

# International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

*Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny*



## *The design and assembly of a long-focal-length telescope with aluminum mirrors*

*Shenq-Tsong Chang*

*Yu-Chuan Lin*

*Chun-Chieh Lien*

*Ting-Ming Huang*

*et al.*



## The design and assembly of a long-focal-length telescope with aluminum mirrors

Shenq-Tsong Chang<sup>a</sup>, Yu-Chuan Lin<sup>a</sup>, Chun-Chieh Lien<sup>a</sup>, Ting-Ming Huang<sup>a\*</sup>, Ho-Lin Tsay<sup>a</sup>,  
Jiun-Jih Miao<sup>b</sup>

<sup>a</sup>Instrument Technology Research Center, National Applied Research Laboratories,  
20 R&D Road VI, Hsinchu Science Park, Hsinchu 300, Taiwan

<sup>b</sup>Department of Aeronautics and Astronautics, National Cheng Kung University,  
1 University Road, Tainan City 701, Taiwan

### ABSTRACT

Three-mirror-anastigmat (TMA) telescopes have been widely used in long-focal length payloads especially in space due to its excellent features for correcting aberrations, wide spectral range and shorter physical requirement. This paper describes the assembly results of the telescope that may be used in the payload of Formosat-5 follow-on mission. The telescope was a pathfinding one that was designed according to the target specifications of National Space Organization. Optical design is of Korsch type with three mirrors in the system, which is different from that in Formosat-5 RSI. Mechanical design and assembly procedures require modification from those of Formosat-5 accordingly. focal length of the telescope was 7714 mm and F-number 14. Diamond-turned aluminum mirrors were adopted due to time and budget constraint. Barrel was selected as structure configuration between primary and secondary mirrors, while struts were designed to support the tertiary mirror. A main plate was used to connect the barrel and struts. Analysis of the structure has been performed.

**Keywords:** Times Roman, image area, acronyms, references

### 1. INTRODUCTION

It is always a demanding request to acquire better ground-sampling-distance (GSD) images for earth observation satellites. As a result, a long-focal-length telescope is required accordingly to have better GSD images. On the other hand, there is size constraint for such long-focal-length telescope especially in space projects. Three-mirror-anastigmat (TMA) was proven to have excellent features of correcting aberrations, wide spectral range and shorter physical requirement [1-3]. TMA telescopes become more and more attractive and have been applied in space projects [4-8].

Formosat-5, launched in 2017, equipped with a Remote Sensing Imager (RSI) with ground sampling distance (GSD) of 2 m for panchromatic band. RSI is a Cassegrain telescope with diameter of 450 mm and F-number of 8. To scale up this telescope to a much better GSD leads to a very large telescope. Different type of optical design is required to meet the goal. A pathfinding project has therefore been raised to build a Korsch TMA telescope. This project is mainly for establish a heritage design and assembly procedure for future projects.

The optical layout is depicted in Fig. 1. The focal length was calculated as 7714 mm and F-number as 14 [9]. Aperture stop locates at the primary mirror (M1) with clear aperture of 550 mm. Symmetric central obscuration was selected in purpose to be 130 mm. Clear apertures for secondary (M2) and tertiary mirrors (M3) were 150 mm and 186 mm x 86 mm, separately. Field of view (FOV) was 1.0 degree, i.e. swath width is 12.56 km when the altitude is 720 km. Target GSD was 0.7 m. Tolerance analysis has been performed and requirements have been given to each optical component. It was found that M3 was roughly one order of magnitude less sensitive than that for M2. Obscuration of M1 located at several mm above the center with rectangular shape due to the focal plane geometry. Straylight analysis has been performed, and preliminary baffle design was obtained accordingly. The configuration for the baffle was designed as circular one at the end near primary mirror, while at the entrance end as rectangular one.

