite (LEO) SPOT-4 and synchronous orbit satellite (GEO) ARTEMIS. Laser communication experiments were carried out in space, with a data transmission rate of 50Mb/s.

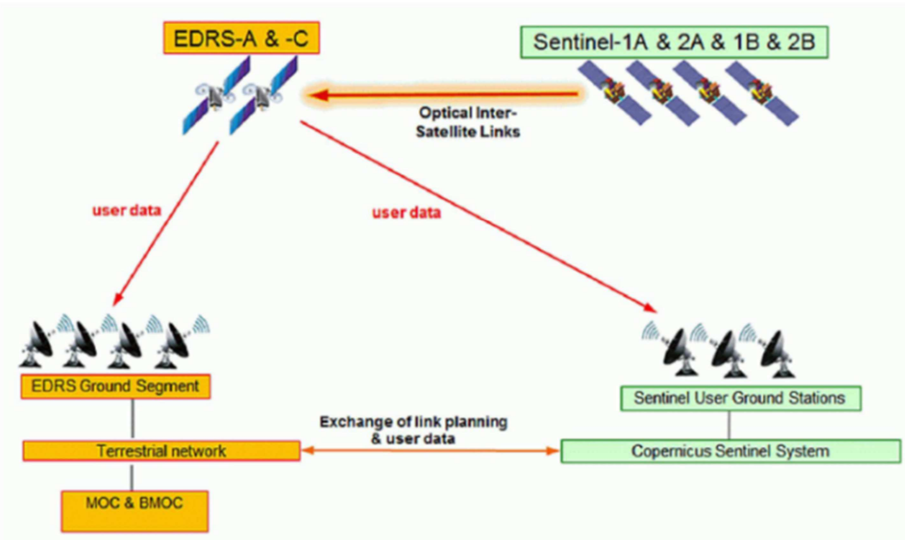

Figure 2. *The European Data Relay Satellite System (EDRS).*

The European Data Relay Satellite System (EDRS) is the world's first space "fiber optic" network based on advanced laser technology. It uses laser communication technology and provides real-time data relay between LEO satellites and ground control centers through three GEO data relay satellites, with a communication rate of 1.8Gbps. The EDRS system consists of three laser communication payloads, EDRS-A, EDRS-C, and EDRS-D. On January 30, 2016, EDRS's first laser communication payload, EDRS-A, was launched into geostationary orbit. On August 6, 2019, EDRS's second laser communication payload, EDRS-C, was launched into space. EDRS's third laser communication payload, EDRS-D, is expected to be launched by satellite in 2024 and located over the Asia Pacific region.

The OSIRIS project plans to develop laser communication technology and systems for direct downlink of LEO small satellites and direct connection between small satellites. In the OSIRIS project, experimental laser communication terminals jointly developed by DLR-IKN and TESAT include OSIRISv1, OSIRISv2, OSIRISv3, and OSIRISv4 CubeSat, with a lightweight, compact design and low power consumption.

