ГЕОМАГНЕТИЗМ И АЭРОНОМИЯ

Том 34 1994 № 6

UDK 550.388.1

A. V. Afonin, V. S. Davydov

A COMBINED SYSTEM FOR ATTITUDE CONTROL OF THE ROTATING GEOPHYSICAL ROCKETS

A system for attitude control of the rotating geophysical rockets comprising an infrared earth horison sensor, a solar sensor and a magnetometer is described. The sensors measure angles between a rocket rotation axis and zenith direction, solar direction, and magnetic field vector. The system allows to determine the rocket spatial orientation at night as well as in the daytime. The redundant information obtained using three vectors measurements allows to increase reliability and accuracy of attitude control in the daytime. Launches of MR-12 rockets with this system have shown that attitude control accuracy isn't worse than one degree. An independent attitude control method based on the comparison of bright planets coordinates and rocket spatial orientation at the moment of carrying out the observation of those planets by rocketborne photometers has confirmed this accuracy value.

1. Introduction

While investigating the upper atmosphere and aurora bightness from geophysical rockets stabilized by rotation, the data interpretation is related with the necessity of accurate determination of sighting directions of optical instruments.

An optical system including an *IR* earth horizon sensor and a solar sensor was created in 1976—1980 at State Optical Institute to produce the attitude control of rotating geophysical rockets of MR-12 type. This system was tested with good results and was used in several rocket launches for spatial referencing of the photometer sighting alignments. During the first two launches a joint control was carried out both over optical and magnetometric system consisting of three magnetometers and a solar rocket rotation sensor created at the Applied Geophysics Institute. The investigations resulted in revealing the opportunities of a combined system for the attitude control of geophysical rotating rockets including an *IR* horizon sensor, a solar sensor and a magnetometer for the operation at any time of the day or night. These instruments measure the angles between the rotation axis coincident with the longitudinal rocket axes and reference field vectors.

2. Description of sensors

2.1. Solar sensor

The angle between the rocket longitudinal axis and alignment toward the Sun, called the scattering angle, is determined by a sensor including two slit fields of view with a distance between them being equal to α-angle and being turned in regard of each other at η-angle. When the rocket is rotating the detectors are illuminated in turn through each slit field of view at time moments $t1$ and $t2$. The electronic channel of the sensor generates impulses with time interval between them $t_i\,(i, 1) = t2 - t1$ having the information on the scattering angle. If the cross line of the slit fields of view is perpendicular to the axis of rotation, the scattering angle is equal to

$$\theta_s = \text{arctg}\,(\text{tg}\,(\eta/2)/\sin\,((\omega \cdot t_i\,(i, 1) - \alpha)/2), \qquad (1)$$

where ω in the angular velocity of rocket rotation. The solar sensor characteristics are given in Table 1.

Table 1

Solar sensor parameters

Entrance pupil diameter, mm	3
Field of view, degree	0.5 · 120
Angle between viewing fields α, degree	120
Angle of slit viewing fields rotation η, degree	60
Type of photodetector	silicon photodiode
Sensitive surface diameter, mm	12

2.2. IR horison sensor

The angle between the longitudinal rocket axis and vertical direction called the tilt angle is measured by an IR horizon sensor. Satellite tilt control stabilized by rotation is based on the measurement of time interval between the moments of crossing of the reference level of planet radiation by the sensor field of view. The time interval value is related to the tilt angle θ by a well-known equation:

$$t = (2/\omega)\,\arccos\,(\cos\,(\Delta)/(\sin\,(\gamma) \cdot \sin\,(\theta)) + 1/(\text{tg}\,(\gamma) \cdot \text{tg}\,(\theta))), \qquad (2)$$

$$\cos\,(\Delta) = [(R + h)^2 - (R + H)^2]^{0,5}/(R + h). \qquad (3)$$

The angle Δ is equal to a half angular Earth size of R radius from the altitude h of the rocket flight accounting for the height of the reference level H of atmospheric radiation whose value corresponds to the sensor switching threshold. The optical system sighting line is aligned at γ degree to the longitudinal axis. The tilt determination error depends on variation of the radiation reference level height, accuracy control of flight altitude and at tilts close to:

$$\theta = \arccos\,(-\cos\,(\gamma)/\cos\,(\Delta)), \qquad (4)$$

the error has a very big value. Such IR horizon sensors can be efficiently used only on the flying vehicles whose altitude and tilt change within small ranges, e. g. on satellites having high kinetic moment on circular orbit.

