A SPATIALLY DISTRIBUTED MICRONAVIGATTION SYSTEM FOR A SYNTHETIC – APERTURE RADAR

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Abstract

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Special features of the functioning of radar systems with synthetic aperture (SAR) are considered. A technology for estimation of and compensation for SAR path instabilities with the use of an integrated micronavigation system (IMNS), based on fiber-optic gyros is proposed. The implementation of such a technology relies on the mutual support of inertial, satellite, and radar systems. A description for the hardware and algorithmic support of the IMNS is given. The results of half-scale tests of the IMNS are presented, which corroborate the fact that it is possible and expedient to apply the proposed technology for increasing the SAR resolution.

Introduction

At present, the problem of increasing the resolution of radar systems (RADS) when large areas of the Earth's surface are scanned from board an aircraft (Acft) still remains topical [1-4]. As is known [2], the angular $\delta\Theta$ and linear δl resolutions in the distance D to an object are determined by the relations $\delta\Theta = \lambda / d$; $\delta l = D\delta\Theta = \lambda D / d$, where λ is the wave length of electromagnetic radiation; d is the antenna size.

The solution of the above-mentioned problem by hardware is apparently not always feasible due to restrictions on the mass and overall dimensions of Acft equipment. Because of this, an analytic completion of the directional pattern is implemented by "sewing together" the images that are obtained by airborne RADS in the path of Acft motion. With such a RADS aperture synthesis, the need arises for compensation for the distortions of a combined image due to instabilities caused by Acft deviation from the rectilinear motion. The path instabilities on the scan interval can be determined with the use of a strapdown inertial satellite micronavigation system that is placed near the antenna phase center (APC). To compensate for the above instabilities, their estimates are converted into corrections to RADS signals.

The potentialities of a synthetic – aperture radar (SAR) are attained when a micronavigation system is combined with the APC. However, due to design constraints, such conditions of the constructions of the SAR are difficult to realize. Therefore, in practice, the need arises for integration of data on APC motion, which come from systems that are separated with respect to the APC.

The purpose of this paper is to theoretically justify and to practically implement the procedures of compensation for path instabilities by the use of a spatially distributed inertial satellite micronavigation system.

The attainment of the above purpose is based on the solution of the following problems:

- formation of kinematic equations that reflect the dynamic behavior of path instabilities on the interval of aperture synthesis, from the data of spatially distributed navigational sensors;
- formation of kinematic equations that reflect the dynamic behavior of corrections to RADS signals, which are connected with path instabilities on the interval of aperture synthesis. The above-mentioned equations are redundant with respect to basic inertial ones;
- formation of error equations for an inertial radar system, which are brought to the level of sensors. In this case, it is apparently possible to implement a tightly-coupled scheme for the damping of dynamic errors of a synthetic – aperture RADS;
- formation of observations and their models for the applications of the Kalman filtering mathematical apparatus in the loop for error estimation of an inertial radar system.

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1. Hardware Support of the SAR Distributed Micronavigation System

A block diagram of such a distributed micronavigation system (DMNS), which is under discussion in this paper is shown in Fig. 1, where the following notation is introduced: IMNS is an integrated micronavigation system; SIMNS is a strapdown inertial micronavigation system; SMNS is a satellite micronavigation system.

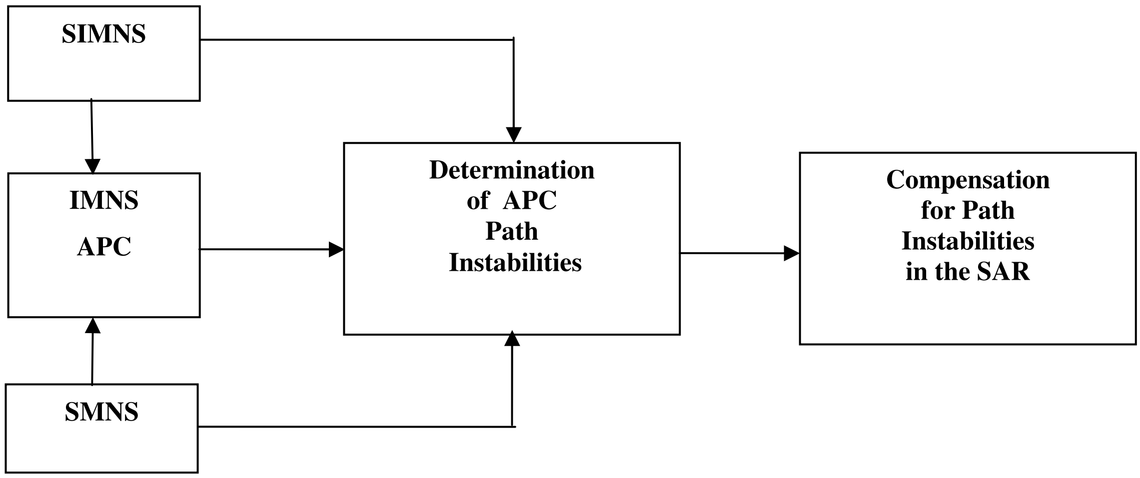

Fig. 1. Block diagram of a SAR spatially distributed micronavigation system

In the present paper, an SMNS is discussed which has no less than two antennas. This permits one to discretely determine and update the reckoned path parameters of SIMNS and APC relative motion. The SIMNS is considered as DMNS kernel. This is connected with the fact that it can continuously determine, with a frequency of up to 1kHz, both path and attitude parameters of the SAR "carrier".

