Application of Parallel Technologies in Navigation Management under the Conditions of Artificial Ionospheric Disturbances

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Abstract: The purpose of this research is to reduce the user positioning errors when utilizing satellite radionavigation systems under the conditions of artificial ionospheric disturbances in the propagation path of navigation radiofrequency signals (NRS). In the event of severe ionospheric disturbances, navigation radiofrequency signals will lead to multiple increases in the pseudo-range measurements error of the relevant navigation satellites (NS). The paper presents an algorithm developed for secondary processing of navigation data, enabling to reduce the positioning error due to multiple pseudo-range measurements in the presence of local region of increased ionization (RII) within the selected operational constellation of navigation satellites. To provide a secondary signal processing on a real time basis, it is proposed to use parallel computing, in particular, residue number system (RNS). Parallelization at an operations level and low-bit data processing makes it possible to increase the number of measurements leading to a decrease in error when determining the spatiotemporal data of the user.

Key words: Satellite radionavigation systems • Artificial ionospheric disturbances • Secondary processing of navigation data • Parallel computing • Residue number system

INTRODUCTION

The development of space technology in recent years expands the application of space communication and navigation systems. The performance efficiency of satellite radionavigation systems (SRNS) is largely dependent on the space communications channel. Studies [1, 2] show that the ionosphere has the greatest impact on the quality of radiofrequency signals of the satellite radionavigation systems. It is state of ionosphere which generates the error when determining the user’s spatiotemporal data (STD).

In the majority of domestic and foreign [1, 3-7] publications devoted to the problem of the ionosphere effect on the positioning errors under the condition of natural disturbances, the analysis of the spatiotemporal data errors is reduced to the study of the effect of centered equally accurate measurement errors when measuring pseudo-ranges. With this approach, it is assumed that all measurements of pseudo-ranges in the selected operational constellation of navigation satellites (NS) have approximately the same accuracy or at least the same order of magnitude.

At the same time, in addition to the natural disturbances in the ionosphere, the artificial disturbances, characterized by the presence of a local region of increased ionization (RII), can occur as well. Artificial ionospheric disturbances (AID) occur as an action result of the various anthropogenic ionization sources, comparable in terms of energy with natural disturbances such as nuclear power plant accidents, large rocket vehicles starts, explosions in the ionosphere, operation of plasma injectors, etc [8].

In the event of severe ionospheric disturbances, navigation radiofrequency signals (RFS) will inevitably be subjected to distortions that will lead to a multiple increase in the user positioning error.

For efficient operation of navigation equipment, first, it is necessary to determine RII based on the navigation radiofrequency signals of the SRNS. Second, to reduce the influence of the ionosphere on the error when determining the spatiotemporal data of the user, it is necessary to improve the processing of radiofrequency signals received from the NS.

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To improve the quality of secondary processing of navigation data under AID conditions is necessary to increase the number of calculations. To ensure high performance of user’s navigation equipment it is proposed to carry out parallel computing in the residue number system (RNS) [9-12]. Therefore the development of high-speed technology for navigation management under the conditions of artificial ionospheric disturbances is a relevant issue.

The Main Part: Suppose that RII with unknown parameters are created as a result of artificial disturbances of the ionosphere at the altitudes of 150-300 km. It is required to determine the presence of RII within the visibility range of terrestrial observer based on SRNS, as well as identify the user’s STD \( q = [X, Y, Z, \tau] \) with a minimum positioning error \( S_q \). Let us consider the navigation management steps under AID conditions.

Algorithm for Identifying the Boundaries of Increased Ionization Region: Creation of AID in the F layer is characterized by quantitative changes in the values of the ionosphere physical parameters such as the intensity of inhomogeneities [betta] and the maximum average electron density (ED) \( \bar{\sigma}_m \), causing an increase of the mean square deviation (MSD) of the ED fluctuations in the ionosphere irregularities \( \sigma_{\Delta N} = \beta \bar{\sigma}_m \).

