THREE-DIMENSIONAL MEASUREMENT METHOD OF FLATNESS OF LARGE DEPLOYABLE FLAT SAR

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KEY WORDS: Photogrammetry, laser ranging, SAR, Digital image correlation, Scheimpflug camera.

ABSTRACT:

In order to improve the detection and surveillance capability of space-based SAR, large-size spaceborne SAR antenna is needed, and the scale will reach the order of 100 meters. Antenna deformation induced by space thermal radiation, deployment error and other factors seriously affects the performance of SAR. it is necessary to measure the shape of the antenna in real time and with high precision through a three-dimensional measurement system in orbit. A three-dimensional measurement method combining laser ranging and digital image correlation (DIC) is proposed in this paper. The selection of target and camera in this measurement method is deeply analyzed, and the results show that the corner reflector target and Scheimpflug camera are suitable for this three-dimensional measurement method. For the irregular image of the target, this paper improves the traditional sub-pixel center location algorithm based on DIC algorithm, and the detection accuracy of the new geometric center location algorithm is less than 0.1 pixel. Finally, a three-dimensional integration algorithm integrating one-dimensional information from laser ranging and two-dimensional information from image detection is proposed, and the measurement accuracy of this method is verified by experiments to be less than 0.2 mm.

1. INTRODUCTION

Spaceborne antennas are widely used in space and ground wireless communication, electronic reconnaissance, navigation, remote sensing, deep space exploration and radio astronomy, etc(Lane et al., 2011; Takano,1999; Deng et al.,2023).After decades of research, especially in recent 20 years, many countries have made great progress in spaceborne deployable antenna technology(Chew et al.,1993). In the late 1980s, NASA (National Aerospace and Space Administration) put forward various forms of deployable antennas in its short-term and long-term development plans. In 2004, the United States started the innovative space-based-radar antenna technology(ISAT) project (Figure 1) (Guerci et al., 2003). The antenna scale of the project can reach 300m after deployment. RSA(Russian Space Agency) has successfully developed Tetrahedral 1'mss antenna used in the mir space station. ESA(European Space Agency) has also conducted in-depth research on large-scale deployable SAR technology in its satellite development plan.

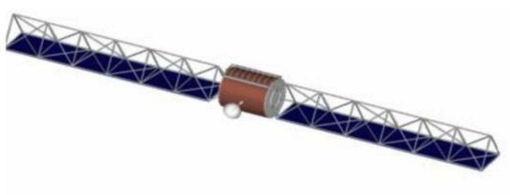

Figure 1. Schematic diagram of innovative space-based radar antenna technology (ISAT) project in USA.

In order to improve the detection and surveillance capability of space-based synthetic aperture radar (SAR), it is necessary to use a larger space-borne radar antenna (a scale of about 100m). Large-scale one-dimensional deployable truss has the characteristics of simple structure, light weight and large folding ratio, and is widely used as the support structure of large SAR antenna (Warren et al., 2003). Manufacturing tolerance, clearance of movable hinge (Yang et al., 2009), temperature gradient caused by thermal radiation (Yang et al., 2005), thermal-induced vibration (Yang et al., 2009), mechanical motion-induced vibration (Salehian et al., 2006) and other factors will lead to the static deformation and dynamic response of the structure, which will affect the antenna performance. The maximum deformation of the antenna support structure can reach about 100mm due to the influence of the on-orbit space environment. Therefore, it is necessary to measure the shape of the antenna in real time and with high precision through a three-dimensional measurement system in orbit, so as to obtain the shape change of SAR antenna for active control and compensation

For the space-based flat millimeter-band SAR antenna, in order to meet the requirements of its wavefront adjustment accuracy, the deformation measurement accuracy of the antenna needs to reach the order of **1 mm**. How to accurately measure the shape (flatness) of the deployable flat antenna in outer space in real time, so as to correct the radar wavefront distortion in real time, has become a key problem to be solved urgently.

