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# COMPUTER MODELING OF ACCURACY CHARACTERISTICS OF STRAPDOWN INERTIAL NAVIGATION SYSTEM

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## ABSTRACT

**Context.** The problem of correction for operation of strapdown inertial navigation system used for unmanned aerial vehicle is urgent because of further increased requirements to autonomous flight in blackout zones. The object of the study was to simulate the accuracy characteristics of strapdown inertial navigation system based on known (or given) instrument errors of its sensors.

**Objective.** The goal of the work is to develop a mathematical and computer model of the strapdown inertial navigation system and estimate its accuracy characteristics based on given values of sensor errors.

**Method.** The mathematical and computer models of the strapdown inertial navigation system based on slow, medium and fast cycles are developed. For the simulation of accuracy characteristics, the strapdown inertial navigation system is represented as a set of dynamic and kinematic equations in local tangent plane coordinate system with the Earth's model taking into account components of gravity acceleration. The models of sensors are developed based on characteristics of low-cost microelectromechanical sensors used onboard. Data fusion algorithms were previously considered and include modified Kalman filter or, for some cases, complimentary filter by compensation scheme, but not considered here in details. Direction cosine matrix for strapdown inertial navigation system algorithms is found by Poisson's method.

**Results.** The developed models have been realized and simulated in MATLAB+Simulink. Initial parameters (errors of the primary information sensors and the flight conditions) during simulation have been varied: medium, high and low latitudes; direction of flight (along and across the meridian; on and against the direction of rotation of the Earth).

**Conclusions.** The developed models and their simulations have been compared with actual testing results of strapdown gyrovertical СБКВ-П2А and confirmed the validity. It allow us to recommend them for use in designing strapdown inertial navigation system of unmanned aerial vehicle, as well as for experimental study of innovative data fusion algorithms for integrated satellite and inertial navigation system.

**KEYWORDS:** strapdown inertial navigation system, satellite navigation system, strapdown gyrovertical, dead reckoning, data fusion.

## ABBREVIATIONS

LTP is a local tangent plane;
MEMS are microelectromechanical sensors;
SINS is a strapdown inertial navigation system;
SNS is a satellite navigation system;
UAV is an unmanned aerial vehicle.

## NOMENCLATURE

$\gamma$ is a roll angle;
$\lambda$ is a longitude;
$\vartheta$ is a pitch angle;
$\Theta$ is an angle of trajectory inclination;
$\varphi$ is a geographic latitude;
$\psi$ is a course angle;
$\Psi$ is a track angle;
$\Omega_0$ is an angular speed of the Earth's rotation;
$\Omega_R$, $\Omega_L$, $\Omega_\Phi$ are the projections of the angular velocity of the Earth's rotation on LTP coordinate axes;
$\omega_{L_\Sigma, R_\Sigma, \Phi_\Sigma}$ are the projections of the angular velocity of the navigation trihedron relative to the inertial space;
$a_{L,R,\Phi}$ are the projections of the apparent acceleration of UAV on the axis of the navigation trihedron;
**B** is a direction cosine matrix;
$g_{L,R,\Phi}$ are the projections of the acceleration vector of gravity on LTP coordinate axes;
$H$ is a flight altitude;
$R$ is a distance to the Earth's center;
$R_m$, $R_p$ are the radiuses of meridian and parallels;
$V_L$, $V_R$, $V_\Phi$ are the components of the flight speed in LTP coordinate system.

## INTRODUCTION

Strapdown gyro vertical is related to the class of SINS and outputs main navigation parameters. They are obtained by dead (deduced) reckoning, that is, by continuous integrating signals corresponding to aircraft accelerations. Information about the acceleration comes from accelerometers located on board UAV. The procedure for integrating vector quantities, which are the accelerations and velocities of UAV, is ensured by reproducing (modeling) the corresponding coordinate system on board. The presence of errors in the SINS sensors, in turn, leads to errors in determining the navigational coordinates of UAV movement. That is why while designing SINS it is necessary to reduce the magnitude of the instrument errors in the primary information sensors.

The subsystem of integration of SINS and SNS into one is implemented in the data fusion scheme (usually it is Kalman filter block). This scheme estimates the position and speed of UAV, and this data can come not only to consumers, but also to the delay and phase tracking blocks of SNS receivers. It is necessary to provide high data rate for these blocks so that the time period between measurements in the SNS subsystem can be divided into a large number of subintervals for the purpose of observation correction contour.


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For UAV, sensors of SINS are usually selected to be small and low-cost, and MEMS are almost fully met these requirements. Here there is a problem to develop a mathematical and computer model of the strapdown inertial navigation system and to estimate its accuracy characteristics based on given values of sensor errors.

**The object of study** is the strapdown inertial navigation systems and its sensors of primary information.

**The subject of study** is the computer and mathematical model of SINS and its accuracy characteristics depending on instrument errors of primary information sensors.

**The purpose of the work** is to develop a mathematical and computer model of the strapdown inertial navigation system and estimate its accuracy characteristics based on given values of sensor errors.

## 1 PROBLEM STATEMENT

As navigation coordinate system, let us use the conditional geographical coordinate system *OLRΦ* (Fig. 1). Position of UAV relatively the Earth is determined by geographic longitude λ, latitude φ and distance to the Earth's center *R*.

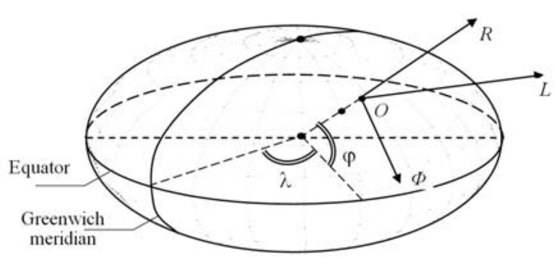


Figure 1 – LTP coordinate system used for navigation

Here there are axes: *OR* coincides with the vertical; *OL* is the tangent to the parallel (equator); *OΦ* is directed in order to form right-handed coordinate system.

