Carrier phase difference measurement method for GNSS-simulator navigation signal

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Abstract. A method for measuring phase difference of carrier frequency of GNSS-simulator navigation signal, based on the use of a multichannel analogue-to-digital converter and phase processing at intervals of its linear change is proposed. The developed method makes it possible to measure the phase difference of carrier frequency of radio navigation signal with a non-excluded systematic error 1.5°.

1. Introduction
Carrier phase difference measurement of navigation signals are in demand in many areas of daily activity (construction, high-precision navigation definitions, GNSS-based attitude determinations, monitoring of deformations of infrastructure facilities, etc.). To confirm the instrumental errors of user receivers used in such applications, it is necessary to generate GNSS signals from different (in the simplest case, two) outputs of GNSS-simulator with a normalized systematic error in the phase of the carrier frequency.

Due to the short antenna bases (from tens of centimetres to several meters), the technology most sensitive to the accuracy of the phase difference at the input of antenna modules is attitude determinations (measurement of Euler angles). To ensure the confirmation of the requirement for attitude determinations by the attitude navigation receivers no more than 3’ (with a distance between antennas of 2 m), it is necessary to ensure the formation of the phase difference of the carrier frequencies of the signals of navigation spacecraft with an error not exceeding 3°. Consequently, the method for measuring the formed phase difference should have a non-excluded systematic error of no more than 1.5°.

The term “phase shift angle between two electrical signals” according to GOST R 8.875-2014 in the article is replaced by the term “phase difference” in accordance with RTM 68-14-01.

2. Problem issues
GNSS signals are not strictly harmonic, as they are modulated in the phase of the carrier frequency with pseudo-random sequences. In this regard, measuring the phase difference of such signals is a complex technical problem.

The existing methods for measuring the phase shift angle between two navigation signals in the L frequency range are based either on the use of equally accurate reference phase reference receivers [1] or on measurements of signal delays using oscillograms. These methods make it possible to determine
the phase difference with an accuracy of several periods of the frequency of the carrier oscillation due to the need to carry out commutation in the measuring circuit (first method) or insufficient resolution of the measuring equipment (second method).

3. Problem statement
When the GNSS-simulator reproduces the navigation signals from two radio frequency outputs, the phase difference of the carrier oscillations can be represented as:

\[ (\phi_2 - \phi_1) = 360^\circ f \left( \frac{PD_2 - PD_1}{c} + \frac{A_2 - A_1}{c} + \frac{\Delta (\phi_2 - \phi_1)}{c} \right) \]

where \((\phi_2 - \phi_1)\) is the phase difference of the carrier frequency of the navigation signal generated from two RF outputs of the GNSS-simulator;

\(PD_1, PD_2\) is the difference of the formed geometric distances between the points of reception of the navigation spacecraft (NSC);

\(A_2, A_1\) are generated delays of the navigation signal in the atmosphere, calculated using mathematical models;

\(\Delta (\phi_2 - \phi_1)\) is error in the difference between the generated unrequested ranges in the carrier frequency phase;

\(c\) is the lightspeed.

In the case of signal generation from one NSC with zero range, zero errors of the NSC signal propagation path, the value of the generated phase difference will be equal to the error of the difference between the generated pseudo-ranges from two radio frequency outputs of the signal simulator.

4. Method description
The developed method is based on the use of an analogue-to-digital converter (ADC) (a digital storage oscilloscope was used in the experiment as ADC) with the subsequent transfer of the data array - the results of the input signal digitization to an external computer for post-processing.

The measurement setup is shown in figure 1.

Figure 1. Measurement setup.

