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Improvement of Metrological Characteristics of the Antenna System Using Smart Angle Sensor.

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Abstract **— Techniques for the improvement of the metrological and functional characteristics of the tracking antenna system due to designed optoelectronic smart angle sensor with built-in functions of detection and compensation of errors in mechanical constructions is considered. Performance characteristics and results of experimental research of dual-channel optoelectronic angle sensor are described.**

Keywords—smart sensor; antenna station; contlol system; encoder; optoelectronic; mechanical constructions

I. INTRODUCTION

Development of space communication systems and Earth Remote Sensing (ERS) from space using high operating frequencies (more than 18 GHz) requires increased accuracy of ground antenna stations (AS) with reflectors of large diameters (3-12 m) up to angular minutes units and less, in order to provide reliable information reception within the range of direction diagram of antenna beam on 3 dB level.

Inside the system of pointing precision control and dynamic support of spacecrafts devices which determine angular positions of AS axis − angle sensors are the main key nodes providing accuracy control by means of such pencil-beam AS. Despite numerous researches and results achieved in designing different types of angle sensors [1], much attention to the problems of effective development of techniques and tools for highly accurate and most efficient angular measurement devices for target problematic area is paid in scientific resources [1-3].

Distinction of large scale AS control weighting from some to dozen tons, is significant influence of support-rotary platforms (SRP) on measurement accuracy of angular positions of AS axes, and as a result - determination of the dimensional pointing angle of AS electrical axis beam.

Tracking of low-orbit ERS satellites additionally requires of full-rotating AS SRP to support wide range of rotation angles covering ±270 degrees sectors and high angular rotation speed, up to ten degrees per second. Error of angle measure in such AS mostly depends on construction of the connection node between sensor and AS axes, and also constructional characteristics of SRP itself, rather than accuracy of angular sensor.

For high-quality operating of AS pointing control system and satellite tracking, especially during short-term connection sessions with ERS satellites, it is important to control quality of installation and connection between angular sensors and AS axes as well because mechanical displacements of turning axes or skewing (break) in measuring mechanisms can cause significant errors while pointing AS at a satellite. Therefore, to realize such functions, more complex smart sensors are required [4].

Techniques of reducing the influence of a number of AS constructional errors using optoelectronic angular devices with built-in microcontroller and software which possess smart functions of rating and correcting of some errors caused by mechanical nodes, adaptation of their characteristics to meet application conditions while processing information about AS angular position is proposed in this article.

Aim of the research – to increase metrological and functional characteristics of the tracking AS using designed smart optoelectronic angle sensor with built-in functions of detection and compensation of errors occurring in mechanical constructions.

II. ANALYSIS OF ANTENNA SYSTEM ERRORS AND METHODS OF THEIR COMPENSATION

Total electrical axis pointing error for AS with reflector diameter more than 3m and direction diagram width not more than 10-20 angular minutes is influenced by numerous instrumental, methodical, astronomical errors factors systematic or random by their nature. The reasons their occurrence are connected with both mirror part of the AS and SRP construction and are analyzed in different sources, for instance [5]. Among them are instrument errors caused by skew in large-scale SRP constructions and joint mechanisms of angle sensors. Their behavior is unchangeable during a large period of time or changes according to the certain law. Such errors are as follows:

- errors from axes deviation from alignment or angle sensors shafts and SRP axes skewing ;
- errors Δ_ψ of vertical AS axis installation (deviation from verticality);

- errors Δ_η from non-perpendicularity of SRP horizontal axis relatively to vertical one (when the latter is properly installed);
- errors Δz from non-perpendicularity of antenna axis relatively to horizontal axis;
- errors caused by deformations of support-turning device and mirror system as a result of gravity and wind loadings and differential solar heating.

Some AS constructions for communication with ERS satellites provide special deviation of vertical axis to avoid connection loss with low-orbit satellites in so-called "dead zones" in case when satellite trajectory lies through zenith relatively to AS location [6]; this also complicates angular position evaluation. In that case antenna beam direction along angle β location in topographometric coordinate system is determined taking into account slope angle γ of the vertical axis and rotation angle in azimuth $\alpha 2$ in ratio:

$$\beta = \operatorname{arctg}\left(\frac{\cos\gamma \cdot \sin(\alpha 2 - \gamma) + \sin\gamma \cdot \cos(\alpha 2 - \gamma) \cdot \cos\alpha 1}{\sqrt{1 - (\sin\gamma \cdot \cos(\alpha 2 - \gamma) \cdot \cos\alpha 1 + \cos\gamma \cdot \sin(\alpha 2 - \gamma))^2}} \right) \quad (1)$$

Constructive methods for AS errors reducing also increase requirements to accuracy, complicate mechanical nodes of SRP and can cause increasing of assembly, setup and support costs. Electronic and program-algorithmic methods of pointing accuracy increasing are much more effective. They are more versatile, do not require high material spending and simultaneously increase functional abilities of antenna complexes in general.

