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INSTRUMENT-MAKING AND-INFORMATION-MEASURING SYSTEMS

ПРИЛАДОБУДУВАННЯ ТА ІНФОРМАЦІЙНО-ВИМІРЮВАЛЬНІ СИСТЕМИ

UDC 681.518

OPTICAL SYSTEM FOR CONTROL OF ANTENNA MIRROR SHAPE

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Summary: *The possibilities of optical triangulation method (triangle method) for investigation of antenna mirror shape are analyzed. It is shown that developed by the authors method of optical triangulation with the variable measuring base reduces the requirements for measurement accuracy by replacing a part angular measurements by linear ones. On the basis of the method the scheme of optical device is designed, the working model is constructed and its experimental testing is carried out. The obtained results proved that the developed method and scheme of the optical device make it possible to control the mirror surface shape with the necessary in antenna engineering accuracy.*
Key words: *optical triangulation, laser, optical device, mirror antenna.*

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Statement of the problem. The efficiency of mirror antennas use for radio communication purposes is determined by their electrical characteristics, such as radiated pattern, directivity coefficient, gain factor, etc. Antenna characteristics are considerably determined by the correspondence of parabolic mirror surface shape to the theoretically calculated one. Thus, while designing large space radio communication antennas (antenna mirror diameter is 3-20 meters), the permissible mirror surface deviations from the theoretical one are limited by ~ ±0.3 mm level [1, 2].

Modern methods of antenna mirror shape monitoring are divided into contact and non-contact. Contact methods are based on mechanical templates and micrometric measuring tools [3]. The main disadvantages of such methods are low accuracy and slow response limiting their practical use.

Non-contact surface control methods based on the remote measurement principle use light or radio- radiation and without these disadvantages but require expensive equipment and high-precision mechanical units [4]. Therefore, the development of measuring devices combining advantages of remote measurement principle and availability for use remains important.

Analysis of the investigation methods. The objective of the paper is to develop the method and appropriate optical system for coordinate measurements of antenna mirror surface.

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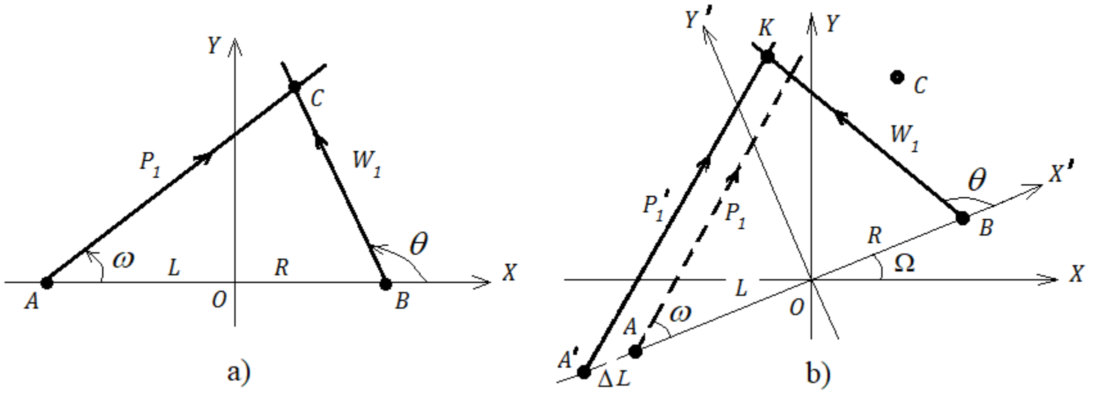


Figure 1. Schemes of surface coordinate measurements in the optical triangulation method (a) and in the optical triangulation method with the variable measuring base (b).

Triangulation optical method (method of triangle) is taken as the basis [5]. According to the method, Fig. 1a), two light beams P_1, W_1 are directed at angles ω, θ from the ends of certain measurement base $AB = R + L$ and intersect at controlled surface point, for example, point *C*, are formed for coordinate measurements.

For analysis we take two dimensional version of the method where points *A, B, C* are located at the same plane *XOY*.

