衛星通信用空間光通信機器の光学設計

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Optical Design of Free Space Optical Communication Devices for Satellite Communications

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カスタムプロダクツ事業部では，宇宙を利用した空間光通信用の光学系開発に携わっている．
フライト品は，開発後打上げて運用に至るまで長い期間を要する．2025年 1 月に，先進レーダ衛星「だいち 4 号」（ALOS-4）の大容量画像が静止軌道の光データ中継衛星を経由してダウンリンクに成功している．これら 2 つの衛星には，弊社で設計製作した光アンテナ（望遠鏡）が搭載されている．
一方，量子暗号通信の地上局について光通信機器の開発にも協力させていただいている．光通信では送信局・受信局で追尾が必要になるが，今回，衛星－地上局間通信における地上局の精追尾光学系を設計製造した．
本報告は，空間光通信の概要と開発した光学系の設計について解説する．

The Customized Products Business Unit is involved in the development of optical systems for space-based optical communications.
Flight products require a long time to be launched and operated after their development. In January 2025, large-volume images from the advanced radar satellite "Daichi-4" (ALOS-4) were successfully downlinked via an optical-data relay satellite in geostationary orbit. These two satellites are equipped with optical antennas (telescopes) designed and manufactured by our company.
Additionally, we are developing optical-communication equipment for the ground stations of quantum cryptography communications through a collaborative effort. Optical communications require tracking at the transmitting and receiving stations. Thus, we have designed and manufactured an optical system for precise acquisition and tracking at the ground station for satellite-to-ground station communications.
This report provides an overview of free-space optical communications and the design of the optical system developed.

Key words　空間光通信，光アンテナ，３枚鏡，精追尾，ファイバー結合
free-space optical communication, optical antenna, three mirrors, fine tracking, fiber coupling

1 Introduction

In recent years, various projects have been planned and implemented toward the practical use of space communications employing light. In space communications, the major challenges comprise ① transmitting large volumes of data in real time and ② ensuring secure information transfer.

One example of a solution to issue 1 is the LUCAS optical inter-satellite communications system, which is already in operation. When large-volume data are directly downlinked from low Earth orbit (LEO) to the ground, the communication time becomes short because the satellite is visible from the ground station only for a limited duration. By relaying the data once from LEO through a geostationary orbit (GEO) relay satellite, the communication time can be extended, and because the ground station can communicate continuously with the relay satellite, the real-time performance of communication can be improved. Communication between LEO and GEO is conducted using laser light in the 1.5 μm band, while communication between GEO and the ground is conducted by radio waves.

Research on optical communications for LEO satellite constellations is also being advanced through national projects. The construction of a network is ongoing in which data from Earth observation constellations are continuously relayed through optical inter-LEO constellation communications and rapidly downlinked to ground stations. Downlinking to ground stations faces the problem that communication cannot be established under adverse weather conditions due to the limited transmittance of light, and studies are being conducted on methods such as selecting a favorable site from multiple ground stations for communication (i.e., site diversity) or employing transportable ground stations (hereafter, transportable stations) that can be moved to locations with good weather for downlinking.

To address the challenge of achieving secure information transfer, research on key distribution employing quantum cryptography via satellites is being conducted under the initiative of the Ministry of Internal Affairs and Communications, with the National Institute of Information and Communications Technology (NICT) playing a central role. In this study, transportable stations are employed to secure the communication link.

Thus, various efforts are being made toward the practical use of space optical communications, and the demand for optical communication equipment to realize such systems is likely on the rise.

The Customized Products Business Unit has performed design and manufacturing based on custom specifications provided by customers. We have long been engaged in products related to space and astronomy, developing optical systems for satellites and optical instruments for astronomical observation. Building on such experience, we now provide optical products related to optical communications to government agencies and companies.

In this paper, we describe the optical design and implementation of optical communication equipment undertaken by our company.

