A method for the autonomous control of navigation information integrity

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Abstract. Currently, the key task of developing navigation systems is to reduce faults in determining the pseudo-range and pseudo-speed of objects. The quality of the solution of this problem significantly affects the accuracy of navigation and time security.

1. Introduction

The article proposes an algorithm for detection and localization of abnormal measurements, which includes, among other things, autonomous control of the integrity of navigation information. It is shown that the classical algorithm for detecting a faulty measurement uses at least one redundant measurement, and its localization – two. However, the RAIM algorithm is more promising, in it for the detection and localization of faulty measurements, the errors (residuals) obtained in solving the problem of an excessive constellation are analyzed. The algorithm consists of two main parts - detection of anomalous measurements and localization of anomalous measurements.

Also, in the article, the possible variants of the solution of the navigation-time problem in various coordinate systems have been chosen and substantiated. Normally, in order to solve the navigational task, in general, it is required to receive signals from four navigation space vehicles, according to the number of unknown parameters - three spatial coordinates and time. However, the number of navigation space vehicles can be reduced by drawing a priori data. In this case, it is advisable to use slowly changing parameters as a priori data. Often, as the a priori data, the height of the object is often used over a quasi-geoid or a common-earth ellipsoid.

From the analysis of faults in the determination of pseudo-range and pseudo-speed, it follows that the magnitude of each component can be from one to dozens of meters in pseudo-range and from a fraction of up to ten meters per second in pseudo-speed [1, 2]. If special measures to reduce these faults are not taken, you cannot expect high accuracy of the navigation temporal definition.

Let us consider some of the measures that make it possible to reduce the errors in the determination of pseudo-range and pseudo-speed [3-6].

1) Compensation for time scale errors.

One of the essential components of faults in the determination of pseudo-range are errors of the onboard time scale. Partial compensation of these errors is due to the accumulation of data, which is carried out by the ground segment of monitoring and control. As a result of such processing, estimates of the following parameters are formed: time-shift of n-th ground segment relatively to the system time scale τn; relative deviation γn = (fn - fn0)/fn predicted value of the carrier frequency fn of n-th ground segment from the nominal value of this frequency for the same ground segment. The values of the parameters τn, γn are transmitted by the ground control system over the communication line to the
ground segment, where they are laid down in the navigation message.

The predicted value of the carrier frequency \( f_c \) is given taking into account the gravitational and relativistic effects at time \( t_p \). The receiver can take into account corrections for relativistic effects.

2) Compensation of the ionospheric error.

There are methods for compensating the ionospheric error for single-frequency receivers, i.e. receivers working only in the \( L1 \) range, and for two-frequency receivers operating in the \( L1 \) and \( L2 \) ranges [1]. The problem of ionospheric error compensation is most simple solved in a two-frequency receiver. Of all the components of the error in determining the pseudo-range, only the ionospheric error depends on the frequency. Errors in the estimation of the ionospheric delay are determined by estimation errors, which, in the first approximation, is determined by errors in estimating the pseudoranges (in the \( L1 \) and \( L2 \) ranges) due to receiver noise. For stationary objects, due to the additional averaging of the pseudo-range estimate over time, the fluctuation error can be made less than 1 m. This error is also a compensation error of the ionospheric delay (residual error after compensation).

In the single-frequency receiver, additional information characterizing the state of the ionosphere is unavailable, therefore only the use one or another ionosphere model is possible [7-10]. The main problem with this approach is that the state of the ionosphere is very variable and depends on many factors. Therefore, it is impossible to predict with high accuracy the electron concentration distribution over the altitude. However, it turned out that it is possible to create a relatively rough model of the ionosphere, which is described by a small number of parameters and allows us to compensate for about 50% of the total errors. This eight-parameter model was developed with reference to the GPS system [11-14]. At the same time, eight parameters are transmitted from the satellite radio navigation system (SRNS) GPS in the navigation message, which makes it relatively easy to implement the compensation procedure at the receiver [15-17]. Later, more complex ionospheric models were developed. However, their use does not allow compensation of the ionospheric error better than 75%. In the navigation message SRNS GLONASS information about the state of the ionosphere is not transmitted, therefore, in order to realize the ionospheric error compensation in a single-frequency receiver, it is necessary to use additional external information on the parameters of the ionosphere.

