

System-level optical and opto-mechanical design and BBM verification of a GEO–Lunar optical communication terminal for orbital and surface applications

Takashi Kan^{*a}, Shin Fukuhara^a, Kensuke Murakami^a, Akihiko Nishitani^a, Akira Akasaka^a,
Hidenori Takahashi^a, Takehiro Tsuritani^a, Masanori Fushimi^b, Kento Kimura^b,
Yuki Kawanishi^c, Ryota Miyake^c, Masato Hayashida^c, Tsuyoshi Kanda^c,
Tsuyoshi Ozaki^d, Akira Nakagoshi^e, Takayuki Hosonuma^f, So Yeon Suk^f, Toshihiro Shibukawa^f,
Johta Awano^g, Yosuke Hashimoto^g, Shota Kimura^g, Katsumi Makino^g

^aKDDI Research, Inc., 2-1-15 Ohara, Fujimino-shi, Saitama, 356-8502 Japan;

^bKDDI CORPORATION, 2-3-2, Nishishinjuku, Shinjuku-ku, Tokyo 163-8003, Japan;

^cTOPCON CORPORATION, 75-1, Hasunuma-cho, Itabashi-ku, Tokyo 174-8580, Japan;

^dTechlab Co., Ltd., Minamino 2-6-3, Tama, Tokyo, Japan;

^eMitsubishi Chemical Corporation, 1-1 Marunouchi 1-chome, Chiyoda-ku, Tokyo 100-8251, Japan;

^fArkEdge Space Inc., 1-3-33 Ariake, Koto-ku, Tokyo 135-0063, Japan;

^gJapan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba-shi, Ibaraki 305-8505, Japan.

ABSTRACT

Driven by growing interest in sustained lunar exploration and utilization, optical communication technologies are being developed to support future high-capacity lunar communication networks. To meet these emerging communication demands, we are developing a 1-Gbps-class optical communication terminal (OCT) for future geostationary Earth orbit (GEO)–lunar optical communication systems. This paper addresses two key technical challenges associated with GEO–lunar optical communications: maintaining optical performance under the extreme lunar thermal environment and achieving high-precision tracking for long-distance optical links between lunar orbiters and GEO relay satellites. For lunar-surface applications, a 100-mm-aperture off-axis three-mirror telescope employing low-thermal-expansion optical and structural materials was designed. Structural, optical, and thermal analyses showed that the telescope can maintain the required optical performance over the anticipated lunar operating temperature range from -170°C to $+110^{\circ}\text{C}$. For long-distance optical links between lunar orbiters and GEO relay satellites, an internal optical subsystem integrating acquisition, tracking, transmit/receive beam handling, and point-ahead-angle compensation functions was developed. The subsystem employs a wavelength-based transmit/receive separation scheme together with a two-stage acquisition and tracking configuration using a wide-field acquisition sensor, a quadrant avalanche photodiode (QAPD), and a tip-tilt mirror. In addition to the subsystem-level designs, preliminary system-level thermal analyses were conducted to assess the thermal feasibility of the proposed terminal architecture. The results indicated that acceptable operating temperatures can be maintained for both lunar-surface and lunar-orbiter deployment scenarios when appropriate heater control is applied. Fabricated BBMs were used for preliminary functional verification. Detailed descriptions of the tracking, acquisition, point-ahead-angle compensation, and communication-performance evaluations are reported separately.

Keywords: Lunar optical communications, GEO-lunar communications, Optical communication terminal (OCT), Opto-mechanical design, Telescope optics, Pointing, acquisition and tracking (PAT), Thermal design, Breadboard model (BBM)

1. INTRODUCTION

Driven by the growing interest in sustained lunar exploration and utilization, the establishment of a high-capacity communication infrastructure has become an important technological challenge. The Artemis program and related international initiatives are expected to accelerate a broad range of lunar activities, including scientific exploration, robotic missions, human exploration, and future commercial operations. As a result, communication demands among lunar surface assets, lunar orbiters, and Earth-based users are expected to increase substantially, potentially exceeding the capabilities of conventional radio frequency (RF) communication systems. This has motivated the development of optical communication technologies capable of supporting future high-capacity lunar communication networks.

Several lunar optical communication demonstrations have been conducted so far. The first laser communication experiments between Earth and lunar orbit were conducted using the Lunar Reconnaissance Orbiter (LRO) and were reported in 2013 [1]. Subsequently, NASA's Lunar Laser Communication Demonstration (LLCD) demonstrated high-rate optical communications between lunar orbit and Earth at data rates of up to 622 Mbps [2]. More recently, the Orion Artemis II Optical Communications System (O2O) successfully demonstrated laser communications on a crewed mission at lunar distance and supported data rates of up to 260 Mbps [3]. These activities have demonstrated the feasibility and benefits of direct Moon-Earth optical communications. Nevertheless, direct Moon-Earth links may experience limited visibility depending on the location of lunar assets and the availability of Earth stations. Future lunar exploration scenarios, particularly those involving operations in the lunar south polar region, are expected to require communication services with higher availability and longer duration than can be achieved through direct Earth visibility alone.

To address these challenges, relay-satellite-based communication architectures are being investigated. Representative examples include ESA's Moonlight initiative, which aims to establish a lunar communications and navigation infrastructure using dedicated lunar relay satellites to provide continuous communication services [4]. In parallel, optical communication technologies are being investigated as part of Japan's Space Development and Utilization Acceleration Strategic Program (Stardust Program), which supports the development of key technologies for future lunar exploration and utilization [5–8]. As part of this effort, we are developing an 1-Gbps-class optical communication terminal (OCT) intended for deployment on lunar orbiters and lunar surface platforms. The communication architecture considered in this study consists of lunar surface nodes, relay satellites on elliptical lunar frozen orbits (ELFOs), geostationary Earth orbit (GEO) relay satellites, and Earth ground stations. By combining ELFO relay satellites with GEO relay satellites, the architecture can provide communication opportunities that are less dependent on the Earth visibility conditions of individual lunar assets, thereby improving communication availability for future lunar missions.

