HALF-SCALE DEVELOPMENT OF THE MATHEMATICAL SOFTWARE SUPPORT FOR THE SINS-500 INERTIAL SATELLITE NAVIGATION SYSTEM BUILT AROUND FIBER-OPTIC GYROS

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Abstract

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Special features of a technology for half-scale development of the mathematical software support (MSS) of strapdown inertial satellite navigation systems (SISNS) are considered. The implementation of such a technology relies on modern recording equipment and permits one to optimize the MSS from the actual signals and on a set of the algorithms under study. A description for the SINS-500 system based on fiber-optic gyros is given as the object of half-scale development. The results of half-scale tests of the SINS-500 system are presented, which corroborate the fact that it is possible and expedient to apply the proposed technology to the creation of different-purpose SISNS which can be made to order.

Introduction

Analytical approaches to the improvement of the operational characteristics of strapdown inertial navigation systems (SINS) involve optimization of their mathematical software support (MSS) under the given hardware constraints. The hardware constraints are determined by the available computational resources as well as by requirements on the SINS dimensions, SINS mass, and SINS cost.

The optimization of a SINS MSS implies a study of the effectiveness of different algorithms for the reckoning and updating of motion parameters of the objects of a given class. The following approaches to the solution of such a problem are possible:

- carrying out a great number of full-scale experiments with different versions of MSS architecture. In this case, SINS output parameters are recorded and analyzed. Such experiments entail a substantial expenditure of cash and time;
- carrying out only one full-scale experiment in a typical path of object motion when the GPS signals and the signals of inertial sensors, such as gyroscopes and accelerometers, are recorded. Such an approach enables one to perform, from the signals recorded, MSS optimization on set of the algorithms under study.

In accordance with the technology proposed for the development of an MSS, when carrying out a full-scale experiment, the signals of fiber-optic gyros (FOG) and accelerometers, and also the GPS signals are recorded. The data recorded are subsequently used for the tuning of operation modes of an inertial satellite navigation system with different algorithms for the reckoning and updating of motion parameters. Tuning quality is determined from the deviations of the reckoned inertial parameters from the GPS parameters. Thus, it is apparently possible to implement an iterative process for the MSS half-scale development.

The purpose of this paper is to justify and to implement, in practice, a technology intended for half-scale development of the mathematical software support of integrated inertial satellite navigation systems from experimental data.

The attainment of the purpose in view relies on hardware/software capabilities of modern avionics , namely:

- on the capabilities of present-day equipment intended for the gathering, conversion, processing, and recording of the signals of navigational sensors;
- on the implementation, in the configuration of navigational sensors, of standard high-speed data exchange channels.

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1. A Technology and Problems for Half-Scale Development of the Mathematical Software Support for Strapdown Inertial Satellite Navigation Systems

A technology for half-scale development of the mathematical software support for strapdown inertial satellite navigation systems (SISNS) can be represented by a scheme shown in Fig.1, where IMU is an inertial measurement unit that contains the triad of accelerometers and the triad of FOGs; EM is an external memory; $\bar{\omega}$ is the vector of FOG output signals; $\bar{a}$ is the vector of accelerometer output signals; φ,λ are the geodetic latitude and longitude of the position of the object in question; $\bar{V}$ is the relative-velocity vector of object motion, given by its components along the axes of the navigation frame; $\bar{\delta}$ is the vector of attitude parameters.

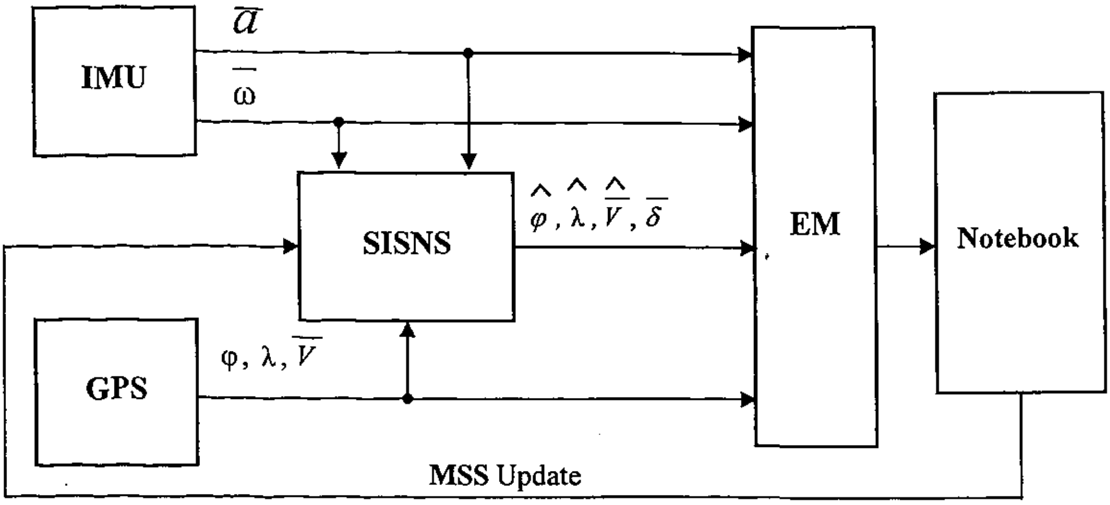

Fig. 1. Scheme for half-scale development of an SISNS mathematical software support

In accordance with the scheme presented here, when carrying out a half-scale experiment, the reckoning and updating of motion parameters are performed, in a Notebook, from the recorded signals of sensors and the GPS. In order that the procedures for full-scale and half-scale MSS development be quite identical in set, recording is made on a frequency at which sensor signals are loaded into the SISNS processor module. In the process of half-scale MSS development, the following problems can be solved:

- tuning the procedures of primary processing of sensor signals [1]. Such tuning includes determination of procedures for SISNS protection from sensor outliers as well as determination of the structure, order, and parameters of a digital filter;
- choosing the methods of integrating the basic equations for the determination of attitude and position of a SINS;
- making the frequency of picking off sensor signals agree with the SINS available computational resources;
- carrying out sensor dynamic calibration that is found to be unfeasible under factory conditions;
- estimation of the misalignment of measurement axes both in accelerometers and in FOGs;
- estimation of and analytical compensation for sensor drifts remained after factory calibration, which manifest themselves in each SINS start under service conditions;
- refinement of the structure and parameters of drift models of sensors [2];
- tuning the procedures of second processing of observed signals, which are based on the application of estimation filters of the Kalman type. Such tuning involves [3] making the parameters and tools used to protect the filter from divergence agree with the SISNS computational resources.

