Integrated manufacturing technology of off-axis three-mirror anastigmatic system

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Received January 13, 2014; accepted March 15, 2014; posted online October 21, 2014

The integrated manufacturing technology is introduced to improve the imaging quality of an off-axis three-mirror anastigmatic (TMA) system. With the integration of system design, manufacturing of highly precise optical elements, simulation and evaluation capabilities of the manufactured system, and testing and alignment with the same fiducial, we can efficiently and precisely achieve high quality of an optical system. In order to prove the efficiency of this technology, we design an off-axis TMA system with MTF invariance better than 0.50 (57 lp/mm), and manufacture the aspherical surfaces of this optical system with surface figure error better than $\lambda/50$ (RMS, $\lambda = 632.8$ nm). We develop an interface software named MetroMax to achieve the connection between the final surface figure and the optical design software. The MetorMax also forecasts the imaging quality of the system, and guide us in aligning the system with a same fiducial with the whole field of view approached $\lambda/14$ and MTF invariance better than 0.95. To confirm the imaging system after integrated manufacturing, we test the system on the ground and orbit; the result proves effective improvement in the imaging quality of the optical system.

OCIS codes: 120.3940, 120.4630, 120.4800, 240.6700.
doi: 10.3788/COL201412.S21202.

During the progression of space remote sensing technology, higher ground sampling distance (GSD) is required, so, an optical system with large diameter, long focal length, small size and light weight is more crucial. Before determining the technology target of a system, we should guarantee the continuity of the autonomous space remote sensing technology by considering the source of technical reserves, raw material, devices, etc. For an optical remote sensing imaging system, a reflective system has to be used widely because it has advantages of non-chromatic aberration, light weight and enfolding. The reflective system is usually classified into three types: two reflective mirrors system, three reflective mirrors system and four reflective mirrors system. Comparing with two reflective mirrors system, we find that the three reflective mirrors system can balance the aberration easily by adding freedom of the system in optimizing[1–4].

Of the most widely used three reflective mirrors system, off-axis three-mirror anastigmatic (TMA) system does not possess central obscuration, high MTF invariance and wide field of view[5-7]. It has become one of important research orientations in optical system design and fabrication. While the difficulties now encountered with the use of off-axis aspherical surfaces are not symmetric and cannot be fabricated by the general method, we have to solve the figure error of convergence of off-axis aspherical surfaces and test such surfaces[8-10]. In addition, due to the introduction of alignment fiducial to decrease the freedom, a computer has to be used to assist in aligning an off-axis system.

With the increasing demand of the space remote sensing technology, challenges have to be faced not only in the imaging quality and response of an optical remote sensing system but also in the capability of the integrated manufacturing technology. SSG-Tinsley Company also used the technology of aspherical surface manufacturing, testing and alignment. It has manufactured a number of highly precise aspherical surfaces and optical systems, and has become the chief supplier of NASA. Germany Jena-Optronik also used the optical system-integrated manufacturing technology to develop rapid-eye camera. Optical system-integrated manufacturing technology is not only a pure fabrication method, but also a technology that involves the optical system design, fabrication, testing, optical and mechanical structure design, and optical system alignment. Here, we employed the integrated manufacturing technology on off-axis TMA system and achieved rapid integration, response and imaging.

In order to efficiently and precisely achieve high quality of an optical system, we used integrated manufacturing technology with Optics CAD, Optics CAM, Optics CAT and CAA together. The process of this technology Fig. 1 and steps involved are as follows:

- Designing the high-quality off-axis TMA system.
- Fabricating and testing the off-axis mirrors of the system, and using the same fabrication and testing technology to confirm the location of the primary mirror and the tertiary mirror and to improve the precision and efficiency.

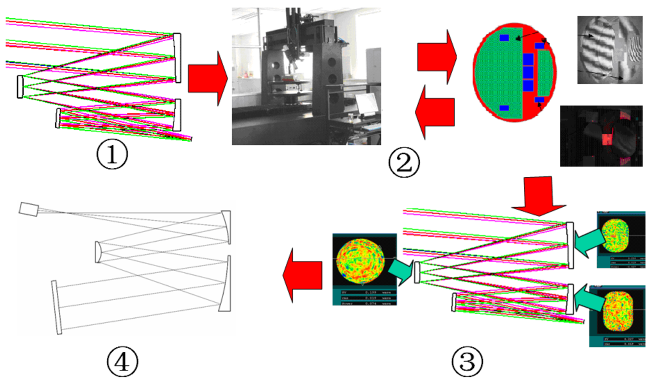

Fig. 1. Technological process of the integrated off-axis TMA system.