2. Compensation of tropospheric error

To compensate for the ionospheric error, one or another model of the troposphere is used. One of the widely used models is determined by the formula:

\[
\Delta \sigma_{trop} = \frac{0.002277}{\sin(\alpha)} \left( p + \left( \frac{1255}{T} + 0.05 \right) e - B \cotg^2(\alpha) \right) + \delta R,
\]

where \( T \) is the temperature in Kelvin at the location of the receiver; \( p \) is the atmospheric pressure in millibars; \( e \) is the partial pressure of water vapor in millibars; \( \alpha \) is the elevation angle of the ground segment for which the correction is calculated; \( B \) and \( \delta R \) are correcting terms that depend on the receiver height \( h \) and angle \( \alpha \), for which exist special tables.

The use of tropospheric models allows to compensate up to 90% of the total error so that the residual error can be \( \leq 0.2 \) m for ground segment signals located at the zenith.

4) Reduction of errors caused by multipath

Methods for reducing errors in pseudo-range determination due to multipath propagation are given below: non-use in processing signals coming from directions below the angle of the mask; elevation of the antenna above the most significant reflecting objects; use of antennas with right circular polarization; use of latency delays with narrow aperture of discriminatory characteristics [18].

5) Reducing receiver errors

The main means of reducing the errors of pseudo-range and pseudo-speed estimation in the receiver is the optimization of algorithms, signal processing devices and information. So, speaking about the optimization of signal processing devices, one can keep in mind: the use of precision low-
noise input amplifiers, which reduce (by 1.5 ... 2 dB) the internal noise power of the receiver; use of highly stable reference generators, for example, with a spectral density of phase noise (cyclic phase) equal to -100 ... -110 dB at a frequency of 1 Hz; the use of analog-to-digital converters with more than two quantization levels; use of bandpass filters in the high-frequency part of the receiver with high selectivity, etc.

If we are speaking about the optimization of information processing algorithms, we can note the following directions: optimization of the structure and parameters of tracking systems behind envelope delay, phase and frequency, taking into account the dynamics of a particular consumer; adaptation of tracking systems to the signal-to-noise ratio at the receiver input; the use of complex tracking systems that jointly process signals from the outputs of range, phase and frequency discriminators; sharing of code (by envelope) and phase measurements for or navigational and temporal definitions; transition from the ideology of constructing receivers with two-stage processing to receivers with one-stage processing; the use of differential methods of navigational and temporal determinations, in which many slowly varying correlated components of errors are eliminated; the integration of signal processing algorithms for the navigation receiver and other navigation systems of the consumer, primarily the inertial navigation system (INS).

As is known, during the process of measuring the parameters of the signals of navigational space vehicles, there may be grave errors [19]. Abnormal measurements can occur as a result of malfunctions of navigational space vehicle or translation of incorrect operative information, failures of the automatic reclosing system and phase-locked loop at small amplitudes of signals of navigational vehicle, errors when receiving operational information, etc. As a result, grave errors arise in the results of calculating coordinates and spatial orientation. Experimental studies show that when measuring spatial orientation of low motion objects in an open terrain, the number of anomalous measurements is small, but when measuring on highly dynamic objects, for example, on a car, the number of anomalous measurements increases abruptly (maybe several times per minute).

The magnitude of the anomalous errors in the measurement of pseudo-range can be different - from tens and hundreds of kilometers to tens of meters, such errors appear as anomalous in differential measurements. In angular measurements, the situation is complicated by the fact that in the case of failures, phase jumps can occur for several phase cycles (periods), which causes disruption of the angular measurements, since the resolution of phase ambiguity is usually only performed upon initialization [5].

