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Precision Two-step Alignment of a Large Optical Telescope for a Satellite Laser Ranging System

Han-Gyol Oh[1,2], Kisoo Park[3], Eui Seung Son[3], Suseong Jeong[4], Sang-Yeong Park[4], Pilseong Kang[1], Jaehyun Lee[1], and Hyug-Gyo Rhee[1,2]*

[1]Korea Research Institute of Standards and Science, Daejeon 34113, Korea
[2]Department of Precision Measurement, University of Science and Technology, Daejeon 34113, Korea
[3]Defense Rapid Acquisition Technology Research Institute, Seoul 04353, Korea
[4]Hanwha Systems Co., Ltd., Seongnam 13524, Korea

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Large optical systems, such as telescopes in satellite laser ranging systems, require precise alignment to realize their optical design. Proper alignment is essential for these systems to function properly. While various alignment methods exist, they often cannot be directly applied to large optical systems due to their scale. Effective alignment ensures that the system's components are accurately positioned, which is important for minimizing optical aberrations. In this study, we propose a two-step alignment process for a 1-meter-class optical telescope assembly (OTA) for use in a satellite laser ranging system. The initial alignment step was performed using a laser tracker, which positioned the components to a degree where interferometric fringes could be observed. This initial step was followed by fine alignment using the root mean square (RMS) wavefront error (WFE) method. This method was applied for the first time to a large optical system in South Korea. The alignment process was successfully completed, achieving a final RMS of 49.03 nm.

Keywords : Alignment, Optical telescope, Satellite laser ranging
OCIS codes : (010.1330) Atmospheric turbulence; (220.1080) Active or adaptive optics; (220.4610) Optical fabrication

I. INTRODUCTION

A large optical system is an optical system with large-scale lenses and mirrors that control light for specific purposes, such as for observing space or communicating with satellites. These systems help us see far into the universe or send and receive signals to and from satellites. Examples of such systems include large telescopes and satellite laser ranging systems. The performance of a large optical system depends on how well it can achieve the purposes set forth during its optical design process. For example, the performance of a large telescope is measured by its ability to show clear images of stars without distortions or aberrations. An optical system can be ideally designed during the optical design process. However, turning the ideal into reality depends on optical component fabrication, assembly and alignment processes. In particular, alignment is important in large optical systems. Alignment refers to the positioning of each optical element in its ideal location along the path of light. Therefore, misalignments of components can significantly affect the final image quality when there is a long optical path length. Moreover, in the final process, it is important to precisely position each component in its designated position to ensure the quality of the entire system.

In this paper, we aligned a 1-m-class optical telescope assembly (OTA) using the root mean square (RMS) wave-

*Corresponding author: hrhee@kriss.re.kr, ORCID 0000-0003-3614-5909

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front error (WFE) method [1]. This type of telescope in laser ranging systems is used for space satellite monitoring. Notably, this is the first time a telescope of this size has been aligned domestically. The type of OTA is designed as a Cassegrain telescope, a type widely used due to its compact design and ability to produce high-quality images with minimal optical aberrations. This design allows for a long focal length while maintaining a controllable physical size. The RMS WFE method provides a robust solution by incorporating additional boundary conditions, ensuring that the alignment process avoids local minima and achieves global minima. This method can be applied when interference fringes are visible. However, for large optical systems, simply placing the components in approximate positions does not produce interference fringes. Therefore, a two-step alignment process is necessary.

Precise alignment of large telescopes is essential for achieving high performance. For example, for a Cassegrain telescope, star images before and after alignment can appear as shown in Fig. 1. Various tools and techniques for aligning large telescopes have been developed continuously over time. In particular, laser trackers have been widely used for initial rough alignment, facilitating efficient positioning of optical elements [2, 3]. Separately, interferometry has been applied for fine alignment, achieving high precision in minimizing residual error [4, 5]. However, previous studies have employed these techniques independently and focused either on laser tracker-based rough alignment or interferometer-based fine alignment. Our research combined both methods into a single workflow to produce optimized results for large optical telescopes. In this study, we present a two-step alignment approach that combines the use of a laser tracker for rough alignment and interferometry for fine alignment, integrated with the RMS WFE method. This combination enables us to achieve optical performance while minimizing time.

