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INFORMATION SUPPORT OF UNMANNED AERIAL VEHICLES NAVIGATION USING PSEUDOLITES

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ABSTRACT

The paper focuses on developing mathematical tools for solving the problem of joint information processing of various sensors of UAVs using pseudolites. These tools are the basis of information support of complex navigation system. The authors found mathematical dependencies establishing an unambiguous link between the errors of the navigation output parameters and those of the navigation model, as well as equivalent errors in the measurement sensors for a given movement of the aircraft.

Keywords: *Complex Navigation System, Unmanned Aerial Vehicle, Pseudolite, Inertial Navigation System, Satellite Navigation System.*

1. INTRODUCTION

Inertial navigation system (INS) for small size unmanned aerial vehicles (UAV) uses measurement data from sensors of the two navigation systems: strapdown inertial navigation system and satellite navigation system for crosschecking and correcting of the measurement data throughout the flight. The modern approach to improve the characteristics of autonomous inertial navigation system is aimed at creating INS, in which signals of the strapdown inertial navigation system (SINS) and the satellite navigation system (SNS) (GPS, GLONASS, Beidou, etc.) are processed simultaneously [1, 2]. The advantages of SINS are autonomy and noise immunity. Its main disadvantage is that measurement errors caused by errors in sensors accumulate over time and require their compensation [3, 4]. SNS signals can be used as standards for the formation of appropriate corrective feedback to improve the SINS accuracy characteristics [5]. The problems of building INS for UAVs related to the improvement of accuracy and reliability of navigation systems are disclosed in the works of G.I. Janjgava, L.I. Avgustov, A.V. Babichenko, M.I. Orekhov, S.Ya. Sukhorukov, V.K. Shkred, N.A. Parusnikov, A.A. Golovan, M.N. Krasilschikov, V.Ya. Raspopov, A.V. Repnikov, O.A. Stepanov, N.A. Parusnikov [5-21]. At the same time, the problems using pseudolites for the solution of navigation problems are of particular importance.

2. STATEMENT OF THE PROBLEM OF JOINT PROCESSING OF MEASUREMENT DATA FROM DIFFERENT UAV SENSORS

The airborne equipment for manned and unmanned aviation vehicles consists of information measuring tools, which perform inertial, aerometric and electromagnetic measurements of various parameters in the navigation space:

- gyro (INS) and strapdown (SINS) inertial navigation systems;
- air data system (ADS) and angle of attack and slideslip sensors (AoAaSS);
- satellite navigation systems (SNS or pseudolite-based positioning system);
- Doppler velocity and drift sensors (DVaDS);
- radar altimeters (RA);
- short-range radiotechnical navigation system (SRRNS) and long-range radiotechnical navigation system (LRNRS);
- optical systems (OS) and radar systems (RS);
- Aircraft Navigation Systems (ANS);
- tools for determining cross-coordinates of aircraft (AC) and other objects (OO).

These sensors and systems, together with the corresponding computational and communication resources are information measuring channels of onboard equipment implementing various navigation methods: dead reckoning, positioning, surveillance and comparison.

A generalized algorithm R^I of information processing in the i-th system (i-th channel of the equipment set) has the form

$$\mathbf{N}^i = R^i(\mathbf{J}^i, \mathbf{K}^i), \quad (1)$$

where: $\mathbf{N}^i$ is a multi-dimensional vector of the object state; $\mathbf{J}^i$ is a multidimensional vector of measurement information, elements of which are directly measurable parameters; $\mathbf{K}^i$ – a multi-dimensional vector of information field parameters of navigation space used in data processing.

3. THE ALGORITHM FOR SOLVING THE PROBLEM OF JOINT DATA PROCESSING USING DIFFERENT MEASURING TOOLS

Algorithms of data processing in the main information- measuring channels are fully described in the literature. The result of these algorithms are multi-dimensional vectors of the state $\mathbf{N}^i$ formed in the computing environment. Generally, they include coordinates and components of linear velocity of the corresponding channel of the measurement center, and orientation parameters connected with the measurement center of the coordinate trihedral relative to the geographical trihedral.

Table 1: Composition Of Vector Operands For Different Channel.

Basic channel system	Vector of state N_i	Measurement vector J_i	Vector of parameters K_i	Fragment of $\{N_i\}$ of state vector for supporting
INS	$\lambda, \varphi, H, V_E, V_N, V_H, \chi, \Psi, \psi_r, \theta, \gamma$	$a_\xi, a_\eta, a_\varsigma$	$g_\xi, g_\eta, g_\varsigma, U_\xi, U_\eta, U_\varsigma, R_E, R_N$	H
SINS	$\lambda, \varphi, H, V_E, V_N, V_H, \chi, \Psi, \psi_r, \theta, \gamma, \omega_x, \omega_y, \omega_z, a_x, a_y, a_z$	$\omega_x, \omega_y, \omega_z, a_x, a_y, a_z$	$g_\xi, g_\eta, g_\varsigma, U_\xi, U_\eta, U_\varsigma, R_E, R_N$	H
AoAaSS	$\lambda, \varphi, V_E, V_N, V_H$	V_x, V_y, V_z	R_E, R_N	Ψ, θ, γ
SNS+ DVaDS	$\lambda, \varphi, H, V_E, V_N, V_H$	α, β, V^a, H^b	$\acute{V}^{wind}, R_E, R_N, H^b(H)$	Ψ, θ, γ
RA	λ, φ, H	H^t	$H^p = f(\lambda, \varphi)$	λ, φ
SNS	$\lambda, \varphi, H, V_E, V_N, V_H$	$D_i, \acute{D}_i$, i=1□4	$\acute{r}_i^{NAES}, \acute{V}_i^{NAES}$, i=1□4	
pulse-phase RNS	λ, φ	(D_i-D_j), i□j	$\acute{r}_i^{cr}$, i=1□3	H
SRRNS	λ, φ	A, D	$\acute{r}_i^{PM}$	H
OO	$\lambda, \varphi, H, V_E, V_N, V_H$	$\varphi_{yi}, \varphi_{zi}, D_i, \acute{D}_i$, i=1□12	$\acute{r}_i^{AC}, \acute{V}_i^{AC}$, i=1□12	Ψ, θ, γ
RS	λ, φ, H	φ_y, φ_z, D	$\acute{r}^{OP}$	Ψ, θ, γ
OS	λ, φ, H	φ_y, φ_z, D	$\acute{r}^{OP}$	Ψ, θ, γ
ANS	$\lambda, \varphi, \Psi, \theta, \gamma$	φ_y, φ_z	α_i, δ_i, S	$\lambda, \varphi, \Psi, \theta, \gamma$

λ, φ, H are geographic coordinates (longitude, latitude, altitude);

V_E, V_N, V_H, V_x, V_y, V_z are components of the UAV relative linear velocity (in axes of the geographical trihedral *OENH* (Figure 1) and connected frame *Oxyz* (Figure 2));

Ψ, θ, γ are the UAV orientation angles (yaw, pitch, roll);

χ, Ψ_r is the azimuth angle of the reference trihedral and gyro drift with respect to it;

