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## *Design and test of a high performance off-axis TMA telescope*

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# Design and Test of a High Performance Off-axis TMA Telescope

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**Abstract**—A new complete Optical Demonstration Model (ODM) of high performance off-axis Three Mirror Anastigmatic (TMA) telescope has been successfully developed in BISME. This 1.75-m focal length, 1/9 relative aperture,  $6.2^\circ \times 1.0^\circ$  field of view visible telescope, which uses the TDICCD detectors of  $7\mu\text{m}$  pixel size, can provide 2.0-m ground sampling distance and 51-km swath from an altitude of 500 km. With some significant efforts, the main goals of the ODM have been reached: a compact light-weight design while realizing high performance and high stability. The optical system and key technologies have been applied in the multispectral camera of ZY-3 Satellite (the first high resolution stereo mapping satellite of China), which was successfully launched on January 9<sup>th</sup>, 2012. The main technology of ODM was described. The test results and applications were outlined.

**Keywords**—telescope; off-axis; TMA; design; alignment; test

## I. INTRODUCTION

In the field of Earth observations, off-axis Three Mirror Anastigmatic (TMA) system provides a good solution to meet the requirements of high resolution and wide swath simultaneously. But compared with co-axis TMA systems, it faces more challenges in design, measuring and alignment. Studies of the correlative technologies have been developed deeply by BISME. A complete Optical Demonstration Model (ODM) (comprising mirrors, structure, baffling and a focal plane simulator) of the off-axis TMA telescope with both wide field of view (FOV) and high resolution has been built and tested at BISME. Its main objectives are:

- To show the feasibility of the telescope.
- To seek the technological solutions for good image quality, high stability and low mass, based on the rules of reducing manufacturing difficulties and simplifying the integration process as much as possible.

As the representative of a flight model with regard to the technologies used, the ODM has been developed to deal with launch and in-orbit constraints. The achievements can easily apply to project products as soon as possible.

## II. TECHNICAL REQUIREMENTS

Technology requirements (such as application goal, orbit, ground sampling distance, pixel size, focal length, FOV, relative aperture) have been discussed time and again. Aiming at demonstration, extremely high performances and huge size will not be sought. The whole time budget, risk management and market demand have been analyzed which leads to the following technical requirements of ODM:

- Imaging mode: push.
- Spectral range: 0.5~0.8 $\mu\text{m}$ .
- Focal length: 1750mm.
- FOV:  $6.0^\circ \times 1.0^\circ$ .
- Relative aperture(F/D): 1/9.
- Pixel size:  $7\mu\text{m}$  (panchromatic spectrum).
- Modulation transfer function (static):  $\text{MTF} \geq 0.37$  (71.4 lp/mm).
- Mass:  $\leq 60\text{kg}$ .

It gives a 51km swath with 2m ground sampling distance (GSD) from an altitude of 500km.

The specified performances impose requirements on the optical and mechanical subassembly. The requirements will insure good stability of the telescope under the different environments (harsh mechanical environment, 0-gravity, vacuum and thermal variations) during its life (on the ground, during launch and in orbit).

## III. TECHNICAL SOLUTIONS

### A. Optical Design

The optical system has chosen the type of off-axis TMA system which evolves from co-axis TMA system. Compared with co-axis TMA system, it has the merits of wide field, unobscured and high quality. Based on the initial structural parameters from co-axis TMA system, the anticipant off-axis TMA system is obtained by means of off-axis and optimization.

Technical difficulties and goals:

- How to achieve wide FOV and achieve (maintain the MTF close to) diffraction limit over the whole FOV?
- How to optimize optical parameters to control distortion which will increase with the FOV?
- A reasonable error budget should be given in order to make mechanical design easier and simplify the alignment process.
- How to optimize and decrease the sensitivity of focal length variation to maintain the stability of the telescope in orbit?
- Realize compact layout to reduce the size and weight of the telescope.

