Autonomous Attitude Reference System for Remote Sensing Satellites

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Abstract: The problems and the design philosophy of precision autonomous gyroscopic attitude reference systems of orbital remote sensing satellites are considered. The peculiar features of these systems are presented in connection with the need for calibrations of gyroscopes and their geometric references to the measurement axes of stellar sensors. The method for performing these procedures is given and an example of their implementation is shown. The state-of-the-art in the development of promising types of gyroscopes (fiber-optic and electrostatic) for the systems under consideration, the lines of their future development and improvement of strapdown attitude reference systems based on them are discussed.

Keywords: satellite, attitude reference, fiber-optic gyroscope, electrostatic gyroscope, stellar sensor, drift model.

1. INTRODUCTION

One of today's most challenging problems in the field of space technology is the development of high-accuracy Remote Sensing Satellites (RSS) (Kozlov et al., 1999, Anshakov et al., 2002a,b, 2005, 2006; Somov et al., 1999).

Among the factors of primary importance, which determine specificity and difficulties in controlling low Earth orbiting high-informative remote sensing satellites as compared to other types of space vehicles, are the following:
- nonstationary and random disturbing effects caused by the incident flow of the upper atmosphere due to the satellite flight with variable geometry on low elliptical orbits (to provide high resolution);
- the need for onboard high-accuracy guidance of the targeting equipment (TA) axis at any object (route) from a specified set to be observed;
- the need for precision satellite retargeting, repeated many times in the same session, from one object (route) under observation to another, located arbitrarily relative to the satellite track;
- the need for controlling the image definition smear in the local plane of the TA in order to provide high-resolution information, using, among the others, satellite attitude control.

The main principles of formation of attitude control programs, with an eye to effective remote sensing, can be reduced to the following issues:

- use of satellite mass center motion parameters determined by the autonomous navigation system for the moment of time which is the maximum close to the beginning of the planned route mapping interval;

- formation of programs for the satellite attitude control (program motion) based on the requirements for the accuracy in determining the image motion compensation rate on route and continuity of control parameters during the satellite flight both on routes and in between the imaging routes.

The satellite attitude parameters for the motion control system are determined by the gyroscopic attitude reference system, and the quality of remote Earth sensing depends on its accuracy. In turn, the property of gyroscopes to maintain accuracy for a long time allows making the intervals between corrections from stellar sensors longer, thus improving self-sufficiency of the attitude reference system, and owing to this, the limitations on the satellite operation regimes can be reduced. This generated interest in creation of autonomous precision attitude reference systems for remote sensing satellites.

The stringent requirements for reliability during long-term orbiting missions, restrictions for weight, dimensions and power consumption determined the Strapdown configuration of Inertial Attitude Reference Systems (SIARS). The main unit of SIARS is a gyroscopic module including several gyroscopes rigidly fixed on a high-stability base. Their main goal is to form a basic inertial trihedron with reference to which satellite attitude control is realized.

The use of precision gyroscopes in RSS calls for solution of the following problems (Yemelyantsev et al., 2004; Emelyantsev et al., 2005; Somov et al., 2009):

- determination of geometric references of the gyro measurement axes to the measurement axes of stellar sensors;

- calibration of gyro drifts after each start in order to eliminate systematic drift components that vary from start to start.

Provided the temporal and thermal stability of the satellite construction are ensured, the first problem can be solved only once, when the satellite is put into operation after it was placed into orbit. The obtained values of referencing matrices provide algorithmic correction of errors in the satellite assembly.

The gyro drift calibration allows for identification of drift model parameters of each gyroscope. In this case it is assumed that the drift model structure of the gyroscope used is known to a sufficient certainty. Solution of the identification problem provides algorithmic correction of the gyro drifts.

Both of these problems can be solved aboard the satellite simultaneously by implementing satellite program turn procedures with a continuously operating stellar sensor. As it takes place, the information generated by the stellar sensor is synchronized with the information about the motion of the inertial trihedron formed by the gyroscopic module of the SIARS with subsequent processing of the information obtained.

It is the state-of-the-art and some prospects for the development of the SIARS for RSS that this paper is devoted to.