It is easy to prove that the following expressions correspond to coordinates of point C:

$$x = \frac{R + L \cdot tg\omega \cdot ctg\theta}{1 - tg\omega \cdot ctg\theta} \quad , \tag{1}$$

$$y = \frac{R + L}{ctg\omega - ctg\theta} \quad . \tag{2}$$

As the result of error in angles ω, θ measurement, the errors in calculation point coordinates Δx, Δy occur. Appropriate differentials are used for their estimation. In such a case the boundary error values Δx, Δy meet the inequalities:

$$|\Delta x| \le \left|\frac{\partial x}{\partial \omega}\right| \cdot \Delta\omega + \left|\frac{\partial x}{\partial \theta}\right| \cdot \Delta\theta \quad , \tag{3}$$

$$|\Delta y| \le \left|\frac{\partial y}{\partial \omega}\right| \cdot \Delta\omega + \left|\frac{\partial y}{\partial \theta}\right| \cdot \Delta\theta \quad , \tag{4}$$

where $\Delta\omega, \Delta\theta$ are boundary permissible errors of the experimental equipment in angles ω, θ determination.

Let us estimate the boundary permissible errors of angles ω, θ measurements for certain experiment geometry. Suppose R = 300 mm, L = 700 mm, θ= 90°, ω=70°. If permissible errors of Δx, Δy coordinates determination are ~ ± 0.3 mm, then using expressions (1-4) and taking into account that $\Delta\omega \approx \Delta\theta$ we get that errors $\Delta\omega$, $\Delta\theta$ should not exceed 1,1´´. In case of reducing requirements to coordinate measurement accuracy up to the value ~ ±0.5 mm, the errors of angles ω, θ determination should not exceed 1,8´´. Thus, analysis of optical triangulation method proves that the control of antenna mirror shape accuracy requires application of high-precision and obviously expensive equipment..

The authors propose the version of optical triangulation method where angles ω, θ values remain constant during coordinates measurements, and intersection of beams P_1 and W_1 at control point, for example, at point K, Fig. 1b), are reached by rotating the measurement base *AB* at angle Ω and changing the measurement base by value ΔL.

The surface points coordinate in the coordinate system XOY are as follows:

$$x = \frac{R + (L \pm \Delta L) \cdot tg\omega \cdot ctg\theta}{1 - tg\omega \cdot ctg\theta} \cdot \cos\Omega - \frac{R + L \pm \Delta L}{ctg\omega - ctg\theta} \cdot \sin\Omega \quad , \tag{5}$$

$$y = \frac{R + (L \pm \Delta L) \cdot tg\omega \cdot ctg\theta}{1 - tg\omega \cdot ctg\theta} \cdot \sin\Omega + \frac{R + L \pm \Delta L}{ctg\omega - ctg\theta} \cdot \cos\Omega \quad . \tag{6}$$

In this case the boundary errors in coordinates Δx, Δy calculation satisfy the inequalities:

$$|\Delta x| \le \left|\frac{\partial x}{\partial L}\right| \cdot \Delta L + \left|\frac{\partial x}{\partial \Omega}\right| \cdot \Delta\Omega \quad , \tag{7}$$

