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Tolerance Analysis of Wide Field of View Confocal Off-Axis Telescope System Using Freeform Mirrors for Common Optics MWIR/LWIR Sensors Onboard UAVs (Linear Astigmatism Free - Three Mirror System D70F1.4)

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ABSTRACT

Linear Astigmatism Free - Three Mirror System (LAF-TMS) is a confocal off-axis system that eliminates linear astigmatism, which is the most critical aberration especially in the large field angle, and therefore, enables the telescope to have a wide field of view. Based on our experience with the telescope, we optimized the LAF-TMS for wavelength ranges of mid-wavelength infrared (3-5 µm) and long-wavelength infrared (8-12 µm) sensors onboard Unmanned Aerial Vehicles (UAVs). It has an entrance pupil diameter of 70 mm, a focal ratio of 1.4, and a wide field of view (FoV) of 6.20° × 4.68°, matching 10.9 mm × 8.2 mm sensor with 17 µm sized pixels (LAF-TMS D70F1.4). The freeform mirrors of LAF-TMS D70F1.4 are optimized to eliminate the high order aberration. As a result, LAF-TMS D70F1.4 can achieve high-quality optical performance over a wide FoV without any additional correcting lenses. We performed the sensitivity analysis and the Monte-Carlo simulations as the feasibility study. During the sensitivity analysis and the Monte-Carlo simulation, decenter, tilt, despace, and surface RMS errors of three mirrors were analyzed. From the sensitivity analysis, we investigated 80% Energy Encircled Diameter by single factor perturbations. The system tolerance limits were calculated using the Monte-Carlo method with a normal distribution of errors. According to the results, we confirmed that the LAF-TMS D70F1.4 was feasible considering general fabrication and alignment tolerances.

Keywords: Dual-band, Freeform mirror, Infrared, Linear astigmatism, Monte-Carlo simulation, Off-axis, Telescope, Tolerance analysis

1. INTRODUCTION

A conventional on-axis reflecting telescope faces a problem when it is used for observing bright high-contrast such as a corona as the optical performance of the telescope is degraded by scattering and diffraction due to the obstruction of the secondary mirror.[1,2] In a common off-axis refracting telescope, there are no such problems, but there is linear astigmatism that becomes dominant toward the edge of the field. Therefore, the common off-axis has limitations in a wide Field of View (FoV) observation.[3]

Linear Astigmatism Free-Three Mirror System (LAF-TMS) is a confocal off-axis reflecting telescope system that uses three mirrors. Optical mirrors in the LAF-TMS share the focus instead of the axis, to get rid of linear astigmatism which only appears at the off-axis systems, and the high-order aberration is reduced by applying the freeform surface.[4,5] As the total dimension of the LAF-TMS is compact, it is suitable for the optical system requiring a small space such as satellites

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or Unmanned Aerial Vehicles. The system is free of obstruction effects that appear in conventional on-axis reflecting system[6] and is not limited in the selection of the lens materials in infrared observation.

In our previous studies, we applied the LAF-TMS on two telescopes. The first is the limb-telescope of the Mesospheric Airglow/Aerosol Tomography Spectroscopy (MATS) satellite, which observes noctilucent clouds and atmospheric band dayglow/nightglow in ultraviolet and infrared wavelength band with 35 mm Entrance Pupil Diameter (EPD) and a field of view of 5.67° × 0.91°[7]. The second is the LAF-TMS D150, which is a prototype telescope for a wide FoV infrared satellites targeting all-sky surveys with a 150 mm EPD, a focal ratio of 3.3, and FoV of 5.51° × 4.13°.[8]

Here we introduce LAF-TMS D70F1.4 targeting wide FoV observation in mid-wavelength infrared (MWIR, 3-5 μm) and long-wavelength infrared (LWIR, 8-12 μm) band. The system has an EPD of 70 mm and a focal ratio of 1.4. As a feasibility study, sensitivity study and Monte-Carlo simulation for tolerance analysis were performed. The sensitivity analysis is an important step in finding out what is the most sensitive parameter of the telescope system through the Monte-Carlo simulation, and we found the tolerance range budget satisfying a required performance.[8]

In this paper, we discuss the sensitivities and system tolerance from the results of the sensitivity analysis and the Monte-Carlo simulation of the LAF-TMS D70F1.4. Section 2 introduces the optical design and characteristics of the LAF-TMS D70F1.4. Section 3 describes the definitions of parameters used in the tolerance analysis. Section 4 shows the result of the sensitivity analysis and explores the relatively sensitive parameters. Section 5 checks the tolerance range budget and confirms the feasibility of the system. Finally, section 6 summarizes and concludes the tolerance analysis results.