The rough alignment step positions two components to a degree where interference fringes can be observed. Subsequently, the RMS WFE method is employed for fine alignment. The ability to predict the final alignment state without physically moving the compensator is suitable for large optical system alignment, as physical adjustment can be inconvenient and time-consuming.

In Section 2, we introduce the OTA and describe the steps taken before alignment. The initial alignment step was done with a laser tracker. In Section 3, we detail the two-step alignment process, starting with the initial alignment and followed by fine alignment using the RMS WFE method. Finally, the results of the OTA alignment process are presented.

II. OPTICAL TELESCOPE ASSEMBLY

2.1. Target Optical Telescope

The optical system we target here for alignment is an op-

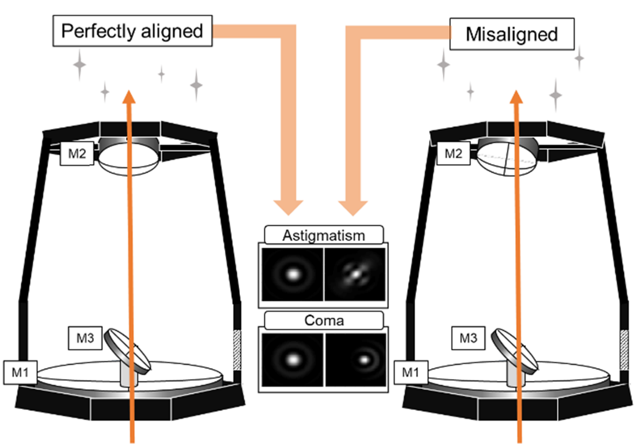

FIG. 1. Comparison of images with aberration before and after alignment in a Cassegrain telescope.

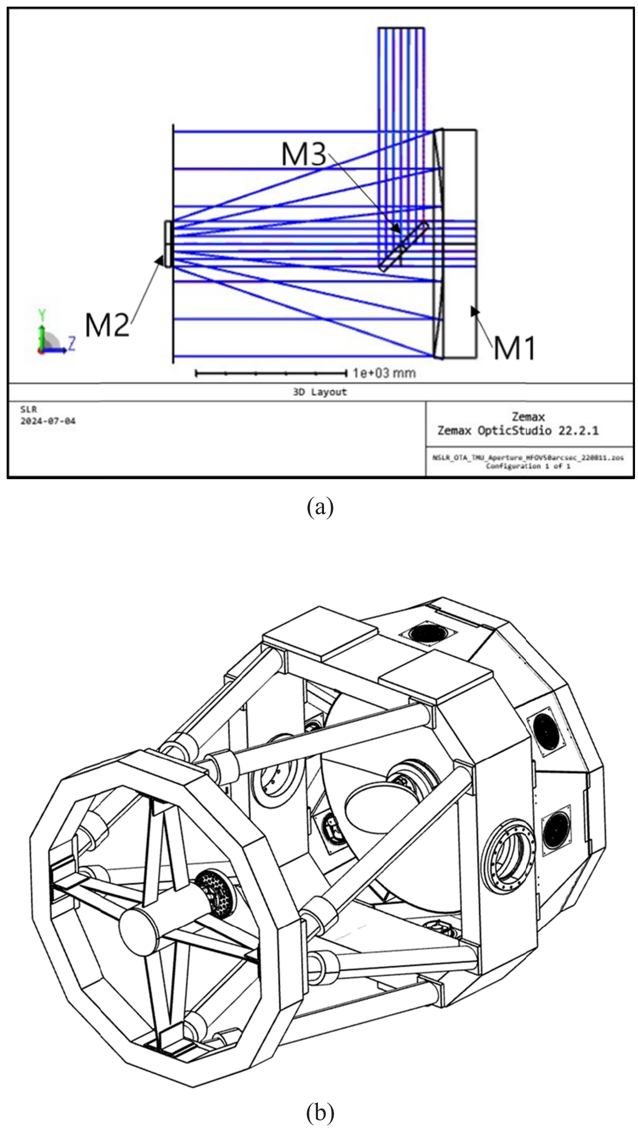

FIG. 2. Layout of proposed optical system: (a) Optical design designed by Zemax, and (b) detailed design of the optical telescope assembly (OTA).