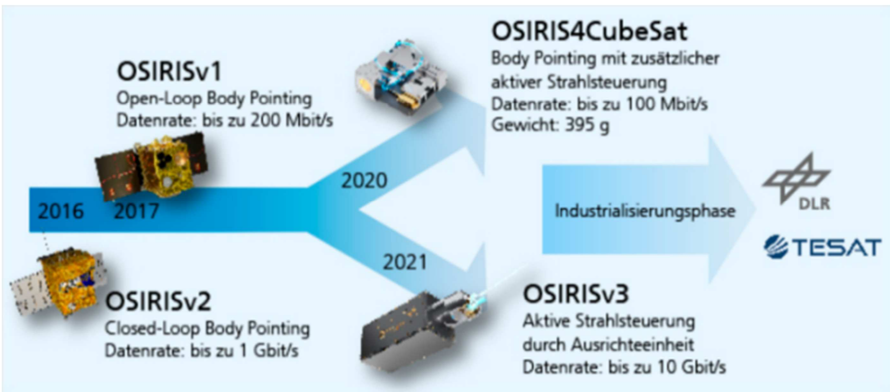

Figure 3. *OSIRIS Project Development Roadmap.*

2.3. Japan

In the early 1970s, Japan began the research on satellite laser communication technology [11, 12], mainly conducting theoretical and experimental research on inter satellite and satellite to earth satellite laser communication technology. Its main research institutions are: Japan Aerospace Exploration Agency (JAXA), Japan National National Institute of Information and Communications Technology (NICT), Advanced Long Distance Communication Research Institute (ART), Communication Research Laboratory (CRL) and Radio Communication Laboratory of the Ministry of Posts and Telecommunications [13].

The Japan Aerospace Exploration Agency (JAXA) has launched an Optical Data Relay Satellite (JDRS) project with the main purpose of demonstrating a high-speed data relay system that will become JAXA's future space communication infrastructure. JDRS uses optical links between low orbit satellites and data relay satellites, as well as Ka band feeder links between data relay satellites and ground stations. The laser communication terminal of the optical data relay system is small, with a wide communication range, and a data transmission rate of up to 1.8Gbps. On November 29, 2020, Japan launched a JDRS-1 high-orbit relay satellite using an H-2A rocket. The JDRS-1 relay satellite has an expected lifespan of 10 years and is equipped with a laser communication system developed by JAXA. It is connected to remote sensing satellites through near-infrared laser beams to achieve high-speed data transmission, with a bandwidth of 1.8Gbps. The laser terminal used for optical relay satellites has a diameter of only 14 centimeters.

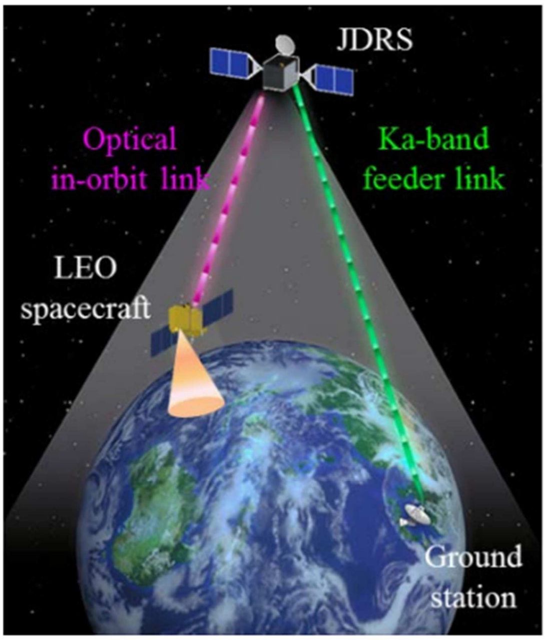

Figure 4. *Japanese data relay satellite (JDRS).*

The National Institute of Information and Communications (NICT) of Japan has launched the High speed Communication with Advanced Laser Instrument (HICALI) project, aimed at achieving 10Gbps level space laser communication from GEO satellites to optical ground stations (OGS). In 2023, the project plans to launch two laser communication terminals carrying the technology experimental satellite ETS9 into geosynchronous orbit.

In February 2021, NICT and DLR conducted optical communication tests between the OSIRIS communication payload of the LEO satellite and the NICT OGS of the HICALI project. NICT OGS successfully received optical signals and evaluated the performance of the tracking system.