The development of OCTs for this architecture involves several technical challenges. In particular, an OCT intended for lunar surface deployment must maintain optical performance over the extreme lunar temperature range, while an OCT intended for long-distance links between ELFO and GEO relay satellites must achieve highly accurate pointing, acquisition, and tracking (PAT) performance over distances approaching 400,000 km. The objective of this work is to establish a system-level optical and opto-mechanical design for a lunar OCT and to verify the feasibility of the proposed design through breadboard model (BBM) implementation and experimental evaluation. Particular emphasis is placed on the design of a compact single-aperture telescope, passive thermal stability over a wide temperature range, polarization-independent optical interfaces, and acquisition and tracking capabilities for GEO–lunar optical links. This paper presents the system-level design of the terminal, including the telescope subsystem, internal optical subsystem, and system-level thermal feasibility analyses. The implementation of the BBMs and the results of preliminary functional verification are also described.

2. SYSTEM-LEVEL DESIGN OF GEO-LUNAR OCT

2.1 Reference Communication Architecture

Figure 1 shows the reference communication architecture considered in this study. The figure is reproduced from the International Lunar Exploration Scenario 2025 proposed by the Japan Aerospace Exploration Agency (JAXA) [9]. The architecture consists of lunar surface nodes, relay satellites on ELFOs, GEO relay satellites, and Earth ground stations. Compared with direct Moon–Earth communication links, this relay-based architecture improves communication availability, particularly for missions operating in regions with limited Earth visibility, such as the lunar south polar region, while enabling high-capacity optical return links to Earth.

The scenario envisions the provision of high-capacity communication services for future lunar-surface activities. As an initial target, an 1-Gbps-class optical return link is assumed to support operational scenarios involving simultaneous transmission of multiple high-definition video streams for lunar surface activities, including infrastructure construction and exploration operations [9]. In the longer term, further expansion toward multi-Gbps-class communication services is anticipated as lunar activities become increasingly sophisticated and data intensive [9]. The OCT presented in this paper has been developed to address the initial 1-Gbps-class communication requirement while maintaining compatibility with future system evolution.

Within this architecture, research and development of GEO-side OCT, including large-aperture optical antennas and adaptive optics technologies, has been conducted under the Stardust Program [5–8]. The present work focuses on the counterpart lunar OCT intended for deployment on lunar surface nodes and ELFO relay satellites.

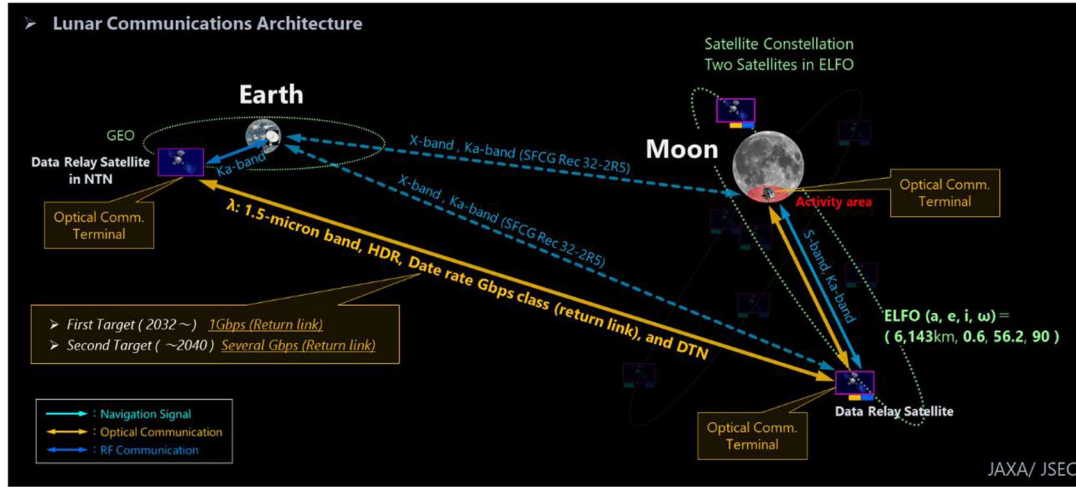


Figure 1. Reference GEO-lunar communication architecture considered in this study. Reproduced from JAXA International Lunar Exploration Scenario 2025 [9]. The architecture consists of lunar surface nodes in the activity area, relay satellites in elliptical lunar frozen orbits (ELFOs), GEO relay satellites, and Earth ground stations.

2.2 Design Considerations

The OCT was designed based on the communication architecture described in Section 2.1. Although the architecture includes both lunar surface nodes and ELFO relay satellites, these applications impose different technical challenges. Lunar surface terminals must maintain optical performance under the extreme lunar thermal environment, whereas terminals supporting ELFO–GEO optical links must achieve highly accurate PAT performance over distances approaching 400,000 km. The present study focuses on these key challenges and investigates them through the development and evaluation of BBMs. Table 1 summarizes the principal design drivers and representative requirements that formed the basis of the optical, opto-mechanical, thermal, and PAT subsystem designs.

Table 1. Key design drivers and representative requirements for the lunar optical communication terminal.

Category	Design consideration	Requirement Origin	Value / Assumption
Communication service	Optical return link data rate	Common among nodes	1 Gbps-class
Interoperability	Operating wavelength	Common among nodes	1550-nm regime
Interoperability	Optical interface	Common among nodes	Polarization-independent
Thermal environment	Operating temperature range	Lunar surface environment (On lunar equator)	−170 °C to +110 °C
Reference link condition	Communication distance	Long-distance ELFO-GEO link	Approximately 400,000 km
Tracking sensor	Received optical power at tracking sensor	Long-distance ELFO-GEO link	Approximately −60 dBm [10]
PAT performance	Tracking accuracy	Long-distance ELFO-GEO link	3 μ rad RMS
Point-ahead compensation	Maximum point-ahead angle	Long-distance ELFO-GEO link	38.3 μ rad [11]

For lunar-surface applications, the optical terminal was required to maintain optical performance over the anticipated operating temperature range from -170°C to $+110^{\circ}\text{C}$. Minimizing thermally induced optical performance degradation over this temperature range was therefore a key design requirement for the telescope optics and opto-mechanical structure.

