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BISCANNING IR EARTH HORIZON SENSOR

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ABSTRACT – *Description of the Earth horizon sensor is presented. The opto-electronic device is intended for usage in a complex of attitude control and stabilisation systems of the spacecraft orbiting at altitudes from 10000 km to 40000 km. The device of small dimensions and mass has high accuracy along two axes due to two parallel scanning trajectories.*

Perspectives of development of space communication and television systems, where a space vehicle (SV) orbiting the Earth on the stationary orbit operates as an active re-transmitter, as well as solution of a series of specific tasks are essentially depend on ability to realise long time operating and high precision attitude control system of the SV.

The most important sensor of the attitude control and stabilisation system is an electro-optical device intended for measuring the SV axis angles of deflection from the Earth local vertical. Already more than three decades the cut scanning devices, sensitive to the Earth IR radiation, are exploited on board of the national SV [Izna 72, Ivan 79]. Further the devices of static type were developed using multy-element detector lines. The Earth horizon sensors of the French company Sodern [Lugh 99] may be noted as the most successful realisation of such devices abroad.

However, according to long experience of exploiting the horizon sensors of different types, the following statement should be done. Till present time the cut scanning device, operating in the spectral range of 14...16 mkm, is the most suitable to measure large deflection angles (more than 30') taking into account mass, dimensions, accuracy and reliability under conditions of space environment.

In a device with the common structure of measuring mechanism the instantaneous field of view performs angular oscillation movements along the scanning trajectory across the Earth disk visible in the IR spectral range. The moments of interception between the centre of the instantaneous field of view and the Earth disk edges are determined by means of comparison of the output signal from the device detector & amplifier channel and the fixed threshold level of the device comparator. The most suitable procedure is registering the moments of entering the Earth disk because of the maximum contrast of the margin "Space-Earth", so the mentioned moments are determined beginning from the edges of the scanning trajectory. The simplest method to produce geometric information of the mentioned moments is comparison of the time intervals between the moments, corresponding to the edge parts of the scanning trajectory.

Let us analyse the procedure of determining the direction towards the Earth centre and corresponding geometric relations.

Two mutually orthogonal measuring axes of the device co-ordinate system (DCS) we shall name the yaw axis and the pitch axis, and also the third axis, which is orthogonal to both measuring axes, we shall name the sensitivity axis. It is assumed to determine the stated direction in the DCS by the angles of rotation about the yaw and pitch axes. Let α is the angle of rotation around the yaw axis,

and β is the angle of rotation around the pitch angle. From the spherical triangle, which has known side ($\pi/2$) and two adjacent angles (α and β), according to the Cosine angles theorem it follows:

$$Z = \arccos \left(\frac{\sin \alpha (1 - \sin \alpha \sin \beta)}{\cos \beta \sin(\arccos(\sin \alpha \sin \beta))} \right), \quad (1)$$

where Z – is the angle between the vector of the stated direction and the yaw axis.

The similar expression for Z' with the corresponding changes is valid, also, concerning the pitch axis.

The expression 1 may be simplified for some vicinity near the sensitivity axis direction, i.e. then $\alpha \rightarrow 0$, $\beta \rightarrow 0$, taking into account the approximation $\sin \alpha$ (or β) = α (or β) and $\cos \alpha$ (or β) = 1. Then $Z = \pi/2 - \alpha$ and similarly $Z' = \pi/2 - \beta$

Thus, small displacements in yaw and pitch may be reviewed independently from each other. Calculation according to the accurate formula 1 shows that the error of such approximation doesn't exceed the value of 0.15° for the displacement area up to 10° and is reduced further by thousand times for the displacement area of 1° .

In the Fig. 1 some projections on the figure plane are conventionally shown, including:

- the Earth disk 1;
- the scanning trajectory 2 with the edges 3 and 4;
- the yaw axis 5 and the pitch axis 6 (the pitch axis 6 is co-linear to the scan axis);
- the angles α and β

Fig. 1: measurement principle for the displacement angles in two mutually perpendicular planes.