The optical schematic of the telescope is shown in Fig. 1. The solutions of the optical system design include:

- The stop is located at the secondary mirror.
- The primary and the tertiary mirrors are off-axis portions of large parent mirrors.
- Optimize the aperture of the convex aspherical secondary mirror to reduce measuring difficulty.
- The primary, the secondary and the tertiary mirrors have no higher order aspherical coefficients leading to easier measuring.
- The flat mirror is used to reduce the system length.
- The optical system is nearly a telecentric system.
- Reasonable tolerance of optical system provides simplicity for fabrication and alignment.
- Compact and proper layout minimizes the optical volume.
- All mirrors are fabricated from low expansion Zerodur made in Schott to ensure shape stability under longitudinal thermal gradients.

Main mirror characteristics are given in Tab. 1. And results of optical design are shown in Tab. 2.

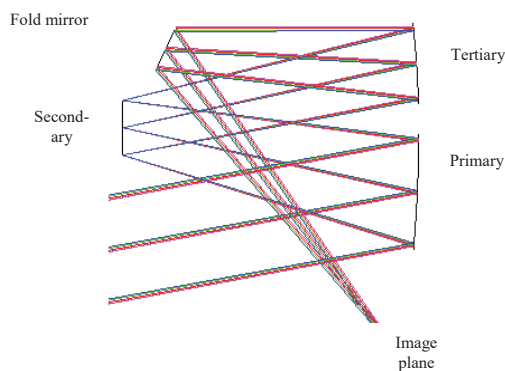


Figure 1. Optical layout

TABLE I. MAIN MIRROR CHARACTERISTICS

Mirror	Surface Shape	Size (mm)	WFE (RMS)
Primary (concave)	2th order Hyperboloid	316×217	0.025λ
Secondary (convex)	2th order Hyperboloid	φ 102	0.02λ
Tertiary (concave)	2th order Ellipsoid	250×150	0.025λ
Flat mirror		217×91	0.03λ

λ=0.63μm

TABLE II. RESULTS OF OPTICAL DESIGN

No.	Parameters	Design Results
1	Focal length(mm)	1750
2	Relative aperture(F/D)	1/9
3	Field of view(°)	6.2×1.0
4	MTF (71.4lp/mm)	0.456
5	Distortion	0.01%

The design result of the optical system is shown MTF is 0.456 in the field of view of 6.2°×1.0°, nearly diffraction limited performance. The relative distortion is 0.01%. The tolerances are not sensitive so that MTF is only reduce 0.01 when mirrors tilt 50μrad or decenter 40μm, the change of the space between mirrors results in little changes on focal length, focal plane position and MTF. Appropriate tolerances reduce the difficulty of mechanical design, fabrication and testing.

### B. Structural Design

The difficulties of structural design:

- How to maintain the surface stability of mirrors to ensure a good image quality?
- The structures of ODM should have minimum weight as well as enough stiffness and stability during ground tests and in space.
- Convenient to assembly and alignment.

The main solutions of structure system design include:

- Four-point ball hinge mount which has the capability of decoupling the Degrees of Freedom (DOF) was used to support the primary mirror, tertiary mirror and fold mirror. Thermal stresses from the unmatched thermal distribution in structures can be filtered while the mounts retain a sufficient high stiffness to withstand launch vibrations. The four-point ball hinge mount for mirrors was shown in Fig. 2.
- The mirrors were made of Zerodur. Thanks to its near zero thermal coefficient, it can keep good thermal stability while existing radial temperature gradient in the mirror. This can reduce the thermal controlling requirements. The invar knots were glued in mounting holes in the back of mirrors. The thermal coefficient of

invar is matched with Zerodur. Supporting structure material is Titanium alloy. Lighting weight ratio of off-axis mirror is over 60%.

- A stable truss structure was chosen for the main structure of telescope, shown in Fig. 3. CFRP, a very light material with extremely low thermal expansion as well as was used to make truss beams. And high volume fraction Sic/Al material which has high stiffness and excellent thermal conductance was used for the front and back frames. With the technologies of topology optimization and finite element analysis, the total weight of the whole structure is 30% less than a normal telescope but has high mechanical and thermal stability.
- The joints between truss beams and frames were designed flexible hinges which can prevent the local moment from transferring to frames. The flexible structures were used to mount the telescope on the magnesia alloy frame of the satellite. By distortions of the flexible blades which acted as filtration elements, the stresses coming from expanding and shrinking of the satellite platform were filtered thus keeping the stability of the optical components and focal plane. According to the test results, while the working temperature of the satellite platform varied between 5°C~35°C and the telescope working temperature remained 20°C, the performance of the telescope had no reduction.

