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Evaluation of the Effectiveness of the Integrity Control Algorithm Integrated Satellite Navigation System and the Functioning of the Inertial Navigation System

By Oleh Dmitriiev, Nadiia Kushnerova & Stanislav Profatilov
National Aviation University

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Methods: Methods of experimental research and mathematical modeling.

Results: A project for an application software package has been developed that allows for a full-cycle simulation of the operation of the algorithm for monitoring the integrity of the SNS and monitoring the correctness of the INS operation.

Discussion: Based on the results of the study, it is proposed to simulate various situations from the point of view of assessing the integrity of the SNS and the correct functioning of the INS at different stages of the flight of the aircraft with different constellations of satellites.

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I. Introduction

When flying along a route, the allowable error levels for determining the coordinates are quite high, which may facilitate the use of satellite navigation system (SNS) as the main means of navigation. During the approach phase, the integrity requirements are significantly increased, and the control parameters, which are calculated using the built-in monitoring method, can exceed the marginal error levels, which can lead to a decrease in the level of integrity evaluation functions.

Significantly improve the work of the integrated monitoring of the integrity of the SNS is possible not only with the help of functional add ons, but also through integrated use with other on board navigation systems, namely the INS.

To solve such problems, the construction of mathematical models of components within the structure of the navigation system of an aircraft (AC) is of great importance, since the adequacy of the models ensures the quality of the system in general.

Author α σ ρ: National Aviation University (Dobrovolskogo str., 25005, Kropyvnytskyi), Ukraine. e-mails: dmitronik70@i.ua, nadiiakushnerov@gmail.com, stanislav.profatilov@gmail.com

Thus, the tasks of synthesis and modeling of the integration algorithms for mixed sources and motion control are important and relevant.

This article analyzes the effectiveness of assessing the integrity of an integrated satellite navigation system and the functioning of an inertial navigation system using computer simulation.

II. Analysis of Latest Research and Publications

Due to the widespread use of satellite navigation technology, the integrity of navigation systems is becoming an important issue, especially to improve safety in air transport. [1-3]. Receiver Autonomous Integrity Monitoring (RAIM) is an important technology developed to assess and maintain the integrity of a GPS system.

The main requirements for ensuring integrity control are set out in the main guidelines [4,5]. According to the specified requirements, the satellite indicator should form control parameters that allow to make a conclusion about the compliance with the requirements for the integrity of the navigation system for a given flight phase of the aircraft and issue warning signals.

The high efficiency of RAIM depends on a sufficient number of visible satellites and their geometrical configuration. Usually, RAIM requires at least five satellites. In addition, the level of protection that is determined by the geometric configuration must be less than the warning limit.

Unfortunately, at the stage of take-off and landing errors and interferences can lead to a loss of signal. In this case, the detection efficiency of RAIM defects is greatly reduced [6-8].

The loss of functions to assess the integrity of the satellite radio navigation system can also occur with insufficient measurement redundancy, with unfavorable mutual geometry of the working constellation of navigation satellites, aircraft and high measurement interferences [9].

The search for algorithms that monitor the integrity of the SNS using navigation information is the subject of [10–12] works. In research [13], an algorithm was proposed for monitoring the integrity of the SNS and monitoring the correctness of the operation of the INS. However, in these works there is no construction of mathematical models of the components included in the structure of the navigation complex of the aircraft.

III. Research Tasks

The purpose of this study is to develop an application software package for the integrated effectiveness of the algorithm for monitoring the integrity of the SNS and assessing the correctness of the operation of the INS.

IV. Analysis the Effectiveness of Assessing the Integrity of an Integrated Satellite Navigation System and the Functioning of an Inertial Navigation System

To find out the effectiveness of the proposed algorithm [13] for autonomous monitoring of the integrity of the SNS and assessing the correctness of the operation of the INS, a project of the applied software was developed. This software package allows you to simulate the work of the entire complex of functions performed in the module of secondary processing of the SNS computer, taking into account the operating hindrance measurements of pseudoranges.

The graphic device developed as part of this software package allows you to directly observe the current parameters of key software modules that implement the developed algorithm for monitoring the integrity of the SNS and monitoring the correct functioning of the INS directly in the course of modeling.