The DMNS is designed according to the modular principle. This has made it possible to space apart the computer and sensory package (SP) of the SIMNS that is placed in immediate proximity to the SAR. Taking into account weight and space restrictions, we have chosen, as an SP, the IMU-500 unit based on the triad of fiber-optic gyros and accelerometers, which were designed by the "OPTOLINK" RPC (Zelenograd).

Moreover, the DMNS includes three K-161 satellite receivers developed by the RIRV (St. Petersburg), a computing module made to the PC-104 standard, power modules, and input-output interface modules.

The basic DMNS modules shown in Fig. 2 are technological in design. A block-diagram of the DMNS hardware support is presented in Fig. 3.

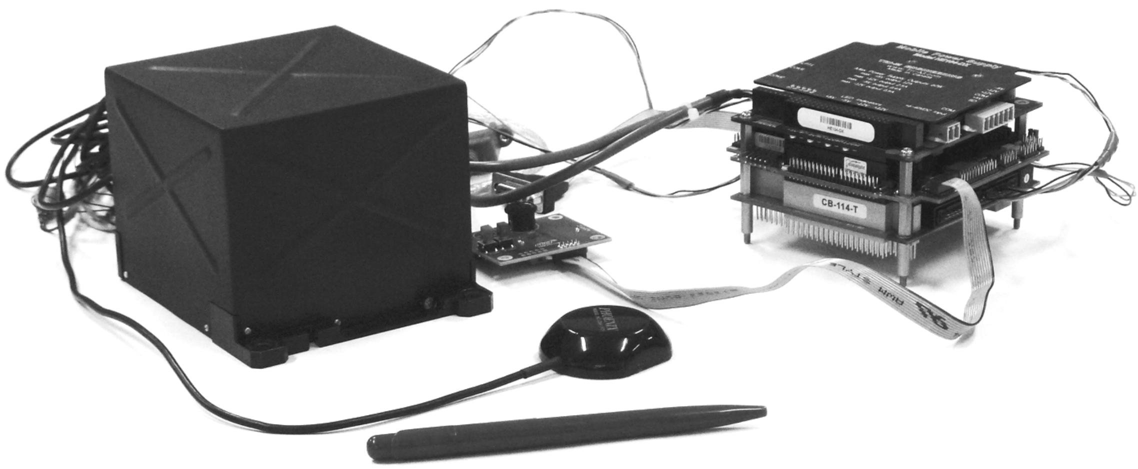

Fig. 2. Breadboard of the SAR distributed micronavigation system

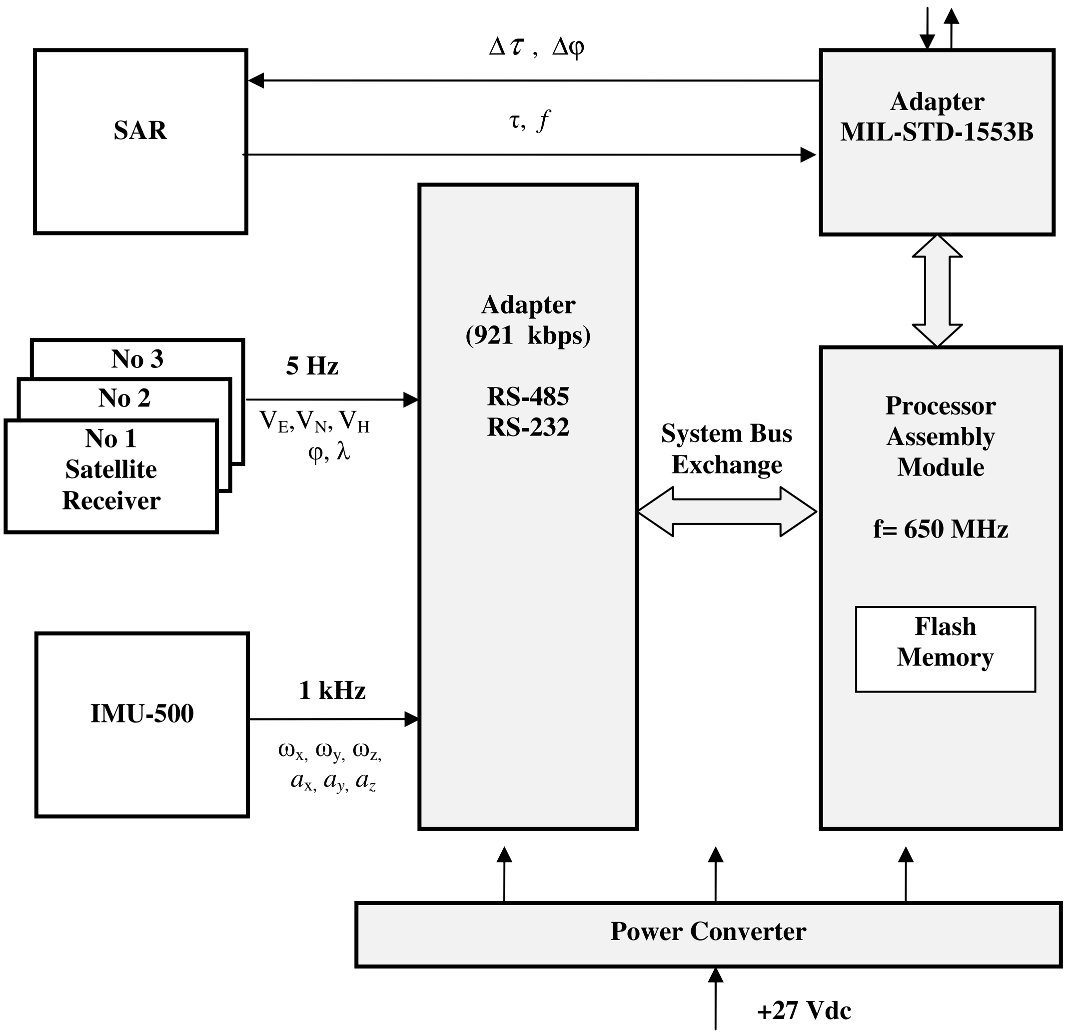

Fig. 3. Block diagram of the hardware support of the distributed micronavigation system

2. Algorithmic Support of the SAR Distributed Micronavigation System

In the synthesis of RADS aperture, it is essential that flight in a given (reference), as a rule, straight path should be provided. The solution of such a problem is entrusted to the integrated flight system (IFS) of an Acft, which contains a navigation system and a flight automatic-control one. However, because of IFS errors and due to external disturbances caused by atmospheric turbulence and airframe elastic vibration [3], departures of the antenna phase center and antenna beam (AB) from their reference positions take place. Taking this into account, the system intended to compensate for path instabilities is entrusted to solve the following problems [1, 2]:

- measurement of path instabilities;
- phase correction of the reference or echo signal;
- correction of the change in echo signal delay;
- fixation of the image obtained to the display coordinate system;
- steering of the actual-antenna beam in order to maintain the given angular position and distance to the scanned area on the ground.

The position of the RADS scanned area is determined by the azimuth α and tilt β of the AB, and the above distance depends on the signal delay $\tau = 2D/c$ (see Fig. 4), where c is the radio-wave propagation velocity; D is the distance from the APC to the ground surface (APC – object distance). The AB parameters mentioned above are determined on the Acft body-fixed coordinate frame oxyz [5], in which the axes ox, oy, oz are pointing, respectively, along the longitudinal, vertical (upwards), and lateral (rightwards) Acft axes. In this paper, a side-looking RADS is dealt with, in which the angles α and β are constant ones in the interval of synthesis.

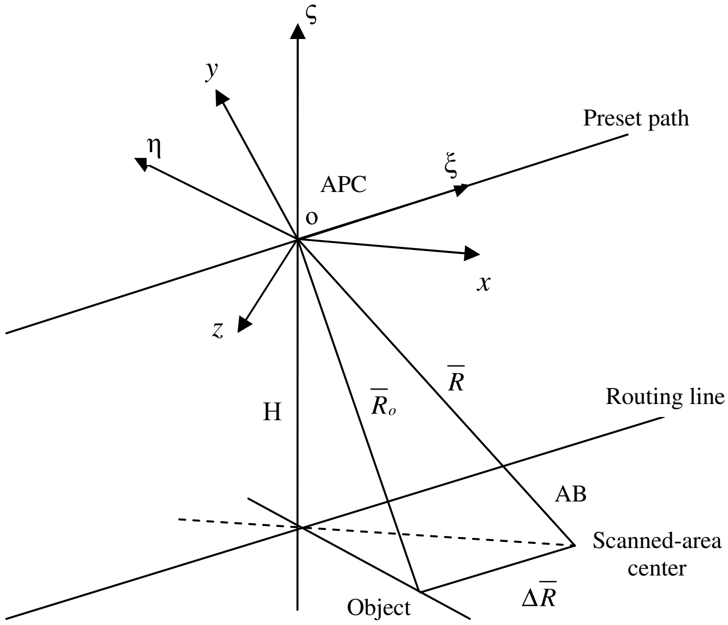

Fig. 4. Scheme for the motion of the SAR antenna phase center

When the Acft deviates from the reference path, the need arises for determining the increments ΔD in distance with reference to its base value.