D_ξ, D_η, D_ς are vector components of the UAV relative position and reference point / target (in the axes of the reference trihedral $O\xi\eta\varsigma$ (Figure 2));

a_ξ, a_η, a_ς, a_x, a_y, a_z are components of the UAV apparent acceleration (in the axes of the reference trihedral $O\xi\eta\varsigma$ and connected frame *Oxyz*);

ω_x, ω_y, ω_z are components of the UAV absolute angular velocity (in the axes of the connected frame *Oxyz*);

α, β are aerodynamic angles of attack and drift;

V^a is the magnitude of the airspeed;

H^t, H^b are true and barometric altitudes;

D_i, $\acute{D}_i$ is the distance from the UAV to the i-th object (navigational artificial Earth satellite (NAES) or pseudolite, LRNRS station, another UAV) and its derivative;

A, D are azimuth and distance to the SRRNS radio beacon;

φ_{yi}, φ_{zi}, D are polar coordinates of the object (reference point / target) (side angle of sight, elevation, slant range distance);

g_ξ, g_η, g_ς are components of the gravity field vector (in the axes of the reference trihedral $O\xi\eta\varsigma$);

U_ξ, U_η, U_ς are components of the drift velocity of the Earth (in the axes of the reference trihedral $O\xi\eta\varsigma$);

R_E, R_N are the principal radii of the surface level curvature;

$\acute{V}^{wind}$ is wind (a vector quantity)

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$H^p=f(\lambda, \varphi)$ is the dependence of the relief height on the coordinates (a digital map of the area);
$\acute{r}_i^{NAES}$, $\acute{V}_i^{NAES}$ are coordinates and speed of the i-th NAES (vector quantities);
$\acute{r}_i^{st}$ are the coordinates of the i-th SRRNS station (a vector quantity);
$\acute{r}_i^{PM}$ are the coordinates of the SRRNS radio beacon (a vector quantity);
$\acute{r}_i^{AC}$, $\acute{V}_i^{AC}$ are the coordinates and velocity of the i-th UVA (vector quantities);
$\acute{r}^{OP}$ are the coordinates of the reference point / target (a vector quantity);
S is the sidereal time;
α_i, δ_i are spherical coordinates (right ascension and declination) of the i-th luminary.

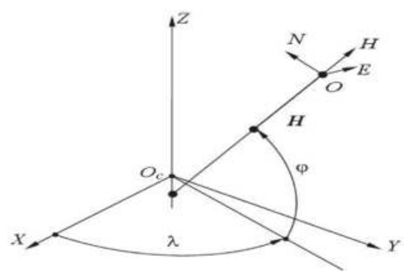

Figure 1: Geographical Trihedral OENH (O_c − ellipsoid center)

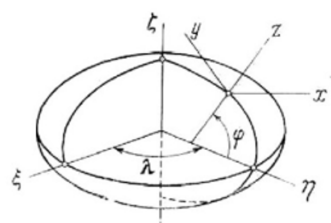

Figure 2: Connected Oxyz and Reference Oξης Trihedrals

Table 1 provides exemplary compositions of input and output vectors for the algorithms of the form (1) to be realized in different information channels.

The measurement center of the data channel is a conventional point, which has the information about navigation parameters: position, velocity, acceleration, etc. Thus, for inertial navigation systems, this "point" is considered to be a sufficiently small amount of space, which houses the measurement centers of accelerometers for satellite radio navigation system, a small amount of which is the receiving antenna, etc.

In order to solve the generalized equation (1) modern equipment uses all the known methods: dead reckoning on the basis of the measured velocity or acceleration, positioning, surveillance and comparative methods. The comparative characteristics of the methods using various sensors as primary systems are presented in Table 2 (navigation systems are conventionally designated as RNS, while generalized characteristics are given for CES (correlated-extremal systems), without taking into account the characteristics of various modes of navigation fields).

Vectors obtained in different channels are different in composition. The most complete and resilient data sets are formed in the inertial and aerometric information channels. For this reason, these channels are the basic information channels, providing a solution to the main problems of UAV navigation and air pilotage, with the inertial channel being the main one, and the aerometric channel being the backup one. Among other information channels, the satellite channel is the most complete (providing the formation of coordinate values, velocity and exact time) and accurate. Other information channels allow for the formation of less complete in composition N^i vectors, but having properties necessary to address specific functional tasks of UAV.

The main method of UAV detection is the use INS or autonomous gyro sensors. An additional method is optical (astronomical) targeting systems and methods for determining the angular orientation of the object by distance and difference-distance measurements of several spaced SNS receivers.

Table 2: Methods For Solving Navigation Tasks

Method		Dead reckoning			Comparing	Positioning			
Main system		INS	DVaDS	ADS	CES	SNS	RNS	OS	ANS
descriptiveness	orientation	yes	no	no	no	no/yes	no	no	yes/no
	coordinates	yes	yes	yes	yes	yes	yes	yes	yes
	velocity	yes	yes	yes	no	yes	no	no	no
	acceleration	yes	no	no	no	no	no	no	no
secrecy		yes	no	yes	yes/no	yes	yes	no/yes	yes
noise immunity		yes	no	yes/no	yes/no	no	no	no	yes/no
self-regulation		yes	yes	yes	yes	no	no	yes	yes
accuracy		yes/no	no	no	yes/no	yes	yes/no	yes	yes/no

In the practical implementation of the algorithm (1) errors are inevitable, and they can be mathematically represented as multi-dimensional vectors: errors of measurement information $\Delta\mathbf{J}^i$; errors in determining the parameters of information field $\Delta\mathbf{K}^i$; initial errors $\Delta\boldsymbol{N}_0^i$; as well as actual algorithmic errors ΔR^i – operator error R^i. In this case all the components of the expression (1) are distorted:

$$\boldsymbol{N}^{im} = R^{im}(\boldsymbol{J}^{im}, \boldsymbol{K}^{im}), \quad (2)$$

where «m» means a modelled value, i.e. a distorted value of the corresponding parameter. Obviously, the following values $\boldsymbol{K}^{im}, \boldsymbol{J}^{im}, \boldsymbol{N}^{im}$ are used, formed and recorded.

The expression (2) may be referred to the full non-linear model of the i-th system. Expression (2) in the vicinity of the exact solution corresponding to the ideal model (1) can be written as a sum of series:

$$\boldsymbol{N}^{im} = \boldsymbol{N}^i + \frac{\partial R^i}{\partial N^i}\Delta\boldsymbol{N}_0^i + \frac{\partial R^i}{\partial J^i}\Delta\boldsymbol{J}^i + \frac{\partial R^i}{\partial K^i}\Delta\boldsymbol{K}_0^i + \Delta R^i(\boldsymbol{J}^i, \boldsymbol{K}^i) + O^2,$$

where O^2 is the value of the second and higher orders of smallness relative to errors.

