Received February 22, 2020, accepted March 6, 2020, date of publication March 13, 2020, date of current version March 24, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2980679

CMOS Multi-Matrix Optoelectronic System for High Speed Measurement of Main Mirror Deformation Large Diameter Radio Telescope

RENPU LI [1], XIAOJUAN QIN [1], IGOR KONYAKHIN [2], MINH HOA TONG [2], ALEXANDER USIK [3], YONGLE LU [1], KE DI [1], AND YU LIU [1]

[1]Chongqing Engineering Research Center of Intelligent Sensing Technology and Microsystem, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
[2]Faculty of Applied Optics, ITMO University, 197101 Saint Petersburg, Russia
[3]NIPK Electron Company, 197758 Saint Petersburg, Russia

Corresponding author: Yu Liu (liuyu@cqupt.edu.cn)

This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFF01010202 and Grant 2018YFF01010201, in part by the National Natural Science Foundation of China under Grant 61705027, Grant 11704053, Grant 51902037, and Grant 61901069, in part by the Government of the Russian Federation under Grant 08-08, in part by the Innovation Leader Talent Project of Chongqing Science and Technology under Grant CSTC-CXLJRC201711, in part by the Basic Research Project of Chongqing Science and Technology Commission under Grant CSTC-2017csmsA40017 and Grant CSTC-2018jcyjax0619, and in part by the Science and Technology Project Affiliated to the Education Department of Chongqing Municipality under Grant KJZH17115, Grant KJQN201800626, and Grant KJQN201900615.

ABSTRACT A complementary metal-oxide semiconductor (CMOS) multi-matrix-based optoelectronic system is proposed and studied to measure the deformation of each connection point of a large full-rotatable radio telescope. The system is based on 18 multi-matrix base units. Theoretical investigations demonstrate that the system can provide real-time measurement of multi-point displacements quickly (within 21 seconds). Experimental investigations reveal that the actual measurement error of the photoelectric measurement unit designed in this paper is 0.024 mm. It is inferred that the measurement displacement error will not exceed 0.05 mm in an actual measurement of the full main mirror of the large diameter radio telescope, thus confirming the feasibility of the system.

INDEX TERMS Measuring deformations, millimeter-range radio telescope, multi-matrix measurement system, optoelectronic system.

I. INTRODUCTION

In modern scientific research systems, large-diameter high-frequency radio telescopes, such as LMT 50 in Mexico, SRT 64 in Italy, GBT 100 in the United States, Tianma in China, and RT-70 (Suffa) in Russia have become the focus of research and development in many countries [1]–[3]. The accuracy of the reflecting surface is an important index of the main mirror surface of a radio telescope. It is not only closely related to the effective aperture. According to J.Ruzes formula, the square of the surface accuracy of the main mirror is also proportional to the maximum gain of the radio telescope [4]. Because the main mirror of a radio telescope is composed of many reflectors, the connection points of these reflectors need to be measured and controlled to prevent joint deformation due to environmental changes (under the influence of temperature and gravity). By analyzing the data of the control point displacement, the reflector of a radio telescope is adjusted by a mechanical compensation system to reach the ideal state [5]. However, the measurement accuracy of the connection points of the main mirror reflectors is usually required to reach tens of nanometers [6]. The most accurate measurement method is ''microwave holography,'' the measurement accuracy of which is between 0.014 mm and 0.030 mm. However, it takes several days to several weeks to complete the deformation measurement of the main mirror of a radio telescope by using this method. Therefore, this method can only be used for establishing the initial model of the main mirror of a radio telescope and for regular preventive maintenance [7]. In addition, the measurement error of photogrammetric technique is about 0.05mm, and the measurement time is tens of hours [8]. To improve the

The associate editor coordinating the review of this manuscript and approving it for publication was Sukhdev Roy.

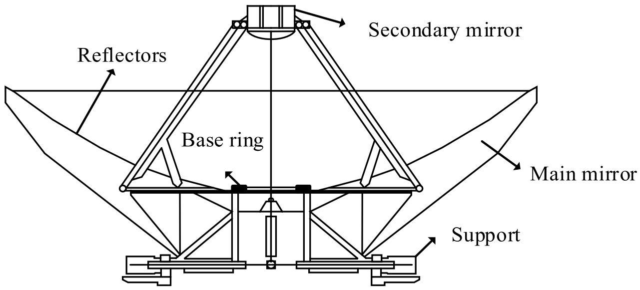

FIGURE 1. **Main structure of the RT-70 radio telescope.**

measurement accuracy of a radio telescope, it is necessary to design a system that can directly measure its actual deformation during its operation to realize a real-time compensation technology for the deformation of its main mirror. To this end, the United States GBT uses a measurement system based on multiple laser trackers [9]–[11]. To obtain the ideal measurement accuracy of this system, each laser tracker needs to measure more than 180 measurement points (up to several hundred times) for a total measurement time of 8 min. According to an official report from the Lebedev Physical Institute of the Russian Academy of Sciences, that measurement speed still cannot meet the requirements of a radio telescope such as RT-70 for the deformation measurement of the main mirror [12]. Therefore, a new measurement system needs to be designed to achieve a real-time accurate measurement of the deformation of the main mirror of a radio telescope. Igor Konyakhin *et al.* proposed a special measurement system for the RT-70 radio telescopes based on the triangular method [13]. This system consists of separate base units, with each containing only one objective lens and a charge-coupled device. The disadvantage of this system is that one base unit measures only one measurement point on the main mirror of the radio telescope; thus, the entire system can measure positions for only 40 points simultaneously. To increase the number of measurement points, this study investigates a set of photoelectric measurement systems. Light-emitting diodes mounted on multiple measurement points are focused and imaged on a corresponding complementary metal-oxide semiconductor (CMOS) through one objective lens, and the positions of these points are measured by an electronic analysis system. The system has strong anti-interference characteristics, a high measurement accuracy, and a fast measurement speed. It is also possible to perform noncontact measurements and simultaneous multipoint measurements, that is, a simultaneous measurement of multiple detection points [14]. Therefore, the system can be used for deformation measurement and can control the connection point of the reflector of a radio telescope.

