

An active reflector antenna using a laser angle metrology system*

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Abstract An active reflector is one of the key technologies for constructing large telescopes, especially for millimeter/sub-millimeter radio telescopes. This article introduces a new efficient laser angle metrology system for an active reflector antenna on large radio telescopes. Our experiments concentrate on developing an active reflector for improving the detection precisions and the maintenance of the surface shape in real time on the 65-meter prototype radio telescope constructed by Nanjing Institute of Astronomical Optics and Technology (NIAOT; <http://65m.shao.cas.cn/>). The test results indicate that the accuracy of the surface shape segmentation and maintenance has the dimensions of microns, and the time-response can be on the order of minutes. Our efforts proved to be workable for sub-millimeter radio telescopes.

Key words: radio radiation — telescopes — adaptive optics — sub-millimeter

1 INTRODUCTION

Almost all the inspiring achievements in radio astronomy are due to advancements in observing equipment and technologies, which work in new bands and provide newer detecting precision or higher resolution in time or space (Xiang 1990). In recent decades, many centimeter/millimeter/sub-millimeter radio telescopes have been built, such as the radio telescope in Effelsberg Germany¹, the Green Bank Telescope (GBT) in the USA² and so on. These telescopes have an extremely large aperture composed by numerous panels, for example, the GBT is composed of 2004 panels. In the process of installation and formal operation, gravitational, thermal and wind-driven effects can induce deformation of a radio antenna's main reflector. In order to permit high performance observation at any time, besides improving the design and providing sufficiently stiff mechanical support for the antenna, active reflector antenna technology is now a key development (Zhang et al. 2010a).

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¹ <http://www.mpifr-bonn.mpg.de/english/radiotelescope/index.html>.

² <https://science.nrao.edu/facilities/gbt>.

So far the measurements of an active reflector mainly use the following three methods: The first is the rangefinder based technique (Levy 1996), like the laser metrology system adopted by the GBT which proved to be a successful design (Parker 1997). The data analysis is rather tedious since the final accuracy depends on the sophistication and volume of data, thus the time-response of this technique is on the order of hours for achieving a limiting accuracy of 100 microns. The second technology is known as microwave holography (Scott & Ryle 1977; Wang & Yu 2007). It uses a Fourier transform pair relation between the antenna aperture field and the far field pattern, which can only be found at some specified elevation angles. The accuracy is quite good (on the order of tens of microns), however the time-response depending on the desired surface resolution can be on the order of many hours. The third one is the photogrammetric system (Fraser 1986; Wang et al. 2007). It reaches an accuracy of tens of microns with a laborious set-up, and time-intensive data acquisition and analysis (usually many hours).

All of the above measurements share the same shortcoming that the precisions cannot satisfy the sub-millimeter radio telescope's active reflector antenna, and the deformation correction cannot be accomplished in real time. Here we introduce a laser-angle-metrology-based active reflector antenna, which approaches the accuracy of microns and has a useful time-response when used in a closed-loop active optics system with an order of magnitude of minutes. Through these experiments, it has proved to be successful.

2 DETECTION PRINCIPLE

In optical telescopes, the Shack-Hartmann wave-front sensor is widely used. The laser angle metrology system can be seen as a simplified Shack-Hartmann-type wave-front sensor. It images the laser spot from a paper screen onto a video CCD camera, which is defined by the laser transmitter modules installed and well aligned on each panel. By calculating the spot's position, it can deduce the normal angle of deflection and axial displacement of the panel (Zhang et al. 2010a,b).

The laser angle metrology system includes angle and range measurements. A sketch of the angle measurement process is drawn in Figure 1. The panel's tilt ($\Delta\theta$) leads to the position change of the laser spots (D). Using the formula $\Delta\theta = \arcsin \frac{D}{L}$, one can easily obtain the tilt of the panel, and thereby achieve the correction to the deflection of the normal angle. Range measurement is sketched in Figure 2. Two different laser spots on the screen are formed by two laser beams with a certain distance; if the panel moves in the axial direction, the distance between the two laser spots would change as well. The axial displacement of the panel is given by the formula $\frac{\Delta s}{S} = \frac{l}{L}$, where S is the distance between the two laser transmitter modules.