The drawbacks of the above mentioned method for flying vehicles with high variations of flight altitude are eliminated using a sensor with two and more viewing fields whose sighting lines are within the plane passing through the rotation axis of the flying vehicle. In this case the tilt is determined by the time intervals $t_i\,(i, 2)$ and $t_i\,(i, 3)$ between the crossing moments of the two viewing fields and the earth horizon.

$$\theta = \text{arctg}\,((\cos\,(\gamma_1) - \cos\,(\gamma_2))/(\cos\,(\omega \cdot t_i\,(i, 2)/2) \cdot \sin\,(\gamma_1) -$$

$$- \cos\,(\omega \cdot t_i\,(i, 3)/2) \cdot \sin\,(\gamma_2))). \qquad (5)$$

The parameters of IR horison sensor used for the attitude control of a geophysical rotating rocket are given in Table 2.

Table 2

Parametrs of IR horizon sensor

Spectral region, μm	8—13
Entrance pupil diameter, mm	30
Relative aperture	1 : 1
Field of view, degree	1.5 · 1.5
Field of view number	2
Angles between the field viewing centers and longitudinal rocket axis γ_1 and γ_2, degree	100,96
Noise equivalent brightness, W · sm^{-2} · sr^{-1}	$5 \cdot 10^{-5}$
Type of detector	pyroelectrical bolometer

The sensor threshold device is tuned to the efficient brightness being equal to perfect radiator brightness at temperature 200° K in order to eliminate sensor malfunctions caused by high cold clouds.

2.3. Magnetometer

To determine the angle between the longitudinal axis and the Earth magnetic field vector a ferroprobe magnetometer is used with a sensivity from 0.04 to 0.06 A/m. The output sensor signal represents a cosine periodic function with a periodic envelope having a period equal to that of rocket nutation. The operation of magnetometers is affected by ferro-magnetic materials and non-magnetic electroconducting materials located where the magnetometer is placed. Therefore, the magnetometer time constant and sensitivity are determined using a non-magnetic mounting with a completely mounted rocket head unit.

The angle value between the longitudinal axis and magnetic field vector is defined as

$$\theta_m = \pi - \arcsin (U_i / H_m \cdot S), \quad (6)$$

where U_i — is the variable signal amplitude, S — is the sensitivity of the magnetometer, H_m — is the magnetic field intensity during measurements.

For average latitudes good calibration results for a magnetometer located perpendicular to the longitudinal axis are obtained using a calibration method by the amplitude of the magnetometer variable component at the moment of rocket revolution while entering dense atmospheric layers. The maximal signal amplitude corresponds to the angle value between the longitudinal axis and magnetis field vector equal to 90°.

3. Attitude control system

The operation of optoelectronic instrumentation and attitude sensors begins after the rocket fairing release. Having received the pulse the rocket flies further performing a nutational motion. Nutational motion has a transient and a stable flight sections. In the stable flight mode the rocket axis is moving along the envelope of the cone centered with regard to the rocket kinetic moment vector [1].

