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Integrated Positioning System With Restricted Access to Navigation Satellite Signals

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Abstract – **Global satellite navigation system (GNSS) is by far the most cost-effective outdoor positioning technology currently available and used for many types of applications. In some cases a user may face difficult conditions, like restricted access to the navigation satellites due to natural or man-made phenomena. This paper presents an idea of an integrated positioning system capable of functioning under limited visibility conditions of navigation satellites. The system includes a digital antenna array, channels for converting radio navigation signals, a phase difference meter, a gyro platform with 3 gyros, an altimeter and a special calculator. With the help of mathematical modeling, the accuracy characteristics of the system are investigated by determining the coordinates of the carrier under conditions of a small number of available satellite signals.**

Keywords – **Accuracy estimation, antenna array, global navigation satellite systems (GNSS), height measurements, inertial navigation system (INS), measurements, navigation satellite, phase difference.**

I. INTRODUCTION

Global satellite navigation system (GNSS) is by far the most cost-effective outdoor positioning technology currently available and used for many types of applications, each requiring different quality. According to [1], those applications are grouped into three macro segments: mass market solutions (different Location Based Services, information services in transport systems, entertainment purposes, etc); transport safety and liability-critical solutions (Aviation and Drones, Road, Rail) [2], [3]; high precision (like agriculture, surveying and maritime), timing and asset management solutions. The type of technology used depends on the user's needs and the desired service level. Depending on this, the following key features of GNSS receivers are typically considered: supported GNSS constellations, frequencies and signals, augmentation systems; complementary technologies in use; size, weight, power consumption, etc. [4].

The development of navigation aids is currently associated not only with the increase in the accuracy and accessibility of relevant services, but also with the expansion of spheres and areas of their application in difficult conditions. It applies to navigation in conditions of limited visibility of satellites or its complete absence, for example, in a city, mountains and enclosed spaces, underground or under water. In addition, the issue of object navigation at large distances from our planet, in particular, on the Moon [5] is considered.

Due to the nature of GNSS, where signals are received with very low power level, these systems are vulnerable to either natural (like ionospheric scintillations) or man-made (like different radio interferences) phenomena that may severely disrupt their operation – up to partial or total interruption of service [4]. One of the ways to mitigate jamming influence is to use array-antennas and corresponding array processing algorithms. This approach is investigated in the given paper.

II. ANALYSIS OF THE LATEST RESEARCHES AND PUBLICATIONS

This paper addresses the problem of determining position under restricted visibility of Navigation Satellites. There are numerous ways of doing it depending on different applications.

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One of the approaches widely used in such situations is the development of corresponding technologies in navigation equipment to be capable of simultaneous reception of existing and upcoming GNSS constellations (so-called “multi-constellation GNSS receivers”), as it has been described in [6]. Indeed, with the increasing number of GNSS satellites (GPS, GLONAS, GALILEO, BeiDou) in the sky in the past decade, the market continues to develop towards fully flexible, multi-constellation GNSS receivers for the mass market [4]. According to study [4], the most common combination remains GPS+GLONASS, followed by GPS+GALILEO, though there are a lot of their variations, including additional signals, like BeiDou in [7] and [8], Japanese Quasi-Zenith Satellite System (QZSS) and SBAS in [9], etc.

Another approach is to additionally (or instead) use the signals from pseudo satellites, as it is described in [10]–[13] and GNSS signal retranslation [14].

However, the above considered methods and approaches require sufficient costs and efforts for their implementation, therefore another approach using antenna array as a basis is investigated in this paper.

III. Problem Statement

The analysis of recent GNSS application development showed that airborne aircraft equipment often contains several navigation antennas and antenna arrays in particular.

The research proposed in this paper is based on the approach described in the monograph [15], in which the antenna array was rigidly installed on the carrier and aligned with its own body-fixed reference frame. Having determined aircraft geographical coordinates and measured navigation signal phase difference on four-element antenna array, it is possible to solve the task of aircraft attitude determination in Earth Centered Earth Fixed (ECEF) coordinate system.

The development of this approach allowed to solve the task of detecting the coordinates of space debris (or other observed objects) by using a laser rangefinder rigidly installed on the space service vehicle [16].

This paper addresses the task of designing and investigating the integrated positioning system with a modernized version of a device for determining attitude [15] with the elements of an inertial navigation system (rate gyros) and an altimeter.

IV. Integrated Positioning System Structure

The structure of the integrated positioning system is presented in Fig. 1.