The experimental and theoretical studies [8] on the impact assessment of scattering properties of artificially disturbed ionosphere on the space communication systems specifications show that under AID conditions scattering properties of the ionosphere cause scintillations, which can be manifested both as a general delinger fading and frequency-selective fading (FSF). At that, the type of occurring fading depends on the carrier frequency \( f_c \) and the spectrum width \( F_c \) of transmitted signals. When using broadband signals in the space transmission facilities, the deterioration of their performance at AID conditions may be more significant than when using narrow-band radiofrequency signals [2]. At AID created at the heights of F-layer, coherence band of the trans-ionospheric communication channel \( F_c \) narrows and becomes less than the spectral width of the NRS. Let us call the ratio \( F_c/F_h > 1 \) in the NRS propagation path.

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It can be assumed that the NRS which is subjected to the FSF will pass through the RII. At that, if only part of the navigation signals will be subjected to FSF, we can conclude that the RII is local. Note that FSF of received NRS may appear after their transmission through the ionosphere. Therefore to make a conclusion about the existence of an ionospheric disturbance it is necessary to determine the MSD fluctuations of ED in the ionosphere irregularities [sigma delta n].

Thus, the indication of RII availability in the ionosphere will be an increase in the MSD of ED fluctuations in ionosphere irregularities [sigma delta n] and the emergence of FSF \( F_c/F_h > 1 \) in the NRS propagation path.

The method to determine the total electron content (TEC) of the ionosphere with due account for its irregularities based on data from two-frequency radio navigation receiver of SRNS is based on the expression [13].

\[
N_S = \frac{f_2^2 \cdot f_1^2}{40.3(f_2^2 - f_1^2)}(L_4 \cdot \lambda_4 - L_2 \cdot \lambda_2),
\]

where \( f_1, f_2 \) are the carrier frequencies of RNS; \( L_1, L_2 \) are radio frequencies phase RPM; \( \lambda \) is wavelength at the frequency \( f_m \) (\( m = 1, 2 \)).

With a number of PEA estimates, conducted over a time interval \( T \), we obtain the MSD value of the PEA:

\[
\sigma_N = \sqrt{\frac{1}{T} \int_0^T (N_S(t) - \bar{N}_S(t))^2 dt},
\]

where \( \bar{N}_S(t) \) is the mathematical expectation of the PEA value.

According to [2], the MSD value of the ED fluctuations in ionospheric irregularities [sigma delta n] on the i-th NRS signal trace can be estimated as

\[
\sigma_{\Delta N} \approx \left(\frac{\sigma_{\Delta}}{\sqrt{\pi \cdot h_3 \cdot \lambda^i}}\right)_{i=1}^{\gamma},
\]

where \( \gamma \) is NS angular altitude; \( h_3 \approx 400 \text{ km} \) is the equivalent ionosphere height, \( \lambda \) is the characteristic size of ionospheric irregularities (generally accepted \( \lambda = 400...600 \text{ m} \)).

It should be noted that this estimate is approximate. In addition, the employment of given method for determining [sigma delta n] requires rejection of one-shot pseudo-range measurements and conduction of measurements during the time interval \( T \).
To determine the existence and the FSF range of radiofrequency signal, the navigation equipment of SRNS user should be provided by the magnitude of coherence bandwidth of the trans-ionospheric communication channel \( F_i \). At the same time, the lack of correct information on the size of ionosphere irregularities \( L_i \) does not allow one to accurately determine the value of \( F_i \).

In order to determine the value of \( F_i \) at a priori unknown \( L_i \), it is proposed to split broadband NRS into its spectral components and check the condition of their correlation [14]. Broadband NRS with a spectral width \( F_0 \) is divided by means of pass filters into the frequency components with increments of \( \delta \omega \) during the time interval \( T = 1 ÷ 5 \) sec. Thereby we allocate spectrum components \( f_1, f_2, f_3, \ldots, f_n \) symmetrical with respect to the spectrum midfrequency \( f_0 \). Next, we determine the correlation coefficient between the symmetric frequency components: \( f_1 \) and \( f_n \); \( f_2 \) and \( f_{n-1} \); \( f_3 \) and \( f_{n-2} \); \ldots; \( f_n \) and \( f_1 \). The correlation function of the navigation signal is given by [14].

\[
K(F_0) = e^{-k(F_0/F_1)^2}
\]

When fulfilling the condition on occurrence of FSF \( F_0/F_1 = 1 \), the correlation coefficient becomes equal to \( K(F_0) = e^{-1} \approx 0.37 \). If within the entire interval of \( F_0 \) the value of \( K(F_0) > 0.37 \), than the condition on FSF occurrence for such NRS is not fulfilled. Frequency space, at which \( K(F_0) = 0.37 \), determines the coherence bandwidth of the carrier channel \( F_i \).