For long-distance ELFO–GEO optical links, high PAT accuracy is required. Link budget analysis [10] indicated that the received optical power at the tracking sensor could decrease to approximately -60 dBm , while the required tracking accuracy was $3\text{ }\mu\text{rad}$ (RMS). In addition, the relative motion of the communicating terminals introduces non-negligible point-ahead angles of up to $38.3\text{ }\mu\text{rad}$ [11]. These requirements were reflected in the design of the internal optical subsystem described in Section 4.

Future lunar communication infrastructures are expected to include communication assets developed by multiple organizations. To facilitate future interoperability, the optical terminal was designed for operation in the 1550-nm wavelength regime and employs polarization-independent optical interfaces.

2.3 Optical Terminal Architecture

To address the design considerations summarized in Table 1, a BBM OCT architecture was investigated. Figure 2 shows its overall architecture. The BBM consists of a telescope subsystem, an internal optical subsystem, and a control subsystem.

The telescope subsystem provides transmission and reception of the communication beams and was designed to maintain optical performance under the extreme lunar thermal environment described in Section 2.2.

The internal optical subsystem performs transmit/receive beam handling, acquisition and tracking, receiver coupling, and point-ahead-angle compensation functions required for long-distance optical links between ELFO and GEO relay satellites. For acquisition and tracking, the subsystem incorporates a Coarse Acquisition Sensor (CAS), a Fine Pointing Sensor (FPS), and a Fine Pointing Mirror (FPM). For point-ahead-angle compensation, a Point Ahead Sensor (PAS) and a Point Ahead Mirror (PAM) are employed. A wavelength-based transmit/receive separation filter is also used to support polarization-independent optical interfaces.

The control subsystem processes signals obtained from the CAS, FPS, and PAS, and controls the FPM and PAM to realize acquisition, tracking, and point-ahead-angle compensation. The detailed designs of the telescope subsystem and internal optical subsystem are described in Sections 3 and 4, respectively.

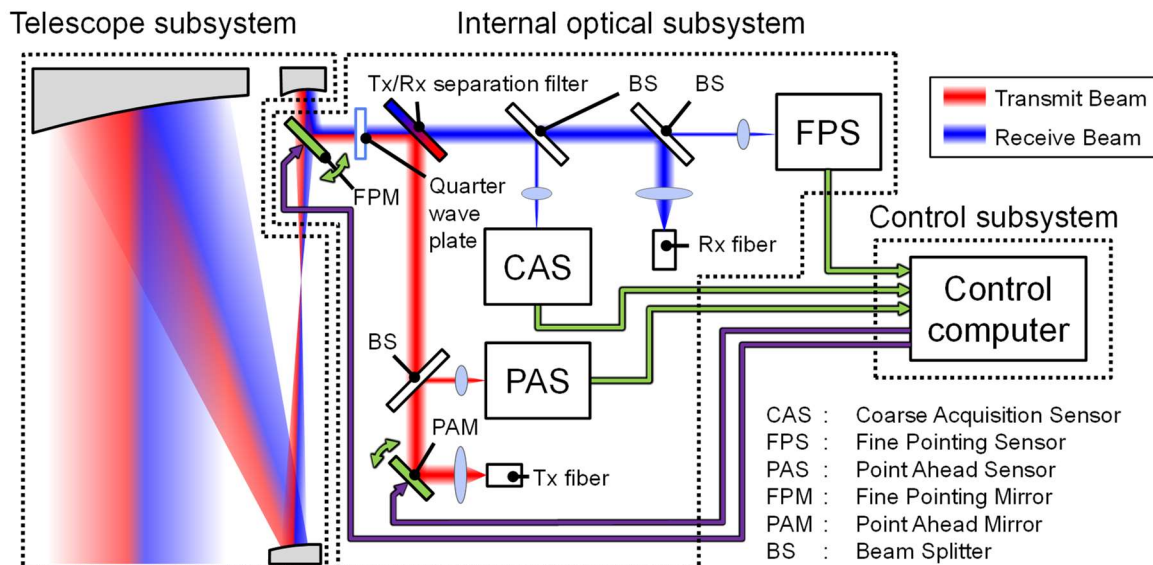


Figure 2. Functional architecture of the OCT BBM. The BBM consists of a telescope subsystem, an internal optical subsystem, and a control subsystem. Acquisition and tracking functions are implemented using the CAS, FPS, and FPM, while point-ahead-angle compensation is implemented using the PAS and PAM.

3. TELESCOPE OPTICAL AND OPTO-MECHANICAL DESIGN

This section describes the optical, opto-mechanical, and thermal designs of the telescope subsystem developed for operation under the extreme lunar thermal environment.

3.1 Optical Design

Among the candidate optical configurations investigated, an off-axis three-mirror telescope was selected as the baseline design because it provides an unobscured aperture and enables a compact optical layout. Figure 3(a) shows the resulting optical design. The telescope employs a 100-mm aperture, a magnification of 20 $\times$, and a field of view of $\pm 0.11^\circ$ ($\phi 0.31^\circ$) to accommodate terminal pointing uncertainties. Clearceram[®], a low-thermal-expansion glass-ceramic material, was selected for the primary, secondary, and tertiary mirrors to minimize thermally induced optical degradation.

The optical-performance requirement was defined as an RMS wavefront error (WFE) of less than $\lambda/14$ at 1550 nm, corresponding to 111 nm RMS. Several mirror-shape combinations were investigated to improve optical performance and reduce sensitivity to manufacturing and alignment tolerances. The final design employs a paraboloidal primary mirror, a hyperboloidal secondary mirror, and a decentered aspheric tertiary mirror. Tolerance analyses were performed by applying 10- μm translational displacements and 1-arcmin tilts to each mirror independently. The selected configuration exhibited lower sensitivity to manufacturing and alignment tolerances than the other investigated designs while satisfying the optical-performance requirement.

