Simulator of GNSS signals for testing of space objects receivers in the earth conditions

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Abstract: A technique for testing space object receivers using global navigation satellite system (GNSS) signal simulator of the navigation field is proposed. Its structure consists of two blocks which allow synthesizing the scenario of reciprocal displacement of the receiver relative to navigation satellites and their signals. In the first block, according to the known coordinates of the receiver which are specified in tabular form or analytically, the distances between the receiver and the navigation satellites are calculated as well as their relative velocities. According to these data, the second block synthesizes the signals of navigational travelers with the specified characteristics which are transmitted via the air or cable with a given attenuation to the receiver. This allows testing on the earth receivers for airplanes and space objects under different scenarios of their movement, which not only reduces the risk of problems during the flight, but also avoids significant economic costs. Based on real data obtained by approaching two spacecraft using a simulator, the receiver was tested, which shows the promise of the proposed technology.

Key words: global positioning system (GPS); global navigation satellite system (GLONASS); global navigation satellite system (GNSS)-simulator; satellite navigation systems (SNS)

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0 Introduction

The development of navigation systems for space objects must end with their testing. During the crash of the Proton-M spacecraft on May 16, 2014, one of the versions of the caused accident was the reversed polarity of the winding in the angular velocity sensor. The ultimate version of the caused accident rejected this assumption. Such situation would not arise if in the conditions of preparation for launch the navigation system was tested. To perform testing of navigation systems in difficult conditions, the simulation technology for dynamic of objects using the global navigation satellite system (GNSS) signal simulator are used[1-2]. The technology was described earlier for sea, land and air objects[3-4]. Fundamental differences of technologies for space objects do not exist. At the same time, there are features associated with high speed for carriers of the receiving devices. The complexity and often the inability to develop signal processing algorithms for receivers installed in space objects, in natural conditions make it urgent to develop GNSS signal simulators. The simulation script software is designed to prepare the scripting environment.

1 Description of GNSS signal simulator

GNSS signal simulator is designed to simulate the movement of satellite navigation equipment in the navigation field, which is generated by radio signals from satellite navigation systems, including global positioning system (GPS), Russian global navigation satellite system (GLONASS), European global navigation satellite system (GALILEO), and wide-band differential subsystem satellite-based augmentation system (SBAS).

GNSS simulator is used for such aspects as:

1) Research of signal processing techniques of satellite navigation systems (SNS);

2) Control and verification of performance of satellite navigation receivers;

3) Certification tests of satellite navigation receivers;

4) Simulated movement of onboard equipment (land, sea, air, space);

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5) Training on the subject of satellite navigation.

1.1 Principle of operation

The GNSS simulator is a 32-channel carrier frequency generator. Carrier frequency parameters can be set by the software. The operator has the ability to modify the software for his own needs. This process is called "creating a simulation scenario".

1.2 Parameters of carrier signals

The values of frequency for channels L1, L2, L5, E5a and E5b from GLONASS, GPS and GALILEO are shown in Tables 1—3. Table 4 shows the characteristics of the reference generator used to generate high-frequency simulator signal.

Table 1 Channel frequency values for L1 and L2 (GLONASS)

	L1 (MHz)	L2 (MHz)
−7	1 598.062 5	1 242.937 5
−6	1 598.625 0	1 243.375 0
−5	1 599.187 5	1 243.812 5
−4	1 599.750 0	1 244.250 0
−3	1 600.312 5	1 244.687 5
−2	1 600.875 0	1 245.125 0
−1	1 601.437 5	1 245.562 5
0	1 602.000 0	1 246.000 0
1	1 602.562 5	1 246.437 5
2	1 603.125 0	1 246.875 0
3	1 603.687 5	1 247.312 5
4	1 604.250 0	1 247.750 0
5	1 604.812 5	1 248.187 5
6	1 605.375 0	1 248.625 0
7	1 605.937 5	1 249.062 5
8	1 606.500 0	1 249.500 0
9	1 607.062 5	1 249.937 5
10	1 607.625 0	1 250.375 0
11	1 608.187 5	1 250.812 5
12	1 608.750 0	1 251.250 0
13	1 609.312 5	1 251.687 5

Table 2 Channel frequency values for L1, L2 and L5 (GPS)