tical telescope to be installed in a satellite laser transceiver [6, 7]. Figure 2 displays the optical system we intend to align. The type of optical telescope is the Cassegrain type, which is widely used for astronomical observations. Its features include a compact design with a large aperture and a long focal length. The structure of the telescope contains a primary mirror (M1), a secondary mirror (M2), and a reflector (M3). Light entering the telescope initially reaches M1, which collects and reflects the light towards M2. M2 then reflects the light to M3, which directs the light to the observation equipment. The optical system we aim to align is set to have a final wavefront RMS of less than 60 nm, excluding environmental effects such as the temperature and humidity.

2.2. Optical Telescope Alignment Method

Optical system alignment is divided into several steps. These steps can be categorized into rough alignment and fine alignment process, each serving distinct purposes in the overall process. The first is the selection of a compensator. The optical system we aim to align operates as a set of three optical elements. Because M3, a flat mirror, does not influence alignment errors, the relative positions of M1 and M2 affect system performance.

For our optical system, M2 serves as the compensator, so we tried to place M2 in an approximate position. The equipment used for this placement is a laser tracker by FARO [8]. The laser tracker uses its laser and reflector to measure the distance between the body and the reflector. This rough alignment step ensures that M2 is positioned within a close tolerance of its theoretical placement, serving as a foundation for the subsequent fine alignment process. Using this principle, we attach a reflector to the outer diameter of M1 and to the back of M2 to measure their relative angles and center positions. A precisely manufactured reflector mount is attached to the back of M2 for accurate determination of its center position.

After the rough alignment step, the fine alignment step is performed using computational methods with an interferometer. An interferometer is used to adjust the relative positions and angles of M1 and M2 with high precision. This step aims to minimize residual errors and achieve the desired optical performance. When the alignment of M1 and M2 is completed, M3 is attached, after which we examine the final wavefront. This two-step alignment approach, which incorporates both rough and fine alignment processes, ensures both efficiency and precision. Unlike conventional alignment processes that may require additional iterative adjustments, our approach optimizes the use of the laser tracker and interferometer to reduce alignment time while achieving high accuracy. The alignment scheme for this optical system as described above is shown in Fig. 3.

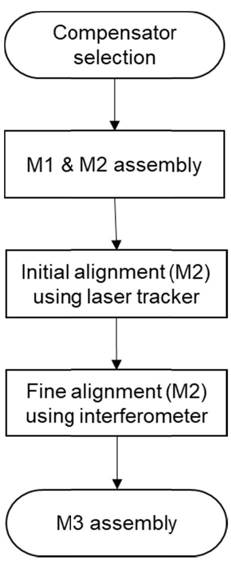

FIG. 3. Alignment scheme for the optical system.

III. EXPERIMENTAL RESULTS

3.1. Step 1: Compensator Selection

Alignment error appears because of the relative positions of the components that make up the optical system. Since the position of each component is a dependent variable, moving all components at once makes it difficult to converge the alignment error. Therefore, one component must be selected for adjustment during alignment. The sensitivity method is commonly used to select the component that causes the most significant change in alignment error when all components are moved on the same scale [8]. Due to the large size and difficulty in adjusting M1, we chose M2 as the compensator regardless of sensitivity method. During the alignment process, only the compensator M2 is moved to correct the alignment error.