2. STATE-OF-THE-ART AND PROSPECTS FOR THE DEVELOPMENT OF THE GYROSCOPES FOR SIARS

2.1. Gyroscopic Angular Velocity Sensors

The SIARS can employ both gyroscopic angular velocity sensors and attitude gyroscopes with a spherical suspension of a rotating rotor and optical data readout. Realization of these two configurations of the SIARS is motivated by the problems that are to be solved: in the first case, it is accuracy increase of the angular velocity sensors; in the second – maintaining the high level of accuracy that has already been gained in gimbaled systems.

The overwhelming majority of the present-day strapdown attitude reference systems for various applications are based on angular velocity sensors. They are mainly ring laser gyroscopes (RLG) or fiber-optic gyroscopes (FOG). In the cases that the requirements for accuracy are not high but low cost and small dimensions are essential, the choice is made in favor of micromechanical gyroscopes (MMG). It is not frequent that hemispheric resonators or dynamically tuned gyroscopes are used. Considering the outlook for application of the above-mentioned angular velocity sensors in precision SIARS for satellites, it seems worthy to grade RLG and FOG as more accurate and more familiar in use. While comparing these two angular velocity sensors, it should be noted that in spite of the fact that RLG enjoy wide application, the tendency for replacement of these gyros with FOGs, less expensive and more convenient in service, is evident. Both in Russia and in foreign countries this situation holds true for the gyros of accuracy class (10.0 – 0.1)°/h, but only abroad – for high-accuracy sensors of class (0.010 – 0.001)°/h. For example, the French company IXSEA has developed a FOG of accuracy class 0.001°/h specially intended for space applications as it provides high space radiation tolerance (www.ixsea.com; Paturel, 2006). In Russia Fizoptika Company is known to be an undisputed leader in the production of a number of FOGs of accuracy class 10.0-1.0°/h (www.fizoptika.ru). The products of this company are competitive in cost and performance characteristics with similar foreign devices and in some cases are even better. In Russia the research into the development of FOG of accuracy class 0.01°/h is being conducted by the Perm Scientific-Industrial Instrument Making Company, JSC, (Ermakov et al., 2007; www.ppk.perm.ru), the Research & Production Company Optolink, Ltd. (Korkishko et al., 2007; www.optolink.ru) and the CSRI Elektropribor (Meshkovsky, et al. 2009). All these three developments are at the completion phase. Now the work on introduction of FOG into the satellite attitude reference systems is in progress. Optolink and RSC Energia have conducted the first joint tests of their FOGs aboard the spacecraft. The CSRI Elektropribor has worked out the draft proposals for creation of an attitude reference and navigation system comprising an inertial measurement unit that includes accelerometers and Fizoptika FOGs, and, besides, two stellar sensors, a GNSS receiver and a controller.

The accuracy characteristics of the present-day Russian FOGs are not always sufficient to provide some promising modes of imaging, such as stereo-photography, for example, because of comparatively high errors during the long-term operation in the autonomous mode. And yet, creation of precision angular velocity sensors, meeting the specific requirements of RSS, remains the topical problem of today. At the initial stage of their implementation they can be used for creation of a backup SIARS for a satellite or integration with precision attitude gyroscopes (Dmitriev et al., 1995).

2.2 Attitude Gyroscopes

Application of high-accuracy attitude gyroscopes makes it possible:

– to increase stability of the satellite control system in the case of failures in the control channels by using "spatial memory" of gyroscopes;

- to provide sufficiently high angular velocity of the satellite, which allows realizing special modes of imaging: coverage photography, stereophotography, imaging with arbitrary azimuth.

At the present time gyroscopes with electrostatic suspension of the spherical rotor are uncompetitive in accuracy (Peshekhonov, 2003). The potential accuracy of these gyros in space conditions has been confirmed by the results of the experimental test of the general theory of relativity (Schiff, 1960; Everitt, 1973, 1978).

The CSRI Elektropribor has developed a strapdown system BIS-EG (Gurevich et al., 2001) intended to determine the attitude of the remote sensing satellite. The system is based around three strapdown electrostatic gyros with a 10 mm solid rotor (Landau, 1993, 2000). The spatial angular position of the rotor spin axis relative to the gyro housing is measured by an electron-optical data readout system. Thus, after the gyros start-up aboard the satellite (the rotor has been suspended in the electrostatic field and spun-up, and nutation oscillations have been damped), each gyroscope simulates the inertial direction within the accuracy of its errors. Any pair of gyroscopes forms a basic trihedron relative to which the satellite attitude is measured and controlled.