L1 (MHz)	L2 (MHz)	L5 (MHz)
1 575.42	1 227.60	1 176.45

Table 3 Channel frequency values for GALILEO

L1 (MHz)	E5a (MHz)	E5b (MHz)
1 575.42	1 176.45	1 207.14

Table 4 Main technical characteristics of reference generator

Characteristic	Value
Frequency (MHz)	10,0
Maximum relative error during the year, no more than	$\pm 2.0\times10^{-8}$
Maximum relative frequency variation during a day, no more than	$\pm 1.0\times10^{-10}$
Allan variance at 1 s, no more than	2.0×10^{-12}
Time of the frequency setting with a relative error of 1.0×10^{-8} after turning, no more than	5 min

1.3 Structure of GNSS simulator

Taking into account the above frequency values, the parameters of carrier frequencies of the GNSS simulator are managed. Fig. 1 shows its simplified structure.

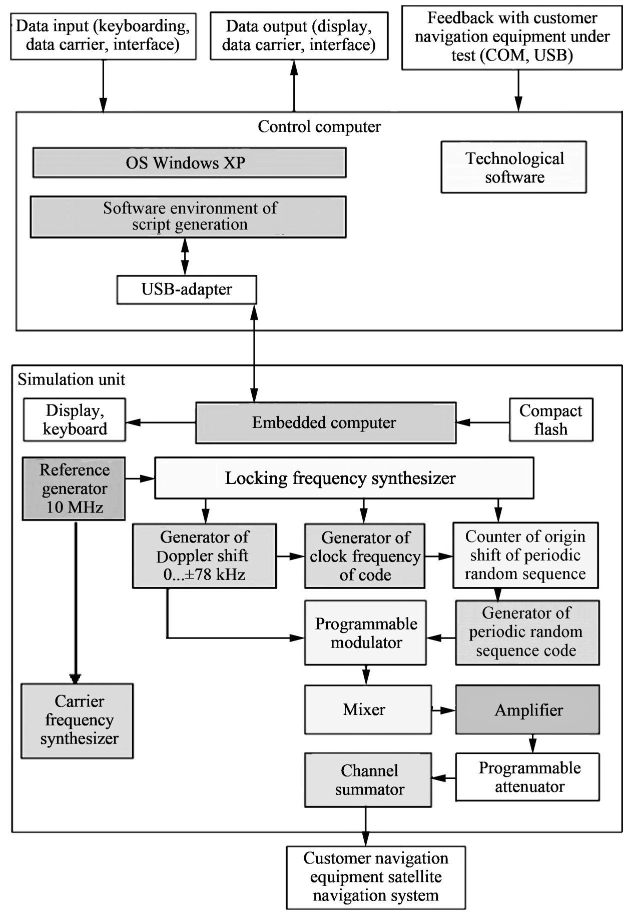


Fig. 1 Structure of GNSS simulator

The control computer on the circuit that performs the GNSS simulator communication function with the satellite navigation receiver operates according to the simulator signals. It is also used to develop and tune simulation scenarios. The created and configured script in the control computer is written to compact flash, and then transferred to the built-in computer. The operator uses the keyboard of the simulator to select the desired operating mode on the display and run the simulation script for execution. The built-in computer has programmatic access to generators of synthesizers, modulator and attenuator. Due to this, software control of the parameters of the nodes is implemented, which ensures the formation of a microwave signal corresponding to the given movement scenario of the receiving equipment carrier. Simplified control process for one simulation channel is shown in Fig. 2.