In the process of SISNS operation, on the basis of solving the above-mentioned problems, loops intended to control sensor condition can be implemented. As applied to aircraft SINS, such loops can be represented by scheme shown in Fig. 2.

To implement the loops intended to control sensor condition, the degree of detail for SINS error equations is to be brought to the level of FOG instrumental drifts and accelerometer biases. In this case, analytical compensation for the above sensor errors can be implemented at the level of primary processing of sensor signals [4].

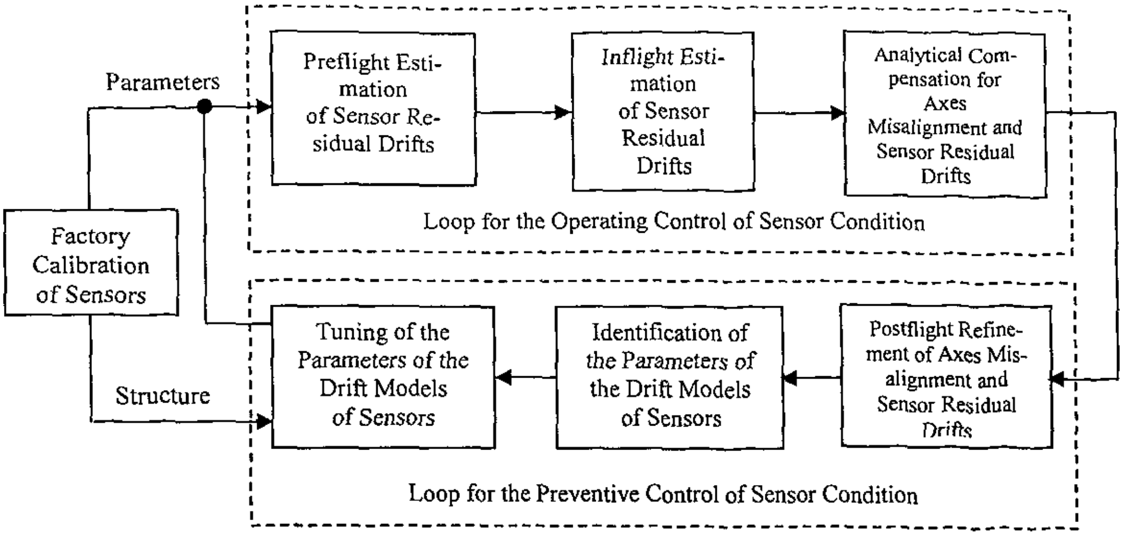

Fig. 2. Loops intended to control the condition of SINS sensors

2. The SINS-500 Strapdown Inertial Satellite Navigation System as the Object of Half-Scale Development

The technology for half-scale MSS development has been approved in the process of testing the SINS-500 strapdown inertial satellite navigation system that was designed by the "OPTOLINK" RPC (Zelenograd). Figure 3 shows a prototype of the SINS-500 system together with technological connecting cables.

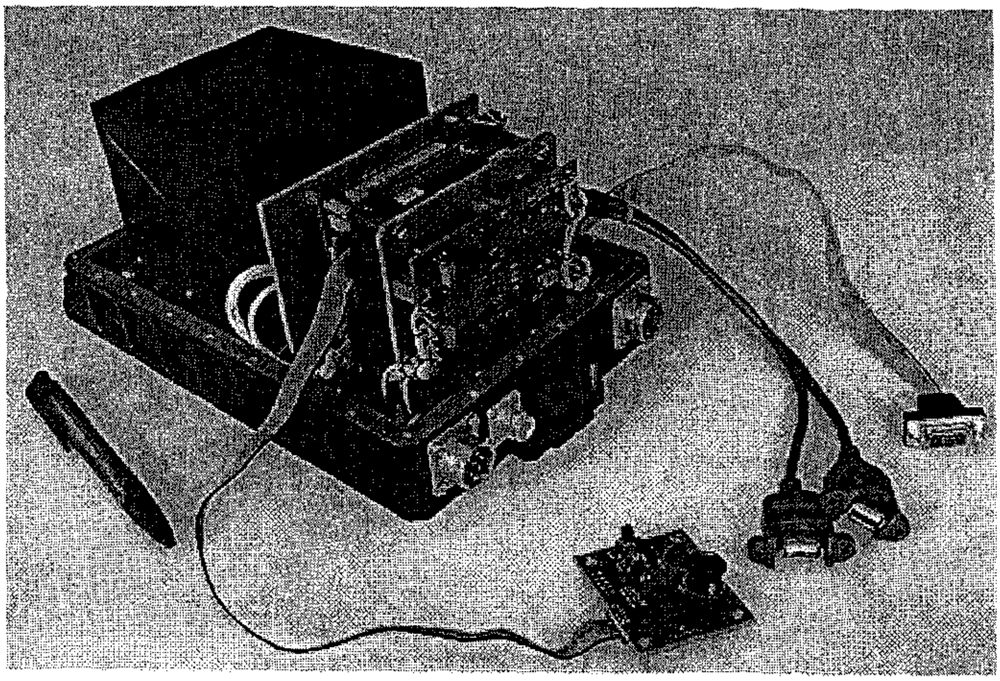

Fig. 3. SINS-500 strapdown inertial satellite navigation system

The major modules of the SINS-500 system are as follows: the TIUS-500 three-axis inertial measurement unit (IMU), based on the triad of fiber-optic gyros and accelerometers; the K-161 satellite receiver developed by the "RIRT" JSC (Saint-Petersburg); a computing module that conforms to the PC/104 standard; a power unit and input/output interfaces. For the SINS-500 system, the hardware and mathematical software support are modular in architecture. Such an architecture is analogous to that of the SINS-1000 system, which was discussed in [5]. However, the SINS-500 system is far less massive (no more then 4.5 kg) and it is much smaller in overall dimensions than the SINS-1000 system.

For FOGs which form part of the SINS-500 system, random residual drifts are of the order of 0.1÷0.3 deg/h, and for accelerometers, the above drifts are of the order of $10^{-4}\,g$.