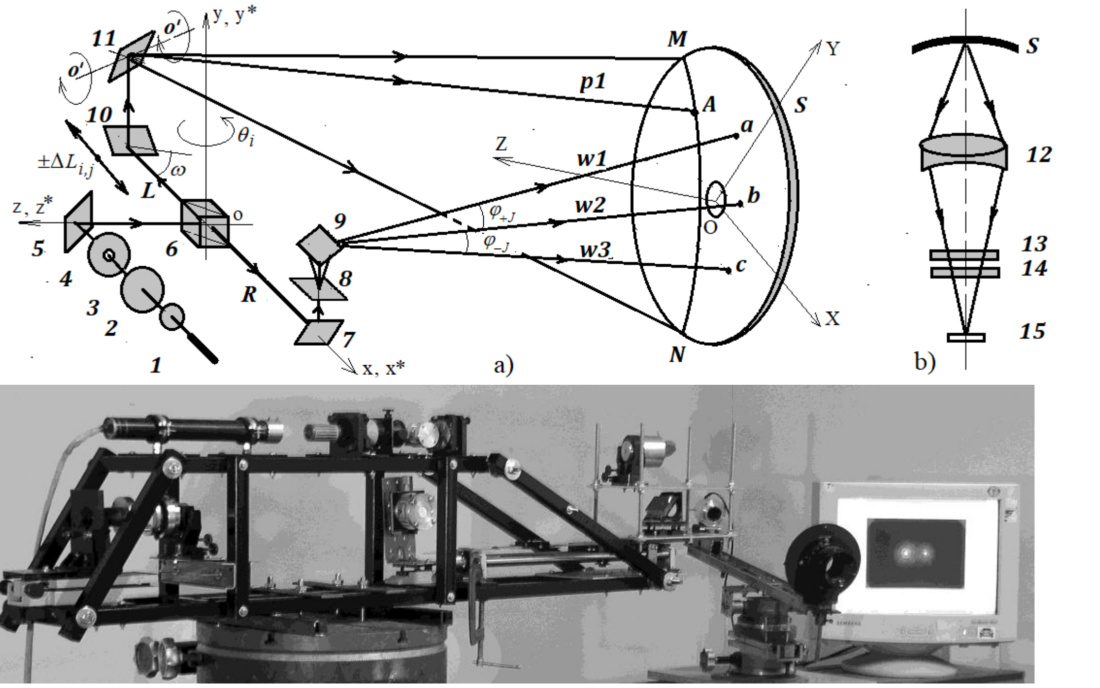
$$|\Delta y| \le \left|\frac{\partial y}{\partial L}\right| \cdot \Delta L + \left|\frac{\partial y}{\partial \Omega}\right| \cdot \Delta\Omega \quad . \tag{8}$$

Using expressions (5 – 8) and taking into account the experiment geometry, as in the previous case, we get requirements concerning the accuracy of measurement base length determination $R + L \pm \Delta L$ and rotation angle Ω. If permissible errors of the length determination are ±0.3 mm, then the boundary errors of the measurement base length determination are ~ 0.1 mm and for rotation angle Ω are ~ 5´´. In case of permissible error of coordinate determination ~ ±0.5 mm, the requirements to the errors of base length determination are reduced and are ~ 0.2 mm, and requirements to the rotation angle are ~ 7´´.

Hence, analysis and quantitative estimates of both methods prove that optical triangulation method with variable measuring base reduces the requirements concerning angular measurement accuracy by several times. The number of angular measurements is also reduced due to the measurements of base length change, and length control with ~ (0.1 – 0.2) mm is technically easier to realize.

Results of the investigations. On the basis of the method with variable measurement base, the device optical scheme is designed and working model is produced, Fig. 2. Optical-mechanical units of the device are mounted on the metal platform rotating in horizontal plane.

In order to analyze the optical scheme let us introduce two rectangular coordinate systems – stationary oxyz and rotational system $o^* x^* y^* z^*$. In the initial state both coordinate systems coincide, moreover axis oy and axis oy^* are directed perpendicular towards the rotating platform plane and passes through its rotation axis. The operation of optical device is as follows, Fig. 2 a).



c)

Figure 2. The optical scheme of the device (a), photographic system (b) and appearance of the working model (c).

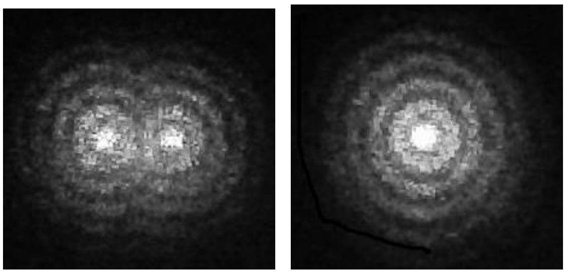
The radiation of *He-Ne* laser 1 is expanded by the system of positive lenses 2, 3, passes through amplitude ring diaphragm 4, and mirror 5 is directed to prism - cube 6. The prism divides the beam into two parallel and oppositely directed parts with length *R* and *L*. The geometric axes of both beams coincide with the coordinate axis ox .

