

Lunar-Earth Optical Communication Architecture Concept and Technology Development Status

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ABSTRACT

Future lunar exploration missions, including the Artemis program, will require communication capacities far beyond those achievable with conventional radiofrequency (RF) and optical communication systems. This study presents the concept and technology development status of JAXA's 1-Gbps-class lunar–Earth optical communication system. JAXA is developing a hybrid RF/optical communication architecture employing relay satellites in elliptical lunar frozen orbit (ELFO), targeting a 1-Gbps optical return link in the early 2030s. A link budget analysis was performed to determine the baseline optical terminal configuration, resulting in a 10 W optical transmitter, a 10-cm transmit aperture on the lunar relay satellite, and a 30-cm receive aperture on the Geostationary Earth Orbit (GEO) relay satellite. A quantitative comparison between photon-counting pulse-position modulation (PPM) and coherent binary phase-shift keying (BPSK) was also conducted for a 1-Gbps Earth–Lunar link under lunar background-light conditions. The analysis supports coherent BPSK as the baseline modulation scheme and establishes baseline optical terminal configuration for a 1-Gbps-class Lunar–Earth link.

Keywords: Optical communication terminal, Pulse Position Modulation (PPM), BPSK, Geostationary Earth Orbit (GEO) - Elliptical Lunar Frozen Orbit (ELFO) communication

1. INTRODUCTION

In recent years, lunar exploration has accelerated significantly through international initiatives such as the Artemis Program. To support lunar orbiters, landers, and future surface infrastructure, space agencies including NASA, ESA, and JAXA are developing advanced Earth–Lunar communication systems.

Lunar-Earth communications have traditionally relied on radiofrequency (RF) technologies operating mainly in the S-, X-, and Ka-bands. These systems have been successfully demonstrated in numerous missions, including Apollo, the Lunar Reconnaissance Orbiter (LRO), and the Korea Pathfinder Lunar Orbiter (KPLO) [1], [2]. Although RF communications provide highly reliable links, their capacity is fundamentally constrained by limited spectrum and transmission power, making it increasingly difficult to satisfy the rapidly growing demand for high-data-rate lunar communications.

Future lunar exploration will require simultaneous operation of multiple spacecraft, teleoperation of lunar surface systems, AI-assisted mission operations, ultra-high-definition video transmission, and large-volume scientific data transfer. These applications will demand communication capacities well beyond the current tens to hundreds of megabits per second, making Gbps-class links essential for the future lunar communication backbone.

Optical communication has emerged as a promising solution to meet these requirements. In 2013, NASA's Lunar Laser Communication Demonstration (LLCD) achieved a 622-Mbps downlink and a 20-Mbps uplink over the Earth–Lunar distance, demonstrating the feasibility of high-speed optical communications [3], [4]. More recently, the Optical Communications System (O2O) for Artemis II has been planning to demonstrate optical communications at approximately 260 Mbps, including real-time data and 4K video transmission [5]. While these demonstrations have validated optical communication technology for cislunar missions, substantially higher capacities will be required for future lunar exploration. In addition to these demonstration missions, plans have been formulated for the future development of lunar communication infrastructure[6], [7].

Motivated by these requirements, this paper presents the system design methodology for a 1-Gbps Earth–Lunar optical communication payload, including link-budget-based aperture optimization, a quantitative trade-off analysis between coherent BPSK and photon-counting PPM under lunar background radiation, and the preliminary design of an optical terminal.

2. EARTH–LUNAR COMMUNICATION SYSTEM CONCEPT

To support future international lunar exploration activities, JAXA is studying a lunar communication architecture based on two fundamental objectives: (1) maintaining Japan's technological competitiveness while providing unique contributions to international exploration programs, and (2) ensuring Japan's autonomy and minimum independent operational capability for lunar exploration. The proposed architecture aims to establish a common communication infrastructure that supports future crew and robotic lunar missions, lunar surface infrastructure, and international cooperative activities. The implementation scenario for this lunar communication architecture was published by JAXA in July 2025 as the Japan International Space Exploration Scenario 2025[1]. The scenario presents a roadmap for developing lunar communication infrastructure throughout the 2030s and beyond, with communication capabilities being enhanced in a phased manner according to the expansion of lunar exploration activities. The roadmap also emphasizes Japan's contribution to an international lunar communication network through the deployment of advanced communication technologies.