Selection of the signal spectrum decomposition step is carried out for the reasons of accuracy required for the measurement of \( F_i \) magnitude and the number of bandpass filters, required for decomposing the source signal into the spectral components (for instance, 10 kHz or 100 kHz).

With multi-channel user navigation equipment (UNE), it is necessary to identify those NSs, out of the entire set \( n \) of observed NSs, which send out a signal passing through the RII and therefore subjected to the FSF. The obtained result serves as an input data to the algorithm of the secondary processing of navigational parameters; the application of the algorithm can reduce the user positioning error.

The Algorithm for Determining the User STD Vector under the Conditions of AID: To assess the value of pseudo-range we use the method of optimal linear filtration (Kalman filter) [15]. For this purpose we propose to conduct \( m \) pseudo-range measurements under the AID action \( \overline{D_0}, \ldots, \overline{D_k} \) during the time period \( T \) with a time increments \( \delta t \). Then, using the measurement data we propose to determine an amended estimate \( \overline{D_m^*} = f_i(\overline{D_k}, k = 1..m) \) for the value of \( D_i \) at a timepoint \( t_o \). Modern UNE makes measurements with a time increments of 20 ms. Measurement model has the following form:

\[
\overline{D_k} = D_k + N,
\]

where \( N \) is a noise error due to the influence of AID, normally distributed with a mathematical expectation \( M(N) = 0 \) and the variance equal \( \sigma_N^2 \).

The initial conditions for the Kalman filter are taken as follows:

\[
D_0 = \overline{D_0}, \quad P_0 = s_D,
\]

where \( s_D \) is MSD when determining the pseudo-range under AID conditions [16].

Expressions (8-13) implement the Kalman filter to refine the pseudo-range values. In this case, the amendments to the measurements are as follows

\[
K_k = P_k^{-1} \left( \overline{P_k} + s_D^2 \right)^{-1}
\]

The posterior estimate of the pseudo-range and the variance of the corrected pseudo-range assessment are determined as

\[
D_k^* = D_k + K_k \left( \overline{D_k} - D_k \right)
\]

\[
P_k^* = (1 - K_k) \cdot P_k^{-1}
\]
Prediction of initial conditions for a new cycle:

\[ P_{k+1}^* = P_k^* + s_k^2. \]  

(11)

A priori estimate of range for the next time point:

\[ D_{k+1}^* = D_k^* + V_k \cdot \Delta t. \]  

(12)

The amended estimate of pseudo-range

\[ D_m^* = D_m^*. \]  

(13)

Here, the symbol "*" indicates a prior estimates; the symbol "+" a posterior estimates; \( k = 1, \ldots, m \) is a filter cycle (\( m \) is the number of measurements).

Thus, the algorithm for determining the user STD vector at AID and FSF of navigation signals involves the following sequential steps:

**Step 1:** Navigation management using the pseudo-range values measured with a high error because of the AID. The result is a distorted vector \( \tilde{q} \) of STD user.

**Step 2:** Defining the MSD when measuring the pseudo-range to NS, whose signal falls into the RII and is subjected to FSF.

**Step 3:** Evaluation of the pseudo-range value by Kalman filter using expressions (8-13). This step results in obtaining the refined value of \( D_m^* \).

**Step 4:** Repeated navigation management using the refined pseudo-range values and initial approximation of \( \tilde{q} \). This results in obtaining the unknown user coordinate vector \( q \) with a positioning error \( S_q \).

Obviously, the calculation accuracy of the spatiotemporal coordinates of the user to a large extent depends on a number of pseudo-ranges computed. Increase in number of such calculations is possible due to the transition to the parallel computing systems, in particular, to the residue number system. The residue number system is defined by a set of prime numbers \( p_1, p_2, \ldots, p_n \) called modules [9-11]. The product of these modules gives the dynamic range of such a system.

\[ P = \prod_{i=1}^{n} p_i. \]  

(14)

For every whole number \( A \) satisfying \( 0 \leq A < P \), assigns *module* uniquely through \( n \)-tuple of residues

For any integer \( A \) satisfying \( 0 \leq A < P \), we uniquely set...

\[ A = (a_1, a_2, \ldots, a_n), \]  

(15)

where \( a_i = A \mod p_i (i = 1, \ldots, n) \).