The light beam *R* serves to create a set of light spots on surface *S*. For this purpose, due to the flat mirrors 7, 9 and diffraction grating 8 the set of discrete-directed beams *w1, w2, ..., wn* is formed in the vertical device plane (only three beams are shown in Fig.2a). On the surface S the beams form light spots defined by points *a, b, c ,...* . The total number of beams *n* and angles φ_j (j = 0, ±1, ±2, … , ±n) between them are definitely determined by grating characteristics such as width, depth, and groove shape. The angle between the beam *R* and the plane with diffracted beams is 90°.

The beam *L* is used to create the measurement base of the device with length *R+L* and values of its changes $\pm\Delta L_{i,j}$ are determined in measurement process (i = 1,2,…, m is numbering of plane cross-sections). For this purpose the beam *L* is directed by mirrors 10, 11 towards the area with spots at the fixed angle ω. The mirror 11, rotating around axis o′o′ perpendicular to its plane of incidence, produces in the vertical plane a continuous set of light spots which trails on the surface *S* are denoted by the curve *MN*. The given beams, as a rule, do not coincide with spots *a, b, c* , … on the plane, therefore for their mutual superposition the mirrors 10, 11 are displaced along the beam *L* at corresponding distances $\pm\Delta L_{i,j}$. It is obvious that measurement base value for each spot *a, b, c* , … is different and equals $R+L\pm\Delta L_{i,j}$ value.

To create the light spots in other vertical cross-sections of the surface *S* the platform together with the optical system 1 – 11 rotates in horizontal plane at corresponding angles θ_i and measurements are repeated. In the given case the values $\Delta L_{i,j}$ are obtained in rotation coordinate system $o^* x^* y^* z^*$.

Observations of the light spots superimposition on the surface is carried out by means of photographic system the scheme of which is shown in Fig. 2 b). It consists of long focus optical lens 12, the set of wide-band 13 and narrow-band 14 (interference) red light filters, necessary for laser radiation filtering from surrounding light, and digital photomatrix 15. The photographic system produces 50-fold spots increase on the computer monitor making it possible to control their alignment with accuracy ~ 0,1 mm, Fig. 3 a,b). In this case, the size of the central maximum of light spots on the surface S was ~ 0.3 mm.



a) b)

Figure 3. Image of light spots on the surface before (a) , and after mutual overlay (b).

The procedure for coordinate measurements of the points of the surface is as follows. At the beginning the light spots coordinates in the device coordinate rotation system– $o^*x^*y^*z^*$ are determined and their recalculation to the stationary coordinate system – oxyz is carried out. The obtained results were transformed into coordinate system OXYZ of the investigated surface for their further comparison with the theoretical data.

The spots coordinates $x_{i,j}, y_{i,j}, z_{i,j}$ in the device stationary coordinate system are connected with moving system according to the following expression:

$$\begin{pmatrix} x_{i,j} \\ y_{i,j} \\ z_{i,j} \end{pmatrix} = \begin{pmatrix} \cos\theta_i & 0 & \sin\theta_i \\ 0 & 1 & 0 \\ -\sin\theta_i & 0 & \cos\theta_i \end{pmatrix} \cdot \begin{pmatrix} x^*_{i,j} \\ y^*_{i,j} \\ z^*_{i,j} \end{pmatrix}, \quad (9)$$

where i = 1, 2,…, n is numbering of the surface cross-sections in vertical plane; j = 0, ±1,…, ±m is numbering of the surface cross-sections in horizontal plane; $x^*_{i,j} = R$; $y^*_{i,j} = (R + L \pm \Delta L_{i,j}) \cdot tg\omega \cdot tg\varphi_j$; $z^*_{i,j} = -(R + L \pm \Delta L_{i,j}) \cdot tg\omega$.

