# MULTI-SENSOR CAMERA MODEL FOR CONTROLLING COORDINATES OF POINTS ON THE SURFACE OF TELESCOPES

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**Abstract**

A new optoelectronic system for measuring the reflective mirror surface distortion of large telescopes is discussed in this study. This system comprises a multi-matrix structure of CMOS sensors, each sensor responsible for capturing an image of a control point on the mirror surface through a common objective. Simulation and calculation studies show that during operation, the position of the multi-sensor camera on the supporting ring is determined by control points on the telescope surface. The more control points, the higher the accuracy of the calculations. Simulation results indicate that the camera position error falls within acceptable limits when using 5 or more control points. Experimental results show that when calculating simultaneously with 3 control points, the error in determining the angular position of the camera reaches a value of $\sigma\bar{\varphi}$ = 0.302 arc minutes, which is 2 - 2.5 times smaller than when calculating with only one control point.

***Keywords:*** *Optoelectronic system; multi-sensor camera; telescope; main reflective mirror; control point.*

## 1. Introduction

Nowadays, with the advancement of science and technology, many large-scale objects with complex structures have been constructed, such as: skyscrapers, stadiums, hydroelectric dams, or large telescopes, etc. These are composed of many small details and need to be continuously monitored and supervised to ensure safety during operation. This raises the requirement to control many different positions such as joints and nodal points on their surfaces. An area of modern science with great potential for exploration and increasing research investment is astronomy. To collect data for research, large radio telescopes with high accuracy are needed and have been researched and developed in many countries, such as LMT 50 in Mexico, SRT 64 in Italy, GBT 100 in the United States, FAST in China and Millimetron (Spektr-M) in Russia [1]. Shape accuracy is a crucial parameter for reflective mirror surfaces in radio telescopes, directly influencing their effective aperture. Large reflective mirrors are often constructed from multiple smaller panels, and these connections can deform due to environmental temperature changes or gravitational forces during operation. Therefore,

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DOI: 10.56651/lqdtu.jst.v2.n02.845.pce

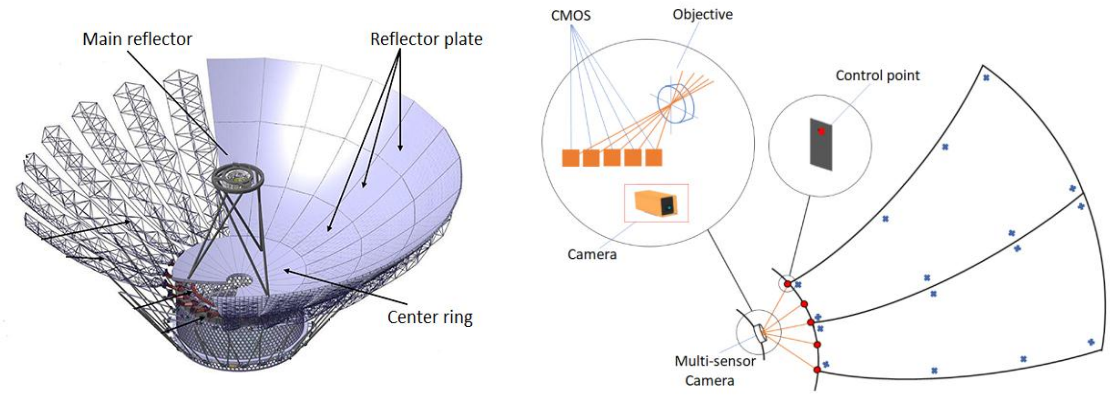
continuous measurement and control of these connection points are essential [2]. The required surface accuracy is typically very high, and several methods can be employed to determine the surface deformation of large radio telescope reflector, including radio holography, digital photogrammetry, and electronic theodolites [3, 4]. However, a common drawback of these methods is the lengthy measurement time, ranging from hours to days or even weeks, rendering them unsuitable for real-time surface monitoring during operation. Alternatively, laser scanning methods using modern equipment like Leica TPS2000, FARO Laser Tracker Xi, and TOPCON DT-200/DT-200L can achieve high accuracy [5]. However, their performance deteriorates significantly in adverse weather conditions such as rain, snow, or fog, and their scanning speed is limited when dealing with thousands of control points. While these methods offer high accuracy, they are not well-suited for real-time monitoring of telescope's reflective mirror surface errors. To address this challenge, the authors propose a specialized optoelectronic system tailored to the specific parameters of the Millimetron telescope. This system comprises individual cameras, each equipped with a single objective lens and multiple CMOS sensor matrices at the rear. Each sensor matrix captures images of infrared light-emitting diodes (LEDs) placed at corresponding control points on the reflective mirror surface [6, 7]. This optoelectronic system enables non-contact measurements with high accuracy, minimal weather influence, rapid measurement speed, and simultaneous monitoring of multiple points. Therefore, this multi-sensor camera model is well-suited for real-time control of reflective mirror surface accuracy during telescope operation.