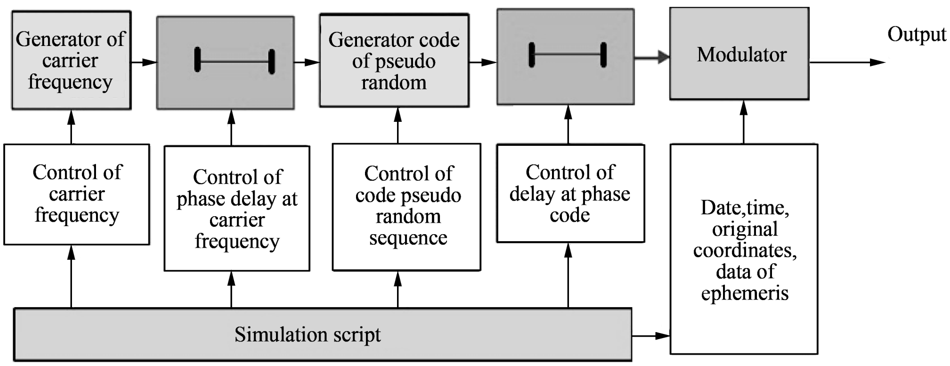


Fig. 2 Control of channel simulator

The general view of the specially developed by LLC "Navis-Ukraine" (Smela) simulator of GNSS signals is shown in Fig. 3. Satellite receivers (except for special applications) have altitude and speed limitations. Satellite receivers for space applications must operate in conditions that exceed the limitation requirements.

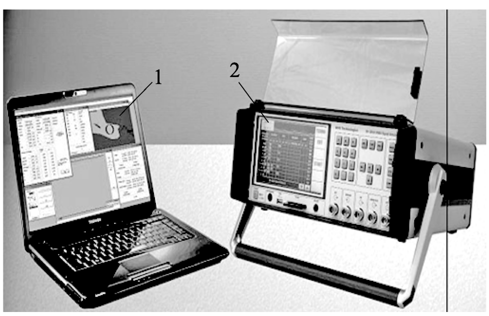


Fig. 3 Signal simulator: 1 is PC with the software for creating scenarios, 2 is simulation block

2 Simulation and results

2.1 Features of GNSS simulation scenarios while approaching of highly dynamic objects

The movement of highly dynamic objects in near-earth space is characterized by some peculiarities regarding to typical kinds of objects movement on the arth surface and in the air. Such features include rapid change of working constellations, presence of GNSS spacecraft signals with negative elevation angle values, increased Doppler frequency, and at altitudes over 300 km above the earth level, possible reception of antipode satellites in the GLONASS system.

The previously developed navigation system of nanosatellite POLYITAN-1 was tested on simulation scenarios for orbital motion. All the features in the requirements were taken into account and the simulation script was built for a complete turnover around the earth. The situation of convergence of space objects is much more complicated due to the fact that the simulation scenario is formed for two material points of space. The primary task is to form the trajectory of the motion of two orbital objects, which mutually converge. Convergence and docking of objects in near-earth orbit is a complex maneuver that can be performed in several ways: using orbital phasing and using a low-cost transient trajectory. Phasing of the orbit is the latitude argument changing of the spacecraft to bring it into the docking orbit. Currently, the convergence and docking of spacecraft are carried out without the use of GNSS technology. An example is the docking of manned spacecraft "Soyuz" with the International Space Station (ISS). During the movement on the third and fourth turns, the ship receives two pulses from its engines, while it is transferred to the orbit of phasing. On this orbit, the transport ship is below the ISS and catching up with the station. For this purpose, 17 and 18 turns receive long-range approaching impulse and then at 30—31 circulation—the final impulse of long-range approaching. After this, the necessary manipulations for the direct docking of objects are carried out.

2.2 Simulation of motion scenario for single and group of objects in space and their docking

Modeling the movement of objects in space begins with the simulation of the motion orbits. For this purpose, formula or tabular data are used. It based on laws of Kepler's celestial mechanics[1]. The development of motion scenarios for one or two objects in space does not differ in essence. In both cases, it is necessary at first to form a mathematical model of the orbit[1-2]. With a mathematical model of motion in orbit, a technical task is developed for the simulation scenario. According to the developed scenarios, specialized GNSS receivers designed by LTD "Navis-Ukraine" (CH-4706 and RNPI) were tested. Receiver CH-4706 is the single-frequency L1 GPS and L1 GLONASS, and receiver RNPI is the two-frequency L1/L2 GLOGASS and L1 GPS. The testing of receivers for each of the scenarios was carried out by comparing the current coordinates, time and speed parameters obtained from the GNSS receivers when they are fed with signals from the simulator of the navigation situation for the given scenario with the predicted scenarios. For this, the GG HUNTER scripting environment software is used. The program is located outside the simulation block, in the PC. It receives simultaneously information from the simulator about the current passage of the control points of the scenario, as well as information from the GNSS receiver. Since the accuracy characteristics for the simulator are metrologically attested and an order of magnitude is better than the same characteristics of GNSS receivers, such verification makes it possible to compare data and to obtain not a deviations but an error. Works that were conducted earlier and did not have orbital dynamic parameters repeatedly confirmed the accuracy characteristics of GNSS receivers. Table 5 shows the data on which scenarios were developed for simulating the approach of two space objects.