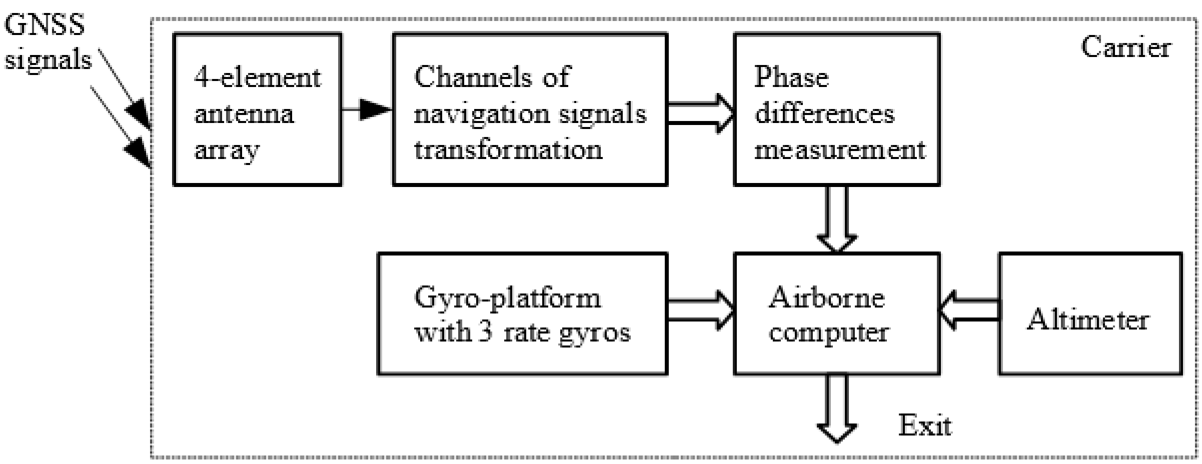

Fig. 1. Structure of the integrated positioning system.

Signals from navigation satellites are received by 4-element antenna array, processed in transformation channels into digital quadrature readings and fed to the phase difference measurement process. The measured phase differences of antenna array signals, the readings of 3 rate gyros and altimeter are sent to the airborne computer. Here the integrated positioning system carrier Cartesians coordinates are calculated with the help of appropriate software.

V. Mathematical Model

Let us introduce some designations first: e_X, e_Y, e_Z – Euler angles between own body-fixed and ECEF coordinate frames; α, β, γ – Euler angles between own body-fixed and topocentric coordinate frame. The relations between the angles are the following:

$$\alpha = e_X - \frac{\pi}{2} + B;$$
$$\beta = e_Y; \tag{1}$$
$$\gamma = e_Z - \frac{\pi}{2} - L;$$

where B – geographic latitude, L – geographic longitude.

According to [15], the relation between Euler angles e_X, e_Y, e_Z and phase differences is defined by the following equation:

$$\boldsymbol{d}_{m,j} = l_m \left(\bar{\boldsymbol{r}}_j^{ECEF}\right)^T \boldsymbol{U}x(e_X)\boldsymbol{U}y(e_Y)\boldsymbol{U}z(e_Z)\bar{\boldsymbol{l}}_m^b, \tag{2}$$

where

l_m – length of line between antenna array elements;

$\bar{\boldsymbol{r}}_j^{\mathrm{ECEF}}$ – directing vector of line between j-th satellite and GNSS receiver in ECEF coordinate frame;

$\boldsymbol{U}xI(e_X)$, $\boldsymbol{U}y(e_Y)$, $\boldsymbol{U}z(e_Z)$ – rotation matrices;

$\bar{\boldsymbol{l}}_m^{\mathrm{b}}$ – directing vector of m-th line of antenna array in body-fixed coordinate frame;

m – number of line between antenna array elements;

j – number of observed satellite.

The iterative algorithm of attitude (vector $\boldsymbol{\psi} = (\alpha, \beta, \gamma)^{\mathrm{T}}$) determination obtained by using maximum likelihood method looks as follows:

$$\hat{\boldsymbol{\Psi}}_k = \hat{\boldsymbol{\Psi}}_{k-1} + \left(\boldsymbol{H}_{k-1}^T\left(\hat{\boldsymbol{\Psi}}_{k-1}\right) \cdot \boldsymbol{H}_{k-1}\left(\hat{\boldsymbol{\Psi}}_{k-1}\right)\right)^{-1} \cdot \boldsymbol{H}_{k-1}^T\left(\hat{\boldsymbol{\Psi}}_{k-1}\right) \cdot \boldsymbol{D}_n^{-1} \cdot \left(\boldsymbol{y}_d - \boldsymbol{h}\left(\hat{\boldsymbol{\Psi}}_{k-1}\right)\right) \tag{3}$$