The proposed Earth–Lunar communication infrastructure consists of two lunar relay satellites deployed in an ELFO. Each relay satellite is equipped with both conventional RF communication systems operating in the S-, X- and Ka-bands and an optical communication system, thereby forming a hybrid communication architecture (Figure 1). In this architecture, RF communications provide highly reliable telemetry, tracking, and command (TT&C) services, while optical communications are responsible for high-capacity payload data transmission. This hybrid approach combines the reliability of RF communications with the significantly higher throughput offered by optical communications.

To realize this architecture, JAXA plans to demonstrate an optical communication link between the lunar relay satellite and a GEO satellite. The demonstration is targeted for the early 2030s, with the objective of achieving a return-link data rate of approximately 1 Gbps, contributing to future Artemis-class exploration missions. As an initial demonstration phase, a direct optical communication link between a lunar lander or rover and an optical earth ground station is also considered as a feasible demonstration scenario before deploying the complete relay architecture. Beyond this initial demonstration, the long-term vision is to establish a multi-Gbps optical communication infrastructure by the 2040s to support sustained lunar surface operations, multiple simultaneous exploration missions, and future lunar bases.

Realization of this vision requires the development and integration of several key technologies, including high-power optical transmitters, high-sensitivity optical receivers, high-efficiency modulation and demodulation techniques, and high-precision pointing, acquisition, and tracking (PAT) systems for long-distance optical links. Demonstrating the feasibility of Gbps-class optical communications over the Lunar–Earth distance is therefore an essential milestone toward establishing future lunar communication infrastructure. Motivated by this demonstration plan, this study investigates the system design and feasibility of a 1-Gbps Lunar–Earth optical communication system. The study focuses on communication link design, optical transceiver architecture, and the key enabling technologies required to realize high-capacity optical communications over the Lunar–Earth distance.

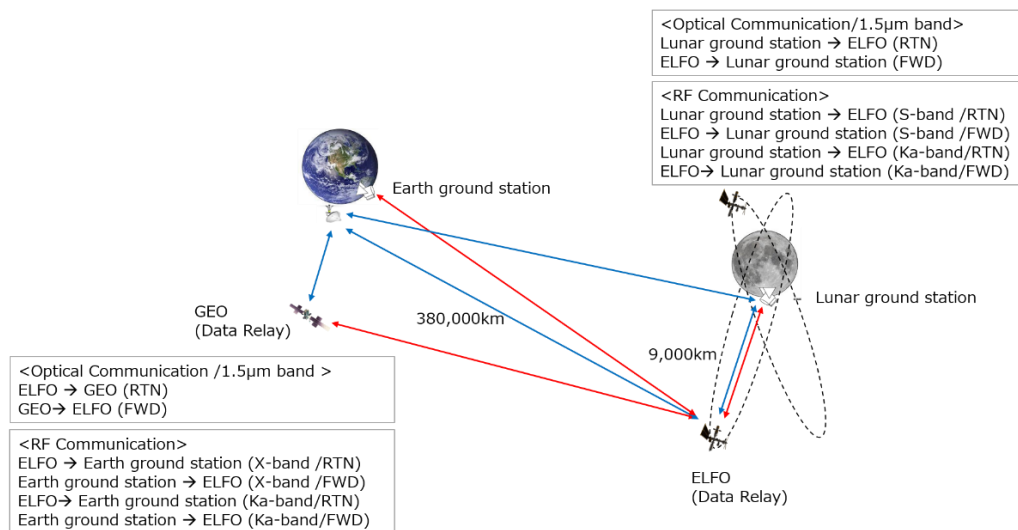


Figure 1. Earth–Lunar Optical Communication system Architecture

3. OPTICAL PAYLOAD DESIGN

3.1 Overall Optical Communication System Architecture

To establish a 1-Gbps optical return link over the approximately 380,000-km Lunar-Earth distance, multiple technical elements must be addressed. The overall optical communication system architecture between Earth and the Moon is shown in Figure 2.