3.2. Step 2: Alignment with Laser Tracker

Before aligning with the interferometer, each component must be placed in an approximate position, for which a laser tracker is used in the initial alignment step. A laser tracker is a measuring device that works by projecting a laser beam onto an optical target, known as a spherically mounted retroreflector (SMR), in contact with the object being measured. The laser emitted from the tracker hits the SMR and returns to the tracker. The distance based on the reflected signal is then calculated. Therefore, it is essential to position the SMR on the optical surfaces of M1 and M2 accurately. Figure 4 shows the SMR attached to M2, along

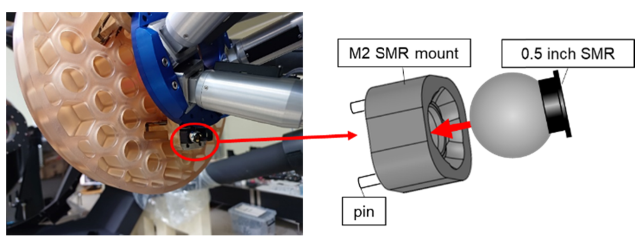

FIG. 4. Spherically mounted retroreflector (SMR) mounted on the mount of M2 fixed with a pin.

with the fabricated SMR mount.

Four SMRs are attached to M1, positioned flush with the edge of M1 to align the center of the SMRs with the center of M1. Additionally, the heights of the four SMR mounts were uniformly fabricated. The exact height is not important because this value can be set in the laser tracker software. Three SMRs are attached to M2. The mount of M2 is designed so that SMR mounts can be mounted. The SMR mount was fixed with two pins. Given that M1 and M2 cannot be measured from a single view, the "move device" function in the FARO software was used for alignment. Figure 5 illustrates the laser tracker alignment scheme. The move device function is essential for measuring elements that are too large to measure within a single field of view. This function enables measurements from multiple fields of view. At least three reference points are needed to integrate the coordinates accurately.

When the measurement method and system are prepared, the first step is to establish the axis on the system to be aligned. Since we selected M2 as the compensator in previous step, we will move the M2. Therefore, the axis should be set based on the movement of M2. Since M2 is mounted on the hexapod, we can set the hexapod as the base axis. To establish the base axis using the hexapod, we first measure the position of 7 SMRs attached to M1 and M2 using the previously mentioned move device method. The center of the three SMRs attached to the back of M2 is set as the origin, which can be considered the center of M2. Then we move the hexapod in a single direction, other than along the *z*-axis. After the movement, we measure the position of 1 SMR and connect the before and after positions to define the *x*- or *y*-axis. By creating an origin and one vector, an axis based on the hexapod is established. Figure 6 shows the established axis. When the axis is set, the previously measured coordinates of M1 and M2 are redefined relative to the base axis. Using software functions, we can calculate the decenter and tilt of M1 and M2.

Their centers and tilts were then aligned by operating a hexapod equipped to move M2 by hexapod. Table 1 shows the status of the angle before laser tracker alignment and after laser tracker alignment. Angle XY is the rotation angle around the *z*-axis of the hexapod. Angle represents a composite of the three angles: Angle XY, Angle XZ and Angle YZ.

3.3. Step 3: Alignment with an Interferometer

After the initial alignment, an interferometer was installed to begin the fine alignment process. This alignment step will begin with a method for aligning optical systems with RMS WFE as the optimization criterion. The alignment process starts with the measurement of the wavefront error, expressed in terms of Zernike polynomials. The formula Eq. (1) is employed.

$$\Delta F = A\Delta X. \quad (1)$$

In this equation, ΔF is the difference between the measured and ideal wavefront error, A is the sensitivity matrix calculated from the ideal optical design, and ΔX is the compensator adjustment needed to minimize the wavefront error. The RMS WFE is computed with Eq. (2).

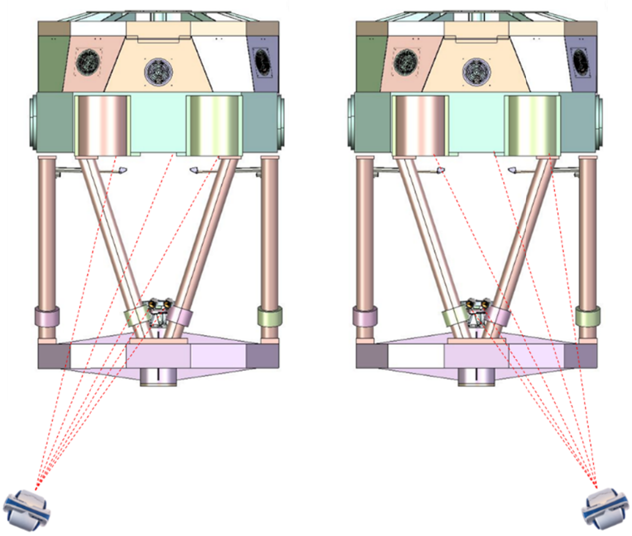

FIG. 5. Measurement scheme of the laser tracker using the move device function of FARO software.