Table 5 Parameters for the development of simulation scenario for converging of two space objects

Parameter	Value
Assignment method	Tabular method
System type	GLONASS, GPS
Channels	L1 GLONASS CT code, L1 GPS C/A code
Duration	No less than 300 min
Ionospheric influence	Absent
Tropospheric influence	Absent
Multipath influence	Absent
Altitude and speed limits	Absent
Parameter monitoring period	1 s
Form of object representation	Material point
Object	Spacecraft
Parameters	Advanced
Altitude	From 1 to 8 000 km
Speed	From 0 to 14 000 m/s
Acceleration	From 0 to 500 m/s^2
Dash	From 0 to 500 m/s^3
Antenna directivity diagram	Spherical

To test the scenario and the operation of the navigation equipment, the receivers used were as follows:

1) Receiver CH-4706 with software version 4 706 k 03.21 from 08.15.2014;

2) Receiver RNPI with software version fgcim 01.03 from 26.08.2009.

The accumulation performed by National Marine Electronics Association (NMEA) protocol, and temp of the solutions for navigation task by receivers is 10 Hz. For accumulation, the current distances between the objects were calculated. In Fig. 4, a graph of the change in the distance between two objects in orbital motion according to data from receivers is shown. The minimum distance between the objects is 1 061.515 m.

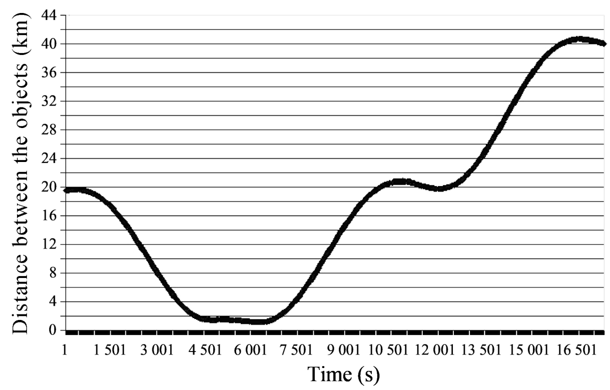


Fig. 4 Dependence of distance between real objects in space

In Fig. 5, the difference in distances between two objects for the planned scenario and the actual obtained results is shown. The discrepancy is from −40 m to +43 m in the entire range of distances between converging space objects was obtained.