Because the test of the normal angle of each panel is influenced by the properties of each laser transmitter module's initial installation, especially the pointing precision, the laser angle metrology

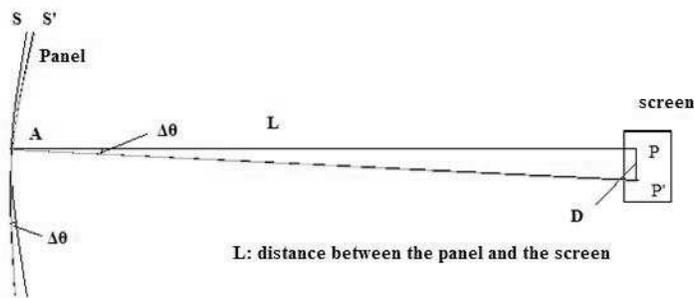


Fig. 1 Illustration of the angle measurement.

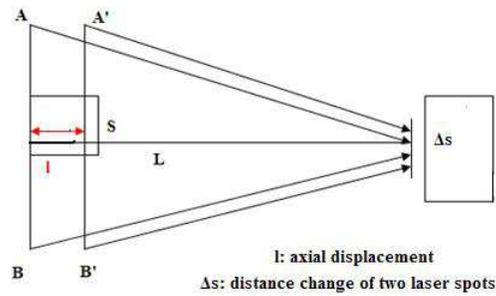


Fig. 2 Illustration of the range measurement based on the angle measurement process.

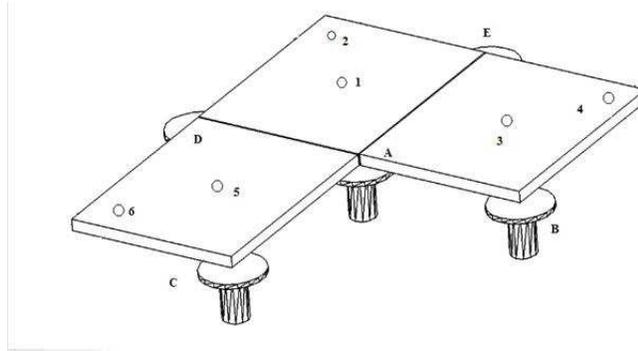


Fig. 3 65-meter prototype radio telescope system with four panels.

system is not suitable for the initial calibration of the surface shape. However, it is simple and of great use for maintaining the active surface shape. The whole system can be easily constructed and functions automatically, with high efficiency and low cost (Zhang et al. 2010a).

3 SYSTEM IMPLEMENTATION

The system is implemented based on the 65-meter prototype radio telescope constructed by NIAOT (Fig. 3). It has four panels segmented on the five support points, like Point A. Under the support points are mechanical displacement actuators, which the panel shares with the neighboring ones at the corner. Each panel has two lasers at positions like 1 and 2. A CCD camera system as a detector is placed in front of the panels to guarantee the accuracy considering the relatively short distance between the panels and the detector position. The actual experimental system is shown in Figure 4.

4 TEST RESULTS

To ensure a radio telescope is working with diffraction-limited performance, the accuracy (root mean square, RMS) of the antenna's surface deformation should be less than $1/40$ wavelength. For a sub-millimeter antenna (0.2 mm), the accuracy of the surface shape is about 5 microns (RMS), and an accuracy of 10 microns (RMS) is usually designed into the specification of all newly-constructed sub-mm radio telescopes.



Fig. 4 Actual equipment of the laser angle metrology system.

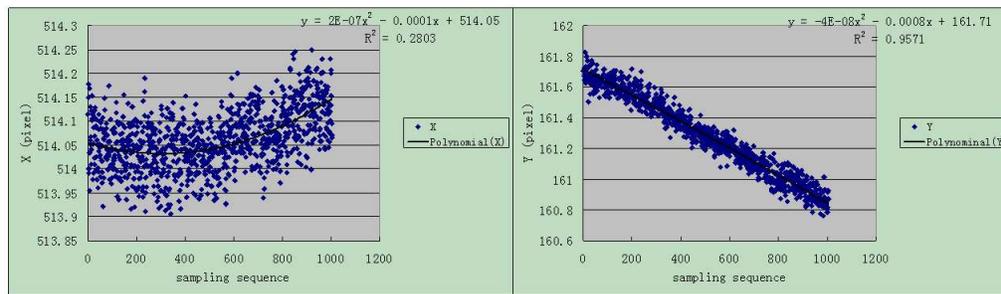


Fig. 5 The X and Y values of the laser spot captured in the sampling tests (unit: pixel, 27°C , the brightness of the system display is 100 and the contrast of the display is 150).