2. OPTICAL DESIGN

The LAF-TMS D70F1.4 is designed with the LAF-TMS configuration to achieve wide FoV observation in MWIR and LWIR bands. The system is designed for wavelength 10 μm and three mirrors of the system were optimized with freeform surfaces to remove high-order aberration such as coma and astigmatism, and each mirror has a y-axis symmetry surface. Figure 1 shows that the LAF-TMS D70F1.4 satisfies the optical performance that the spot diagrams are smaller than the Airy disk in all fields.

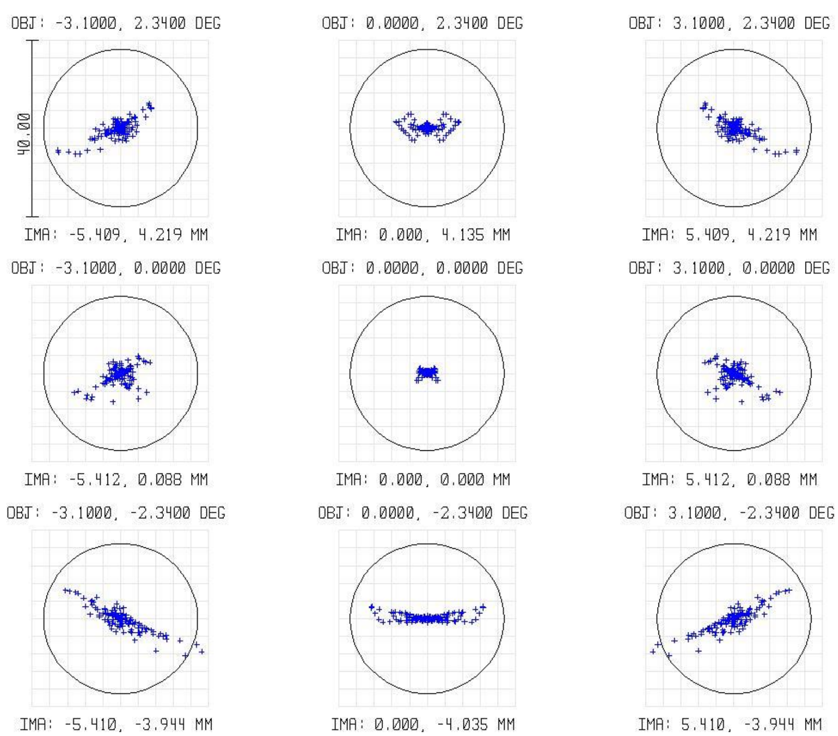

Figure 1. Spot diagram of 9 field angles. Airy disks for 10 μm wavelength are shown as black circles. All the diagrams appear in y-axis symmetry.