From the Fig. 1 it is obvious that the difference of the mentioned above intervals is equal to zero then $\beta=0$, independently on the angle α and in some vicinity near zero the difference is proportional to the angle β

Disadvantages of such a procedure are:

- reduction of measurement accuracy for angle β at increase of deflection of the sensitive axis from the Earth disk centre;
- absence of ability to measure the angle α i.e. in the plane, which is perpendicular to the scanning trajectory.

Therefore, to provide orientation along two axis, it is needed to install the second (orthogonal) similar device. It increases mass, dimensions and power consumption of the attitude control system.

Let us analyse possibility of determination of the second angle (the angle α) with known values of angular dimension of the Earth disk with the radius RE and the curvature radius RS of scanning trajectory, taking into account that displacements in yaw (the angle α) and pitch (the angle β) are small. From the spherical triangle, which has three known sides (RE , $(\pi/2 - \alpha)$ and RS), according to the Cosine sides theorem it follows:

$$\cos(\varphi \pm \beta) = \frac{\cos RE - \sin \alpha \cos RS}{\cos \alpha \sin RS}, \quad (2)$$

where φ – are the rotation angles of the scanning axis from the central position, which corresponds to the direction of the device sensitivity axis, to the positions, which correspond to interception of the detector channel axis with the Earth disk edge.

According to 2, then $\alpha=0$ and $\beta=0$ $\cos \varphi = \cos RE / \sin RS$. Taking into account the mentioned above approximation small increment of α ($d\alpha$) being substituted to 2 gives

$$\cos \varphi = \frac{\cos RE - d\alpha \cos RS}{\sin RS}.$$

Therefore the increment of the value $\cos \varphi$ ($d\cos \varphi$) is $\cos \varphi' - \cos \varphi = -d\alpha \operatorname{tg} RS$, and

$$\frac{d\alpha}{d\varphi} = \sin \varphi \operatorname{tg} RS, \quad (3)$$

Alternatively, after approximation of the initial expression 2 we may have

$$\alpha = \frac{\cos \varphi \sin RS - \cos RE}{\cos RS}, \quad (4)$$

and then take the differential of the expression 4 by φ It gives the result, which coincides with 3.

The given relation 3 may be used for estimation of the angle α determination error, if the angles φ are measured with an error $d\varphi$

In accordance with the expression 3, Fig. 1 illustrates the fact, that the error $d\alpha$ increases then the scan trajectory approaches to the Earth disk diameter, and decreases then the trajectory approaches to the Earth disk tangent. From the expression 2 and the Fig. 1 it is obvious, also, that $d\beta/d\varphi = 1$, i.e. the angle β determination error is determined only by the angles φ measurement error.

In its turn, the error of the angles φ measurement depends on the angular slope of the detector & amplifier channel signal. This slope is maximum if the scanning trajectory is perpendicular to the tangent of the Earth disk edge, and is equal approximately

$$S_{\max} = U_{\max}/D, \quad (5)$$

where $U_{\max}$ – is the maximum value of the signal from the Earth disk edge;
 D – is the diameter of the detector channel instantaneous field of view.

In a common form the signal slope is equal to

$$S = S_{\max} \sin \vartheta \quad (6)$$

where ϑ – is the angle between the direction of the scanning trajectory and the tangent to the Earth disk edge in the point of interception.

The angle ϑ is formed by the sides, which are correspondingly perpendicular to the scan radius and the Earth disk radius. Therefore the angle ϑ is equal to the angle at the point of interception for the reviewed above spherical triangle, which has the sides (RE , $(\pi/2 - \alpha)$ and RS). Similarly, from the Cosine sides theorem it follows:

$$\cos \varphi = \frac{\sin \alpha - \cos RS \cos RE}{\sin RS \sin RE}, \quad (7)$$

and also $\cos \vartheta = -1/(\operatorname{tg} RS \operatorname{tg} RE)$ then $\alpha = 0$.