Apparently, in solving navigation problems it is possible to neglect the values of higher order and get a linearized model in the form of:

$$\boldsymbol{N}^{im} \approx \boldsymbol{N}^i \Xi\left(\boldsymbol{J}^i, \boldsymbol{K}^i, \Delta\boldsymbol{N}_0^i, \Delta\boldsymbol{J}^i, \Delta\boldsymbol{K}^i\right) = \boldsymbol{N}^i + \Delta\boldsymbol{N}^i. \quad (3)$$

On the one hand, these expressions establish unequivocal, but not the only link between the errors of the output navigation parameters, and, on the other hand, the errors of the navigational space model and the equivalent errors in the measurement sensors for a given movement of the object. The specific form of the operator Ξ^i depends on the operator R^i.

3.1 Reprojection Errors By Dead Reckoning Of The Horizontal Components Of Linear Velocity

When solving navigation tasks it is necessary to reproject vectors of absolute and relative linear velocities from the reference trihedral $O\xi\eta\varsigma$ into a geographic trihedral $OENH$, and vice versa. Formulas relating to the errors in determining the components of linear velocity referred to different coordinates of trihedral are of practical interest. Using the "scalar" method of error presentation, these formulas can be obtained by varying the above-mentioned reprojection formulas.

We write the expressions for the two versions of the azimuthal orientation of a reference trihedral $O\xi\eta\varsigma$ relative to the geographical trihedral $OENH$.

If the azimuth angle χ of the orientation of the first axis $O\xi$ of the reference trihedral is reckoned from the northern axis ON of the geographical trihedral, the expression for linear velocity errors have the form:

– relative velocity:

$$\Delta V_\xi = \Delta V_E \cdot \sin\chi + \Delta V_N \cdot \cos\chi + V_E \cdot \cos\chi \cdot \Delta\chi - V_N \cdot \sin\chi \cdot \Delta\chi = \Delta V_E \cdot \sin\chi + \Delta V_N \cdot \cos\chi - V_\eta \cdot \Delta\chi;$$

$$\Delta V_\eta = -\Delta V_E \cdot \cos\chi + \Delta V_N \cdot \sin\chi + V_E \cdot \sin\chi \cdot \Delta\chi + V_N \cdot \cos\chi \cdot \Delta\chi = -\Delta V_E \cdot \cos\chi + \Delta V_N \cdot \sin\chi + V_\xi \cdot \Delta\chi;$$

$$\Delta V_\varsigma = \Delta V_H; \quad (4a)$$

$$\Delta V_E = \Delta V_\xi \cdot \sin\chi - \Delta V_\eta \cdot \cos\chi + V_\xi \cdot \cos\chi \cdot \Delta\chi + V_\eta \cdot \sin\chi \cdot \Delta\chi = \Delta V_\xi \cdot \sin\chi - \Delta V_\eta \cdot \cos\chi + V_N \cdot \Delta\chi;$$

$$\Delta V_\eta = \Delta V_\xi \cdot \cos\chi + \Delta V_\eta \cdot \sin\chi - V_\xi \cdot \sin\chi \cdot \Delta\chi + V_\eta \cdot \cos\chi \cdot \Delta\chi = \Delta V_\xi \cdot \cos\chi + \Delta V_\eta \cdot \sin\chi - V_E \cdot \Delta\chi;$$

– drift velocity:

$$\Delta V_\xi{}^E = \Delta V_E{}^E \cdot \sin\chi + \Delta V_E{}^E \cdot \cos\chi \cdot \Delta\chi = \Delta V_E{}^E \cdot \sin\chi - V_\eta{}^E \cdot \Delta\chi;$$

$$\Delta V_\eta{}^E = -\Delta V_E{}^E \cdot cos\,\chi + \Delta V_E{}^E \cdot \sin\chi \cdot \Delta\chi = -\Delta V_E{}^E \cdot \cos\chi + V_\xi{}^E \cdot \Delta\chi; \quad (5a)$$

$$\Delta V_E{}^E = \mathrm{U} \cdot R_E \cdot \Delta R_E \cdot \cos\varphi \cdot \Delta\chi - \mathrm{U} \cdot R_E \cdot \sin\varphi \cdot \Delta\varphi;$$

– absolute velocity:

$$\Delta V_\xi = \Delta V_E \cdot \sin\chi + \Delta V_N \cdot \cos\chi + V_E \cdot \cos\chi \cdot \Delta\chi - V_N \cdot \sin\chi \cdot \Delta\chi = \Delta V_E \cdot \sin\chi + \Delta V_N \cdot \cos\chi - V_\eta \cdot \Delta\chi = \left(\Delta V_E + \Delta V_E{}^E\right) \cdot \sin\chi + \Delta V_N \cdot \cos\chi + \left(V_E + V_E{}^E\right) \times \cos\chi \cdot \Delta\chi - V_\eta \cdot \sin\chi \cdot \Delta\chi = \left(\Delta V_E + \Delta V_E{}^E\right) \cdot \sin\chi + \Delta V_N \cdot \cos\chi - (V_\eta - V_\eta{}^E) \cdot \Delta\chi$$

$$\Delta V_\eta = -\Delta V_E \cdot cos\,\chi + \Delta V_N \cdot \sin\chi + V_E \cdot \sin\chi \cdot \Delta\chi + V_N \cdot \cos\chi \cdot \Delta\chi = -\Delta V_E \cdot \cos\chi + \Delta V_N \cdot \sin\chi - V_\xi \cdot \Delta\chi = -\left(\Delta V_E + \Delta V_E{}^E\right) \cdot \cos\chi + \Delta V_N \cdot \sin\chi + \left(V_E + V_E{}^E\right) \cdot \sin\chi \times \Delta\chi + V_N \cdot \cos\chi \cdot \Delta\chi = -\left(\Delta V_E + \Delta V_E{}^E\right) \cdot \cos\chi + \Delta V_N \cdot \sin\chi + \left(V_\xi + V_\xi{}^E\right) \cdot \Delta\chi;$$

$$\Delta V_\varsigma = \Delta V_H = \Delta V_H \quad (6a)$$

$$\Delta V_E = \Delta V_\xi \cdot \sin\chi - \Delta V_\eta \cdot \cos\chi + V_\xi \cdot \cos\chi \cdot \Delta\chi + V_\eta \cdot \sin\chi \cdot \Delta\chi = \Delta V_\xi \cdot \sin\chi - \Delta V_\eta \times \cos\chi + V_N \cdot \Delta\chi = \left(\Delta V_\xi + \Delta V_\xi{}^E\right) \cdot \sin\chi - \left(\Delta V_\eta + \Delta V_\eta{}^E\right) \cdot \cos\chi + \left(V_\xi + V_\xi{}^E\right) \times \cos\chi \cdot \Delta\chi + \left(\Delta V_\eta + \Delta V_\eta{}^E\right) \cdot \sin\chi \cdot \Delta\chi = \left(\Delta V_\xi + \Delta V_\xi{}^E\right) \cdot \sin\chi - \left(\Delta V_\eta + \Delta V_\eta{}^E\right) \cdot \cos\chi - V_N \cdot \Delta\chi;$$

$$\Delta V_N = \Delta V_\xi \cdot \cos\chi + \Delta V_\eta \cdot \sin\chi - V_\xi \cdot \sin\chi \cdot \Delta\chi + V_\eta \cdot \cos\chi \cdot \Delta\chi = \Delta V_\xi \cdot \cos\chi + \Delta V_\eta \times \sin\chi - V_E \cdot \Delta\chi = \left(\Delta V_\xi + \Delta V_\xi{}^E\right) \cdot \cos\chi + \left(\Delta V_\eta + \Delta V_\eta{}^E\right) \cdot \sin\chi - \left(V_\xi + V_\xi{}^E\right) \times \sin\chi \cdot \Delta\chi + \left(\Delta V_\eta + \Delta V_\eta{}^E\right) \cdot \cos\chi \cdot \Delta\chi = \left(\Delta V_\xi + \Delta V_\xi{}^E\right) \cdot \cos\chi + \left(\Delta V_\eta + \Delta V_\eta{}^E\right) \times \sin\chi - \left(\Delta V_E + \Delta V_E{}^E\right) \cdot \Delta\chi.$$