II. MEASUREMENT SCHEME

Fig. 1 shows the structure of the millimeter-wave radio telescope RT-70 built in the Suffa plateau of Uzbekistan, where Russia is implementing a large-scale project [15]. The main

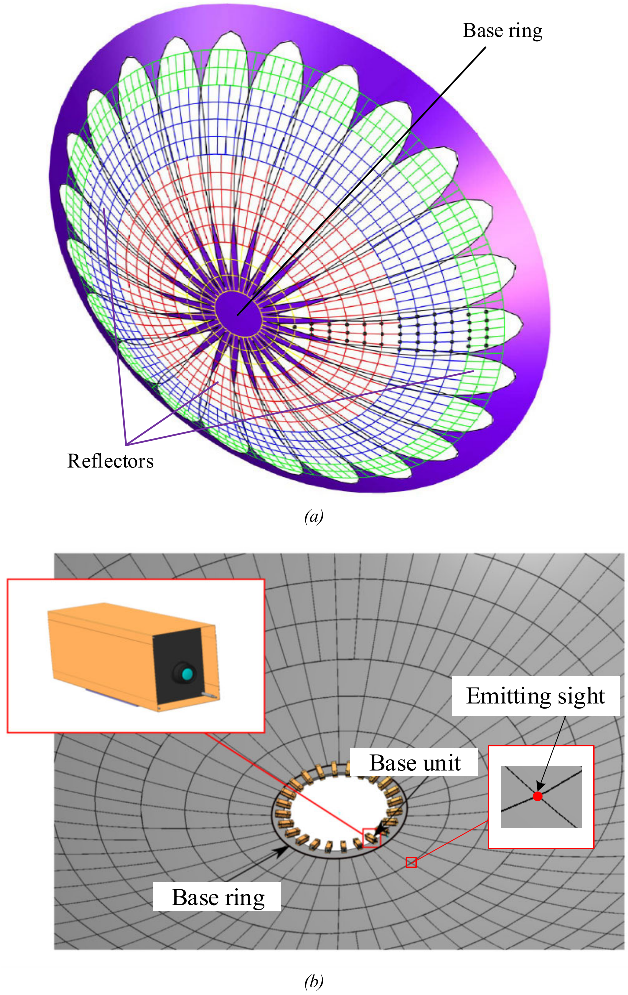

FIGURE 2. **Schematic of the measurement system. (b) The suggested measurement system.**

mirror of the radio telescope consists of 1200 reflectors. Every reflector is a part of a parabolic mirror with a size of approximately 2 × 3 m, and the displacement of each reflector from the theoretical parabolic position should be no more than 0.1 mm. The main mirror and its base ring have diameters of 70 m and 6 m, respectively.

Fig. 2(a) illustrates the geometry of the parabolic main mirror surface of the RT-70 radio telescope, whose 6 m diameter base ring can be used as a base rigid body. The measurement system proposed in this study is shown in Fig. 2(b). It includes 18 measurement base units, which are located in the base ring as shown in Fig. 2(a) [15], [16]. The field angle of the entire measurement system covers the reflectors of the main mirror. The measurement points are located at the joint angles of the four adjacent mirrors. Each base unit measures the displacement of 19 emitting sights (Fig. 3(a)).

According to the structure of the RT-70 radio telescope, there are corresponding load-bearing brackets at connection points of every four reflector. Since the design of the radio telescope uses the homologous principle of antenna

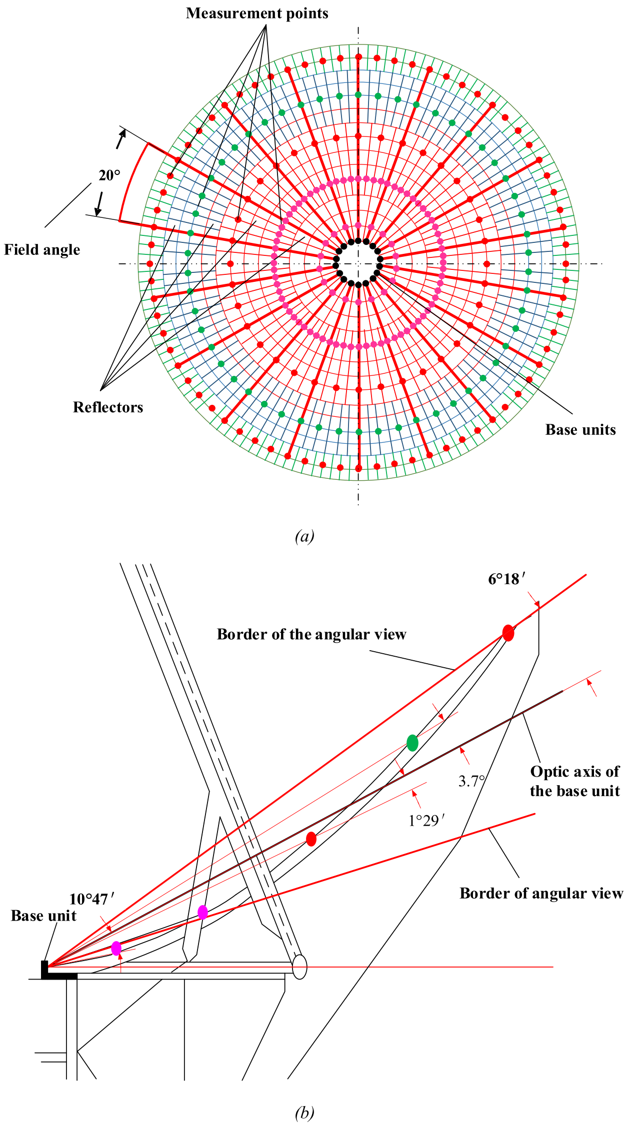

FIGURE 3. (a) Measurement points required for the main mirror surface of the RT-70 radio telescope on the longitude profile. (b) Measurement points on the latitudinal section of the main mirror.