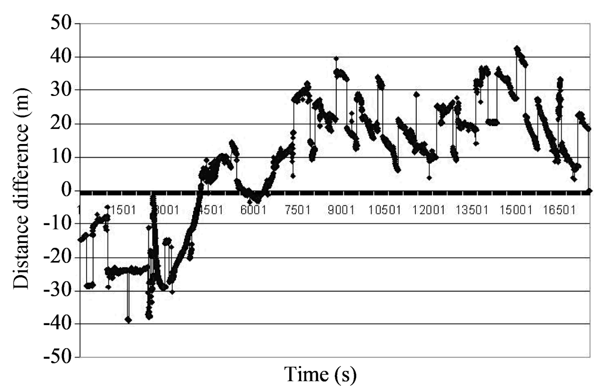
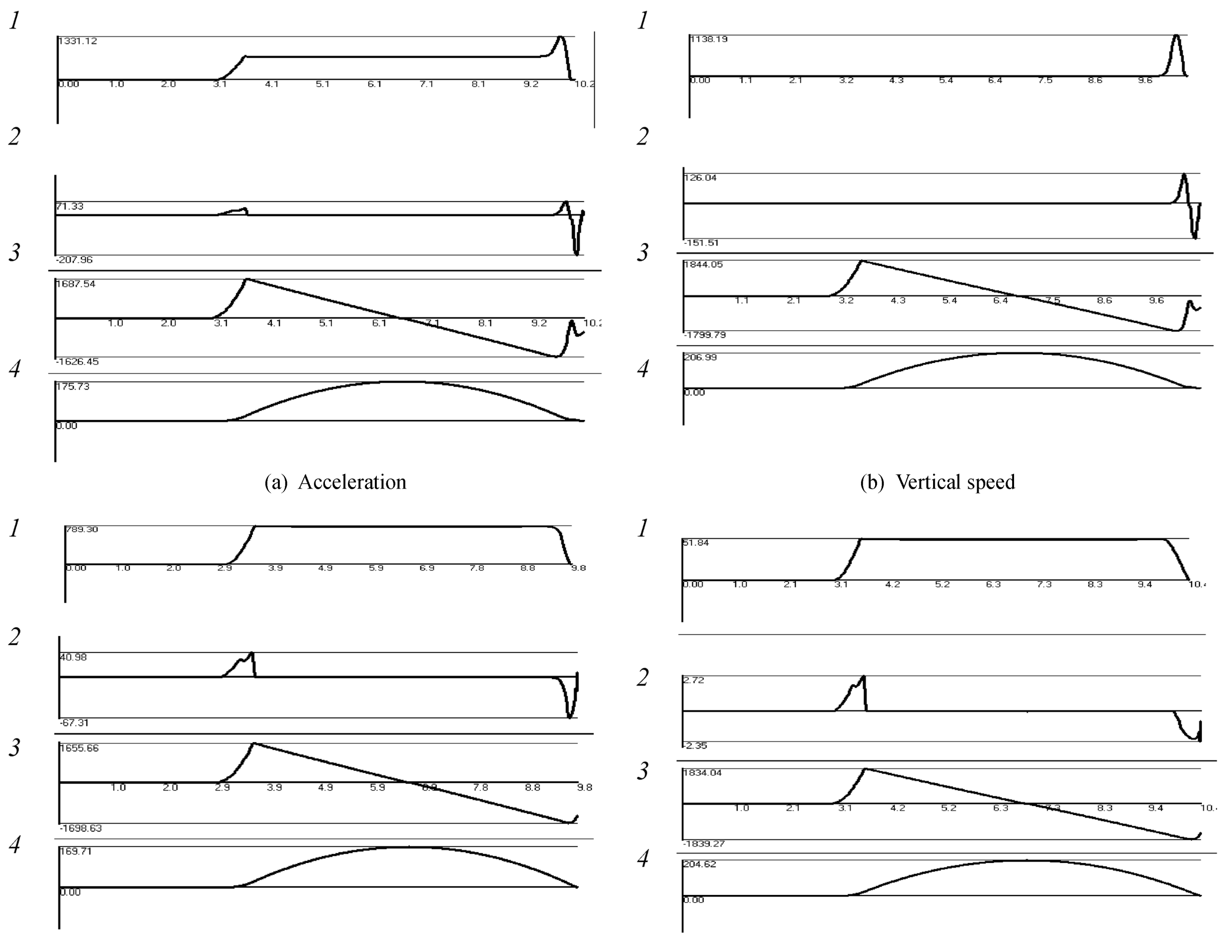


Fig. 5 Difference between scenario and actual data

2.3 Checking for errors in the simulator for various operating modes, different ranges of altitude and speed of objects convergence in space

To determine the source of receiver location errors in space objects of the real source data from

"Yuzhnoe" Design Bureau, four simulation scenarios differing flight dynamics parameters were formed additionally, as shown in Fig. 6. Moreover, in the first scenario, two variants of the rate of issuing decisions of 10 ms and 100 ms were considered. It was used to test the equipment and to determine the effect on measurement errors of various parameters. The obtained are shown in Tables 6-9.



(a) Acceleration (b) Vertical speed (c) Altitude (d) Under different flight scenarios

Fig. 6 Behavior of horizontal velocity

Table 6 Results of estimating the parameters for 1 scenario and the rates of issuing of solution per 10 ms/100 ms

	Receiver CH-4706		RNPI	
	Mean	RMS	Mean	RMS
Latitude (m)	0.263/0.406	2.139/1.829	0.216/0.179	1.426/1.696
Longitude (m)	−0.811/−0.786	0.336/0.263	−0.080/0.099	0.323/0.342
Altitude (m)	1.826/1.616	2.651/2.436	2.351/2.509	3.063/2.923
Velocity (m/s)	2.599/2.547	2.214/2.026	2.417/2.590	2.347/2.333