This direction of the axes of the navigation trihedron was chosen taking into account the simplification of the further transition from the geographical to the great-circle coordinate system, since in the great-circle coordinate systems *OL* axis coincides with the tangent to the great-circle course. It is in this convention of the selected geographical coordinate system. The difference between a conventional geographical and a standard geographical coordinate system is the opposite sign of the latitude value and the course reckoning.

In SINS algorithms, dynamic and kinematic equations are usually distinguished. Dynamic equations realize the three-component SINS scheme in which the coordinates λ, $\varphi_y$, $H$ are determined by integration of the following equations:

$$\dot{\lambda} = \frac{V_L}{R_p}; \dot{H} = V_R;$$
$$\dot{\varphi}_y = \frac{V_\Phi}{R_m}; \varphi = -\varphi_y. \quad (1)$$

The components of the flight speed $V_L$, $V_R$, $V_\Phi$ in the navigation coordinate system are determined by projecting the vector equation on the corresponding axes of the navigation trihedron:

$$\dot{V}_L = a_L + V_R \omega_{\Phi_\Sigma} - V_\Phi \omega_{R_\Sigma} + g_L;$$
$$\dot{V}_R = a_R + V_\Phi \omega_{L_\Sigma} - V_L \omega_{\Phi_\Sigma} + g_R; \quad (2)$$
$$\dot{V}_\Phi = a_\Phi + V_L \omega_{R_\Sigma} - V_R \omega_{L_\Sigma} + g_\Phi,$$

where

$$\omega_{\Phi_\Sigma} = \omega_{\Phi_V} + 2\Omega_\Phi;$$
$$\omega_{R_\Sigma} = \omega_{R_V} + 2\Omega_R;$$
$$\omega_{L_\Sigma} = \omega_{L_V} + 2\Omega_L.$$

In turn, the components of the relative angular velocity of the navigational trihedron and the rotation speeds of the Earth are determined by the relations:

$$\omega_{L_V} = \frac{V_\Phi}{R_m} = \dot{\varphi}_y;$$
$$\omega_{RV} = -\frac{V_L}{R_p}\sin\varphi_y = -\dot{\lambda}\sin\varphi_y;$$
$$\omega_{\Phi_V} = -\frac{V_L}{R_p} = -\dot{\lambda}; \quad (3)$$
$$\Omega_L = 0; \Omega_R = \Omega_0 \sin\varphi; \Omega_\Phi = -\Omega_0 \cos\varphi.$$

Here $\Omega_0$ is equal to $7.27 \cdot 10^{-5}$ rad/sec.

## 2 REVIEW OF THE LITERATURE

The inertial navigation systems error models were proposed in [1] which also puts all of the known models in the same framework and shows the equivalence between them. The authors proposed the methodology when any new model which will ever be developed can be added to general one, but such unification had several weak spots like impossibility to get combination of several error sources.

The most significant error source is computational one, namely connected with recalculation of DCM or using quaternions as it is done and analyzed in [2]. Authors adopted dual quaternion algebra, as unified mathematical tool for representing the general displacement of a rigid body, to analyze error characteristics of the strapdown INS. Accuracy characteristics for using Poisson's equation to find DCM is studied in [3], and it is more traditional approach for integrated SINS.

The development of novel miniature sensory of SINS is considered in [4]. It covers the sources of modern MEMS together with [5]. The research of MEMS models is done in [6], where low-cost sensors are represented as error sources with short-term (high-frequency) and long-term (low-frequency) components, via Allan variance, wavelet de-nosing and the selection of the level of decomposition for a suitable combination between these techniques. The same technique (Allan variance analysis)


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is used in [7], where the error model is simply represented in the form of the root mean square random drift error varied with averaging time.

The Earth's model is selected by researcher depending on the given tasks and depends of accuracy requirements to gravity acceleration components like in [8] where for integration SINS with SNS the standard GPS Earth Centred Earth Fixed reference frame was selected together with Earth's model.

Used here models of instrument errors of SINS are previously studied by authors and gathered in book [9].

An integrated SINS-SNS based on the theory of multisensor data fusion is presented in [10]. Error models for the inertial measurement unit are generated and included in the extended Kalman filter for SINS. An improved decentralized Kalman filter is developed to eliminate obvious error of SNS data and reduce the load of calculation. An adaptive federal Kalman filter is used for data fusion between SINS and SNS to provide smoothed and continuous positioning data against the presence of radio blackout or communication dropouts and the unbounded SINS errors growing with time.

## 3 MATERIALS AND METHODS

Scheme of navigational calculation algorithm is the following.

Performing some transformations and taking into account the equality of the individual components of the initial dynamic and kinematic equations (1)–(3) to zero, the algorithm for performing navigation calculations in the geographic coordinate system can be represented as it is given in [11, 12]. In case of insufficient speed of the airborne processor of the navigation computer, the SINS operation algorithm can be divided by two or even three levels according to the required calculation speed (by the duration of the sampling period), which are characterized the correspondingly fast, medium, and slow calculation cycles.