If the azimuth angle χ of the orientation of the first axis $O\xi$ of the reference trihedral is reckoned from the eastern axis OE of the geographical trihedral, the expression for linear velocity errors have the form:

- relative velocity:

$$\Delta V_\varepsilon = \Delta V_E \cdot \cos\chi - \Delta V_N \cdot \sin\chi - V_E \cdot \sin\chi \cdot \Delta\chi - V_N \cdot \cos\chi \cdot \Delta\chi = \Delta V_E \cdot \cos\chi - \Delta V_N \cdot \sin\chi - V_\eta \cdot \Delta\chi;$$

$$\Delta V_\eta = \Delta V_E \cdot \sin\chi + \Delta V_N \cdot \cos\chi + V_E \cdot \cos\chi \cdot \Delta\chi - V_N \cdot \sin\chi \cdot \Delta\chi = \Delta V_E \cdot \sin\chi + \Delta V_N \cdot \cos\chi + V_\varepsilon \cdot \Delta\chi;$$

$$\Delta V_\varsigma = \Delta V_H;$$

$$\Delta V_E = \Delta V_\varepsilon \cdot \cos\chi + \Delta V_\eta \cdot \sin\chi - V_\epsilon \cdot \sin\chi \cdot \Delta\chi + V_\eta \cdot \cos\chi \cdot \Delta\chi = \Delta V_\varepsilon \cdot \cos\chi + \Delta V_\eta \cdot \sin\chi + V_N \cdot \Delta\chi;$$

$$\Delta V_N = -\Delta V_\varepsilon \cdot \sin\chi + \Delta V_\eta \cdot \cos\chi - V_\epsilon \cdot \cos\chi \cdot \Delta\chi - \Delta V_\eta \cdot \sin\chi \cdot \Delta\chi = -\Delta V_\varepsilon \cdot \sin\chi + \Delta V_\eta \cdot \cos\chi - V_E \cdot \Delta\chi;$$

- drift velocity:

$$\Delta V_\varepsilon^E = \Delta V_E^E \cdot \cos\chi - V_E^E \cdot \sin\chi \cdot \Delta\chi = \Delta V_E^E \cdot \cos\chi - V_\eta^E \cdot \Delta\chi;$$

$$\Delta V_\eta^E = \Delta V_E^E \cdot \sin\chi + V_E^E \cdot \cos\chi \cdot \Delta\chi = \Delta V_E^E \cdot \sin\chi + V_\varepsilon^E \cdot \Delta\chi; \qquad (5b)$$

$$\Delta V_E^E = U \cdot R_E \cdot \Delta R_E \cdot \cos\varphi - U \cdot R_E \cdot \sin\varphi \cdot \Delta\varphi;$$

- absolute velocity:

$$\Delta V_\varepsilon = \Delta V_E \cdot \cos\chi - \Delta V_N \cdot \sin\chi - V_E \cdot \sin\chi \cdot \Delta\chi - V_N \cdot \cos\chi \cdot \Delta\chi = \Delta V_E \cdot \cos\chi - \Delta V_N \cdot \sin\chi - V_\eta \cdot \Delta\chi = (\Delta V_E + \Delta V_E^E) \cdot \cos\chi - \Delta V_N \cdot \sin\chi - (V_E + V_E^E) \cdot \sin\chi \cdot \Delta\chi - V_N \cdot \cos\chi \cdot \Delta\chi = (\Delta V_E + \Delta V_E^E) \cdot \cos\chi - \Delta V_N \cdot \sin\chi - (V_\eta + V_\eta^E) \cdot \Delta\chi;$$

$$\Delta V_\eta = \Delta V_E \cdot \sin\chi + \Delta V_N \cdot \cos\chi + V_E \cdot \cos\chi \cdot \Delta\chi - V_N \cdot \sin\chi \cdot \Delta\chi = \Delta V_E \cdot \sin\chi + \Delta V_N \cdot \cos\chi + V_\varepsilon \cdot \Delta\chi = (\Delta V_E + \Delta V_E^E) \cdot \sin\chi + \Delta V_N \cdot \cos\chi + (V_E + V_E^E) \cdot \cos\chi \cdot \Delta\chi - V_N \cdot \sin\chi \cdot \Delta\chi = (\Delta V_E + \Delta V_E^E) \cdot \sin\chi + \Delta V_N \cdot \cos\chi + (V_\varepsilon + V_\varepsilon^E) \cdot \Delta\chi;$$

$$\Delta V_\varsigma = \Delta V_H = \Delta V_H; \qquad (6b)$$

$$\Delta V_E = \Delta V_\varepsilon \cdot \cos\chi + \Delta V_\eta \cdot \sin\chi - V_\epsilon \cdot \sin\chi \cdot \Delta x + V_\eta \cdot \cos\chi \cdot \Delta\chi = \Delta V_\varepsilon \cdot \cos\chi + \Delta V_\eta \cdot \sin\chi + V_N \cdot \Delta\chi = (\Delta V_E + \Delta V_E^E) \cdot \cos\chi + \left(\Delta V_\eta + \Delta V_\eta^E\right) \cdot \sin\chi - (V_\varepsilon + V_\varepsilon^E) \cdot \sin\chi \cdot \Delta\chi + \left(V_\eta + V_\eta^E\right) \cdot \cos\chi \cdot \Delta\chi = (\Delta V_\varepsilon + \Delta V_\varepsilon^E) \cdot \cos\chi + \left(\Delta V_\eta + \Delta V_\eta^E\right) \cdot \sin\chi + V_N \cdot \Delta\chi;$$

$$\Delta V_N = -\Delta V_\varepsilon \cdot \sin\chi + \Delta V_\eta \cdot \cos\chi - V_\epsilon \cdot \cos\chi \cdot \Delta\chi - \Delta V_\eta \cdot \sin\chi \cdot \Delta\chi = -\Delta V_\varepsilon \cdot \sin\chi + \Delta V_\eta \cdot \cos\chi - V_E \cdot \Delta\chi = -(\Delta V_\varepsilon + \Delta V_\varepsilon^E) \cdot \sin\chi + \left(\Delta V_\eta + \Delta V_\eta^E\right) \cdot \cos\chi - (\Delta V_\varepsilon + \Delta V_\varepsilon^E) \cdot \cos\chi \cdot \Delta\chi - \left(V_\eta + V_\eta^E\right) \cdot \sin\chi \cdot \Delta\chi = -(\Delta V_\varepsilon + \Delta V_\varepsilon^E) \cdot \sin\chi + \left(\Delta V_\eta + \Delta V_\eta^E\right) \cdot \cos\chi - (V_E + V_E^E) \cdot \Delta\chi.$$

3.2 Statement Of The Problem Of Joint Processing Of Measurement Data From Different UAV Sensors

Vectors N^iobtained in various information channels overlap partially, so by comparing them we can make cross-measurements of information from different channels. In the most general form the measurement equation can be written as:

$$\boldsymbol{Z} = Z\left(\boldsymbol{N}^{\Im}, \boldsymbol{N}^{jm}\right), \qquad (7)$$

where: i,j (i≠j) are numbers of information channels; **Z** is the vector of measurements (or data

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discrepancies between channels i and j), the dimension of which is determined by the number of similar values in the i-th and j-th information channels.