Table 2 presents the room-temperature optical performance (+20 $^\circ\text{C}$), while the thermal effects are evaluated separately in Section 3.3. The nominal RMS WFE was $\lambda/113$ to $\lambda/60.1$ (13.7 to 25.8 nm) and increased to $\lambda/14.9$ to $\lambda/14.2$ (104.1 to 109.4 nm) when manufacturing and alignment tolerances were included, remaining below the $\lambda/14$ requirement. Figure 3(b) shows the corresponding RMS WFE distribution, confirming that the requirement is satisfied across the full field of view.

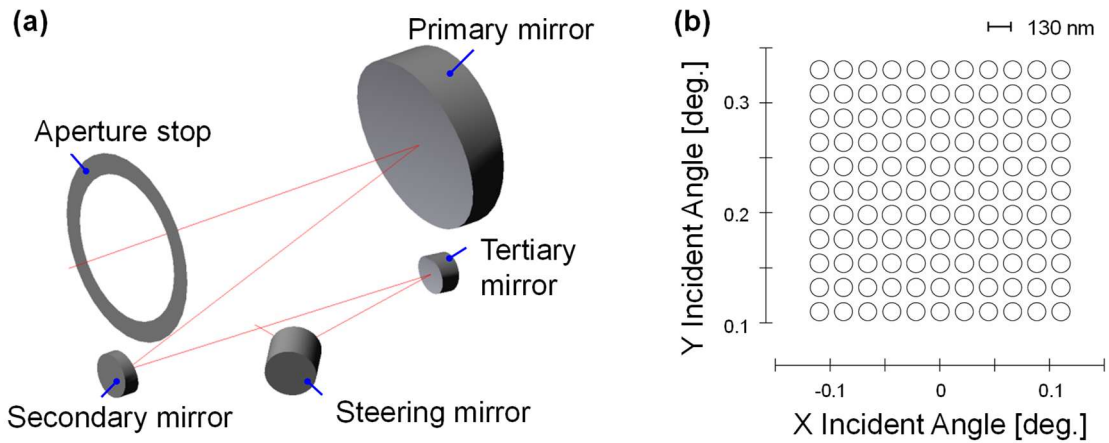


Figure 3. Optical design of the off-axis three-mirror telescope. (a) Optical layout. A steering mirror is used to direct the beam to the internal optical subsystem. (b) RMS WFE distribution including manufacturing and alignment tolerances. The design satisfies the $\lambda/14$ WFE requirement (111 nm at 1550 nm) over the full $\pm 0.11^\circ$ field of view at 1550 nm.

Table 2. Optical performance of the selected telescope design.

Parameter	Value (at +20 $^\circ\text{C}$)
RMS wavefront error (WFE) (nominal)	$\lambda/113$ to $\lambda/60.1$ (13.7 to 25.8 nm)
RMS WFE (with manufacturing and alignment tolerances)	$\lambda/14.9$ to $\lambda/14.2$ (104.1 to 109.4 nm)
Strehl ratio (with manufacturing and alignment tolerances)	0.803 - 0.822

3.2 Opto-Mechanical Design

The telescope support structure was required to provide high stiffness, low mass, and low thermal expansion while maintaining optical alignment under the severe lunar thermal environment. To satisfy these requirements, a CFRP-based structural architecture consisting of an all-CFRP honeycomb sandwich optical bench and CFRP truss pipes was adopted.

To realize low-thermal-expansion structures, pitch-based carbon fibers (K13916) and PAN-based carbon fibers (TR50S) were investigated together with a cyanate-based matrix material. PYROFIL #290 was selected as the matrix material because of its low moisture absorption, high toughness, high glass-transition temperature, and good manufacturability. Figure 4(a) shows the measured thermal strains of representative CFRP specimens. The K13916-based CFRP exhibited a near-zero coefficient of thermal expansion (CTE) of approximately 0.08 ppm/°C, demonstrating the suitability of pitch-based carbon fibers for thermally stable optical structures. Following the material-level evaluation, a full-scale 200-mm-long CFRP pipe was fabricated and evaluated. As shown in Fig. 4(b), the measured CTE was approximately 0.034 ppm/°C, confirming near-zero thermal expansion at the structural-component level. In addition, gamma-ray irradiation tests corresponding to GEO and lunar mission environments of up to 15 years showed no significant degradation in interlaminar shear strength.

Based on these results, the telescope opto-mechanical design shown in Fig. 5 was developed. The telescope employs Clearceram mirrors, a CFRP optical bench, and CFRP truss pipes. Mirror supports and alignment mechanisms at critical optical interfaces were implemented using specialized Invar-based materials for cryogenic applications to reduce thermally induced alignment errors. The resulting design achieved a calculated mass of approximately 2.96 kg.

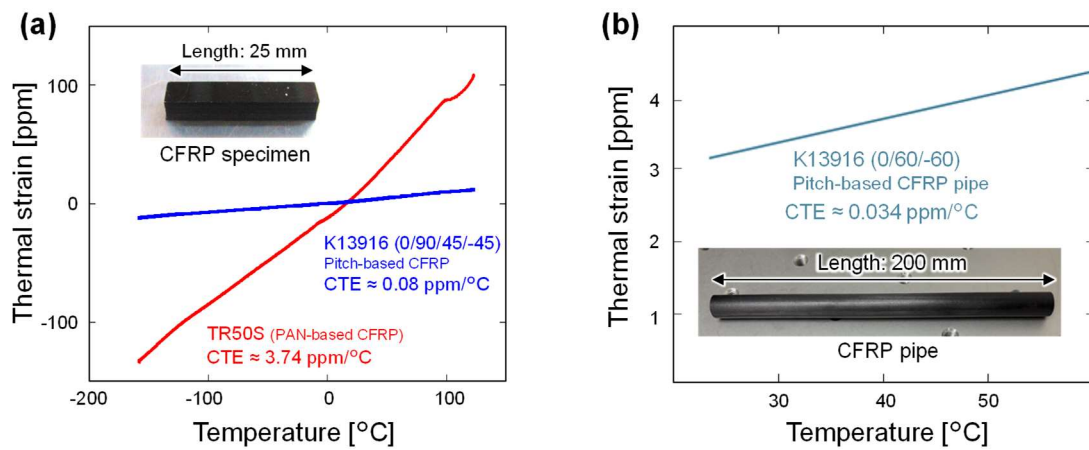


Figure 4. Evaluation of CFRP materials and structural components. (a) Measured thermal strain of CFRP specimens. The pitch-based CFRP (K13916) exhibited a near-zero CTE of ~ 0.08 ppm/°C. (b) Measurement of a fabricated full-scale CFRP truss pipe. The CTE was ~ 0.034 ppm/°C, confirming near-zero thermal expansion at the structural-component level.