Whether the laser angle metrology system is able to correct the deformation of the surface shape of a sub-millimeter radio telescope or not depends on if the detection precision is satisfied with regard to the required 10 microns. Therefore, we carefully measure the precision of the laser spot detection, then test the accuracies of the surface shape segmentation and maintenance.

4.1 The Precision of the Laser Spot Detection

As the sampling of the laser spot shown in Figure 5 demonstrates, the positions of the spot change over time according to a second order power law. This trend, described by the power law, is possibly caused by the heating and gravitational deformation of the laser transmitter module. The precision is strongly influenced by this deformation, especially the peak-to-valley (PTV) value, see Figure 6(1); the PTV value is down to 0.6 pixel.

In the following experiments of angle and range measurement, considering the trend, the data we adopt are the average of a hundred sampled points. The real precision of the laser spot detection is indicated by the residuals obtained from sampling 100 spots and removing the trend described by the second order power law. As shown in Figure 6(2), the precision can be up to 0.02 pixel RMS and 0.06 pixel PTV.

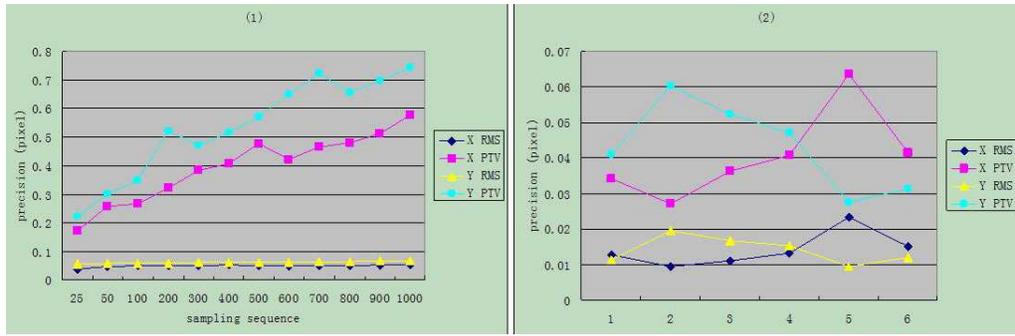


Fig. 6 (1) Precision of the laser spot detection; (2) Precision after removing the trend.

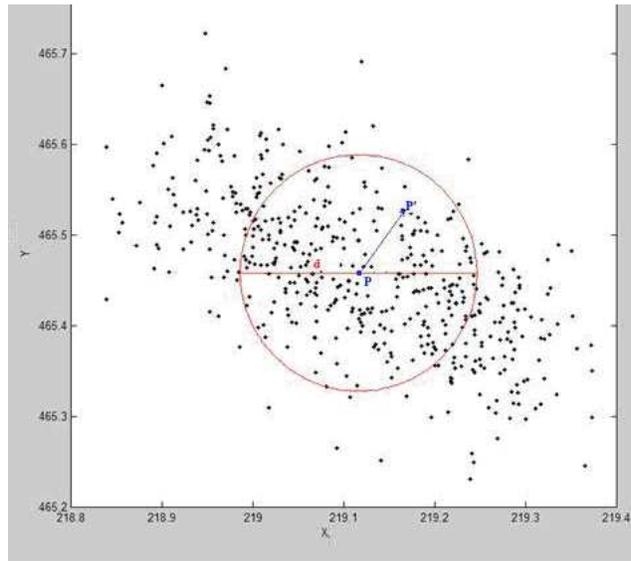


Fig. 7 Schematic diagram of the laser spot (unit: pixel, 25°C, the brightness of the system display is 150 and the contrast of the display is 150).

Next, we can discuss the accuracy of the position of the laser spot. As the schematic diagram of the laser spot in Figure 7 shows, Point P is the average of the sampled points, P' is any point being detected, and $\Delta P = |P' - P|$ represents the distance between them. Based on a Gaussian model, the discrete diameter of the laser spot (80% of the encircled energy in the laser spot distribution) characterizes the accuracy of the position. The accuracy from experimentation is about 0.2 pixel, as shown in Figure 8.

4.2 Precision of Angle Measurement and Surface Shape Segmentation

The precision of the angle measurement can be directly derived from the precision of the laser spot detection. In our experiment, 764 pixels of the CCD camera can receive a laser spot with a size

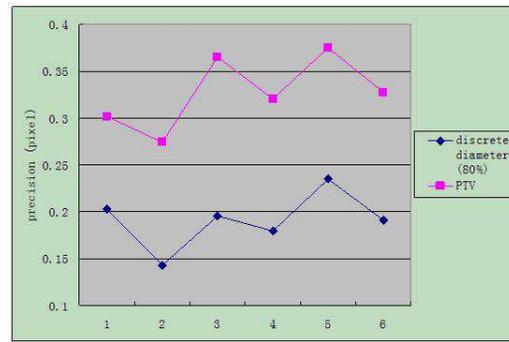


Fig. 8 Accuracy of the laser spot position.