At present, the main existing measurement methods are photogrammetry (Yi Li et al., 2016), laser interference measurement method (Yi Li et al., 2016) and laser collimation measurement method (Hu et al., 2005). Photogrammetry can be divided into single camera photogrammetry and stereo vision photogrammetry. Single camera photogrammetry has the advantages of simple installation, high measurement accuracy (using image processing methods such as feature matching), but displacement information along the direction of incident light can not be obtained. Stereo vision photogrammetry solves the shortcoming that a single camera can't obtain three-dimensional information. It is based on the principle of triangulation. Two or more cameras shoot the measured object from different positions at the same time. By using the difference of imaging angles on different image planes, the corresponding points of the objects in two images are found by image feature matching method, then, the three-dimensional coordinates and deformations of the target objects can be calculated, and the accuracy can usually reach 0.1 to 1 pixel (Mikolajczyk and Schmid, 2005). Stereo vision photogrammetry requires cross-field of view, and high relative installation position accuracy of two cameras (The two cameras need to be separated by a certain distance and rigidly connected), while thermal deformation greatly disturbs the reference position of the two cameras, so it is difficult to meet the measurement accuracy requirements. Photogrammetry is also affected by the depth of field of the camera, it is required that the cameras are placed near the central vertical line of the antenna to be measured, and the distance from the antenna is equivalent to the antenna length. (Figure 2). Obviously, it is difficult to find such a camera installation position on satellite. Both the measurement methods based on laser interference and laser collimation can not achieve multi-point simultaneous measurement, which makes the application scene extremely limited (Liebe et al., 2008).

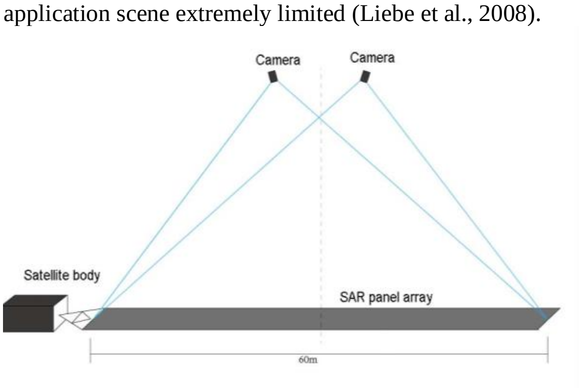

Figure 2. Stereo vision photogrammetry for large-scale SAR antenna

After comprehensive analysis and experiment of the existing measurement methods, it is found that the existing methods can not be effectively used for the real-time shape measurement of large space deployable antenna in orbit. In this paper, a high-precision on-orbit real-time measurement method of spatial position and attitude of large satellite antenna panel is proposed, which combines the single camera measurement method based on digital image correlation (DIC) with laser rangefinder, and the shift-axis imaging technology is considered to break through the limitation of depth of field of traditional imaging system.

2. OVERALL SCHEME OF MEASUREMENT

In this paper, it is assumed that the length of SAR antenna is about 120m, and it is deployed to both sides, then each side is deployed to about 60m. Because of symmetry, only the flatness measurement of single-sided antenna of about 60 m is studied. In general, a measuring rod with a length of about 5m can be extended from the satellite body in the direction perpendicular to the antenna plane, and measuring devices can be placed at the top of the measuring rod to measure the antenna deformation in real time, and the accuracy of three-dimensional measurement within 60m is less than 1mm. The schematic diagram of flatness measurement of large flat antenna is shown in Figure 3.

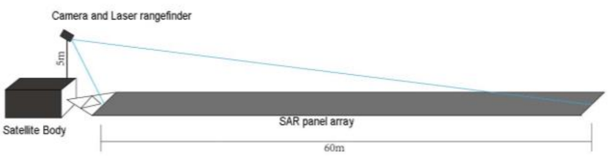

Figure 3. The schematic diagram of flatness measurement method of large flat SAR antenna

A camera and a laser rangefinder are placed at the top of the measuring rod to measure the antenna deformation. The deployable SAR antenna is generally composed of several panels, each of which is about 1~3m in size. The calculation shows that the internal deformation of each panel is generally less than 0.2mm because of the small size of each panel, then each single SAR panel can be considered as rigid. At least three targets are arranged on each SAR panel, and the attitude and position of each SAR panel are determined by measuring the positions of the targets.