In obtaining APC motion parameters by inertial reckoning, path instabilities can first be determined on the normal coordinate frame (CF) [5], and then they can be transformed to the body-fixed frame. As a normal CF, the geodetic moving frame (MF) O_AENH [6] can be used. The moving frame O_AENH is a rectangular Cartesian frame, the vertex of which coincides with the APC, and the axes O_AN, O_AE, O_AH are directed, respectively, at a tangent to the geographical meridian, parallel, and the geodetic vertical. I the normal mode, the APC MF vertex is to move along the reference path, and position angles are to be fixed. Under actual conditions, in synthesizing the aperture, the initial position of the MF vertex in the reference path and Acft attitude in relations to the MF, and also the initial value of the distance D_0 to the ground surface are fixed. In what follows, in the interval of image synthesis, the increment $\Delta D = D - D_0$ in distance, which is caused by Acft evolutions with respect to the reference path is determined and compensated for in terms of SAR signals. It should be noted that in the side-looking RADS, unlike a tracking RADS, APC motion along the reference path is not to be taken into account when path instabilities are determined. Therefore, we can write $\Delta D = \Delta D(\Delta S, \Delta H, \Delta\psi, \Delta\vartheta, \Delta\gamma)$, where $\Delta S, \Delta H$ are, respectively, the sideward altitude deviation and altitude increment with relation to the reference path; $\Delta\psi, \Delta\vartheta, \Delta\gamma$ are the increments of the heading angle, pitch angle, and roll angle with respect to their reference values. In this case, as a normal coordinate frame, it is expedient to use the reference frame $O_A\xi\eta\varsigma$, the axis $O_A\xi$ of which is parallel with the given-path line (at the initial time of synthesizing the aperture, the above axis is parallel with the projection of the Acft longitudinal axis on the horizontal plane), the axis $O_A\varsigma$ is directed upwards perpendicularly to the horizontal plane, and the axis $O_A\eta$, together with the axes $O_A\xi$ and $O_A\varsigma$, makes up a right-hand frame. The relative angular position of the frames $O_A\xi\eta\varsigma$ и O_AENH is determined by the azimuth angle A (by the course angle).

At the initial point of aperture synthesis, the position of the frame $O_{A(0)}\xi\eta\varsigma$ is fixed. For this position of the reference frame, the reckoning of the path instabilities $\Delta\xi, \Delta\eta, \Delta\varsigma$ is performed by solving the following basic equation of strapdown inertial navigation

$$\dot{\overline{V}} = C_5^{\mathrm{T}}\overline{a} + \overline{g} - 2\overline{\Omega}\times\overline{V} - \overline{\omega}\times\overline{V} - \overline{\Omega}\times\left(\overline{\Omega}\times\overline{R}\right), \qquad (1)$$

where, $\overline{V} = [V_\xi \quad V_\eta \quad V_\zeta]^{\mathrm{T}}$ is the ground speed vector of APC motion, given by its components along the axes of the reference navigation frame; $\overline{a} = [a_x \quad a_y \quad a_z]^{\mathrm{T}}$ is the vector of output signals of accelerometers; $\overline{g} = [g_\xi \quad g_\eta \quad g_\zeta]^{\mathrm{T}}$ is the vector of gravitational acceleration; $\bar{\Omega} = [\Omega_\xi \quad \Omega_\eta \quad \Omega_\varsigma]^{\mathrm{T}}$ is the vector of the angular velocity of Earth rotation; $\bar{R} = [0 \quad 0 \quad R]^{\mathrm{T}}$ is the APC position vector; $(\times)$ is the operator of vector product; $C_5^T = C_0 C_2^T C_1^T P_3^T$ is the direction cosine matrix (DCM), which characterizes the IMU angular position with respect to the reference frame $O_A\xi\eta\varsigma$; $C_0(\bar{\psi}, \bar{\vartheta}, \bar{\gamma})$ is the DCM that characterizes the IMU angular position with respect to the inertial frame $OX_IY_IZ_I$ [5]. In forming the above DCM, we assume that turns are made as follows [6]: the first turn is done by an angle of $\bar{\psi}$ radn. about the third axis OZ_I ; the second turn is performed by an angle of $\bar{\vartheta}$ radn. about a new position of the first axis OX'_I; the third turn is done through an angle of $\bar{\gamma}$ radn. about a new position of the second axis OY'_I;

C_1 is the DCM that characterizes the angular position of the reference frame $O_A\xi\eta\varsigma$ with respect to the Earth-centered Earth-fixed frame [5]. The initial values for this DCM have the following form: $C_1(t_0) = C_4(t_0) P_3 \tilde{C}_1(t_0)$; $C_4(t_0) = C_4(A,0,0)$; $\tilde{C}_1(t_0) = \tilde{C}_1(\lambda, 0, -\varphi)$; $\varphi;\lambda$ are the APC geodetic latitude and longitude; $C_2(\Omega\Delta t, 0, 0)$ is the DCM that takes into account the angle through which the Earth turns in the time $\Delta t = t - t_0$ of RADS functioning;

$P_3 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$ is the permutation matrix [7], which takes into account the given change sequence of axes when turns are made through the corresponding angles. For instance, turns for the Acft body-fixed frame (BFF) are made as follows: the first turn is done by an angle of ψ radn. about the axis oy, the second turn is performed by an angle of ϑ radn. about a new position of the axis oz′, the third turn is done through an angle of γ radn. about a new position of the axis ox′.

Equations for the reckoning of the DCMs C_0, C_1 and their quaternion analogs are given in [7] and [8], respectively.

Based on the above-mentioned features of the SAR navigational support, the following algorithm for determining APC path instabilities, which includes the stages of the initial alignment and micronavigation can be formed.