The angular position of the gyro angular momentum vectors is corrected by the information from the stellar sensor. The design philosophy of the satellite attitude control system based on a Strapdown ElectroStatic Gyroscope (SESG) was proposed earlier in (Elwell, 1973).

At starting the angular momentum vectors of two SESG lie in the orbital plane ("equatorial" orientation), whereas the vector of the third SESG is perpendicular to the orbital plane ("polar" orientation).

Five special-purpose processors are provided in the BIS-EG to process information, solve orientation problems, control the system performance, communicate with external devices, form TeleMetering Information (TMI). In addition to it, BIS-EG contains the rotor spin-up and damping units, automation devices, and a secondary power unit.

3. SOLVING THE PROBLEMS OF REFERENCING AND GYRO DRIFT CALIBRATION ABOARD THE SATELLITE

After BIS-EG has been put into operation in orbital conditions, it is calibrated, which is intended to refine the gyro Drift Model Coefficients (DMC) (calibration) and align the measurement axes relative to the reference axes of the stellar sensor (affixment). Among the procedures used to achieve these goals are the following:

– synchronous recording of the output information from BIS-EG and the stellar sensors over the time span of 100-300 min (calibration orbit passes);

– receiving and processing TMI, its interpolation;

– determining the values of geometric basic references and preliminary DMC estimates (calibration) with the subsequent data transmission aboard the satellite;

– synchronous checking recording of the output information from BIS-EG and stellar sensors over a time span of 300-600 min (checking orbit passes);

– office studies of the TMI from the checking orbit passes with the aim to determine the efficiency of the DMC introduced before and the geometric references, and also refine the DMC values, if necessary.

4. STATE-OF-THE-ART AND PROSPECTS FOR MODERNIZATION OF THE BIS-EG

The specific features of the BIS-EG mentioned above allowed creating a new satellite control system for the satellite *Resurs-DK* (Anshakov et al., 2005), a unique structure of satellite-borne and ground-based control facilities, improving the performance of the targeting equipment.

High-accuracy monitoring of the *Resurs-DK1* angular motion programmed trajectory is performed by the BIS-EG which measures information about the angular position of the trihedron of the axes fixed to the satellite body relative to a certain stored basic inertial trihedron.

The star coordinates sensors in the attitude reference control system are used to fix the basic inertial trihedron of the axes to the inertial reference system (IRS) in which the program of the satellite angular motion control is specified. They allow algorithmic determination of both the initial alignment of the basic inertial trihedron of the axes relative to the IRS and determination of information for correction of this inertial trihedron as it drifts from its initial position (trihedron drift). Fig.1 shows the results of the corrections of referencing and refinement of the DMC aboard *Resurs-DK1*.

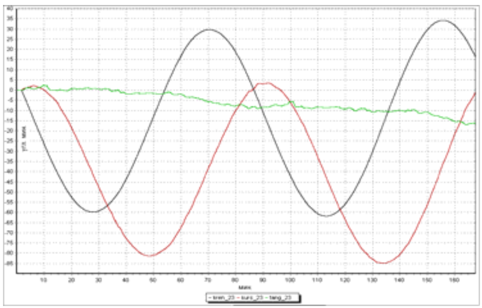

Fig. 1 Measurement errors before calibration

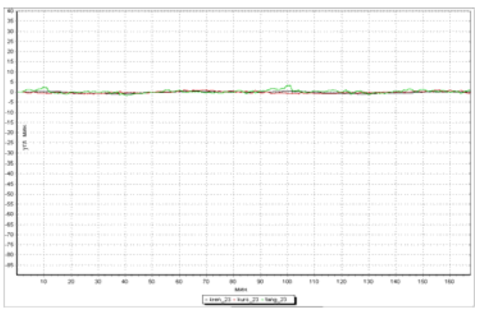

Fig. 2. Measurement errors after calibration

Since the *Resurs-DK1* launch it has been verified that the satellite motion control system performs its functions with the specified characteristics. The methods and techniques for alignment of the stellar sensors have been proved by the results of their in-flight measurement processing, resulting in the satellite attitude reference with an accuracy of 2 arc min.