Hardware that was formed according to the "effectiveness-cost" criterion gives ground to classify the SINS version presented here among the systems of medium accuracy. Such systems are just the ones in which it is apparently expedient to implement procedures for analytical compensation for sensor residual drifts.

The timing diagram of SINS operation includes the following stages: coarse initial alignment, fine initial alignment, and a navigational mode that includes operation both in the submode of autonomous inertial navigation and in the submode of inertial satellite navigation.

At the stage of coarse initial alignment, IMU angular position is approximately determined using sensor output signals.

At the stage of fine initial alignment, errors in the IMU angular position and also sensor residual drifts are estimated, along with the parameters of their dynamic models. This problem is solved on a basis of the sequentially processing, by a robust Kalman filter [3], of the observed signals z_i of the following form:

$$z_{\Theta(i)} = C_{0(i)}^{\mathrm{T}} \int_{t_{i-1}}^{t_i} \dot{\bar{\Theta}}(\tau)d\tau - [0 \vdots 0 \vdots \Omega\Delta t_i]^{\mathrm{T}} ; \tag{1}$$

$$z_{k(i)} = [\varphi_i\lambda_i]_{\mathrm{SINS}}^{\mathrm{T}} - [\varphi_i\lambda_i]_{\mathrm{PIA}}^{\mathrm{T}} ; \tag{2}$$

$$z_{\mathrm{v}(i)} = [V_\xi V_\eta V_\zeta]_{(i)\mathrm{SINS}}^{\mathrm{T}} , \tag{3}$$

where PIA stands for the position of the initial alignment; φ_i, λ_i are the geodetic latitude and longitude of the SINS position; $\Delta t_i = t_i - t_{i-1}$ is an observation step;

$\bar{\Omega} = [\Omega_\xi \quad \Omega_\eta \quad \Omega_\zeta]^{\mathrm{T}}$ is the vector of the angular velocity of Earth rotation, given by its components along the axes of the semiwander azimuth reference frame $o\xi\eta\zeta$;

$\dot{\bar{\Theta}} = \begin{bmatrix} \dot{\Theta}_x & \dot{\Theta}_y & \dot{\Theta}_z \end{bmatrix}^{\mathrm{T}}$ is the vector of FOG output signals, given by its components along the IMU axes;

C_0 is the direction cosine matrix that characterizes the angular position of the IMU- fixed frame $oxyz$ with respect to the inertial frame $OX_IY_IZ_I$;

$\bar{V} = [V_\xi \quad V_\eta \quad V_\zeta]^{\mathrm{T}}$ is the relative-velocity vector of IMU motion, given by its components along the axes of the reference navigation frame $o\xi\eta\zeta$.

For the inertial satellite navigation, a combined mode of operation is implemented on a basis of the sequentially processing, by the robust Kalman filter [3], in the following position observations and velocity ones:

$$z_{k(i)} = [\varphi_i\lambda_i]_{SINS}^{\mathrm{T}} - [\varphi_i\lambda_i]_{GPS}^{\mathrm{T}} ; \tag{4}$$

$$z_{\mathrm{v}(i)} = C_{3(i)}^{\mathrm{T}}[V_\xi V_\eta V_\zeta]_{(i)SINS}^{\mathrm{T}} - [V_E V_N V_H]_{(i)GPS}^{\mathrm{T}} , \tag{5}$$

where C_3 is the direction cosine matrix that characterizes the angular position of the reference frame $o\xi\eta\zeta$ with respect to the geodetic frame $oENH$.

The autonomous inertial mode is implemented taking into account that the predicted FOG drift estimates and the predicted biases of accelerometers are compensated for.

The basis state vector is comprised of 17 parameters, namely: the errors $\Delta V_\xi, \Delta V_\eta, \Delta V_\zeta$ in the reckoning of components of the relative-velocity vector; the errors Δq_0 and Δq_1 in the reckoning of quaternion elements; the angular drifts $\Delta\dot{\Theta}_x$, $\Delta\dot{\Theta}_y$, $\Delta\dot{\Theta}_z$ of FOGs and also the biases $\Delta a_x, \Delta a_y, \Delta a_z$ of accelerometers, where q_0 is a quaternion that characterizes the angular position of the IMU-fixed frame $oxyz$ with respect to the inertial frame $OX_IY_IZ_I$; q_1 is a quaternion that characterizes the angular position of the reference navigation frame $o\xi\eta\zeta$ with respect to the ECEF frame $OX_EY_EZ_E$.

Equations for sensor errors are formed in the IMU-fixed frame. This makes it possible to estimate and damp the sensor errors in real time.

In all SISNS operating modes, at the level of primary processing of sensor signals, their combined digital filtering is carried out which includes the following procedures:

- input predictive checking of signals by the combined goodness-of-fit test χ^2/ϑ^2 [6];
- localization and counteraction of outliers [6];
- suppression of noise components of sensor errors through the use of recurrent smoothing of the signals [4];
- taking into account calibration coefficients that reflect sensor systematic errors, misalignment of their axes, and also thermal drifts.

The first three procedures of primary processing of sensor signals can be combined into a unified structure of a robust digital filter [4,6].

To implement the loop for preventive control of sensor condition, in the course of half-scale MSS development, scale factors and coefficients characterizing the misalignment of sensor sensitivity axes are, in addition, included in the