According to AS SRP construction characteristics, technological process of pointing and tracking, especially of low-orbit satellites, angular measuring devices should provide not only high static and dynamic accuracy of angle measurement, but also a wide range of angular positions measurement associated to solar coordinates, long-range data transition, high reliability and simple interaction with AS pointing control, convenience of initial setup and association with solar coordinates (justification) with high accuracy ($\leq$ 1 angular minute). Angle sensor should provide absolute measurement of the angle directly after turning on power, because association with initial measurement point as in incremental sensors needs long time, or is complicated due to SRP constructive limitations.

III. STRUCTURE AND OPERATING PRINCIPLE OF SMART ANGLE SENSOR

Angle sensor operation principle is based on a method of absolute angular position determination using one route with pseudo-random code sequence from sectors of different width and code reading and processing by means of one-row photo matrix located along the chord of the disk.

Similar principle is described in patents in USA, Germany, etc [7, 8]. Disadvantages of the given angle determination methods are measurement errors caused by deviations of the code disk axis which in its turn can be resulted by eccentricity of the code disk, bearings wear, and also by influence of joint mechanisms of shafts and connections between the sensor and antenna axis.

According to the method of determination of code disk axis deviations patented by us [9], we have design optoelectronic sensor of absolute angular position able to determine and compensate errors caused by technological reasons of manufacturing, as well as constructive-technological factors occurring at connection of sensor shaft with AS axis. .

Structural scheme of optical-electronic angle sensor and ruler fragment are shown in figure 1.

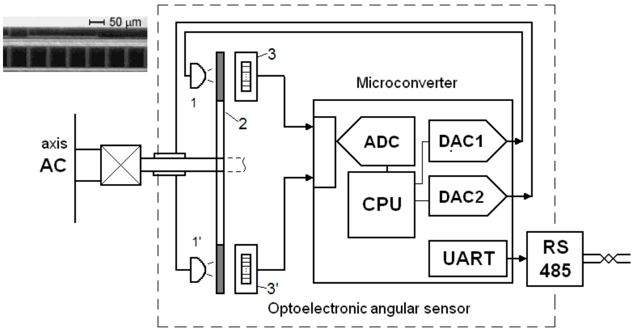

Figure 1. Structural scheme of angle sensor with compensation of axis deviation

Disc 2 with code sequence of different width sectors marked on it is attached to sensor axis, which loose end is connected to antenna axis. Along the disks chord there are two one-row multi element photodetector devices 3, 3', formed by 128 photoelectric detectors (pixels) sized 55,5*62,5 μm each, located in one row. Using light sources 1, 1' (light diodes in SMD-0603 case) image of code routed is projected on light-sensitive surface of one-dimensional photo matrix into code sequence of light and dark bands.

Code sequence of the disc is built in such way that any sector fragment projected onto photo matrix occurs only once in the whole code sequence. Using micro converter ADC, in the dynamic storage we get unique images of code disc fragments for given position (2) projected onto each sensor array (Figure 2).

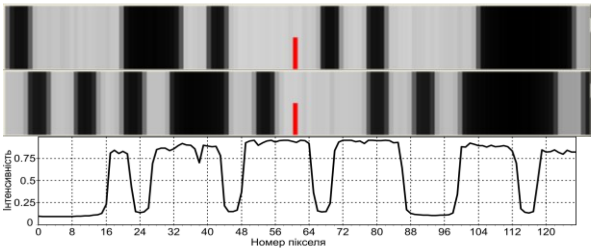

Figure 2. Image and sygnal, received from photo matrix

Using table processing in the micro converter and recognition of code sequence fragment, we obtain rough calculation of angular position of sensor axis with the accuracy of sector angular width in form of angle α_1

between disk reference point (beginning of sector 0) and beginning of sector ***s***, which is projected onto the center of photodetector ruler (α_3 − for the upper sensor array) (figure 3).