construction frame truss [12], the deformation at the connection point mainly occurs in the normal direction of the parabola. Therefore, by measuring the position information of these measurement points, establishing the real-time parabola information of the main mirror, and calculating the angle between each measurement point and the parabola normal, the deformation displacement of the main mirror can be obtained, as shown in Figs. 3(a)–(b). Each basic unit of the measurement system mentioned in this study is designed with a field of view greater than 20°. The above designs will further improve the measurement reliability and accuracy because five measurement points on the border of the field angle for every base unit will be measured by two base units jointly. As a result, the whole system measures the deformation shifts of 252 measurement points on the main mirror surface. By measuring these measurement points, an approximate parabolic model of the main mirror can be established. According to a computer simulation, the error of the approximate parabolic model is less than 0.1 mm, when the measurement error of the position by the reflectors on the main mirror surface is no more than 0.05 mm. The proposed measurement system guarantees that there are enough measurement points. The specific Mathcad simulation methods are as follows:

1) m points on the parabolic surface of the main mirror of the radio telescope are selected as the modeling objects. The selected modeling points are equidistant. Because the entire system consists of 18 basic measurement units, the number of measurement points of each measurement unit is n, and the number of modeling points for the entire paraboloid selected is

$$m = 18 \cdot n \tag{1}$$

2) It is assumed that the axis OZ of the coordinate system is aligned with the axis of the parabola. Using the parabola equation (2), the coordinates (x_i, y_i, z_i) of the m points, where $i = 1, \ldots, m$, are calculated.

$$x^2 + y^2 = 2pz \tag{2}$$

3) In the direction perpendicular to the parabola, the error displacement δ is 0.05 mm of a random given modeling point root mean square (RMS) (Note: this assumption is used to simulate the error of the measurement system).
4) Using the polyfitc function command in Mathcad 15 and combining the coordinates of the measurement points after a given error, the coefficients c_k ($k = 0, \ldots, 5$) are determined and an approximate parabolic model is constructed as follows:

$$z(x, y) = c_0 + c_1 x + c_2 y + c_3 xy + c_4 x^2 + c_5 y^2 \tag{3}$$

5) Using equation (1), the coordinates (X_I, Y_I, Z_I) of the measurement points are calculated before the error is given according to the number of reflecting surfaces $I = 1, \ldots, 1200$.
6) According to the Z_I value of the measurement point obtained in step 5, combined with equation (3), the point coordinates (X_i, Y_i, Z_i) of the approximate parabolic surface with Z_I value are calculated.
7) The coordinate error of the same Z-value point on the exact parabola and approximate parabola is calculated:

$$\Delta_I = \sqrt{(X_I - X_{-I})^2 + (Y_I - Y_{-I})^2} \tag{4}$$

where $I = 1, \ldots, 1200$.
8) The RMSσ of the error multi-matrix Δ_I, where σ is the error of the model with respect to the main surface of the actual radio telescope, is determined.
9) Using the above steps, the modeling accuracy of the number of measurement points n of the measurement

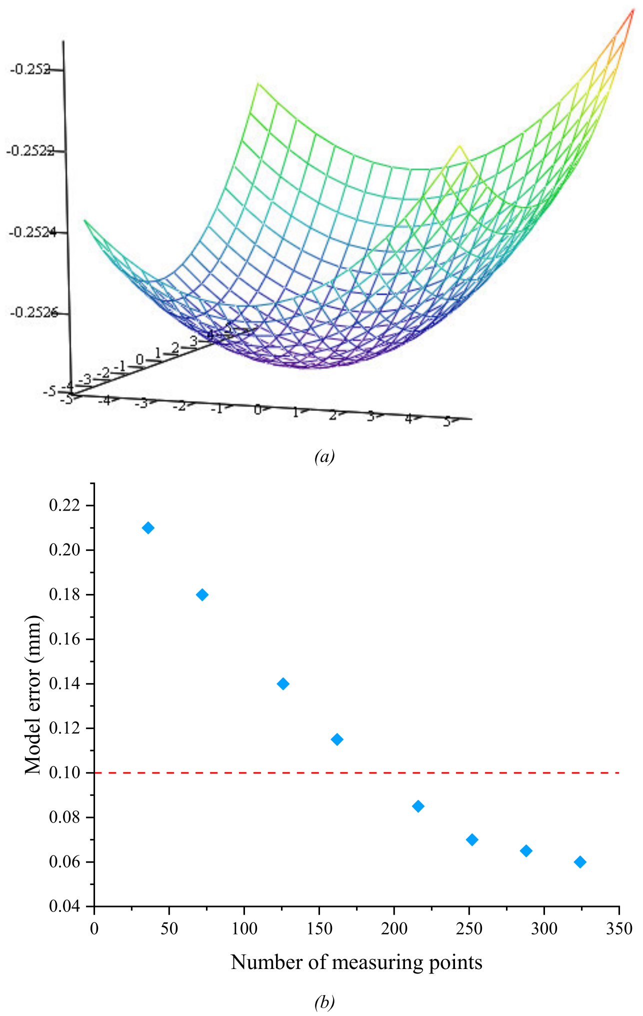

FIGURE 4. (a) Approximate parabolic model with random errors. (b) Relationship between the number of measurement points and model error.

unit ranges from 2 to 18, and the number of system measurement points m ranges from 36 to 324.

As can be seen from Figs. 4 (a)–(b), when the number of measurement points is greater than 200, the structural accuracy of the approximate paraboloid is greater than 0.1 mm.

According to the above conclusions, the number of measurement points of the measurement system proposed in this paper is sufficient to meet the measurement requirements of the main surface deformation of a radio telescope. During the assembly of the system or the regular maintenance of the radio telescope, the initial model of the main mirror of the radio telescope is established through the system, and the position of the main optical axis of the 18 independent measurement units is calibrated, so as to ensure that the measurement error of the measurement system only depends on the measurement error of each basic unit.