The optical transmitter consists of a high-power optical amplifier (HPA) with an output power exceeding 10 W and an optical modulator capable of generating a 1-Gbps data stream. The transmitted optical beam is radiated through a 10-cm class telescope. Since the relative motion between the lunar relay satellite and the GEO satellite introduces a point-ahead angle, the transmitter also incorporates a point-ahead angle compensation mechanism consisting of an angle sensor and a steering mirror to accurately direct the optical beam toward the receiver.

The receiver employs a large aperture optical telescope to compensate for the large free-space propagation loss over the Lunar-Earth distance. After optical collection, the received signal is amplified using a phase-sensitive amplification (PSA) based on a Periodically Poled Lithium Niobate (PPLN) device to achieve high receiver sensitivity with low noise. To establish and maintain the optical link, the receiver includes a coarse acquisition sensor for initial target acquisition and a fine-tracking subsystem employing a fast-steering mirror to compensate for spacecraft attitude disturbances and relative orbital motion.

The optical payload is supervised by an integrated control unit that coordinates the optical transmitter, receiver, pointing, acquisition and tracking (PAT) subsystem, modulation and demodulation circuits, and the interface with the spacecraft bus. The control unit also manages mission data input/output, communication sequencing, synchronization with spacecraft attitude information, and overall payload operation.

At the physical layer, coherent optical communication combined with PSA technology is employed to maximize receiver sensitivity and improve the achievable link margin. At the data-link layer, powerful forward error correction (FEC), such as Low-Density Parity-Check (LDPC) coding, is applied to further enhance communication reliability and increase the effective receiver sensitivity. By integrating the optical subsystem, high-power transmitter, high-sensitivity receiver, PAT subsystem, payload control electronics, and advanced error-correction techniques, the proposed system is designed to realize a 1-Gbps-class optical communication link over the Lunar-Earth distance.