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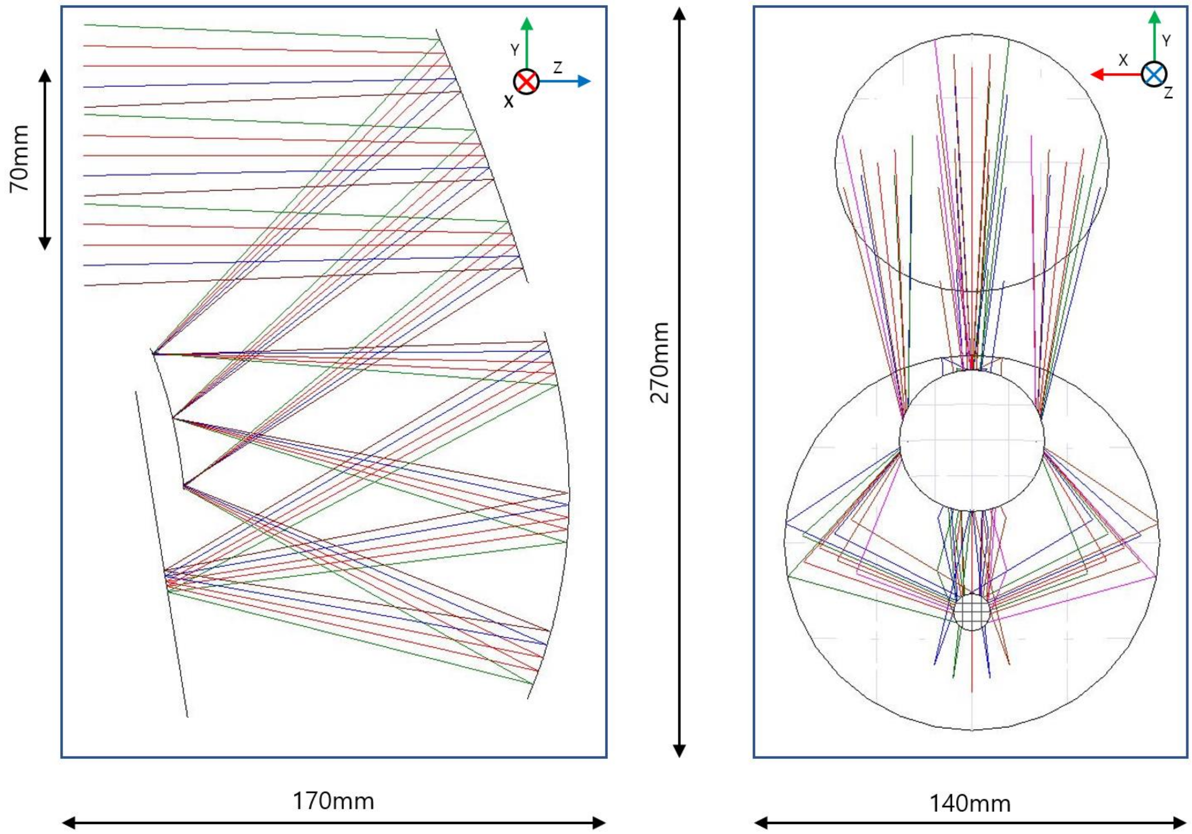

Figure 2. LAF-TMS D70F1.4 optical design. It has a dimension of 270 (L) × 170 (W) × 140 (H) mm, entrance pupil diameter of 70 mm, focal ratio of 1.4, and FoV of 6.20° × 4.68°. Mirrors have freeform surfaces to eliminate high-order aberrations.

A sketch of the LAF-TMS D70F1.4 is shown in Figure 2. The system has the entrance pupil diameter of 70 mm, the focal length of 100 mm, focal ratio of 1.4, wide FoV of 6.20° × 4.68°, and the system size of 270 (L) x 170 (W) x 140 (H) mm, allowing spacial advantage while considering fast focal ratio. Diameters of the mirrors are about 100 mm, 50 mm, and 140 mm for primary (M1), secondary (M2), and tertiary (M3) mirrors, respectively. A target sensor is DB640-17C-A (microbolometer) with a pixel size of 17 μm, an array of 640 × 480, and a sensor size of 10.9 × 8.20 mm. Table 1 summarizes the specifications of the LAF-TMS D70F1.4 and the microbolometer.

Table 1. Specifications of the LAF-TMS D70F1.4 and the sensor.

Type	**Specification**	**Type**	**Specification**	**Type**	**Specification**
Entrance pupil diameter	70 mm	Sensor type	microbolometer	Sensor array	640 × 480
Focal ratio	1.4	Sensor pixel size	17 μm	Total dimension	270(L) × 170(W) × 140(H) mm
Field of View	6.20° × 4.68°	Sensor size	10.9 × 8.2 mm	Reference Wavelength	10 μm