Fast cycle is described as following:

$$\begin{aligned} \omega_{y_\Sigma} &= \omega_y - \omega_{y_{\Phi LR}}; \\ \omega_{x_\Sigma} &= \omega_x - \omega_{x_{\Phi LR}}; \\ \omega_{z_\Sigma} &= \omega_z - \omega_{z_{\Phi LR}}. \end{aligned} \quad (4)$$

$$\begin{aligned} \dot{\psi} &= \left(\omega_{y_\Sigma}\cos\gamma - \omega_{z_\Sigma}\sin\gamma\right)\sec\vartheta; \\ \dot{\gamma} &= \omega_{x_\Sigma} + \mathrm{tg}\vartheta\left(\omega_{z_\Sigma}\sin\gamma - \omega_{y_\Sigma}\cos\gamma\right); \\ \dot{\vartheta} &= \omega_{y_\Sigma}\sin\gamma + \omega_{z\Sigma}\cos\gamma; \\ \psi_g &= (90^\circ - \psi). \end{aligned} \quad (5)$$

$$B = \begin{bmatrix} \cos\psi\cos\vartheta & \sin\psi\sin\gamma - \cos\psi\sin\vartheta\cos\gamma & \sin\psi\cos\gamma + \sin\psi\cos\vartheta\sin\gamma \\ \sin\vartheta & \cos\vartheta\cos\gamma & -\cos\vartheta\sin\gamma \\ -\sin\psi\cos\vartheta & \cos\psi\sin\gamma + \sin\psi\sin\vartheta\cos\gamma & \cos\psi\cos\gamma - \sin\psi\sin\vartheta\sin\gamma \end{bmatrix} \quad (6)$$

Medium cycle is described as following:

$$\begin{bmatrix} a_L \\ a_R \\ a_\Phi \end{bmatrix} = \mathbf{B}\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}; \quad (7)$$

$$\begin{aligned} \dot{V}_L &= a_L + V_R\left(\omega_{\Phi_V} + 2\Omega_\Phi\right) - V_\Phi\left(\omega_{R_V} + 2\Omega_R\right); \\ \dot{V}_R &= a_R + V_\Phi\omega_{L_V} - V_L\left(\omega_{\Phi_V} + 2\Omega_\Phi\right) + g_R; \\ \dot{V}_\Phi &= a_\Phi + V_L\left(\omega_{R_V} + 2\Omega_R\right) - V_R\omega_{L_V}. \end{aligned} \quad (8)$$

Slow cycle is described as following:

$$\begin{aligned} \dot{\lambda} &= -\omega_{\Phi_V} = \frac{V_L}{R_p}; \\ \dot{H} &= V_R; \\ \dot{\varphi}_y &= \omega_{L_V} = \frac{V_\Phi}{R_m}; \end{aligned} \quad (9)$$

$$\begin{aligned} \omega_{RV} &= \omega_{\Phi_V}\sin\varphi_y; \\ \varphi &= -\varphi_y; \\ \Omega_R &= \Omega_0\sin\varphi; \\ \Omega_\Phi &= -\Omega_0\cos\varphi. \end{aligned} \quad (10)$$

$$\begin{bmatrix} \omega_{x_{\Phi LR}} \\ \omega_{y_{\Phi LR}} \\ \omega_{z_{\Phi LR}} \end{bmatrix} = \mathbf{B}^T\begin{bmatrix} \omega_{\Phi_V} + \Omega_\Phi \\ \omega_{R_V} + \Omega_R \\ \omega_{L_V} \end{bmatrix}. \quad (11)$$

The Earth's model is described as following:

$$\begin{aligned} R_p &= \frac{a\cos\varphi}{\sqrt{1 - e^2\sin^2\varphi}} + H\cos\varphi; \\ R_m &= \frac{a\left(1 - e^2\right)}{\left(1 - e^2\sin^2\varphi\right)^{\frac{3}{2}}} + H; \\ g_R &= -g\left(1 + 5.2884\cdot 10^{-3}\sin^2\varphi\right)\left[1 - \frac{2H}{R_0}\left(1 - e\ \sin^2\varphi\right)\right]. \end{aligned} \quad (12)$$

The initial parameters for navigational calculations are: strapdown gyrovertical information about the projections of angular velocities and accelerations on the axes of the body-fixed coordinate system, initial values of the geographic course $\psi_{g0}$, roll $\gamma_0$, pitch $\vartheta_0$ obtained as a result of the initial alignment of gyrovertical. Also initial coordinates are used: geographic longitude $\varphi_0$, geographic longitude $\lambda_0$ and initial flight altitude $H_0$. In the case of alignment on vehicle, projections of the initial speed of UAV are introduced as initial conditions: $V_{L0}$, $V_{H0}$, $V_{\Phi 0}$.

The constants in the algorithms of navigation calculations are:

– the Earth's angular velocity: $\Omega_0 = 7.27\cdot 10^{-5}$ rad/sec;

– semi-major axis of the ellipsoid of revolution $a = 6378388$ m;

– eccentricity of rotation ellipsoid $e^2 = 6.7227\cdot 10^{-3}$;

– acceleration of gravity force at the equator $g = 9.78045$ m/sec$^2$;


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– radius of a sphere equal to the geoid $R_0 = 6371116$ m.

Initial conditions are calculated as following:

$$R_{p_0} = \frac{a\cos\varphi_0}{\sqrt{1-e^2\sin^2\varphi_0}} + H\cos\varphi_0;$$

$$R_{m_0} = \frac{a\left(1-e^2\right)}{\left(1-e^2\sin^2\varphi_0\right)^{\frac{3}{2}}} + H_0;$$

$$g_{R_0} = -g\left(1+5.2884\cdot10^{-3}\sin^2\varphi_0\right)\left[1-\frac{2H_0}{R_0}\left(1-e\ \sin^2\varphi_0\right)\right];$$

$$\omega_{\Phi_{V0}} = \frac{V_{L0}}{R_{p_0}};\ \omega_{L_{V0}} = \frac{V_{\Phi_0}}{R_{m_0}};$$

$$\varphi_{y_0} = -\varphi_0;\ \omega_{RV0} = \omega_{\Phi_V 0}\sin\varphi_{y_0};$$

$$\Omega_{R0} = \Omega_0\sin\varphi_0;\ \Omega_{\Phi_0} = -\Omega_0\cos\varphi_0.$$

Moreover, the initial transposed direction cosine matrix is calculated by the initial values of the geographic course $\psi_{g0}$, roll $\gamma_0$, pitch $\vartheta_0$. It must be noted that geographic course $\psi_g$ is converted to the yaw angle as $\psi_0 = 90° - \psi_{g0}$.