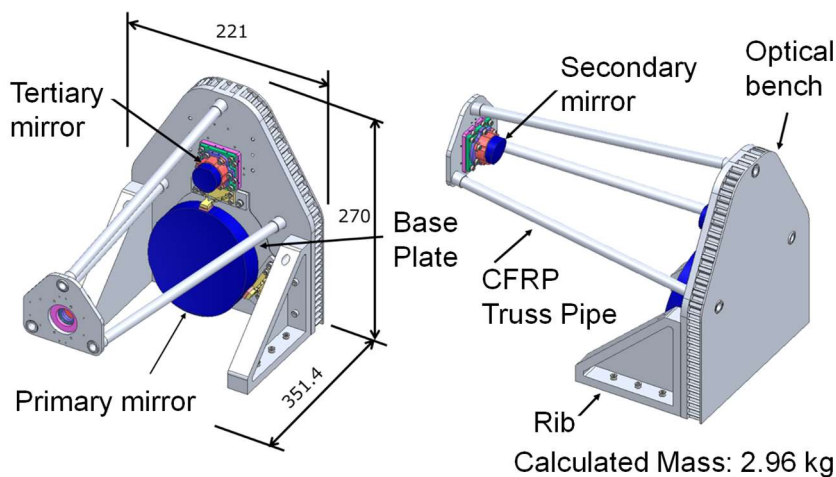


Figure 5. Final opto-mechanical design of the telescope subsystem.

3.3 Thermal Stability Analysis

The thermal stability of the telescope subsystem was assessed through structural and optical analyses under representative lunar thermal environments. Uniform temperatures of $-170\text{ }^{\circ}\text{C}$ and $+110\text{ }^{\circ}\text{C}$ were applied to the telescope structure to represent the anticipated lunar temperature extremes. Temperature-dependent coefficients of thermal expansion were applied to the Clearceram mirrors, CFRP structural members, and Invar-based components.

Figure 6 shows the predicted structural deformation of the final telescope opto-mechanical design. The relative displacements of the mirrors remained within several micrometers under both temperature conditions, indicating that thermally induced misalignment was effectively suppressed by the low-thermal-expansion structural design.

Table 2 demonstrates compliance with the optical requirements at the reference temperature of $+20\text{ }^{\circ}\text{C}$. To assess thermal robustness, the same analysis was performed over the anticipated lunar operating temperature range. As summarized in Table 3, the predicted RMS WFE ranged from $\lambda/16.9$ to $\lambda/14.7$ at $-170\text{ }^{\circ}\text{C}$ and from $\lambda/18.1$ to $\lambda/16.4$ at $+110\text{ }^{\circ}\text{C}$, while the Strehl ratio remained above 0.83 in all cases. These results confirm that the telescope subsystem satisfies the optical-performance requirements throughout the anticipated lunar operating temperature range.

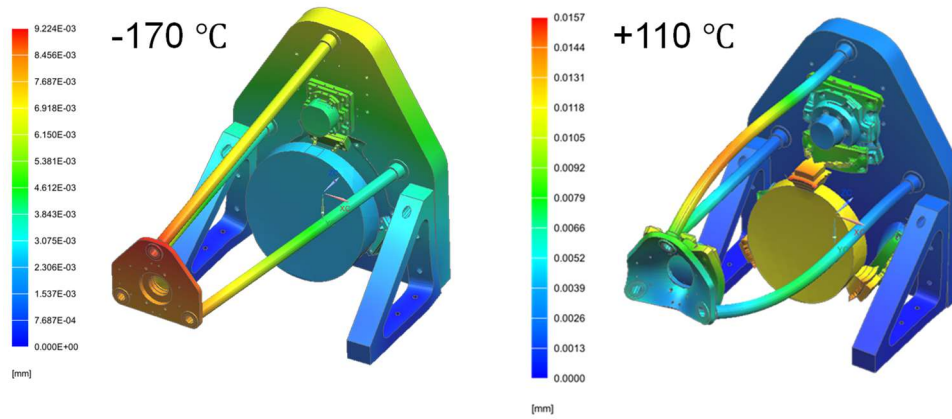


Figure 6. Predicted structural deformation of the telescope subsystem at the lunar temperature extremes of $-170\text{ }^{\circ}\text{C}$ and $+110\text{ }^{\circ}\text{C}$. The analysis was performed using the final telescope opto-mechanical design. The resulting optical performance is summarized in Table 3.

Table 3. Predicted optical performance of the telescope subsystem under lunar thermal environments. RMS WFE and Strehl ratio including manufacturing and alignment tolerances are summarized for representative temperatures.

Temperature	RMS WFE	Strehl ratio
-170°C	$\lambda/16.9$ to $\lambda/14.7$ (91.7 to 105.4 nm)	0.834 to 0.871
$+20^{\circ}\text{C}$	$\lambda/18.8$ to $\lambda/17.9$ (82.4 to 86.6 nm)	0.884 to 0.894
$+110^{\circ}\text{C}$	$\lambda/18.1$ to $\lambda/16.4$ (85.6 to 94.5 nm)	0.864 to 0.887

4. INTERNAL OPTICAL SYSTEM DESIGN

The internal optical subsystem was designed to realize transmit and receive beam handling, acquisition, tracking, receiver coupling, and point-ahead-angle compensation functions for GEO–lunar optical links. This section describes the optical, opto-mechanical, and thermal designs of the subsystem.