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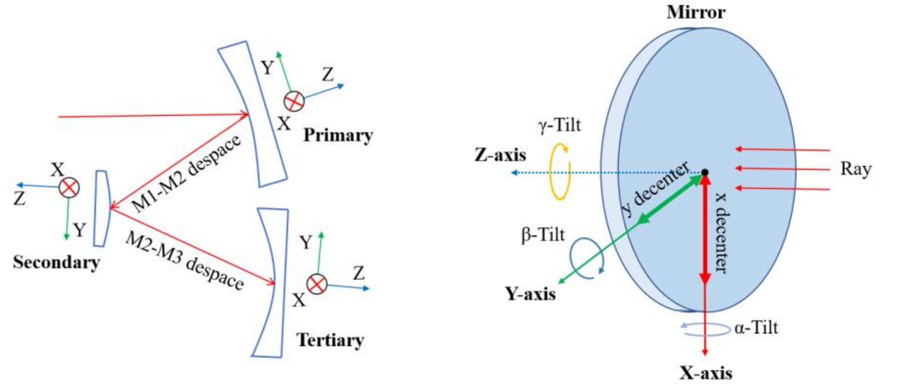
3. PARAMETER DEFINITION

In the sensitivity analysis and the Monte-Carlo simulation, 21 parameters were used: tilt (α, β, γ), decenter (x, y), surface Root Mean Square (RMS) error for the three mirrors, and despace (M1-M2, M2-M3). Figure 3 illustrates the system coordinates and tolerance parameters. A local coordinate system of each mirror was defined by determining the normal direction of the mirrors as -Z-axis direction. α- and β-tilts are defined with left-handed rotations on the +X and +Y axes, respectively. The right-handed rotation on the +z axis represents γ-tilt.



(a) Despace and local coordinates of mirrors (b) Tilt and Decenter and local coordinate of the mirror

Figure 3. Local coordinate systems in which the Z-axis is parallel to the normal direction of the mirror. (a) shows despace and the local coordinates of the mirrors. (b) shows tilt and decenter with the local coordinate. Each surface has its own local right-handed coordinate system.

A tool for the sensitivity analysis is CODE V and the performance criterion is 80% Encircled Energy Diameter (EED). The Monte-Carlo simulation was performed via OpticsStudio and the criterion was the RMS spot diameter. For analysis of the entire fields, we performed the sensitivity analysis over 5 field angles (F1: [-3.10°, -2.34°], F2: [-1.55°, -1.17°], F3: [0.00°, 0.00°], F4: [1.55°, 1.17°], and F5: [3.10°, 2.34°]) and averaged the results to get the final results. The reference wavelength of the analysis is 10 µm.

For the surface RMS error, we generated XY polynomial patterns by considering aberrations that could appear due to the mirror fabrication. The target pattern was oblique astigmatism which is one of the Zernike polynomial patterns. Figure 4 shows the target pattern, and the 4th term of extended XY polynomial and oblique astigmatism term of Zernike polynomial are listed below:[9]

$$\mathrm{S}(\mathrm{x},\mathrm{y}) = axy \tag{1}$$

$$\mathrm{S}(r,\theta) = ar^2 sin\theta cos\theta = \frac{a}{2} r^2 sin2\theta \tag{2}$$

$$Z_2^{-2}(r,\theta) = \sqrt{6} r^2 sin2\theta. \tag{3}$$

The equations (1) and (2) are the 4th term of XY extended polynomial of cartesian coordinate and spherical coordinate. The equation (3) is oblique astigmatism term of Zernike polynomial. The equation (2) and (3) have the same pattern and we used the equation (1) to insert the oblique astigmatism pattern of Zernike polynomial into the CODE V.

$$\mathrm{RMS} = \sqrt{\frac{\sum(S(r,\theta))^2}{N}} = \sqrt{\frac{\sum(ar^2 sin\theta cos\theta)^2}{N}} \tag{4}$$

Equation (4) is an RMS of the pattern and it is directly proportional to the coefficient. By changing the coefficient, error surfaces with the desired RMS were generated. Since real fabricated surfaces include various error patterns besides oblique astigmatism pattern, the tolerance result of surface RMS error is evaluated slightly broader than the actual.

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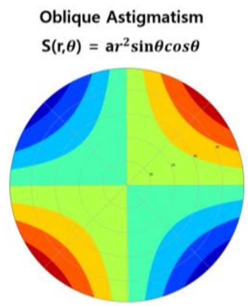

Figure 4. Oblique astigmatic Zernike polynomial pattern was used as a target surface pattern representing a mirror manufacturing error.