\*tmw@itrc.narl.org.tw; phone 886 3 577-9911; fax 886 3 577-3947; www.itrc.narl.org.tw

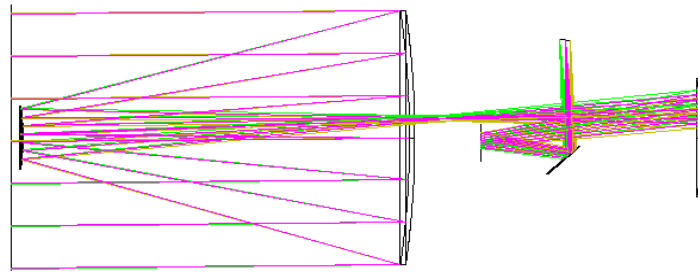


Figure 1. The optical layout of TMA telescope.

Diamond-turned aluminum mirrors were selected from the beginning due to project time constraint [9]. A carbon fiber reinforced polymer (CFRP) barrel was designed between primary and secondary mirrors, as shown in Fig. 2. Supporting vanes inside the barrel were designed to increase the stiffness. Primary mirror was supported by three flexures that attached to an aluminum main plate. Three spiders were designed to support the secondary mirror set. Baffle was attached to main plate was arranged to suppress stray light. Tertiary mirror was linked to main plate by truss. As shown in Fig. 1, two folding mirrors were arranged to allocate the focal plane. While first folding mirror (M4) was set at the main plate, second folding mirror was supported by another truss structure. Coordinate system was also illustrated in Fig. 2.

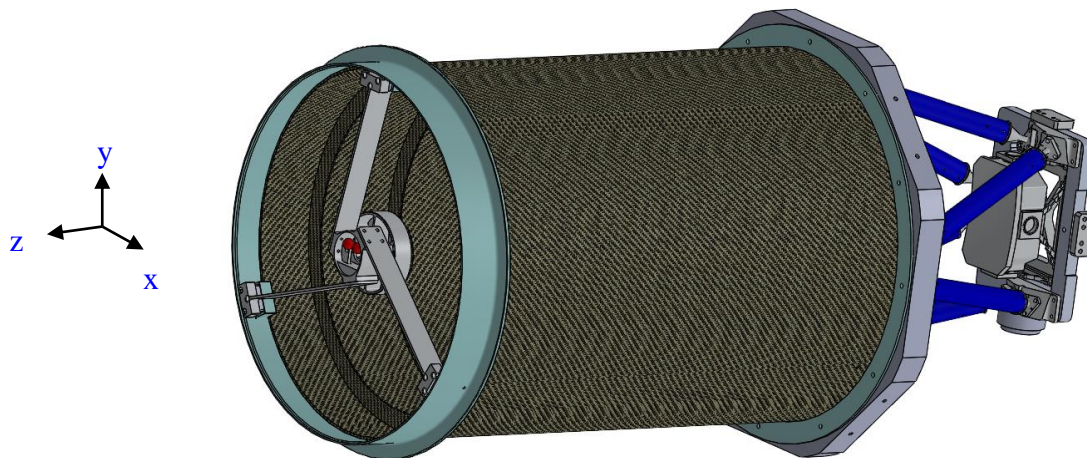


Figure 2. mechanical design of the TMA telescope.

## 2. THE ASSEMBLY AND TEST

### 2.1 Assembly of Primary and Secondary Mirrors

Coordinate measurement machine (CMM) was the main facility applied during the component inspection and first assembly stage. The nominal absolute accuracy of position measurement CMM was reported  $\pm(2+L/1000)$   $\mu\text{m}$  where L is the measurement range in mm. However, local relative accuracy measurement was performed and found to be within 0.4  $\mu\text{m}$  comparing with Panasonic UA3P system. An in-house procedure has been developed to measure the profiles and contours of mirrors. Peak-to-valley (pv) and root-mean-square (rms) deviation relative to the designed profile were reported. Rms deviations were found in the order of 7  $\mu\text{m}$  for three mirrors. Flexure mounting were glued on the neutral planes of primary and tertiary mirrors respectively. The in-house procedure can also measure the position and optical axis of mirrors through the CMM data.