To determine the rocket attitude in a geographical coordinate system it is necessary to determine the tilt and azimuth angles of the rocket longitudinal axis. Fig. 1 shows the tracks of spherical triangles on unit sphere allowing to determine the relationship of the angles. The processing of sensor registrograms being registered using telemetric instruments with frequency 100 Hz for each channel starts with the determination of time operation moments of optical sensor threshold devices,

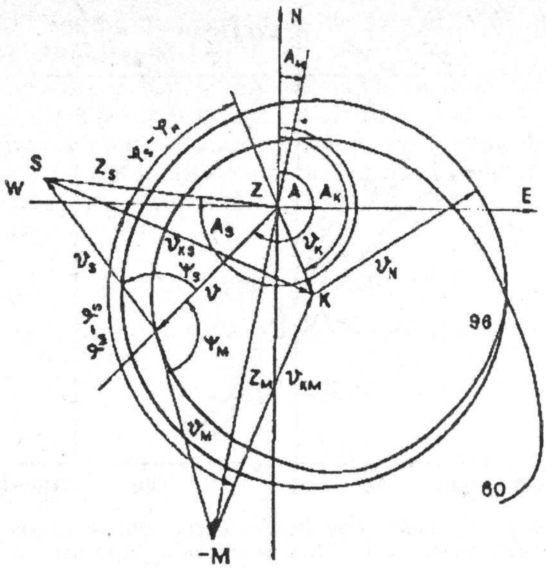

Fig. 1. Tracks of nutation motion trajectory and spherical triangles on the unit sphere surface. Z — zenith direction, N — Nothern direction, Z_s — solar zenith angle, Z_m — zenith angle of magnetic field vector, K — nutation cone center

time referencing and determination of extreme values of magnetometer cosine by the RMS method. Time series arrays of optical sensors are formed t_i $(i, 1) \ldots t_i$ $(i, 3)$ and t_m $(i, 1) \ldots t_m$ $(i, 3)$. The array t_m $(i, 1) = (t1 + t2)/2$ contains the passing time moments of the solar sensor basic plane when it is aligned towards the Sun; the arrays t_m $(i, 2)$ and t_m $(i, 3)$ contains the passing time moments of IR-horizon sensor basic plane of the rocket tilt plane corresponding to the time moment of signal midst from the Earth of the two channels of the horizon sensor. Time series are subjected to efficient digital filtration that actually eliminates any casual errors of time interval measurements. By sensor indications the corresponding angles are determined, while the tilt, additionnally, and the longitudinal rocket axis azimuth are determined by joint sensor indications. In the daytime during the operation of the most accurate solar sensor and IR-horizon sensor the attitude angles are equal to

$$\theta = \operatorname{arctg}((\cos^2(Z_s) - \cos^2(\theta_s))/(\sin(\theta_s) \cdot \cos(\theta_s) \cdot \cos(\psi_s) +$$

$$+ \cos(Z_s) \cdot (\sin^2(Z_s) \sin^2(\theta_s) \cdot \sin^2(\psi_s))^{0.5})) \tag{7}$$

$$A = As + \operatorname{arctg}(\cos((\theta - \theta_s)/2)/\cos((\theta + \theta_s)/2) \cdot \operatorname{ctg}(\psi_s/2)) -$$

$$- \operatorname{arctg}(\sin((\theta - \theta_s)/2)/\sin((\theta + \theta_s)/2 \cdot \operatorname{ctg}(\psi_s/2)), \tag{8}$$

where τ is the IR-horizon sensor time constant.

At night the formulae of attitude control remain the same, only the parameters are used corresponding to the earth magnetic field vector and magnetometer measurement data. Coincidence of tilts measured by the IR-horizon sensor and determined by joint system indications is evidence of the correctness of sensor adjustment, operation and calibration. The surplus information obtained during the operation of a combined system including the three sensors allows in the daytime, in the stabilized flight mode, to determine geometrically and analytically with high accuracy the parameters of nutation cone of the rocket longitudinal axis by the difference of the phase angles φ_s, φ_m and φ_n of the current values θ_s, θ_m and θ independently from possible measurement errors of sensors and deviation of the