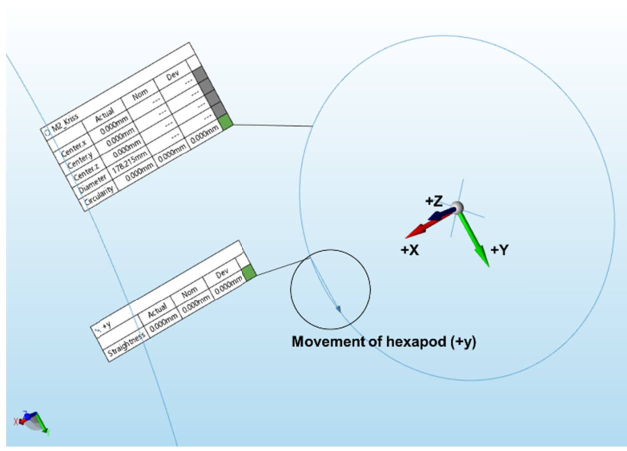

FIG. 6. Picture of reference axis based on hexapod movement from the FARO software.

TABLE 1. Angles before and after laser tracker alignment

Feature	Before Alignment	After Alignment
	Degree (deg.)	Degree (deg.)
Angle	3.10	0.962
Angle XY	0.000	13.831
Angle XZ	2.386	0.902
Angle YZ	1.982	0.026

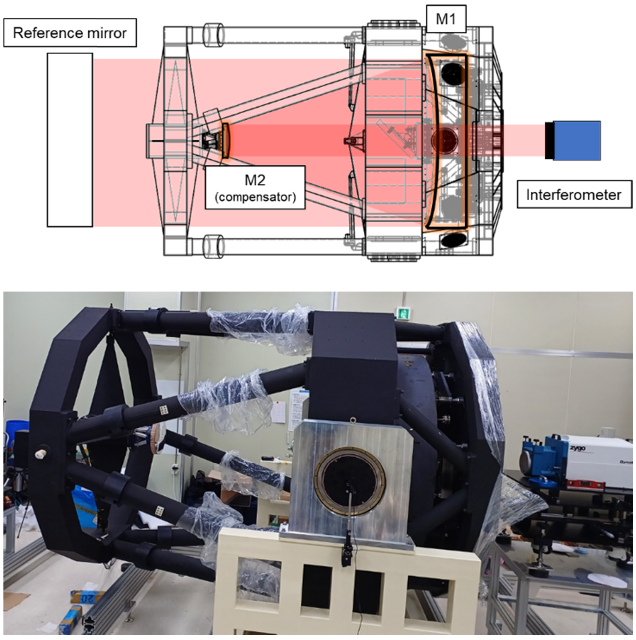

FIG. 7. Alignment setup of the interferometer and the optical telescope assembly (OTA).

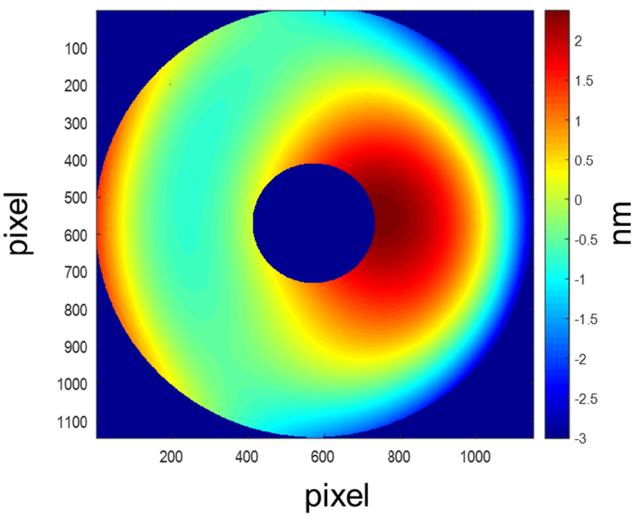

FIG. 8. Alignment results of the optical telescope assembly (OTA) after initial alignment (RMS: 644.08 nm).