The goal of the alignment is to keep the decenter of secondary mirror (M2) relative to primary mirror (M1) within  $\pm 10 \mu\text{m}$  and tilt within  $\pm 10$  arc-seconds. First step of the assembly is to align M1 and main plate such that the position accuracy of optical axis of M1 was within  $\pm 10 \mu\text{m}$  and the tilt within  $\pm 5$  arc-minutes. The in-house procedure for measuring the apex and optical axis direction includes applying commercial optical software and the measurement data

of optical surface. Since all the measurement was performed in the same machine, positions and altitude of alignment targets can be determined. The assembly result of M1 and main plate is such that decenter of M1 relative to main plate is that (2, -3)  $\mu\text{m}$  and tilt is (2.2, 2.7) arc-minutes in (x, y) directions. The knowledge of the positions was found in the order ten  $\mu\text{m}$  and pointing of optical axes were of order of several tens arc-seconds. Left-hand side of Fig. 1 shows the gluing result of primary mirror with respect to main plate.

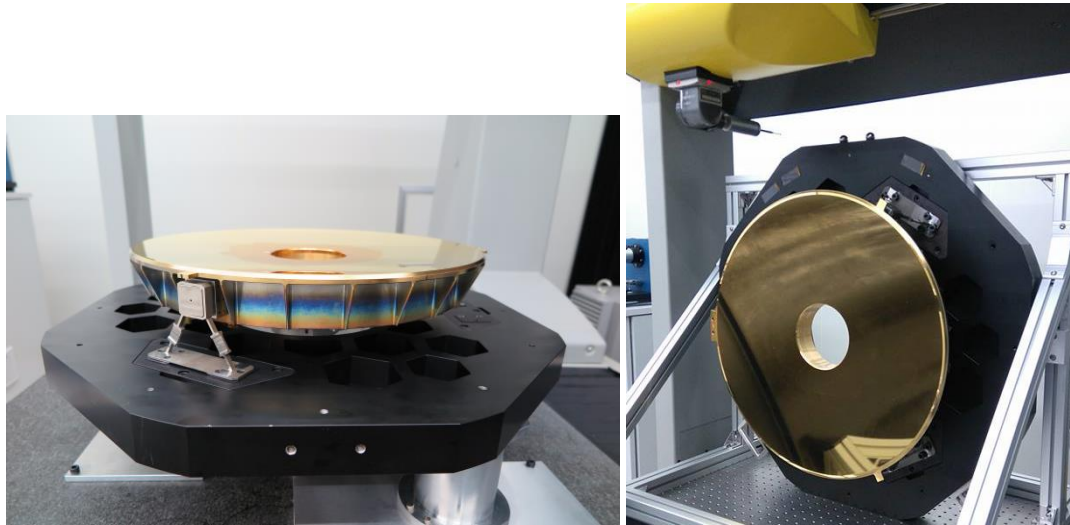


Figure 3. Assembly of primary mirror (left) and M1 sub-assembly (right)

Due to the existence of barrel, there is no chance for the CMM to measure the surfaces of mirrors during alignment. Coordinate transfer needs to be performed before assembly of CFRP barrel. The consideration was that measurement shall be implemented to the points that can be reached rather than mirror surface during the alignment. Right-hand side of Fig. 1 shows the M1+main-plate sub-assembly under measurement. The measurement results are listed in Table 1. The new coordinate is named as ‘M1 represent’ and was found about (33.2, -393.9, 96.4) mm with respect to M1 apex and tilt values can be found in Table 1. The same procedure was applied to M2, and ‘M2 represent’ was found about (-14.6, 15.1, 89.8) mm with respect to M2. M2 represent was illustrated as two red spheres in Fig. 5.

Table 1 Results of coordinate transfer

	‘M1 represent’ w.r.t. M1	‘M2 represent’ w.r.t. M2
Offset-x (mm)	33.226	-14.569
Offset-y (mm)	-393.909	15.074
Offset-z (mm)	96.384	89.813
Rotate-x (deg)	-0.0016	-30.7935
Rotate-y (deg)	-0.0027	0.00896
Rotate-z (deg)	-	-0.1273