Initial direction cosine matrix is calculated by (6) and then the initial values of angular speed components can be obtained:

$$\begin{bmatrix}\omega_{x_{\Phi LR_0}}\\ \omega_{y_{\Phi LR_0}}\\ \omega_{z_{\Phi LR_0}}\end{bmatrix} = \mathbf{B}_0^T\begin{bmatrix}\omega_{\Phi_{V0}}+\Omega_{\Phi_0}\\ \omega_{R_{V0}}+\Omega_{R0}\\ \omega_{L_{V0}}\end{bmatrix}.$$

Further, at each step, using the information from strapdown gyrovertical about the projections of angular velocities and accelerations on the axes of the body-fixed coordinate system, equations (4)–(12) given in the algorithm are successively solved.

If necessary, the navigation algorithms can be supplemented by the equations for calculating the ground speed Vg, the track angle Ψ and the angle of trajectory inclination Θ

$$V_g = \sqrt{V_L^2+V_\Phi^2};$$

$$\Theta = \arcsin\frac{V_R}{\sqrt{V_L^2+V_\Phi^2+V_R^2}};$$

$$\Psi = \arccos\frac{V_L}{\sqrt{V_L^2+V_\Phi^2}}.$$

Also, if necessary, the SINS operation algorithm can be divided according to the required calculation speed into three stages characterizing the fast, medium and slow calculation pace. Strapdown gyrovertical algorithms are carried out at the fast calculation rate (about 200 Hz). Here the updating and precise processing of signals are done for integrating the primary information sensors. SINS algorithms use the already processed information on the projections of angular velocities and accelerations on the axes of the body-fixed coordinate system.

In the above algorithms, the SINS alignment algorithms and algorithms for pre-flight calibration of primary information sensors are not implemented. It is believed that this problem is solved in the strapdown gyrovertical at the stage of pre-flight preparation.

## 4 EXPERIMENTS

The studies were carried out using Simulink visual modeling program, which is part of the MATLAB universal mathematical programming package.

During the simulation, the following subsystems were created and used: subsystems of the reference (ideal) navigation system "E_HC" and the investigated SINS "BINC", subsystems of the Earth model (reference "E_Zemlya" and simplified "Zemlya"), subsystem of automatic control system and of primary information sensors «САУ-Datchiki». In addition, the subsystem for registering simulation results "Registration" and the subsystem for specifying parameters (initial conditions) of simulation "Start_napametru" were created.

The general interface of simulation block diagram is shown in Fig. 2.

Mathematical models of the reference navigation system and the studied SINS were built on a hierarchical principle. The subsystem "BINC" (Fig. 3a) consists of the several subsystems: "Accelerations" (Fig. 3 b), "Angular speeds" (Fig. 3 c), "Linear speeds" (Fig. 3 d), "Coordinates" (Fig. 3 e).

In the subsystem "Accelerations" equations (5)–(8) of the SINS algorithm are solved, and the transposed matrix **B** is also formed.

The subsystem "Angular speeds" models equation (4) for the components of the angular velocity in equation (9) and equation (12).

The subsystem "Speeds" simulates the equations (9) and projections speed vector components on LTP coordinate system.

The subsystem "Coordinates" solves equations (10) of the SINS algorithm.

The block diagram of ideal navigation system is represented in Fig. 4 without opening the corresponding subsystems since they are much similar to previously explained except including sources of errors (both instrument and measurement-method ones).

The Earth model is simulated in the block "Zemiya". Here the components of the angular velocity of the Earth's rotation $\Omega_R$, $\Omega_\Phi$, are calculated together with components of gravity force according to equations (12). Depending on the given assumptions, the Earth can be represented by a sphere or spheroid; rotating or not rotating. These changes are made from the "Start_napametru" subsystem.


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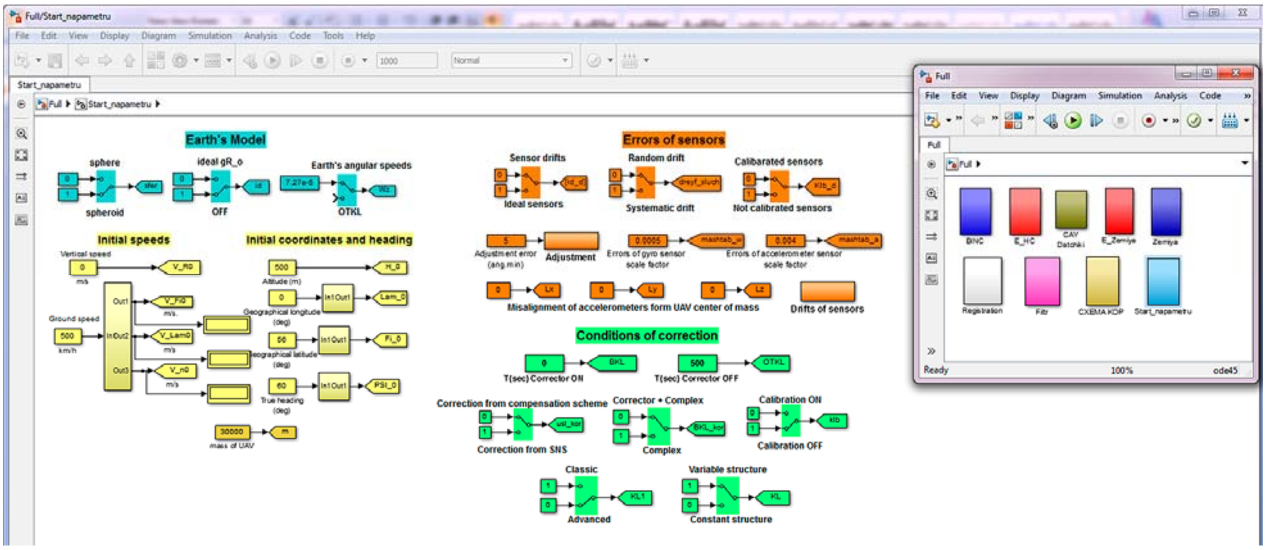