The function Z(), which is in the right side of the equation, in most tasks of joint data processing from navigation channels is a variation of the same type of parameters $\Pi^{\Im}$ and Π^{jm} which, in turn, are linear functions of vector argument $\boldsymbol{N}^{\Im}$and $\boldsymbol{N}^{jm}$of, so the measurement equation takes the form:

$$\boldsymbol{Z} = \Pi^{\Im} - \Pi^{jm} = f(\boldsymbol{N}^{\Im}) - f(\boldsymbol{N}^{jm}). \quad (8)$$

In the simplest, but very frequent case, the parameters $\Pi^{\Im}$and Π^{jm} are the same type subsets of vectors $\boldsymbol{N}^{\Im}$ and N^{jm}:

$$\boldsymbol{Z} = \{\boldsymbol{N}^{\Im}\} - \{\boldsymbol{N}^{jm}\}. \quad (9)$$

Substituting linearized expressions (3) in (8), we obtain the expression for the right side of the measurement equation:

$$\boldsymbol{Z} = f(\boldsymbol{N}^i + \Delta\boldsymbol{N}^i) - f(\boldsymbol{N}^j + \Delta\boldsymbol{N}^j),$$

where $\Delta\boldsymbol{N}^i$ and $\Delta\boldsymbol{N}^j$ are determination error of vectors $\boldsymbol{N}^i$and $\boldsymbol{N}^j$in the i-th и j-th channels.

Because of the linearity of the function f():

$$\boldsymbol{Z} = f(\Delta\boldsymbol{N}^i) - f(\Delta\boldsymbol{N}^j). \quad (10)$$

For the case (9) this expression is simplified:

$$\boldsymbol{Z} = \{\Delta\boldsymbol{N}^m\} - \{\Delta\boldsymbol{N}^j\}. \quad (11)$$

In almost all cases of building information discrepancies between the different channels, the right side of expressions (11) can be written as:

$$\boldsymbol{Z} = \mathbf{H} \cdot \boldsymbol{X} + \varepsilon, \quad (12)$$

where: **X** is the state vector of the channel errors system; **H*X** is a linear combination of errors included in the state vector **X**; ε is a measurement noise vector whose elements are uncorrelated Gaussian random variables.

It is necessary to distinguish between (8) - (9) and (10) - (12): the right sides of formulas (8) and (9) describe the algorithm for calculating vector **Z** values; right sides of formulas (10), (11) and (12) describe the internal structure of vector **Z**.

Next, we consider the specific form of formulas for some combinations of information channels commonly used in onboard equipment of modern and perspective aircraft.

3.3 The Formation And Structure Of Errors Of Inertial And Satellite Channels

Both of these channels form values of aircraft coordinates and its linear velocity. As vertical and horizontal channels of INS differ fundamentally in the nature of errors, joint processing of INS and SNS data is performed separately for these channels.

Algorithm for calculating the residual vector Z values for the horizontal channels is a variation of the formula (9), that is the simple difference between the corresponding values obtained by INS and SNS:

residuals of geographical coordinates:

$$Z_\lambda = \lambda^{INS} - \lambda^{SNS};\ Z_\varphi = \varphi^{INS} - \varphi^{SNS}; \quad (13)$$

residuals of the relative velocity in the axes of geographical trihedral:

$$Z_{VE} = V_E^{INS} - V_E^{SNS};\ Z_{VN} = V_N^{INS} - V_N^{SNS}; \quad (14)$$

residuals of the relative velocity in the axes of the reference trihedral (the azimuth angle χ of the orientation of the first axis *O*ξ of the reference trihedral is reckoned from the northern axis *ON* of the geographical trihedral):

$$Z_{V\xi} = V_\xi^{INS} - (V_E^{SNS} \cdot sin\chi^{INS} + V_N^{SNS} \cdot cos\chi^{INS});$$
$$Z_{V\eta} = V_\eta^{INS} - (-V_E^{SNS} \cdot cos\chi^{INS} + V_N^{SNS} \cdot sin\chi^{INS}); \quad (15a)$$

residuals of the relative velocity in the axes of the reference trihedral (the azimuth angle χ of the orientation of the first axis *O*ξ of the reference trihedral is reckoned from the eastern axis *OE* of the geographical trihedral):

$$Z_{V\xi} = V_\xi^{INS} - (V_E^{SNS} \cdot cos\chi^{INS} - V_N^{SNS} \cdot sin\chi^{INS});$$
$$Z_{V\eta} = V_\eta^{INS} - (V_E^{SNS} \cdot sin\chi^{INS} + V_N^{SNS} \cdot cos\chi^{INS}); \quad (15b)$$

residuals of the absolute velocity in the axes of the reference trihedral (the azimuth angle χ of the orientation of the first axis *O*ξ of the reference trihedral is reckoned from the northern axis *ON* of the geographical trihedral):

$$Z_{V\xi} = V_\xi^{INS} - (V_E^{SNS} \cdot sin\chi^{INS} + V_N^{SNS} \cdot cos\chi^{INS} + V_E^{ESNS} \cdot sin\chi^{INS});$$
$$Z_{V\eta} = V_\eta^{INS} - (-V_E^{SNS} \cdot cos\chi^{INS} + V_N^{SNS} \cdot sin\chi^{INS} - V_E^{ESNS} \cdot cos\chi^{INS}); \quad (16a)$$

residuals of the absolute velocity in the axes of the reference trihedral (the azimuth angle χ of the orientation of the first axis *O*ξ of the reference trihedral is reckoned from the eastern axis *OE* of the geographical trihedral):

$$Z_{V\xi} = V_\xi^{INS} - (V_E^{SNS} \cdot cos\chi^{INS} - V_N^{SNS} \cdot sin\chi^{INS} + V_E^{ESNS} \cdot cos\chi^{INS});$$
$$Z_{V\eta} = V_\eta^{INS} - (V_E^{SNS} \cdot sin\chi^{INS} + V_N^{SNS} \cdot cos\chi^{INS} + V_E^{ESNS} \cdot sin\chi^{INS}); \quad (16b)$$

Algorithm for calculating the residual vector Z values for the vertical channels is a variation of the formula (9), that is the simple difference between the corresponding values obtained by INS and SNS:

residual coordinate altitude:

$$Z_{H=}H^{INS} - H^{SNS}; \quad (17)$$

residual vertical velocity:

$$Z_{VH=}V_H^{INS} - V_H^{SNS}. \quad (18)$$

It should be mentioned that the values H^{INS} and V_H^{INS}, are in turn, the result of joint data processing of INS and SHS, i.e. baro-inertial altitude and vertical velocity.