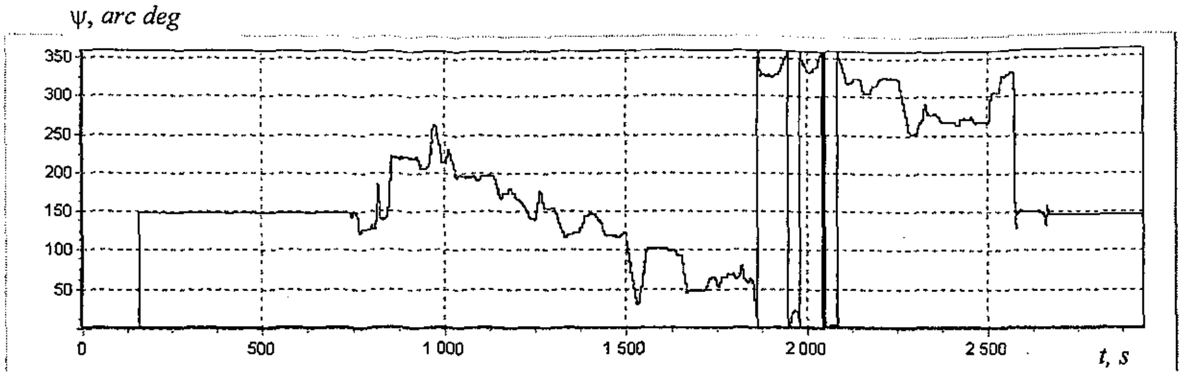

Fig.5. True heading

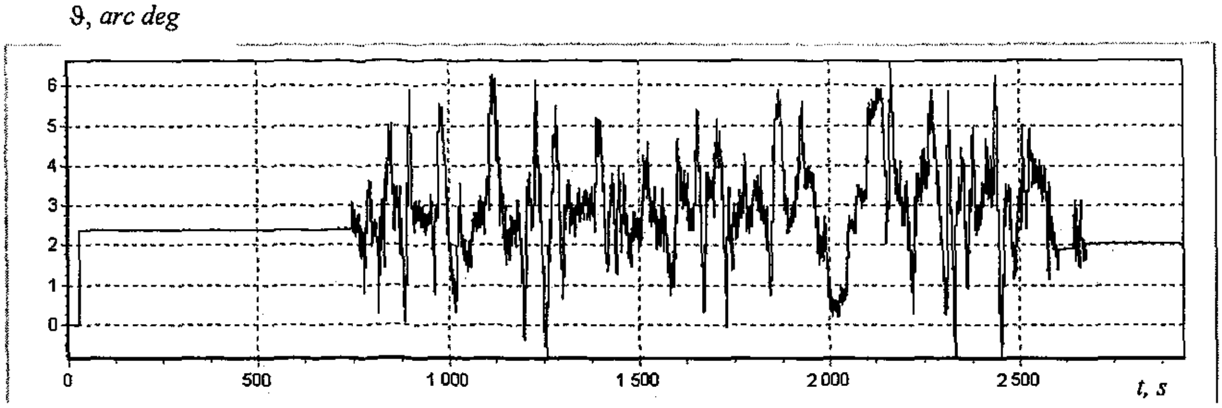

Fig.6. Angle of pitch

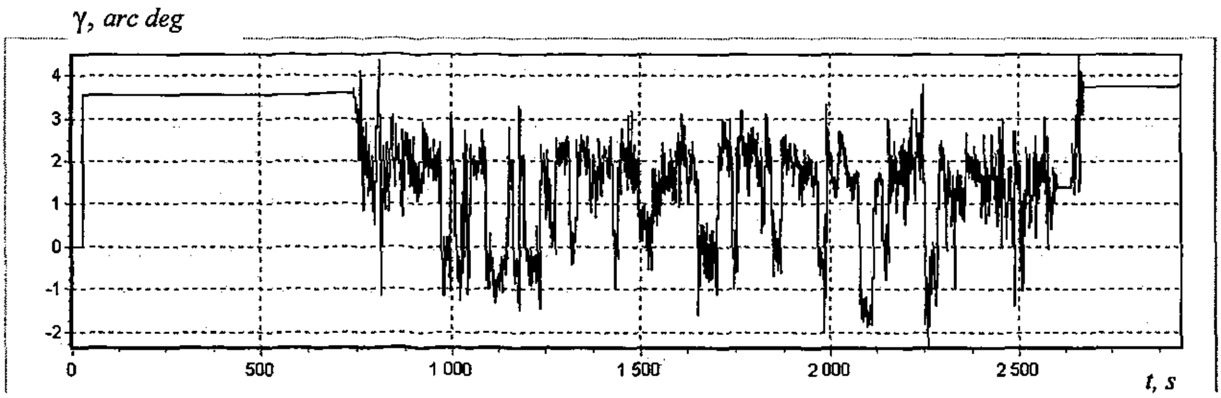

Fig.7. Angle of rool

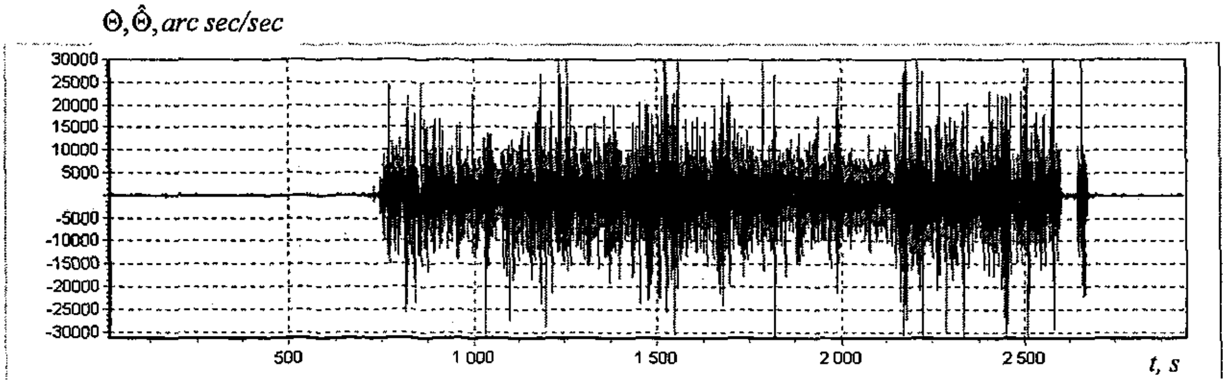

Fig.8. Output signal of one of the gyros

basis vector of SINS errors; these factors and coefficients have been determined under factory calibration conditions. Technological extension of the vector of SINS errors [2] enables one to carry out postflight refinement of the abovementioned factors and coefficients from the recorded sensor signals in the dynamic mode of SINS operation.

3. Analysis of the Results of Studies

Experiments have been carried out on the ground when the necessary equipment was housed in a mobile laboratory on the basis of an automobile. The timing diagram of operation of the SINS-500 system included the following stages: coarse initial alignment (t=0÷100s), fine initial alignment (t=100÷600s), and a navigational mode (t>600s).

Certain of the results of an experiment on the estimation of accuracy characteristics of the SINS - 500 system are shown in Figs. 4-19. The results of a comparison analysis of SINS operation when using different schemes for the damping of sensor errors were obtained on a basis of the reckoning of motion parameters from the recorded signals of sensors of the IMU and the GPS.