Consider the work of the software package (Fig. 1).

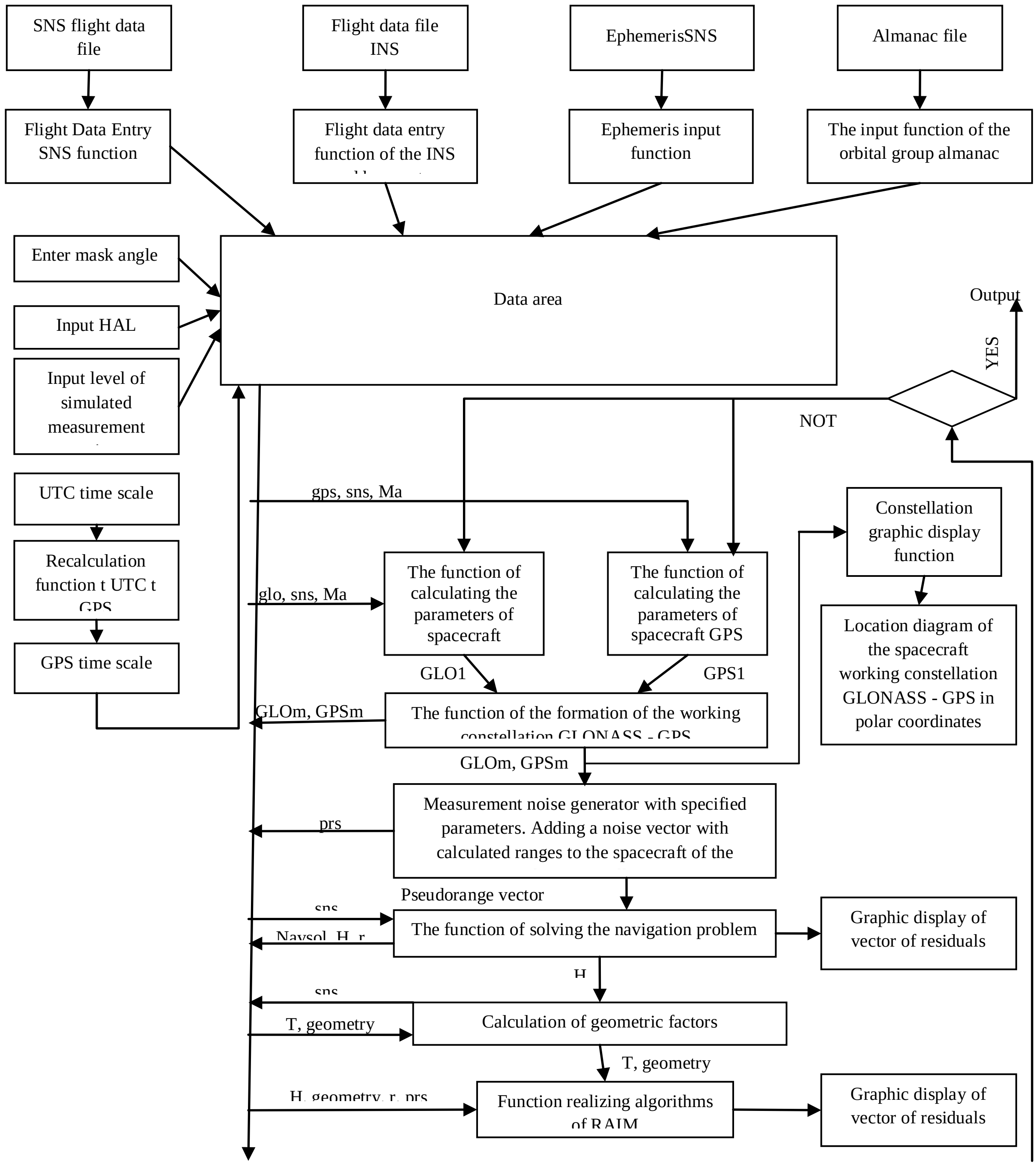

Figure 1: Structural diagram of an application software package for studying the effectiveness of the algorithm for monitoring the integrity of the SNS and evaluating the correctness of the operation of the INS at a given stage of the flight of the aircraft