Table 7 Results of estimating the parameters for 2 scenario and the rates of issuing of solution per 10 ms

	Receiver CH-4706		RNPI	
	Mean	RMS	Mean	RMS
Latitude (m)	0.610	0.849	0.253	0.833
Longitude (m)	−0.533	0.170	0.091	0.324
Altitude (m)	3.802	4.147	2.276	2.726
Velocity (m/s)	0.178	1.344	0.144	1.273

Table 8 Results of estimating the parameters for 3 scenario and the rates of issuing of solution per 10 ms

	Receiver CH-4706		RNPI	
	Mean	RMS	Mean	RMS
Latitude (m)	0.285	1.552	0.326	0.573
Longitude (m)	−0.767	0.245	−0.103	0.254
Altitude (m)	1.518	2.342	2.161	3.130
Velocity (m/s)	2.776	1.876	2.606	1.900

Table 9 Results of estimating the parameters for 4 scenario and the rates of issuing of solution per 10 ms

	Receiver CH-4706		RNPI	
	Mean	RMS	Mean	RMS
Latitude (m)	0.483	0.118	0.255	0.290
Longitude (m)	−0.612	0.118	−0.043	0.253
Altitude (m)	3.193	4.000	2.298	2.767
Velocity (m/s)	0.170	0.172	0.165	0.208

The following designations are used: Mean is mathematical expectation, RMS is standard deviation. When assessing the performance of the CH-4706 and RNPI receivers in the developed scenario, the deviation of the speed data reaches the values greater than 2 m/s, which is much worse than the characteristics of the receivers. The deviation of the coordinates is within the limits of errors. For such a scenario, the flight trajectory of a missile is almost the entire flight with a horizontal velocity of about 750 m/s (except for take-off and fall sections). At the end of the flight, the horizontal velocity ejected is up to 1 331 m/s. In this case, the acceleration of the vertical component acts.

In assessing the results of the receivers CH-4706 and RNPI, according to the developed scenario, deviations in the speed data reach 1.34 m/s. With this version of the trajectory, almost the whole flight passes at a horizontal speed of less than 9 m/s. At the end of the flight, the horizontal velocity is released to 1 138 m/s.

In assessing the results of the receivers CH-4706 and RNPI, according to the developed scenario, deviations in the speed data reach 1.9 m/s. With this version of the trajectory, almost the whole flight passes at a horizontal speed of less than 800 m/s, excluding the areas of take-off and fall.

In this version of the rocket's trajectory, almost the whole flight passes at a horizontal speed of about 52 m/s, excluding the areas of take-off and fall.

In general, it can be noted as the satisfactory results of both receivers for all four scenarios of rocket motion.

2.4 Program module of GNSS signal simulation scenario for low dynamic space objects during docking

The simulation scenario was created for stop mode, the length of the baseline in the scenario was laid at 2.00 m, and the azimuth is 45°. The scenario duration is approximately 65 min. The following results are in the form as they are generated by the program "Saturn".

Tables 10-11 show that the errors regarding the scenario parameters obtained by code measurements are much higher than that for phase measurements.

Table 10 Code solution

Direction (1t>2t)				Baseline length (2.873 7 m)			
X (m)	RMS (m)	*Z* (m)	RMS (m)	*Y* (m)	RMS (m)	Azimuth	Excess (m)
−2.410 7	0.018 4	1.534 5	0.026 4	0.303 1	0.015 7	32°10′58.656 0	−0.071 3

Table 11 Phase solution

Direction (1t>2t)				Baseline length (2.873 7 m)			
X (m)	RMS (m)	*Z* (m)	RMS (m)	*Y* (m)	RMS (m)	Azimuth	Excess (m)
−1.656 2	0.000 2	0.9254	0.0001	0.636 2	0.000 1	44°59′20.963 1	0.001 0

As a result of the work, it was not possible to obtain a fixed solution, but only a floating one.

However, the errors of the floating solution, as can be seen from Table 11, are satisfied for solving technical problems in the orientation of space objects during docking (1 mm along the length of the baseline and 0.79 angular minutes in azimuth). Technically, the task was accomplished, but the lack of a fixed solution does not yet provide an opportunity to move on to the next stage which is the development and testing of a scenario for connecting highly dynamic objects.