The relationship of the obtained surface coordinate points with coordinates in its own coordinate system OXYZ is denoted by the following linear transformation:

$$\begin{pmatrix} X_{i,j} \\ Y_{i,j} \\ Z_{i,j} \end{pmatrix} = \begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} \cdot \begin{pmatrix} x_{i,j} \\ y_{i,j} \\ z_{i,j} \end{pmatrix} + \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}, \quad (10)$$

where $\begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix}$ is the matrix of rotation coefficients, $\begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}$ is the vector of parallel coordinate origin transfer from oxyz to coordinate system OXYZ .

In order to determine the matrix of rotation coefficients and vector of parallel transfer, let us assume that on the investigated surface in the device coordinate systems oxyz and OXYZ of the surface itself, the coordinates of four arbitrary chosen spots are known. Let it be spots with indices (i, j) equal (1, 0), (1, 1), (1, -1) and (2, 0). In this case, using expression (10) we get three independent systems of equations for determination of matrix rotation coefficients and components of parallel transfer vector, such as:

:

$$\begin{pmatrix} t_{11} \\ t_{12} \\ t_{13} \\ X_0 \end{pmatrix} = \begin{pmatrix} x_{1,0} & y_{1,0} & z_{1,0} & 1 \\ x_{1,1} & y_{1,1} & z_{1,1} & 1 \\ x_{1,-1} & y_{1,-1} & z_{1,-1} & 1 \\ x_{2,0} & y_{2,0} & z_{2,0} & 1 \end{pmatrix}^{-1} \cdot \begin{pmatrix} X_{1,0} \\ X_{1,1} \\ X_{1,-1} \\ X_{2,0} \end{pmatrix}, \tag{11}$$

$$\begin{pmatrix} t_{21} \\ t_{22} \\ t_{23} \\ Y_0 \end{pmatrix} = \begin{pmatrix} x_{1,0} & y_{1,0} & z_{1,0} & 1 \\ x_{1,1} & y_{1,1} & z_{1,1} & 1 \\ x_{1,-1} & y_{1,-1} & z_{1,-1} & 1 \\ x_{2,0} & y_{2,0} & z_{2,0} & 1 \end{pmatrix}^{-1} \cdot \begin{pmatrix} Y_{1,0} \\ Y_{1,1} \\ Y_{1,-1} \\ Y_{2,0} \end{pmatrix}, \tag{12}$$

$$\begin{pmatrix} t_{31} \\ t_{32} \\ t_{33} \\ Z_0 \end{pmatrix} = \begin{pmatrix} x_{1,0} & y_{1,0} & z_{1,0} & 1 \\ x_{1,1} & y_{1,1} & z_{1,1} & 1 \\ x_{1,-1} & y_{1,-1} & z_{1,-1} & 1 \\ x_{2,0} & y_{2,0} & z_{2,0} & 1 \end{pmatrix}^{-1} \cdot \begin{pmatrix} Z_{1,0} \\ Z_{1,1} \\ Z_{1,-1} \\ Z_{2,0} \end{pmatrix}. \tag{13}$$

Having the values of the rotation coefficients and the parallel transfer vector, it is easy by means of the expression (10) to carry out coordinate recalculation for the rest points of the investigated surface into its own coordinate system OXYZ.

The estimation of the technical capabilities of the developed method and the device optical scheme was carried out by experimental investigation the known a priori plane surface shape and the parabolic surface of the antenna mirror. The device base was 1000 mm, the distance to the investigated surface was ~ 3000 mm.

The graphs of dependence z = f(x) and measurement errors for flat surface in the device coordinate system oxyz are represented in Fig. 4 a, b). Measurements were carried out in three cross-sections of the surface S, namely in the directions of zero, plus the first and minus the first orders of diffraction grating. The interval of measurement base θ_i rotation angle was 10 degrees with 1 degree step.

