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METHOD OF DETERMINING THE ACCURACY CHARACTERISTICS OF THE SATELLITE NAVIGATION SYSTEM

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Abstract**—***The key actions for the implementation of the global navigation satellite systems are described in this article. At the testing stage, the conformity of the system with the operating standards is established, its accuracy characteristics are proved, the temperature of the control bodies and the units are measured, in addition, the composition of the aircraft explores the electromagnetic compatibility of the navigation satellite systems with the equipment of the aircraft.Failure to recognize the deficiencies at the testing stage will lead to significant economic losses in the implementation and refinement of already certified fleet of aircrafts, and worsening of safety flights. Therefore, it is very important to consider all the factors that may affect the work of the system, such as: the temperature of the outside air, the position of the aircraft in space, the connection of the navigation satellite systems with the equipment of the aircraft with partial and complete failure of this equipment, etc. The main but not the only parameter of the navigation satellite systems is precision characteristics, which together with the precise characteristics of manual or automatic control of the aircraft, allow us to meet the requirements of the concept of zonal navigation, which greatly expands the technical capabilities of the aircraft. Therefore, the article pays special attention to the precision characteristics of the navigation satellite systems, methods for increasing the accuracy of statistical analysis of data by: 1) the method of maximum likelihood or nonlinear least squares; 2) the method of simultaneous determination of state variables and Kalman filtration parameters and nonlinear estimation.*

Index Terms—Navigation systems; exact characteristics; concepts of area navigation; horizontal separation.

I. INTRODUCTION

The global navigation satellite systems (GNSS) benefit aviation by enabling aircraft to fly direct from departure to destination using the most fuel-efficient routes and to navigate complicated terrain at low altitude. Satellite navigation provides the flexibility to design new procedures that enable aircraft to fly closer together to increase the arrival and departure rates and fly continuous climb and descent operations to minimize fuel consumption, noise, and carbon emissions. Using the language of the aviation community, GNSS enables performance-based navigation, which consists of area navigation (RNAV) and required navigation performance (RNP). Both RNAV and RNP enable unrestricted point-to-point flight paths. RNP differs from RNAV, because it also provides a monitoring and alerting function to warn the pilot when a correction is required, enabling aircraft to fly tighter flight paths. GNSS is the only navigation source approved for RNP operations.

Testing procedures comprise an important element in the development, manufacturing, and integration of GNSS devices. Essentially, everybody involved in GNSS will be involved in or affected by testing at one time or another.

Global Navigation Satellite System that is used for certification of aircraft process navigation systems includes a set of accurate tests. Flight test is an integral part of certification of navigation systems.

Satellite navigation systems (SNS) testing of the aircraft establish stability at receiving satellite data that contain the maximum operating values of the roll and pitch, system availability failures partially of both the SNS and the systems that affect its operation.

That is why; test is incredibly complicated, multi-stage process, which includes stages of in-flight (flight) tests, half-test (bench) tests and statistical modeling.

Multi-stage process of tests, planning and organization might be considered satisfactory for each subsequent stage of the tests if it confirms the results of the previous stage. Empirical evidence for test conformity and correctness of test stages, allows using experimental information obtained at all stages in order to enforce compliance with requirements set of the experimental information.

Thus, volume testing can be determined according to required reliability of results and degrees of their adequacy.

According to volume flight testing, its accuracy and reliability one can elaborate the required volume testing, semi-natural stands, math modelling.

The statistical and natural modeling cannot give a complete assessment of SNS in general, though it provides actual information about the system. Precise assessment could be given only after specialized flight testing as the structure – 'aircraft – devices – pilot – environment' has a great amount of factors hard to simulate. The hardest thing to do is stimulating such complex segment as "pilot".

Thatis why; ergonomics and manual mode testing are carried out by six pilots. They give assessment of the simplicity and convenience of system control, intelligibility of the information that system induces the recognition of various failures during takeoff.