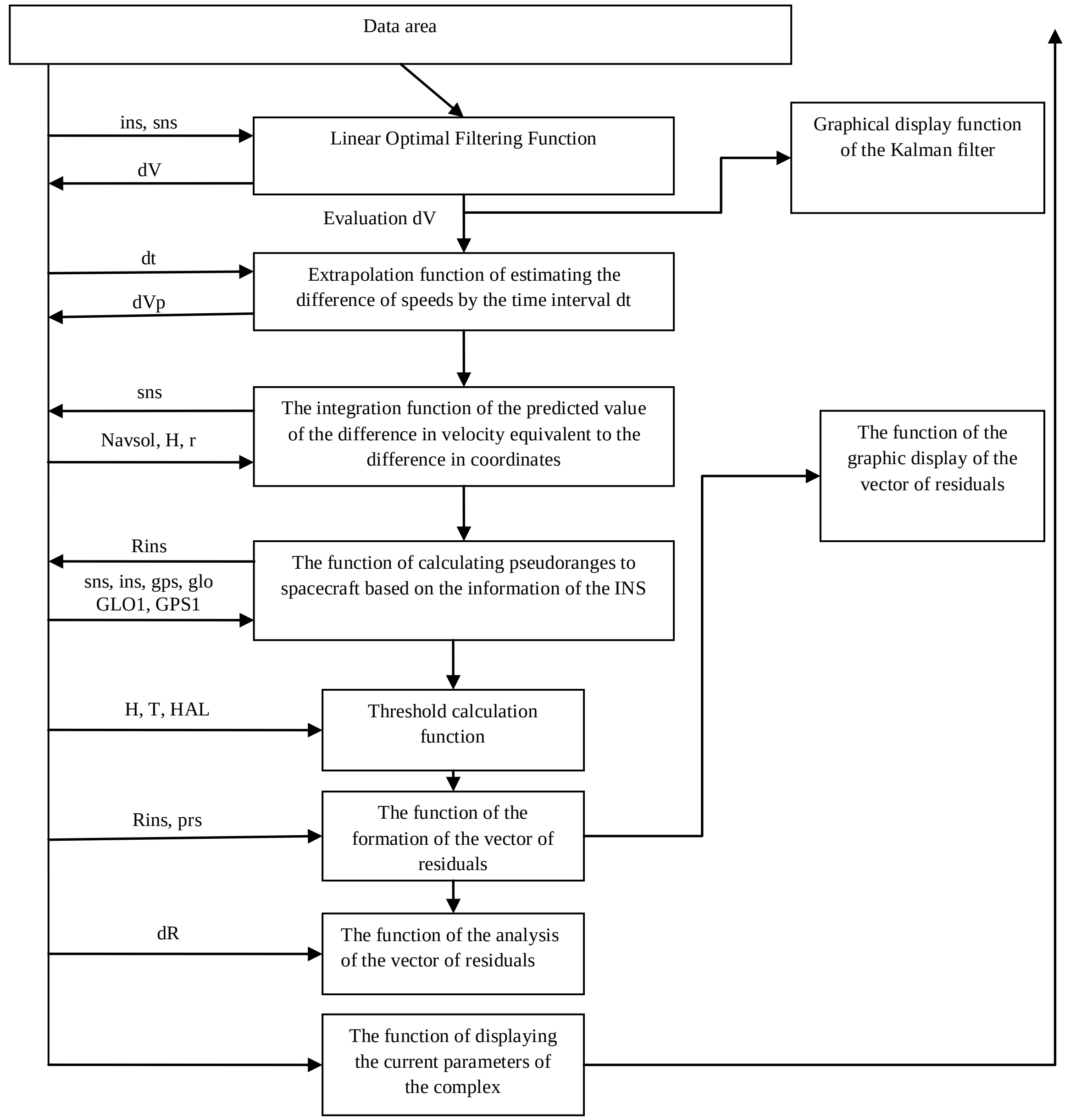

Figure 2: Structural diagram of the application software package for studying the effectiveness of the algorithm for monitoring the integrity of the SNS and evaluating the correctness of the operation of the INS at a given stage of the flight of the aircraft (continued)