III. BASE UNIT SCHEME

Fig. 5 depicts the structure of the base unit. Each base unit includes only one objective lens and 19 CMOS multi-matrix

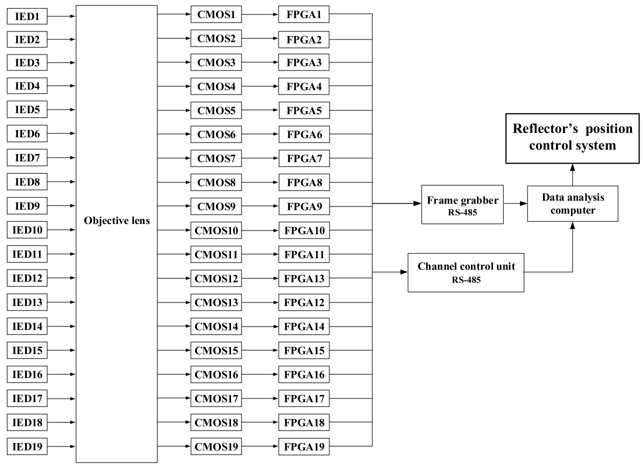

FIGURE 5. Scheme of the base unit.

receivers as image analyzers. Infrared emission diodes (IEDs) were installed at 19 measurement points on the main mirror and imaged in the corresponding CMOS multi-matrix by the objective lens.

To reduce the displacement measurement time of all IEDs on the main surface of the radio telescope, the electronic components of each basic unit adopt a parallel structure. It turns out that this structure can determine the coordinate information of 19 images on the CMOS multi-matrix at the same time t_m [17]. The electronic structure of the basic unit includes 19 Altera field-programmable gate arrays (FPGAs), and each FPGA is used to process the frame information of the corresponding CMOS multi-matrix. To improve the accuracy of the measurement, the FPGA needs to capture 30 frames from the CMOS multi-matrix and calculate the average value to determine the coordinates of the image. The information-processing algorithm and FPGA parameters of the measurement unit mentioned in this study can be found in [14], [18]. Then the frame grabber is used and the image coordinate information is transmitted to the data analysis computer through the CMOS multi-matrix interface RS-485. The data analysis computer then calculates the measurement data and establishes a measurement model of the main mirror of the radio telescope. With this model, the reflector's position control center will generate execution commands for electromechanical compensation systems. At the same time, the data analysis computer uses the channel control unit to issue work instructions to the CMOS multi-matrix of the measurement unit through an RS-485 interface.

IV. EXPERIMENTAL BASE UNIT SETUP

To prove that the base unit meets the performance requirements, a computer simulation with a simpler structure was performed to verify the experimental base unit setup [19], [20].

As shown in Fig. 6, the experimental setup mainly includes the objective lens with fasteners and five CMOS multi-matrix receivers with adjustment means. The objective and multi-matrix receivers are fixed on the base plates. The three pillars

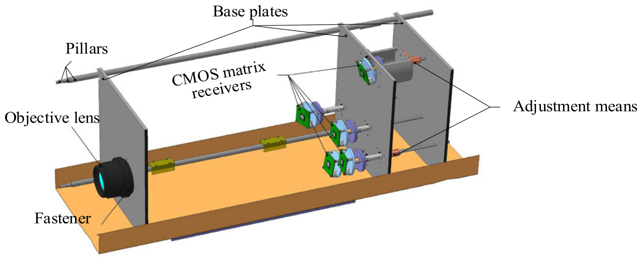

FIGURE 6. Experimental base unit setup.

realize the stiffness of the design. This design can use adjustment means to quickly adjust the CMOS alignment direction to simplify the experimental process, but in a real measurement system of a radio telescope, it is necessary to strictly install and fix the CMOS at its corresponding spot imaging position. Each CMOS multi-matrix receiver is connected to the computer via a USB interface. We used CMOS multi-matrix receivers OV05620 Color CMOS QSXGA with 2592 $\times$ 1944 pixels and a pixel size of 2.2 $\times$ 2.2 μm produced by Omni Vision as image analyzers [20]. According to the design parameters, the distance from the objective lens to the CMOS receiver in the experimental unit is about 465 mm, the angle between the two adjacent CMOS is 0.0083 rad and the center distance is 40 mm. The CMOS module selected in the experiment was a thin square shape with a side length of 30 mm, which left enough space for the base unit to install all CMOS receiving modules. To select the objective lens of the base unit, we compared the aberrations of different objective lenses at an angle of view of 26°. According to the experimental results, we chose photo-objective lens RF-5 (Lomo Ltd., Russia) with a focal length of 450 mm, the necessary field angle, and small aberrations [16].

In the simpler structure, only a single CMOS multi-matrix receiver was used to measure the displacement of a single sight. The experimental results show that the measurement error is 8.7 $\times$ 10^{-3} mm when the measurement distance is 5500 mm, which confirms that the system has the required sensitivity [19] and the design has a high measurement speed. According to the official information of the components used in the experiment, the shooting time of each frame of CMOS is within 0.125 s. To obtain reliable coordinate information of the sight, it is necessary to shoot at least 30 frames. The average value of the captured information is faster than 7 s, and combined with the transmission path, the signal conversion and modeling time is faster than 10 s; therefore, the single measurement time for the main telescope shape of a radio telescope will be faster than 21 s [17]. A measurement system consisting of a single objective lens and CMOS multi-matrix has a strong anti-interference ability, and it is easier to install temperature control, humidity control, IR filters, and other devices inside the system to calibrate the impact of environmental changes on the measurement accuracy. Therefore, the accuracy of the system measurement in a complex environment such as a wide temperature range, rain, and snow climate is guaranteed [18]. The above characteristics provide the basic experimental support for the engineering design proposed in this study.