2 Configuration of Optical Communication Equipment and Optical System Specifications

As in radio communications, optical communications propagate optical signals spatially from the transmitting station to the counterpart optical communication station (hereafter, counterpart station), where the counterpart receiving station receives the optical signals. Figure 1 shows a schematic diagram of the link between the transmitting and receiving stations. The light source used is a laser, and for communication to be established, the emitted laser must be detectable by the detector of the receiving station. Therefore, a link budget is performed for the transmitted laser light to ensure that the link from transmission to reception is established, calculating the power gains and losses up to the receiving station, and the parameters are designed to secure sufficient margin relative to the sensitivity of the detector. The transmitted laser is expanded by the antenna within the transmitter and directed toward the receiving station. The larger the antenna aperture, the smaller the beam divergence becomes, and the greater the gain that can be obtained. The longer the propagation distance, the greater the diffraction loss becomes, and pointing errors also cause losses due to the intensity profile. The larger the aperture of the receiving antenna, the more light it can collect, resulting in higher gain. The parameters of each element, including the sensor employed, laser power, and antenna gain, are optimally designed as a system, taking feasibility into account [1].

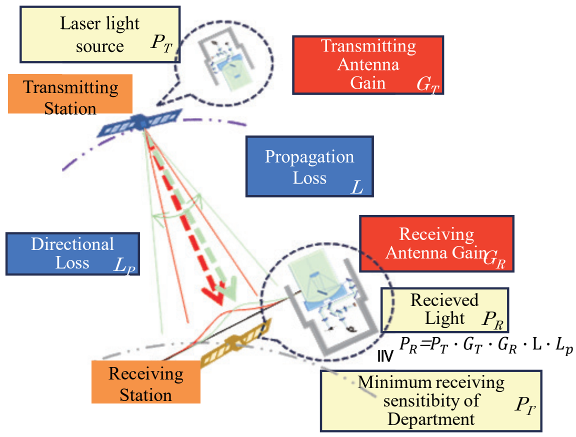

Fig. 1 Conceptual diagram of the link between the transmitting and receiving stations

Figure 2 shows an example of a conceptual diagram of the optical components of an optical communication equipment. The receiving system supports the optical antenna, which serves as the aperture for the transmitted and received light, and, through coarse pointing control by the coarse pointing mechanism and the coarse pointing sensor (CPS), together with fine pointing control by the fine pointing sensor (FPS) and fine pointing mirror (FPM), transmits the received laser light to the receiver (RX), whose axis is aligned with the center of the FPS field of view. Figure 3 shows the relationship between the fields of view observed by the sensors in coarse pointing and fine pointing.

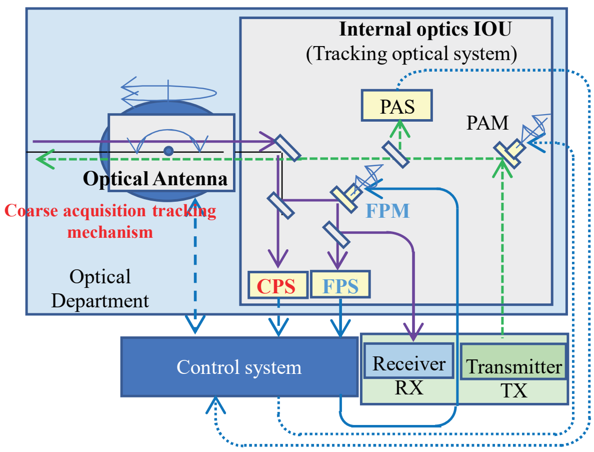

Fig. 2 Conceptual block diagram of the optical components of the optical communication equipment

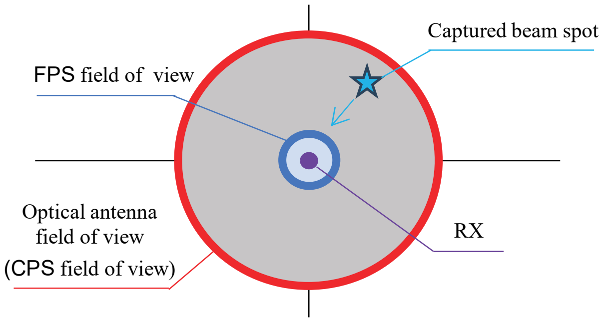

Fig. 3 Conceptual diagram of sensor fields of view and beam spot control

Meanwhile, in the transmitting system, because the counterpart station moves relative to the local station during the propagation of the laser light emitted from the transmitter (TX) until it reaches the counterpart station, the transmission is performed through the point-ahead mirror (PAM) to compensate for this effect (Fig. 4). The figure shows an example of satellite-to-satellite communication, but the same applies to satellite-to-ground communication.