There are many factors that greatly affect the accuracy of the measurement that need to be studied, one of which is the influence of the multi-sensor camera position error on determining the coordinates of the control points during the operation of the telescope. Therefore, controlling the camera position during the operation of the system is a task that needs to be studied and calculated accurately. To solve this problem, the author proposes a new method based on the stereoscopic principle, the camera position determined by solving the equations of the straight line connecting the control points through the main point of the objective to the sensor matrices. The specific details are presented in the next section of this article.

## 2. Multi-sensor camera system for reflective mirror surface control in telescopes

The optoelectronic system described in this study comprises multi-sensor cameras designed to monitor the reflective mirror surface of the Millimetron telescope. The cameras are mounted on a support ring of the reflective mirror, aligning their optical axes radially from the center to the edge of the mirror. Each camera consists of an objective lens and multiple sensor matrices, each matrix tasked with capturing the displacement of a corresponding control point on the reflective mirror surface (Fig. 1a) [8].

The accuracy of the radio telescope's reflective mirror surface depends on the precision of the control point displacement measurements during operation. One of the most significant factors affecting measurement accuracy is the position of the multi-sensor camera, or more precisely, its angular coordinates ψ, θ, ξ and linear coordinates Ux, Uy, Uz relative to the telescope's main coordinate system [9, 10].




*a) Millimetron telescope* *b) Structure of the multi-sensor camera*

*Fig. 1. Multi-sensor camera model controlling the reflective mirror surface of the Millimetron telescope.*

Therefore, to achieve high-precision control point displacement measurements, it is crucial to accurately determine the values of the angular coordinates ψ, θ, ξ and the linear coordinates Ux, Uy, Uz of the multi-sensor camera during telescope operation. These coordinates are subsequently compared to the initial reference data to identify camera position errors, the computer then calculates the necessary compensation to align the camera to its nominal position [11, 12].

In the case of the Millimetron telescope, the reflective mirror is composed of 24 small bamboo tape-shaped segments, each equipped with 8 control points. Each multi-sensor camera monitors two adjacent mirror segments simultaneously. To determine the camera's position during telescope operation, the study group proposed utilizing auxiliary control points located closest to the center of the reflective mirror because these points are considered the most stable and experience minimal displacement during telescope operation (Fig. 1b).

To determine the spatial coordinates of the multi-sensor camera, a new method is proposed in this study based on the stereoscopic principle. Accordingly, the spatial position of the base of the pyramid is uniquely determined by the trihedral angle created from the three sides originating from the top of that pyramid. In the multi-sensor camera model built in this study, the tops of the pyramids are the main points of the objective lens; the sides of the trihedral angle are lines of sight that intersect at the main point of the objective lens; the base of the trihedral angle is determined by infrared diodes placed at control points on the reflector surface (numbered *i*, *i* + 1, *i* + 2) and their images on corresponding sensors *i*, *i* + 1, *i* + 2 (Fig. 2).

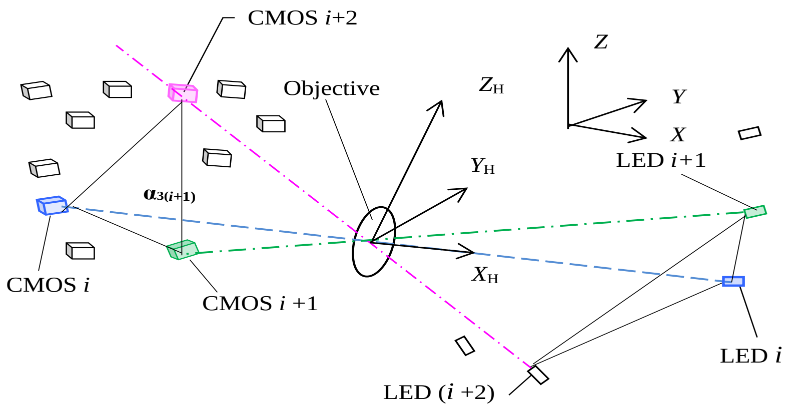



*Fig. 2. Stereoscopic principles to determine the camera's coordinates in space.*