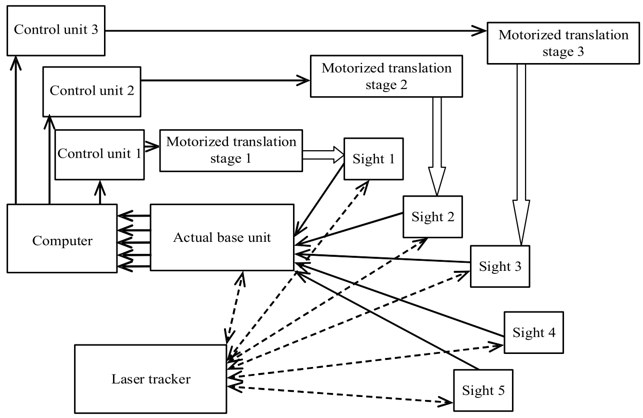

FIGURE 7. Structure of the experimental platform.

V. EXPERIMENT AND RESULT

A. EXPERIMENTAL PLATFORM AND STEPS

This section discusses in detail the verification of the experimental base unit setup. Fig. 7 displays the structure of the platform for researching the experimental base unit. To simulate the deformation of the main mirror surface, five IEDs (Kingbright L-34SF4C) with an irradiance of 20 mWt are replaced by sights, wherein sights 1–3 are mounted on electric motorized translation stages (8MT30-50DCE; Standa Ltd., Lithuania) 1–3, and sights 4 and 5 are fixed to the immovable base. Control units (8DCMC1-USB-B1-1; Standa) 1–3 control the linear displacements of the moving table on motorized translation stages 1–3 by the sequence of commands generated by the computer. The optical emission by sights 1–5 are incident on the corresponding CMOS multi-matrix receivers in the experimental base unit. API's Radian Laser Tracker 80 (Automated Precision Inc., USA) is used to measure the displacement of sights 1–3 and monitor the stability of the experimental base unit position and the fixed sights 4 and 5. To this end, a cube corner reflector of API's Radian Laser Tracker 80 is added to each sight.

The experiment was conducted in a 4 $\times$ 18 m room that simulates the shape of the RT-70 radio telescope. Support frames of different heights were installed on the wall and floor of the room for mounting the sights. Thus, the room is similar to the target field structure of the main mirror of the radio telescope.

To simulate most of the real measurement environment of the measurement system, two experiments were performed in July 2019 and December 2019. The test environment in July 2019 was as follows. The experimental ambient temperature was within 5–20 °C. The relative air humidity ranged from 65% to 80%, and the pressure range was 1006 hPa to 1020 hPa. Note that the time of the experiment was from 1 am to 4 am.

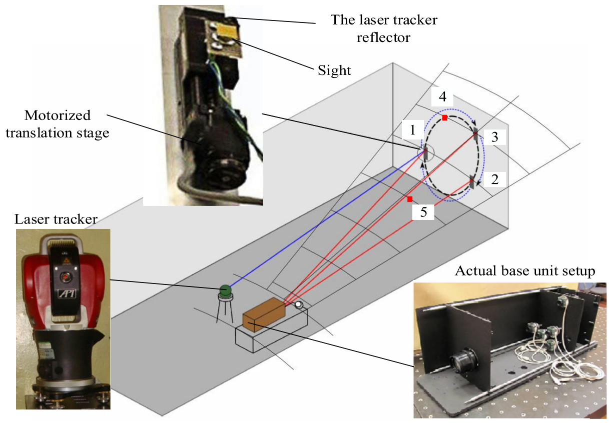

FIGURE 8. Schematic of the experimental simulation.

The experiment was carried out in accordance with the schematic shown in Fig 8. Here, an anti-vibration bracket is used to simulate the base ring on the main mirror of the RT-70 radio telescope, and the experimental base unit is installed on the anti-vibration bracket. Five IEDs are used as sights 1–5. The laser tracker reflector is used for monitoring the position of the sight and experimental base unit. The motorized translation stage is used for the linear movement of sights 1–3. The laser tracker is mounted on the industrial tripod attached to the instrument, which in turn measures the position of the five cube corner reflectors rigidly connected to sights 1–5 and the experimental base unit.

As presented in Fig. 9, the experimental steps are as follows: First, by establishing a two-coordinate system model, the coordinate system of the laser tracker is used to measure the spatial coordinates of sights 1–5 and the experimental base unit. Second, sights 1–3 are moved 5 mm along the vertical coordinate axis by motorized translation stages. Third, the laser tracker measures the coordinate change in moving sights 1–3 along the vertical coordinate axis and the stability of the fixed sights 4 and 5 and experimental base unit. In addition, the CMOS is used to measure the coordinates of the imaging spot and the measured displacements of sights 1–3 are calculated. Finally, steps 2 and 3 are repeated.

In the experiment, the base unit can be considered as composed of five independent measurement channels, with each corresponding to one IED and one CMOS. Each measurement channel consists of three components, as shown in Fig. 10. In the channel, the objective lens images the IED as the sight in the sensitive area of the CMOS multi-matrix receiver, and the displacement ΔX of the sight IED corresponds to the displacement Δx of the image in the CMOS.

The displacement ΔX is calculated by measuring Δx:

$$\Delta X = \frac{\Delta x}{S} \tag{5}$$

whereby S is the geometric sensitivity factor of the measurement channel and is determined by the following expression:

$$S = \frac{u}{L} \tag{6}$$

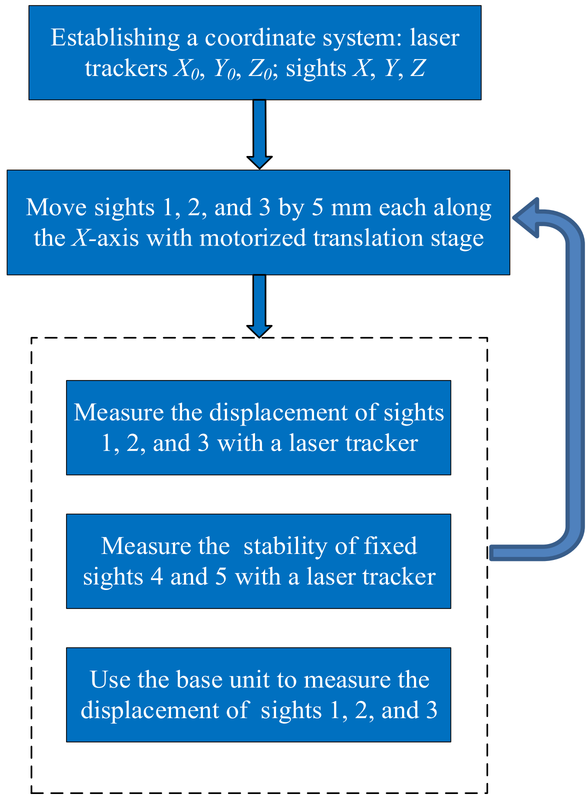

FIGURE 9. Experimental flowchart.