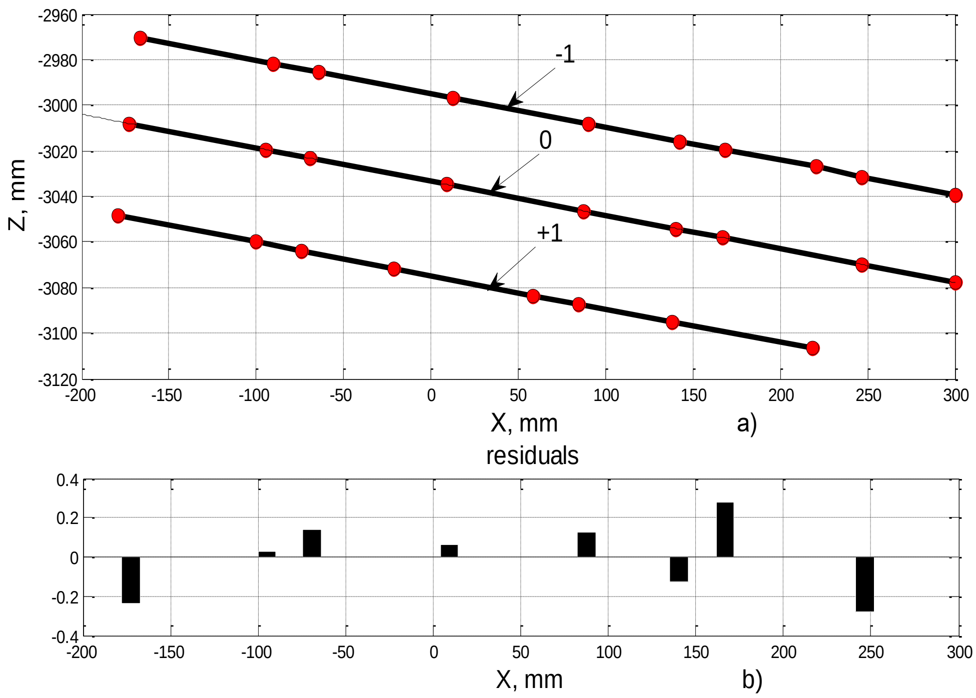
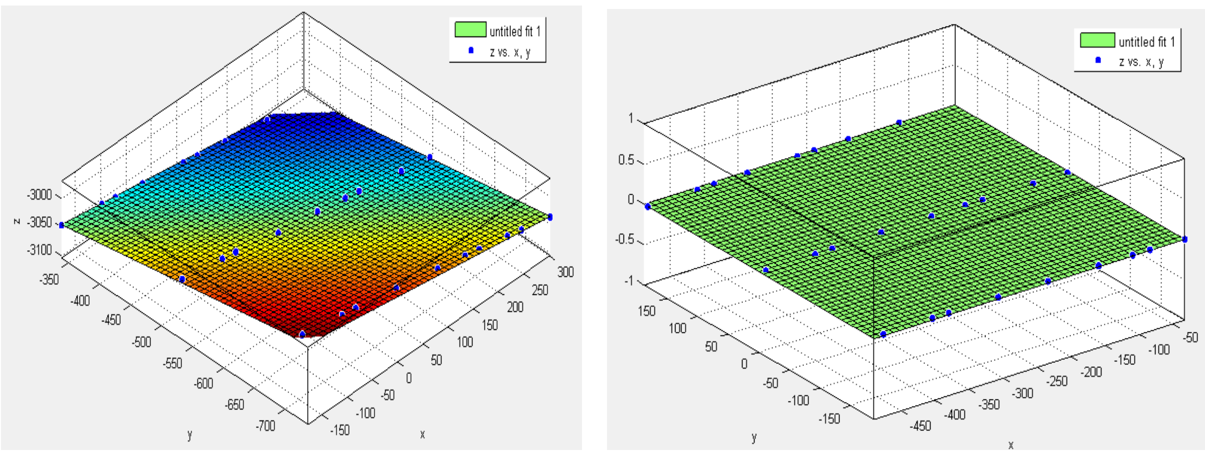


Figure 4. The graphs of the dependence z=f(x) for three plane surface cross-sections corresponding to zero diffraction order (0), plus the first order (+1) and minus first order (-1) (a).
Deviations of experimental data from line (b).

Approximation of experimentally obtained data by line indicates that for the cross-section corresponding to zero diffraction order, the deviations of the coordinates are located in ± 0.4 mm range, Fig. 4 b). For other cross-section coordinates deviations from approximation lines are within the same limits.