- Importing the surface figure error of each mirrors to the simulation software of optical system design, evaluating the imaging quality, and obtaining the optimal solution of the optical system to guide the alignment.
- Aligning the secondary mirror and accomplishing the alignment of the system, and achieving the imaging quality.

In order to meet the requirement of the system target, capacity of the fabrication, testing and alignment, the trend of the space remote sensing, adopting no-blocking off-axis optical system are considered (Fig. 2), which includes three aspherical surfaces: primary mirror, second mirror and tertiary mirror. After establishing the aberration correction model of this complex optical system, the corresponding optimizing function is constructed. The MTF invariance of the system is better than 0.50 (57 lp/mm), and aberration (RMS) of all fields of view is better than 0.02 λ (Fig. 3).

According to the manufacturing criterion of SiC mirror, which is based on small tools and the deconvolution iterative model to make surface figure error convergence

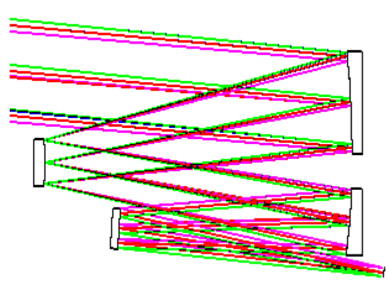

Fig. 2. The structure of COOK-TMA system.

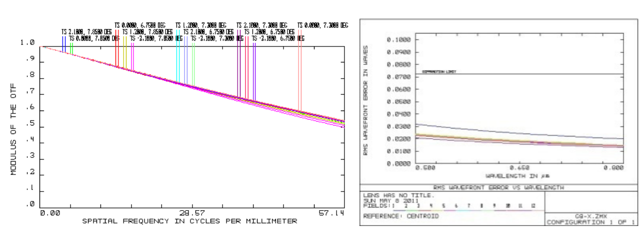

Fig. 3. Result of optical system design.

(Fig. 4), we manufacture off-axis aspherical mirror precisely. The PVD-Si surface coating technique of SiC mirror in low temperature improves the optical surface quality of SiC material by PVD aggradation technology of Si layer. The microcosmic structure of the reflecting mirror is improved and the roughness of the surface is better than 1 nm Ra (Fig. 5). The surface figure error of SiC aspherical mirror after manufacturing is better than $\lambda/50$ as shown in Fig. 6.

As the off-axis aspherical primary and tertiary mirrors have the same optical axis, a special structure has been designed for optical testing and alignment of the primary mirror and tertiary mirror with same fiducial. The platform of testing with same fiducial is shown in Fig. 7. Advantages of this platform are that the locations of the primary mirror and tertiary mirror in the

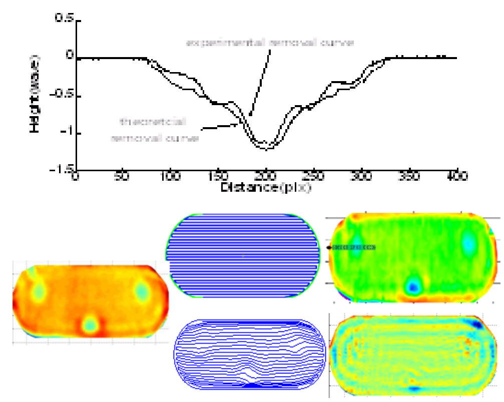

Fig. 4. Technology of off-axis aspherical surface and optimization of manufacturing tool path.

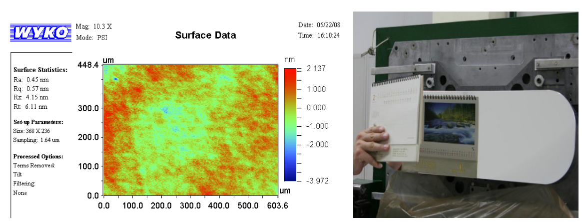

Fig. 5. PVD surface coating technique.

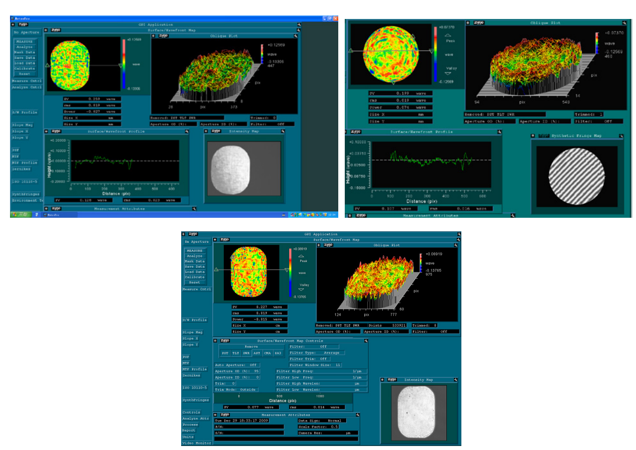

Fig. 6. Final surface figure of asphere.