At the stage of the initial alignment, the following procedures are carried out.

1. At the initial time of the aperture synthesis, the rectangular components x_0 , y_0 , z_0 of the reference position vector " APC-object" along the axes of the IMU-fixed frame are determined, i.e.,

$$\begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} = C_{A(0)}^T \begin{bmatrix} x_A \\ y_A \\ z_A \end{bmatrix} + \begin{bmatrix} x_{A(0)} \\ y_{A(0)} \\ z_{A(0)} \end{bmatrix},$$

where $x_A = R_0 \cos\beta \cos\alpha$; $y_A = R_0 a \sin\beta$; $z_A = -R_0 \cos\beta \sin\alpha$;

$x_{A(0)}, y_{A(0)}, z_{A(0)}$ are APC coordinates in the IMU-fixed frame;

$C_{A(0)}$ is the DCM that characterizes the mutual angular position of the IMU and APC;

2. The initial angles of IMU attitude in relation to the reference frame $\psi_0, \vartheta_0, \gamma_0$ are stored together with the corresponding matrices $C_0 \div C_5$ of direction cosines. It is assumed that the axes of the IMU-fixed frame and SAR-fixed frame are collinear ones.
3. The initial rectangular components of the reference position vector "APC-object" along the axes of the frame $O_A\xi\eta\varsigma$ are determined, i.e.,

$$[\xi_0 \quad \eta_0 \quad \varsigma_0]^T = C_{5(0)}^T [x_0 \quad y_0 \quad z_0]^T .$$

At the stage of SAR micronavigation, the following procedures are performed.

1. APC path current instabilities are reckoned by integrating Eq. 1in terms of projections on the axes of the reference frame $O_A\xi\eta\varsigma$, i.e.,

$$\Delta\eta_t = \int_{t_0}^{t} V_\eta(\tau) d\tau \quad \text{is the sideward deviation from the routing line;}$$

$$\Delta\varsigma_t = \int_{t_0}^{t} V_\varsigma(\tau) d\tau \quad \text{is the vertical deviation from the routing line;}$$

2. Rectangular components of the vector of APC path instabilities along the APC-fixed frame axes are determined, i.e.,

$$\begin{bmatrix} \Delta x_t \\ \Delta y_t \\ \Delta z_t \end{bmatrix} = C_{A(0)} C_5 \begin{bmatrix} 0 \\ \Delta \eta_t \\ \Delta \varsigma_t \end{bmatrix} - \begin{bmatrix} x_{A(0)} \\ y_{A(0)} \\ z_{A(0)} \end{bmatrix}.$$

3. Current rectangular components of the reference position vector "APC-object" along the axes of the body-fixed frame are determined, i.e.,

$$x_t = x_0 + \Delta x_t \qquad y_t = y_0 + \Delta y_t \qquad z_t = z_0 + \Delta z_t \, .$$

4. Current "APC-object" distance that takes into account path instabilities is determined, i.e.,

$$D = \sqrt{x_t^2 + y_t^2 + z_t^2} \, .$$

5. An increment in the reference distance and delay due to APC path instabilities is determined, i.e.,

$$\Delta D = D - D_0 \, ; \qquad \Delta \tau = \tau - \tau_0 \, .$$

It is known [1, 2], that the highest accuracy of measuring the change in (increment in) distance is provided by the phase method. With the availability of the radial velocity $V_D = \dot{D}$ to an object, the phase of the signal being received has the following form [2]:

$$\varphi = \omega_0 [t - \tau(t)] = 2\pi f_0 (t - \frac{2D_0}{c} \pm \frac{2V_D t}{c}) = 2\pi (f_0 + f) t - \varphi_0 \, ,$$

where $\omega_0 = 2\pi f_0$ is the carrier frequency; t is the time of SAR frame formation;

$\varphi_0 = \frac{4\pi f_0}{c} D_0 = \frac{4\pi}{\lambda} D_0$ is the reference phase of radiation with the wavelength λ;

$f = \pm 2V_D / \lambda$ is the Doppler shift. The sign of frequency shift is determined by the direction of APC motion.

Thus, in the process of the aperture synthesis the need arises for determination of corrections to the phase $\Delta\varphi = 2\pi f t$, caused by Acft evolutions in relation to the reference phase. To do this, we can be made of the reckoning values of rectangular components of the path velocity vector along the axes of the APC-fixed frame, i.e.,

$$\begin{bmatrix} \Delta \dot{x}_t & \Delta \dot{y}_t & \dot{z}_t \end{bmatrix}^T = C_{A(0)} C_5 \begin{bmatrix} 0 & V_\eta & V_\varsigma \end{bmatrix}^T . \qquad (2)$$

In view of the above vector components (2), the rate of change of the "APC-object" distance, which is caused by path instabilities can be computed:

$$V_D = (\tilde{x} \Delta \dot{x}_t + \tilde{y} \Delta \dot{y} + \tilde{z} \Delta \dot{z}_t) \tilde{D}^{-1} ,$$

where $\tilde{x} = x_t - \Delta x_t$; $\tilde{y} = y_t - \Delta y_t$ $\tilde{z} = z_t - \Delta z_t$; $\tilde{D} = \sqrt{\tilde{x}^2 + \tilde{y}^2 + \tilde{z}^2}$.