Since these pyramids share a common apex at the principal point of the objective lens and their edges are formed by sightlines (sensor - principal point - diode), it is possible to obtain parameters of the angular and linear position in space of the pyramid apex - i.e., the position of the multi-sensor camera, by solving a system of equations consisting of straight lines coinciding with the sightlines in space.

The image coordinates of the control points, depending on the camera position, are theoretically determined by the system of equations:

$$\begin{cases} \left(p_{Hj}\right)_{2,1} = y(U_x, U_y, U_z, \psi, \theta, \xi)_j \\ \left(p_{Hj}\right)_{3,1} = z(U_x, U_y, U_z, \psi, \theta, \xi)_j \end{cases} \tag{1}$$

where *j* is the index of the sensor matrix installed in the camera.

The image coordinates of the control points on the “calibrated” mirror surface are determined by the microprocessor system of each sensor, expressed as follows:

$$\begin{cases} \left(p_{H0j}\right)_{2,1} = y_{0j} \\ \left(p_{H0j}\right)_{3,1} = z_{0j} \end{cases} \tag{2}$$

where $y_{0j}$, $z_{0j}$ are the image coordinates of the control point displayed on the $j_{th}$ sensor of the camera.

With the image coordinate array obtained from all control points from equation (2), substitute and solve the system of equations (1), the angular and linear positions of the camera at the time of "calibration" are determined. as:

$$S_0 = (U_{x0}, U_{y0}, U_{z0}, \psi_0, \theta_0, \xi_0) \tag{3}$$

During system operation, the camera position is distorted, leading to error in determining the coordinates of the control points. Then the image coordinates obtained on each CMOS sensor are determined with the error as:

$$\begin{cases} y_j = y_{0j} + \delta y_j \\ \tilde{z}_j = z_{0j} + \delta z_j \end{cases} \tag{4}$$

In this case, the results is a system of nonlinear equations:

$$\begin{cases} y(U_x, U_y, U_z, \psi, \theta, \xi)_j = y_j \\ z(U_x, U_y, U_z, \psi, \theta, \xi)_j = \tilde{z}_j \end{cases} \tag{5}$$

When solving the nonlinear equation system (5) by the Levenberg-Marquardt method, 6 spatial positioning parameters of the camera during operation are determined:

$$S = (U_x, U_y, U_z, \psi, \theta, \xi) \tag{6}$$

Comparing the resulting array $S$ from equation (6) with the nominal values of the array $S_0$ found earlier from equation (3) allows calculating the errors in determining the angular and linear positions of the multi-sensor camera during system operation.

The error in determining the spatial position of the multi-sensor camera depends on the number of equations to be solved in the system - which corresponds to the number of auxiliary control points on the reflective mirror surface of the telescope that are shown in Fig. 3.