Figure 2 – Block diagram of Simulink scheme with specifying parameters (initial conditions) of simulation together with subsystems

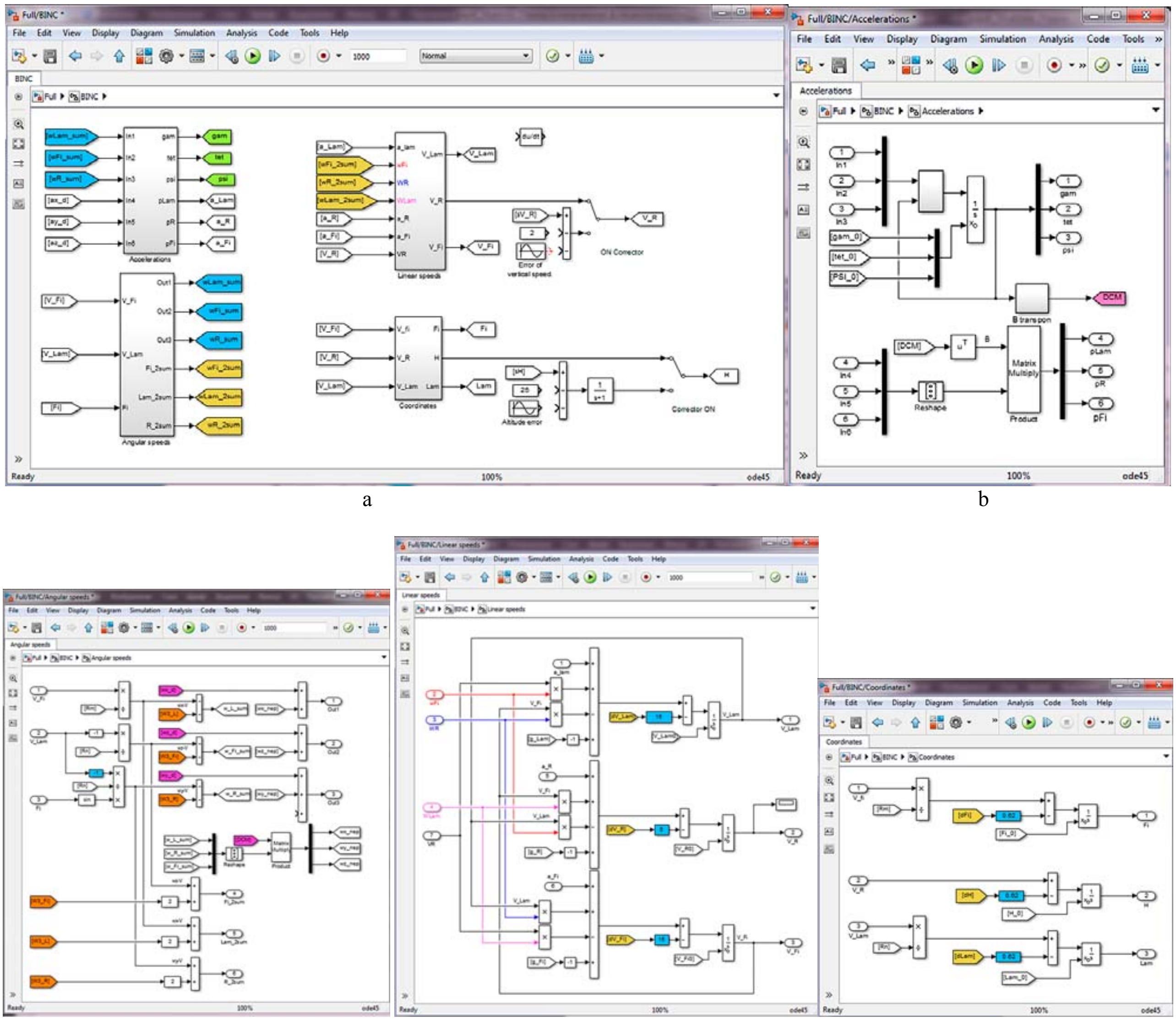
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Figure 3 – Block diagram of Simulink scheme of subsystem "BINC" (with all four subsystems)