To determine the accuracy of the SNS, the aircraft is equipped with a trajectory measurement system. This system, in combination with ground control station, gradually produced positioning accuracy up to 3 ft. which makes it possible to determine the true value of lateral vibration parallel to a line across specified path.

II. Problem Statement

The model will be used to evaluate the likelihood that an aircraft remains within a containment volume based on lateral, vertical, and along-track position error data. An important aspect of the containment modeling is the nature of the random variation in TSE, NSE, and FTE. The frequency and magnitude of these errors, measured as the aircraft moves along its route, influences the likelihood estimate that the aircraft remains in the containment volume for a prescribed confidence interval. The errors are measured in three-dimensional space such that there is an along-track error, a horizontal position error taken perpendicular to the track heading (i.e., the lateral error), and a vertical error taken perpendicular to the altitude profile at a position on the route. The FTE for a set of B747 simulations were analyzed, where the FTE is the difference between the indicated position and desired route (RTCA, 2002). The NSE is the difference between the actual and defined routes and the TSE is a combination of the FTE and NSE.

The statistical analysis of the FTE provides important information for the containment surface modeling because FTE is typically larger than NSE. Therefore, it is necessary to accurately characterize the probability density function and the parameter estimates for the FTE. Inappropriate analysis can lead to the overestimation of the required containment surface dimensions, which is inefficient. The underestimation of containment surface dimensions given a stipulated probability causes unsafe conditions.

The statistical analysis is more accurate with an adequate sample size, the correct use of analysis techniques, and suitable probability density functions (pdfs), such as Johnson curves. The Johnson curves can be used to model FTE data, which typically are skewed and which have more mass under the distribution tails than a normal distribution. The selection of the Johnson curve is guided by an algorithm (Hill et al., 1976) based on the sample estimates from the data set. These estimates become more accurate given larger sample sizes. The sample size for analysis can be increased if the lateral and vertical data are uncorrelated (i.e., cross-correlation) and the use of marginal data can be avoided [16].

III. Main Part

A. *Stages of exact characteristics analysis*

There are three groups of the methods of exact characteristics. They are experimental, analytical and staticmodeling. The last two groups are being joined by general concept of modeling.

B. *Navigation Performance Analysis Procedure*

Monte Carlo simulations were performed for each formation to quantify the expected distribution in the absolute andrelative solution errors as a function of variations in the random measurement errors. The following ensemble errorstatistics were accumulated for the ensemble of navigation solutions obtained by processing 25 sets of simulatedGlobal Positioning System (GPS) pseudorange measurements that were created by varying the random number seeds used for the GPS ephemerisand clock, receiver clock, and random measurement errors:

– The ensemble RMS/maximum error, which is the RMS/maximum of the true error (difference betweenthe estimated and the true state) at each time computed across all Monte Carlo solutions.

– The steady-state time-wise ensemble RMS/maximum error, which is the RMS/maximum of theensemble true errors computed along the time axis, omitting the initial convergence period.

– The extended Kalman filter algorithm available in the GEODE flight software was used to process thesemeasurement sets. The filter was "tuned" by adjusting the process noise parameters and measurement standarddeviation to produce an estimated state error root variance that was consistent with the ensemble RMS state errorobtained in the Monte Carlo analysis. Table 3 lists the GEODE processing parameters common to all cases.

Atmospheric drag and solar radiation pressure forces were included in the state propagation using atmospheric dragand solar radiation pressure coefficients that were offset by 10 percent and 5 percent respectively from the valuesused in the truth ephemeris generation.

The absolute navigation errors were computed by differencing the truth and estimated absolute state vectors. Theestimated relative state vectors were computed by differencing the estimated absolute state vectors for the twosatellites. The relative navigation errors were computed by differencing the true relative state vectors and theestimated relative state vectors. Static modeling stage consists of realization of the dynamic model within computer or analog-digital complexesin the conditions of the action of random influences, multiple modeling of the system and the subsequent processing of the solutions for obtaining probability characteristics of ccoordinate system.