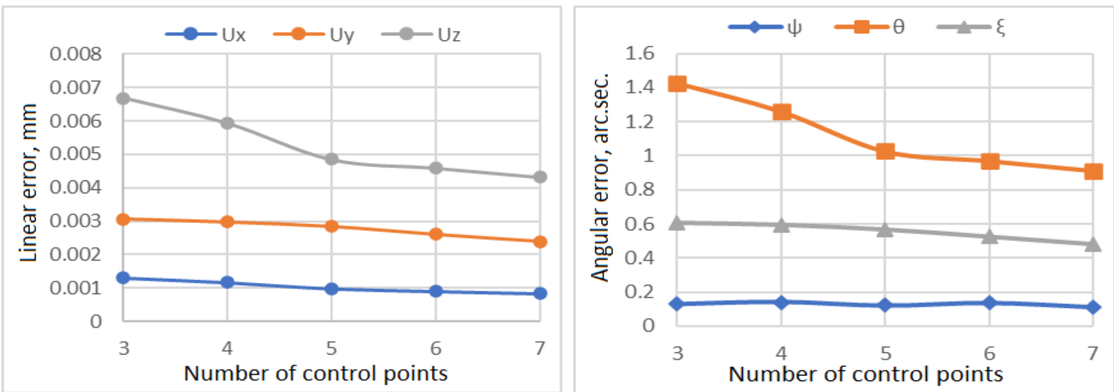



*Fig. 3. Position error of camera depends on the number of control points.*

Based on the simulation results obtained above, it can be clearly seen that the error in determining the spatial position of the camera decreases as the number of equations in the system to be solved increases, which is actually the number of control points increases. When the number of control points increases to 5 points, corresponding to using all 10 equations to solve the system, the angular position determination error does not exceed 1.0 arcsecond and the linear position is not more than 0.005 mm. During the operation of the telescope, the spatial position of the multi-sensor camera with these error values ensures that the impact on the error of the control point displacement measurement is within the allowable limit. Therefore, to determine the position of the camera during the operation of the telescope, the number of necessary control points is 5.

## 3. Experimental results and discussion

The simulation results show that the error in determining the relative position of the multi-sensor camera relative to the telescope during operation will gradually decrease as the number of observation lines "sensor - principal point of the objective lens - control point on the surface of the reflective mirror" increases. The purpose of this experiment is to verify the simulation results above. The simulation results also show that compared to the linear error, the angular position error component of the camera will be the main factor affecting the error of the control point displacement measurement, so it is necessary to have experimental research to evaluate and verify the error of determining the angular coordinates of the camera.

The experiment was conducted in the laboratory with a multi-sensor camera model mounted on a rotary table with a minimum scale division of 5 arcminutes; with 3 infrared diode sources mounted at the observation point, the distance from the observation point to the camera corresponding to the actual distance on the Millimetron telescope. There is also a computer to display and process the images obtained from the camera.

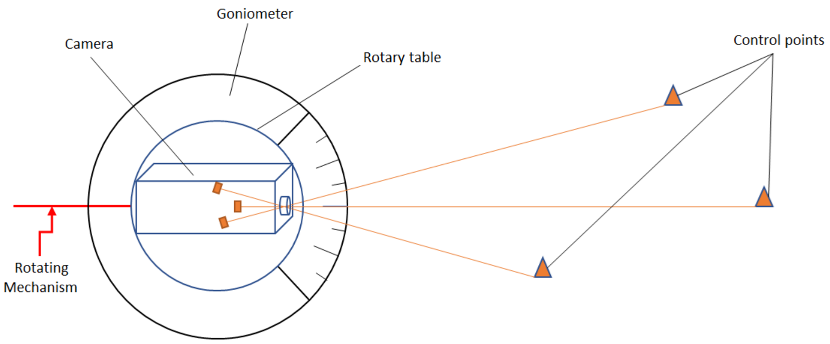



*Fig. 4. Experimental diagram to determine the relative position of the multi-sensor camera compared to the telescope during operation*

The sensor matrix used for the camera in this experiment is Omni Vision OV05620 Color CMOS QSXGA 5 MP, 2592 × 1944 pixels and pixel size of 2.2 × 2.2 µm. The infrared diodes used are L-34SF4C (GaAlAs), with a power of 20 mW, emission wavelength of 880 nm.

The images of each diode source are captured on each corresponding sensor matrix through the camera's common objective lens (due to laboratory conditions, the camera used in this experiment consists of 3 sensors). With the support of the rotary table, the multi-sensor camera is rotated around a vertical axis passing through the principal point of the objective lens by an angle of rotation $\Phi$ (deviation angle from the main optical axis of the camera) with a rotation step of $\Delta\Phi$ = 5 arcminutes, with $\Phi$ in the range from 0 to 45 arcminutes (Fig. 4).

The process of processing the image signals obtained from the sensors, determining the image coordinates of each infrared diode and calculating the rotation angle $\varphi$ of the multi-sensor camera. At each position of the camera, the result is determined by averaging the coordinates of 20 images obtained. Then the difference ($\Phi$ - $\varphi$) is determined as the error in calculating the angular position of the multi-sensor camera at each rotation angle. The actual experimental setup in the laboratory is shown in Fig. 5.