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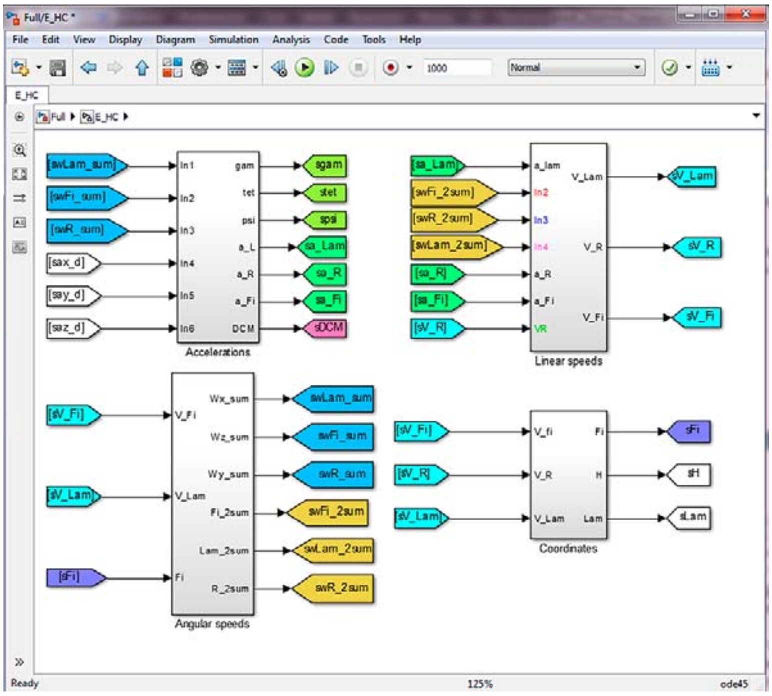


Figure 4 – Block diagram of ideal navigation system in Simulink

## 5 RESULTS

The main contribution to the dead reckoning errors of the navigation parameters is still made not by the measurement-method errors of the SINS algorithms, but by the instrumental errors of the primary information sensors. The available technical documentation for strapdown gyrovertical СБКВ-П2А (Operation Manual КИНД. 402113.029) contains information on the measurement error of the components of the angular velocity (±2σ) = ±0.1 °/sec and overload (±2σ) =± 0.01 (i.e., errors in acceleration measurement (±2σ) = ±0.1 m/sec$^2$). Considering the type of sensors used in sensor unit (besides it is thermostated): angular velocity sensors based on dynamically tuned gyroscopes and linear acceleration sensors based on pendulum accelerometers, it can be assumed that the characteristics of such sensors should be three...four orders of magnitude more accurate than declared in manual.

In particular, strapdown gyrovertical СБКВ-П2А has the alignment mode based on gyrocompassing. This mode involves measuring the angular velocity of the Earth s rotation $\Omega_0$ = 0.00416°/sec, i.e. the accuracy characteristics of the angular velocity sensors should allow such a value to be measured. Given that in the course channel, strapdown gyrovertical СБКВ-П2А has two angular velocity sensors, in order to increase the accuracy of measuring small angular velocities, it can be assumed that the accuracy characteristics of the used gyros are at the limit acceptable for systems of this class. In the future, we assume that the measurement error of the components of the angular velocities should be at least an order of magnitude smaller than the angular velocity of the Earth's rotation and be (±2σ) = ±0.0001...0.0005°/sec.

Given that the primary information sensors should be equivalent, i.e. the influence of the errors of the angular velocity sensors and accelerometers on the overall error of the navigation system should be approximately the same; it can be approximately calculated that the error of the accelerometer should be within the range (±2σ) = ±0.01…0.05 m/sec$^2$.

With such maximum values of the errors of the primary information sensors, a series of experiments were carried out to evaluate the accuracy of the calculation of navigation parameters using truncated SINS algorithms. As output parameters, errors in calculating the angular orientation parameters of UAV: roll and pitch angles, course angle, as well as components of the UAV speeds, were estimated. During the research, the errors of the primary information sensors and the flight conditions of the aircraft varied: medium, high and low latitudes; direction of flight (along and across the meridian; on and against the direction of rotation of the Earth), etc.

Figure 5 illustrates the typical behavior of the change in the dead reckoning errors of navigation parameters: heading, roll, pitch by using algorithms of strapdown gyrovertical under for measurement errors of the components of the angular velocity by roll and pitch in 0.0002°/sec, in course 0.0001°/sec ( in the course channel of the system, in order to improve the accuracy of course reckoning, two angular velocity sensors are installed). The accelerometer errors were 0.02 m/sec$^2$ (the error sign was chosen arbitrarily for different sensors). Launch conditions were: 10° of northern latitude, 50° of eastern, initial ground speed was 400 km/h; initial flight altitude was 500 m.

With such errors of the primary information sensors, the strapdown gyrovertical fully meets its functionality as


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attitude-and-heading reference system. The errors in dead reckoning of roll and pitch angles do not exceed 0.4° per hour of flight (the errors declared in the system specification sheet are 0.5°). The dead reckoning errors of course does not exceed 0.25° per hour of flight (the errors declared in the system specification sheet are 0.3°). Such level of accuracy characteristics of the sensors are used for further research.

If the errors in determining the roll and pitch angles, changing with the period of Schuler pendulum, do not exceed the required values, then the error in determining the course has a component that grows proportionally to the flight time. Namely this fact forces the developers to use the magnetometer as a correction device in the course channel.

In addition to estimating the errors in dead reckoning the parameters of the angular orientation, the study was also conducted to investigate the accuracy of the dead reckoning of the navigation parameters of the UAV trajectory motion: coordinates and velocity components under the same errors of the primary information sensors. Errors in dead reckoning the parameters of the UAV trajectory motion substantially depend on the launch conditions, in particular, on the latitude and direction of flight. Moreover, it was revealed that a change in the start condition causes, as it were, "overflowing" of errors from the latitude channel to the longitude channel and vice versa. Figure 6 shows the typical behavior of the change in the errors of dead reckoning coordinates and velocities with an approximately uniform distribution of errors in two channels.

