Improvement and automation of the test process of attitude navigation receivers used in the aerospace industry due to the application of GNSS simulators

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Abstract. A model of the error of synchronized navigation signals simulating of the global navigation satellite system (GNSS) simulator is proposed. A method for estimating the error of attitude determination of GNSS simulator was developed and tested.

1. Introduction
The current state of the technical means of assessing the accuracy characteristics of the aerospace industry attitude navigation receivers (ANR) is characterized by the presence of fixed and rotary stands and mobile laboratories [1-3]. The first ones do not allow assessing the accuracy characteristics of the ANRs in dynamic mode, the second ones do not provide the required accuracy margin (in most cases being equal) and are limited to the vehicle speed range of the mobile laboratory, which does not meet the requirements for determining measurement errors in specified speed ranges for the development and testing of ANRs. This contradiction can be resolved through the use of GNSS signal simulators with several radio-frequency outputs.

To use a GNSS signal simulator with multiple radio-frequency outputs for assessing the accuracy characteristics of ANR, it is necessary to determine the simulator’s errors in terms of the angle reproduction of the object spatial orientation.

2. Problem issues
Nowadays, the Federal Information Fund on ensuring the uniformity of measurements has introduced a method for measuring the angles of spatial orientation with consumer goniometric navigation equipment using the global navigation satellite system signal simulator (No. FR.1.33.2016.24673) [4]. The technique establishes the procedure for measuring the angles of spatial orientation of the ANRs in the ranges from 0 to 360 ° in azimuth, from minus 90 to 90 ° in roll, from minus 90 to 90 ° in yaw based on the reproduction of navigation signals by the GNSS signal simulator GNSS. In the method, the root mean squared (RMS) of the measurement of spatial orientation angles (azimuth, roll, yaw) is normalized to 5´ with a distance between antennas of ANR not less than 1 m, that is, only a random error in the formation of angles of spatial orientation with a GNSS signal simulator. Rationing only the random error of the formation of angles of spatial orientation does not explain the results of the comparative
measurements of ANR when working on real GNSS signals and using the GNSS signal simulator (see figure 1).

| Heading (α) | Roll (γ) | Yaw (β) |
|-------------|----------|---------|
| ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |

**Figure 1.** ANR comparative measurements when working on real GNSS signals and using a GNSS signal simulator: L – distance between ANR antennas, m; $\delta_{\text{αβγ}}$ – RMS of the error in the formation of spatial orientation angels, calculated by the measurement method, angular minutes.

ANR measurement results on the GNSS signal simulator are obviously not stationary, the errors differ for the worse from the results of measurements on real GNSS signals. It is necessary to develop a method for determining the systematic component of the error in reproducing the angles of spatial orientation with a GNSS signal simulator when transferring a unit of magnitude from working standards of the second discharge to ANR.

### 3. Theory

The absolute error in the formation of a GNSS signal simulator by the angles of spatial orientation of the object ($\delta$) is determined by the formula:

$$\delta = \frac{2\pi}{\lambda} \cdot ADOP \cdot \delta_{\Delta\phi} \cdot \frac{L}{L},$$

where $\lambda_i$ - wavelength carrier signal of the navigation spacecraft (NSC), m; L – distance between antennas, m; ADOP (Attitude Dilution of Precision) – the factor of the spatial orientation precision; $\delta_{\Delta\phi}$ - the absolute error of the phase difference formation between the carrier signal of the NSC, reproduced from two different radio frequency outputs of the GNS signal simulator, rad.

The expression for the phase difference error of the NSC carrier signal, adopted by two spatially separated ANR antennas, in general form can be presented as the following [5]:

$$\delta_{\Delta\phi} = 2\pi \cdot k_i + \Delta\varphi_{ci} + \sigma_i,$$

where $k_i$ – the number of integer cycles of ambiguity $2\pi$ in the systematic component of the error in measuring the phase difference of the i-th satellite carrier signal; $\Delta\varphi_{ci}$ - fractional part of the $2\pi$ ambiguity cycle in the systematic component of the measurement error of the phase difference of the i-th NSC carrier signal; $\sigma_i$ - RMS of the phase difference of the i-th NSC carrier signal.

