

# Advances and Future Directions in Deep Space Laser Communication

Yihang He

Department of Leeds, Southwest Jiaotong University, Chengdu, China

1711329653@qq.com

**Abstract.** Exploring deep space is paramount to humanity in exploring the more distant universe, providing a core value for human survival and future development. With the expansion of deep-space exploration, traditional radio frequency (RF) communication faces bottlenecks such as limited bandwidth, high power consumption, and vulnerability to interference, restricting missions like crewed Mars expeditions and outer planetary exploration. Consequently, this review aims to systematically analyze the development of deep-space laser communication, clarify its advantages over RF technology, and prospect its future directions, thereby providing a comprehensive reference for advancing next-generation deep-space communication systems. The study integrates global research progress to achieve this objective, including historical milestones, key technological breakthroughs, and comparative laser and RF communication analyses. Specifically, data is sourced from authoritative project reports, experimental results, and academic literature to ensure comprehensiveness and reliability. This synthesis shows that deep laser communication has significant advantages: it achieves lightweight terminals, strong anti-interference ability, and high security. This review confirms that laser communication is a critical technology that can break through RF limitations. Its development trajectory and future directions lay a foundation for high-speed, reliable deep-space communication, ultimately accelerating humanity's exploration of the solar system and beyond.

**Keywords:** deep space optical communication; deep space laser communication; radio frequency (RF) communication; data rate.

## 1. Introduction

Since the dawn of the space age, humanity's relentless pursuit of cosmic mysteries has driven the expansion of deep-space exploration—from Apollo's first lunar footprints and Perseverance's Mars chemical analyses to Voyager's interstellar voyages—each mission pushing the boundaries of knowledge yet fundamentally constrained by communication infrastructure [1-3]. Radio frequency (RF) communication, operating in S, X, and Ka bands, has been the backbone for over six decades, enabling milestones like the 2003 Mars rovers' 128 kbps downlink [4]. However, RF's inherent limits now bottleneck grander frontiers such as crewed Mars missions and outer planetary outposts.

RF bandwidth, restricted by spectrum rules and physics, caps near-Earth rates at hundreds of Mbps and plummets to kilobits for distant targets—exemplified by New Horizons' 1-2 kbps during its 2015 Pluto flyby [5]. At extreme distances, RF efficiency collapses: a 1-watt Mars signal suffers over 280 dB loss, demanding bulky, power-hungry 70-meter antennas, impractical for small spacecraft or constellations.

Using 1550 nm/1064 nm optical carriers, deep space laser communication offers  $10 - 1000 \times$  RF's bandwidth, enabling terabit speeds—a 1GB Mars panorama takes <1 minute vs. >1 hour via RF. Narrower beams ( $\leq 10 \mu\text{rad}$ ) reduce interference, allowing smaller hardware: NASA's 2022 TBIRD mission achieved 10 Gbps with a 15cm transceiver, far lighter than RF equivalents [6]. China's Tianwen-1 laser experiments [7] and NASA's Psyche mission (targeting Mars flyby and Asteroid landing in 2026) [8].

This paper comprehensively reviews deep-space laser communication, elaborating on its development against RF limitations. It traces deep-space communication history, highlights RF's performance limits, analyzes laser communication's advantages (high speed, low power, strong anti-interference, security, low-latency real-time), elaborates domestic and foreign technological

breakthroughs, and outlines future directions. The primary objective is to facilitate international development integration, identify pivotal breakthroughs, and predict future research directions.

## 2. History development

The history of deep space laser communication can be divided into several phases: the Early Technology Exploration Phase (Early 2000s), the Lunar-Earth Communication Verification Phase (2010s), the International Technological Collaboration Breakthrough Phase (Mid-2000s), and the Planetary Communication Milestone (2020s).

In 2003, NASA launched the Mars Laser Communication Demonstration (MLCD) project to accumulate experience in deep-space optical link technology. Although the project was eventually terminated due to internal planning adjustments, it laid the foundation for subsequent key technology research and development [9]. Later, the Lunar Atmosphere and Dust Environment Explorer (LADEE), carrying the Lunar Laser Communication Demonstration (LLCD) terminal, was launched. In November of the same year, the test achieved a significant breakthrough: the on-board terminal successfully captured and tracked the ground beacon light, achieving communication rates of 622 Mbps for downlink and 20 Mbps for uplink [10].