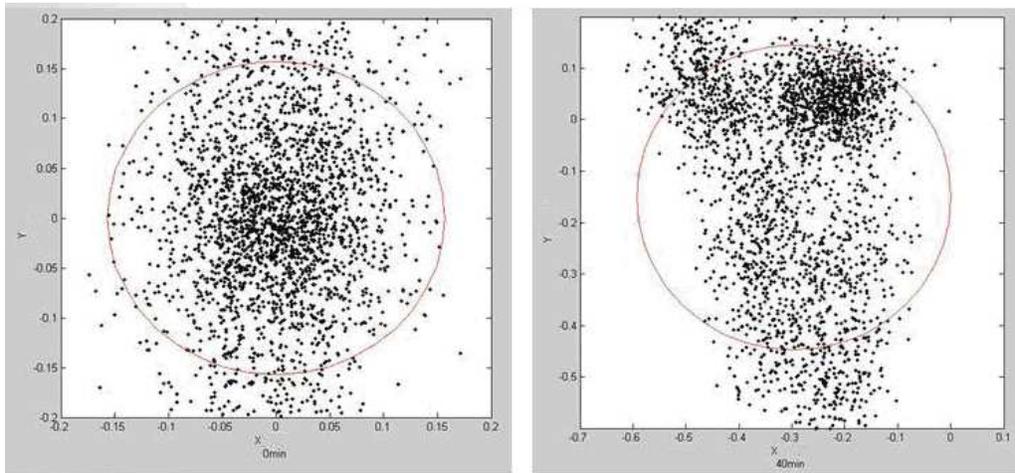


Fig. 9 Schematic diagram of the repeated measurements of the laser spot (unit: pixel).

of 50 mm, when the distance between the panel and the screen is 2315 mm. Calculating from the formula $\Delta\theta = \arcsin \frac{D}{L}$ discussed in Section 2, the precision of the angle measurement is up to 0.11 arcsec.

Transforming all the laser spots from the lasers on four panels to the same coordinate system, with zero time for the origin, the position accuracy of the laser spot indicates the precision of the surface shape segmentation. From Figure 9, the diameter of the circle is the discrete diameter of the laser spot (80% of the encircled energy in the image spot distribution) based on a Gaussian model. We fit the surface shape segmentation with the ANSYS software package on the normal tilt of each panel at certain moments, as shown in Figure 10. It is obvious that the more widely the laser patches are dispersed, the worse the deformation of the surface shape becomes. The precision of the surface shape segmentation is up to 2 μm (RMS), which can easily satisfy the constraint of the sub-millimeter antenna.

4.3 Maintaining the Shape of the Active Reflector's Surface

We correct the deformation of the surface shape using the stiffness matrix of this system, which is a 16×5 matrix describing the performance of the equipment and obtained by repeated testing.

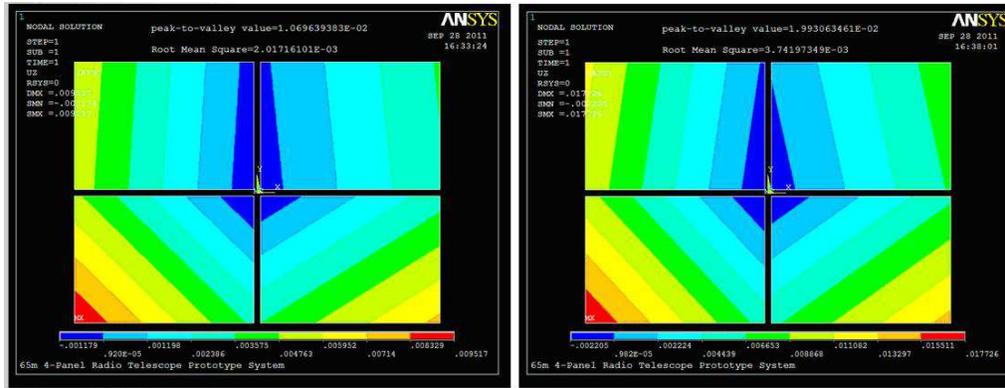


Fig. 10 Surface shape segmentation computed with ANSYS related to Fig. 9 (unit:mm).