4.1 Optical Design

The internal optical subsystem was designed to satisfy the tracking and point-ahead-angle compensation requirements of ELFO–GEO optical links. Figure 7(a) shows the resulting optical layout. For acquisition and tracking, a two-stage sensor architecture consisting of the CAS, FPS, and FPM was adopted. The CAS employs an area sensor to provide a wide acquisition field of view, while the FPS employs a QAPD for high-precision tracking of weak optical signals.

For point-ahead-angle compensation, the PAS and PAM were incorporated into the transmit optical path. The PAS also employs a QAPD, providing component commonality with the FPS, and was designed to accommodate point-ahead angles of up to ± 50 μ rad.

To support future interoperability, a wavelength-based transmit/receive separation scheme was adopted in place of polarization-dependent beam separation. A dichroic mirror was used to combine and separate transmit and receive optical beams while maintaining compatibility with polarization-independent optical interfaces and future polarization-multiplexed communication systems. Figure 7(b) shows the measured spectral characteristics of the fabricated transmit/receive separation filter. Because the filter was designed for 45° incidence to achieve a compact optical layout, suppression of polarization dependence was an important design consideration. The measured polarization dependence was less than 0.1 dB for the reflected port and approximately 0.4 dB for the transmitted port. Although residual polarization dependence remains, the results indicate that wavelength-based transmit/receive separation can be implemented in a compact 45° -incidence configuration while maintaining low polarization dependence.

4.2 Opto-Mechanical and Thermal Design

Figure 8 shows the resulting opto-mechanical design of the internal optical subsystem. The subsystem integrates the transmit/receive separation filter, acquisition and tracking optics, and point-ahead-angle compensation optics on a common baseplate. The receive optical signal is coupled into a single-mode optical fiber, while the transmit optical signal is emitted from a single-mode optical fiber and collimated for transmission.

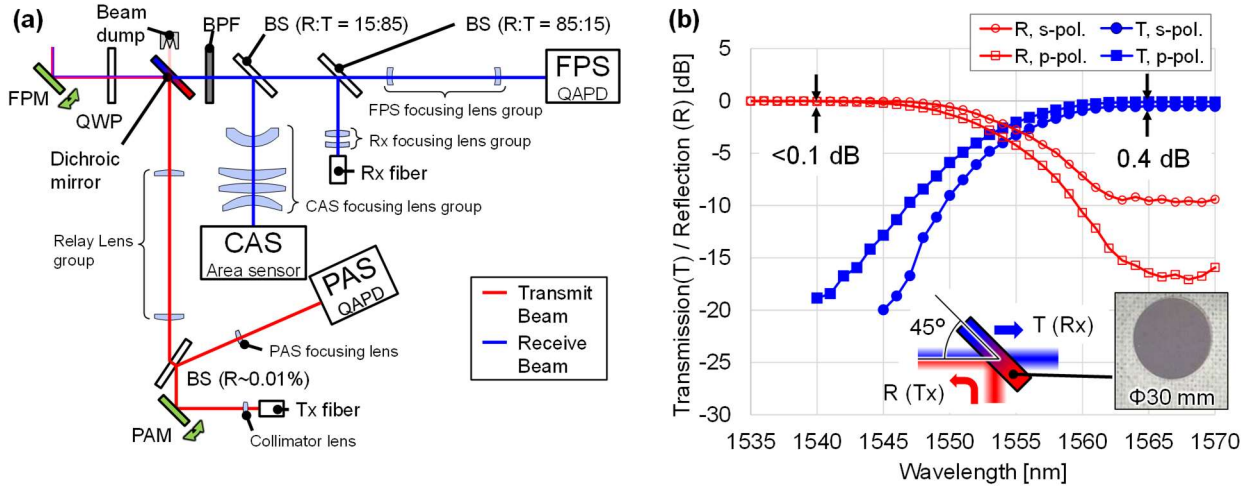


Figure 7. Internal optical subsystem design. (a) Optical layout integrating transmit/receive beam separation, acquisition, tracking, receiver coupling, and point-ahead-angle compensation functions. The receive beam is distributed to the CAS, FPS, and receiver paths, while the transmit beam is routed through the PAM for point-ahead-angle compensation. (b) Measured spectral characteristics of the fabricated transmit/receive separation filter under 45° incidence. Reflection characteristics were obtained from the measured transmission characteristics using $R = 1 - T$. The measured polarization dependence was less than 0.1 dB for the reflected port and approximately 0.4 dB for the transmitted port.

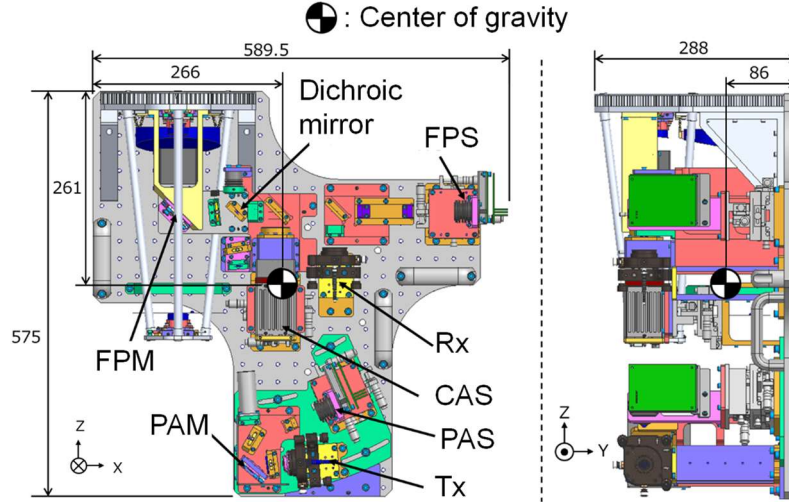


Figure 8. Final opto-mechanical implementation of the internal optical subsystem. The optical assembly integrates acquisition, tracking, receiver coupling, transmit optics, and point-ahead-angle compensation functions using the CAS, FPS, PAS, FPM, PAM, Rx, and Tx modules.