In late 2005, NASA's Advanced Relay and Technology Mission Satellite (ARTEMIS) and JAXA's Optical Inter-orbit Communications Engineering Test Satellite (OICETS) completed the first space laser communication test. In 2006, Italy's LUCE terminal completed optical communication experiments with the ground optical station of Japan's National Institute of Information and Communications Technology and the mobile ground optical station of the German Aerospace Center, promoting the development of international technological collaboration. [11]

In 2023, NASA's Psyche probe was launched. Its Deep Space Optical Communications (DSOC) technology successfully sent laser signals to Earth from 16 million kilometers away on November 14. It achieved laser communication beyond the Earth-Moon distance for the first time, marking a new stage in deep-space communication technology [12]. In March 2025, the Psyche probe transmitted asteroid spectral data in real-time from 460 million kilometers away, and ground scientists completed the analysis in just 5 minutes, marking the official entry of deep-space communication into the "real-time interaction" era. [13]

## 3. Technological Breakthroughs

### 3.1 Laser Communication for Deep Space Exploration

The Deep Space Optical Communication (DSOC) technology demonstration project, led by NASA, was initiated in conjunction with the Psyche mission launched in August 2022. The project aims to verify the capabilities of laser communication within the range of 0.1 to 2.7 astronomical units. The core equipment of the system includes a Flying Laser Transceiver (FLT), a ground-based Laser Emitter (GLT) based on a 1-metre telescope, and a ground-based Laser Receiver (GLR) installed on the 5-metre Halle Telescope at the Palomar Observatory. The latter is equipped with a 64-pixel tungsten-silicide superconductor nanowire single-photon detector array. The device can receive an optical signal with a wavelength of 1550nm and can support data rates ranging from 56kbps to 265Mbps. The project completed weekly optical link demonstrations from November 2023 to December 2024. The downlink data rate was successfully achieved at a rate of 6.25-267Mb/s at a distance of 0.2-2.7AU, and the uplink communication rate was successfully achieved at a rate of 1.8kb/s at a distance of 0.2-3.3AU. The verification process encompassed critical technologies such as photon counting reception and link capture tracking, with the subsequent confirmation of deep-space optical communication capability, including managing long round-trip optical times and substantial lead angles. The project under discussion constitutes the basis for enhancing the equivalent omnidirectional radiation power of flight systems in the future and developing low-cost ground

systems. The project will facilitate high-data-rate communication on Mars and in deeper space beyond [14-16].

### 3.2 High-speed Laser Communication in Free Space

In 2023, the Xi Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, achieved a breakthrough in ultra-high-speed space laser communication, achieving a rate of 1.02 terabits per second. This milestone represents a substantial advancement in optical communication, utilizing microcavity soliton optical frequency combs as a novel multi-carrier light source, replacing traditional semiconductor laser arrays. The experiment demonstrated the efficacy of this approach by successfully transmitting large volumes of data at a rate of 1.02 terabits per second over a free-space optical communication link spanning a distance of 1 kilometer. This provides new ideas and means for future larger-capacity free-space laser communication [17].

### 3.3 Deep Space Laser Ranging

At 02:00 hours on 23 April 2025, a research team comprising the Space Application Engineering and Technology Centre of the Chinese Academy of Sciences, the Yunnan Astronomical Observatory, and the Shanghai Astronomical Observatory successfully detected the laser echo signal of the single-angled cone reflector of China's long-range retrograde orbit satellite (DRO-A) using the laser ranging system of the 1.2-metre telescope of the Yunnan Astronomical Observatory. The mean distance between the satellite and the Earth is approximately 350,000 kilometers. This represents a significant milestone for China in deep space satellite laser ranging technology, as it is the first time the country has achieved satellite laser ranging at the Earth-Moon distance scale [18].

### 3.4 Satellite Constellation Laser Communication

On 14 May 2025, the "Three-Body Computing Constellation" inaugural satellite was successfully launched from Jiuquan aboard a Long March 2D rocket. Domestic enterprise Helium Starlink provided 24 sets of laser communication terminals, setting a national record for the most laser communication models launched in a single launch, the most significant number of terminals, and the most established communication chains. This mission successfully achieved breakthroughs in three core technologies: real-time inter-satellite data transmission, dynamic computing power scheduling, and spatial networking coordination. The maximum rate of inter-satellite laser communication is reported to be 100 Gbps [19].