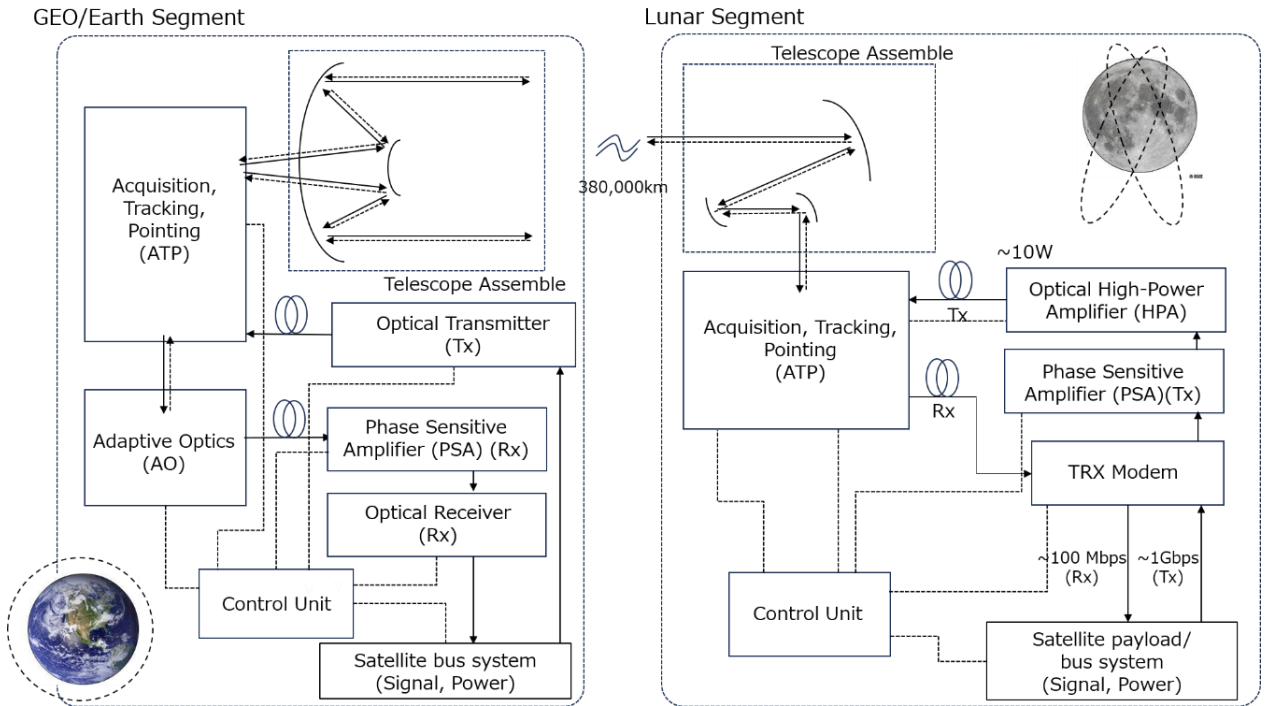


Figure 2. The overall optical communication system architecture between Earth and the Moon

3.2 Link Budget Analysis and Baseline Optical Aperture Design

Prior to the detailed design of the optical communication payload, a link budget analysis was performed to investigate the relationship between the transmitter/receiver aperture diameters and the receiver sensitivity for a 1-Gbps Lunar-Earth optical communication link. The analysis assumed a transmitter optical power of 10 W, based on the achievable output performance of current spaceborne HPAs, an operating wavelength of 1550 nm, and a Lunar-Earth communication distance of 380,000 km, corresponding to a total propagation loss of approximately 310 dB. The transmitter and receiver optical losses were assumed to be 1 dB and 5 dB, respectively, where the receiver loss includes approximately 3 dB of optical fiber coupling loss. The assumed 3-dB fiber coupling loss represents a key performance driver for the coherent receiver. In addition, PSA was adopted because its theoretically achievable 3-dB noise figure improvement enables coherent reception near the quantum limit, which is also essential for Gbps-class Lunar-Earth optical links.

Three receiver sensitivity values of -60 dBm, -55 dBm, and -50 dBm were evaluated. For each sensitivity, the combinations of transmitter and receiver aperture diameters satisfying the required link budget were calculated. The resulting feasible aperture regions for the three receiver sensitivity levels are shown in Figure 3. It was confirmed that a communication link can be established with a combination of 0.1-m and 0.3-m aperture diameters. Our previous studies on digital coherent optical communication demonstrated that a receiver sensitivity of approximately -55 dBm is achievable. Accordingly, a receiver sensitivity of -55 dBm was adopted as the baseline design target for the present study.

The aperture sizes were determined by considering both the link budget analysis and the resource constraints of the communication terminals. Since the lunar relay satellite in ELFO is subject to stringent limitations on mass, power consumption, and payload volume, the transmitter aperture should be kept as small as possible. In contrast, the GEO relay satellite can accommodate a larger optical terminal with relatively relaxed resource constraints. Based on these considerations, the transmitter telescope diameter on the ELFO lunar relay satellite was selected as 0.10-m (10-cm), while the receiver telescope diameter on the GEO satellite was set to 0.30-m (30-cm). The optical communication payload and the overall communication system presented in the following sections are designed and evaluated based on these baseline aperture sizes. It should be noted that these aperture sizes are not unique. Alternative combinations, such as 0.20 m/0.20 m are also feasible, provided that sufficient mass, power, and volume resources are available on the lunar relay satellite. The optimal aperture allocation ultimately depends on the overall communication architecture, including spacecraft resource constraints, system-level design trade-offs, and mission requirements.