With light-weight materials and a new structure design, the whole telescope (including mirrors, structure, baffles and a focal plane) weighs less than 60kg. The first frequency of the telescope is higher than 120Hz. Working within 20°C~35°C temperature range, the focal plane location remains stable and the maximum reduction of the telescope MTF is less than 0.02 without any focal plane adjustment.

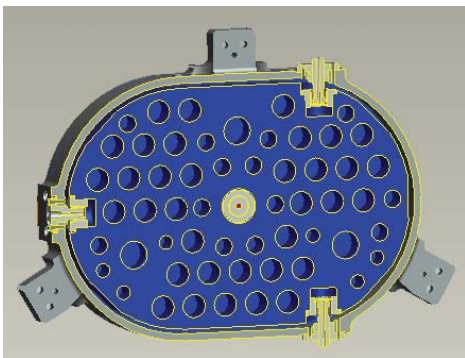


Figure 2. Four-point ball hinge mirror mount

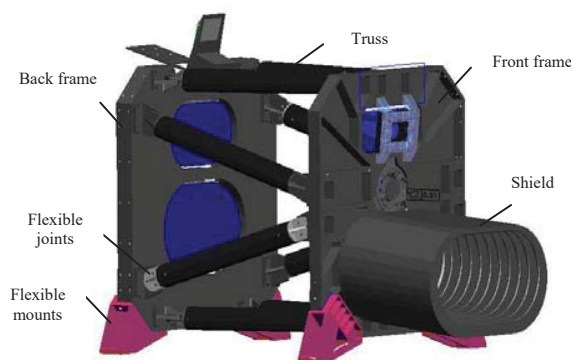


Figure 3. Truss structure of telescope

### C. Mirror Measuring

The difficulties of off-axis aspheric mirror measuring:

- Measuring of non-circular area Zernike coefficient, vertex radius and off-axis quantity.
- Design, manufacture of compensators and calibration of alignment error.

Solutions:

- By acquiring inscribed circle of different fields, we can transform the immeasurable non-circular domain Zernike Coefficients into measurable circular domain Zernike Coefficients.
- Developing multi-section sampling of the mirror with high-precision three-coordinate instrument and partial aperture surface fitting, measurement of key parameters of off-axis mirror was solved.
- With related functions of Metropro software, we have solved precision measurement of off-axis mirror decenter.
- Using high precision plane wave and spherical wave compensator to contrast detecting result. We should rotate compensators around the optical axis to correct the alignment errors.

### D. Optical Alignment

The difficulties of optical system alignment:

- How to connect “the error of design and manufacture” with “the precision of alignment”?
- How to finish the alignment with high performance in a shorter period?
- How to keep the system stability when separating mirrors from the alignment mechanisms and fixed on the frames?

The whole optical alignment consists of three phases: initial alignment, fine alignment, fastened and fixed, alignment results measurement and check.

Initial assembly phase is a primary phase before computer-aided alignment. Obtaining the initial assembly precision depends on optic-mechanical manufacturing precision. The key problem of this phase is how to give appropriate initial assembly precision not only to provide condition for computer-aided alignment but also to reduce manufacture difficulty.

As shown in Fig.4, a self-collimation measurement system for off-axis TMA telescopes has been developed. The given computer assistant alignment method included:

- Aspheric mirrors pre-alignment positioning accuracy control.
- Set up an accurate self-collimated interfering system.
- Errors extracted from the interference figure of off-axis mirrors.
- The adjusting and fastening of multi-degrees and independent mounting structure.

When the optical alignment was almost finished, it was necessary to separate the adjusting mechanisms from the mirror assemblies, and to fasten the joints. At this time, the system state will be easy to vary. We have studied the fasten processes and have found out the know-how to ensure the system stable after separating and fastening.

Measurements of specifications of the telescope included modulation transfer function (MTF), focal length, field of view (FOV) and transmittance. The static MTF in the whole FOV of the telescope was better than 0.41.

#### E. Fabrication

We have solved two problems in fabrication of ODM:

- For off-axis mirrors, we optimized fabricating and measuring process to find ways to finish mirror edge shaping, accurate positioning of mount holes, precise vertex curvature control and off-axis mirror decenter control.