where

$$\boldsymbol{H}_{k-1}\left(\hat{\boldsymbol{\Psi}}_{k-1}\right) = \frac{\partial \boldsymbol{h}\left(\hat{\boldsymbol{\Psi}}_{k-1}\right)}{\partial \boldsymbol{\Psi}};$$

$$\boldsymbol{h}(\boldsymbol{\Psi}) = \left| \begin{array}{c} l_1 \left(\bar{\boldsymbol{r}}_1^{ECEF}\right)^T \boldsymbol{U}x\left(\alpha + \frac{\pi}{2} - B\right)\boldsymbol{U}y(\beta)\boldsymbol{U}z\left(\gamma + \frac{\pi}{2} + L\right)\bar{\boldsymbol{l}}_1^b \\ \vdots \\ l_M \left(\bar{\boldsymbol{r}}_1^{ECEF}\right)^T \boldsymbol{U}x\left(\alpha + \frac{\pi}{2} - B\right)\boldsymbol{U}y(\beta)\boldsymbol{U}z\left(\gamma + \frac{\pi}{2} + L\right)\bar{\boldsymbol{l}}_M^b \end{array} \right|.$$

To solve the inversed task, i.e. geographical coordinate determination, it is necessary to accept that $\boldsymbol{\psi} = (B, L)^{\mathrm{T}}$ and correspondingly transform matrix $\boldsymbol{H}(\boldsymbol{\psi})$. Then using equation (1), B, L are determined.

With the help of additional altimeter measurements and the known relations [17], it is possible to determine the Cartesian coordinates of the integrated positioning system carrier:

$$X = (v+h)\cdot\cos B\cdot\cos L;$$
$$Y = (v+h)\cdot\cos B\cdot\sin L; \qquad (4)$$
$$X = \left(v\left(1-e^2\right)+h\right)\cdot\sin B,$$

where $v = a \Big/ \sqrt{1-e^2\left(\sin B\right)^2}$, $e^2 = 2f - f^2$, $f = \dfrac{a-b}{a}$, and *a*, *b* – are big and small semi-axes of the ellipsoid in WGS-84 or PZ-90 coordinate systems (depending on the one used in the positioning system).

VI. Results of Mathematical Modeling

The model is represented as software in the Mathcad environment. It allows performing statistical studies of the spherical error in *B* and *L* determination, depending on errors in phase difference measurements and in height measurements under different numbers of observed navigation satellites (NS). Errors are specified as normally distributed random numbers with the following parameters: $m_g = 0$ and σ_g for GNSS phase difference measurements, $m_h = 0$, σ_h for height measurements. Averaging was performed for 1000 implementations.

The following input data was used for simulation: real coordinates of 10 navigation satellites in ECEF obtained from the navigation receiver at some fixed moment of time; height and geographical coordinates of the carrier. Then the following parameters were varied during simulation activities: number of navigation satellites observed and used in the solution; errors magnitudes in GNSS phase difference measurements and height measurements by altimeter.

The dependence of geographical coordinate determination spherical error (mathematical expectation and standard deviation) on the number of observed (and used in solution) navigation satellites under phase difference measurement errors set as $\sigma_g = 1.0°$ and $\sigma_g = 0.1°$ correspondently is presented in Table I.

TABLE I

Dependence of Spherical Error on the Number of Observed Navigation Satellites

σ_g,	**NS**	**1**	**2**	**3**	**4**	**5**	**10**
1.0°	m_θ, rad	5.7	$1.0 \cdot 10^{-3}$	$5.0 \cdot 10^{-4}$	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$
	σ_θ, rad	5.9	$6.5 \cdot 10^{-4}$	$3.2 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
0.1°	$m_{\theta 1}$, rad	$3.9 \cdot 10^{-3}$	$1.0 \cdot 10^{-4}$	$5.0 \cdot 10^{-5}$	$4.4 \cdot 10^{-5}$	$4.2 \cdot 10^{-5}$	$2.3 \cdot 10^{-5}$
	$\sigma_{\theta 1}$, rad	$2.9 \cdot 10^{-3}$	$6.9 \cdot 10^{-5}$	$3.0 \cdot 10^{-5}$	$2.6 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$

The dependence of geographical coordinate determination spherical error (mathematical expectation and standard deviation) on the difference measurement error (standard deviation σ_g) for three cases of navigation satellite number (2, 3 and 4 NS) used in the solution is presented in Table II and Fig. 2. Black solid lines designate here the mathematical expectations of spherical error of geographical coordinates determination, and dashed lines – standard deviations.