In this case, the structure of residuals will have a corresponding form which follows directly from the general equation (11) by substituting in it the errors of models discussed above. When recording the following expressions, the superscripts "INS" and "SNS" denoting the parameter membership are omitted; notation of INS errors begins with the letter "Δ", and that of SNS errors starts with the letter "δ".

The structure of residual coordinates vector is generated by the algorithm (13):

for the first version of the azimuthal orientation of the reference trihedral with respect to geographical meridian (angle x is reckoned from the northern axis):

$$Z_\lambda = \frac{cos\chi}{cos\varphi} \cdot \Phi_\xi^0 + \frac{sin\chi}{cos\varphi} \cdot \Phi_\eta^0 + (-\delta\lambda);$$

$$Z_\varphi = -sin\chi \cdot \Phi_\xi^0 + cos\chi \cdot \Phi_\eta^0 + (-\delta\varphi); \quad (19a)$$

for the second version of the azimuthal orientation of the reference trihedral with respect to geographical meridian (angle x is reckoned from the eastern axis):

$$Z_\lambda = \frac{-sin\chi}{cos\varphi} \cdot \Phi_\xi^0 + \frac{cos\chi}{cos\varphi} \cdot \Phi_\eta^0 + (-\delta\lambda);$$

$$Z_\varphi = -cos\chi \cdot \Phi_\xi^0 - sin\chi \cdot \Phi_\eta^0 + (-\delta\varphi); \quad (19b)$$

The structure of the residuals vector of relative velocity is formed by the algorithm (14):

for the first version of the azimuthal orientation of the reference trihedral with respect to geographical meridian (angle x is reckoned from the northern axis):

$$Z_{VE} = \Delta V_E + (-\delta V_E) = \Delta V_\xi \cdot sin\chi - \Delta V_\eta \cdot cos\chi + V_\xi \cdot cos\chi \cdot \Delta x + V_\eta \cdot sin\chi \cdot \Delta\chi + (-\delta V_E)$$

$$\Delta V_\xi \cdot sin\chi - \Delta V_\eta \cdot cos\chi + V_N \cdot \Delta x + (-\delta V_E);$$

$$Z_{VN} = \Delta V_N + (-\delta V_N) = \Delta V_\xi \cdot cos\chi + \Delta V_\eta \cdot sin\chi - V_\xi \cdot sin\chi \cdot \Delta x + V_\eta \cdot cos\chi \cdot \Delta x + (-\delta V_N)$$

$$\Delta V_\xi \cdot cos\chi + \Delta V_\eta \cdot sin\chi - V_E \cdot \Delta\chi + (-\delta V_N);$$

where

$$\Delta x = cos\chi \cdot tg\varphi \cdot \Phi_\xi^0 + sin\chi \cdot tg\varphi \cdot \Phi_\eta^0 - \Phi_\varsigma^0; (20a)$$

for the second version of the azimuthal orientation of the reference trihedral with respect to geographical meridian (angle x is reckoned from the eastern axis):

$$Z_{VE} = \Delta V_E + (-\delta V_E) = \Delta V_\xi \cdot cosx + \Delta V_\eta \cdot sinx - V_\xi \cdot sinx \cdot \Delta x + V_\eta \cdot cosx \cdot \Delta x + (-\delta V_E) = \Delta V_\xi \cdot cosx + \Delta V_\eta \cdot sinx + V_N \cdot \Delta x + (-\delta V_E);$$

$$Z_{VN} = \Delta V_N + (-\delta V_N) = -\Delta V_\xi \cdot sin\chi + \Delta V_\eta \cdot cos\chi - V_\xi \cdot cos\chi \cdot \Delta\chi - V_\eta \cdot sin\chi \cdot \Delta\chi + (-\delta V_N) = -\Delta V_\xi \cdot sin\chi + \Delta V_\eta \cdot cos\chi - V_E \cdot \Delta\chi + (-\delta V_N);$$

where $\Delta\chi = -sin\chi \cdot tg\varphi \cdot \Phi_\xi^0 + cos\chi \cdot tg\varphi \cdot \Phi_\eta^0 - \Phi_\varsigma^0$; (20b)

The structure of the residuals vector of relative velocity is formed by the algorithm (15):

for the first version of the azimuthal orientation of the reference trihedral with respect to geographical meridian (angle x is reckoned from the northern axis):

$$Z_{V\xi} = \delta V_\xi - (\delta V_E \cdot sin\chi + \delta V_N \cdot cos\chi + V_E \cdot cos\chi \cdot \Delta x - V_N \cdot sin\chi \cdot \Delta\chi) = \delta V_\xi - \left(\delta V_E \cdot sin\chi + \delta V_N \cdot cos\chi - V_\eta \cdot \Delta\chi\right) = \delta V_\xi + V_\eta \cdot \Delta x - (\delta V_E \cdot sin\chi + \delta V_N \cdot cos\chi;$$

$$Z_{V\eta} = \delta V_\eta - (-\delta V_E \cdot cos\chi + \delta V_N \cdot sin\chi + V_E \cdot sin\chi \cdot \Delta\chi + V_N \cdot cos\chi \cdot \Delta\chi) = \delta V_\eta - \left(-\delta V_E \cdot cos\chi + \delta V_N \cdot sin\chi - V_\xi \cdot \Delta\chi\right) = \delta V_\eta + V_\xi \cdot \Delta\chi - (-\delta V_E \cdot cos\chi + \delta V_N \cdot sin\chi);$$

where

$$\Delta\chi = cos\chi \cdot tg\varphi \cdot \Phi_\xi^0 + sin\chi \cdot tg\varphi \cdot \Phi_\eta^0 - \Phi_\varsigma^0;$$

for the second version of the azimuthal orientation of the reference trihedral with respect to geographical meridian (angle x is reckoned from the eastern axis):

$$Z_{V\xi} = \delta V_\xi - (\delta V_E \cdot cos\chi + \delta V_N \cdot sin\chi - V_E \cdot sin\chi \cdot \Delta\chi - V_N \cdot cos\chi \cdot \Delta\chi) = \delta V_\xi - \left(\delta V_E \cdot cos\chi - \delta V_N \cdot sin\chi - V_\eta \cdot \Delta\chi\right) = \delta V_\xi + V_\eta \cdot \Delta\chi - (\delta V_E \cdot cos\chi - \delta V_N \cdot sin\chi);$$

$$Z_{V\eta} = \delta V_\eta - (\delta V_E \cdot sin\chi + \delta V_N \cdot cos\chi + V_E \cdot cos\chi \cdot \Delta\chi - V_N \cdot sin\chi \cdot \Delta\chi) = \delta V_\eta - \left(\delta V_E \cdot sin\chi + \delta V_N \cdot cos\chi + V_\xi \cdot \Delta\chi\right) = \delta V_\eta - V_\xi \cdot \Delta\chi - (\delta V_E \cdot sin\chi + \delta V_N \cdot cos\chi);$$

where

$$\Delta\chi = -sin\chi \cdot tg\varphi \cdot \Phi_\xi^0 + cos\chi \cdot tg\varphi \cdot \Phi_\eta^0 - \Phi_\varsigma^0 .$$