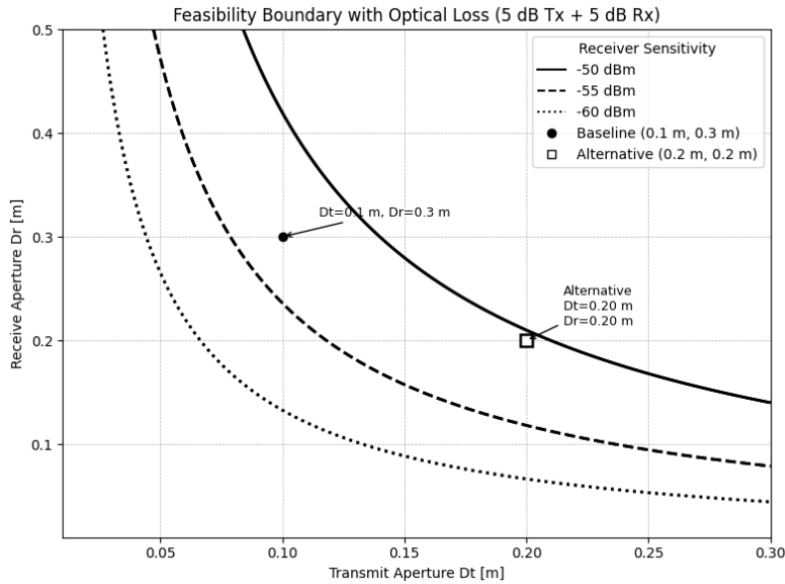


Figure 3. Feasible aperture regions for the three receiver sensitivity levels

3.3 Modulation Scheme

At present, no standardized physical-layer specification has been established specifically for Lunar-Earth optical communications. Existing documents define only limited parameters, such as the operating wavelength (1550 nm) and representative modulation formats, while detailed physical-layer specifications remain under development. Since Lunar-Earth optical links operate under extremely low signal-to-noise ratio (SNR) conditions, the selection of the modulation format and receiver architecture is critical to system performance.

Pulse-position modulation (PPM)-based high-photon-efficiency (HPE) schemes provide excellent receiver sensitivity under photon-limited conditions. In contrast, coherent binary phase-shift keying (BPSK)-based high-data-rate (HDR) schemes offer higher spectral efficiency and can achieve high sensitivity with relatively low transmitter and receiver resource requirements through digital coherent detection. In addition, coherent communication is well suited to advanced forward error correction (FEC) and phase-sensitive amplifier (PSA) technologies, further enhancing its potential for high-performance Earth–Moon optical communications.

In addition, reflected sunlight from the lunar surface acts as background radiation and must be considered in the link design. Therefore, this study quantitatively compares the communication performance of PPM- and coherent BPSK-based systems to identify a suitable modulation scheme for future Gbps-class Lunar-Earth optical communications.

Assuming the same link parameters, including the communication distance and wavelength, as those introduced in the previous section, the theoretical BER characteristics of the PPM and BPSK schemes were derived as functions of the received optical power. In this analysis, the data rate was set to 1 Gbps, the PPM order was set to $M = 16$ as an example and the background photon noise N_b was introduced as a parameter. To enable a fair comparison between PPM and coherent BPSK, the received optical power P_r is converted into the equivalent number of received photons per bit.

The number of received signal photons N_s is given by:

$$N_s = \frac{P_r T_b \lambda}{hc}$$

where P_r is the received optical power, T_b is the bit duration, and λ is the optical wavelength. For an Lunar-Earth optical communication link, assuming a received optical power of approximately -55 dBm, which includes a 5 dB receiver loss from the antenna received power of -50 dBm, a data rate of 1 Gbps, and an optical wavelength of 1550 nm, the number of received signal photons is estimated to be approximately 25 photons/bit.