After the alignment of barrel, spiders were assembled inside the barrel. M2 has been assembled to spiders before spider assembly. M1 represent and M2 represent were measured instead of mirror surfaces. M2 position and altitude with respect to M1 were measured. Barrel was adjusted by suitable shims attached to main plate such that M2 locates inside the adjustable range. M2 tilt was adjusted through changing thickness of shims attaching to the spiders in optical axis. The directional cosine of M2 with respect to M1 was found as (0.0000401, -0.0000182, 1) in (x, y, z) direction respectively. After tilt alignment, decenter of M2 was measured and aligned by two special designed jigs that attached to spiders. The advantage for the jigs was that the altitude can be hold and measured simultaneously. The decenter of M2 can be adjusted with the aid of the jigs. The final decenter result was (-3.6, 6.7, 2.8)  $\mu\text{m}$  in (x, y, z) directions. Figure 4 illustrates the condition when M1 represent and M2 represent were measured.



Figure 4. Alignment of M2 with respect to M1

## 2.2 Assembly of baffle

Geometry of baffle was measured by CMM after the gluing of CFRP baffle and aluminum flange. The perpendicularity of the baffle and flange was found as 89.902 degrees. Shims were placed at the aluminum flange and main plate to control the position of baffle entrance. After the assembly, the error was estimated as shown in Fig. 5, where the smooth surface was the real baffle and the mesh-grey surface the designed one. It was found the entrance of baffle was manufactured larger than design value. Decision has been made that alignment margin at -x side is large while at +x side near zero after ray tracing. The alignment margins at +y and -y sides were set nearly the same.

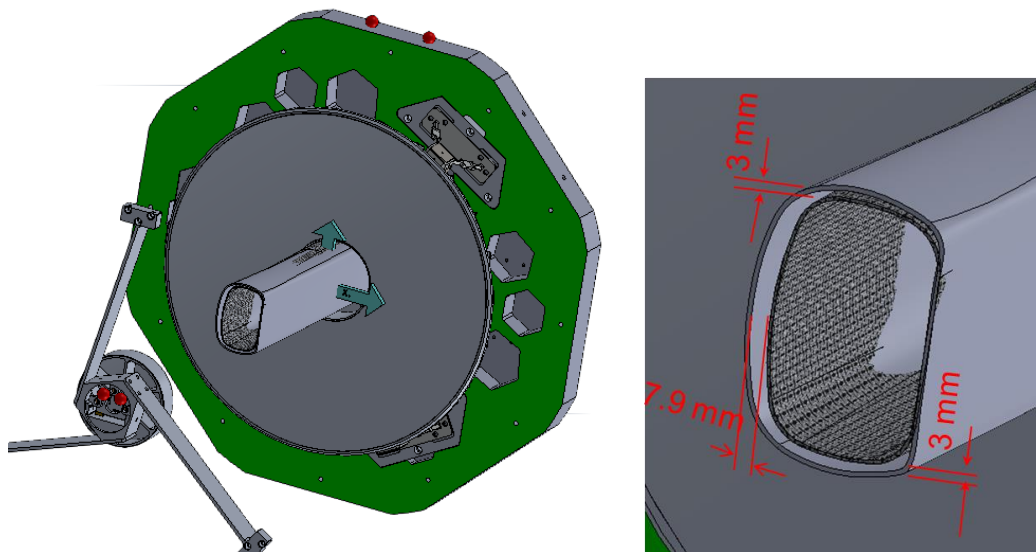


Figure 5. Assembly result of baffle

M4 and M5 were also aligned before aligning tertiary mirror. M4 was aligned such that the deviation with respect to the optical axis was 0.016 degrees and position deviation 0.15 mm. All were within the tolerance margins. M5 and supporting truss were also aligned afterwards.

## 2.3 Assembly of Tertiary Mirror

Struts were designed to connect the main plate the tertiary mirror. Due to the constraint of CMM machine, whole M1-M2 assembly was shifted to a position such that M 1 represent and M3 represent can be measured as shown in Fig. 6. The alignment shows that direction cosine vales of tilt in (x, y, z) directions were (0.0000797, -0.0000123, 1) and the decenter in (x, y, z) directions were (7.1, -22.4, 4.6)  $\mu\text{m}$ .