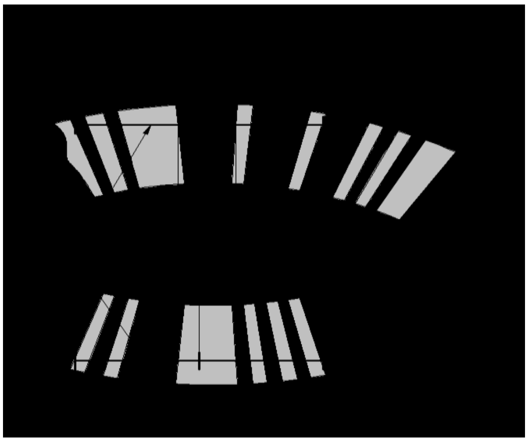

Figure 3. Scheme of disc turning angle determination

Further for each sensor array we determine distances from the center of sensor array to edges of corresponding "central" sector $b_1 \ldots b_4$ (fig.3). Application of subpixel image processing algorithm [10,11] allows us to determine distances to sector edges with the resolution higher than pixel's width that is 2 µm.

Angular position of the disc is determined from trigonometric transformations:

$$\phi_r = \frac{\begin{pmatrix} \left(\alpha_2 - \frac{3\pi}{2}\right)\cdot(\alpha_4-\alpha_3)\cdot b_1 + \left(\alpha_1 - \frac{3\pi}{2}\right)\cdot(\alpha_4-\alpha_3)\cdot b_2 + \\ \left(\alpha_4 - \frac{\pi}{2}\right)\cdot(\alpha_2-\alpha_1)\cdot b_3 + \left(\alpha_3 - \frac{\pi}{2}\right)\cdot(\alpha_2-\alpha_1)\cdot b_4 \end{pmatrix}}{(\alpha_4-\alpha_3)(b_1+b_2)+(\alpha_2-\alpha_1)(b_3+b_4)}, \quad (2)$$

where ϕ_r – disc turn angle relatively to the reference point;

$\alpha_1 \ldots \alpha_4$ – angles from the start of zero sector (disc reference point) to the sectors boundaries that are projected onto the centers of both sensor arrays (fig.3);

$b_1 \ldots b_4$ – linear deviations of sector boundaries relatively to the center of corresponding sensor array.

Code disc axis shift Δx along sensor array axes can be determined by formula:

$$\Delta x = \frac{\begin{pmatrix} \left(\left(\alpha_4-\alpha_2+\pi\right)\cdot b_3 + \left(\alpha_3-\alpha_2+\pi\right)\cdot b_4\right)\cdot b_1 + \\ \left(\left(\alpha_4-\alpha_1-\pi\right)\cdot b_3 + \left(\alpha_3-\alpha_2+\pi\right)\cdot b_4\right)\cdot b_2 \end{pmatrix}}{(\alpha_4-\alpha_3)(b_1+b_2)+(\alpha_2-\alpha_1)(b_3+b_4)} \quad (3)$$

Information about this shift allows us to identify deviations in mechanical constructions of the connection between the sensor and AS axis and compensate them within some limits by means of software processing of two diametrically opposite sensor array images.

IV. ESTIMATING ERRORS OF SMART ANGLE SENSOR

Results of the researches of eccentricity influence the accuracy of angle determination by means of simulation are shown in fig. 4, as a graph of errors change in the full range (0..360°) of angle measuring. «Curve a» represents error change during the disc angular position change for dual method of angle determination comparing to single method («curve f») and with presence of eccentricity 0,2 mm.

As the graph shows, eccentricity error is compensated by dual scheme in case of accurate installation of sensor arrays and absence of shaft skew (code disc plane is parallel to sensor arrays plane).

Some other constructive-technological deviations during sensor installation can cause increase of error influenced by eccentricity and disc shift. Thus, disc axis shift for 1°, and second photo receiver shift along axis z leads to increased sensitivity to eccentricity (curves c, d, e). Shift of one photo detector relatively to another by 0,25 mm leads to additive error (curve b), which is systematical and is easily compensated by software.