4. SENSITIVITY ANALYSIS

During the sensitivity analysis, we investigated the optical performance change by single parameter perturbation and checked the sensitivities of parameters. All increment ranges were set based on general fabrication or alignment tolerances that are about ±10 arcmin, ±1.0 mm, ±1.0 mm, and 0.8 µm for tilt, decenter, despace, and surface RMS error respectively. The parameters were changed by independently incrementing tolerances. The increments are 1.0 arcmin for tilt (α, β, γ), and 0.1 mm for decenter (x, y) and despace (M1-M2, M2-M3). Surface RMS error has an increment of 0.02 µm for a range of 0.0 to 0.1 µm and 0.1 µm for a range of 0.1 to 0.8 µm.

According to the result shown in Figure 5, α-, β-tilt of M3, and decenter of M2 and M3 are the relatively sensitive parameter of the system. The α-, β-tilt are more sensitive than γ-tilt and despace is more insensitive than decenter on all mirrors. Surface RMS errors of the mirrors have a similar sensitivity level. A dashed line indicates 34 µm what is the Nyquist sampling requirement of the sensor. Since all parameters show similar symmetric results for both signs, Figure 5 shows only the result of a slightly more sensitive direction.

M1 satisfied its required 80% EED within a range of 9.5 arcmin tilt and over 1.0 mm decenter. M2 also satisfied the required 80% EED within a range of 4.1 arcmin tilt and 0.1 mm decenter. M3 reached the requirement at a point of 1.3 arcmin tilt and 0.09 mm decenter. Specifically, the despace of M1-M2 hardly affected the performance within a range of 1 mm. The despace of M2-M3 satisfied the required performance within a range of 0.82 mm tolerance. The surface RMS errors of the mirrors met the required performance limit at 0.35 µm. The sensitivity of a single element shown in Table 2 can be satisfied with the general manufacturing tolerance and alignment tolerance level.

Table 2. The sensitivity analysis result. The tolerance limit shows the maximum value that satisfies the requirement.

Type	Tolerance Limit	Type	Tolerance Limit
M1 α tilt	±9.4′	M1 x decenter	Larger than ±1.0 mm
M1 β tilt	±9.9′	M1 y decenter	Larger than ±1.0 mm
M1 γ tilt	Larger than ±10′	M2 x decenter	±0.10 mm
M2 α tilt	±4.1′	M2 y decenter	±0.11 mm
M2 β tilt	±4.6′	M3 x decenter	±0.09 mm
M2 γ tilt	±5.7′	M3 y decenter	±0.10 mm
M3 α tilt	±1.3′	M1 surface RMS error	0.42 µm
M3 β tilt	±1.3′	M2 surface RMS error	0.35 µm
M3 γ tilt	Larger than ±10′	M3 surface RMS error	0.37 µm
M1-M2 despace	Larger than ±1.0 mm	M2-M3 despace	±0.82 mm