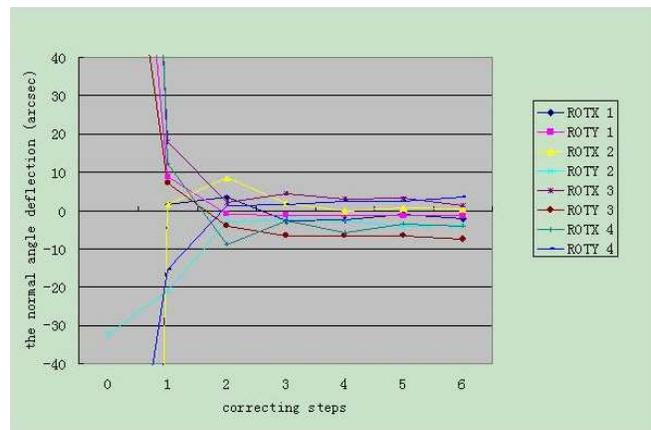


Fig. 11 Normal angle deflection of each panel.

For a surface having a random disturbance, the steps below have been taken: First, we calculate the normal angle deflections of the panels and the displacement calibrations of the actuators by the stiffness matrix. After the movement of the actuators, we test the panel tilts as an iteration. The time-response of one cycle is less than five minutes, including two minutes of data acquisition and about two minutes for the separate calculation of each panel's deflection. With a completely automatic experimental system, the time-response can be achieved within three minutes.

The result of the correction test is shown in Figure 11. After three steps, the deflections of the panels tend to be stable in the range of 5 arcsec, which is equal to the detection accuracy of the stiffness matrix as demonstrated by systematic residuals. As shown in Figure 12, the surface shape segmentation computed with ANSYS indicates that, within three steps, the accuracy of the surface shape segmentation decreases from 1 mm down to 4 μm (RMS). The time-cost of the correction procedure is amazingly short (less than 15 minutes), and the total precision satisfies the demand of a sub-millimeter antenna. The feasibility of the laser angle metrology system for a sub-millimeter radio telescope is thus successfully proved.

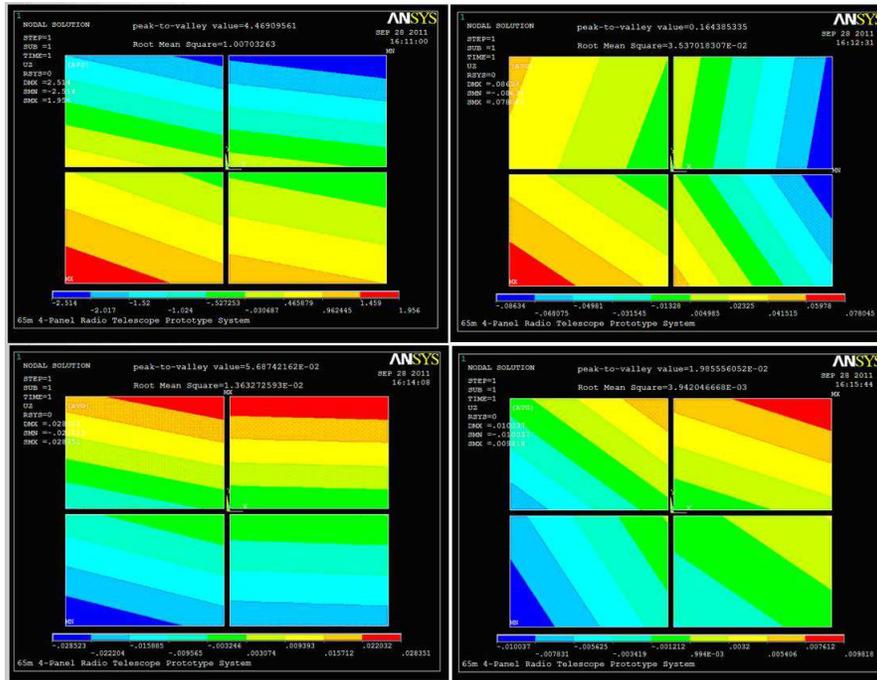


Fig. 12 Surface shape segmentation computed with ANSYS using a 16×5 stiffness matrix (unit: mm, *Upper left*: shape segmentation after a random disturbance; *Upper right*: after one correction step; *Lower left*: after two steps; *Lower right*: after three steps).