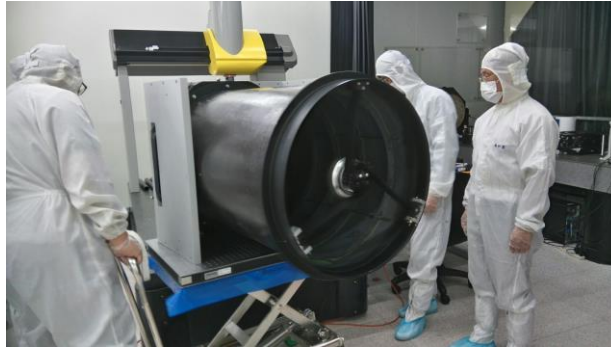


Figure 6. Assembly of Tertiary Mirror

## 2.4 Test

Focal length of the telescope was measured by  $f = \tan \theta$  method. Theodolites were arranged to measure the angle difference of target at the focal plane. Best focal position has been determined by the way described in ISO 11421:1997. The focal length was determined as 7725 mm while the design value was 7714 mm. Since the surface profiles were of order of  $7 \mu\text{m}$ , interferometry measurement was skipped. Images were also taken outdoors as shown Fig. 7. On the left-hand side of Fig 7 was the image taken by Canon 550D with a focal-length 500 mm lens, while right-hand side taken by TMA with Sony A-6 II camera and some focal shift from long-distance imaging.



Figure 7. Imaging test of TMA telescope

## 3. CONCLUSION

The assembly results of the Korsch TMA telescope that may be used in the payload of Formosat-5 follow-on mission were reported. Assembly procedures were reported. The alignment of M1 and M2 of a TMA telescope has been discussed and the status of alignment of secondary mirror with respect to primary one. The alignment result of M2 with respect to M1 was found that decenter is  $(-3.6, 6.7, 2.8) \mu\text{m}$  and direction cosines  $(0.0000401, -0.0000182, 1)$ . Alignment results for M3 with respect M1 were found that direction cosine values of tilt in  $(x, y, z)$  directions were  $(0.0000797, -0.0000123, 1)$  and the decenter in  $(x, y, z)$  directions were  $(7.1, -22.4, 4.6) \mu\text{m}$ . The result was within the alignment tolerance. The focal length was determined as 7725 mm, 0.1% deviated from design value. Images were taken to test the performance of the telescope.

## REFERENCES

- [1] R. N. Wilson, *Reflecting Telescope Optics I*, 2<sup>nd</sup> ed., Berlin: Springer-Verlag, pp. 223-238, 2007.
- [2] L. G. Cook, "Wide field of view three-mirror anastigmat (TMA) employing spherical secondary and tertiary mirrors," Proc. SPIE vol. 766, pp. 158-162, 1987.
- [3] J. U. Lee and S. M. Yu, "Analytic design procedure of three-mirror telescope corrected for spherical aberration, coma, astigmatism, and Petzval field curvature" *Journal of the Optical Society of Korea*, vol. 13, pp. 184-192, 2009.
- [4] H. J. Kramer, *Observation of the earth and its environment*, 3<sup>rd</sup> ed., Berlin: Springer-Verlag, 1996.
- [5] J. P. Gardner et al., "The James Webb space Telescope," *Space Science Reviews* vol. 123, pp. 485-606, 2006.
- [6] P. A. Lightsey, C. Atkinson, M. Clampin, L. D. Feinberg, "James Webb Space Telescope: large deployable cryogenic telescope in space," *Optical Engineering* 51(1), 011003, 2012.
- [7] Vincent Costes, Guillaume Cassar, Laurent Escarrat, and Sophia Conseil, "Optical design of a compact telescope for the next generation earth observation system," International Conference on Space Optics (ICSO), 2012.
- [8] M. Lampton and M. Sholl, "Comparison of On-Axis Three-Mirror-Anastigmat Telescopes," Proc. SPIE vol. 6687, 2007.
- [9] Shenq-Tsong Chang, Yu-Chuan Lin, Kun-Huan Wu, Chun-Chieh Lien, Ting-Ming Huang, Ho-Lin Tsay, Chia-Yen Chan, "The design and assembly of aluminum mirrors of a three-mirror-anastigmat telescope," International Conference on Space Optics (ICSO 2016), Biarritz, France, October 2016.