Figure 4 shows the horizontal path when the testing laboratory is moving under urban conditions.

In Figs. 5-7, the true heading angle, pitch angle, and roll angle of the IMU are shown, respectively.

Figure 8 depicts the following signals: the output signal (a light-colored graph, arc secs/sec) of one of the gyros; the output signal (a dark-colored graph) of the same gyro, which was smoothed by means of a robust digital filter [4].

In Fig. 9, the following signals are shown: the output signal (a light-colored graph, m/sq.sec) of one of the horizontal accelerometers; the output signal (a dark-colored graph) of the same accelerometer, which was smoothed with the aid of a robust digital filter [4]. The above smoothing has been performed when sensor signals were picked off with a frequency of 1 kHz.

Figures 10-12 show estimates of FOG residual drifts. These estimates were obtained in the processing of observations (1)-(5) with a frequency of 1 Hz during the fine initial alignment and in the navigational mode.

Moreover, Fig. 12 depicts the FOG actual instrumental drift (deg/h), which was determined as the mean value of "zero" bias on the time intervals of 10 sec during the fine initial alignment.

In Fig. 13, an estimate of the bias of the accelerometer in question is shown.

Beginning with the moment t=600 sec, the SINS-500 system was functioning in the autonomous inertial mode and in the mode of compensation for estimated residual drifts and estimated biases in sensor signals.

Figures 14-18 show the components V_E , V_N of the object ground velocity, which were reckoning by the SINS (dark – colored graphs) and determined with the help of the GPS (light-colored graphs).

Figures 14,15 depict the dynamics of variation of the above velocities when the coefficients of carry and diffusion [2,7] in the model of FOG angular drifts are tuned properly, and Figs. 17,18 depict the above dynamics when the coefficients mentioned differ from the required ones by a factor of 10.

Figure 16 reflects the presence of the GPS signals when moving under urban conditions, namely: "1" shows that the signals are present; "0" shows that the signals are not present.

A comparison of the results shows that with the parameters of models of sensor errors tuned inaccurately, SINS accuracy characteristics become substantially worse.

Figure 19 shows the circular error ΔS of the object position estimation, which corresponds to the reckoning of SINS velocities depicted in Figs. 14 and 15, where

$$\Delta S=\sqrt{\delta_{\varphi}^{2}+\delta_{\lambda}^{2}}\ ; \qquad \delta_{\varphi}=(\varphi_{SINS}-\varphi_{GPS})R\ ; \qquad \delta_{\lambda}=(\lambda_{SINS}-\lambda_{GPS})R$$

