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DEVELOPMENT OF PPP-METHOD REALIZATION FOR LOW EARTH ORBIT SATELLITE TRAJECTORY DETERMINATION USING ON-BOARD GPS-OBSERVATIONS

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Представлені результати розробки нової реалізації PPP-методу (Precise Point Positioning) високоточного визначення траєкторій низькоорбітальних космічних апаратів (НКА) з використанням бортових GPS-спостережень. Описано особливості та характеристики запропонованого варіанту PPP-методу траєкторних визначень. На прикладі обробки GPS-спостережень спеціалізованих супутників COSMIC показано, що запропонована реалізація PPP-методу дозволяє визначати параметри траєкторій НКА з субдециметровою точністю

Ключові слова: GPS, кодові і фазові спостереження, метод точного позиціонування PPP

Представлены результаты разработки новой реализации PPP-метода (Precise Point Positioning) высокоточного определения траекторий низкоорбитальных космических аппаратов (НКА) с использованием бортовых GPS-наблюдений. Описаны особенности и характеристики предложенного варианта PPP-метода траекторных определений. На примере обработки GPS-наблюдений специализированных спутников COSMIC показано, что предложенная реализация PPP-метода позволяет определять параметры траекторий НКА с субдециметровой точностью

Ключевые слова: GPS, кодовые и фазовые наблюдения, метод точного позиционирования PPP

1. Introduction

Equipping of Low-Earth Orbit Satellites (LEOS) with global navigation satellite systems (GNSS) receivers, in particular, GPS system, opens unique opportunities of scientific researches in such areas as geodesy, geodynamics, updating of geoid, space weather monitoring, meteorology etc. In some applications (Earth remote sensing, the researches of gravitational field, the study of melting glaciers etc.), determination of LEOS current coordinates (positioning) shall be made on decimeter and even centimeter-accuracy level.

The classic way of achievement of high-precision accuracy of navigation determinations is using the differential method in which the observations of mobile ("rover") user receiver are combined with the observations of one or more ground reference stations. However, the implementation of the differential method for LEOS trajectories determination is conjugated with considerable difficulties due to the drastically different conditions of observations on board the LEOS and on the Earth, small intervals of the conjoint radio visibility of medium-orbit GNSS satellites from board the LEOS and reference stations, LEOS positioning difficulties over the oceans. Another method of precision determination of LEOS trajectory parameters is to use only autonomous GNSS-observations on board the LEOS without using the measurements of reference stations. This alternative method is called the method of Precise Point Positioning (PPP) described in detail, for example, in [1, 2] and [3], where the comparison between the differential and autonomous PPP methods of precision positioning is carried out.

In Ukraine, the developments of precision positioning technologies using the PPP-method began to be carried out rather recently. In particular, such works were prescribed within the Special-Purpose Package Programme of the National Academy of Sciences of Ukraine for scientific space researches including the interests of the program of carrying out the international scientific space experiment "Ionosat-Micro" [4].

Thus, the current interest is the creation of hardware and software means for high-precision coordinate-timing support of spacecrafts of various purposes and, in particular, the implementation of LEOS PPP-positioning with sub-decimeter accuracy using GNSS signals.

2. Literature review and problem statement

To compensate the basic errors of observations the PPP method implies the use of high-precision parameters of orbits (ephemeris) and satellite clocks, inter-frequency delays in the analog tracks of GNSS satellites [1–3, 5, 6], which are given for use by the international and national centers of

GNSS-observations processing, such as IGS, CNES, JPL etc. [2, 5, 7]. When implementing the PPP-method the accounting (compensation) of specific sources of errors, such as the effect of the additional carrier-phase shift caused by the rotation of satellite antennas ("wind-up" effect), relativistic, geodynamic effects, irregularity of phase characteristics of satellite antennas etc. is of great importance [2, 3, 5–9]. The use of the PPP-method implies the use of carrier-phase measurements with millimeter/centimeter accuracy level as the main ones, along with that the code measurements, unambiguous, but relatively rough observations have the auxiliary character during the observation processing. Carrier-phase GNSS observations, along with high precision, have two important distinctive features – they are ambiguous and, as a rule, for a number of reasons contain cyclic slips. The solution exactly of these two tasks is the foundation for achieving high accuracy GNSS-positioning, and the methods of solving the given tasks in one or another positioning mode determine the peculiarities and characteristics of one or another implementation of coordinate determinations, including the PPP method [2, 5–8].