Data approximation by the plane was carried out for three surface cross-sections on coordinate array. The corresponding graphs z = f (x, y) in the device coordinate system - oxyz and the plane surface - OXYZ are shown in Fig. 5 a, b).



a) b)

Figure 5. The graphs z = f (x,y) for the plane surface in the device coordinate system – oxyz (a) and the plane surface coordinate system – OXYZ (b).

The graph of z = f(x) dependence for parabolic antenna mirror in cross-section corresponding to zero order diffraction is shown in Fig. 6 a). The data are given for the coordinate system of the mirror.

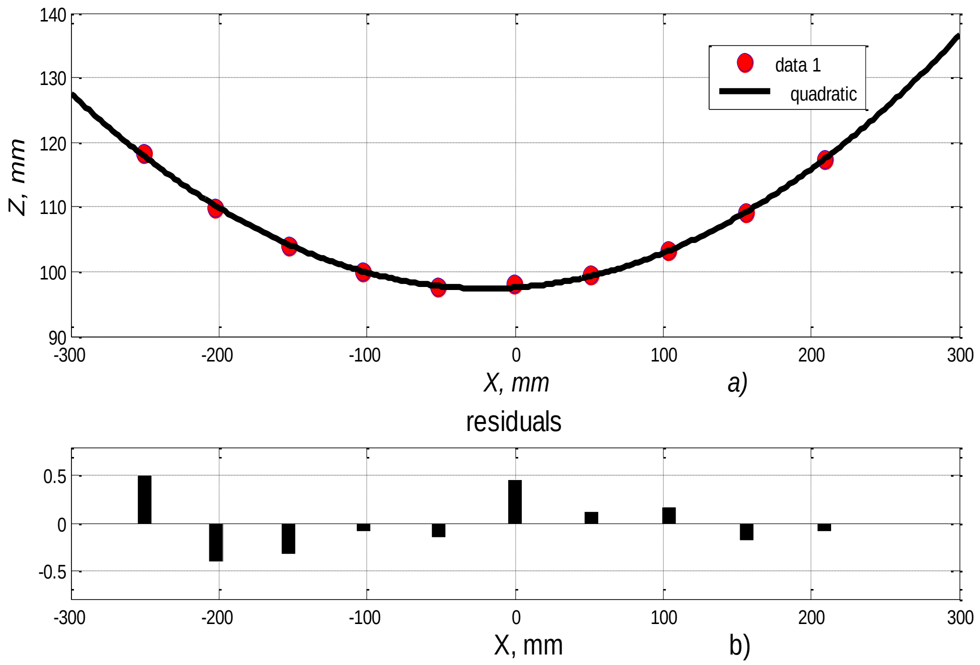
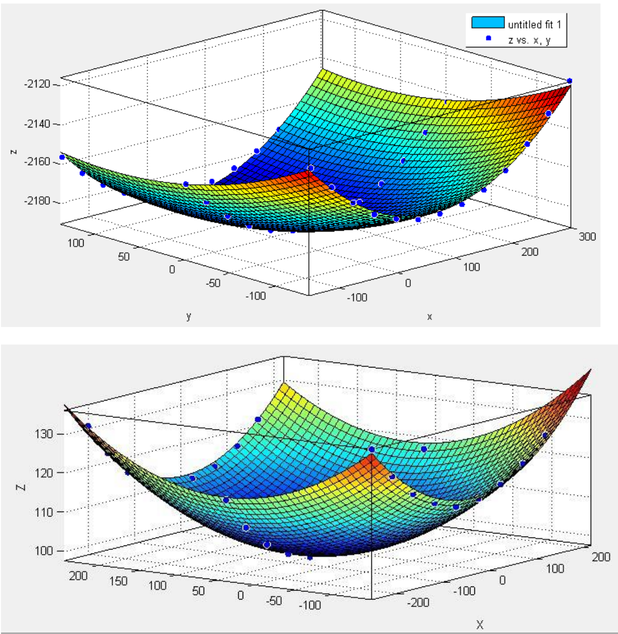


Figure 6. The graph of the dependence z = f (x,y) in the mirror coordinate system – OXYZ (a). Deviations of the coordinates of the surface when approximating by the curve of the second order (b).