## 4. Advantages of Optical Communication

Compared to RF communication, optical communication operates at higher carrier frequencies and features lower diffraction losses, better directivity, and higher transmission efficiency. As a result, it can achieve high transmission rates and excellent communication performance with lower transmission power and smaller antenna sizes [20].

### 4.1 High Data Transmission Rate

The advent of a plethora of spaceborne detectors, coupled with the concomitant growth in data volume and the expansion of detection fields, has given rise to a persistent and escalating demand for enhanced ground communication rates in deep space exploration. Laser communication's efficacy in data transmission rates has been demonstrated remarkably. The frequency band of satellite optical communication is 300THz,  $10^3$  to  $10^6$  times lower than the 300MHz-300GHz frequency band utilised by satellite microwave communication. In optical communication, the bandwidth available for modulation can be considerably expanded, thereby enabling communication data rates to approach several Gbps and, in some cases, higher speeds [21].

## **4.2 Terminal Lightweighting and Low Power Consumption**

In the context of space missions, the weight and power consumption of spacecraft are subject to stringent constraints. Laser communication terminals' lightweight and low-power consumption characteristics are conducive to spacecraft carrying more equipment and performing more complex tasks. The high and low transmission rates of free-space laser photonic communication systems are advantageous, and the equipment has greater weight and power consumption when compared with traditional communication equipment. This renders it a significant research direction for future deep-space communication. In the context of deep space exploration missions, such as asteroids, there is a stringent set of requirements for small remote-controlled detectors regarding volume and power consumption. The advent of laser communication technology has the potential to address these challenges, with the prospect of miniaturizing detectors and reducing power consumption [22].

## **4.3 Anti-electromagnetic Interference Ability**

The deep space environment is complex and characterized by various electromagnetic interferences. The basis of laser communication is optical signal transmission, a method that is less affected by electromagnetic interference. This ensures the stability and reliability of communication. The deep space environment is characterized by a substantial presence of electromagnetic radiation emanating from celestial bodies, including the sun. Traditional radio frequency communication is vulnerable to such interferences, which can result in signal distortion or loss. The concept of laser communication is predicated on using laser propagation in space. The frequency band under consideration falls outside the main range of electromagnetic interference. This is a significant factor in ensuring the effective resistance of electromagnetic interference and the subsequent stability of deep space communication links [23].

## **4.4 High Security**

The laser beam is narrow, which makes the signal less likely to be intercepted or interfered with, thereby enhancing the security of communication. This is of paramount importance for the transmission of sensitive data in deep space communication. Laser communication diverges less than traditional radio frequency communication, and the energy is concentrated in a narrow range. This makes it difficult for the enemy to intercept the signal over long distances. In the context of deep space exploration missions, the transmission of detailed detection data about specific celestial bodies is of considerable scientific research value. The high security of laser communication can effectively ensure that the data transmission process is not stolen or interfered with [23].

# **5. Future Directions**

## **5.1 Enhance the capability of ultra-long-distance communication:**

The implementation of deep-space laser communication projects by the United States has resulted in a continuous augmentation of communication distances. For instance 2013, LLCD achieved laser communication from the moon to the Earth at 400,000 kilometers. In 2023, DSOC conducted experiments in the orbit of the asteroid Psyche at a distance of 0.06 to 2.7AU (approximately 90 million to 405 million kilometers), demonstrating that the transmission distance of laser communication has been constantly setting new records [24].

## **5.2 Networked construction and the lightweight and low-cost development of terminals:**

The LunaNet programme, administered by NASA in the United States, is developing a communication network about the moon. This initiative signifies the progression of deep-space laser communication from its initial manifestation as single-point links to the subsequent evolution of networked architectures. Concurrently, due to the stringent limitations imposed by parameters such as volume, weight, and power consumption, the optical engines of deep space laser communication

terminals are capable of adopting SiC (Silicon carbide) materials to reduce weight, thus exhibiting a development trend towards lightweight and cost-effective solutions [24].