There are two basic approaches in realization of the PPP-method. The first (and main) method involves estimation of unknown discrete/integer carrier-phase ambiguities as the continual variables (i.e. float-solution) [2, 3, 7, 8] and has been actively used by researchers and developers for a long time. However, in the recent years there has been considerable interest in the realization of another method, which involves searching the discrete/integer carrier-phase ambiguity resolution (i. e. fixed-solution) [6, 7, 10, 12], and has significantly improved characteristics (in terms of accuracy and rate of solution convergence). The analysis shows that practically all foreign large companies-developers of hardware and software for GNSS-positioning have their own implementation of the PPP-method in both options. The leaders are Trimble (USA), Septentrio (Belgium), NovAtel (Canada), GMV (Spain). With regard to the considered task of high-precision LEOS trajectory determination by the PPP-method there may be noted papers [13, 14], where are proposed and examined in detail the variants of realization of the discrete carrier-phase ambiguity resolution applied to on-board LEOS GPS-observations and described the properties and experimental results.

In general, despite the progress made in the world, the PPP-method has a number of disadvantages compared with the differential method. One of them is a relatively long interval of convergence/solution initialization which restricts the use of the method when real time positioning is carried out [3, 7, 8, 10, 12]. Therefore, the solution of the problem of development of new and upgrading of the existing options for implementing high precision LEOS positioning, searching the ways of reducing the influence of factors limiting the accuracy and performance characteristics of the PPP-solutions is very prospective.

3. The purpose and tasks of the research

The purpose of research has been the creation of algorithmic and software means of determination of LEOS trajectory parameters according to the results of on-board GPS-observations by PPP centimeter/sub-decimeter accuracy.

To achieve this goal the following tasks were solved:

– modeling the components of errors of GPS-observations, assessing their impact on the quality of the functioning of the algorithms and accuracy estimation of determining the parameters of the LEOS movement;

– development of new algorithms for processing on-board GPS-observations, including the elimination of carrier-phase cycle slips and carrier-phase ambiguity resolution (CPAR) [15–19] to obtain reliable and accurate "float" and "fixed" solutions in conditions of LEOS high motion dynamics;

– verification of the proposed realization of the PPP-method using real GPS-observations and evaluation of solutions quality indicators (accuracy, convergence, reliability of carrier-phase ambiguity resolution).

4. Method and algorithms for GPS-observation processing and LEOS positioning. The tools used

For the purpose of testing of the experimental software the gathering and analysis of on-board GPS-observations of the specialized foreign LEOS COSMIC/FORMASAT-3 are carried out. In the process of the research the results of trajectory PPP-determinations using precise (final) estimates of GPS satellites ephemeris, clocks and other supporting information from the IGS International Service and the French space agency CNES were obtained.

For the conditions of LEOS motion high dynamics in the process of development there were solved the conventional tasks at the implementation of precision positioning – the elimination of carrier-phase cycle slips [15, 16] and carrier-phase ambiguity resolution [6, 7, 10, 11, 13, 17–19]. The presence of unambiguous carrier-phase observations and their linear combinations (on the tracks "GPS satellites – LEOS") makes it possible to perform precise trajectory determination. Satellite observations processing by the PPP-method (the original author's method realization) was performed using modified in respect to the tasks of processing of on-board GPS-observations of previous own developments [9, 15–19] – methods, algorithms and software tools. When building the CPAR task solution it was used the author's universal statistically correct methodology of the joint assessment of information and non-information "interfering" parameters [18], developed in [17, 19]. This approach has a number of distinctive features in relation to the foreign analogues. In particular, it is proposed to use:

– as a preliminary a priori solution a single-frequency code P1-solution with the compensation of ionospheric delays, which are previously estimated by code and carrier-phase "geometry-free" [15, 16] observations;

– the original model of equations of carrier-phase Iono-Free (IF) observations which implies their reparametrization in accordance with [17–19] and allows improving the stipulation of the system of observation equations, the reliability of solution and principle ability to work without the use of code observations;

– a new realization of a discrete algorithm of carrier-phase ambiguity resolution which implies stage-by-stage reparametrization and conversion of the system of observation equations according to the author's method [18]; this allows reducing the dimensionality of the problem until the sought number of discrete phase constants and optimally using the information of all the sample of observations.