$$R=a(1-0{,}5e^{2}\sin^{2}\varphi);\ a=6378245\ \text{м};\ e^{2}=0{,}0066934.$$

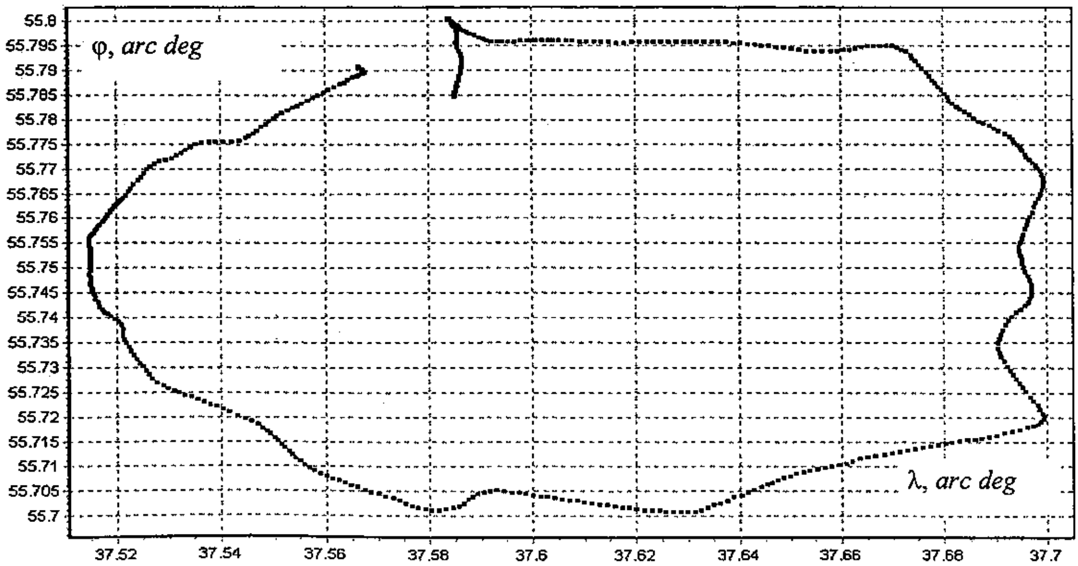

Fig.4. Horizontal path of the testing-laboratory motion under urban conditions

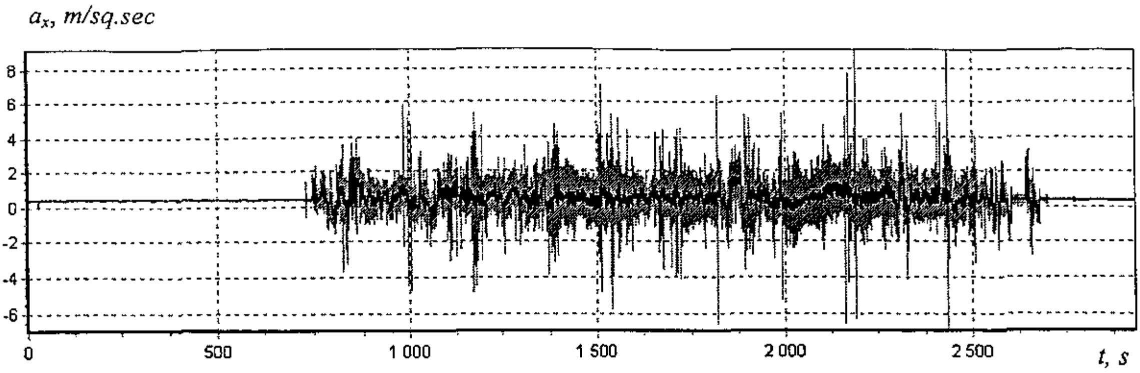

Fig.9. Output signal of one of the horizontal accelerometers

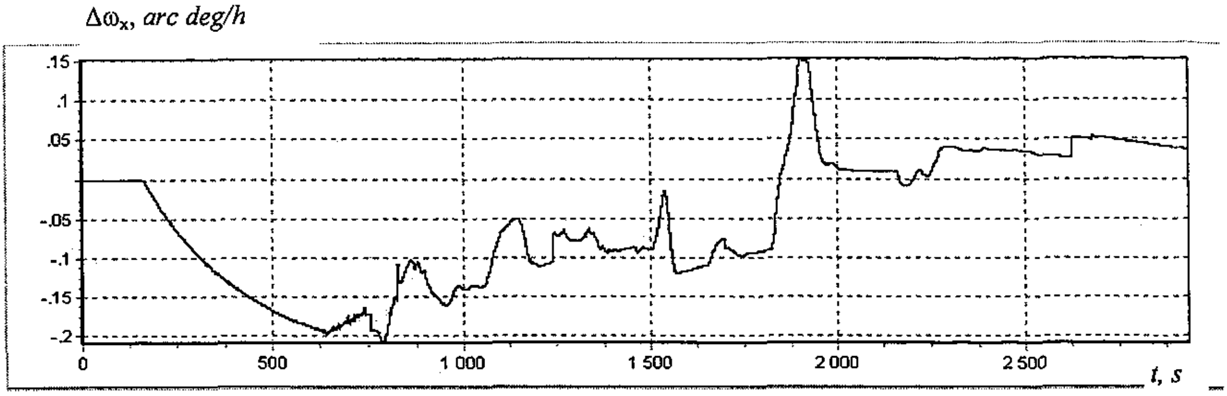

Fig.10. Estimate of the residual drift for the *ox* FOG

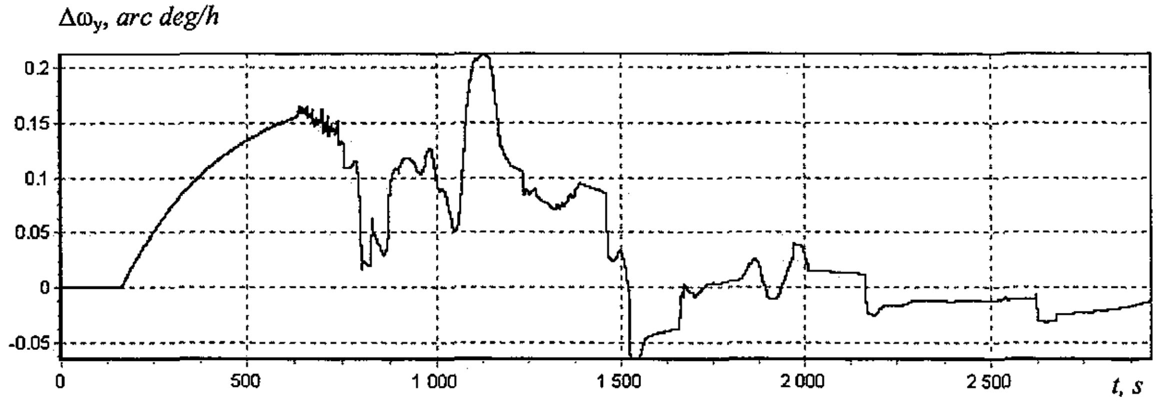

Fig.11. Estimate of the residual drift for the *oy* FOG

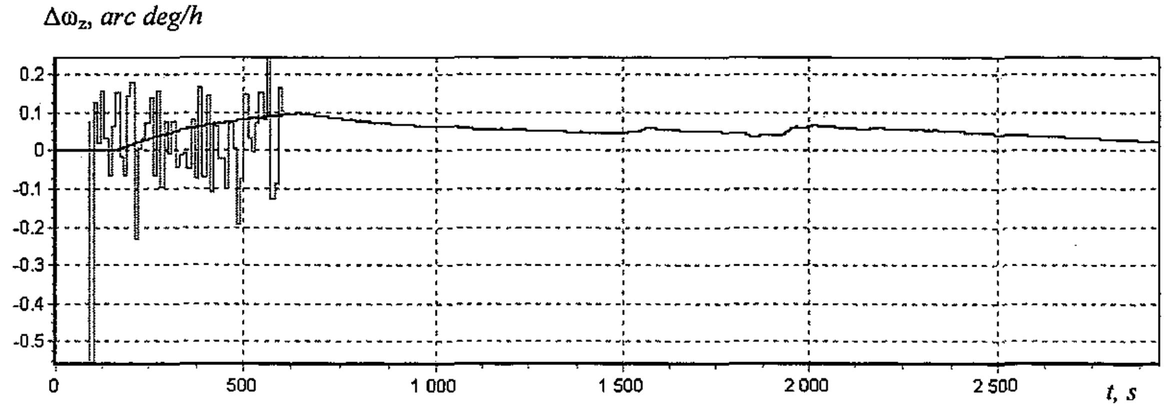

Fig.12. Actual residual drift for the vertical *oz* FOG and its estimate

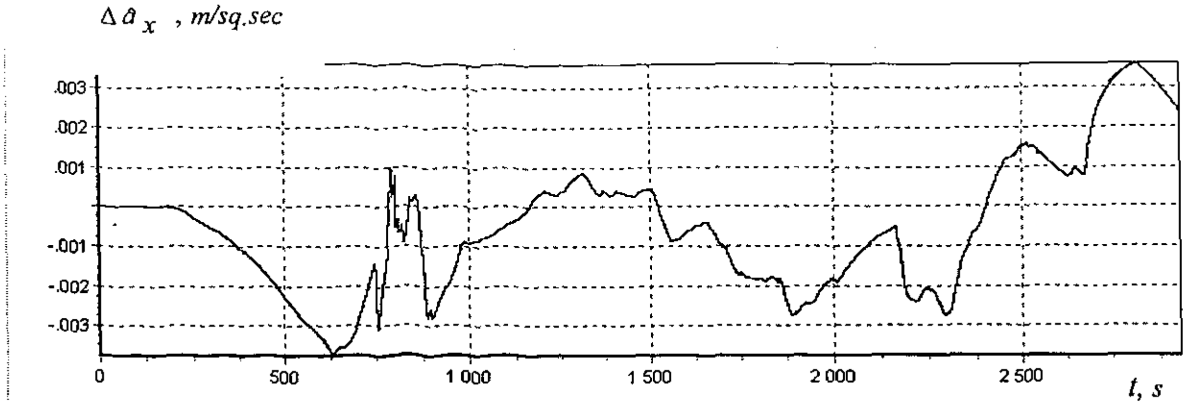