Monte Carlo Statistical Method is a universal method of statistical modeling. Advantages of the method of statistical modeling; a wide range of statistical material possibilities, the flexibility of test conditions, priori probability and fair value less cost to realize results are but a few of the factors that make it one of the basic accuracy analysis of SNS.

This does not mean that the statistical modeling is the only method for the proof of accuracy. Full compliance with the actual operating conditions, high accuracy and reliability of the results can be achieved only on the basis of pilot experiment.

Consequently, the analysis and certification process ends with a phase of system pilot tests and confirm results of modeling [15].

An important aspect of modeling is to develop experiment planning models. This stage includes a range of modeling techniques, coherence process, the required rate of testing, modeling results and pilot test. The optimal solution for these problems is to minimize the cost of temporary, material and human resources in order to achieve the goal of model restrictions. Research properties of disturbance influences are one of the major issues to be solved at this stage. A large range of variation factors, those affecting the determination of accuracy test leads to heterogeneous experimental data content. This seriously complicates the ability to use classical mathematical statistics methods for accuracy processing and evaluation of SNS. In some cases different shape forms of distributed processing modeling results may be incorrect or just wrong.

For this reason, application of mathematical experiment planning methods makes possible to point out homogeneous groups (factor complex) powerful features models of external conditions that apply in the factorial space. Distribution law belongs to a number of selective values of the output coordinate system.

The solution of the problem is based on the methods of dispersion and factor analysis and experiment planning.

The factorial space of powerful features that is divided into homogeneous groups and accuracy assessment of SNS must be performed separately for each group. Accuracy evaluation of the process is presented as a function of powerful features complexes. If probability of occurrence of such factors in airports is known, the accuracy model can be obtained by using total probability formula.

C. Flight Test Stage

Satellite navigation systems testing is carried out in exploitation of real estate with subsystems interaction of the object and the impact of environmental factors complex.

Determination of particular characteristics of mathematical statistics methods are made on the basis of experimental data output coordinates.

The confirmation of the hypothesis adequate for output coordinated distribution for SNS accuracy analysis builds upon the parametric methods of determination of the accuracy characteristics automatic landing process analysis and accuracy of onboard systems of flight automatic control tests [15].

Consequently, one should use integral methods. On the basis of the theory, a probability is depicted by P = 0.96 with a confidence probability 0.9. It is necessary to conduct n_0 = 3x106 tests in the absence of outputs for tolerance or n_1 = 4.76x106 tests with one output. At y = 0.99, these volumes are respectively n_0 = 5.3x106 and n_1 = 7.43x106 landings. Real time volume testing may always be achievable. Consequently, a full-scale experiment cannot be established on the basis of accuracy characteristics statistics.

D. Flight Data Processing methods

While processing Flight Data one should exclude regular traps from the trajectory parameters of the aircraft, especially this is important for the parameters that is used to configure general parameters of calculation in the power dependence; then a slight error of one parameter will essentially affect the result of the calculation. We consider two methods:

1) Method of maximum likelihood or nonlinear least squares.

2) The method of simultaneous determination of state variables and parameters of Kalman filtering and nonlinear estimation.

Equation of motion for the center of mass is given by (Axe Connected).

$$\frac{dV_x}{dt} = \omega_z V_y - \omega_y V_z + g\left(n_x - \sin\vartheta\right). \quad (1)$$

$$\frac{dV_y}{dt} = \omega_x V_z - \omega_z V_x + g\left(n_y - \cos\vartheta\cos\gamma\right). \quad 2)$$

$$\frac{dV_z}{dt} = \omega_y V_x - \omega_x V_y + g\left(n_z - \cos\vartheta\sin\gamma\right). \quad (3)$$

Euler kinetic relation

$$\frac{d\vartheta}{dt} = \omega_y \sin\gamma + \omega_z \cos\gamma, \quad (4)$$

$$\frac{d\psi}{dt} = \cos^{-1}\vartheta\left(\omega_y \cos\gamma + \omega_z \sin\gamma\right), \quad (5)$$

$$\frac{d\gamma}{dt} = \cos^{-1}\vartheta\left(\omega_y \cos\gamma + \omega_z \sin\gamma\right). \quad (6)$$