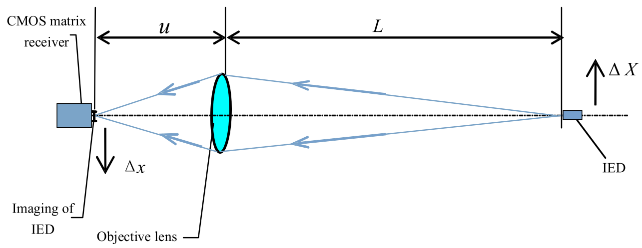

FIGURE 10. Independent measurement channel structure.

where L is the object distance from the objective lens to the IED and u is the image distance from the objective lens to the CMOS.

B. ANALYSIS OF THE EXPERIMENTAL RESULTS

The correctness of the design method is verified by establishing a functional relationship from the experimental results.

Let us consider a function

$$x = \psi_n(X) \tag{7}$$

where X is the coordinate along the vertical axis of the sight (in mm), x is the coordinate of the sight imaged on the CMOS (in pixels), ψ_n is a transducer function, and n is the moving sight number ($n = 1, 2, 3$).

To establish the parameters of the transducer function ψ_n, the following measurements were made. Sights 1–3 were shifted 8 times along the vertical coordinate axis with a step

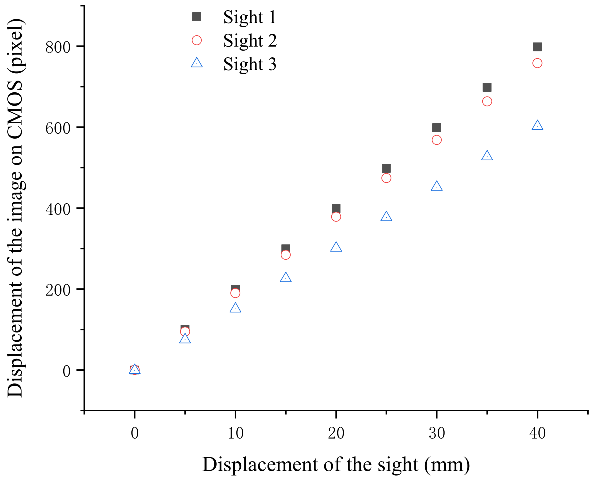

FIGURE 11. Imaging displacement measurement data of three mobile sights.

of 5 mm from 0 to 40 mm, respectively. As a result, 9 points with coordinates X_i $(i = 1, \ldots, 9)$ were obtained. The coordinate positions of sight 1, sight 2, and sight 3 correspond to CMOS 1, CMOS 2, and CMOS 3 as the coordinate positions of images $x_i (i = 1, \ldots, 9)$, in pixels. Every coordinate position of the image was measured 100 times, and data arrays $\mathrm{x}_{i,j}$ $(i = 1, \ldots, 9; j = 1, \ldots, 100)$ were obtained. The fixed sights 4 and 5 were installed on the unchanged coordinate X_0 position corresponding to the position x_0 of the imaging on CMOSs 4 and 5. The images were also measured as 9 series and for each series, the measurements were repeated 100 times. Subsequently, we obtained data arrays $x_{0i,j}$ $(i = 1, \ldots, 9; j = 1, \ldots, 100)$.

The measurement data were mathematically processed, and 100 datasets of each series had an average $\hat{x}_i$. The average value of the image coordinates for the fixed sights was determined in the same way. The coordinate measurement error x_i of each position i for the image of the sights can be obtained by finding the standard deviation of the measurement result value series of $x_{i,j}$ $(j = 1, \ldots, 100)$. Table 1 presents the average $\hat{\sigma}x$ of the measurement errors of the image coordinate for each of the sights in pixels. From Table 1, it can be concluded that the root mean square (RMS) values σx of all the average values $\hat{\sigma}x$ are less than 0.003 pixels.

The function ψ_n $(n = 1, \ldots, 3)$, as shown in Fig. 11, satisfies the linear relationship

$$x = A_n + B_n \cdot X \tag{8}$$

Fig. 11 shows the transducer function of the experimental base unit in measuring the displacement changes of sight 1 (black), sight 2 (red), and sight 3 (blue). The X-axis represents the displacement of the sight (in mm), and the Y-axis represents the displacement (in pixel) of the image in the CMOS. The coordinate position of the image spot irradiance center was obtained by using a weighted summing algorithm.

The coefficients A and B are given in Table 1. It can be found that the RMS values of B coefficients of sights 1, 2, and

TABLE 1. Measurement results for the sights.

	Sight 1	Sight 2	Sight 3	Sight 4	Sight 5
L, mm	10712	11251	14045	13825	8126
$\hat{\sigma}x$,pixel	0.32	0.33	0.36	0.33	0.34
B, pixel/mm	19.94	18.95	15.06	-	-
A, pixel	-0.135	0.32	-0.153	-	-
S	0.0439	0.0417	0.0331	-	-
σX, mm	0.016	0.017	0.024	-	-
σX, mm	0.016	0.017	0.024	-	-

3 are $\sigma B_1 = 0.003$ pixels/mm, $\sigma B_2 = 0.0028$ pixels/mm, and $\sigma B_3 = 0.0025$ pixels/mm, respectively.