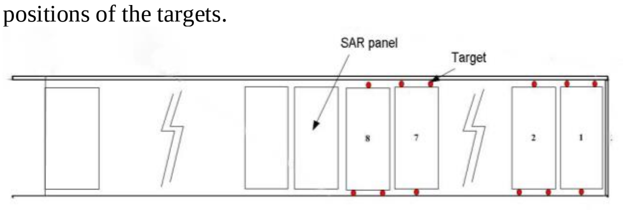

Figure 4. Target layout on SAR antenna

The characteristic of the target is that the incident direction and reflection direction of light are the same. The installation diagram of targets on SAR panel array is shown in Figure 4.
In order to measure the three-dimensional deformation of each SAR panel, in the coordinate system as shown in Figure 5, it is necessary to use digital image correlation method and laser ranging method to obtain the deviation of target in Y,Z direction and X direction respectively. The two methods share the targets.

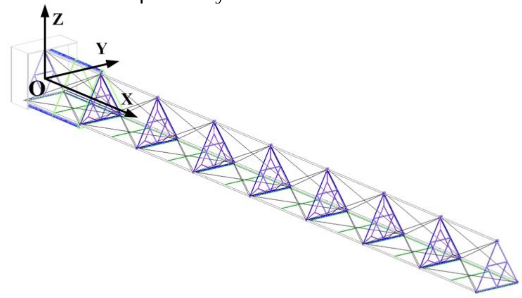

Figure 5. Measurement coordinate system

3. TARGET SELECTION

3.1 Corner reflector target

In order to realize digital image correlation measurement combined with laser ranging measurement to obtain three-dimensional displacement information, the two measurement methods need to share a target. In order to ensure the measurement accuracy, the identification of the target need to be consistent between the two measurement methods. In the measurement of flatness of large-size SAR antenna, the distance between the target and the measuring devices is more than 50m. If common painted or pasted targets are used, their low reflection efficiency will lead to the low brightness of the captured image, resulting in low recognition accuracy or even unrecognizable. In addition, in the special environment of outer space, we should not only consider the identification accuracy, energy consumption and stability of the target, but also avoid too complicated target arrangement.
In order to solve the above problems, the corner reflector target (as shown in figure 6) with the characteristics of returning to the original path and high reflectivity is selected in this paper. The corner reflector is often used as a target in laser ranging technology, and its high reflection efficiency is also suitable for long-distance imaging of cameras.

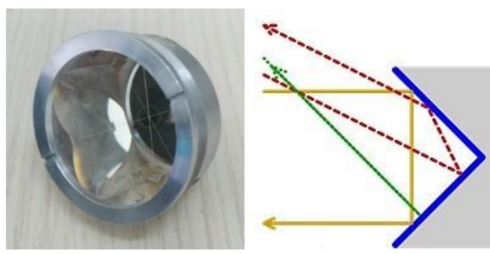

Figure 6. Schematic diagram of corner reflector and its optical path

3.2 Long-distance reflection image of corner reflector

The feasibility of the long-distance corner mirror as the target of digital image correlation method is verified by experiment. In the experiment, the corner mirror is fixed on a translation stage 50 meters away from the camera, and the experimental equipments are as follows: IDS camera (UI-3370CP) with a resolution of 2048*2048 and a pixel size of 5.5μm, Zoom lens (VZ16100M) with a focal length of 16-100mm; light source with power of 5W; corner reflector; micron precision translation stage. The image of the corner reflector captured by the camera is shown in figure 7. It can be seen that the image of the corner reflector at 50m on the camera has high contrast and brightness, which can meet the requirements of DIC measurement.

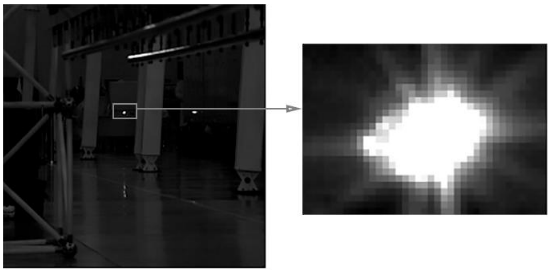

Figure 7. The image of the corner reflector

4. GEOMETRIC CENTER LOCATION ALGORITHM AND EXPERIMENTAL VERIFICATION

4.1 Geometric center location algorithm of target image

It can be seen that the image of the corner reflector (as shown in figure 7) in the camera is not a circle because of the star-awn effect, Therefore, it is necessary to improve the accuracy of geometric center locations of corner reflector image by algorithm. The conventional sub-pixel circle center recognition algorithm obtains the sub-pixel edge through the sub-pixel algorithm, and then obtains the center of the circle through ellipse fitting, so it has high recognition accuracy for very regular circular spots. However, this method depends on ellipse fitting, and the detection accuracy of the spot with poor roundness will decrease, so it is difficult to locate the center of corner reflector image with high accuracy. DIC method mainly uses the gray information in the sub-region of the target point (geometric center of target image). As long as there is gray texture information near the point, it can be matched with high precision. However, this method can not obtain the geometric center of the feature point.