On evidence from telemetric information, the program value of the angular velocity in the survey area is realized with an accuracy of $5 \cdot 10^{-4}$°/s. Of vital importance is continuation of work on in-flight refinement of the BIS-EG DMC. Thus, for example, after the introduction of the refined DMC values obtained as a result of the work on July 10, 2008, the maximum values of the attitude errors over the 300 min flight time span were as follows:

δ_x – 1.3 arc min;
δ_y – 1.3 arc min;
δ_z – 3.0 arc min.

It should be noted that the stellar correction was performed each orbit pass.

It is necessary to take into consideration the fact that the attitude reference error obtained with the use of the BIS-EG increases due to convergence of the ESG angular momentum vectors in the measuring channels, which also calls for repeated corrections.

For example, the attitude reference error in a 50-day flight aided with stellar correction performed at each orbit pass was 10 arc min, which, nonetheless, makes stereo-photography possible.

By now this motion control system has been operated successfully in two flights aboard the remote sensing satellites of another type, among the others, in the case that stellar corrections were performed with a two-orbit pass intervals.

The results obtained allowed determining the basic lines for improving the operational performance of the BIS-EG, which are mainly as follows:

1. Development of a gyroscope of a higher accuracy and improved reliability due to doubling the number of channels of the rotor electrostatic suspension. In this case, the gyro drifts decrease from run to run, hence, the requirements for calibration at the BIS-EG restart aboard the satellite also become less stringent. It should be stressed that the gyroscope remains operative even if any channel of the suspension fails. The practical test results of these devices have validated the adopted decisions.
2. Development of software for BIS-EG with the use of Kalman filter in the flight program which will allow automatic drift correction, excluding office studies of telemetric information.
3. Implementation of the digital gyro rotor spin-up units, which will allow preventing impermissible convergence of the gyro angular momentum vectors.

5. CONCLUSION

The theoretical and practical results obtained in the creation of precision autonomous aids for determining attitude reference of remote sensing satellites and prospects for their improvement in the future show the possibility for creation of a new-generation high-accuracy motion control systems for these satellites.

REFERENCES

Anshakov, G.P., Manturov, A.I., Antonov, Yu.G., and Ustalov, Yu.M. (2002a). Attitude motion control of spacecraft for the Earth remote sensing. In *Proc. of Aii-russian Workshop on the vehicle motion control and navigation.* 5-16. SSAU, Samara. In Russian.

Anshakov, G.P., Manturov, A.I., Antonov, Yu.G., Ustalov, Yu.M., Peshekhonov, V.G., and Landau, B.Ye. (2002b). Integrated attitude motion control system of spacecraft for the Earth remote sensing. In *Proc. of IX Saint Petersburg International Conference on Integrated Navigation Systems.* 77-84. CSRI "Elektropribor", Saint Petersburg.

Anshakov, G.P., Kirilin, A.N., Laputin, Yu.A. et al. (2005). Space complex *Resurs-DK* for the Earth remote sensing with high linear terrestrial resolution. In *Proc of 4th International Conference «Aviation and Cosmonautics-2005»*. 94-95. MAI, Moscow. In Russian.

Anshakov, G.P., Manturov, A.I., Ustalov, Yu.M., and Gorelov Yu.N. (2006). Attitude motion control of the remote sensing spacecraft. *Polyot*, (6). 12-18. In Russian.

Manturov, A.I., and Mostovoy, Ya.A. (2007). Techniques and facilities to control high-resolution imaging of the earth from space. In *Proc. of 16th Saint Petersburg International Conference on Integrated Navigation Systems*, 178-185. CSRI "Elektropribor", Saint Petersburg.

Gurevich, S.S., Gusinsky, V.Z., Landau, B. Ye., Lesyuchevsky, V.M., Levin, S.L., Litmanovich, Yu.A., Peshekhonov, V.G., and Tsvetkov, V.N. (2001). An attitude reference system with solid-rotor ESGs for orbital satellites. *In Proc. of 8th Saint Petersburg International Conference on Integrated Navigation Systems*, 57-64. CSRI "Elektropribor", Saint Petersburg.

Dmitriev, S.P., Landau, B.Ye., Levin, S.L., and Martynenko, Yu.G. (1995) An electrostatic gyroscope with a solid rotor. Application to the satellite attitude reference system. In *Proc. of 2nd Saint Petersburg International Conference on Integrated Navigation Systems,* 115-143. CSRI "Elektropribor", Saint Petersburg.