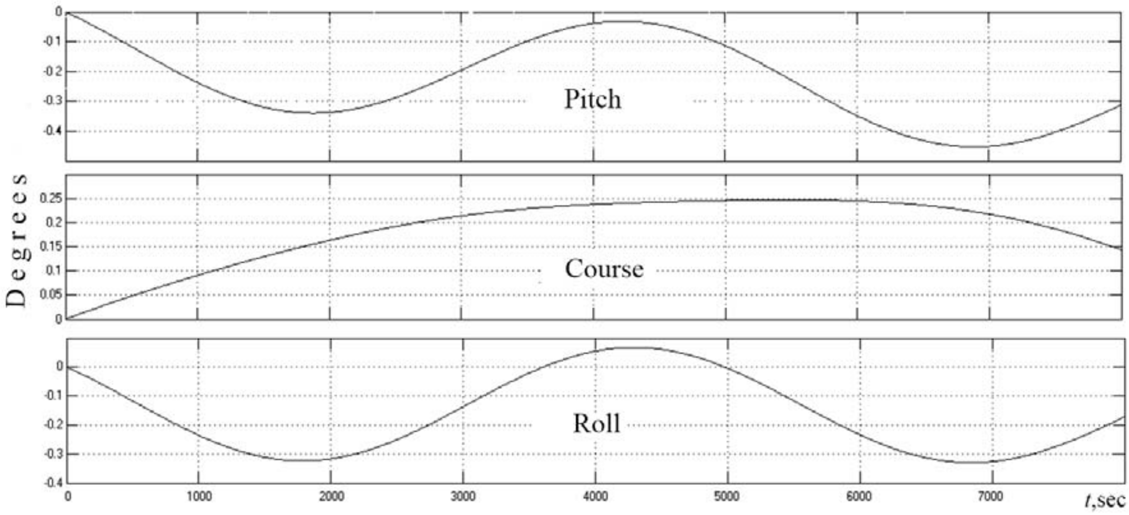


Figure 5 – Errors in pitch, roll and course angles for the given values of errors of primary information sensors

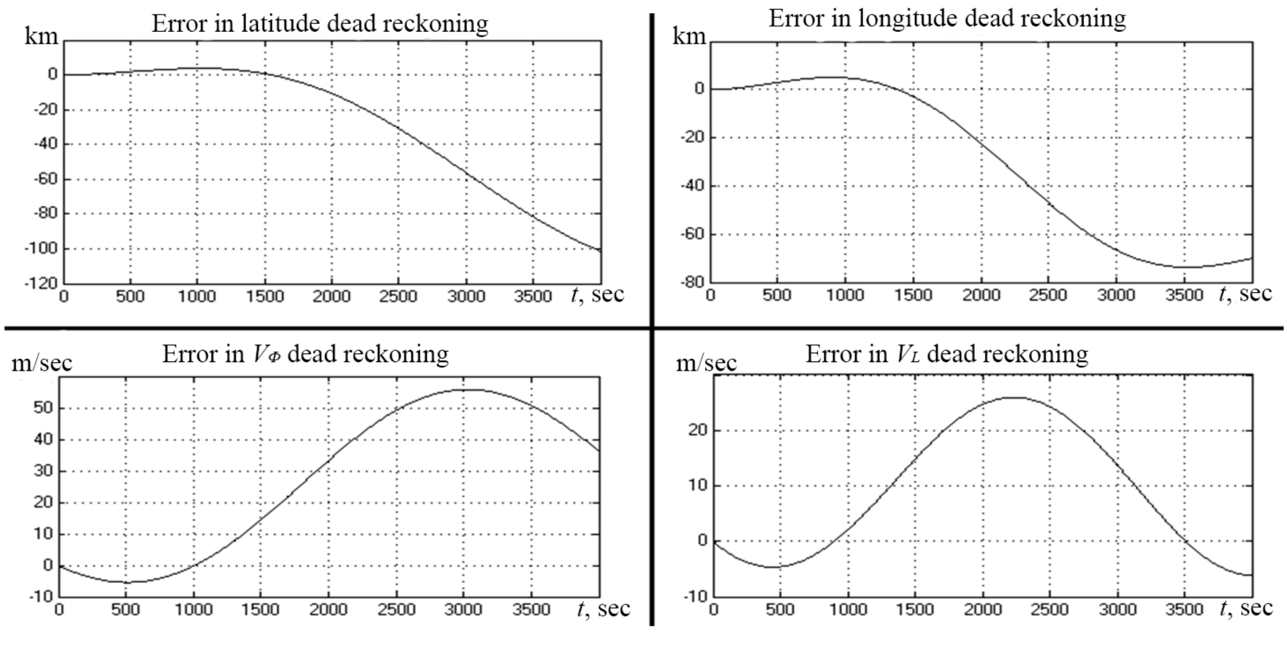


Figure 6 – Errors in coordinates and velocity components


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## 6 DISCUSSION

Errors of the components of the aircraft speed reach 30...50 m/s per hour of flight and this information is practically not used by consumers (a similar situation occurs in the platform gyrovertical). Errors in the calculation of coordinates with such primary information sensors are generally unacceptable (70...80 km per hour of flight), which once again confirms the impossibility of creating an autonomous SINS on their basis.

Systems of this type can only be used when integrating them with other navigation systems, in particular with SNS. In this case, SINS interpolates the values of the navigation parameters between two adjacent moments of information coming from SNS, and also provides navigation information to consumers with a short-term loss of signals from satellites. With long interruptions in the SNS operation, SINS should be integrate with other navigation systems.

## CONCLUSIONS

The urgent problem of mathematical support development is solved to automate the sampling at diagnostic and recognizing model building by precedents.

**The scientific novelty** is the following. At first the novel approach has been proposed in the using two models of SINS instead one: ideal one, free from all errors, and the real one with selected variants of error sources. Unlike known approach, such technique allows us to estimate accuracy characteristics of SINS and degree of participation of primary information sensor errors in them.