The proposed CPAR solution consists of three steps. *The first stage* includes carrying out code P1-solution (in view of dual-frequency ionospheric corrections) and a carrier smoothed code solution for the current position of the satellite on-board receiving antenna; these solutions are used then as a priori information in the performance of CPAR. *The second stage* is to perform discrete/integer CPAR of the difference frequency carrier-phase combination Wide-Lane (WL) [5, 6, 13, 17, 20] using a known linear combination of code and carrier-phase observations Melbourne-Wübbena [12, 13, 17]. Along with that, code and carrier-phase corrections of GPS satellites hardware delays (the auxiliary information from the CNES processing center) are used. After determining the initial carrier-phase ambiguities of WL-observations it is carried out their verification using the known principle of ambiguities loop closures along the contours formed by GPS satellites constellations. Thereafter, it becomes possible to perform a discrete/integer CPAR for observations the first carrier frequency L1 (and then L2), using the Iono-Free (IF) combination [5, 6, 13, 17, 20] and this is the *third processing stage*. In order to implement CPAR the authors proposed to use a discrete searching for the best combination of phase ambiguities with respect to the initial approximation estimated using float-solutions [18, 19] with searching discrecity equal not to cycle but to half cycle of the combined frequency (Narrow-Lane phase combination) unlike the foreign procedures [7, 10, 11, 13]. This makes it possible to fend off the impact of the residual ephemeris-time errors of corrections which may reach according to the analysis ~5–10 cm. The obtained discrete/integer CPAR solution is subjected to verification procedure, i.e. confirmation of correctness of estimation of ambiguity parameters based on the chosen one or another statistics and criteria. After full realization of the CPAR and the implementation of corrections in carrier-phase observations it becomes possible to determine the final, most precise current coordinates of the antenna phase center of the on-board LEOS receiver and the divergence of receiver and GPS time scales.

For the purpose of coordinate-timing LEOS determinations it is used its own development – prototype of mathematical-software complex “OCTAVA” (Ukraine). The complex “OCTAVA” [21, 22] allows performing the traditional and network positioning of centimeter-level accuracy in single and dual-frequency modes. For the PPP-method realization the appropriate modernization of a number of software modules and the formation of new modules was carried out. The proposed generalized scheme of realization of PPP-method and algorithms of processing of on-board LEOS observations and precise positioning is shown in Fig. 1.