There may be other kinematic relations according to appropriate dimensions, such.

$$\frac{dH}{dt} = V_x \sin\theta + V_y \cos\theta\cos\gamma - V_z \cos\theta\sin\gamma, \quad (7)$$

$$\alpha = \vartheta - \theta, \quad \sin\alpha = -\frac{V_y}{\sqrt{\left(V_x^2 + V_y^2\right)}}, \qquad \sin\beta = -\frac{V_z}{\sqrt{\left(V_x^2 + V_y^2 + V_z^2\right)}}. \quad (8)$$

Equations V_x, V_y, V_z are projection of motion for the center of mass; n_x, n_y, n_z is the multi-weight vector projection; ω_y, ω_z, ω_x is the projection of aircraft angular-velocity vector; ϑ, ψ, γ are angles of pitch, course, roll; H is the height; α, β are angles of attack and yaw. According to Klein, all variables are divided into two groups: one – conventionally called a group of variables “state”, the other – conventionally called a group of variables “management”. Projection of angular-velocity and multi-weight vector projection are given in the text above by control variables ω_y, ω_z, ω_x, n_x, n_y, n_z. The measurement model is taken as $z = (1+k)x + \Delta + \eta$. Different methods are used for different variables. Therefore, it is proposed that variables “management” measures with additive systematic error and additive noise.

$$\bar{\omega}_x = \omega_x \Delta_{\omega_x} + \eta_{\omega_x}, \quad \bar{n}_x = n_x \Delta_{n_x} + \eta_{n_x}, \quad \bar{\omega}_y = \omega_y \Delta_{\omega_y} + \eta_{\omega_y}, \quad \bar{n}_y = n_y \Delta_{n_y} + \eta_{n_y},$$
$$\bar{\omega}_z = \omega_z \Delta_{\omega_z} + \eta_{\omega_z}, \quad \bar{n}_z = n_z \Delta_{n_z} + \eta_{n_z}, \quad (9)$$

where $\eta_{\omega x}$, $\eta_{\omega y}$, $\eta_{\omega z}$, η_{nx}, η_{ny}, $\eta_{nz}$are assuming white Gaussian noises which are not correlated with each other. It is assumed according to state variables that their measurement models are given by

$$\bar{V} = \left(1 + k_V\right)\sqrt{V_x^2 + V_y^2 + V_z^2} + \Delta_V,$$

$$\bar{\alpha} = -\left(1 + k_\alpha\right)\arcsin\frac{V_y}{\sqrt{V_x^2 + V_y^2}} + \Delta_\alpha,$$

$$\bar{\beta} = -\left(1 + k_\beta\right)\arcsin\frac{V_z}{\sqrt{V_x^2 + V_y^2 + V_z^2}} + \Delta_\beta, \quad (10)$$

$$\bar{H} = \left(1 + k_H\right)H, \qquad \bar{\vartheta} = \left(1 + k_\vartheta\right)\vartheta + \Delta_\vartheta,$$

$$\bar{\gamma} = \left(1 + k_\gamma\right)\gamma, \qquad \bar{\psi} = \left(1 + k_\psi\right)\psi.$$

These formulas characterized by absence of error related to the measurement signal delay. Although, it is known that delay can be significant at speed changing V. We make assumptions that ΔH i $\Delta\psi$ equals zero because any starting point is set arbitrarily.

Substituting the equations (1) – (6) with values ω_z, ω_z,ω_x, n_x, n_y, n_z expressed by formulas (9), state variables expressed by measurements and unknown measurement errors, equation (1) – (6) formally becomes a nonlinear stochastic differential equation. To obtain grades in Klein’s papers and others, the technique of maximum likelihood, or the technique of an extended nonlinear Kalman filtering is used. The weak link between stated methods is feeling of unsureness about static characteristics (dispersions) of the noise components η_i, particularly relating to formulas (9).