The structure of the residuals vector of absolute velocity is formed by the algorithm (16):

for the first version of the azimuthal orientation of the reference trihedral with respect to geographical meridian (angle x is reckoned from the northern axis):

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$$Z_{V\xi} = \Delta Z_\xi - ((\delta V_E + \delta V_E^E)\cdot sinx + \delta V_N \cdot cos\chi - V_\eta \cdot \Delta\chi) = \Delta Z_\xi + V_\eta \cdot \Delta x - \left((\delta V_E + \delta V_E^E)\cdot sin\chi + \delta V_N \cdot cos\chi\right);$$

$$Z_{V\eta} = \Delta Z_\eta - (-(\delta V_E + \delta V_E^E)\cdot cos\chi + \delta V_N \cdot sin\chi - V_\xi \cdot \Delta\chi) = \Delta Z_\eta - V_\xi \cdot \Delta x - \left((\delta V_E + \delta V_E^E)\cdot cosx + \delta V_N \cdot sin\chi\right);$$

where $\Delta x = cos\chi \cdot tg\varphi \cdot \Phi_\xi^0 + sin\chi \cdot tg\varphi \cdot \Phi_\eta^0 - \Phi_\varsigma^0$;

for the second version of the azimuthal orientation of the reference trihedral with respect to geographical meridian (angle x is reckoned from the eastern axis):

$$Z_{V\xi} = \Delta Z_\xi - ((\delta V_E + \delta V_E^E)\cdot cos\chi - \delta V_N \cdot sin\chi - V_\eta \cdot \Delta x) = \Delta Z_\xi + V_\eta \cdot \Delta x - \left((\delta V_E + \delta V_E^E)\cdot cos\chi - \delta V_N \cdot sinx\right);$$

$$Z_{V\eta} = \Delta Z_\eta - ((\delta V_E + \delta V_E^E)\cdot sin\chi + \delta V_N \cdot cos\chi + V_\xi \cdot \Delta\chi) = \Delta Z_\eta - V_\xi \cdot \Delta\chi - \left((\delta V_E + \delta V_E^E)\cdot sin\chi + \delta V_N \cdot cos\chi\right);$$

where $\Delta\chi = -sin\chi \cdot tg\varphi \cdot \Phi_\xi^0 + cos\chi \cdot tg\varphi \cdot \Phi_\eta^0 - \Phi_\varsigma^0$.

The structure of altitude and vertical velocity residuals is generated by an algorithm (17) and (18):

$$Z_H = \Delta H - \delta H;$$
$$Z_{VH} = \Delta V_H - \delta V_H;$$

If we introduce the the state vector X of INS errors, including in it values $\Phi_\xi^0, \Phi_\eta^0, \Phi_\varsigma^0, \Delta V_\xi(\Delta V_E), \Delta V_\eta(\Delta V_N), \Delta V_\varsigma(\Delta V_H)$ or $\Delta V_\xi, \Delta V_\eta, \Delta V_\varsigma$, the form of a linear combination of H * X from the right side of (12) obviously follows from the equations (19a) - (19b), (20a) - (20b), (21a) - (21b), (22a) - (22b). The structure of measurement noise vector ε should include SNS errors $\delta\lambda, \delta\varphi, \delta H, \Delta V_E, \Delta V_N, \Delta V_H$.

4. THE RESULTS OF MODELING

In the process of the UAV flight, its speed, direction and altitude of the flight are continually changing. In this case, the UAV position, its velocity and acceleration are information on its movement trajectory, while the angles and angular velocities are information about the spatial orientation of the UAV. The main purpose of the flight trajectory generator is to create a source of navigation information (linear accelerations and angular velocities) for inertial sensing elements of SINS (accelerometers and angular rate sensors), and to build a reference trajectory of the UAV flight. In accordance with the given parameters of the synthesized UAV flight trajectory it is possible to calculate the parameters of its motion (linear accelerations and angular velocities), which will be the input variables in the model of inertial measurement sensors of the ISNS.

We assume that the UAV performs a flight at low speed, without complex and abrupt maneuvers, i.e., the flight process is quite stable and typical. We assume that the coordinates of the UAV initial position are λ = 104.06° (longitude), φ = 30.68° (latitude) and H = 150 *м* (altitude); the initial velocity is V = 30 m/s (it remains unchanged in the flight); initial orientation angles ψ = 45° (yaw), θ = 0° (tangage), γ = 0° (roll), flight duration is 3000s.

With the help of the developed generator, we synthesized the UAV flight trajectory and calculated the corresponding changes in the orientation angles and linear velocities shown in Fig. 3-4.

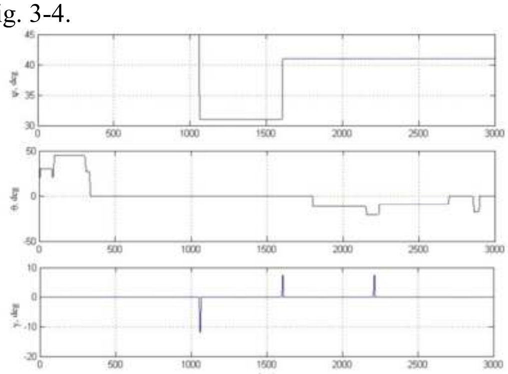

Figure 3: Changes In The UAV Orientation Angles

When modeling the algorithm for joint processing of data from various sensors in a complex environment we used the following parameters and their values INS parameters: the period of SINS solution was 0.01s; angular errors of orientation of ISNS mathematical platform were 1′; linear velocity errors were 0.05 m/s; location coordinates errors were 1m; systematic drift of angular velocity sensors (AVS) was $0{,}01^o$/h; rms AVS perturbation error was 0,001°/h; AVS perturbation error correlation interval was 7200; rms AVS measurement error was $0{,}001^o/$h ; rms of accelerometer perturbations was $5 \times 10^{-5} g$;; correlation interval of accelerometer perturbation error was 1800.

SNS parameters: the period of SNS solution was 1 s; rms error of coordinate measurement was 1m; rms error of noise velocity measurement was 0.05 m/s.