Here, we propose a high-precision matching method combining sub-pixel circle center point recognition and digital image correlation. In this method, firstly, the sub-pixel circle center recognition algorithm is used to obtain the relatively accurate geometric center point of the initial image, and then the point is used as the starting point of the reference image to track and match through DIC method, so as to obtain high-precision measurement results.

Generally, the target point on the reference image will be selected at the whole pixel position, while the point obtained by the sub-pixel circle center recognition algorithm is generally at the sub-pixel position, so we need a DIC method with the target point at the sub-pixel position on the reference image. As shown in figure 8, (x, y) is the sub-pixel center position calculated in the reference picture, and we need to use DIC to find its deformed position, that is, (x_d, y_d). Four integer pixel points (x_1, y_1), (x_2, y_2), (x_3, y_3) and (x_4, y_4) adjacent to (x, y) is obtained, and through the conventional DIC method, we can easily obtain the matching positions of these four integer pixel points in the deformation image, that is, (x_{d1}, y_{d1}),(x_{d2}, y_{d2}),(x_{d3}, y_{d3}),(x_{d4}, y_{d4}).

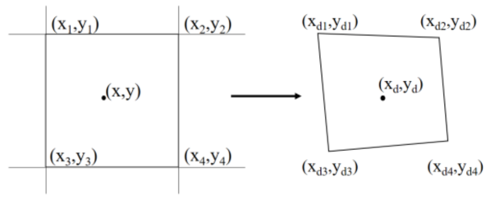

Figure 8. When the central point on the reference image is sub-pixel, the transformation between the reference image and the deformation image.

The deformation image and the displaced target satisfy the following relationship.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{1}$$

(X Y Z) is the coordinates of the target after moving. [a_{ij}] is the camera perspective transformation matrix (unknown) after the target is moved, therefore

$$x_d = \frac{X}{Z} \qquad y_d = \frac{Y}{Z} \tag{2}$$

By combining the above two formulas, we can get

$$x_d = \frac{a_{11}x + a_{12}y + a_{13}}{a_{31}x + a_{33}y + a_{33}} \qquad y_d = \frac{a_{21}x + a_{22}y + a_{22}}{a_{31}x + a_{32}y + a_{33}} \tag{3}$$

Because the deformation image is not sensitive to the change of Z direction, it can be assumed that a_{33}=1, then

$$\begin{cases} a_{11}x + a_{12}y + a_{13} - a_{31}xx_d - a_{32}x_d y = x_d \\ a_{21}x + a_{22}y + a_{23} - a_{31}xy_d - a_{32}yy_d = y_d \end{cases} \tag{4}$$

There are similar transformation relations between (x_1, y_1), (x_2, y_2), (x_3, y_3) , (x_4, y_4) and(x_{d1}, y_{d1}),(x_{d2}, y_{d2}),(x_{d3}, y_{d3}),(x_{d4}, y_{d4}), which are written in the form of a matrix equation.

$$\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & -x_1 x_{d1} & -x_{d1} y \\ 0 & 0 & 0 & x_1 & y_1 & 1 & -xy_{d1} & -yy_{d1} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix} \begin{bmatrix} a_{11} \\ a_{12} \\ \vdots \\ a_{32} \end{bmatrix} = \begin{bmatrix} x_{d1} \\ y_{d1} \\ \vdots \\ \vdots \end{bmatrix} \tag{5}$$

According to equation (5), [a_{ij}] can be calculated, and then (x_d, y_d) can be calculated according to equation (3).