Algorithms of the aircraft dynamic and kinematic motion parameters based on aperiodic link types (1) – (8), can be called algorithms of coordinate measuring of results with existing kinetic constraints. In Figure 1 is showed the results of the coherence of some parameters of the longitudinal motion according to one of the medium-haul aircraft operation modes.

The arrays of pitch ϑ, angular velocity ω, measuring speed deviceV_{dev}, attack angle α, overloads n_x, $n_y$registered by onboard measurement system, were taken as output arrays. Well-specified consistent arraycan be competed witharrays obtained by direct integration according to measurement data. The solid lines indicate the output (uncoordinated) results of measurement. Assessment of the pitch ϑ

was obtained by integrating the longitudinal equation where overload and angular velocity are considered as "management" [15].

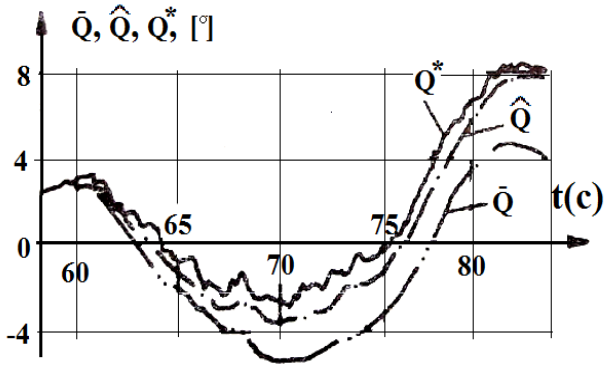

Fig. 1. Results of the coherence of some parameters of the longitudinal motion according to one of the medium-haul aircraft operation modes

Free distribution methods remove limitations of adequacy, but such criteria (especially fast-track criteria) has very little power, in comparison to/with parametric methods. A rational approach to solving the problem of choosing a processing method is as follows. In accordance to well-known criteria (Kolmogorov–Smirnov), the hypothesis of the adequacy of the law of PC source coordinates distribution is performed under selected complex of external influences.

Methods that meet the accurate analyses of hypothesis of normality with selective data are good for accuracy analysis, like that presented at our work. It is indeed unreasonable to expect methods of normal theory to maintain their efficiency under methods free of distributions in case of rejection of hypothesis of normality [15]. It is necessary to use asymptotic and nondistributional methods taking into account possibilities of statistical modeling method in the set of statistical material. Possible consequences of deviations from normality hypothesis for solving the problem of modeling processing results and accuracy analyses according to flight control system criteria can be concluded as follows.

A mistaken assumption of normality of the distribution typically assumed to be dissimilar in different tasks [15]. Deviations from normality on distribution "tails" to some extent have not a strong influence on hypothesis significance criteria. For example, rejection of the hypothesis on the significance level equal to 0.001 is not able to influence the quality of statistical conclusions. Important to admit that adequate distribution provides a center reasonable approximation for number of random variables, but it is not suitable for large deviations values.

IV. Conclusion

Conditions of the work of dynamical systems are themselves still not completely known, at least part of the impact cannot be determined in advance. At the same time it is possible to obtain not precise description of motion, but only general Laws of Probability. Hence, regularities which happen not in each exact event but in a set amount of events should be described statistically. Then influence which is a set of valued probability measure is given as a random process. Statistical characteristics should be followed by multiple realization traced to averaging and information relating to the reserved characteristics for its future use.

That is, the initial data must be taken for the same range of external conditions changes. The system should work without "reformation" (the general scope of the sample that is used for statistics should coincide with the general scope of decisions they are based on). In fact, it is almost impossible to hope that there will always be an item in a range that matches external conditions changes; obtain the initial data, and evolve these data to statistical processing.