TABLE II

DEPENDENCE OF SPHERICAL ERROR ON PHASE DIFFERENCE MEASUREMENT ERROR

# NS	**σ_g, deg**	**0.010**	**0.050**	**0.075**	**0.100**	**0.200**	**0.500**
2	m_{X2}, m	62	313	476	620	1230	3100
	σ_{X2}, m	44	212	340	430	860	2150
3	m_{X3}, m	29	142	213	290	588	1480
	σ_{X3}, m	19	89	139	189	370	930
4	m_{X4}, m	26	134	192	282	527	1297
	σ_{X4}, m	16	85	124	170	347	828

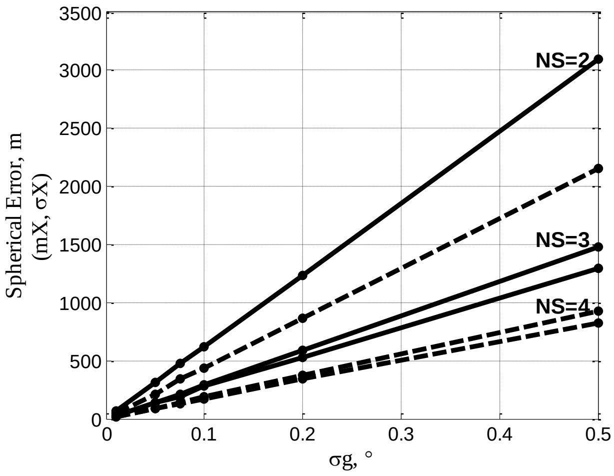

Figure 2 – Dependence of geographical coordinates determination spherical error on the phase differences measurements error under different quantities of navigation satellites.

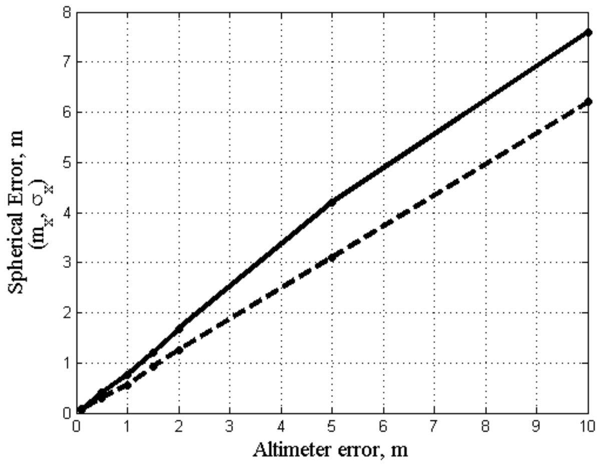

Figure 3 – Dependence of geographical coordinates determination spherical error on the altimeter measurements error.

The dependence of geographical coordinate determination spherical error (mathematical expectation and standard deviation) on the altimeter measurement error (standard deviation σ_g) under the condition that only two navigation satellites were used in the solution and a phase difference measurement error was absent is presented in Table III and Fig. 3. Designations for the Fig. 3 are the same as for Fig. 2.

TABLE III

DEPENDENCE OF SPHERICAL ERROR ON ALTIMETER MEASUREMENT ERROR

σ_h, m	**0.1**	**0.5**	**1.0**	**1.5**	**2.0**	**5.0**	**10.0**
m_X, m	0.08	0.40	0.77	1.20	1.68	4.20	7.60
σ_X, m	0.06	0.30	0.56	0.92	1.25	3.10	6.20

The research shows that the dependence of spherical error in *B* and *L* determination on the errors in GNSS phase difference measurements and altimeter height measurements is directly proportional. It follows from the presented algorithm of calculations and results of simulations.

VII. CONCLUSION

The performed simulations have shown that the proposed integrated positioning system can be operable when receiving signals from at least 2 navigation satellites. The main issue here is to ensure the accuracy of the phase difference measurements of the signals received by 4-element antenna array. Thus, with a root mean square (RMS) error of phase difference measurements 0.1° and received signals from no more than 3 satellites, the error of linear coordinate determination is about 200 m to 400 m, which is quite high.

The altimeter error is less significant and contributes in a directly proportional way to the spherical error of linear coordinate determination.

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