### 5.3 Enhance Communication Efficiency

Several deep-space laser communication programs have been initiated in the United States to enhance the communication rate between satellites and the ground. A notable example is the Orion EM-2 Optical Communication (O2O) experiment, which has successfully demonstrated an augmentation in communication rate between satellites and the ground [24]. The transmission of optical signals in deep space is subject to the effects of the atmosphere. The ground must increase the aperture of the receiving optical antenna. Employing a single large-aperture or multi-aperture optical antenna array is a viable option, given the acknowledged fact that deep-space laser communication is beset by a plethora of external environmental interferences, many of which remain to be addressed [24].

## 6. Conclusion

This paper systematically reviews the development of deep space laser communication, clarifies its advantages over traditional radio frequency (RF) communication, and explores its future directions. It provides a comprehensive reference for the design of next-generation deep-space communication architectures.

This paper's contribution and significance lie in two aspects: First, it integrates global research progress to form a comprehensive review of deep space laser communication, filling the gap of a systematic summary in current literature. Second, clarifying the technical advantages and practical achievements of laser communication provides a theoretical and empirical basis for decision-making in deep-space mission design, helping to accelerate the application of laser communication in future exploration.

However, this paper also has limitations. Due to the rapid development of deep-space laser communication, some cutting-edge technologies (e.g., real-time adaptive optics for atmospheric interference mitigation) may have new progress beyond the scope of this review. Additionally, the paper focuses more on technical performance and historical development, with relatively less discussion on economic feasibility (e.g., cost-benefit analysis of large-scale ground station construction) and policy coordination (e.g., international spectrum allocation for laser communication), which could be explored in future studies.

## References

- [1] NASA. (n.d.). Apollo program overview. <https://www.nasa.gov/apollo>
- [2] NASA. (2021). Perseverance Mars rover mission. <https://mars.nasa.gov/perseverance/>
- [3] NASA. (n.d.). Voyager: Interstellar mission. <https://voyager.jpl.nasa.gov/>
- [4] Crisp, J. A., Arvidson, R. E., Bell, J. F., III, Catalano, J. G., Crumpler, L. S., Farrand, W. H., Gellert, R., Golombek, M. P., Greeley, R., Herkenhoff, K. E., Hviid, S. F., Johnson, J. R., Klingelhofer, G., Knoll, A. H., Li, R., Madsen, M. B., Malin, M. C., McSween, H. Y., Jr., Ming, D. W., ... Zimmerman, R. R. (2003). Mars Exploration Rover mission. *Journal of Geophysical Research: Planets*, 108(E12), 8063. <https://doi.org/10.1029/2002JE002038>
- [5] Ennico, K. (2015). New Horizons successful completes the historic first flyby of Pluto and its moons. NASA Technical Reports Server. <https://ntrs.nasa.gov/citations/20150018394>
- [6] Piazzolla, S., Biswas, A., Srinivasan, M., Hoppe, D., Israel, D., Moision, B., Murphy, D., & Farr, W. (2023). TBIRD 200-Gbps CubeSat downlink: System architecture and mission plan. NASA Technical Reports Server (NTRS). <https://ntrs.nasa.gov/citations/20230005711>
- [7] China National Space Administration. (2021). Tianwen-1 Mars mission. <http://www.cnsa.gov.cn/>