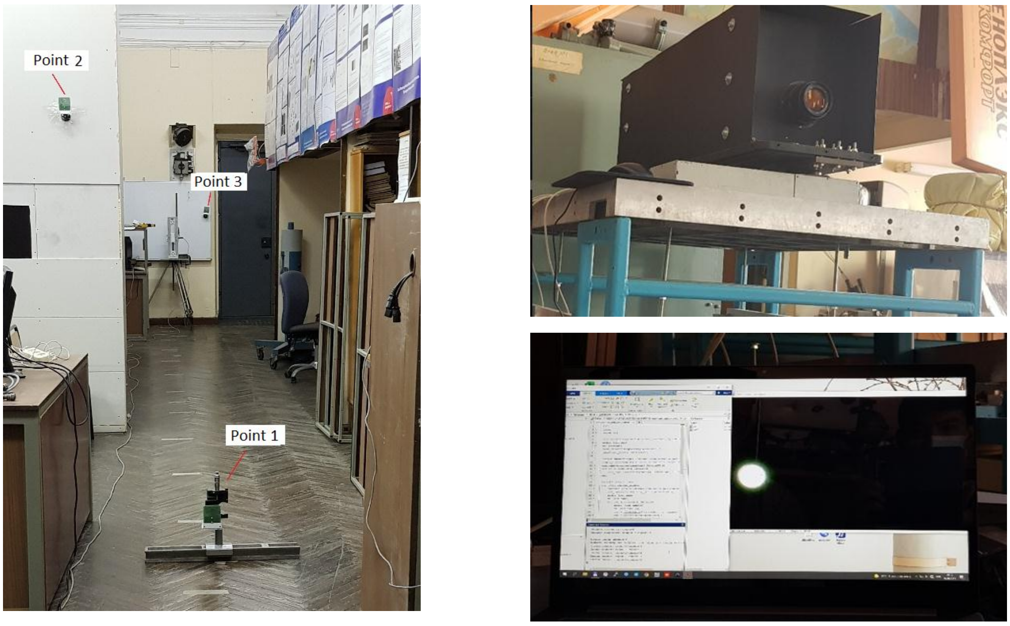



*Fig. 5. Experimental setup with multi-sensor camera model, signal processing computer and control points equipped with infrared diodes.*

Each rotation step $\Delta\Phi$ = 5 arcminutes corresponds to a displacement step $\Delta x_i$ ($i = 0\ldots9$ - number of rotation steps) of the image on the CMOS sensor head.

The average displacement value $\Delta x$ for each sensor matrix is shown in the second row of Table 1.

*Table 1. Calculation results*

| | *Control point 1* | *Control point 2* | *Control point 3* |
|---|---|---|---|
| $L$, mm | 10750 | 11274 | 14115 |
| $\Delta x$, mm | 0.667 | 0.665 | 0.654 |
| σφ, arcminutes | 0.622 | 0.684 | 0.759 |
| $\overline{\sigma\varphi}$, arcminutes | 0.302 | | |

Then the rotation angle $\varphi_i$ is calculated according to the displacement of the image on one of the three CMOS sensors, after each camera rotation step is calculated according to the following formula:

$$\varphi_i = \text{arctg}\left(\frac{\Delta x_i \cdot i}{u}\right) \tag{7}$$

where $i$ is number of rotation steps ($i$ = 0...9), $\Delta x_i$ is displacement of the image on the CMOS sensor after the $i^{th}$ rotation step and $u$ is the rear peak focal length corresponding to each sensor.

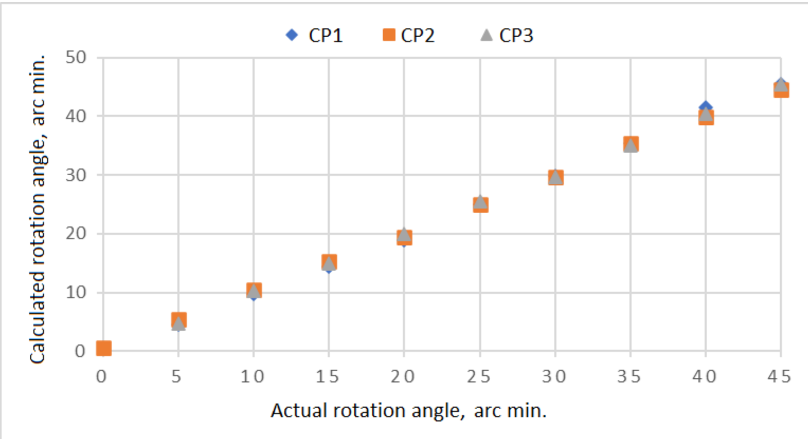



*Fig. 6. Graph of dependence of calculated rotation angle on actual rotation angle.*

The dependence of the calculated rotation angle value $\varphi_i$ on the actual rotation angle value $\Phi_i$ is shown on the graph in Fig. 6. The error in determining the angular position of a multi-sensor camera can be calculated as the mean square error value $\sigma\varphi$ – the deviation of the experimental values corresponding to each CMOS sensor from their approximate line (shown in the third row of Table 1).