Fig.13. Bias estimate for the accelerometer in question

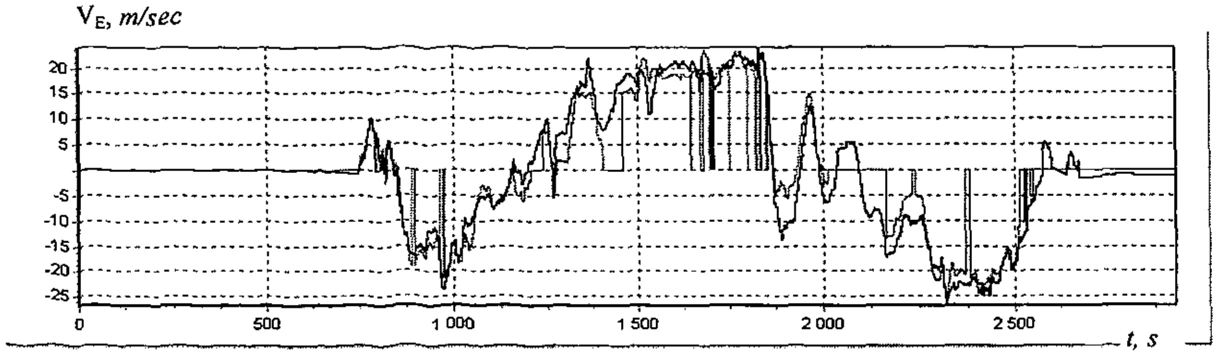

Fig.14. Dynamics of variation of the velocity V_E when the coefficients in the model of FOG drifts are tuned properly

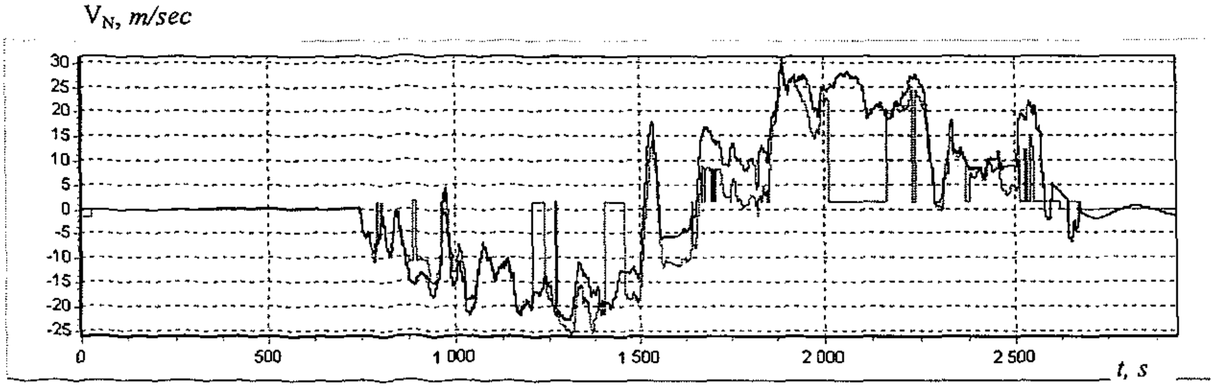

Fig.15. Dynamics of variation of the velocity V_N when the coefficients in the model of FOG drifts are tuned properly

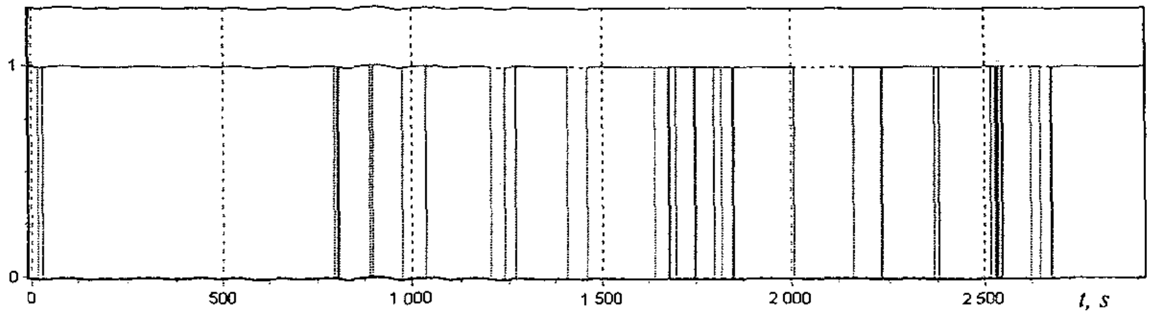

Fig.16. Indicators of the presence of the GPS signals when moving under urban conditions

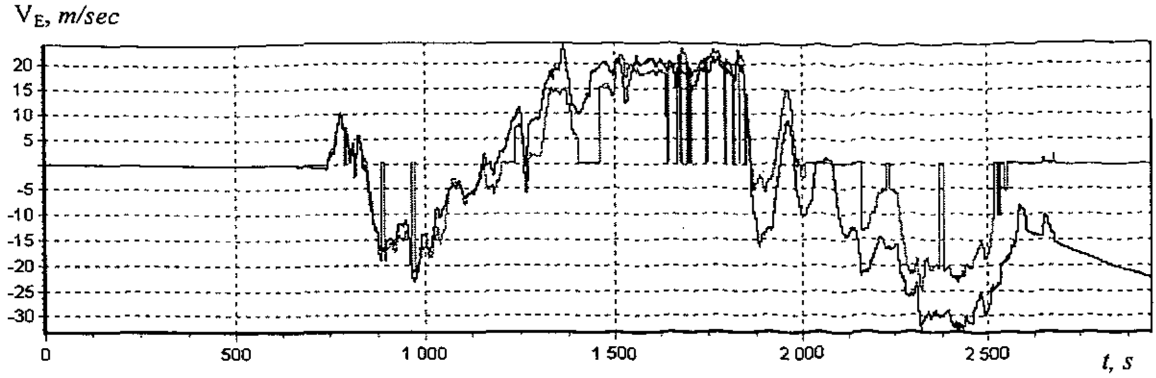

Fig.17. Dynamics of variation of the velocity V_E when the coefficients in the model of FOG drifts are tuned improperly