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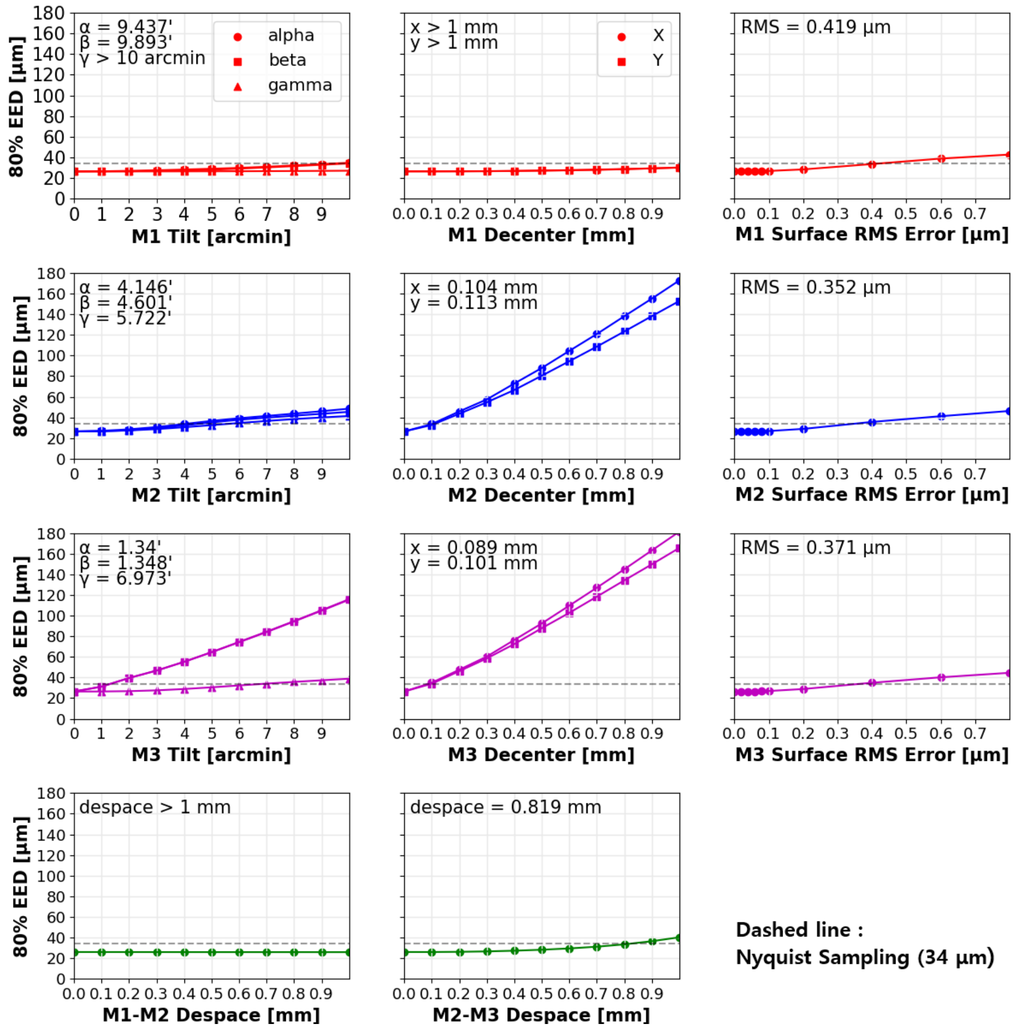

Figure 5. The sensitivity analysis result shows 80% EED changes by single parameter perturbation. The decenter of M2, M3, and the tilt of M3 is more sensitive than M1 and despaces. Nyquist sampling (34 μm) is shown as a dashed line. Left-up side values mean the maximum tolerance satisfying the requirement.

5. MONTE-CARLO SIMULATION

In the Monte-Carlo simulation, we investigated the tolerance range limit that satisfies the required performance. 5000 Monte-Carlo trials were performed with combinations of tilt, decenter, and despace tolerances within defined ranges. The probability of tolerance value followed the normal distribution and the surface RMS error was a constant value.

The defined tolerance range was set considering the sensitivities, manufacturing tolerance, and optomechanical design. Based on the optomechanical design of the former LAF-TMS setting, about 0.017 mm precision manufacturing level is required for 1 arcmin change of the mirrors. However, the manufacturing error level we considered is 0.05 mm which allows the minimum tilt as ±3 arcmin. We set the focus as a compensator, and the same type tolerances were common for the mirrors. According to the sensitivity analysis, the surface RMS error was set as 0.2 um for all mirrors during the Monte-Carlo simulation. Figure 6 shows the frequency of cases and RMS spot diameter at 90% accumulative point obtained from 5000 repetitions. A histogram represents the number of cases that have the same spot diameter and a red dashed line indicates an RMS spot diameter at 90% cumulative point. A blue solid line shows the cumulative line of the cases.

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According to the Monte-Carlo simulation result, the tolerance range budget is ±4.3 arcmin for tilt and ±0.10 mm for decenter and despace. The tolerance range shown in Table 3 is satisfied with the general manufacturing tolerance level. The result of the tolerance analysis confirms the feasibility of the LAF-TMS D70F1.4.