Variations in delay on the synthesis interval are taken into account by the corresponding shift of signal samples, and phase variations are taken into account by shifting the phase of the reference function through the use of shifter.

3. Algorithmic Support of the SAR Integrated Micronavigation System

Improvement of the accuracy and noise immunity of determining corrections to the phase and delay on the interval of SAR aperture synthesis relies on the integrated primary and second signal processing.

The following approaches to the integration at the level of second signal processing are possible:

- implementation of the inertial and satellite mode of reckoning path instabilities;
- SIMNS updating according to information obtained from the RADS that is functioning in the self-focusing mode [1, 2] or in the mode of the Doppler navigator;

The implementation of the inertial and satellite mode is based on the estimation of and compensation for SIMNS errors by processing, with the help of a robust Kalman filter (RKF) [8], both position and velocity observations:

$$z_{P(i)} = [\varphi_i \lambda_i H_i]^{\mathrm{T}}_{\mathrm{SIMNS}} - [\varphi_i \lambda_i H_i]^{\mathrm{T}}_{\mathrm{SMNS}} \, ; \qquad (3)$$

$$z_{\mathrm{V}(i)} = C^{\mathrm{T}}_{3(i)} [V_\xi V_\eta V_\zeta]^{\mathrm{T}}_{(i)SIMNS} - [V_E V_N V_H]^{\mathrm{T}}_{(i)SMNS} \, , \qquad (4)$$

where $C_3(A,0,0)$ is the direction cosine matrix that characterizes the mutual angular position of the reference frame $o_A\xi\eta\zeta$ and the geodetic frame $O_A ENH$.

The inertial and Doppler mode can be implemented on the basis of processing observations of the following form:

$$\tilde{z}_{V(i)} = [V_\xi V_\eta V_\zeta]^{T}_{(i)SIMNS} - C_5^T C_{A(0)}^T [V_{x_A} V_{y_A} V_{z_A}]^{T}_{(i)RADS} . \quad (5)$$

Inertial and radar observations in the self-focusing mode can be formed, for instance, by the comparison of distances to prescribed ground cues, which are computed by the SIMNS and measured by the RADS.

Improvement of the micronavigation accuracy at the level of the primary processing of SAR signals can be based on the comparison of the predicted values $\Delta\hat{\tau}_{i/i-1}$ and measured values $\Delta\tau_i$ of corrections to delay. The prediction can be done by means of the Chebyshev polynomial extrapolation [10] over the moving selection signal samples. For the predicted signal, the updating procedure has the following form:

$$\Delta\hat{\tau}_{i/i} = \Delta\hat{\tau}_{i/i-1} + K_i(\Delta\tau_i - \Delta\hat{\tau}_{i/i-1}) , \quad (6)$$

where K_i is the amplification factor that is formed by the RKF technique for scalar observations.

The structure of procedure (6) permits us to carry out checking over the corrections $\Delta\tau_i$ by the combined goodness-of-fit test χ^2/ϑ^2 [9], which provides possibility to recognize and counteract outlying signals.

4. Analysis of the Results of Studies

Requirements for accuracy characteristics of the SAR integrated micronavigation system follow from the interrelation between the errors of determining the distance D and the difference $\Delta\varphi$ in phases of the outgoing and incoming signals. The phase difference is determined by the signal delay τ:

$$\Delta\varphi = \omega_0\tau = 2\pi f_0\tau = 2\pi\frac{c}{\lambda}\tau ,$$

which is connected with the measured distance by the following relation:

$$D = \frac{c\tau}{2} = \frac{\lambda}{4\pi}\Delta\varphi . \quad (7)$$

From relation (7) it is obvious that for the centimetric-wave band and millimetric distance variations due to path instabilities, phase difference changes may reach tens of degrees. Thus, for the centimetric-wave band, position errors of determining path instabilities on the interval of aperture synthesis are to be at the level of millimeters or several units of centimeters. In order that the possibilities of obtaining such accuracy characteristics be estimated, half-scale experiments have been carried out with the integrated inertial-and-satellite micronavigation system presented in item 1. The technology for half-scale development of the mathematical software support [11] from the recorded IMU signals and the GPS signals was applied.

The experiments have been conducted on the ground when the necessary equipment was housed in a mobile laboratory. Certain of the results of the above experiments are shown in Figs. 5-8.

In Figs. 5, 6, the SIMNS pitch angle and SIMNS roll angle are shown, respectively, on the interval of micronavigation when the heading is constant. Figure 7 depicts the errors of reckoning, by the SIMNS, the polar component of path velocity of the antenna phase center on the intervals of aperture synthesis, the length of which is Δt_{SA} = 5 sec, where

$$\Delta V_D = \sqrt{\Delta V_\eta^2 + \Delta V_\varsigma^2} ; \qquad \Delta V_\eta = V_{\eta(SIMNS)} - V_{\eta(SMNS)} ; \qquad \Delta V_\varsigma = V_{\varsigma(SIMNS)} - V_{\varsigma(SMNS)} ;$$

$$V_{\eta(SMNS)} = V_{N(SMNS)}\cos A - V_{E(SMNS)}\sin A ; \qquad V_{H(SMNS)} = V_{\varsigma(SMNS)} .$$

The dynamics of variation of the above parameters imitates the helicopter flight in a straight path on the interval of the aperture synthesis. The SIMNS was functioning in the mode of autonomous inertial navigation when the predicted estimates of errors, together with FOG residual drifts and accelerometers biases, were compensated for. Estimation was made from inertial-and-satellite observations (3), (4) before aperture synthesis, i.e. with a frequency of 0.2 Hz.