For the measurement scheme shown in figure 1, the measured value model (phase difference) can be described by the formula:

\[ (\phi_2 - \phi_1) = \phi_{RF_2}^{AD} - \phi_{RF_1}^{AD} - \phi_2^{cable} + \phi_1^{cable} + |\Theta| \]

where \((\phi_{RF_2}^{AD} - \phi_{RF_1}^{AD})\) is the phase difference of the carrier oscillation of the NSC signal, measured indirectly using the ADC of the oscilloscope;

\(\phi_2^{cable}\) is the phase of the transmission coefficient of connecting cables, measured by a vector network analyser;

\(\phi_1^{cable}\) is the phase of the transmission coefficient of connecting cables, measured by a vector network analyser;

\(\Theta\) is the residual systematic error in measuring the phase difference.

A technological scenario is created on the GNSS-simulator before measurements are taken. The technological scenario provides the formation of a signal from one stationary NSC to the radio
frequency outputs of GNSS-simulator. The generated navigation signals do not contain models of the components of errors due to the path of propagation of signals from the NSC.

Samples of the navigation signal recorded on an oscilloscope from different RF outputs of the simulator were processed. Based on the capabilities of the used oscilloscope, the analogue-to-digital conversion frequency was 40 GS/s (the value required to provide the required NSP of the developed method), the sampling duration was 25 μs.

In a phase-shift keyed signal, the carrier frequency received from the NSC must be restored using one of the well-known methods: squaring, cross-correlation, Z-tracking et al. [3], [8].

The phase difference of the carrier frequency of the navigation signal was calculated by the formula (1) [2]:

\[ (\varphi_2 - \varphi_1) = \arcsin \left( \frac{2 S_1[k] S_2[k]}{A_1[k] A_2[k]} \right) \]  

where \( S_1[k] \) and \( S_2[k] \) - the average value of the element-wise averaging of the arrays \( S_1[k] \) and \( S_2[k] \) over a time interval of 50 ns (1/10 of the length of the ranging code chip);

\( A_1[k] \) and \( A_2[k] \) are the amplitudes of the recorded signals at the k-th sample values.

The sampling reports used to calculate the carrier phase difference are selected according to the rule \( S[k] \in \Delta T \) (\( \Delta T \) are the processed sampling intervals) if \( S[k] \cdot S[k+1] > 0 \). If \( S[k] \cdot S[k+1] < 0 \), then \( S[k-m] \ldots S[k-1], S[k], S[k+1] \ldots S[k+m] \) are excluded from the time interval \( \Delta T_i \) (the number of excluded reports (m) generally depends on the edge length of the pseudo-random sequence chip of a particular type of GNSS-simulator).

The applied method for calculating the phase difference was selected from the measurement methods adapted for use in digital information-measuring systems, since it has the smallest error at the boundaries of the measurement range [4].

Since formula (1) allows you to calculate the signed phase difference in the range \((-\pi / 2; \pi / 2)\), the GNSS-simulator must be pre-calibrated in terms of the relative delays in the formation of pseudoranges between the radio frequency outputs of the signal simulator with a tolerance limit of \( \leq 10 \) cm (less than half the wavelength of the carrier frequency) according to the method [5].

5. Calculation of the non-excluded systematic error of method

The boundaries of the non-excluded systematic error of the phase difference measurement method are calculated by the formula:

\[ \Theta = \pm 1.4 \sqrt{\Theta_{\varphi_1}^2 + 2 \left( t_{0.99} \Theta_{\varphi_2} \right)^2 + 2 \left( c_{\varphi_3} \Theta_{\varphi_3} \right)^2} \]

where \( \Theta_{\varphi_1} \) is the confidence limit of the error (p = 0.99) for measuring the phase difference with an oscilloscope;

\( \Theta_{\varphi_2} \) - confidence limit of error (p = 0.95) for measuring the length of the connecting cable;

\( \Theta_{\varphi_3} \) is the boundary of the non-excluded systematic error component arising from the mismatch between the outputs of the signal simulator and the inputs of the oscilloscope;

\( c_{\varphi_3} \) – coefficient of influence (calculated as a partial derivative \( \Theta_{\varphi_3} \) according to the measured values);

\( t \) – Student's coefficient for a given confidence level and number of measurements.