- [8] Ishola, M. F. (2021). Free-space optical communications for resource-limited small satellites [Doctoral dissertation, Kyushu Institute of Technology]. Kyushu Institute of Technology Repository. [https://kyutech.repo.nii.ac.jp/record/7525/files/kou\\_k\\_537.pdf](https://kyutech.repo.nii.ac.jp/record/7525/files/kou_k_537.pdf)
- [9] Boroson, D. M., Biswas, A., & Edwards, B. L. (2004). MLCD: Overview of NASA's Mars laser communications demonstration system. In Proceedings of SPIE - The International Society for Optical Engineering (Vol. 5338, pp. 1–12). SPIE. <https://doi.org/10.1117/12.543014>
- [10] D. Boroson, B. Robinson, D. V. Murphy, D. Burianek, F. Khatri. (2014). Overview and results of the Lunar Laser Communication Demonstration. Photonics West - Lasers and Applications in Science and Engineering. <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/8971/1/Overview-and-results-of-the-Lunar-Laser-Communication-Demonstration/10.1117/12.2045508.full>
- [11] Jono, T., Takayama, Y., Shiratama, K., Mase, I., & Demellenne, B. (2007). Overview of the inter-orbit and orbit-to-ground laser communication demonstration by OICETS. In Proceedings of SPIE - The International Society for Optical Engineering (Vol. 6456, pp. 1–10). SPIE. <https://doi.org/10.1117/12.708864>
- [12] NASA. (2025). Deep Space Optical Communications (DSOC) on Psyche. <https://www.nasa.gov/mission/deep-space-optical-communications-dsoc/>
- [13] Science Popularization China Resource Service. (2025, March 24). Graphic details — Deep-space communication enters the era of "real-time interaction". <https://cloud.kepuchina.cn/h5/detail?id=7303528710877794304>
- [14] Biswas, A., Srinivasan, M., Piazzolla, S., & Hoppe, D. (2018). Deep Space Optical Communications. In Free-Space Laser Communication and Atmospheric Propagation XXX (Vol. 10524, 105240U). SPIE. <https://doi.org/10.1117/12.2296426>
- [15] Srinivasan, M., Alerstam, E., Wollman, E., Murphy, D., Hoppe, D., Maruyama, Y., Moision, B., & Biswas, A. (2023). The Deep Space Optical Communications Project Ground Laser Receiver. In Free-Space Laser Communications XXXV (Vol. 12413, 124130R). SPIE. <https://doi.org/10.1117/12.2649577>
- [16] Biswas, A., Srinivasan, M., Andrews, K., Alerstam, E., Zimmerman, M., Murphy, D., Hoppe, D., & Moision, B. (2025). Overview of the Deep Space Optical Communications (DSOC) technology demonstration. In Free-Space Laser Communications XXXVII (Vol. 13355, 133550J). SPIE. <https://doi.org/10.1117/12.3043966>
- [17] Chinese Academy of Sciences. (2023, June 12). Xi'an Institute of Optics and Precision Mechanics of CAS: Building a "high-speed road" in the field of future space ultra-high-speed photonic networks. [https://www.cas.cn/cm/202306/t20230612\\_4895120.shtml](https://www.cas.cn/cm/202306/t20230612_4895120.shtml)
- [18] Chinese Academy of Sciences. (2025, April 26). China achieves satellite laser ranging at the Earth-Moon distance scale. [https://www.cas.cn/cm/202504/t20250427\\_5066253.shtml](https://www.cas.cn/cm/202504/t20250427_5066253.shtml)
- [19] Douyin Encyclopedia. (2025, July 29). Three-body Computing Constellation. [https://m.baik.com/wiki/%E4%B8%89%E4%BD%93%E8%AE%A1%E7%AE%97%E6%98%9F%E5%BA%A7/7504166909765599244?baike\\_source=1](https://m.baik.com/wiki/%E4%B8%89%E4%BD%93%E8%AE%A1%E7%AE%97%E6%98%9F%E5%BA%A7/7504166909765599244?baike_source=1)
- [20] Wu, W. R., Chen, M., Zhang, Z., Liu, Y., & Tang, C. W. (2018). Overview of deep space laser communication. Science China Information Sciences, 61(4), 040301. <https://doi.org/10.1007/s11432-017-9216-0>
- [21] Tan, L. Y., & Sun, Z. H. (2019). High speed laser information transmission technology of deep space between Moon and Earth. Journal of Deep Space Exploration, 6(6), 515-522. <https://doi.org/10.15982/j.issn.2095-7777.2019.06.001>
- [22] Ye, Q., Li, J., Liu, Y., & Tang, C. W. (2012). Deep space, free space, non-line-of-sight scattering and underwater laser photon communication. Infrared and Laser Engineering, 41(9), 2476–2481. <https://doi.org/10.3969/j.issn.1007-2276.2012.09.032>
- [23] Liu, Y., Li, J., Ye, Q., & Tang, C. W. (2024). Research progress and development direction of deep space laser communication (invited). Laser & Optoelectronics Progress, 61(7), 0700001.
- [24] Wang, X., Zhang, L., Li, M., & Zhao, J. (2024). Development status and trend analysis of deep-space laser communication. Optics Journal. <https://www.opticsjournal.net/Articles/OJ45d75690df62b9be/FullText>