3 Discussion

According to Refs. [3-4], a floating solution is the initial solution of phase ambiguity. With the method of least squares (MLS), a non-integer solution of phase ambiguities is searched. The solution simultaneously contains corrections to the coordinates and ambiguities of the phase measurements. The fixed solution is the final stage of solving the phase ambiguity. At this stage, an integer number of phase cycles is calculated based on the floating solution, as well as the phase fraction values that GNSS receivers measure. Unfortunately, in practice, even taking into account the hardware capabilities, several variants of the integer solution are possible. To find the true solution, priori information about phase measurements at the second frequency L2, knowledge of the baseline and information from inertial navigation systems (INS) are used. In recent years, for transtion to an integer solution, the Lambda method has been used, which uses decorrelation of the output data (the first and second phase differences are correlated) and provide solutions in the form of some integer sets of ambiguities that are most suitable for the resulting floating solution. There can be many of such sets. The contrast of a fixed solution is the ratio of the root-mean-square errors of the residual deviations of the phase measurements obtained by substituting two integer sets in the output data that give the best mean-square estimates. The criterion for a fixed solution has a threshold contrast value of at least 2.

4 Conclusions

The created software controlled navigation field simulator allows synthesizing GNSS signals at the receiver location. This provides the possibility of its testing on the earth for various scenarios of the motion of its carrier. Especially its using in the development of receivers and their software for space objects is relevant when the development of technical solutions involves a lot of technical problems and significant economic costs. The processing of files of several real scenarios of space objects motion makes it possible to estimate the errors of the orbit passage parameters and to form a general approach to the technology of testing the navigation systems of spacecraft in the laboratory. Also, testing shows an unpredictably large speed error in standard GNSS receivers for large vertical accelerations of the carrier. The obtained results serve as a starting point for the investigation of the Doppler signal tracking rings in GNSS receivers in order to localize the source of increased errors in velocity. The results of the experiments allowed to formulate the following conclusions:

1) For all four scenarios of motion, there are no unacceptably large errors in the coordinates. The error in the coordinates is obtained less than the technical documentation of the receivers.

2) For all four scenarios of motion, there is a large error in determining the speed. Excess reaches up to two orders of magnitude.

3) The magnitude of the speed itself does not have a decisive influence on the speed error. A decrease in speed by an order of magnitude reduces the error in estimating the speed itself by a factor of 2.

4) The presence of a vertical component of the velocity, especially vertical acceleration, makes a significant contribution to the velocity error overall.

5) Relatively small values of the coordinate errors indicate that the values from Fig. 5 are due to the inaccuracy of the forecast scenario relative to the actual location of the object. The final decision on the scenario should be taken based on the results of testing and not according to the forecast.

6) A significant error increase in estimating the speed is evidently from the fact that, depending on the implementation of Doppler frequency filtering and the determination of object speed, the weighting factors for vertical speed and vertical acceleration require correction. The development for most receivers, including for aviation purpose, was carried out at low vertical speeds and acceleration. At the same time, space objects is characterized by the presence of large vertical accelerations, especially when they start.

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基于 GNSS 信号模拟器的地球条件下空间物体接收器的测试

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摘　要： 提出了一种利用导航场 GNSS 信号模拟器对空间物体接收器进行测试的技术。其结构由两大模块组成，用以合成接收器与导航卫星的相对位移的场景及信号。在第一个模块中，根据已知的以表格形式或分析方法得到的接收器坐标，计算出接收器与导航卫星之间的距离以及它们的相对速度。根据这些数据，在第二个模块中，将导航旅行者信号和特定特征进行了合成，这些信号通过空气或电缆传输，到达接收器有一定的衰减。这允许在不同的运动场景下对飞机和太空物体的地面接收器进行测试，既降低了飞行过程中出现问题的风险，又可以避免巨大的经济成本。利用模拟器接近两艘宇宙飞船获得的真实数据对接收器进行了测试，展示了所研究技术的前景。

关键词： 全球定位系统(GPS)；俄罗斯全球导航卫星系统(GLONASS)；全球导航卫星系统模拟器；卫星导航系统(SNS)

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