Since lunar surface reflection introduces background photons into the receiver, the corresponding photon count per bit is evaluated as follows:

$$N_b = \frac{L_\lambda A_r \Omega_{FOV} \Delta\lambda \eta T_b \lambda}{hc}$$

For the worst daytime lunar surface environment, the spectral radiance was assumed to range from $L_\lambda = 10^4 \sim 10^6 \text{ W m}^{-2} \text{ sr}^{-1} \text{ m}^{-1}$. Using a 30-cm receiving telescope (A_r), a receiver field of view (Ω_{FOV}) of approximately 10 μrad , a 1-nm optical filter bandwidth ($\Delta\lambda$), and a quantum efficiency of the photodetector η of 0.5, the resulting background photon count N_b is estimated to be in the range of $10^{-3} \sim 10^{-1}$ photons/bit.

Assuming heterodyne reception with a sufficiently strong local oscillator, the signal contribution from the LO–signal beating can be expressed as $2N_s^2$, letting F denote the noise factor, the noise variance for the BPSK scheme can be expressed as follows.

$$N_s + (F - 1)N_s + FN_b$$

Here, N_s represents the shot-noise associated with the signal photons, $(F - 1)N_s$ denotes the excess noise introduced by the optical amplifier, and FN_b represents the amplifier-enhanced background-noise variance. Therefore, the BER of BPSK can be expressed as follows.

$$P_{e_BPSK} = \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{2N_s^2}{F(N_s + N_b)}} \right)$$

Here, F is set to 2 for an ideal phase-insensitive amplifier (EDFA) and 1 for an ideal phase-sensitive amplifier (PSA).

In case of PPM scheme, considering the Poisson process [9], [10], the probability of detecting photons in a single PPM slot is given by

$$P_s(k) = \frac{(N_s + N_b)^k}{k!} e^{-(N_s + N_b)}$$

Similarly, the probability of detecting k or fewer photons in an empty slot

$$F_b(k) = P_r(K \leq k) = \sum_{j=0}^k \frac{N_b^j}{j!} e^{-N_b}$$

Averaging over all values of k , the symbol error rate is given by

$$P_e^{SER} = \sum_{k=0}^{\infty} P_s(k) [1 - F_b(k)]^{M-1}$$

the BER of PPM scheme can be expressed as follows

$$P_{e_PPM} \approx \frac{M}{2(M-1)} P_e^{SER}$$

Figure 4 left shows the uncoded BER of BPSK as a function of the signal photon number for different levels of background light. Three background-light levels, namely 0.001, 0.01, and 0.1, are plotted. Even with increasing background light, the BER degradation is relatively small. Therefore, the current receiver sensitivity of approximately -55 dBm (25 photons/bit) provides sufficient margin to meet the target BER of 10^{-3} , at pre FEC point and the impact of background light on the BER is considered negligible for this scheme.

Figure 4 right shows the BER performance of 16-PPM ($M=16$) under the same three background-light levels as those used for BPSK. Under the assumed lunar background-light conditions, PPM exhibits greater performance degradation than BPSK. PPM also presents several challenges for satellite onboard implementation. It requires high peak optical power despite its low spectral efficiency, while the receiver must detect extremely weak optical pulses with precise slot synchronization. Achieving this often requires low-noise or cooled photon-counting detectors, whose performance can also be limited by dead-time effects at high count rates. Consequently, the receiver architecture becomes more complex and resource-intensive than that of continuous-wave modulation schemes such as BPSK.

Considering the mentioned disadvantages and the scalability toward future data rates of 1 Gbps and beyond, this study assumes the adoption of a coherent BPSK communication scheme as the baseline.