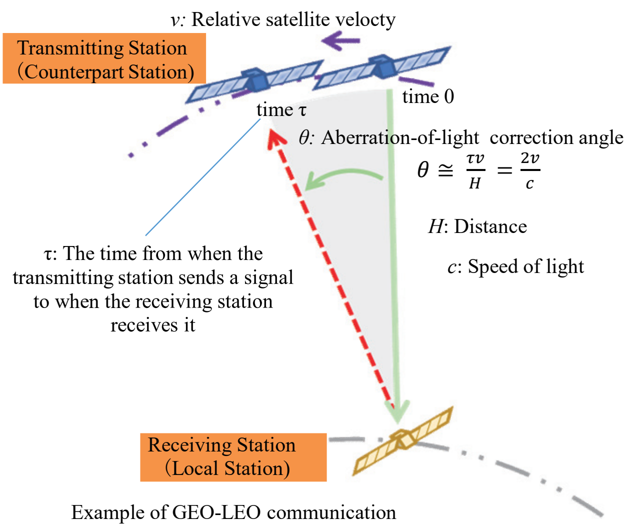

Fig. 4 Aberration-of-light correction

The optical system of the optical communication equipment must efficiently deliver the communication light to the counterpart station without attenuation. The antenna gain shown in Fig. 1 is determined by the wavelength λ, aperture area A, and efficiency η, as expressed by the following equation:

$$G = \frac{4\pi}{\lambda^2} A \cdot \eta$$

Factors related to the efficiency η attenuate the gain, and specifications of the optical system include obscuration ratio, transmittance, polarization loss, and wavefront aberration. In addition, the noise characteristics (stray light) of the transmitted and received beams are also important factors related to η.

Because the optical antenna and internal optical unit (IOU) may be handled by different teams, their specifications are reallocated, and each optical system is designed accordingly.

3 Optical Antenna of the LUCAS Optical Inter-Satellite Communication System

Here, we describe the optical antenna system that constitutes the LUCAS optical inter-satellite communication equipment.

The optical antennas of the optical inter-satellite communication equipment mounted on the optical data relay satellite and Earth observation satellite employ a common architecture, with the aperture diameters determined according to the allocations of each system. While NEC was responsible for the development of the optical inter-satellite communication system, Nikon was in charge of the optical design, optical component fabrication, and optical system assembly of the optical antenna. In this section, we introduce Nikon's responsibilities.

3.1. Optical System Design

The main specifications of the optical antenna system are listed in Table 1. These items were determined based on the system allocation values and Nikon's optical system study. The optical antenna is an afocal telescope system with an angular magnification of 20x. During reception, light enters the aperture of the optical antenna, and the beam is reduced in size and guided to the subsequent IOU.

Table 1 Main Specifications of the Optical Antenna

	GEO	LEO
Aperture diameter	ϕ150	ϕ100
Angular magnification	20x	20x
Wavefront error	λ/30	λ/30
Field of view	± 0.1 deg	± 0.2 deg
Polarization preservation	2 %	2 %
Transmission loss	0.3 dB	0.3 dB
Back reflection	65 dB	65 dB

During transmission, the beam from the IOU is expanded by the optical antenna and emitted. The received and transmitted beams have different wavelengths but pass through the common optical path of the optical antenna. Figure 5 shows the optical path diagram of the GEO optical antenna. As shown in the figure, the antenna is composed of three off-axis mirrors and a flat folding mirror that directs the beam to the subsequent IOU, and it is designed to be compact. The three-mirror system has a concave–convex–concave configuration, with the respective surfaces being parabolic, hyperbolic, and elliptical. This configuration suppresses field curvature, reduces wavefront error, and accommodates a wide field of view. The advantages of the optical system are that, with no central obscuration and the use of high-reflectivity coatings on the mirror surfaces, it achieves high transmittance with extremely low loss, and the return light from the transmission beam emitted by the IOU does not pose a problem. Meanwhile, it is not a configuration that can correct distortion aberration, and it has the drawback of a magnification distribution within the field of view due to distortion. Therefore, to align the incoming light with the center of the field of view, it is necessary to perform pointing by nonlinear control of the angular adjustment of the pointing mechanism.