Elwell, D.F. (1973). An attitude reference system with electrically suspended gyros. *Navigation,* (4), 321-328.

Yemelyantsev, G. I., Landau, B. Ye., Levin, S.L., and Romanenko, S.G. (2004). In-flight calibration of the ESG-based spacecraft attitude reference system using a stellar sensor. In *Proc. of 11th Saint Petersburg International Conference on Integrated Navigation,* 81-82. CSRI "Elektropribor", Saint Petersburg. In Russian.

Emelyantsev, G. I., Landau B.Ye., Levin, S.L., and Romanenko, S.G. (2005). Drift calibration for ESG-based spacecraft orientation using celestial viewfinder. *Gyroscopy and Navigation,* (2(49)), 69-79. In Russian.

Ermakov, V.S. et al. (2007). Tests of the Fiber-Optical Gyros Unit in a Structure of the Integrated Navigation System NSI-2000MTF. In *Proc. of 14th Saint Petersburg International Conference on Integrated Navigation*

Systems, 133-137. CSRI "Elektropribor", Saint Petersburg.

Everitt, C. W. F. (1973). *The Gyroscope Experiment I: General Description and Analysis of Gyroscope Performance, Experimental Gravitation* (B. Bertotti, ed.), 361-380. Academic Press, New York.

Everitt, C. W. F. (1978). A Superconducting Gyroscope to Test Einstein's General Theory of Relativity. In *Proc. of the Society of Photo-Optical Instrumentation Engineers,* 175-188.

.Korkishko, Yu. N. et al. (2007). Navigation-Grade Interferometric Fiber Optical Gyroscope. In *Proc. of 14th Saint Petersburg International Conference on Integrated Navigation Systems,* 138-143. CSRI "Elektropribor", Saint Petersburg.

Kozlov, D.I, Anshakov, G.P., Antonov, Yu.G., Makarov, V.P., and Somov, Ye.I. (1999). Precision Flight Control Systems of Russian Remove Sensing Spacecraft. *Space Technology*, 19 (3&4), 149-163.

Landau, B. Ye. (1993). The electrostatic gyro with a solid rotor. *Gyroscopy and Navigation*, (1), 6-12. In Russian.

Landau B. Ye., Dyugurov, S.M., Zavgorodny, V.I., Levin, S.L., Romanenko S.G., and Tsvetkov, V.N. (2000). An electrostatic gyro with the solid rotor for strapdown navigation and orientation systems. *Gyroscopy and Navigation*, (4(31)), 50. In Russian.

Meshkovsky, I. K., Strigalyov, V. I., Deineka, G. B., Peshekhonov, V. G., and Nesenyuk, L.P. (2009). A three-axis fiber-optic gyroscope for marine navigation systems. In *Proc. of 16th Saint Petersburg International Conference on Integrated Navigation Systems*, 7-11.

Paturel, Y., Rumoroso, V., Chapelon, A., and Honthaas, J. (2006). MARINS, the First FOG Navigation System for Submarines. In *Proc. of Symposium on Gyro Technology 2006*, 17-1 – 17-11. Stuttgart, Germany.

Peshekhonov, V.G. (2003). Gyroscopes in the early XXI century. *Gyroscopy and Navigation*, (4(43)), 5-18. In Russian.

Schiff, L. I., (1960). Possible Now Experimental Test of General Relativity Theory. *Physical Review Letters*, 4(5), 213-217.

Somov, Ye.I., Butyrin, S.A., Matrosov, V.M., Anshakov, G.P., Antonov, Yu.G., Makarov, V.P., Sorokin, A.V., Bashkeyev, N.I., and Kondgat'ev, O.A. (1999). Ultra-Precision Attitude Control of a Low-Orbital Space Telescope. *Control Engineering Practice*, 7(7), 1127-1142.

Somov Ye. I. (2009) Multiple algorithms for filtration, integration and calibration of a strapdown inertial system for a spacecraft attitude determination. In *Proc. of 16th Saint Petersburg International Conference on Integrated Navigation Systems,* 110-113. CSRI "Elektropribor", Saint Petersburg.

www.fizoptika.ru

www.ixsea.com

www.optolink.ru

www.ppk.perm.ru