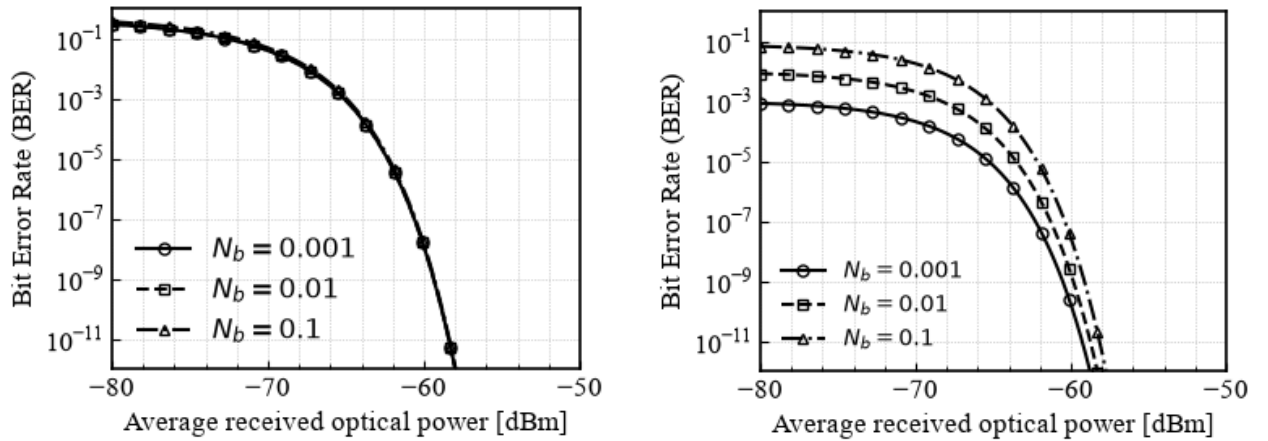


Figure 4. (left) BPSK BER vs. Average received optical power, (right) PPM BER vs. Average received optical power

4. LUNAR RELAY OPTICAL TERMINAL DESIGN

Figure 5 illustrates the proposed optical terminal architecture for the lunar relay satellite, which forms the core of the Lunar-Earth optical communication system. The terminal employs an off-axis three-mirror telescope as a shared transmit/receive aperture, consisting of a primary parabolic mirror, a secondary hyperbolic mirror, and a tertiary aspheric mirror to achieve high optical efficiency without central obscuration. A transmit/receive separation filter directs the received beam to the receiver path, where a band-pass filter (BPF) suppresses background light and extracts the communication wavelength.

The filtered signal is split into the pointing, acquisition and tracking (PAT) path and the coherent receiver path. A two-dimensional Coarse Acquisition Sensor (CAS) performs initial beam acquisition, while approximately 15% of the received optical power is directed to a quadrant avalanche photodiode (QAPD)-based Fine Pointing Sensor (FPS). Closed-loop control with a Fine Pointing Mirror (FPM) reduces the pointing error from approximately 10 μ rad after coarse acquisition to about 3 μ rad. The remaining power is coupled into a single-mode fiber for optical amplification, coherent detection, and digital signal processing. The QAPD was newly developed by Hamamatsu Photonics.

The transmitter shares the same telescope aperture. A QAPD-based Point-Ahead Sensor (PAS) monitors the transmit beam, while a Point-Ahead Mirror (PAM) compensates for the point-ahead angle caused by relative satellite motion. Dedicated control electronics coordinate the transmitter, receiver, PAT subsystem, sensors, and spacecraft interface, enabling both high receiver sensitivity and pointing accuracy.

A Breadboard Model (BBM) was fabricated to validate acquisition, tracking, and telescope optical performance. Based on these results, an Engineering Model (EM) will be developed through design refinement and environmental qualification, including verification of thermal robustness for lunar missions.