The expression for Δx in equation (5) is

$$\Delta x = (x_{i+1} - x_i) \cdot p \tag{9}$$

From equations (5) and (9), we can obtain

$$S = \frac{(x_{i+1} - x_i) \cdot p}{\Delta X} \tag{10}$$

From equations (8) and (10), we can get

$$(x_{i+1} - x_i) = B \cdot (X_{\mathrm{i}+1} - X_i) = B \cdot \Delta X \tag{11}$$

where $p = 2.2 \times 10^{-3}$ mm is the pixel size of the CMOS and $\Delta X = (X_{i+1} - X_i)$. By equations (9) and (11), the sensitivity S of the measurement channel formed by the CMOS-IDE pair can be obtained. It is expressed as

$$S = B \cdot p \tag{12}$$

The error value σX of measuring the displacement ΔX of the sights can be expressed as

$$\sigma X = \frac{\hat{\sigma}x \cdot p}{S} \tag{13}$$

where $\hat{\sigma}x$ is the measurement error of the image coordinate by each of the sights, in pixels. The σX values of sights 1–3 are shown in Table 1.

From Table 1, we can observe that when the distance is 14.045 m the sensitivity S (14) = 0.0331 and the error of measuring the displacement for sight 3 is $\sigma X = 0.024$ mm. According to the RT-70 radio telescope construction, the distance from the base unit to the measurement point in the last row (Fig. 3a) is approximately 29 m. For this distance, from equation (5), the value of the sensitivity is S (31) = 0.016 and the estimation of the error of measuring the displacement can be calculated as

$$\sigma X \approx \frac{0.024 \cdot S(14)}{S(31)} = 0.05\text{mm} \tag{14}$$

The above accuracy is sufficient for measuring the shifts of points on a radio telescope main mirror.

VI. CONCLUSION

This study introduces a new photoelectric monitoring system to measure the distortion of the main mirror of a radio telescope rapidly. The system consists of 18 base units, and each base unit is used to monitor 19 measurement points. The distortion is determined by measuring the displacement (relative to the initial state without distortion) of the measurement point on the radio telescope main mirror. The initial state is obtained by a periodic flatness measurement of the ideal three-dimensional (3D) parabolic structure of the main mirror of the radio telescope. When the radio telescope is operating, the system can complete the displacement measurement of 252 measurement points in 21 s to obtain the difference in the data structure between the main mirror and the 3D ideal paraboloid. In addition, this study introduces the internal structure of the base unit in detail. Each base unit has a common objective lens and 19 photo receiver matrices and measures the displacement change of the corresponding sight. These sights are mounted on the measurement point on the main mirror of the radio telescope. The structure of the base unit ensures the stability of each line of sight from the photo-receiver multi-matrix to the sight.

Owing to the limitation of the experimental environment, the measurement distance needs to be reduced from 30 m, which is the radius of the millimeter-level radio telescope main mirror, to 14 m. The actual measurement error of the photoelectric measurement experimental base unit setup designed in this study is less than 0.024 mm for the distance of 14 m. It is inferred that in the actual measurement of the full main mirror of a millimeter-wave radio telescope, the measurement displacement error will not exceed 0.05 mm, thus confirming the theoretical accuracy of the test design method. This type of measurement structure with only objective lens and CMOS multi-matrix has been proven to have a high measurement speed (faster than 21 s). At the same time, the system has a high anti-interference ability, and it is easier to calibrate the impact of changes in the measurement environment on the measurement accuracy. This guarantees the system's measurement accuracy under environment temperatures of -20 °C to 20 °C and in complicated environments such as rain and snow. The above performance shows that the design is suitable for the deformation measurement of the main mirror of a large diameter radio telescope.

The improvement of the multi-matrix base unit stability with the use of a common objective lens for several photoreceiver matrices can also be used in other measurement systems to measure the shifts of components in large constructions such as bridges, dams, and buildings. Future research should focus on how to further improve the vibration stability and measurement accuracy of multi-matrix systems.

REFERENCES

[1] P. Bolli, F. Gaudiomonte, R. Ambrosini, C. Bortolotti, M. Roma, C. Barberi, and F. Piccoli, "The mobile laboratory for radio-frequency interference monitoring at the sardinia radio telescope," *IEEE Antennas Propag. Mag.*, vol. 55, no. 5, pp. 19–24, Oct. 2013.

[2] G. Swarup, S. Ananthakrishnan, and V. K. Kapahi, "The giant metre-wave radio Telescope," *Current Sci.*, vol. 60, no. 2, pp. 95–105, 1991.

[3] Y. Wu, K. F. Warnick, and C. Jin, "Design study of an L-band phased array feed for wide-field surveys and vibration compensation on FAST," *IEEE Trans. Antennas Propag.*, vol. 61, no. 6, pp. 3026–3033, Jun. 2013.

[4] J. Ruze, "Antenna tolerance theory—A review," *Proc. IEEE*, vol. 54, no. 4, pp. 633–640, Apr. 1966.

[5] *An Introduction to Ray Tracing*. Amsterdam, The Netherlands: Elsevier, 1989.

[6] G. Cortes-Medellin and P. F. Goldsmith, "Analysis of active surface reflector antenna for a large millimeter wave radio telescope," *IEEE Trans. Antennas Propag.*, vol. 42, no. 2, pp. 176–183, Feb. 1994.

[7] J. Baars, R. Lucas, J. Mangum, and J. Lopez-Perez, "Near-field radio holography of large reflector antennas," *IEEE Antennas Propag. Mag.*, vol. 49, no. 5, pp. 24–41, Oct. 2007.

[8] M. Süss, D. Koch, and H. Paluszek, "The sardinia radio telescope (SRT) optical alignment," *Proc. SPIE*, vol. 8444, Sep. 2012, Art. no. 84442G.

[9] A. L. Petticrew, "Laser rangefinder deflection measurements of the GBT derrick," NRAO GBT Memo Series, Tech. Rep. 160, 1996.