**The practical significance** of obtained results is that the software realizing the proposed three-level algorithms of SINS operation is developed, as well as simulation to be conducted and proved by comparing with test results of strapdown gyrovertical СБКВ-П2А.

**Prospects for further research** are the following. The conducted studies confirm the dependence of the accuracy of the dead reckoning navigational parameters on the performance of UAV maneuvers and on other factors, in particular, on the mismatch of the installation location of SINS block with the center of mass of UAV, but with sufficiently vigorous maneuvering. For further research, information is required on the aerodynamic characteristics of a particular type of UAV, as well as on the algorithms of its control system.

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## КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ТОЧНІСНИХ ХАРАКТЕРИСТИК БЕЗПЛАТФОРМЕННОЇ ІНЕРЦІАЛЬНОЇ НАВІГАЦІЙНОЇ СИСТЕМИ

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### АНОТАЦІЯ

**Актуальність**. Розглядається задача корекції роботи безплатформенної інерціальної навігаційної системи, що використовується на борту безпілотного літального апарату. Завданням дослідження було моделювання точнісних характеристик безплатформенної інерціальної навігаційної системи на основі відомих (або заданих) інструментальних похибок її датчиків.

**Мета роботи** – розробити математичну та комп'ютерну модель безплатформенної інерціальної навігаційної системи та оцінити точнісні характеристики на основі заданих значень похибок датчика.

**Метод**. Розроблено математичну та комп'ютерну моделі безплатформенної інерціальної навігаційної системи на основі повільних, середніх та швидких циклів обчислення. Для моделювання точнісних характеристик безплатформенна інерціальна навігаційна система подається у вигляді системи динамічних та кінематичних рівнянь у місцевій геотопічній системи координат із обраною моделлю Землі з урахуванням компонентів прискорення сили тяжіння. Моделі датчиків розроблені на основі характеристик недо-


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рогих мікроелектромеханічних датчиків, що використовуються на борту. Алгоритми синтезу даних раніше вже були розглянуті і включають модифікований фільтр Калмана або, в деяких випадках, компліментарний фільтр за схемою компенсації, але тут детально не розглядаються. Матриця напрямних косинусів для алгоритмів числення шляху інерціальної навігації знайдена за методом Пуассона.

**Результати**. Розроблені моделі були реалізовані та змодельовані в середовищі MATLAB + Simulink. Початкові параметри (похибки первинних датчиків інформації та умови польоту) під час моделювання були різноманітними: середні, високі та низькі широти; напрям польоту (вздовж і проти меридіану; за та проти напрямку обертання Землі).

**Висновки**. Розроблені моделі та їх випробування були порівняні з фактичними результатами тестування безплатформенної курсовертикалі СБКВ-П2А та підтвердили свою обгрунтованість. Це дозволяє рекомендувати їх для використання при проектуванні інерціальної навігаційної системи безпілотного літального апарату, а також для експериментального вивчення інноваційних алгоритмів синтезу обробки даних для інтегрованої супутникової та інерціальної навігаційної системи.

**КЛЮЧОВІ СЛОВА:** безплатформенна інерціальна навігаційна система, супутникова навігаційна система, безплатформенна курсовертикаль, числення шляху, комплексування інформації.

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## ОЦЕНКА ТОЧНОСТНЫХ ХАРАКТЕРИСТИК БЕСПЛАТФОРМЕННОЙ ИНЕРЦИАЛЬНОЙ НАВИГАЦИОННОЙ СИСТЕМЫ

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### АННОТАЦИЯ

**Актуальность.** Рассматривается задача коррекции работы бесплатформенной инерциальной навигационной системы, используемой на борту беспилотного летательного аппарата. Задачей исследования было моделирование точностных характеристик бесплатформенной инерциальной навигационной системы на основе известных (или заданных) инструментальных погрешностей ее датчиков.

**Цель работы** – разработать математическую и компьютерную модель бесплатформенные инерциальной навигационной системы и оценить точностные характеристики на основе заданных значений погрешностей датчика.

**Метод**. Разработана математическая и компьютерная модели бесплатформенной инерциальной навигационной системы на основе медленных, средних и быстрых циклов вычисления. Для моделирования точностных характеристик бесплатформенная инерциальная навигационная система представляется в виде системы динамических и кинематических уравнений в местной геотопической системе координат с выбранной моделью Земли и с учетом компонентов ускорения силы тяжести. Модели датчиков разработаны на основе характеристик недорогих микроэлектромеханических датчиков, используемых на борту. Алгоритмы синтеза данных ранее уже были рассмотренные и включают модифицированный фильтр Калмана или, в некоторых случаях, комплиментарный фильтр по схеме компенсации, но здесь подробно не рассматриваются. Матрица направляющих косинусов для алгоритмов исчисления пути инерциальной навигации найдена методом Пуассона.

**Результаты**. Разработанные модели были реализованы и смоделированы в среде MATLAB + Simulink. Начальные параметры (погрешности первичных датчиков информации и условия полета) при моделировании были разнообразными: средние, высокие и низкие широты; направление полета (вдоль и против меридиана, по и против направления вращения Земли).

**Выводы**. Разработанные модели и их испытания были сравнены с фактическими результатами тестирование бесплатформенной курсовертикали СБКВ-П2а и подтвердили свою обоснованность. Это позволяет рекомендовать их для использования при проектировании инерциальной навигационной системы беспилотного летательного аппарата, а также для экспериментального изучения инновационных алгоритмов синтеза обработки данных для интегрированной спутниковой и инерциальной навигационной системы.

**КЛЮЧЕВЫЕ СЛОВА**: бесплатформенная инерциальная навигационная система, спутниковая навигационная система, бесплатформенная курсовертикаль, счисление пути, комплексирование информации.

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