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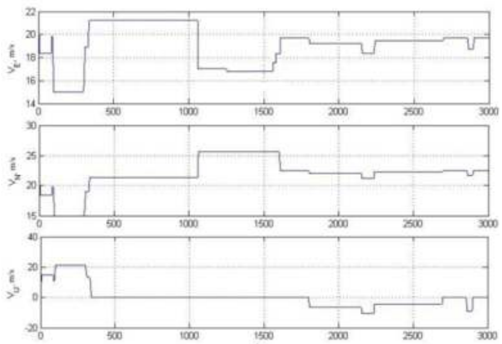
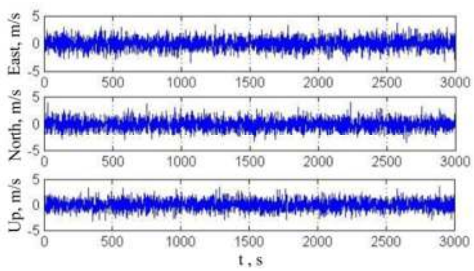


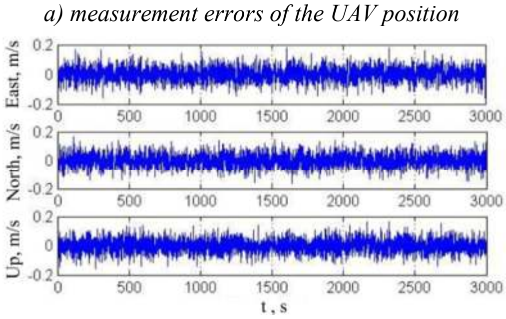
Figure 4: Changes In The UAV Linear Velocities

Option 1: The measurement information is complete.

Measurement errors of the UAV position and velocity by SNS data are shown in Fig. 5. The results of modeling of the algorithm for joint data processing from different INS sensors are shown in Fig. 6.

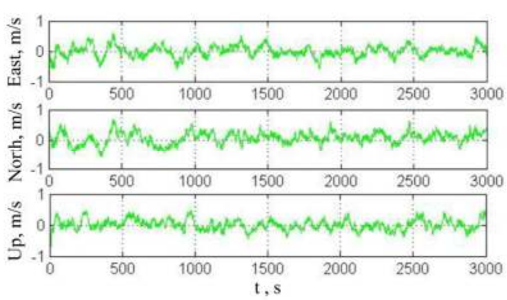


a) measurement errors of the UAV position

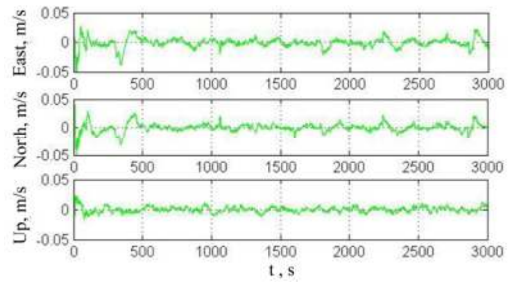


b) measurement errors of the UAV velocity

Figure 5: Measurement errors by the SNS readings



a) measurement errors of the UAV position



b) measurement errors of the UAV velocity

Figure 6: Measurement Errors By The INS Readings Using The Algorithm For Joint Data Processing Form Different Sensors

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The results of modeling (Fig. 6) proved that for the case of complete measurement information, position and velocity errors for UAVs by INS readings were within acceptable limits of accuracy: position errors were mostly limited to within ± 0.5 m, velocity errors were within ± 0.05 m/s.

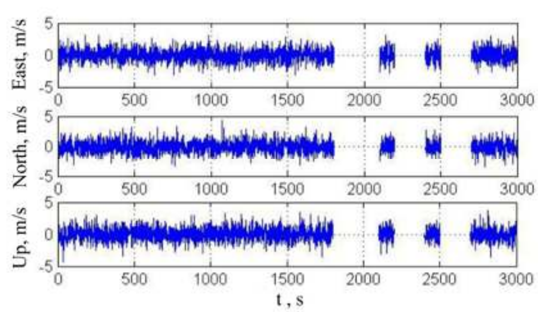
Thus, the algorithm of joint processing of information from different ISNS sensors most effectively reduced the growth of INS errors, and at the same time corrected SNS position and velocity errors, i.e. the optimal evaluation effect was achieved.

Option 2: The measurement information is incomplete.

The effect of the relief obstacles on the UAV movement trajectory related to the disappearance of SNS signals was recorded on the following time intervals: 1800-2100 s, 2200-2400 s and 2500-2700s.

The UAV position and velocity measurements errors by the SNA readings related to the disappearance of the signals are shown in Fig. 7.

The results of modeling of the algorithm for joint processing of information from different ISN sensors are shown in Fig. 8.



a) measurement errors of the UAV position

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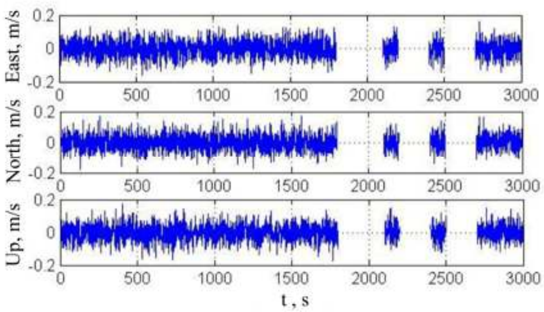
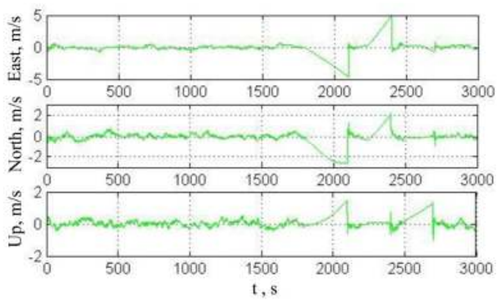
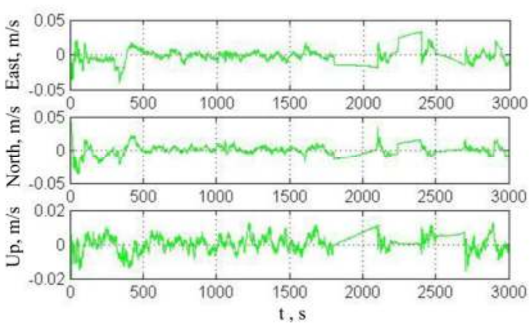


b) measurement errors of the UAV velocity

Figure 7: Measurement Errors By The SNS Reading



a) measurement errors of the UAV position



b) measurement errors of the UAV velocity

Figure 8: Measurement Errors By The INS Readings Using The Algorithm For Joint Data Processing Form Different Sensors

The results of modeling (Fig. 6) showed that in the three time intervals due to the loss of SNS signals, INS could not receive the measurement information from the SNS. Therefore, in these intervals the UAV position and velocity accuracy by INS readings underwent certain changes and influence. The position and velocity errors tended to increase. For example, in the first two time intervals, position and velocity errors in the northern direction became bigger, with the maximum value of position errors in the northern direction reaching the value of about ± 5 m. The position and velocity errors in the eastern and vertical directions were slightly smaller. Based on the nature of the results, it was clear that in a short interval the INS could be control position and velocity errors within acceptable limits of accuracy, with the values of their estimates closer to the true values, and without abrupt changes. When the UAV again received a signal from four or more SNS satellites, the SNS operating conditions returned to normal, and INS again gained full measurement information. In this case, the filtering algorithm resumed the normal operation, and the INS was able to get the exact value estimates to determine the navigation parameters with high accuracy.

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