In this regard, the problem of detecting anomalous measurements, searching for abnormal signals of a navigation space vehicle, their localization, and, if it is impossible, issuing an error message and re-initializing the algorithms is topical.

For the task of determining the coordinates, this problem is called Receiver Autonomous Integrity Monitoring (RAIM); moreover, according to some standards, for example, the RAIM aviation algorithm must be implemented without fail.

The simplest way to detect faulty measurements is the way in which navigation-time problems are solved for various constellations of navigation space vehicles (with the exception of one of the navigation space vehicle). If the difference in the calculated parameters for different constellations of the navigation space vehicles exceeds the threshold value, then a conclusion is made about the presence of a faulty measurement. To localize the faulty measurement, the navigation satellite is repeatedly searched for each of the initial constellations. Thus, to detect a faulty measurement, it is necessary to have at least one excessive measurement, and for its localization - two.

More promising is the RAIM algorithm, in which, to detect and localize faulty measurements, the residuals obtained in solving the problem of an excessive constellation are analyzed. The algorithm consists of two main parts: detection of anomalous measurements and localization of anomalous measurements. In the algorithm for detecting anomalous measurements, it is necessary to consider the solution of the navigation and angular problems, which reduces to a system of linear or linearized equations of the form:

\[ R = KX, \]
where \( X \) is the state vector, \( K \) is the matrix of known coefficients, \( R \) is the vector of measured parameters.

In this case, the dimension of the vector \( X \) is less than the dimension of the vector \( R \); the equation system is redundant. Solution by the method of least squares is written as:

\[
X = (K^T K)^{-1} K^T R.
\]

Since the measured parameters contain measurement errors, and the system of equations is redundant, it becomes incompatible. The residuals of the solution by the method of least squares are:

\[
\Delta R = R - KX.
\]

Suppose that, in the absence of anomalous measurements, the residuals of the solution by the method are normal independent random variables with zero mathematical expectation and the root-mean-square deviation \( \sigma \). Then the sum of the squares \( n \) of the residuals is equal to the logarithm of the likelihood function.

\[
Z = \sum_{i=1}^{n} \Delta R_i^2
\]

distributed according to the law \( \chi^2 \) with \( n \) degrees of freedom. In the presence of a faulty measurement, one can represent discrepancies with nonzero mathematical expectations due to the solution bias and the standard deviation \( \sigma \). In this case, the distribution law is described by formula:

\[
W(x) = \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} \left(1 - 2i\sigma^2 v\right)^{-\frac{n}{2}} e^{iv\sigma^2 - iux} dv,
\]

which depends only on the sum of squares of mathematical expectations. The upper limit of the total mathematical expectation is determined by the magnitude of the failure. Indeed, if the true coordinates of the base vector are known, then the sum of the squares of the mathematical expectations of the residuals is equal to the sum of the squares of the anomalous errors. When solving the problem by the method of least squares, a state vector \( X \) is determined, under which the total residual is minimized, so the sum of the squares of the mathematical expectations will be less than the sum of the squares of the anomalous errors. In any case, in the presence of anomalous measurements, the sum of the squares of the residuals increases.

The threshold of the AINM algorithm can be determined based on the given probability of false alarms on the distribution function \( \chi^2 \) with \( n \) degrees of freedom. If the total residual exceeds the threshold value, then a decision is made about the presence of a faulty measurement.

The detection of anomalous measurements is possible only with an excessive constellation of navigation space vehicles, when solution by the method of least squares has nonzero residuals. At the same time, the algorithm for detecting anomalous measurements does not require additional computational resources.

From the calculation, the signal of one of the navigation space vehicles is alternately eliminated, the goniometry task is solved, and the magnitude of the total residual is analysed. If, when one of the navigation space vehicles is excluded from calculation, the anomalous measurement still remains, then the total discrepancy remains large, if the anomalous measurement is excluded from the calculation, the total discrepancy sharply decreases and becomes less than the threshold value. Thus, an anomalous measurement is the one with the exception of which the minimum value of the total residual is reached.