Input parameters are databases of flight navigation data received from receiver-indicators (RI) of the SNS, INS and barometric altimeter. The format of the navigation data can be represented as:

$$SNS = \begin{bmatrix} \phi_1^{SNS} & \lambda_1^{SNS} & h_1^{SNS} & V_{N1}^{SNS} & V_{E1}^{SNS} & V_{h1}^{SNS} \\ \phi_2^{SNS} & \lambda_2^{SNS} & h_2^{SNS} & V_{N2}^{SNS} & V_{E2}^{SNS} & V_{h2}^{SNS} \\ - & - & - & - & - & - \\ \phi_i^{SNS} & \lambda_i^{SNS} & \lambda_i^{SNS} & V_{Ni}^{SNS} & V_{E2}^{SNS} & V_{hi}^{SNS} \\ - & - & - & - & - & - \\ \phi_N^{SNS} & \lambda_N^{SNS} & \lambda_N^{SNS} & V_{NN}^{SNS} & V_{EN}^{SNS} & V_{hN}^{SNS} \end{bmatrix}.$$

$$INS = \begin{bmatrix} \phi_1^{INS} & \lambda_1^{INS} & h_1^{BARO} & V_{N1}^{INS} & V_{E1}^{INS} & V_{h1}^{BARO} \\ \phi_2^{INS} & \lambda_2^{INS} & h_2^{BARO} & V_{N2}^{INS} & V_{E2}^{INS} & V_{h2}^{BARO} \\ - & - & - & - & - & - \\ \phi_i^{INS} & \lambda_i^{INS} & \lambda_i^{BARO} & V_{Ni}^{INS} & V_{E2}^{INS} & V_{hi}^{BARO} \\ - & - & - & - & - & - \\ \phi_N^{INS} & \lambda_N^{INS} & \lambda_N^{BARO} & V_{NN}^{INS} & V_{EN}^{INS} & V_{hN}^{BARO} \end{bmatrix}.$$

The length N of arrays of the SNS and INS is determined by the duration of the flights of the aircraft $N = \frac{T_{flig\,ht}}{0.1}$. Accumulated flight material contains arrays of length $N=(2\div4)\times10^5$.

All calculations are made in the time scale of the GPS system, formed by recalculating computer time, synchronized with the UTC time scale (Fig. 1).

At the time t_gps1, the parameters of all spacecraft of orbital groupings are calculated, for which the orbital elements in the almanac are determined. The satellite coordinates are calculated according to the algorithms given in the interface control documents of these systems [14, 15].

As a result of the work of the functions of calculating the parameters of navigation spacecraft (NSC), the matrices GLO1 and GPS1 are formed, corresponding to the NSC GLONASS and GPS. The matrices contain the same type of data, the format of which can be represented as*: [№NSC, A, E, R, X, Y, Z],* where A is the azimuth of NSC, E is the elevation angle of NSC, R is the geometric range to NSC, [X, Y, Z] - coordinates of satellites in the geocentric coordinate system.

Calculation of parameters A, E, R is made according to the algorithm

$$A = arctan\left(\frac{E}{N}\right),$$

$$E = arctan\left(\frac{H}{\sqrt{N^2+E^2}}\right), \qquad (1)$$

$$R = \sqrt{(X-x)^2 + (Y-y)^2 + (Z-z)^2},$$

where $\begin{bmatrix} N \\ E \\ H \end{bmatrix} = T_1 \begin{bmatrix} (X-x) \\ (Y-y) \\ (Z-z) \end{bmatrix}$, *x, y, z* - geocentric coordinates of the aircraft. T_1 matrix is defined in $H_{NEH}=H_{XEZ}\cdot T^T$

Thus, at the time t_gps1, the parameters of all the NSCs of the existing SNS are known. The working constellation is determined by selecting the NSC whose elevation angle A is more than or equal to the specified angle of the mask Ma. This procedure is performed by the function configure_constellation. This function also makes it possible to exclude or, on the contrary, include NSCs of interest from the solution of the navigation problem directly in the modeling process, which provides an analysis of the operation of the algorithm under study with the desired geometric factors of GDOP.