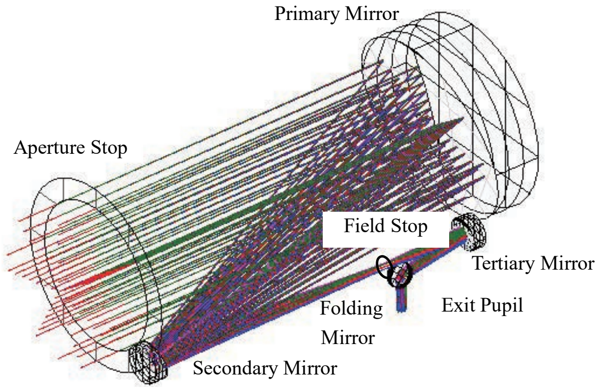

Fig. 5 Optical path diagram of the optical antenna section

During reception, the transmitted light enters the IOU with power P_R, attenuated to a weak level by the loss factors described in Section 2, as shown in Fig. 6. Meanwhile, during transmission, a strong laser power $P_{R'}$ is emitted, and in this optical system, a scattered light power $P_{N'}$ enters the receiver optical path within the IOU. This light noise can be addressed by the design and fabrication of each mirror component. In addition, there are strong stray light sources, such as sunlight, from outside the field of view. Gaps that exist in the optical design are filled with a mechanical structure, field stop, and stray light cover to prevent this from mixing into the IOU. Fig. 7 shows the fabricated mirrors. Weight reduction is required for components of satellite-mounted hardware, and because the primary mirror of the optical antenna has a larger aperture than the other parts, its backside is hollowed out to reduce weight.

The mirror surfaces were processed into aspheric shapes by grinding and polishing. The wavefront accuracy of the

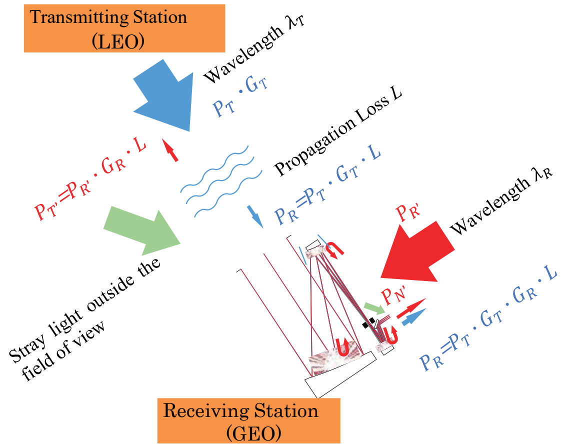

Fig. 6 Received light and scattered light noise

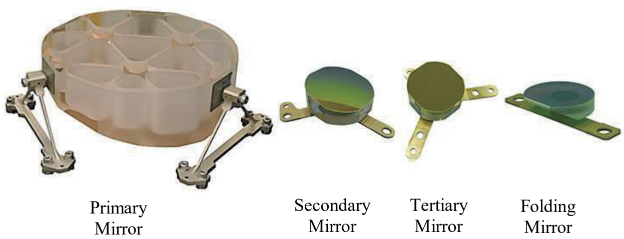

Fig. 7 Fabricated mirrors of the optical antenna

optical antenna in orbit is specified as λ/30 at a wavelength of λ = 1530 nm. Because the surface accuracy requirements for the mirrors are also stringent, the desired accuracy was achieved through polishing based on null testing using CGHs and other methods with an interferometer.

3.2. Coating

The transmission loss and polarization dependence of the optical system depend on the performance of the reflective coatings of the optical components. From the perspective of transmission loss, each component required coatings with high reflectance and low polarization dependence. To meet both requirements in the design, aspheric mirrors with small incident angles were coated with metal plus dielectric films, while the folding mirrors with large incident angles were coated with dielectric films. The design was made to ensure high manufacturability. The reflectance measurement results obtained with test pieces are shown in Fig. 8.