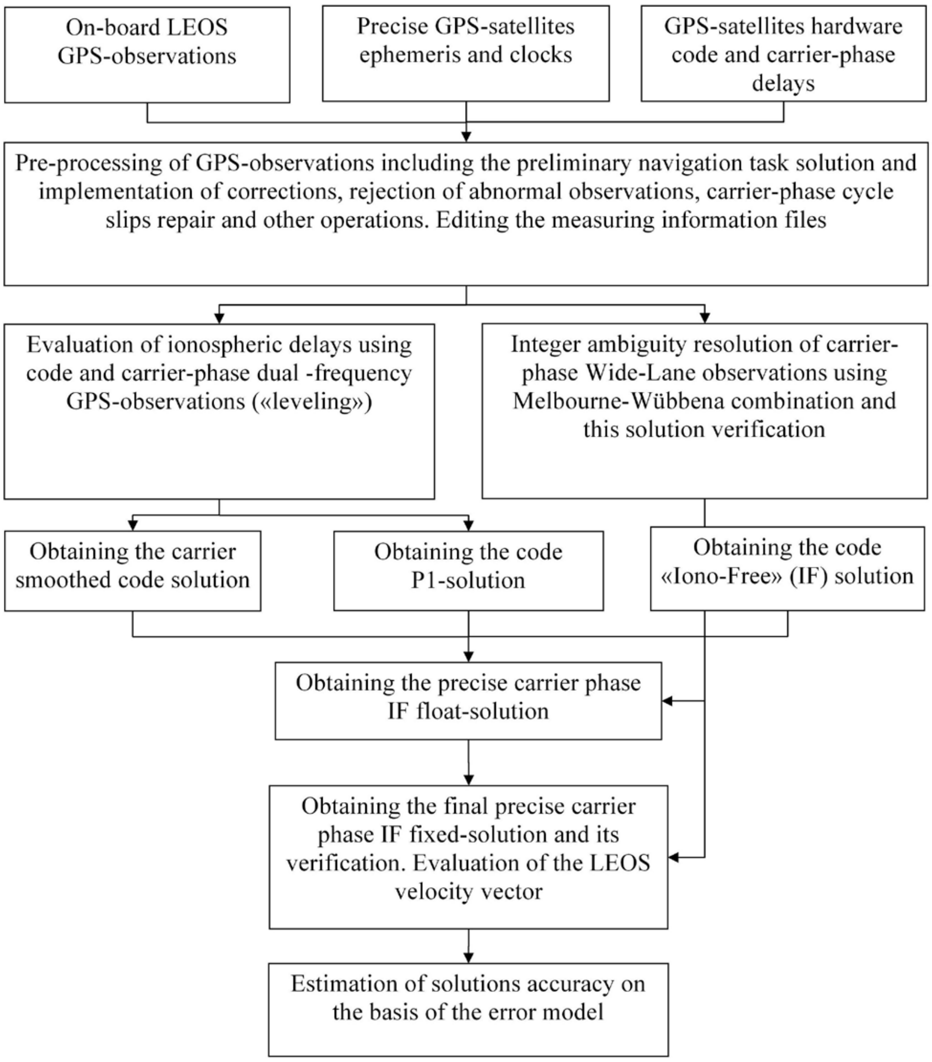


Fig. 1. The proposed scheme of realization of PPP-method and algorithms

It is advisable to perform comparing of not considered in this paper differential positioning technology (using observations of ground reference stations) and PPP technology. The use of the differential method of LEOS positioning has a number of serious limitations, primarily in zones of the joint radio visibility of satellites – no more than 30 minutes that for precise LEOS determinations requires using the observations of global dense networks of reference stations which, moreover, still do not cover the area the world's ocean.

COSMIC program satellites are characterized by the fact that the receiving GPS antennas have orientation not to zenith but to the side (to implement the Radio-Occultation technology [5]) which limits the composition of the working constellation of GPS satellites. In the case of using the differential method of determinations the number of GPS satellites in the current working constellation with high probability decreases due to the need to have the joint radio visibility of GPS satellites from LEOS board and from the ground stations. This leads to a significant increase (and even the appearance of large outliers) of the geometric factor (dilution of precision) and, accordingly, to a proportional increase (several times) of the errors of LEOS trajectory determinations. These realities together significantly limit the use of the differential positioning method.

In case of using the PPP-method, except the possibility of trajectory determinations over any region in the world, it is observed a decrease in several times of the geometric factor compared with the differential method.

The accuracy of the differential method is also limited by the need of excluding (adjustment) of tropospheric errors (on the tracks "GPS satellites – ground reference stations") of observations with very small errors (~1 cm for zenith delay), which does not allow using the standard tropospheric models and requires the evaluation of zenith delays on the ground network of reference GPS-stations with the required accuracy.

Initial data for testing of the proposed realization of the PPP-method

In this work for realization of discrete/integer carrier-phase ambiguity resolution ensuring the highest accuracy of coordinate determinations the data of the French space agency CNES were used, as described above. These data include the information about the precise ephemeris, precise corrections of GPS-satellites time scales as well as the precise corrections of code and phase hardware delays of GPS satellites. Just the latter corrections (code and phase delays) allow performing the discrete/integer carrier-phase ambiguity resolution of non-differential phase observations which was confirmed in this study.

For working off and testing of the developed algorithms and experimental software the GPS-observations of LEOS COSMIC grouping (Constellation Observing System for Meteorology, Ionosphere, and Climate) were used. The data were obtained from the archives of CDAAC (COSMIC Data Analysis and Archive Center) which are posted on the site http://cdaac-www.cosmic.ucar.edu/cdaac/indecs.html. Beside the data of on-board LEOS GPS-observations the authors performed searching and analysis of the available scientific references about the COSMIC satellites. This allowed obtaining the important additional information about the parameters of the on-board LEOS measuring system, parameters of orientation and position of the receiving antennas and spacecrafts themselves, about the used approaches to observation processing by foreign scientific organizations etc.

The chosen observations underwent pre-processing (data quality control, elimination of phase cycle slips etc.). Further processing was carried out in the PPP mode. For conversion of the reference trajectories of LEOS mass centers (presented together with GPS-observations in the archive of COSMIC-center) to the current position of the GPS antennas phase centers the additional information about the parameters of orientation and position of the receiving antennas and the LEOS themselves was used.

5. PPP positioning results, their analysis and discussion

Below in Fig. 2–6 there are the illustrations of coordinate determination results by the PPP-method and their accuracy estimation for the chosen COSMIC satellite.