To simulate the noise accompanying the pseudorange measurement process in real RI SNS, a random vector ξt_gps is formed in the software package at each time instant, representing the Markov process with standard deviation = s0, the value of which can be specified directly during the simulation.

The expression for the vector of pseudoranges can be written as

$$prs(j)_{t\_gps}=R(j)_{t\_gps}+\xi(j)_{t\_gps} \qquad (2)$$

The failure of the *j-th* NCA is formed by entering an additional value e into the *j-th* component of the pseudorange vector *prs*:

$$prs(j)_{ei\_gps}=prs(j)_{t\_gps}+e. \qquad (3)$$

The software package allows you to simulate the failure of any of the NSC of the visible constellation by selecting the appropriate number on the graphic console of the pseudorange determination process control console.

After the formation of databases of GLOm, GPSm, containing the coordinates of the NSC, as well as the vector of pseudoranges *prs*, all the necessary data for solving the navigation problem are prepared.

In the case of determining the coordinates when using measurements carried out on the NSC of two SNS, which takes place in the developed software package, the algorithm can be written as

$$H_x = \begin{bmatrix} -\frac{X^1_{gps}-x_{t\_gps-1}}{prs(l)^{GPS}_{t\_gps}} & -\frac{Y^1_{gps}-y_{t\_gps-1}}{prs(l)^{GPS}_{t\_gps}} & -\frac{Z^1_{gps}-z_{t\_gps-1}}{prs(l)^{GPS}_{t\_gps}} & 1 & 1 \\ -\frac{X^1_{gps}-x_{t\_gps-1}}{prs(i)^{GPS}_{t\_gps}} & -\frac{Y^1_{gps}-y_{t\_gps-1}}{prs(i)^{GPS}_{t\_gps}} & -\frac{Z^1_{gps}-z_{t\_gps-1}}{prs(i)^{GPS}_{t\_gps}} & 1 & 1 \\ - & - & - & - & - \\ -\frac{X^1_{glo}-x_{t\_gps-1}}{prs(l)^{GLO}_{t\_gps}} & -\frac{Y^1_{glo}-y_{t\_gps-1}}{prs(l)^{GLO}_{t\_gps}} & -\frac{Z^1_{glo}-z_{t\_gps-1}}{prs(l)^{GLO}_{t\_gps}} & 1 & 0 \\ -\frac{X^1_{glo}-x_{t\_gps-1}}{prs(k)^{GLO}_{t\_gps}} & -\frac{Y^1_{glo}-y_{t\_gps-1}}{prs(k)^{GLO}_{t\_gps}} & -\frac{Y^1_{glo}-y_{t\_gps-1}}{prs(k)^{GLO}_{t\_gps}} & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_{t\_gps-1} \\ y_{t\_gps-1} \\ z_{t\_gps-1} \\ cdy_{t\_gps-1} \\ cdy'_{t\_gps-1} \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} \hat{x}_{t\_gps} \\ \hat{y}_{t\_gps} \\ \hat{z}_{t\_gps} \\ cd\hat{t}_{t\_gps} \\ cd\hat{t}'_{t\_gps} \end{bmatrix} = (H^T H)^{-1} H^T prs,$$

$$\begin{aligned} x_{t_{gps}} &= x_{t_{gps}-1} + \hat{x}_{t_{gps}}, \\ y_{t_{gps}} &= y_{t_{gps}-1} + \hat{y}_{t_{gps}}, \\ z_{t_{gps}} &= z_{t_{gps}-1} + \hat{z}_{t_{gps}}. \end{aligned} \quad (5)$$