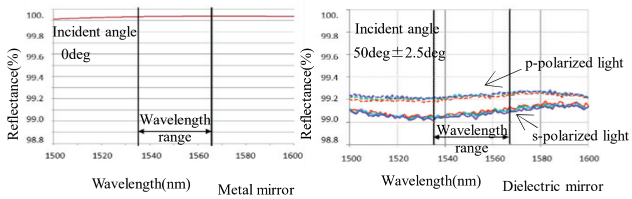

Fig. 8 Mirror reflectance

As shown in the optical path diagram of Fig. 5, the clearance between the beam from the field stop to tertiary and folding mirrors is narrow, and the folding mirror is shaped, as illustrated in Fig. 7, with its disk sides flattened and back-side tapered. During the fabrication of the folding mirror, the reflective coating was a multilayer film, and the surface deformation due to film stress was significant, making it difficult to achieve the required surface accuracy despite it being a flat mirror. Therefore, the mirror shape was corrected in anticipation of deformation by film stress, thereby improving the transmitted wavefront accuracy.

Because relatively high-power lasers are used in LUCAS, it is necessary for the reflective coatings to have laser resistance. The maximum incident laser power was specified as 5 W, requiring resistance at a maximum power density of 0.3 W/mm^2 for the LEO optical antenna with its smaller beam. Before fabricating the components, irradiation tests were conducted using test pieces. The appearance and reflectance were measured before and after irradiation, and because no significant changes were observed in either evaluation item, the components were confirmed to be problem-free and installed in the product.

3.3. Assembly

The primary mirror is supported by a structure in which Super Invar pads are placed at three points on its side and held by flexures. The secondary, tertiary, and folding mirrors were bonded at their back-center areas to holders to minimize distortion in the mirrors, and these units were mounted onto the support structure provided by NEC to assemble the entire optical antenna. To measure the wavefront accuracy of the optical antenna, an interferometer was placed in the direction of the exit pupil, and a flat mirror was positioned on the aperture-stop side of the antenna to configure the measurement system. The required wavefront accuracy was achieved by adjusting the decentering and spacing errors, mainly between the primary and secondary mirrors, to the micrometer level.

After assembly, vibration tests and other evaluations were conducted to verify that performance could be maintained during flight and operation, and the optical antennas for both GEO and LEO applications were delivered to NEC.

4 Optical Design of Ground Stations for Satellite Quantum Cryptography Communications

To ensure security through the use of space, the development of satellite quantum cryptography communications is ongoing. As shown in Fig. 9, quantum keys are delivered as signal light from the satellite to the ground station, but the signal itself is extremely weak. For acquisition and tracking, beacon light stronger than the signal light is transmitted from the satellite, and the signal is received while tracking the beacon light. Nikon also contributed to this development through design and manufacturing.

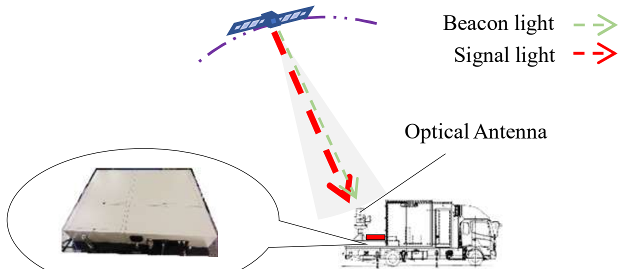

Fig. 9 Conceptual diagram of optical communication between a satellite and transportable ground station

The configuration of the optical system consists of, as mentioned above, the optical antenna and IOU. The optical antenna is a Cassegrain telescope with a central obstruction, and the IOU is the precise acquisition and tracking optical system, which was designed with only a receiving function for a downlink-only experiment. Therefore, laser transmission was not conducted.