4.2 Experimental verification

Using an industrial camera (2048*2048 pixels) and a wide-angle lens with a focal length of 8mm. Targets are arranged at 5m, 20m and 55m away from the camera respectively. At these three distances, the target is translated with a three-axis high-precision platform and each image is recorded. The measurement results are shown in Figure 9, and the standard deviation is kept within 0.02 pixels. Therefore, it can be concluded that the new algorithm based on digital image correlation has achieved good performance in the experiment at medium and long distances, and the accuracy is kept within 0.1pixel, which meets the requirements of high-precision flatness measurement.

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
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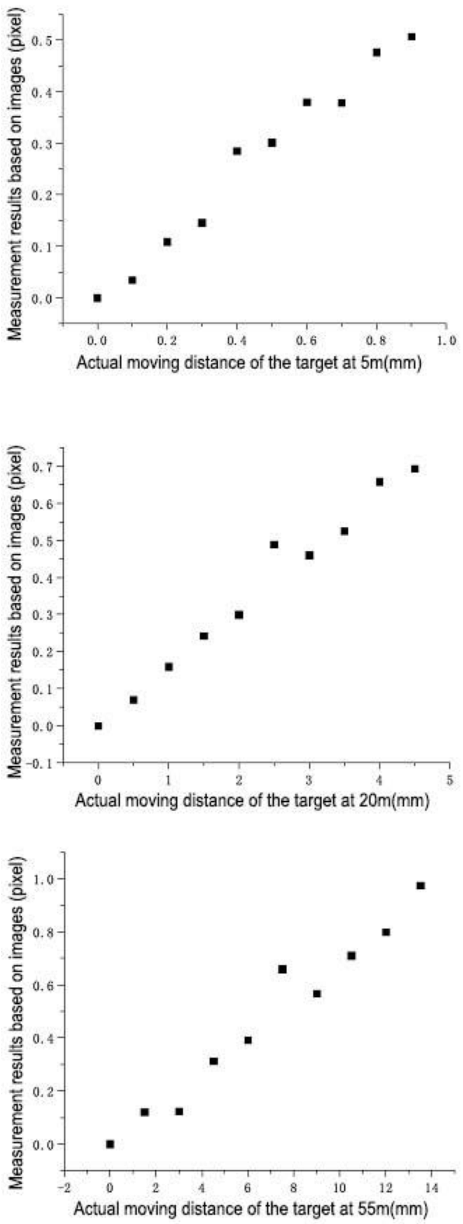

Figure 9. Experimental measurement results based on the new geometric center location algorithm

5. CAMERA SELECTION

The depth of field of a camera is difficult to adapt to simultaneous short-distance and long-distance imaging. Multi-camera segmentation measurement not only makes the measurement system complicated, but also causes great error transmission when solving the relative position between cameras. In the method proposed in this paper, camera based on Scheimpflug lens is suggested to be used. Scheimpflug lens is a special lens designed according to Scheimpflug law, as shown in figure 10, the positional relationship among imaging plane, lens plane and image plane satisfies Scheimpflug law. The Scheimpflug camera can clearly image the whole measurement area.

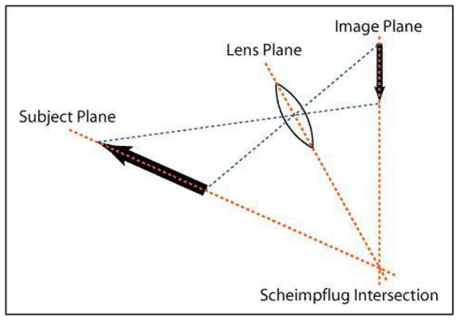

Figure 10. Scheimpflug camera

6. LARGE-SCALE AND HIGH-PRECISION THREE-DIMENSIONAL MEASUREMENT METHOD AND EXPERIMENTAL VERIFICATION

6.1 Overview of the measurement method

Two-dimensional information of the target can be obtained from the image of a single camera, and one-dimensional information can be obtained from laser ranging, that is, the distance from the laser radar to the target. The measurement method can be simplified as the following model. In the figure below, O_L-$X_LY_LZ_L$ is the coordinate system of laser rangefinder, and O_C-$X_CY_CZ_C$ is the camera imaging coordinate system. This measurement method is essentially a triangulation method. The rangefinder points at the target can obtained the length of O_LP, and the camera calculates the direction of light pointing to the target (O_CP) through the coordinates of image points. The line O_LP intersects with the O_CP, according to the principle of triangulation, the coordinates of point P can be obtained. This solution needs to calibrate the spatial relative position [tx ty tz] and attitude [φ ω κ] between the laser rangefinder and the camera.