5.1. Calculation of \( \Theta_{\varphi_1} \)

The component of the error due to the measurement of the phase difference with the oscilloscope by the indirect method is calculated by the formula:

\[ \Theta_{\varphi_1} = f_{0.99}(v \geq 200) \]

(2)
In formula (2):
\[
S_{(\phi_2-\phi_1)} = \frac{360}{\pi} \Theta_{osc} \sqrt{\frac{1}{3} \left( \frac{\sqrt{5}}{2A_1} \right)^2 + \left( \frac{\sqrt{5}}{2A_2} \right)^2 + \frac{1}{5kA_1A_2}}
\]

where \( \Theta_{osc} \) is the limit of the permissible absolute error in measuring the DC voltage with an oscilloscope;

\( A_{1,2} \) – signal amplitudes;

\( k \) is the number of averaging.

For \( A_1 = A_2 = 0.7 \text{ B}, k = 2000 \) (ensuring at least two measurements on the chip of the quadrature component of the navigation signal) with an oscilloscope sampling resolution of at least 40 GS/s and \( \Theta_{osc} = 25 \text{ mV} \) [6], \( \Theta_{\phi_1} = 0.1^\circ \).

5.2. Calculation of \( \Theta_{\phi_2} \)

\( \Theta_{\phi_2} = 0.5^\circ \) is the confidence limit of the error at a confidence level of 0.95 for measuring the phase of the transfer coefficient of each connecting cable (measurements were carried out on the first class working standard of the unit of wave resistance in coaxial waveguides in accordance with GOST R 8.813-2013).

5.3. Calculation of \( \Theta_{\phi_3} \)

\[
\Theta_{\phi_3} = 360 f T \frac{2|G_g||G_u|}{1 - 2|G_g||G_u|} \quad \text{the margin of error in measuring the carrier phase due to mismatches between the signal simulator and the oscilloscope in the connecting cable [7],}
\]

where \( f \) is the frequency of the carrier signal of NSC;

\( T \) is the electrical length of the connecting cable;

\( G_g \) – coefficient of reflection from the output of the GNSS-simulator;

\( G_u \) is the reflection coefficient from the oscilloscope input.

For \( f = 1.605375 \text{ GHz} \) and \( G = 0.05 \), \( \Theta_{\phi_3} = 1.3^\circ \).

The final value of the non-excluded systematic error of the developed method is \( \Theta = 1.4^\circ \).

6. Experimental results

Figure 2 shows the results of measuring the phase difference by the developed method and the state secondary standard of units of complex transmission coefficients in the range from 0 to minus 60 dB and complex reflection coefficients in the range from 0.002 to 1 in the frequency range from 0.05 to 65 GHz (as the comparison was made by a passive signal divider). The convergence of the results is \( 0.7^\circ \) for the frequency range from 1 to 2 GHz.

![Figure 2. Comparison of measurement results by the developed method and the state secondary standard.](image)
7. Conclusion
A new method has been developed for measuring the phase difference of the carriers of the navigation signals generated by GNSS-simulator, which, in contrast to the currently used oscillogram method, is based on the use of a multichannel high-frequency analogue-to-digital conversion to measure the parameters of the GNSS-simulator.

For the developed method, the non-excluded systematic error for measuring the phase difference of the carrier frequency of 1.5 ° is provided (which is equivalent to the non-excluded systematic error for the formation of attitude determinations of 1.3ʹ with a distance between the antennas of attitude navigation receiver of 2 m).

For the developed method, limitations are set:
- the GNSS-simulator must be pre-calibrated in terms of the relative delays in the formation of pseudo-ranges between the radio frequency outputs of the GNSS-simulator with a tolerance limit of ≤10 cm (less than half the carrier wavelength);
- complex reflection coefficients of the GNSS simulator outputs and the inputs of the analogue-to-digital converter should be no more than 1.1;
- the ability to form a GNSS-simulator of one NSC with zero pseudo range and Doppler frequency shift;
- ADC sampling rate not lower than 40 GHz;
- the number of ADC channels is not less than 2.

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