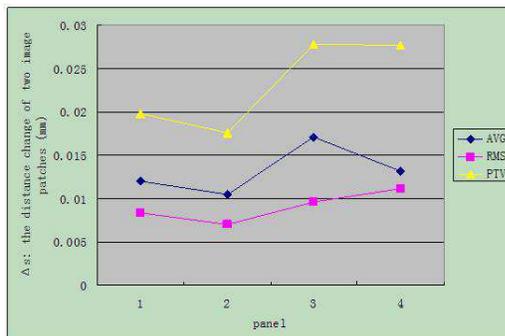


Fig. 13 Precision of Δs for four panels.

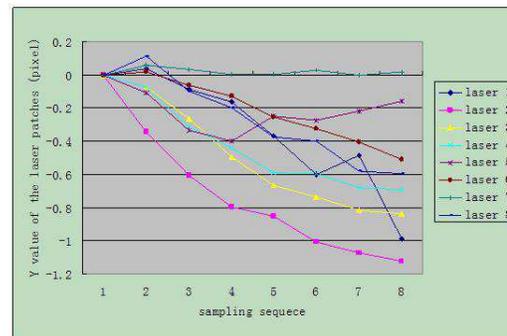


Fig. 14 Y values of the laser patches decrease with time.

4.4 The Precision of Range Measurement

According to the formula $\frac{\Delta s}{S} = \frac{l}{L}$ in Section 2, the precision of the range measurement is represented by the precision of Δs . We measure the distance changes of the image patch positions for four panels. The accuracy, shown in Figure 13, reaches a scale of $10 \mu\text{m}$ (RMS). The reason why the accuracy is limited is the gravity deformation of the laser transmitter module. As shown in

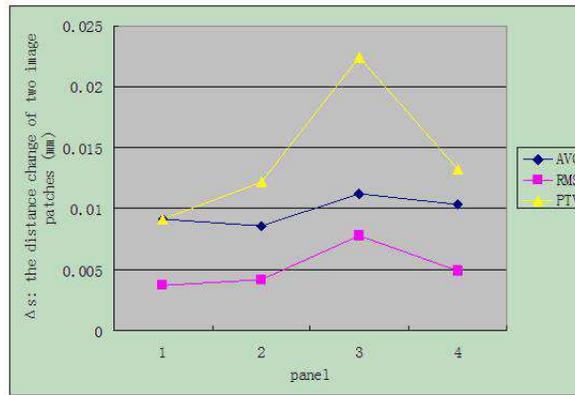


Fig. 15 Precision of Δs for four panels with improved devices.

Figure 14, the Y values of the laser patches decrease with time, that is to say, the positions of the image patches shift down with time, which apparently has a negative influence on the detection of Δs . The experiment with improved devices shows that the accuracy can be up to $5 \mu\text{m}$ (RMS) in Figure 15.

4.5 Elimination of the Influence of Lateral Deformation in the Reflector

The lateral deformation of a single panel is very small, in accordance with the technical requirements of the panel installation simulated by finite element analysis; and in addition, the actual installation and alignment. Moreover, the panel, as a basis for the laser measurement and a locator of the optical axis of the system, is sensitive to the lateral displacement (in proportion of 1:1), after correcting the normal angle deflection and axial displacement. Thus, the precision of lateral displacement of the reflector can be directly given by the precision of the laser spot detection (0.02 pixel RMS in Sect. 4.1). In our experiment, the detection precision of lateral displacement of the reflector is $50 \text{ mm} * 0.02 \text{ pixel} / 764 \text{ pixel} = 1.3 \mu\text{m}$ (the data are given in Sect. 4.2).

The influence of the lateral deformation would be eliminated by the secondary reflector and feed system of the radio telescope, which can normally be adjusted with a high-accuracy.

5 CONCLUSIONS

With the continuous extension from millimeter to sub-millimeter wavelengths in radio astronomy, the operating requirements for radio telescopes are becoming increasingly strict. Through many experiments on a 65-meter prototype radio telescope, we found that the precision of the laser spot detection is 0.02 pixel, the precision of the surface shape segmentation is up to $2 \mu\text{m}$, the precision of range measurement is up to $5 \mu\text{m}$, and the accuracy of maintaining the surface shape achieves $5 \mu\text{m}$ (RMS) with a time-response less than a quarter of what was previously available. All the results above strongly prove that the laser angle metrology system is available for a sub-millimeter radio telescope antenna, both in terms of accuracy and time-response. This technology can be applied to the reconstruction of the active reflector antenna that has already been built in China, and it will play a central role in promoting the new area of sub-millimeter radio astronomy.

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