[10] D. H. Parker and J. M. Payne, "Metrology system for the green bank telescope," in *Proc. Annu. Meeting Amer. Soc. Precis. Eng. (ASPE)*, 1999, pp. 21–24.

[11] S.-J. Zhang, Y.-G. Gao, X.-Y. Xue, G. Wang, and H.-D. Li, "Design and functional test of a novel optical testing target," *Optoelectron. Lett.*, vol. 14, no. 6, pp. 461–464, Nov. 2018.

[12] [Online]. Available: http://asc-lebedev.ru/index2.php?engdep=16&engsuffa=2

[13] I. Konyakhin, Y. Artemenko, and A. Timofeev, "Control of the deformation for the millimeter wave range radiotelescope mirrors," in *Proc. 5th Int. Symp. Instrum. Sci. Technol.*, vol. 7133, Jan. 2009, Art. no. 71333R.

[14] D. V. Zhukov, I. A. Konyakhin, and A. A. Usik, "Iterative algorithm for determining the coordinates of the images of point radiators," *J. Opt. Technol.*, vol. 76, no. 1, pp. 36–38, Jan. 2009.

[15] V. V. Korotaev, I. A. Konyakhin, A. N. Timofeev, and S. N. Yaryshev, "High precision multimatrix optic-electronic modules for distributed measuring systems," in *Proc. 6th Int. Symp. Precis. Eng. Meas. Instrum.*, Aug. 2010, Art. no. 75441E.

[16] I. K. M. H. Tong, "Multi-matrix optic-electronic systems for measuring the line shifts of the points on the radio-telescope main mirror," *Proc. SPIE*, vol. 11053, Mar. 2019, Art. no. 1105307.

[17] M. Klaiber, L. Rockstroh, Z. Wang, Y. Baroud, and S. Simon, "A memory-efficient parallel single pass architecture for connected component labeling of streamed images," in *Proc. Int. Conf. Field-Program. Technol.*, Dec. 2012, pp. 159–165.

[18] A. V. Vasileva, A. S. Vasilev, and I. A. Konyakhin, "Vision-based system for long-term remote monitoring of large civil engineering structures: Design, testing, evaluation," *Meas. Sci. Technol.*, vol. 29, no. 11, Nov. 2018, Art. no. 115003.

[19] I. K. M. H. Tong, "Optic-electronic multi-matrix system for measuring the positions of the reflecting panels on the main mirror of the large radio-telescope," *Proc. SPIE*, vol. 11056, Jun. 2019, Art. no. 110562J.

[20] R.-P. Li, K. Igor, T. M. Hoa, and M. Zhou, "Multi-matrix opto-electronic system for measuring deformation of the millimeter range radiotelescope elements," *Optoelectron. Lett.*, vol. 15, no. 2, pp. 144–146, Mar. 2019.

RENPU LI received the B.S., M.S., and Ph.D. degrees from ITMO University, in 2012, 2014, and 2017, respectively. He is currently an Assistant Professor with the School of Optoelectronic Information, Chongqing University of Posts and Telecommunications, China. His research interests include integrated optics and optical systems.

XIAOJUAN QIN was born in Chongqing, China, in 1995. She received the B.E. degree in electronic science and technology from the Chongqing University of Posts and Telecommunications, in 2018, where she is currently pursuing the master's degree in electronics and science.

IGOR KONYAKHIN was born in Russia in 1953. He received the B.S., M.S., and Ph.D. degrees in autocollimation optical-electronic devices and systems from National Research ITMO University, Russia, in 1976, 1981, and 1998, respectively.

He is currently a Professor with the Department of Optical-Electronic Devices and Systems, National Research ITMO University. Since 2004, he has been the project director and the supervisor of studies in advanced research of the optical-electronic system for control of construction elements for grand radio-telescope RT-70 Suffa (Russia). He is the author of three scientific monographs, nine certificates publications of inventions, 37 reports at the scientific conferences, and more than 90 published articles. He received the Honorary Professor of University Education of Russia, in 2009.

MINH HOA TONG was born in Bac Giang, Vietnam, in 1991. He received the B.S. and M.S. degrees in optical engineering from ITMO University, Saint Petersburg, Russia, in 2017, where he is currently pursuing the Ph.D. degree in optical engineering.

Since 2018, he has been a Research Assistant with the Faculty of Applied Optics, ITMO University. His research interest is development and research of an optoelectronic device for monitoring the displacement of points on the surface of a large object in space.

ALEXANDER USIK received the B.S. and M.S. degrees in optoelectronics from the Saint Petersburg State University of Information Technologies, Mechanics and Optics, Russia, in 2010, and the Ph.D. degree in optics and optoelectronic systems from National Research ITMO University, Saint Petersburg, Russia, in 2014.

From 2007 to 2014, he held various positions at the Research and Production Laboratory of Opto-Electronic Systems, National Research ITMO University. From 2012 to 2014, he was a Research Engineer with the Research and Production Laboratory of Opto-Electronic Systems. He is currently the Algorithms Testing Team Leader with the Testing Department, NIPK Electron Company, Saint Petersburg. He is the author of ten articles. His research interests include computer vision, X-ray image processing and enhancing algorithms, and computed tomography reconstruction algorithms.

YONGLE LU received the M.S. degree from the Chongqing University of Posts and Telecommunications, in 2011, and the Ph.D. degree from Chongqing University, in 2015. He is currently a member of the Chinese Society of Inertial Technology and the Chinese Society of Astronautics. His main research interests include GPS/INS, navigation system and signal processing, and sensors.

KE DI was born in Shanxi, China, in 1985. He received the B.S., M.S., and Ph.D. degrees from Shanxi University, in 2010 and 2013, respectively.

YU LIU received the Ph.D. degree from Chongqing University, in 2006. He is currently a Professor with the Chongqing University of Posts and Telecommunication. His research interests include inertial sensors, navigation systems, and signal processing.

• • •