2.4. China

With the increase of national research on space technology, satellite laser communication has attracted great attention and developed rapidly. Many universities and research institutions have carried out a lot of theoretical and experimental work on satellite laser communication, completed a lot of technology and achievements accumulation, and now it has entered the engineering stage [13]. The research of satellite laser communication involves the key technology of communication link design and the influence of atmosphere on communication link, the influence of atmospheric cloud layer, boundary layer, vibration and turbulence and other factors on satellite laser communication, PAT technology of satellite laser communication [14] and payload testing technology [15]. In 2011, the satellite laser communication payload researched and manufactured was successfully carried out laser communication experiments with the ground using the "Ocean 2" satellite, achieving high-speed direct laser communication between satellites and the ground for the first time, with a maximum data communication rate of 504Mb/s [13]. In 2016, the developed coherent laser communication terminal was equipped with the "Mozi" quantum experimental satellite to conduct the first satellite to ground coherent laser communication in orbit experiment [16], with a maximum communication rate of 5.12Gb/s downstream. In 2017, the Shijian No. 13 high-throughput laser communication satellite was successfully launched, completing the GEO ground laser communication experiment for the first time [17], with a maximum communication rate of 5Gb/s. In 2019, the high-speed high-order coherent laser communication terminal equipped with the Practice 20 satellite conducted the first QPSK coherent system laser communication in orbit test, with a speed of up to 10Gb/s.

3. The Main Technologies of Satellite Laser Communication

Satellite laser communication (SLC) involves a complex set of technologies that enable high-speed, secure, and reliable communication between satellites and ground stations. In this section, we will analyze the main technologies of SLC in detail.

3.1. Laser Transmitter

The laser transmitter is a critical component of an SLC system, as it generates and amplifies the laser beam that carries the communication signal. The laser transmitter must be compact, lightweight, and capable of producing high-power laser beams with stable wavelength and polarization. The most common laser transmitter for SLC is the semiconductor laser diode, which is highly efficient and has a long operational lifetime. The development of high-power and high-efficiency laser diodes has improved the signal-to-noise ratio and extended the range of SLC systems.

3.2. Laser Receiver

The laser receiver is responsible for detecting and converting the incoming laser beam into an electrical signal that can be processed and decoded by the ground station. The laser receiver must be sensitive to low-power laser signals and operate over a wide range of wavelengths and polarization states. The most common laser receiver for SLC is the avalanche photodiode (APD), which is highly sensitive and has a low noise floor. The development of high-performance APDs and other types of detectors, such as superconducting nanowire single-photon detectors (SNSPDs), has improved the sensitivity and bandwidth of SLC systems.

3.3. Adaptive Optics

Atmospheric turbulence can cause the laser beam to scatter and degrade the signal in SLC. Adaptive optics is a technology that can compensate for atmospheric turbulence and maintain a stable laser beam. Adaptive optics systems use a wavefront sensor to measure the distortion of the laser beam caused by atmospheric turbulence and a deformable mirror to adjust the shape of the laser beam and compensate for the distortion. The development of advanced adaptive optics systems, such as multi-conjugate adaptive optics (MCAO) and tomographic adaptive optics (TAO), has improved the performance of SLC systems in the presence of atmospheric turbulence.

3.4. Modulation Schemes

Modulation schemes are used to encode the information signal onto the laser beam in SLC. The modulation scheme must be compatible with the laser transmitter and receiver and provide high spectral efficiency and error correction capability. The most common modulation schemes for SLC are pulse position modulation (PPM) and quadrature amplitude modulation (QAM). PPM is a simple and efficient modulation scheme that encodes the information signal onto the time position of the laser pulses. QAM is a more complex modulation scheme that encodes the information signal onto the amplitude and phase of the laser beam. The development of advanced modulation schemes, such as orthogonal frequency-division multiplexing (OFDM) and differential phase-shift keying (DPSK), has increased the data rate and improved the spectral efficiency of SLC.

3.5. Pointing and Tracking

Precise pointing and tracking of the laser beam are essential for maintaining a stable and high-quality communication link in SLC. SLC systems must be able to track the movement of the satellite and ground station and adjust the direction of the laser beam in real-time. The pointing and tracking system typically consists of a gimbal-mounted telescope, a high-precision encoder, and a closed-loop control system. The development of advanced pointing and tracking systems, such as the use of machine learning algorithms and image-based tracking, has improved the accuracy and speed of SLC systems.