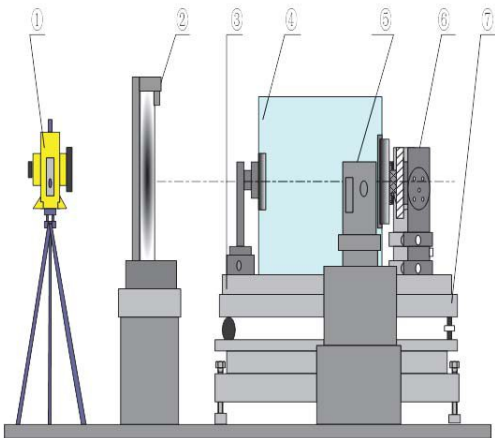


Figure 4. Schematic of self-collimation Interference Measure

1)Theodolite,2)Planar Mirror,3)Flat table,4)Camera,6)Interferometer,7)Multi-degrees Adjustable Structure,8)Two-degrees Adjustable Table.

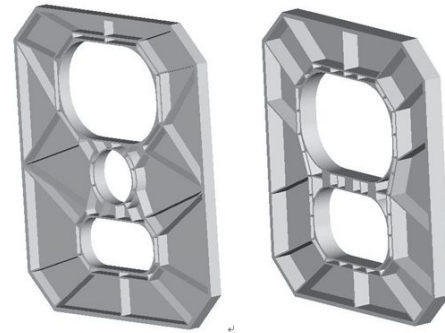


Figure 5. Front and back frame of telescope

- For front and back frames made of high volume fractions Sic/Al (fig.5), we have successfully developed new fabricating processes including pressureless infiltration near net shaping blank making, diamond milling cutter rough machining, ultrasonic electrical discharge machining finishing process, Ultrasonic welding and so on.

#### IV. ENVIRONMENTAL TEST

##### A. Vibration test

To demonstrate stiffness and stability of telescope structure, sinusoidal vibration test and random vibration test on the ODM prototype have been respectively conducted. Before and after tests, the telescope MTF remained stable.

##### B. Thermal test

In vacuum condition, the MTF of the ODM prototype was consistent and focal plane position was stable when the environmental temperature changed between -172°C and 232°C.



Figure 6. Photograph taken by the ODM on ground



### C. Simulation image test

Simulation image test on ODM has been conducted. A taken picture is shown in Fig. 6. The imaging results show good sharpness and rich gradation.

The test results showed that the ODM prototype possessed high stiffness and thermal stability and could meet the mission requirements.

### V. PERFORMANCES VERIFIED IN ORBIT

The optical system and key technologies of the ODM have been applied in the multispectral camera of ZY-3 Satellite (the first high resolution stereo mapping satellite in China), which was successfully launched on January 9<sup>th</sup>, 2012.

From January 11<sup>th</sup>, 2012, ZY-3 satellite began to provide multi-spectral image data. A composite color picture is shown in Fig. 7. It is composite of blue, green and red band.

Performances of the multispectral camera have been measured in orbit. The technologies of off-axis TMA camera has been verified and will have extensive prospects and greatly promote the development of follow up projects.

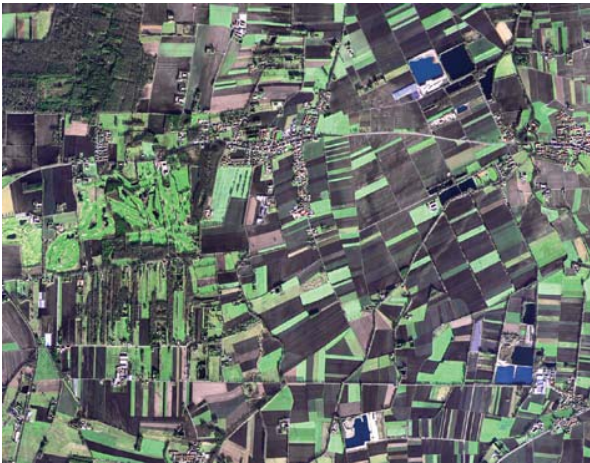


Figure 7. Photograph taken by the multispectral camera of ZY-3 in orbit  
(true color images)

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