GNSS signal simulator is characterized by the following:

- Pseudorange on the phase of the NSC carrier is reproduced with discretion (the discrete value depends on the digit capacity of the digital-analogue converters used in the signal simulator);
- Whole cycles of ambiguity in reproducing the carrier phase difference in the systematic component of the error in reproducing signals of the GNS from different RF outputs are absent.
(it is provided by circuit solutions for synchronizing the reproduced navigation signals). The fractional part of the 2π ambiguity cycle in the pseudo range reproduced by the simulator of the GNSS signals by the phase of the satellite signal carrier can be expressed in terms of the whole number of pseudo-range playbacks of the NSC carrier phase;

- Reproduction of the phase pseudo range has a random component of the error. So the error model of the phase difference formation of one NSC carrier signal, reproduced from two different RF outputs of the GNS signal simulator, will be described by the expression:

\[
\delta = \frac{2\pi}{\lambda} \cdot ADOP \cdot \left( \frac{2k\rho}{L} + \frac{\sigma_{pd}^2}{L} \right),
\]

(1)

where \( \rho \) – discrete phase adjustment of the radio carrier signal, mm; \( k \) – coefficient of proportionality \((k = 0; 1; 1.5; 2...); \sigma_{pd} \) - the standard deviation of the random error component of the radio carrier signal pseudorange formation, mm.

Information about the phase restructuring of the carrier-carrying radio navigation signal is not contained in the brochures and technical documentation of the GNSS signal simulator manufacturers. In this regard, it is necessary to develop a method for determining the discrete phase reorganization of a radio navigation signal carrier.

In order to determine the phase restructuring of the radio navigation signal carrier, the equipment for monitoring the characteristics of MRK-113 navigation signals (hereinafter referred to as MRK-113 equipment) [6] was used.

Studies to determine the absolute error of measuring the pseudorange increment over the phase of the navigation signal carrier are presented in [7]. The limit of the permissible absolute error of the pseudo-range increment measurement in the carrier of the navigation signal by the MRK-113 equipment does not exceed ± 0.25 mm.

In order to determine the phase re-alignment of the radio navigation signal carrier on the signal simulator, scenarios were created that simulate a stationary NSC at heights: \( H_0 \), \( (H_0 + 0.3) \) mm, \( (H_0 + 0.7) \) mm, \( (H_0 + 1) \) mm, \( (H_0 + 1.5) \) mm.

Then, each scenario was sequentially reproduced, measurements were carried out with MRK-113 equipment, the increments were calculated according to the phase of the navigation signal carrier and the errors of the increment reproduction.

The results of determining the absolute errors of reproducing the increments of the navigation signal carrier phase with the signal simulator are shown in figures 2-3 (the abscissa axis is simulated in the environment of creating the script of the increment signal simulator, mm; the vertical axis is the absolute reproduction errors of the carrier phase pseudo-range increments, mm).

![Figure 2](image1.png) **Figure 2.** Absolute errors of reproduction by the simulator of the delay increment signals of the navigation GLONASS signal (L1SF, satellite’s frequency channel number -7) on the phase of the carrier.

![Figure 3](image2.png) **Figure 3.** Absolute errors of reproduction by the simulator of the delay increment signals of the navigation GLONASS signal (L1SF, satellite’s frequency channel number +6) on the phase of the carrier.

As one can see from the results presented in figures 2-3, the absolute error of a signal simulator reproduction by the increments of the navigation signal carrier phase with an accuracy to the error of
the MRK-113 equipment is proportional to 0.7 mm. Consequently, the discrete phase adjustment of the radio navigation signal carrier for this type of signal simulator \( \rho = \lambda / 2^8 \).

4. Experimental results

For the studied type of GNSS signal simulator:

- The standard deviation of the error in the formation of the pseudorange of the radio carrier signal is 0.9 mm;
- The phase reorganization discrete of the radio navigation signal carrier is 0.73 mm (average value for the L1 GLONASS frequency range);
- The standard deviation of the calibration error on the phase of the radio navigation signal carrier is 0.9 mm;
- The proportionality coefficient (see formula (1)) for the studied type of the GNS signal simulator is \( k = 1 \).

Thus, for the type of GNS signal simulator under study, the error in reproducing the spatial orientation angles (with ADOP = 1) is 5.6' (for the distance between antennas 2 m) and 1.9' (for the distance between antennas 6 m).

The resulting absolute errors in determining the angles of spatial orientation of ANR based on the results of the work on the signals of the GNS signal simulator are presented in figure 4.

![Figure 4](image_url)

**Figure 4.** Comparative measurements of ANR when working on real GNSS signals and using a GNSS signal simulator, the error of which is calculated according to the refined model of error.

5. Conclusions

Thus, for the scenario of the GNSS signal simulator, which provides the ratio of the errors of the GNSS signal simulator calculated using the refined model of error, at least ½ of the tested ANR, the metrological characteristics of the ANR correspond to the declared ones.

The developed model of the phase difference error of the NSC carrier signal, reproduced from two different RF outputs of the GNSS signal simulator, and the method for determining the discrete phase adjustment of the GNSS carrier signal in the signal simulator, make it possible to determine the possibility of using a signal simulator to estimate the accuracy characteristics of ANR types used,
including aerospace field. The use of GNSS signal simulators provides reliable semi-natural tests of ANR, makes it possible to automate the processes of measurement and processing of results.

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