Figure 8 depicts the dynamics of variations in the error $\Delta\hat{D}$ of inertial reckoning of the polar coordinate of the antenna phase center on the intervals of aperture synthesis, where

$$\Delta\hat{D}(t) = \int_{t_i}^{t_i+\Delta t_{SA}} \Delta V_D(\tau)d\tau , \quad \text{where} \quad V_{\eta(SIMNS)}(t_i) := V_{\eta(SMNS)}(t_i) ; \quad V_{\varsigma(SIMNS)}(t_i) := V_{\varsigma(SMNS)}(t_i) .$$

The studies conducted and the results obtained corroborate the fact that it is possible to determine, by the use of the micronavigation system considered, relative path instabilities on the interval of aperture synthesis, which is up to 5 sec long at the level of millimeters or several units of centimeters.

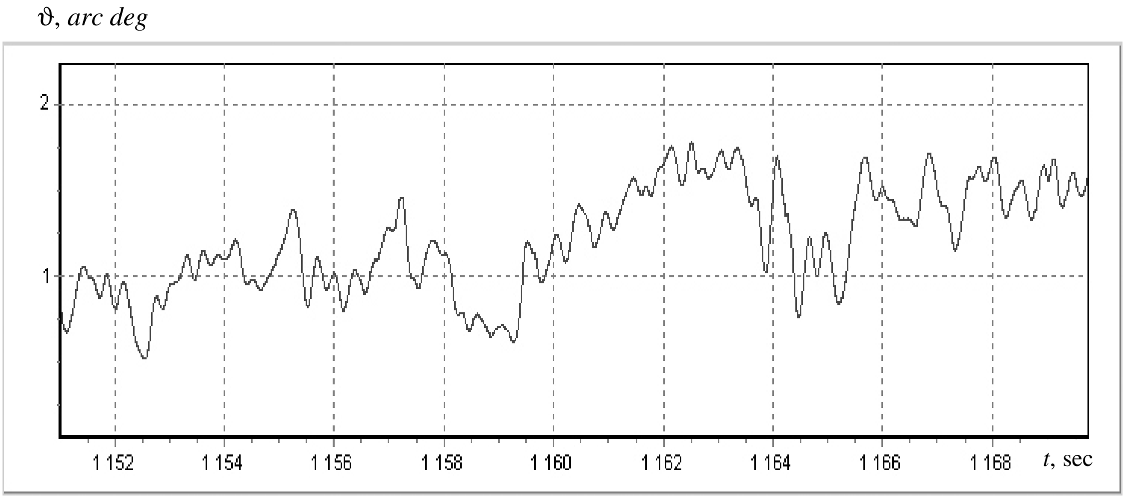

Fig. 5. Dynamic of variation of the of pitch angle on the interval of micronavigation

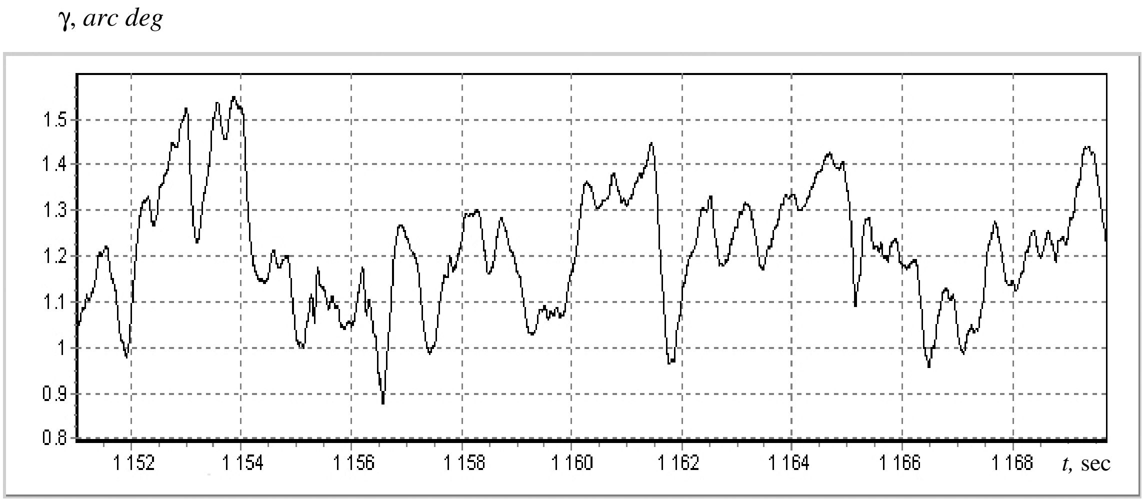

Fig. 6. Dynamic of variation of the of roll angle on the interval of micronavigation