4.1. Optical Interface with the Transportable Ground-Station Optical Antenna

Table 2 shows the specifications and optical interface of the transportable ground-station optical antenna. Light is collected by a 355-mm aperture Cassegrain telescope, and after being relayed through a Coudé optical path, it is directed to the precise acquisition and tracking optical system. The exit pupil position of the Coudé path was defined as the optical interface, and the end face of the optical bench on which the precise acquisition and tracking optical system is mounted was defined as the mechanical interface.

Table 2 Optical Interface between the Transportable Ground-Station Optical Antenna and Precise Acquisition and Tracking Optical System

Item	Specification
Telescope format	Cassegrain/Coude type
Effective aperture diameter	ϕ355 mm
Magnification	17.75x
Field of view	ϕ1 mrad
Exit pupil diameter	ϕ20 mm
Telescope exit pupil position	1774 mm from the edge of the optical surface table

4.2. Functional Configuration of the Precise Acquisition and Tracking Optical System

The functional configuration of the precise acquisition and tracking optical system is explained with reference to Fig. 10.

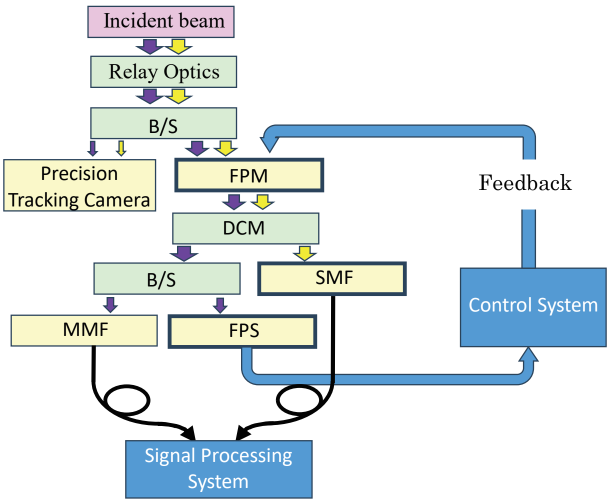

Fig. 10 Functional configuration of the precise acquisition and tracking optical system

The beam incident from the optical antenna is divided by a beam splitter (B/S) into a coarse tracking path and precise tracking path. The role of observing the CPS field of view in Fig. 3 corresponds to the precise tracking camera.

An FPM is placed in the precise tracking path, which serves to suppress seeing effects, i.e., tilts of the beacon light caused by disturbances.

Because the beacon and signal light are at different wavelengths in the 1.5-μm band, a dichroic mirror (DCM) is placed behind the FPM to separate them.

The beacon light is split by the B/S into the multimode fiber (MMF) and FPS. The MMF receives the beacon light and is used for synchronization of signal detection.

The signal and beacon light are transmitted coaxially. The FPS, a sensor for detecting beam spot fluctuations caused by seeing effect, and a quadrant detector (QD) were used. The beacon light is directed to the QD, forming a beam spot on the QD. The centroid is calculated from the QD output of the beam spot, and based on this, feedback is applied to the FPM to control the tilt.

As shown in Fig. 11, when disturbances are suppressed by the FPM and the beam spot is held at the center of the FPS, the signal light coaxial with the beacon light is stably focused onto the end face of the single-mode fiber (SMF), enabling efficient fiber coupling.

The design requires the selection of devices, such as the FPM, FPS, SMF, and MMF, from commercially available

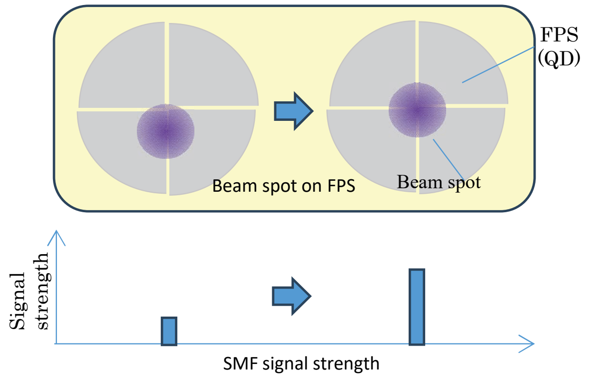

Fig. 11 Conceptual diagram of beam spot control and signal intensity effect in the feedback system

products. Based on the system specifications of the precise acquisition and tracking optical system, appropriate devices are selected, and the specifications of the optical elements are determined accordingly.