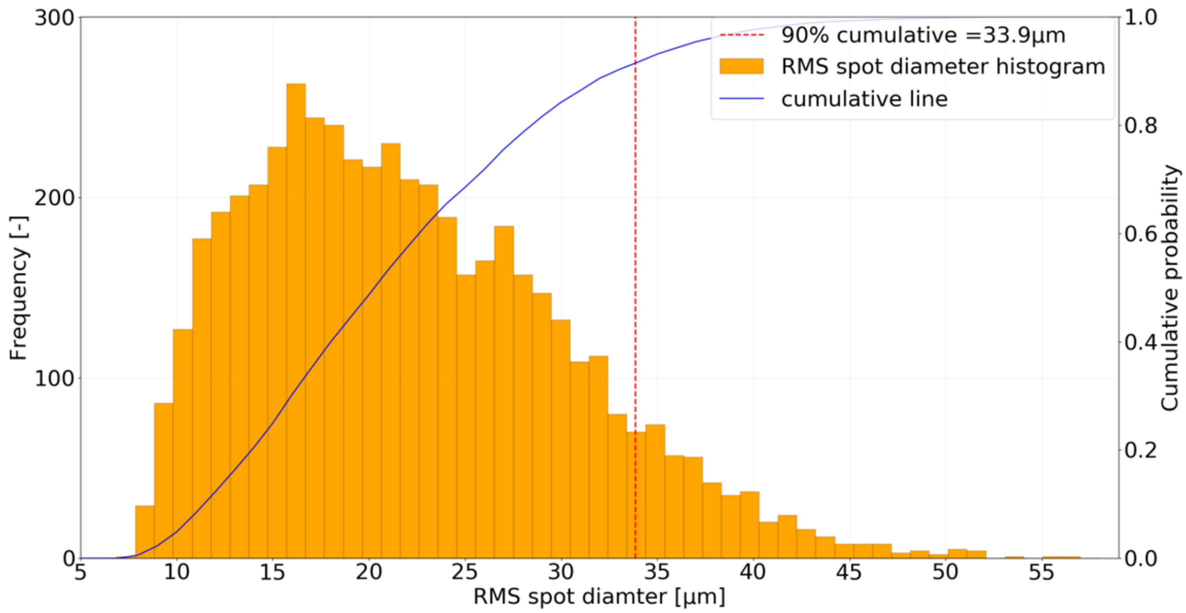

Figure 6. The Monte-Carlo Simulation result. The Blue solid line indicates a cumulative curve. The orange histogram represents a frequency of cases. The 90% cumulative RMS spot diameter is 33.9 μm and is shown as the red dashed line.

Table 3. The Monte-Carlo Simulation tolerance ranges. The surface RMS error is a constant as 0.2 um. The focus is compensator and all the tolerance is common for mirrors.

Type	Tilt	Decenter	Despace	Surface RMS error	Focus	90% cumulative
Range	± 4.30′	± 0.10 mm	± 0.10 mm	0.20 μm	± 1.0 mm	33.9 μm

6. SUMMARY AND DISCUSSION

The LAF-TMS is an obscuration-free confocal off-axis system that eliminates linear astigmatism, which is the most critical aberration in the common off-axis system. Therefore, the LAF-TMS can achieve a high-quality image over the wide FoV.

We developed the LAF-TMS D70F1.4 for the wide FoV telescope in MWIR and LWIR wavelength band. The telescope has the EPD of 70 mm, focal ratio of 1.4, FoV of 6.20° × 4.68°, and pixel scale of 35″/pixel. The mirrors are optimized with the freeform surface to reduce the high-order aberrations.

To confirm the manufacturing feasibility of the telescope, we performed the sensitivity analysis and the Monte-Carlo simulation. In the two methods, we used 21 parameters: tilt (α, β, γ), decenter (x, y), surface Root Mean Square (RMS) error for the three mirrors, and despace (M1-M2, M2-M3).

The sensitivity analysis was performed via CODE V and we checked the 80% EED degradation by single parameter changes. Also, the Monte-Carlo simulation was performed via OpticsStudio and we investigate a tolerance range budget with RMS spot diameter.

According to the sensitivity analysis tilt of M3 and decenter of M2 and M3 are relatively sensitive than other parameters. The Monte-Carlo simulation result shows that the tolerance range budget is ±4.3 arcmin for tilt, ±0.10 mm for decenter

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and despace, and ± 0.20 μm for Surface RMS error. The tolerance analysis results represent that the LAF-TMS D70F1.4 has enough tolerance budgets for the fabrication and alignment of the system.

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