For future lunar applications, an athermal design was investigated for the internal optical subsystem. A CFRP baseplate and specialized Invar-based optical barrels for cryogenic applications were considered to minimize thermally induced displacement and focus variations. For the receiver optics, thermal analyses indicated that the required optical performance can be maintained over the anticipated lunar operating temperature range from $-170\text{ }^{\circ}\text{C}$ to $+110\text{ }^{\circ}\text{C}$ under vacuum conditions.

In the present BBM, priority was given to functional verification rather than miniaturization and mass reduction. Therefore, aluminum was adopted for the baseplate and optical barrels. Optical analyses confirmed that the transmit and receive optical systems can maintain sufficient performance over the laboratory temperature range from $+10\text{ }^{\circ}\text{C}$ to $+30\text{ }^{\circ}\text{C}$ under atmospheric conditions. Because subsystem performance is sensitive to alignment errors, precision adjustment mechanisms were incorporated for the optical fibers and sensor modules, enabling accurate optical alignment during assembly.

5. SYSTEM-LEVEL THERMAL FEASIBILITY ANALYSIS

The thermal feasibility of the proposed optical communication terminal was assessed based on the subsystem designs described in the previous sections. Two application scenarios were considered: installation on a lunar-surface pressurized rover and accommodation on an ELFO relay satellite. Although the telescope and receiver optics were designed to maintain optical performance over the temperature range from $-170\text{ }^{\circ}\text{C}$ to $+110\text{ }^{\circ}\text{C}$, the allowable operating temperature of the terminal was assumed to be $-35\text{ }^{\circ}\text{C}$ to $+80\text{ }^{\circ}\text{C}$ considering the limitations of electronic components.

5.1 Analysis Conditions

Simplified thermal models were developed for the OCT, a lunar-surface pressurized rover, and an ELFO relay satellite. The terminal was assumed to be housed within a low-thermal-expansion CFRP enclosure covered by multilayer insulation (MLI). Thermal isolation was assumed between the terminal and the rover or satellite structure, as well as between the optical assemblies and the enclosure. For simplicity, the telescope aperture was modeled using the same thermal properties as the CFRP enclosure, although an optical window would be incorporated in the actual system. Internal heat dissipation of 10 W was assumed for the internal optical subsystem, with an additional 5 W allocated to the telescope pointing mechanism. Both operational and non-operational conditions of the internal optical subsystem were evaluated, and heater operation was considered when necessary.

5.2 Pressurized Rover Installation Case

Figure 9(a) shows the thermal model used for the pressurized rover installation scenario. The terminal was assumed to be installed on the roof of the rover. The lunar surface and rover were modeled as fixed-temperature boundaries. Transient

thermal analyses covering a three-week period were performed for both high-temperature and low-temperature cases corresponding to representative lunar day and lunar night conditions. The analysis indicated that the terminal temperature exceeded the allowable range in the high-temperature case, reaching approximately 95 °C and 70 °C with the internal optical subsystem on and off, respectively. Additional heat-rejection measures would therefore be required to satisfy the allowable temperature range under this condition. In the low-temperature case without heater operation, terminal temperatures of approximately −16 °C and −110 °C were predicted with the internal optical subsystem on and off, respectively. When a 16.5 W heater was applied, the terminal temperature after two weeks of lunar night was maintained at approximately −8 °C, satisfying the allowable temperature range. A representative result is shown in Fig. 9(c).

5.3 ELFO Relay Satellite Accommodation Case

Figure 9(b) shows the thermal model used for the ELFO relay satellite accommodation scenario. Spacecraft internal power dissipation of 50 W and 300 W was considered, and thermal isolation between the spacecraft and terminal was assumed. Several representative ELFO trajectories satisfying a 12-hour orbital period, an eccentricity of 0.6, and a semi-major axis of 6143 km were evaluated. Transient thermal analyses covering 30 orbital revolutions were performed until the terminal temperature reached steady-state conditions. The highest-temperature and lowest-temperature cases among the evaluated trajectories were then identified. For the highest-temperature case, corresponding to a spacecraft power dissipation of 300 W with the internal optical subsystem operating, the terminal temperature converged to approximately −45 °C after approximately 15 orbital revolutions. For the lowest-temperature case, corresponding to a spacecraft power dissipation of 50 W with the internal optical subsystem off, the terminal temperature decreased to approximately −120 °C after 30 orbital revolutions. These results indicate that heater operation is required even under the highest-temperature ELFO accommodation condition. Figure 9(d) shows a representative low-temperature case with a 22.5 W heater. Under this condition, the terminal temperature was maintained above −35 °C, satisfying the allowable temperature range.

5.4 Summary of Thermal Feasibility

The analyses indicate that thermal feasibility can be achieved for both application scenarios when appropriate heater control is applied. These results provide a preliminary assessment of the proposed terminal architecture and support further development toward future lunar communication missions.