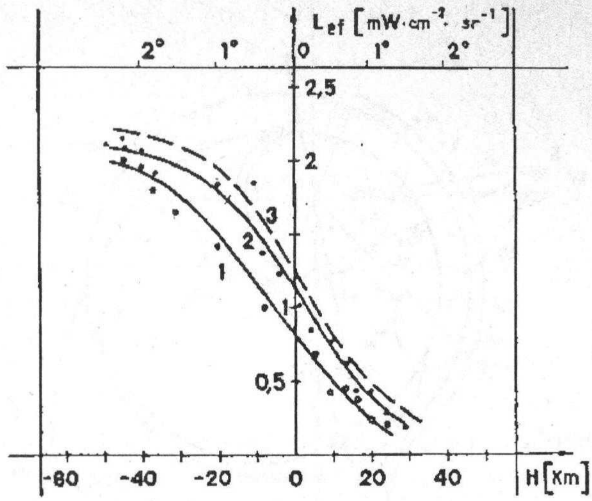

Fig. 2. Comparision of measurements results of the Earth horizon brightness measured by IR-horizon sensor with calculated data. 1 — measurements on the transient section of flight path, 2 — measurements on the stable path section, 3 — calculated data

rocket inertial rotation axis from the longitudinal building axis. This considerably increases the reliability, simplifies the process of the processing data with the aim to achieve the necessary attitude measuring accuracy.

4. Attitude measuring accuracy estimation

Fig. 1 shows the track of the path projection of the rocket nutational motion on the unit sphere surface having been registered during the first test launch of the rocket. A parametric equation describing the tilt variation in the stabilized flight mode from 96 s has the form:

$$\theta = \arccos(\cos(\theta_k) \cdot \cos(\theta_n) + \sin(\theta_k) \cdot \sin(\theta_n) \cdot \cos(\omega_n \cdot t + \varphi_n)), \quad (10)$$

where the zenith angle nutation cone center θ_k, the cone angle θ_n, the initial phase φ_n and the velocity of axis rotation along the nutation cone ω_n are equal to 6.6°, 13.30°, —6.09 rad and —0.17357 rad/s, respectively. Nutation cone center azimuth $A_k = 158°$.

To estimate the accuracy of spatial referencing of sighting alignment of the instrumentation the IR-horizon sensor signals at the threshold device input were output for telemetry. The sensor was calibrated in units of brightness. Since the frequency of telemetric interrogation was not sufficient for a continuous recording of signals from telemetric recordings of the reference signal the samples were selected whose calculated spatial referencing corresponded to the sighting line height above the Earth horizon within ±50 km at flight altitudes 70—110 km and 120—140 km during nutation rocket revolution. According to the samples in Fig. 2 the curves of the efficient brightness were plotted in the transient (curve 1) and stabilized (curve 2) flight modes including a calculated curve (curve 3) of the altitude dependence of the transition Earth-to-Space brightness for experimental conditions allowing for the angular function of the horizon sensor sensitivity. The discrepancy of the calculated and experimental data is determined by the spatial reference error using the zenith angle of sensor observation which can be calculated by the height difference ΔH of the equal levels of brightnesses

$$\Delta Z = \mathrm{arctg}\,(\Delta H/((R + h)^2 - R^2)^{0.5}), \quad (11)$$

and is equal to 0.61° for the transient flight mode and 0.15° on the stabilized flight mode for the flight altitude 100 km.

Thus we can draw a conclusion that the determination accuracy of the sighting alignment coordinates of the airborne optical instrumentation of a geophysical rotating rocket by a combined attitude control system is not worse than 1°. This accuracy was confirmed by an independent control based on a comparison of bright planets coordinates and spatial orientation at the moment of planet observation by means of rocket photometers.

REFERENCES

1. *Bertin F., Papet-Lepine J.*, Restitution de l'attitude des engines., Sciences et Techniques de l'armement, v. 41, N 4, p. 869—941, 1967.

State Optical Institute, St. Petersburg, Russia