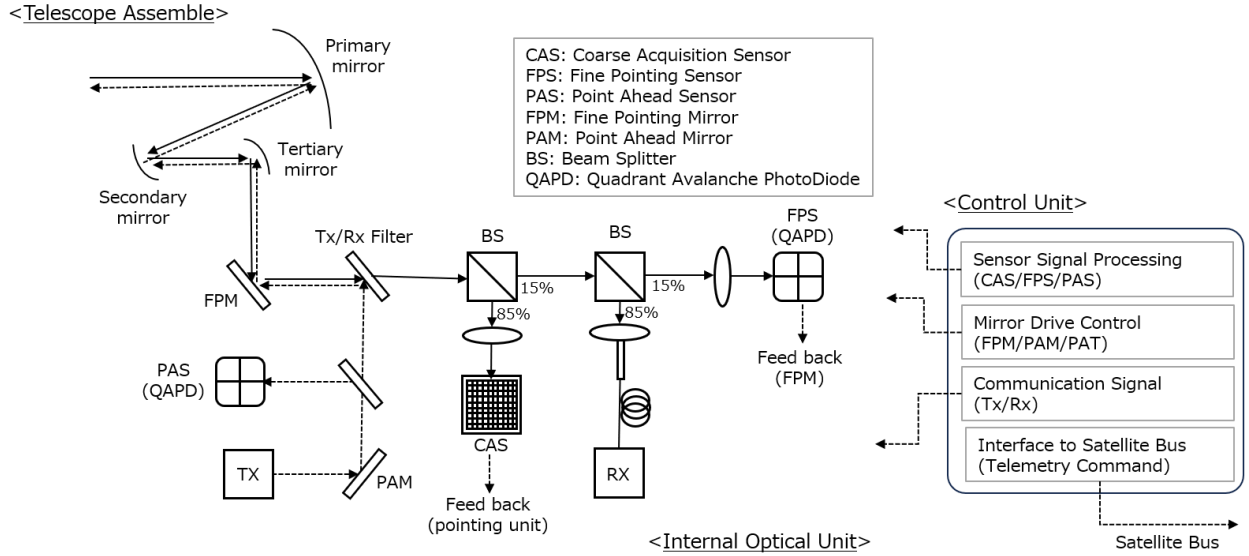


Figure 5 Conceptual optical layout of the OCT system.

5. FUTURE WORK

The key technologies for the lunar relay optical terminal, including the telescope unit, coarse-pointing subsystem, and fine-pointing subsystem, have been successfully developed and their functionality and performance have been verified. The next phase of the study will focus on end-to-end performance validation by integrating these technologies with the optical communication subsystems being developed for the GEO segment. In parallel, system-level design of the optical communication subsystem will be accelerated through the integration of the optical terminal with other enabling technologies under development, including the HPA, PSA, and digital coherent communication technologies. Furthermore, in accordance with the planned lunar exploration roadmap, which targets an on-orbit demonstration of Lunar-Earth optical communications in the early 2030s, future work will include the development of space-qualified, environmentally robust components suitable for long-term operation in the lunar exploration environment.

6. CONCLUSION

As lunar exploration activities continue to accelerate under international initiatives such as the Artemis Program, communication technologies are becoming one of the key enabling technologies for sustainable lunar exploration. To establish a 1-Gbps-class Lunar-Earth optical communication system, JAXA has formulated and published the lunar communication system architecture as part of the Lunar Exploration Scenario 2025. In parallel, the development of an optical communication terminal for a lunar relay satellite has been carried out since 2023, and the development and performance verification of the key enabling technologies, including a 10-cm-class telescope, coarse-pointing subsystem, and fine-pointing subsystem, have been successfully completed. Furthermore, a system concept based on coherent binary phase-shift keying (BPSK) modulation was investigated instead of the pulse-position modulation (PPM) scheme employed in previous Lunar-Earth optical communication demonstrations. The proposed approach provides improved robustness against background light while offering architecture capable of supporting future multi-gigabit data rates. The next phase of the project will focus on the design and fabrication of space-qualified components with sufficient environmental robustness for lunar missions, with the objective of demonstrating Lunar-Earth optical communications in the early 2030s. Through continued system architecture studies and technology development, this work is expected to contribute to Japan's participation in the first Lunar-Earth optical communication demonstration and the realization of a lunar communication infrastructure in the mid-2030s and beyond.

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