The method of localization of one anomalous measurement can be greatly simplified, since, as a rule, an anomalous measurement has a maximum absolute discrepancy. However, if the number of anomalous measurements is more than one, then, according to the results of experimental studies, a maximum in absolute magnitude discrepancy can correspond to a measurement that does not contain
anomalous errors. Therefore, the most general method for localizing abnormal measurements is to use the criterion of the minimum total discrepancy.

If there is more than one anomalous measurement, then if one of the navigation space vehicles is excluded from calculation, the total residual in any case will exceed the threshold value, since the anomalous measurements will be present in the calculation. The localization of anomalous measurements at multiple failures can be made by the minimum total discrepancy of solutions in which one of the navigation space vehicles is excluded from the calculation. The principal possibility of such localization is because, when one anomalous measurement is excluded from calculation, the upper limit of the sum of the squares of the mathematical expectation, equal to the sum of the squares of the failures, decreases. If we exclude from the calculation one of the normal navigation space vehicles, the upper limit of the sum of the squares of the mathematical expectation remains unchanged.

As a result, the minimal total discrepancy will have a solution with an excluded anomalous measurement, while in the case of multiple failures the magnitude of the total residual remains above the threshold value. Excluding one anomalous measurement from the calculation, the same method is used to localize the next anomalous measurement. The search for anomalous measurements is repeated until the total residual is below the threshold value, or until the number of navigation space vehicles in the calculation becomes equal to the minimum constellation. In the latter case, it is concluded, that it is impossible to localize abnormal measurements. The difference between the goniometric mode of operation and the conventional navigational mode is that anomalous measurements can occur in jumps in phase shifts for one or several full periods. These errors are removable. Therefore, after localization of faulty measurements, it is necessary to check the anomalous measurements and restore the eliminated errors.

Experimental studies show that this method works stably for three anomalous measurements out of nine. At the same time, with the increase in the number of abnormal navigation space vehicles, the reliability of localization of anomalous measurements is reduced. In this regard, if the calculation of coordinates is carried out in several stages, then the AIMR algorithm should be introduced at each stage. For example, when working in the differential mode, the first step is to make the calculation in the offline mode. In this case, the RAIM algorithm detects and localizes coarse measurement errors exceeding the corresponding RAIM threshold, for example, 50 m. Errors less than this threshold for the solution in the offline mode practically do not have effect. In the second stage, differential corrections are introduced and a solution is made in the differential mode. At the same time, the RAIM threshold is reduced, for example, to 5 m, and anomalous errors exceeding this threshold are detected and localized. In this case, the total number of faulty measurements in the differential mode decreases due to the localization of significant errors in the solution in the autonomous mode, which significantly improves reliability.

To ensure the required reliability of the results of navigation measurements, the navigation task should include an Autonomous Integrity Monitoring Receiver (AIMR) algorithm that detects abnormal navigation satellites. Currently, there are a number of methods for autonomous integrity monitoring. In the case of solving only the time problem, that is, calculating the deviation of the receiver time scale from the system time and deviating the frequency of the reference oscillator for a priori given coordinates, the algorithm for solving the navigation problem is greatly simplified. Accordingly, it is possible to simplify the algorithm of autonomous integrity control, while improving its reliability.

Like usual AIMR algorithms, the algorithm of autonomous integrity control for the time task (T-AIMR) uses the redundancy of the constellation of navigation satellites.