Approximation of the measurements results by the second order curve proves that its deviations are located within the range ±0,5 мм, Fig. 6 b). For other surface cross-sections deviations from the approximation curve are at the same limits.

Data array coordinate approximation by the second order surface is carried out for three surface cross-sections. Approximation results in the coordinate system of device oxyz and antenna mirror OXYZ are shown in Fig. 7 a,b) relatively.



a)

b)

Figure 7. The graphs z = f (x,y) of the parabolic mirror in the coordinate system of the device – oxyz (a) and in the coordinate system of the mirror – OXYZ (b).

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Conclusions. The method of optical triangulation with variable measurement base which makes it possible to reduce the requirements for measuring equipment accuracy due to replacing the part of angle measurements by linear ones was developed. On the basis of the given method the device optical scheme for measurement of the points coordinates of antenna mirror surface is designed. Diffraction grating use for light spot formation provides constant angle relations between them, makes it possible to reduce the number of angular measurements and simplify the optical device structure. On the basis of the designed optical scheme the optical device operating model was produced. The procedure of the surface points coordinates transfer from the optical device coordinate system into the coordinate system of surface investigated is developed. The test of the developed method and optical device while investigating the shape of flat and parabolic surfaces is carried out. The obtained experimental results proved the possibility of their use for control of antenna mirror surface with accuracy ~ (0,3 – 0,5) мм.

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ОПТИЧНА СИСТЕМА ДЛЯ КОНТРОЛЮ ФОРМИ ДЗЕРКАЛА АНТЕНИ

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Резюме: *Аналізуються можливості методу оптичної тріангуляції (метод трикутника) із постійною вимірювальною базою для дослідження форми дзеркала антени. Встановлено, що для проведення вимірювань координат поверхні з точністю порядку (0.3-0.5) мм необхідно проводити кутові вимірювання з точністю ~ (1.1-1.8) секунд. Такі вимоги приводять до потреби використання дорогого по собівартості вимірювального обладнання. Авторами статті пропонується певна модифікація методу, а саме метод оптичної тріангуляції із змінною вимірювальною базою, який дозволяє у декілька разів знизити вимоги до точності кутових вимірювань. При вище вказаній точності вимірювань форми поверхні вимоги до кутових вимірювань зменшуються і складають ~ (5 -7) секунд. Крім цього, зменшується загальна кількість кутових вимірювань за рахунок проведення лінійних вимірювань зміни довжини бази. Необхідна точність контролю величини бази складає у даному разі (0.1-0.2) мм , що не є технічно складною задачею. На основі методу розроблено відповідну схему оптичного пристрою. Особливістю схеми являється спосіб формування світлових марок на дослідній поверхні. Використання спеціальної форми амплітудної фільтруючої лазерне випромінення діафрагми дозволяє формувати малорозмірні марки , діаметром порядку 0.3 мм із збереженням їх величини на глибину 2-3 метри по ходу лазерних пучків. Малі розміри марок дозволяють збільшити точність взаємного суміщення марок в методі оптичної тріангуляції і тим самим збільшити точність вимірювань координат точок поверхні. З метою зменшення кількості кутових вимірювань пропонується дискретно-направлене опромінення поверхні в різних площинах. Для цього застосовано фазову дифракційну решітку, яка створює множину світлових марок з фіксованими напрямками розповсюдження . На основі розробленої схеми виготовлено діючий макет оптичного пристрою та проведено його експериментальне опробування. В якості об'єктів дослідження вибирались завідомо плоска розсіююча світло поверхня та параболічне дзеркало антени. Результати опробувань засвідчили, що розроблений метод оптичної тріангуляції із змінною вимірювальною базою та відповідний оптичний пристрій дозволяють проводити контроль форми дзеркала антени з необхідною в антенобудуванні точністю. Для перерахунку координат точок поверхні, отриманих в системі координат пристрою до системи координат дослідної поверхні розроблено відповідний математичний апарат.*

Ключові слова: *оптична тріангуляція, лазер, оптичний пристрій, дзеркальна антена.*

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