Flight tests provide information about the behavior of the system in conditions and are likely to be duplicated close to the conditions of real operation, however, they cannot yet copy them completely. Unfortunately these tests comes with a number of potential disadvantages, which affects the accuracy of the estimates because of conditions difficult to regulate. It is useful to spend some time studying materials and results of similar studies at the preparation stage.

Particular attention should be paid to an analysis of all the capabilities of the material base. Its compliance with the necessary conditions and resources which should ensure the possibility of recording tests results with the necessary accuracy of their measurements.

Calculation and analysis of flight data to exclude systematic errors should be followed by Method of maximum likelihood, nonlinear least squaresor Kalman filtering.

In this process, particular attention should be given to analyzing parameters where a minor error affects the result of calculationsignificantly.

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Д. О. Шевчук, М. П. Кравчук, Л. В. Пунчук, С. М. Гальченко. Методика визначення точнісних характеристик системи супутникової навігації
В статті описано ключові етапи випробування системи супутникової навігації, які є завершальним і водночас відповідальним етапом розробки ситеми. На етапі випробувань встановлюється відповідність ситеми діючим нормам, доказується її точностні характеристики, ергономіка, заміряється температура органів керування та блоків, додатково, в складі літака досліджується електромагнітна сумістність системи супутникової навігації з обладнанням літака. Невиявлення недоліків на етапі випробування призведе до значних економічних втрат при внесені доопрацювань у вже сертифікований парк літаків, та погіршеню безпеки польотів. Тому дуже важливо

врахувати всі фактори які можуть вплинути на роботу ситеми таких як: температура зовнішнього повітря, положення літака в просторі, зв'язок системи супутникової навігації з обладнанням літака при частковій та повній відмові даного обладнання тощо. Основним але не єдиним параметром системи супутникової навігації є точностні хараетристики, які в сукупності з точностними характеритсиками ручного або ж автоматичного пілотування, дозволяють відповідати вимогам концепції зональної навігації, що значно розширює технічні можливості літака. Тому в статті особливу увагу приділено точностним характеристикам системи супутникової навігації а саме методам підвищення точності статистичного аналізу даних на прикладі: 1) методу максимальної правдоподібності або нелінійних найменших квадратів; 2) методу одночасного визначення змінних стану та параметрів фільтрації Калмана та нелінійного оцінювання.
Ключові слова: навігаційні системи; точністні характеристики; концепція навігації; горизонтальна навігація.

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Д. О. Шевчук, Н. П. Кравчук, Л. В. Панчук, С. Н. Гальченко. Методика определения точностных характеристик системы спутниковой навигации

В статье описаны ключевые этапы испытания системы спутниковой навигации, которые являются завершающим и одновременно ответственным этапом разработки ситемы. На этапе испытаний устанавливается соответствие системы действующим нормам, доказывается ее точностные характеристики, эргономика, замеряется температура органов управления и блоков, дополнительно, в составе самолета исследуется электромагнитная совместимость системы спутниковой навигации с оборудованием самолета. Невыявления недостатков на этапе испытания призведет к значительным экономическим потерям при внедрениии доработок в уже сертифицирован парк самолетов, и ухудшения безопасности полетов. Поэтому очень важно учесть все факторы, которые могут повлиять на работу ситемы таких как: температура наружного воздуха, положение самолета в пространстве, связь системы спутниковой навигации с оборудованием самолета при частичном и полном отказе данного оборудования и т.п.. Основным но не единственным параметром системы спутниковой навигации является точностные хараетристики, которые в совокупности с точностными характеритсиками ручного или автоматического управления самолетом, позволяют соответствовать требованиям концепции зональной навигации, что значительно расширяет технические возможности самолета. Поэтому в статье особое внимание уделено точностным характеристикам системы спутниковой навигации а именно методам повышения точности статистического анализа данных на примере: 1) метода максимального правдоподобия или нелинейных наименьших квадратов; 2) метода одновременного определения переменных состояния и параметров фильтрации Калмана и нелинейного оценивания.
Ключевые слова: навигационные системы; точностные характеристики; концепция навигации; горизонтальная навигация.

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