When solving a time task, the initial data are:
1. Measured pseudo-ranges \( R_i \).
2. Measured Doppler frequencies \( F_{di} \) (when measuring the frequency deviation of the basic generator).
3. The a priori values of the consumer's coordinates \( X_n, Y_n, Z_n \).
4. The a priori value of the velocity vector of the consumer \( V_{Xn}, V_{Yn}, V_{Zn} \) (equal to zero).
The navigation equation for determining the deviation of the time scale of a multifunctional radio complex from the system time is written as:

\[ C \cdot \Delta T = R_i - \sqrt{(X_{ci} - X_n)^2 + (Y_{ci} - Y_n)^2 + (Z_{ci} - Z_n)^2}, \]

where \( C \) is the speed of light.

The equation contains one unknown value \( \Delta T \), so to compare the time scales, it is sufficient to receive signals from one navigation satellite. To implement the regime \( \tau \)-RAIM an excessive constellation is necessary, and there should be at least two redundant navigational space vehicles. Since the minimum constellation consists of only one navigational space vehicle, the necessary redundancy is easily achieved even when working on a single space station, for example GLONASS.

The \( \tau \)-AIMR algorithm comes down to the following procedure:

1. Calculate the value \( \Delta T_i \) calculated by the signals of each navigation space vehicle:

\[ \Delta T_i = \frac{1}{C} \left( R_i - \sqrt{(X_{ci} - X_n)^2 + (Y_{ci} - Y_n)^2 + (Z_{ci} - Z_n)^2} \right). \]

2. Calculate the average value \( \Delta T \):

\[ \Delta T = \frac{1}{n} \sum_{i=1}^{n} \Delta T_i, \]

Where \( n \) is the number of navigational space vehicles under calculation.

3. Calculate the standard deviation \( \sigma_{\Delta T} \) and discrepancies \( \Delta(\Delta T) \):

\[ \Delta(\Delta T)_i = \Delta T_i - \Delta T, \]

\[ \sigma_{\Delta T} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\Delta T_i - \Delta T)^2}. \]

4. If \( \sigma_{\Delta T} \) is greater than a certain threshold value, then a decision is made about the presence of an abnormal (anomalous) measurement. The threshold value is selected from the allowable probability of skipping a failed satellite.

5. In the presence of anomalous measurements (faulty satellites), one navigation satellite (in order of decreasing the discrepancy in absolute value) is in turn eliminated, and points 2 and 3 are fulfilled. A satellite is recognized as abnormal (faulty) with the exception of which, from the calculation, the minimum standard deviation \( \sigma_{\Delta T} \) is obtained. This satellite is recorded in the list of abnormal satellites. Further, point 4 is fulfilled, the exceeding of the threshold value \( \sigma_{\Delta T} \) is checked. If it is greater than the threshold, a decision is made about the presence of another anomalous measurement, and the calculations are repeated until all anomalous satellites are deduced from the calculation.

6. After excluding all faulty satellites from the calculation, anomalous measurements are checked, since for double, triple, etc. faults, from the calculation can also be excluded normal satellites. For this purpose, the residuals of the failed satellites (from the list) are calculated in accordance with point 3, using the value \( \Delta T \), which was calculated in the absence of anomalous measurements. The satellite is finally recognized as anomalous if its residual exceeds the permissible value, otherwise it is excluded from the list of faulty satellites and is again taken into account.

3. Conclusion
The article presents methods for reducing the error in determining pseudo-range and pseudo-speed. If you do not take special measures to reduce errors, then you cannot expect high accuracy of
navigational and temporal support.

In addition, an algorithm for detecting and localizing abnormal measurements is considered, which includes an autonomous control of the integrity of navigation information. It is shown that the classical algorithm for detecting a faulty measurement uses at least one redundant measurement, and its localization - two. The RAIM algorithm is also shown (it is more promising), in which the discrepancies obtained for solving the problem of an excessive constellation are analyzed to detect and localize faulty measurements. The algorithm consists of two main parts - detection of anomalous measurements and localization of anomalous measurements.

Acknowledgements

This work was supported by the Ministry of Education and Science of the Russian Federation (State assignment to higher education institutions and research organizations in the field of scientific activity; agreement No. 2.7711.2017/8.9)

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