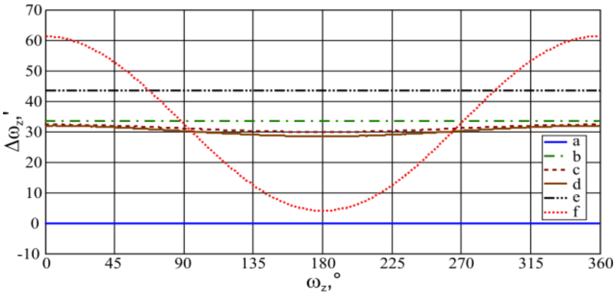

Figure 4. Change of angle measurement error during change of disc angular position caused by the influence of mechanical factors

Presence of two angle measurement channels also increases reliability of code disc position determination. In case of one channel failure, disc position is determined by the image from one sensor array. Herewith angular position should be changed on appropriate correction Δ_0 or Δ_1, while user receives a diagnostic warning. Values Δ_0 and Δ_1 are calculated in case of successful recognition of both channel images or from coefficients stored in the memory on the sensor calibrating stage.

For the sensor activity investigation we developed technological software that allows to update sensor position, edit configuration parameters, perform semi-automatic testing and diagnosis of sensor, retrieve unprocessed image from sensors for investigation of subpixel boundary definition, calculate and edit calibrating coefficients, update controller's microprogram, etc.

V. EXPERIMENTAL RESEARCH

The main elements of the sensor electric circuit are: microconverter (CPU) ADuC841 produced by Analog Devices firm, and two sensor arrays TSL1401 (Texas

Instrument) used to obtain an image from the code disc (fig.3). Microconverter based on MCS-52 core contains high-speed 12-order 8-channel ADC and two channels of DAP used to control light sources. It provides functions of digitizing analog signals output from pixels of sensor arrays, image processing with subpixel precision of sector boundaries [12], determination of sector shift and disc angular position, and interaction with AS control system as well.

Interaction between each sensor and control system in AS is carried out by means of RS485 interface in half-duplex asynchronous mode. Sensor control protocol except the angular position reading command also contains commands to setup necessary position, resolution, diagnosis; service information interrogation such as illumination level, temperature inside the sensor; parameters configuration, communication speed, calibrating coefficients, date, serial production number etc. stored in non-volatile memory (Flash-Data). Remote update of microconverter software is provided.

Figure 5 illustrates disassembled experimental sample of optical-electronic angle sensor and AS "Vityaz-7m" with mounted sensors.

Figure 5. Experimental sample of optical-electronic angle sensor and AS "Vityaz-7m" with mounted sensors

Sensor testing was carried out on full-rotating AS THA-57 by comparing readings of azimuth sensor with theodolite ones. Antenna was pointed by means of developed control system in semi-automatic mode of software pointing at given coordinates, angular distance between which were 20º. At the same time static pointing error of pointing at coordinates was tested.

The main technical characteristics of optical-electronic angle sensor are shown in table 1.

TABLE I. TECHNICAL CHARACTERISTICS OF ANGLE SENSOR

№	Appearance (table col head)		
	Parameter	***Unit***	***Value***
1	Measure range	deg.	0..360^0
2	Angle measure discretness	ang. sec.	20"
3	Absolute measure error	min.	±2'
4	Time for image receipt	ms	1,62
5	Transformation time	ms	4..5
6	Output signal, interface		Digital code, RS485, RS232
7	Power supply	V	7..35 B
8	Case protection type		IP65

According to the experimental investigations compared to sinus-cosines rotational transformators (Resolvers BT-5) optical-electronic sensor provides 2-3 times higher accuracy of angular position determination.

Developed sensors are used as a part of several types of large-scale radio monitoring AS, namely "Vityaz-7m" (fig.5), "Quasar plus 7,6m" with reflector diameter 7,6m, which in Ku-band of frequencies (12 GHz) require precision pointing at satellites with errors not more than 1,3 angular minutes.

Developed construction of sensor case is durable to environmental influences according to IP65 standard recommendations. Sensor power supply (constant voltage 7...35 V) is provided by control system; consumption current is around 50 mA.

Due to the offered system and constructive decisions requirements to optical system of angle sensor are reduced in comparison with raster or multichannel systems; reliability of angle measuring device is improved. During the last 3 years optical-electronic sensors with control systems have shown reliable operation within AS.

CONCLUSION

Developed smart optical-electronic sensor of absolute angular position determination, due to the offered processing algorithms of measurement information directly inside a sensor, allowed to reduce influence of several factors related to imperfections of mechanical constructions of connections between measuring devices shafts and antenna axes with SRP of AS. Moreover, sensor increases reliability of angular position determination due to dual-channels measuring, has additional self-diagnosis functions, provides easier justification and interaction with the control system on large distances.

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