Experimental rotation angle results are calculated as the average of the 3 calculated rotation angles from the 3 CMOS sensor matrices according to the following formula (8):

$$\bar{\varphi}_i = \frac{1}{3}\left(\varphi_{1i} + \varphi_{2i} + \varphi_{3i}\right) \quad (8)$$

in which $\bar{\varphi}_i$ is the calculated average value of the camera's rotation angle corresponding to the $i^{th}$ actual rotation step; $\varphi_{1i}$, $\varphi_{2i}$, $\varphi_{3i}$ are calculated camera rotation angle, corresponding to sensors 1, 2 and 3 at the $i^{th}$ actual rotation step.

After the approximation is constructed, it can be determined by calculating in a similar way that the mean square error value of the rotation angle when calculated simultaneously by three sensor matrices reaches a value of $\sigma\bar{\varphi}$ = 0.302 arcminutes (the fourth row in Table 1). This is 2 - 2.5 times smaller than the value of $\sigma\varphi$ - calculated using a single sensor matrix.

The experimental results have proven the correctness of the mathematical model, which is that the position error of the multi-sensor camera will decrease with increasing the number of control points and the number of sensor matrices corresponding to each control point.

## 4. Conclusion

This study presents an optoelectronic method for controlling the surface of large objects, specifically the reflective mirror surface of the Millimetron telescope. The optoelectronic system is set up on the basis of multi-sensor cameras, through an objective lens each sensor matrix will be responsible for monitoring the displacement of a control point on the reflective mirror surface. During the operation of the telescope, the position of the multi-sensor camera is one of the main factors that determine the accuracy of the displacement measurement. Therefore, it is necessary to accurately determine the position of the camera in space in real time.

To determine the spatial position of the camera, the study group proposed to apply the principle of stereo. Using separate control points, in combination with the principal point of the objective lens, to form triangular angles. The more control points there are, the lower the position error of the camera, according to the simulation, 5 control points are needed to ensure that the position error of the camera is within the allowed limits. Experimental results show that when using 3 control points simultaneously, the angular position error of the camera has been reduced by 2 - 2.5 times compared to using only one control point.

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# MÔ HÌNH CAMERA ĐA CẢM BIẾN ĐỂ KIỂM SOÁT TỌA ĐỘ CÁC ĐIỂM TRÊN BỀ MẶT CỦA KÍNH THIÊN VĂN

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**Tóm tắt**: Một hệ thống quang điện tử mới để đo độ biến dạng bề mặt gương phản xạ của kính thiên văn kích thước lớn được đề cập đến trong nghiên cứu này. Hệ thống này bao gồm cấu trúc đa ma trận cảm biến CMOS, mỗi cảm biến đảm nhiệm thu hình ảnh của một điểm kiểm soát trên bề mặt gương thông qua một vật kính chung. Các nghiên cứu mô phỏng, tính toán cho thấy trong quá trình vận hành, vị trí của camera đa cảm biến trên vòng đỡ được xác định bởi các điểm kiểm soát trên bề mặt của kính thiên văn. Số lượng điểm kiểm soát càng nhiều thì độ chính xác của tính toán càng cao, kết quả mô phỏng cho thấy sai số vị trí của camera nằm trong giới hạn cho phép khi sử dụng từ 5 điểm kiểm soát. Kết quả thực nghiệm cho thấy khi tính toán với đồng thời 3 điểm kiểm soát thì sai số xác định vị trí góc của camera đạt giá trị $\sigma\overline{\varphi}$ = 0,302 phút góc, nhỏ hơn từ 2 - 2,5 lần so với khi tính toán chỉ với một điểm kiểm soát.

***Từ khóa:*** *Hệ thống quang điện tử; camera đa cảm biến; kính thiên văn; gương phản xạ chính; điểm kiểm soát.*

Received: 23/07/2024; Revised: 19/09/2024; Accepted for publication: 30/10/2024

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