For carrying out computations of the \( n \)-tuple of residues we use the isomorphism between the ring of integers modulo \( P(Z(P)) \) and the direct sum of the rings \( Z(P_i), (i = 1, 2, \ldots, n) \). In this case the arithmetic operations in the ring \( Z(P) \) are replaced by respective independent operations with residues. For \( 0 \leq A, B, Z < P \) the following is true

\[ Z = (A \circ B) \mod P = (z_1, z_2, \ldots, z_n); \]

\[ Z_i = (a_i \circ b_i) \mod p_i \quad (i = 1, 2, \ldots, n) \]  

(16)

where \( \circ \) is the addition, subtraction or multiplication.

Expression (16) reflects the basic characteristics of modular arithmetic: any system consisting of a large number of additions, subtractions and multiplications can be represented by multiple independent channels operating in parallel. At that, the digit capacity of the data being processed will be determined by the selected module \( p_i \) of a small digit capacity. This results in higher performance of the computing system.

Thus, the arithmetic operations of addition, subtraction and multiplication are performed without-staging in contrast to the usual radix notation and for each value of \( p_i \) module the arithmetic operations are done by corresponding subtractions in parallel. At that, the subtractions have a much lower digit capacity than the source operands \( A \) and \( B \). The introduction of the \( p \)-modulo metric in the ring allows us to consider it as a finite-dimensional metric space of finite dimension vectors.

The transformation from the modular code into a radix numeration system (RNS) is based on the Chinese Remainder Theorem (CRT) [12]. Based on the known representation of a number in the NRS \( (a_1, a_2, \ldots, a_n) \), CRT makes it possible to determine the number in the RNS \( \{A | p\} \) if the greatest common divisor of any pair of modules is equal to 1. Then

\[ |A|_p = \sum_{i=1}^{n} p_i |\frac{a_i}{p_i}|_p, \]  

(17)

where \( p_j = p_j/p_i, \quad p = \prod_{i=1}^{n} p_i; (p_i; p_j) = 1, i \neq j \)

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We use various forms of the Chinese Remainder Theorem. It follows from (17) that from the CRT we obtain just $|A|_p$, rather than $A$ itself. If it is known that $A$ is between 0 and $P-1$, then we can write

$$A = \sum_{i=1}^{n} p_i \left\lfloor \frac{a_i}{p_i} \right\rfloor , \text{ for } 0 \leq A < P$$

(18)

In some cases it is desirable to have a CRT in a form, where the sum does not include module operator $P$. This can be done by determining an auxiliary function $R(iA)$, so that

$$A = \sum_{i=1}^{n} p_i \left\lfloor \frac{a_i}{p_i} \right\rfloor - P \cdot R(A)$$

(19)

where $R(A) = \frac{1}{P} \sum_{i=1}^{n} p_i \left\lfloor \frac{a_i}{p_i} \right\rfloor - A$, $R(A)$ is a rank of $A$ number.

It is obvious that the operation of translation in position code leads to poor performance of the computing device operating in the RNS. However, the parallel processing of low-bit residues enhances the data processing speed. Studies have shown that the use of RNS in the processing of 16-bit numbers can reduce the span time by factor of 4.12, compared with a radix numeration system. At that, increase in the digit capacity of processed data leads in an increase of above mentioned index.

**CONCLUSION**

The paper presents a technique that includes a RII detection algorithm and modification of the algorithm for the secondary processing of navigation data. This allows one to reduce the user positioning error under the impact of the local region of increased ionization. In case of severe distortion of navigation radio-frequency signals it is proposed to increase several-fold the number of measurements. In order to increase computing speed of pseudo-ranges it is proposed to use parallel computing in the residue number system. The studies have shown that even when processing 16-bit numbers, the residue number system can reduce the span time by factor of 4.12 compared with a radix numeration system. Thus, due to employment of secondary treatment of RNS, the developed algorithm enables to reduce the error when determining the spatiotemporal coordinates of the user.

**REFERENCES**