SLC involves a complex set of technologies, including laser transmitters and receivers, adaptive optics, modulation schemes, and pointing and tracking systems. The development of these technologies has enabled high-speed, secure, and reliable communication between satellites and ground stations. The ongoing research and development of SLC technologies will continue to improve the performance and capabilities of SLC systems in the future.

4. Development Trend

Satellite laser communication (SLC) is a rapidly evolving technology that has the potential to revolutionize space communication. The development of new laser technologies, standardization, and commercialization are driving the growth of SLC in the future. In this section, we will analyze the development trend of SLC in detail.

4.1. New Laser Technologies

The development of new laser technologies is a key driver of the growth of SLC. Quantum cascade lasers (QCLs) and terahertz lasers are promising candidates for next-generation SLC systems. QCLs are semiconductor lasers that operate in the mid-infrared region, providing high output power, narrow linewidth, and high spectral purity. Terahertz lasers operate at frequencies between the microwave and infrared regions, offering the potential for high-bandwidth, long-range communication.

4.2. Standardization

The standardization of SLC protocols and interfaces is essential to facilitate the commercialization of SLC technology and increase its adoption in the industry. Several organizations, such as the Consultative Committee for Space Data Systems (CCSDS) and the International Telecommunication Union (ITU), have developed standard protocols for SLC, including modulation schemes, error correction codes, and packet formats. The standardization of SLC will enable interoperability among different SLC systems and reduce the cost and complexity of implementing SLC.

4.3. Commercialization

The commercialization of SLC is an important trend that will drive the growth of SLC in the future. Several companies, such as Mynaric, Laser Light Communications, and BridgeComm, are developing SLC systems for commercial applications, including satellite-to-satellite communication, earth observation, and broadband internet access. The commercialization of SLC will increase the demand for SLC technology and accelerate its adoption in the industry.

4.4. Regulatory Issues

The regulatory environment for SLC is complex and varies by country. The use of lasers in space is regulated by international agreements, such as the Outer Space Treaty and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). In addition, national regulatory bodies, such as the Federal Communications Commission (FCC) in the United States and the European Space Agency (ESA) in Europe, regulate the use of SLC systems within their respective jurisdictions. The harmonization of regulations and the establishment of international standards will facilitate the deployment and operation of SLC systems.

4.5. Cost-Effectiveness

The cost-effectiveness of SLC is a crucial factor in its adoption in the industry. SLC systems require specialized hardware and software, including laser transmitters and receivers, adaptive optics, and pointing and tracking systems. The development of low-cost, high-performance components and the economies of scale from commercialization will reduce the cost of implementing SLC.

4.6. Market Demand

The market demand for SLC is driven by the need for high-speed, secure, and reliable communication in space. SLC has several potential applications, including satellite-to-satellite communication, earth observation, and space exploration. The increasing demand for data-intensive applications, such as remote sensing and broadband internet access, will drive the growth of SLC in the future.

The development of new laser technologies, standardization, and commercialization are driving the growth of SLC in the future. The harmonization of regulations, the reduction of cost, and the increasing market demand will accelerate the adoption of SLC in the industry. SLC is a promising technology that can enable new discoveries in space exploration and earth observation, and provide new opportunities for scientific research and commercial applications.

5. Conclusion

Satellite laser communication technology has made significant progress in recent years and has the potential to revolutionize space communication. The development of new laser technologies, standardization, and commercialization will drive the growth of SLC in the future. SLC is a promising technology that can enable new discoveries in space exploration and earth observation, and provide new opportunities for scientific research and commercial applications. With the development of navigation, especially e-navigation, intelligent ships, and autonomous ships, the demand for maritime communication is increasing day by day. Satellite laser communication, with its advantages of high communication speed, no frequency interference, strong anti-interference ability, and longer communication distance, will make up for the shortcomings of maritime satellite communication and promote the further development of navigation.

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