As a design requirement for the optical layout of the FPM, the exit pupil of the optical antenna is relayed and imaged onto the FPM. The FPM must control tilt at high speed; therefore, it is desirable for it to be compact and lightweight. In addition, the driving range of tip-tilt in commercial FPMs is specified and therefore cannot be exceeded. Meanwhile, as a design requirement for the relay system, the overall length had to be shortened to make the entire apparatus compact while still allowing the placement of optical elements, such as the previously mentioned B/S for beam-path division and filters.

Fig. 12 shows an optical model of the precise acquisition and tracking system. In the most basic configuration (Configuration 1), as the distance from the optical antenna exit pupil to the f1 lens becomes longer, the image position of the pupil where the FPM is placed approaches closer to the f2 lens. To solve this problem, as in Configuration 2, a concave field lens is placed at the focal position to change the direction of the off-axis rays, and by increasing the ray height incident on the f2 lens, the position (pupil) where the rays refracted by the f2 lens intersect the optical axis shifts farther back. In principle, this concept was aimed at miniaturizing the relay system. As a result, it became possible to place the FPM at the pupil position while securing space for the B/S and filters, achieving low loss and reduced aberrations with a minimal lens configuration. Fig. 13 shows the configuration, including the holding structure of the lens system.

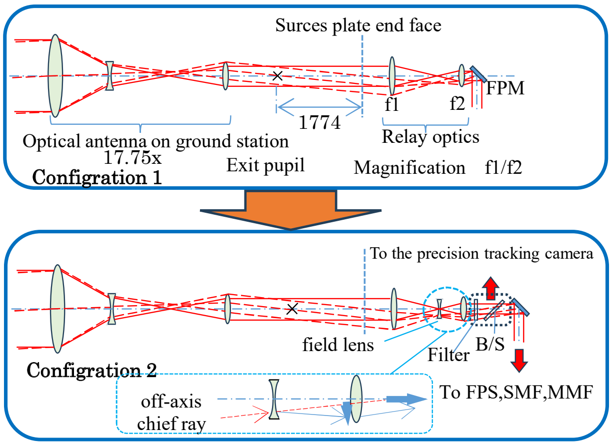

Fig. 12 Optical model of the precise acquisition and tracking system

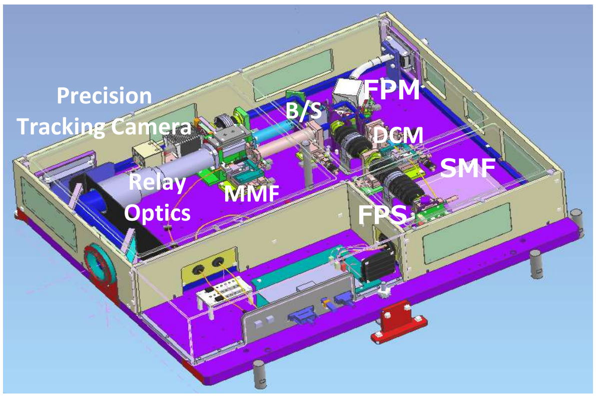

Fig. 13 Configuration diagram of the precise acquisition and tracking optical system

5 Conclusion

Among our recent products for space optical communications, we have introduced the optical antenna for the LUCAS inter-satellite optical communication equipment, along with the design and fabrication of the precise acquisition and tracking optical system for quantum cryptography communications.

LUCAS has been operated for optical communications between GEO and LEO, to which the optical systems manufactured by our company were able to contribute.

A demonstration of key transmission by optical means between the ISS and a ground station was conducted with the aim of social implementation of the quantum cryptography communication system. The precise acquisition and tracking optical system of the transportable ground station, manufactured by our company, also contributed to the demonstration.

The development of the optical antenna for the LUCAS inter-satellite optical communication device was performed under the guidance of JAXA and NEC. In addition, the development of the precise acquisition and tracking optical system for the transportable ground station was conducted in collaboration with NICT and SKY Perfect JSAT. We would like to express our gratitude to all those involved for their cooperation.

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