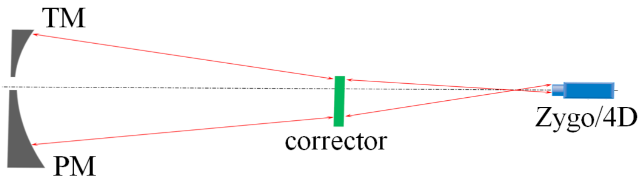

Fig. 7. ‘Co-fiducial’ testing platform.

system are easily confirmed after manufacturing, and the precision and efficiency of the alignment are enhanced greatly as the only alignment step is adjusting the secondary mirror.

The interface software MetroMax (Fig. 8) connects the final surface figure of reflecting mirrors and optical design software. With this software, the imaging simulation results of the optical system can be easily obtained based on the final surface figure after manufacturing. The imaging quality of the optical system can be forecast then. The MTF invariance of the system is better than 0.45 and the MTF invariance of the manufacturing reaches 0.9 (Figs. 9 and 10).

By testing and aligning with the same fiducial based on the character of the system, we can test the surface figure error and the location of the primary mirror and tertiary mirror at the same time, complete the alignment of the primary mirror and tertiary mirror, manufacture and test the mirrors simultaneously. As the only alignment step is adjusting the secondary mirror, it decreases the freedom of the alignment from 18 to 6 by reducing the difficulty and improving the efficiency of the alignment process.

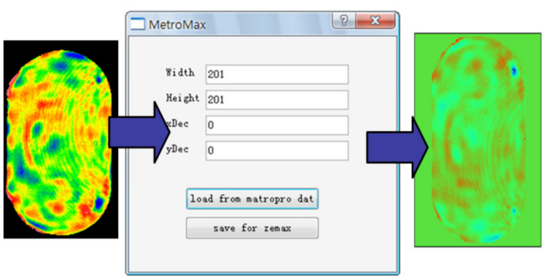

Fig. 8. Interface software of switching the manufacturing result of reflecting mirror.

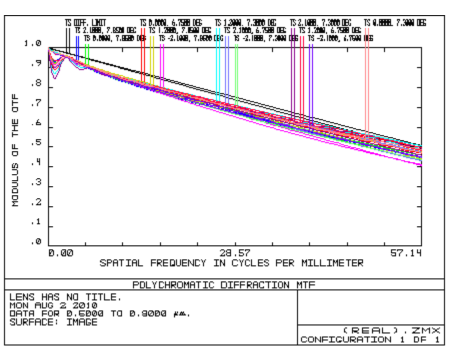

Fig. 9. Result of MTF analysis of introducing the surface figure of asphere.

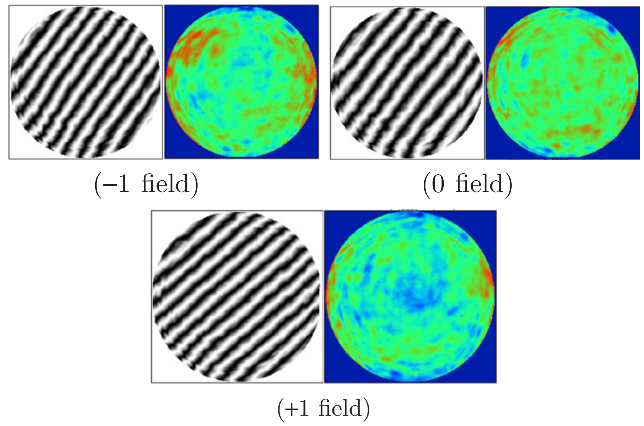

Fig. 10. Simulation results of optical system after introducing the surface figure.

After rough alignment of the secondary mirror, we choose one field of view of the optical system and test the wavefront error of the system based on the interference optical layout with an autocollimation method and then get the magnitude and direction of third coma and astigmatism to adjust the two pistons and tilt until the magnitude of coma and astigmatism is 0. The aligned optical system is shown in Fig. 11. Wavefront errors of the system in the whole field of view are shown in Fig. 12. The result shows that the wavefront error in the whole field of view is approaching $\lambda/14$. This result proves the method

Fig. 11. Off-axis TMA system after alignment.