$$\text{RMS WFE} = \sqrt{\sum_{j=1}^{b} Z_j^2}. \tag{2}$$

Here, Z_j denotes the Zernike coefficients. In this way, we iteratively adjust the compensators to minimize the RMS WFE across all fields. Due to the large size of the optical system, this method was applied to only the center field. Double-pass interferometric measurements were taken. Therefore, a scale factor of 0.5 was applied. Figure 7 shows the laser light path during the interferometric measurements and actual alignment setup.

Figure 8 shows the interferometer measurements after the initial alignment with the laser tracker. In the second alignment step, we apply the RMS wavefront error (WFE) method [1]. The method uses the RMS WFE value as an additional boundary condition during the optimization process. The alignment results show that we achieved an RMS value of 49.03 nm, as shown in Fig. 9, satisfying the development goal.

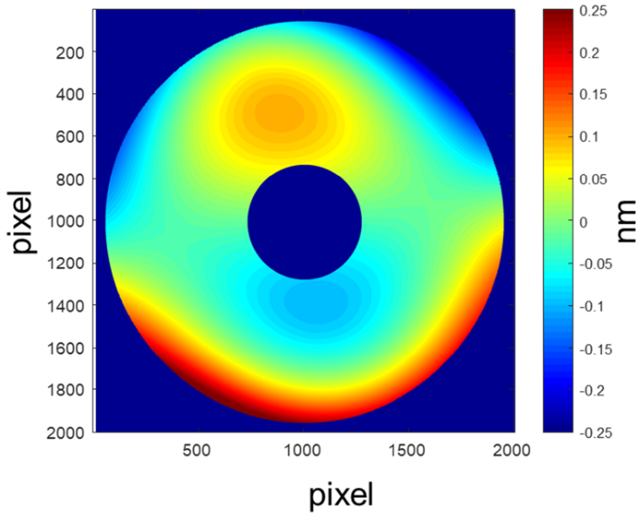

FIG. 9. Final alignment results of the OTA after fine alignment (RMS: 54.24 nm).

IV. CONCLUSION

We aligned a large optical telescope for a satellite laser ranging system. Initially, we set a target RMS of 60 nm for our alignment process. Before starting the alignment, we used the sensitivity method to select the compensator. Then the initial alignment was performed using a laser tracker. Precision-fabricated SMR mounts were attached to M1 and M2. Their positions were measured using the later tracker. The reference axis was set based on M2, which had been selected as the compensator. Using this reference axis, we checked how much M1 and M2 were misaligned after assembly and adjusted accordingly, reducing the angular misalignment from 3.1 degrees to 0.96 degree. This process positioned the components to a degree where interferometric fringes could be observed.

Following the initial alignment, we employed the RMS WFE method for fine alignment. Interferometric measurements showed that the initial alignment error was around rms 644 nm. After fine alignment with the interferometer, we achieved a final rms WFE of 54 nm, which successfully satisfied the development goal.

The two-step alignment process presented in this study, combining laser tracker-based rough alignment with interferometry fine alignment, can be generalized to other large optical systems. By leveraging the advantages of each technique, this approach addresses the challenges of aligning components with long optical path lengths and offers a practical and efficient solution to achieve an RMS WFE of 60 nm. This method provides a framework for aligning other large optical systems, such as astronomical telescopes, high-energy laser systems, or optical communication platforms.

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DISCLOSURES

The authors declare no conflicts of interest.

DATA AVAILABILITY

All data generated or analyzed during this study are included in this published article.

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