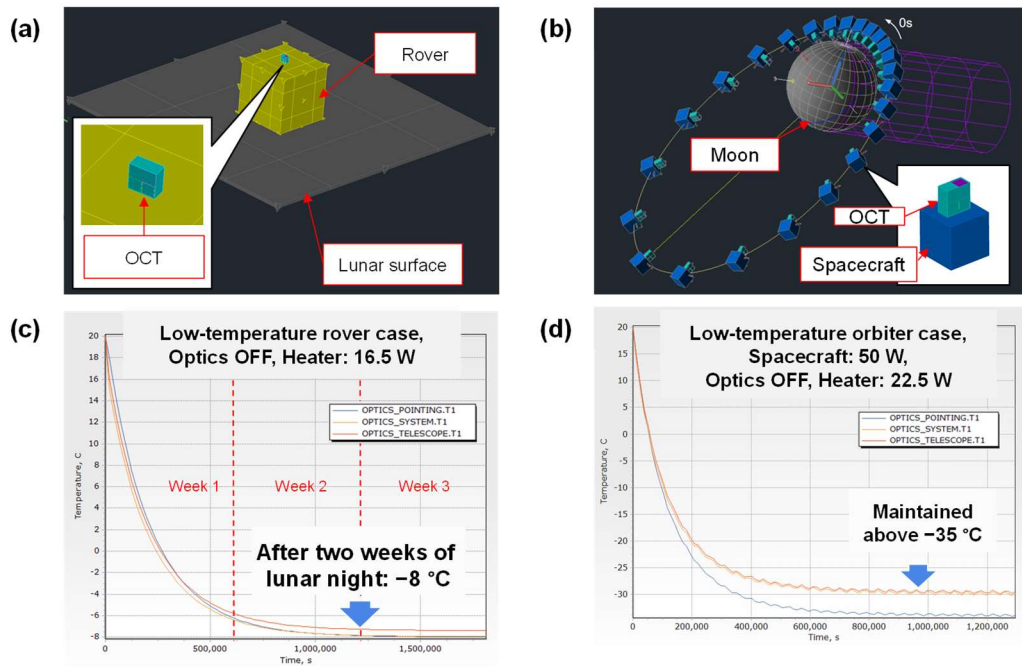


Figure 9. System-level thermal feasibility analysis of the OCT. (a) Thermal model for lunar rover deployment. (b) Thermal model for ELFO relay satellite accommodation. (c) Representative low-temperature rover case. (d) Representative low-temperature orbiter case. The analysis results indicate that the terminal temperature can be maintained within the allowable range through appropriate heater control for both deployment scenarios.

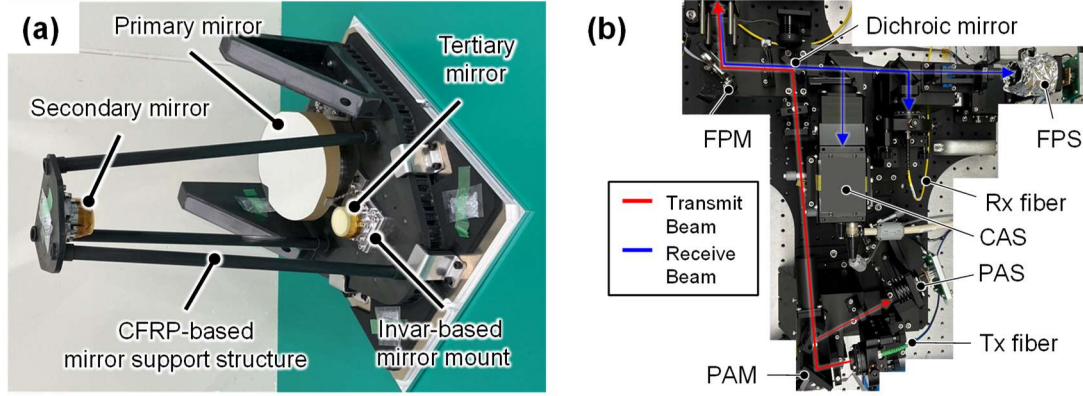


Figure 10. Fabricated breadboard models (BBMs) of the optical communication terminal subsystems. (a) Telescope subsystem BBM incorporating a 100-mm-aperture off-axis three-mirror telescope, a CFRP-based mirror support structure, and Invar-based mirror mounts. (b) Internal optical subsystem BBM integrating the CAS, FPS, PAS, FPM, PAM, transmit/receive optical interfaces, and dichroic-mirror-based transmit/receive beam separation optics.

6. BBM DEVELOPMENT

To verify the proposed design, BBMs of the telescope subsystem and internal optical subsystem were fabricated. Figure 10 shows photographs of the developed BBMs. The telescope subsystem incorporates the optical and opto-mechanical designs described in Section 3, while the internal optical subsystem implements the acquisition, tracking, and point-ahead-angle compensation functions described in Section 4.

The telescope subsystem BBM has completed fabrication of the major optical components and support structures, and final integration is currently in progress. Thermal-vacuum testing is planned to verify the thermal stability of its optical performance. The internal optical subsystem BBM has completed fabrication and optical alignment, and functional evaluations of the acquisition, tracking, and point-ahead-angle compensation functions have been conducted.

Preliminary functional verification was conducted using the fabricated BBMs. Tracking-performance evaluations demonstrated that the tracking-accuracy requirement derived from the link budget can be achieved under representative disturbance and received-power conditions for the assumed ELFO–GEO optical link. Communication experiments using commercially available 100G ZR coherent optical transceivers were also conducted to evaluate communication functionality under tracking operation. Detailed results of the tracking, acquisition, point-ahead-angle compensation, and communication-performance evaluations are reported separately [10].

7. CONCLUSION

This paper presented the system-level optical and opto-mechanical design of a GEO–lunar OCT. Two key technical challenges were addressed: maintaining optical performance under the extreme lunar thermal environment and achieving high-precision tracking for long-distance ELFO–GEO optical links. To investigate these challenges, BBMs of a telescope subsystem and an internal optical subsystem were developed.

A system-level terminal architecture was described based on the GEO–lunar communication scenario, associated link requirements, and anticipated lunar operating environments. Key design drivers included operation over the lunar temperature range from $-170\text{ }^{\circ}\text{C}$ to $+110\text{ }^{\circ}\text{C}$ and support for long-distance optical links of approximately 400,000 km.

For the telescope subsystem, a 100-mm-aperture off-axis three-mirror telescope employing low-thermal-expansion optical and structural materials was designed. Structural and optical analyses showed that the telescope can maintain the required optical performance throughout the anticipated lunar operating temperature range.

For the internal optical subsystem, an architecture integrating acquisition, tracking, receiver coupling, transmit-beam handling, and point-ahead-angle compensation functions was developed. A wavelength-based transmit/receive separation scheme was adopted in place of polarization beam separation to support future interoperability.

System-level thermal analyses were conducted for both lunar-surface and ELFO deployment scenarios. The results indicated that thermal feasibility appears achievable for both applications when appropriate heater control is applied.

BBMs of the telescope and internal optical subsystems were fabricated and evaluated. Preliminary functional verification confirmed the feasibility of the proposed acquisition, tracking, point-ahead-angle compensation, and communication functions. Detailed verification results are reported separately.

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