Covariance matrix $\Sigma_{\text{ГСК}} = (H^T H)^{-1}$ carries information about the error of the estimate of coordinates, which takes place at the current mutual geometrical arrangement of the NSC and AC:

$$\Sigma_{GSK} = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} & |\sigma_{X,cdt} & \sigma_{X,cdt'} \\ \sigma_{XY} & \sigma_Y^2 & \sigma_{XZ} & |\sigma_{Y,cdt} & \sigma_{Y,cdt'} \\ \sigma_{ZY} & \sigma_{ZY} & \sigma_Z^2 & |\sigma_{Z,cdt} & \sigma_{Z,cdt'} \\ - & - & - & - & - \\ \sigma_{cdt,X} & \sigma_{cdt,Y} & \sigma_{cdt,Z} & |\sigma_{cdt}^2 & \sigma_{cdt',cdt} \\ \sigma_{cdt',X} & \sigma_{cdt',Y} & \sigma_{cdt',Z} & \sigma_{cdt,cdt'} & \sigma_{cdt'}^2 \end{bmatrix}. \quad (6)$$

To calculate the geometric factors, the Σ_{GSK} matrix, defined in the geocentric coordinate system, must be transformed into the local coordinate system NEH. Designating the matrix block (6),which determines the deterioration of the coordinate determination accuracy as

$$S = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{XY} & \sigma_Y^2 & \sigma_{ZY} \\ \sigma_{ZX} & \sigma_{ZY} & \sigma_Z^2 \end{bmatrix},$$

we write the expression for the covariance matrix in the local coordinate system:

$$\Sigma_{NEH} = \begin{bmatrix} \sigma_N^2 & \sigma_{NE} & \sigma_{NH} \\ \sigma_{NE} & \sigma_E^2 & \sigma_{EH} \\ \sigma_{HN} & \sigma_{HE} & \sigma_H^2 \end{bmatrix} = T_1^T \Sigma_{\text{ГСК}}(3\times 3) T_1. \quad (7)$$

Having determined the Σ_{NEH}, matrix, we can find the corresponding degradation of accuracy for the two-system RI SNS:

geometrical: $GDOP = \sqrt{\sigma_N^2 + \sigma_E^2 + \sigma_H^2 + \sigma_{edt}^2 + \sigma_{edt'}^2}$ (8)

horizontal: $HDOP = \sqrt{\sigma_N^2 + \sigma_E^2}$ (9)

coordinates: $PDOP = \sqrt{\sigma_N^2 + \sigma_E^2 + \sigma_H^2}$ (10)

heights: $HDOP = \sigma_H$ (11)

time: $TDOP = \sigma_{edt}$ (12)

Integration of information from RI SNS and INS occurs in the software block displaying the work of the Kalman filter. The result of the function is an optimal linear estimate of the velocity difference $\Delta\hat{v}_{t\_gps}$.

The predicted velocity difference vector dVp is calculated by the method of numerical integrated one into the equivalent value of the predicted divergence of the coordinates of the PI SNS and INS.

The next step in the algorithm for monitoring the integrity of the SNS and assessing the correct operation of the INS is the calculation of the pseudoranges Rins to the NSC of the working constellation based on the current navigation information of the INS.

After calculating the threshold for detecting and localizing anomalous measurements, the vector of pseudorange residuals is formed, measured in the SNS and calculated on the basis of the INS navigation definitions. Next, the vector of residuals is transmitted as an input parameter and the following possible solutions are made:

- The decision on the presence of an anomalous measurement in the vector of measured pseudoranges RI SNS.
- The decision to detect the malfunction of the INS.

The considered software package allows you to simulate a failure in the INS directly in the simulation process by entering an additional x_e^{HHC} error into the INS coordinate vector:

$$\begin{aligned} \phi_{t_{gps}}^{INS} &= \phi_{t_{gps}}^{INS} + \phi_e \\ \lambda_{t_{gps}}^{INS} &= \lambda_{t_{gps}}^{INS} + \lambda_e. \end{aligned}$$

At the final stage, the current parameters of the studied algorithm are output to the information console. At the next time point t_gps2, if the sign of completion of the simulation is not established, a new cycle of calculations begins in the sequence described.

V. Conclusions

In order to determine the effectiveness of the proposed algorithm [13], a project of an applied software complex was developed that allows performing a full cycle of modeling the operation of an algorithm at a given AC flight stage using the orbital parameters of the existing SNS groupings, as well as experimental navigation definitions of the SNS and INS receiver and indexer, registered during the AC flights.

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