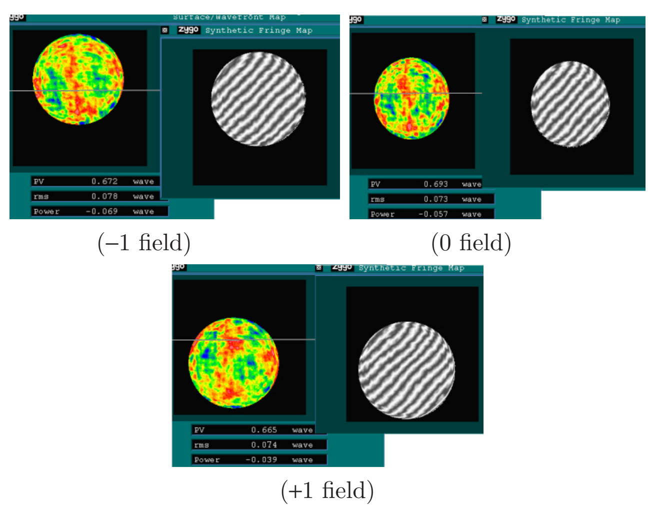

Fig. 12. Wavefront testing result of optical system in all fields of view.

that manufacturing, testing and manufacturing with the same fiducial can make the wavefront error in whole field of view reach diffractive limit and can improve the imaging quality efficiently.

To verify the quality of the optical sensing system after integrating, we test the system on the ground and orbit. The result of imaging on the ground is shown in Fig. 13 and on orbit is shown in Fig. 14. These images have clear gradations and details. The results show that

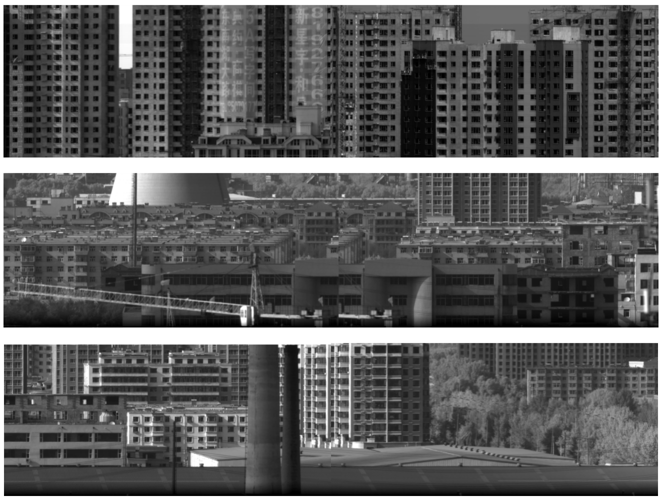

Fig. 13. Imaging experimental results.

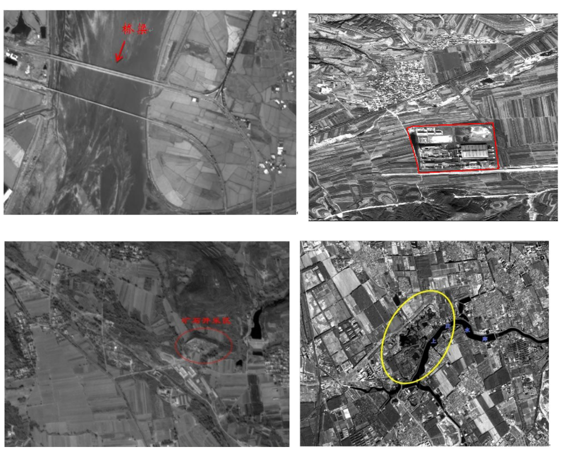

Fig. 14. Imaging results on orbit.

it can result in an efficient and precise manufacturing with the integrated manufacturing technology.

In conclusion, we provide an integrated manufacturing technology which integrates optical design, optical elements manufacturing, testing, alignment and simulation. Applying the integrated manufacturing technology, we can make the system manufacturing MTF invariance better than 0.85. Employing the interface software MetroMax, which connects the final surface figure of the mirror and the optical design software, we forecast the imaging quality of the system and guide the alignment of the system. We test and align the system with a same fiducial. Using this method, we complete the alignment of the primary mirror and tertiary mirror simultaneously, reduce the difficulty, and improve the efficiency of alignment due to reduced freedom of the alignment. We achieve alignment MTF invariance better than 0.95, the whole field of view approaching $\lambda/14$ and MTF invariance better than 0.95. We efficiently and precisely achieve high quality of an optical system with the integrated manufacturing technology. The test results on the ground and orbit confirm the system with a high-quality imaging capacity.

This work was supported by the National Natural Science Foundation of China (No. 61036015) and the National High Technology Research & Development Program of China (No. O8663NJ090).

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