The formulae 1 – 7 provide comprehensive analysis of relations between the errors then two angles of the sensitivity axis displacement from the direction towards the Earth disk centre to be determined according to the scanning device information. In particular, the optimal parameters of scanning may be chosen taking into account the Earth disk dimension and the required range of the displacement angles in the working area.

Presently, Scientific & Production Association (Russian abbreviation – NPP) “Geofizika-Cosmos” has developed advanced IR Earth horizon sensor of cutting type, which uses information simultaneously from two parallel scanning trajectories. The given device has both high accuracy and ability to measure the angles α and β in two mutually orthogonal planes.

The principle of measuring these angles is illustrated in the Fig. 1. The device has two identical optical heads, those instantaneous fields of view (IFOV) scan across the Earth IR disk 1 with the centre C along the trajectories 2 and 7. The optical system of each head deals with the Earth thermal irradiation in the spectral range of 14,2...16,2 mkm.

The scanning angles $N1...N4$ are determined in the device directly in the digital form (by means of the code unit), that eliminates scanning velocity instability influence on accuracy of the displacement angles measurement. Four scanning angles $N1...N4$ are determined in the device from the following signals:

- sequence of the information pulses (IP) of the code unit;
- pulses (LEP and REP) of the scanning trajectories left and right edges;
- pulse signals (LOH1 and LOH2) of interception with the line of horizon for the first and the second scanning trajectories correspondingly.

Counting the angles $N1...N4$ is started then the IFOV of each optical head are in the marginal positions and is finished then the IFOV centres intercept (in the points 8 ... 11) the edges of the Earth IR horizon. The device outputs the information in the digital form by means of a standard interface into the onboard host computer (OHC). The angles α and β may be calculated in the OHC,

taking into account the mentioned above formulae 1 – 7, in accordance with the measured values of the angles $N_1...N_4$ and using:

- optimal approximation of the accurate calculation formulae;
- individual weights for every series of the measured angles;
- flexible logic of usage the measurement from one or both scanning trajectories depending on mutual attitude of the scanning trajectories and the Earth disk;
- autonomous check on validity of the measurement information due to geometric excess of four points for determination the circle of the Earth disk;
- autonomous determination of the effective angular dimension of the Earth disk, that eliminates influence of some error sources, including seasons' and daily instabilities of the Earth atmosphere, degradation of the characteristics of the signal processing channel during long time operation, variations of the SV flight altitude, etc.

Usage of two scanning trajectories provides full stability of the device against impact of radiation from the Sun or the Moon due to autonomous detection of the influence source presence near one of four points of interception the scanning trajectories with the Earth disk edge. The corresponding initial angle is temporally excluded from the measurement processing.

The only difficulty (and temporal one) is simultaneous presence of the Sun and the Moon in close vicinity of two points from the mentioned ones. However, frequency of forming such a configuration may be compared with frequency of viewing the Sun osculation from the fixed point of the Earth surface, i.e. it may be neglected.

Device main characteristics

Operating altitude range	(12000 – 40000) km;
Operating measurement area for α and β	up to 2° ;
Limit error for β	not more than $3.0'$;
for α	not more than $3.6'$;
(for geo-stationary orbit, taking into account elimination of some error components in the OHC)	
Instantaneous field of view, diameter	3° ;
Scanning amplitude (B)	28° ;
Angular spacing between two scanning trajectories (2E)	10° ;
Mass	not more than 1.4 kg;
Consumption	not more than 3 W;
Resource	140000 h.

Thus, the developed methods have allowed to implement in the NPP “Geofizika-Cosmos” high precision IR Earth horizon sensor of cutting type with simultaneous measuring the displacement angles in two mutually perpendicular planes. The analytic approach presented in the paper may be utilised as the foundation for optimisation of some parameters for the devices of given type, and also for development of the algorithms for on-board processing their information.

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