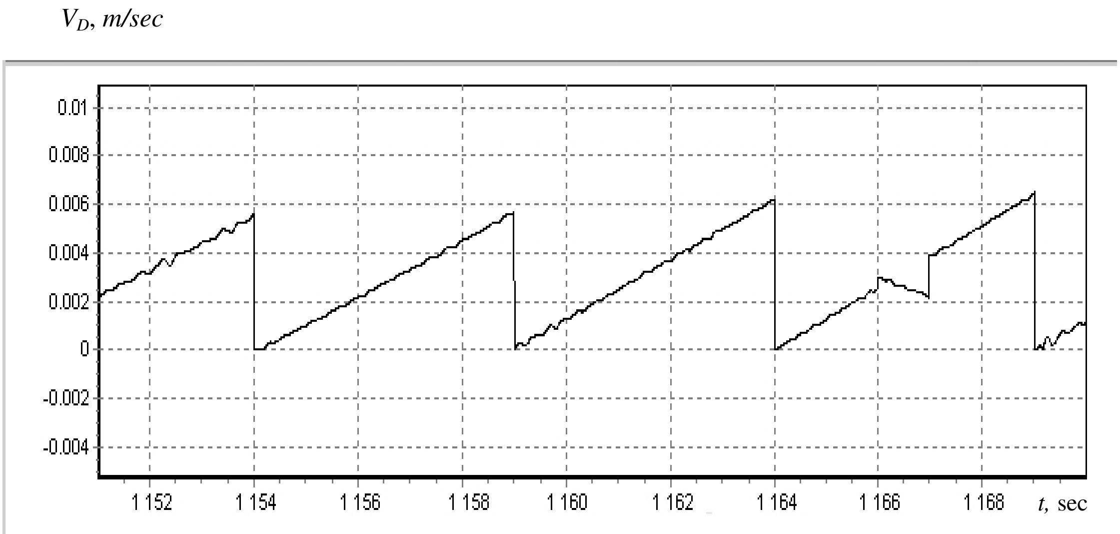

Fig. 7. Dynamic of variation in the error of inertial reckoning of the polar component of path velocity of the antenna phase center on the intervals of aperture synthesis

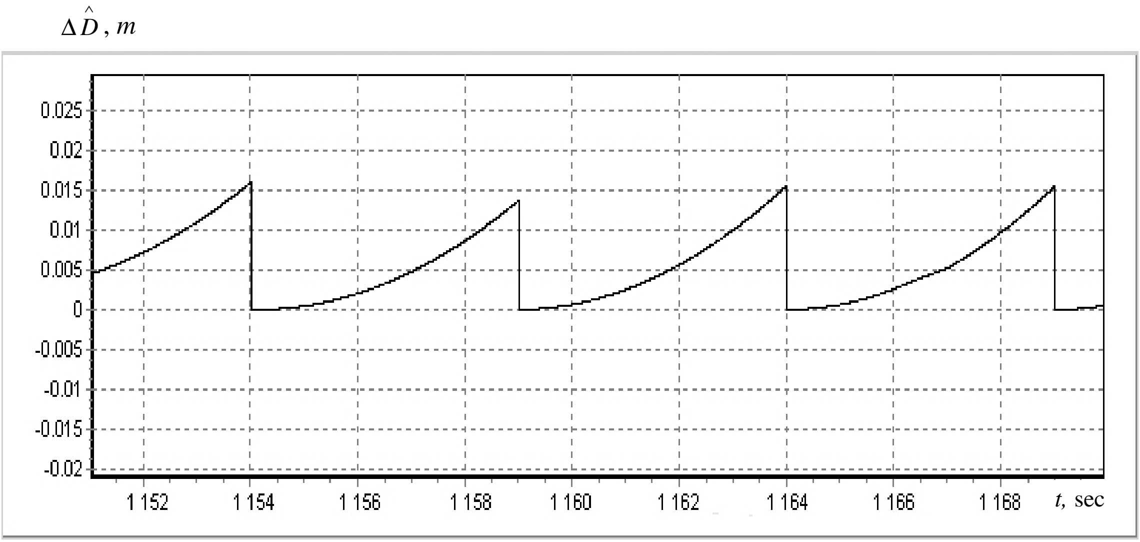

Fig. 8. Dynamic of variation in the error of inertial reckoning of the polar coordinate of the antenna phase center on the intervals of aperture synthesis

Conclusions

Synthesis of the antenna aperture is one of the promising leads for radar development. The major advantage of this lead is multiple increase in the RADS angular resolution. In this case, there is the feasibility of detection and radio-vision of small-size objects, of improvement in the accuracy and noise immunity of RADS. Compensation for path instabilities in RADS signals reflects tightly-coupled interaction of the RADS and inertial satellite micronavigation system. With such an interaction of airborne systems, mutual support is implemented at the level of primary and second signal processing. Moreover, under SAR autofocusing and Doppler navigator conditions, it is apparently possible to update distributed micronavigation system parameters.

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