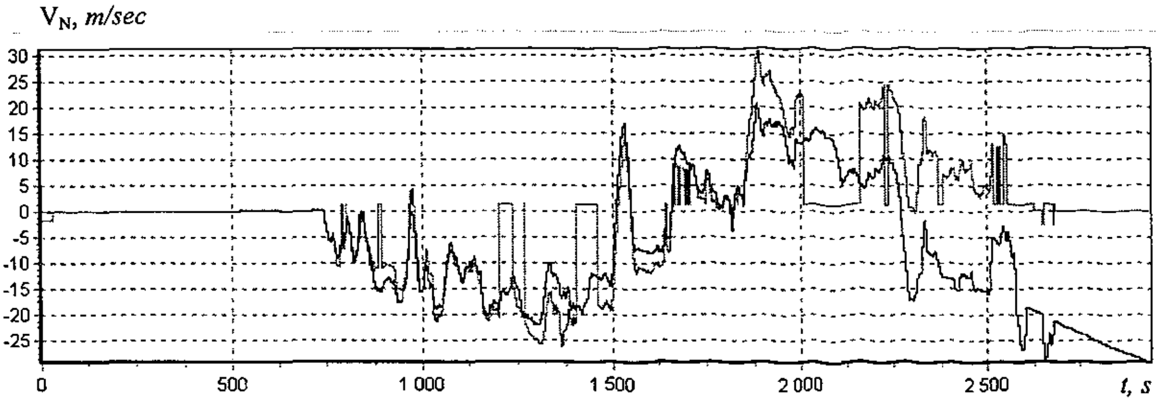

Fig.18. Dynamics of variation of the velocity V_N when the coefficients in the model of FOG drifts are tuned improperly

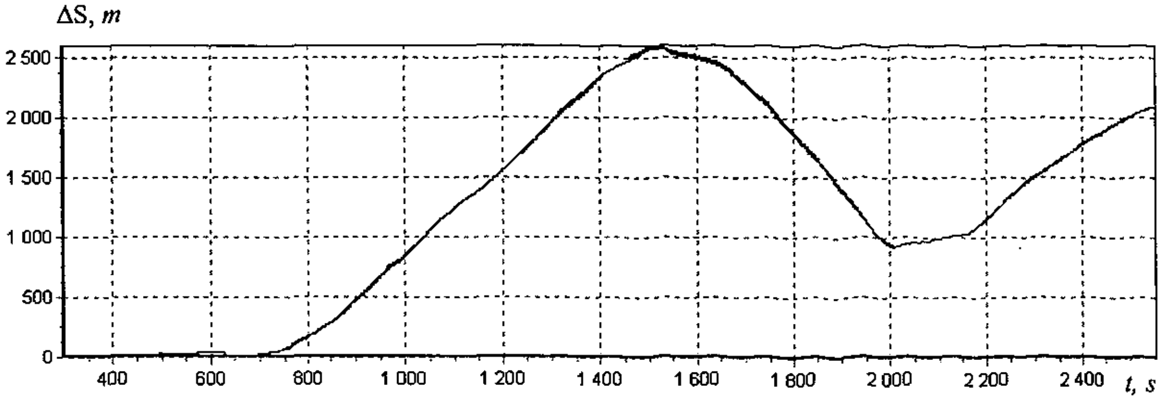

Fig.19. Dynamics of variation of the circular error of the object position estimate when sensor drifts are damped

The studies conducted and the graphs presented here corroborate the fact that it is expedient to include the stage of half-scale simulation in the structure of a technological process intended for developing the hardware and mathematical software support of strapdown inertial satellite navigation systems.

Conclusions

Half-scale development of the mathematical software support (MSS) for strapdown inertial satellite navigation systems (SISNSs) can be carried out from the recorded sensor signals. Such an approach enables one to simulate actual operating conditions and to perform MSS optimization on a set of the algorithms under study. The capabilities of modern avionics and also of signal gathering and signal processing equipment permit making use of the technology intended for half-scale development in order to control SISNS technical condition and to update the MSS at all stages of the life cycle.

References

1. **Chernodarov A.V., Perelyaev S.E.** Monitoring and Estimation of the Inertial-Sensor Condition During Integrated Primary Processing of Signals // Proc. of the 14-th Saint Petersburg International Conference on Integrated Navigation Systems. – SPb: CSRI «Electropribor», 2007, pp. 91-93.
2. **Chernodarov A.V., Patrikeev A.P., Platonov A. Ju., Budkin V.L., Golikov V.P., Larionov S.V.** Parametric Identification of Integrated Navigation Systems in Real Time and from Flight Data [In Russian] // Gyroscopy and Navigation. – 2007. – №4 (59), p. 17-31.
3. **Chernodarov A.V., Patrikeev A.P., Budkin V.L., Golikov V.P., Larionov S.V.** Flight Development of Onboard Estimating Filters // Proc. of the 11th Saint Petersburg International Conference on Integrated Navigation Systems. – SPb: CSRI "Electropribor", 2004, pp. 27-35.
4. **Chernodarov A.V.** Monitoring and Multilevel Protection of the Integrity of Tightly-Coupled Navigation Systems for Maneuverable Aircraft // Prepr. IFAC Workshop «Aerospace Guidance, Navigation and Flight Control Systems», Samara, Russia. 2009, Sess. WeG – 1.
5. **Korkishko Yu.N., Fedorov V.A., Patrikeev A.P., Chernodarov A.V., Perelyaev S.E.** An Object-Oriented Technology for the Integration of Navigation Sensors and its Implementation in the SINS-1000 Strapdown Inertial System Built Around Fiber-Optic-Gyros // Proc. of the 16-th Saint Petersburg International Conference on Integrated Navigation Systems. – SPb: CSRI «Electropribor», 2009, pp. 18-27.
6. **Kolodezny L.P., Chernodarov A.V.** Reliability and Engineering Diagnostics [in Russian]. – M.: Zhukovsky and Gagarin Air Force Academy, 2010, 452 pp.
7. **Korolyuk V.S., Portenko N.I., Skorokhod A.V., Turbin A.F.** A Handbook of Probability Theory and Mathematical Statistics [In Russian]. – M.: Nauka, GRFML, 1985.