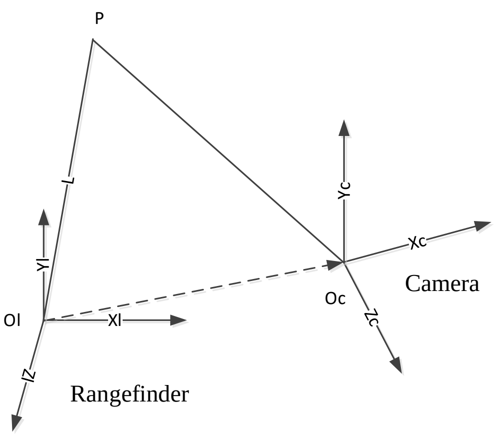

Figure 11. Mathematical model of the measurement method

6.2 Experimental verification

In order to verify the measurement accuracy of the three-dimensional measurement method, an industrial camera (2048*2048 pixels, wide-angle lens with a focal length of 8 mm) and a laser rangefinder (measuring accuracy of 0.2mm) are used. the truss is placed at a distance of 12m from the camera and rangefinder, and 6 targets are installed on the truss(see figure 12, only four targets are shown). In the process of measuring with the camera, the rangefinder is used to measure synchronously, and finally the three-dimensional positions of the targets are obtained by the new method. Because of the high reflection efficiency of the target, we can adjust the exposure time of the camera to be very short, which can not only eliminate stray light in the environment, but also ensure that the imaging has no smear and ensure the imaging quality.

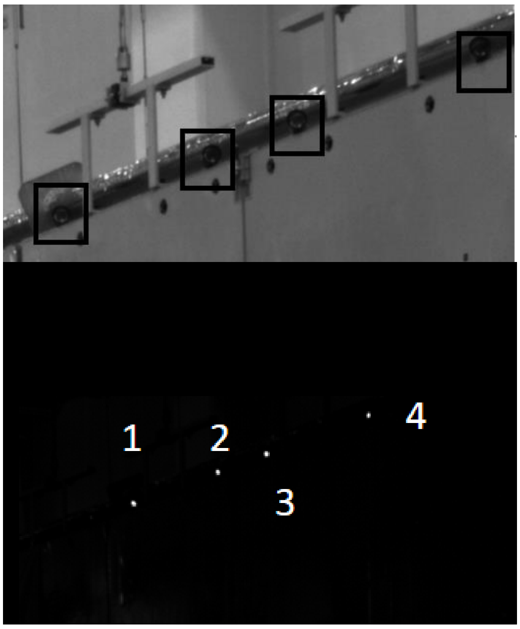

Figure 12. The layout of targets in the experiment and images of four corresponding target points under low exposure

On the other hand, The three-dimensional coordinates of the targets in the camera coordinate system can be directly obtained by using multiple theodolites, and the measurement accuracy of theodolite-based method can reach 0.2mm, so the three-dimensional coordinate data measured by theodolite-based method can be used as our reference data to verify the measurement accuracy.

By pulling the truss, the positions of the six targets move. Figure 13 shows the three-dimensional displacement results measured by the two measurement methods. It can be seen that after pulling the truss, the displacements of the six targets are close but not the same, which is in line with expectations. The displacement results given by combining laser ranging and digital image correlation algorithm are very close to those of theodolite, and the measurement accuracy is less than 0.2mm (Less than the measuring accuracy of theodolite-based method).

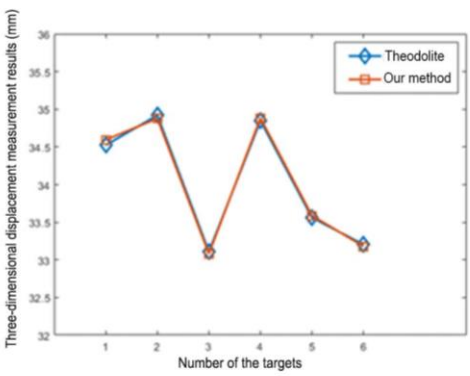

Figure 11. Three-dimensional displacement results measured by theodolite-based method and the method proposed in this paper.

7. CONCLUSION

In this paper, the difficulties of flatness measurement of large deployable SAR are comprehensively analyzed, such as large scale, high precision, complex environment and multi-point measurement, and it is found that the traditional measurement methods are difficult to meet the requirements. A three-dimensional measurement method combining laser ranging and digital image correlation is proposed in this paper. The selection of target and camera in this measurement method is deeply analyzed, and the results show that the corner reflector target and Scheimpflug camera are suitable for this three-dimensional measurement method. For the irregular image of the target, this paper improves the traditional sub-pixel center location algorithm based on DIC algorithm, and the detection accuracy of the new geometric center location algorithm is less than 0.1 pixel. Finally, a three-dimensional integration algorithm integrating one-dimensional information from laser ranging and two-dimensional information from image detection is proposed, and the measurement accuracy of this method is verified by experiments to be less than 0.2 mm.

REFERENCES

Steven A. Lane, Thomas W. Murphey, Michael Zatman, 2011: Overview of the innovative space-based radar antenna technology program. *Journal of Spacecraft and Rockets*, 48(1),135-145.

T. Takano, 1999. Large deployable antennas-concepts and realization. *IEEE Antennas and Propagation Society International Symposium. Held in conjunction with: USNC/URSI National Radio Science Meeting (Cat. No.99CH37010)*, Orlando, FL, USA, 1999, pp. 1512-1515 vol.3, doi.org/ 10.1109/APS.1999.788230.

Warren P, Hinkle J, Harvey T J, 2003. Recent Developments in High Efficiency, Elastically Deployed Tubular Trusses.*44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. 2003-1823. doi.org/10.2514/6.2003-1823

Yulong Yang, Fuling Guan, 2009: Theoretical analysis of surface error for deployable truss antenna. *Chinese Journal of Space Science*. 29(5),529-533.

Yulong Yang, Fuling Guan, Shujie Zhang, 2005: Thermal-structural analysis of deployable truss antenna. *Chinese Journal of Space Science*. 25(3), 253-06.

Yulong Yang, Fuling Guan, 2009: Numerical analysis of thermally induced vibration for deployable truss antenna. *Chinese Journal of Space Science*. 29(4), 432-437.

Salehian A, Inman D, Cliff E, 2006. Natural frequencies of an innovative space based radar antenna by continuum modeling. *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. 2006-2101. doi.org/ 10.2514/6.2006-2101

Chew M, Kumar P, 1993: Conceptual design of deployable space structures from the viewpoint of symmetry. *International Journal of Space Structures*. 8(1-2), 17-27.

J. Guerci and E. Jaska, 2003. ISAT - innovative space-based-radar antenna technology. *IEEE International Symposium on*

Phased Array Systems and Technology, Boston, MA, USA, 2003, pp. 45-51, doi.org/ 10.1109/PAST.2003.1256955.

Yi Li, Tao Wei, Gao Wenjun, Zhao Hui, 2016: Research on the Multipoint Real-time Measurement of Large Truss. *JOURNAL OF ASTRONAUTIC METROLOGY AND MEASUREMENT.* 36(4),51-54.

Changde Hu, Jiahai Lu, Qi Xing, Juan Gao, 2008: Long guide linearity error measurement based on laser interference. *Optical Instruments.* 30(6), 10-15.

Mikolajczyk K, Schmid C. A, 2005: Performance evaluation of local descriptors. *IEEE transactions on pattern analysis and machine intelligence,* 27(10),1615-1630.

C. C. Liebe et al. 2008. Optical Metrology System for Radar Phase Correction on Large Flexible Structure. *IEEE Aerospace Conference,* Big Sky, MT, USA, 2008, pp. 1-7, doi.org/ 10.1109/AERO.2008.4526391.

Deng Yunkai, Zhang Heng, Fan Huaitao, Yu Weidong, Wang Yu, Tang Xinming, Ge Daqing, Xu Feng, Liu Guoxiang, 2023: Forthcoming development trend of spaceborne SAR technology for earth environment monitoring. *Chinese Space Science and Technology*, 43(2),1-11.