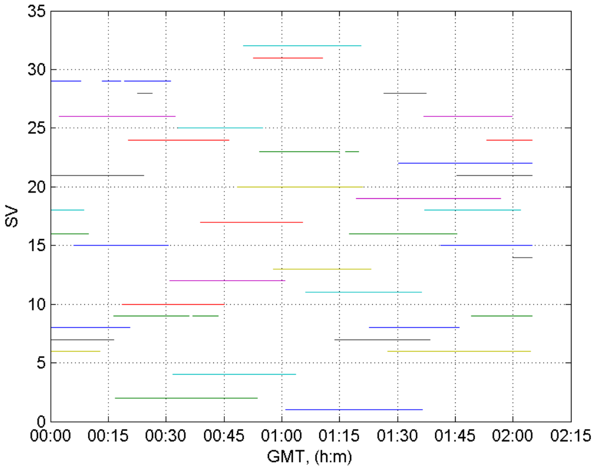


Fig. 2. Radio visibility zones of GPS satellites relative to LEOS

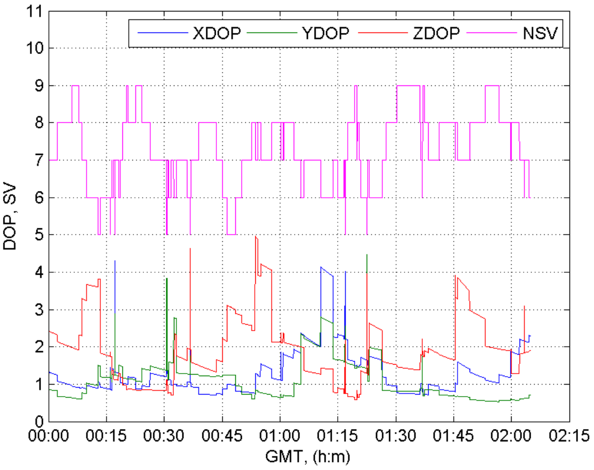


Fig. 3. Geometric factors (geometric dilution of precision — DOP) of the current GPS satellite vehicles (SV) operational constellation

As reference LEOS trajectory during a posteriori accuracy evaluation there were used LEOS coordinates estimations (with declared errors at the level of ~5 cm) obtained by the performers of the COSMIC space program by the combined processing of on-board GPS observations with kinematic and dynamic methods.

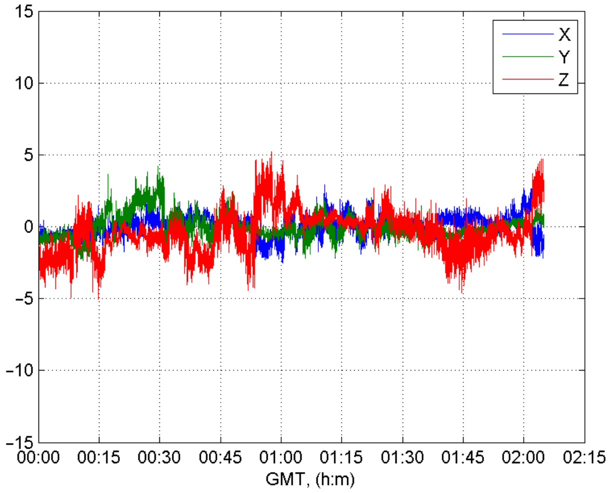


Fig. 4. The discrepancies (in meters) of the code P1-solution relative to the reference LEOS trajectory

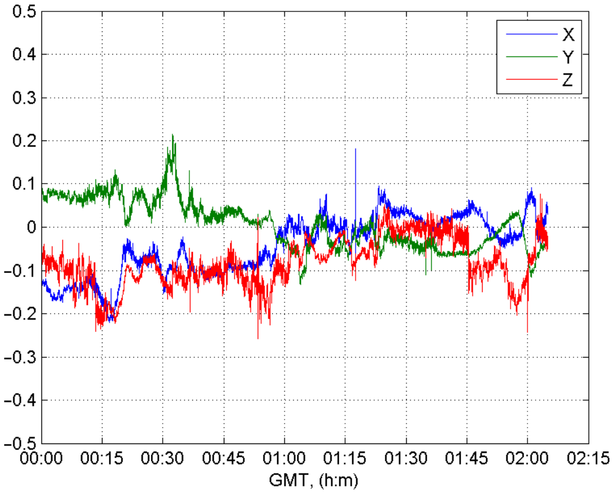


Fig. 5. The discrepancies (in meters) of the float IF-solution relative to the reference LEOS trajectory

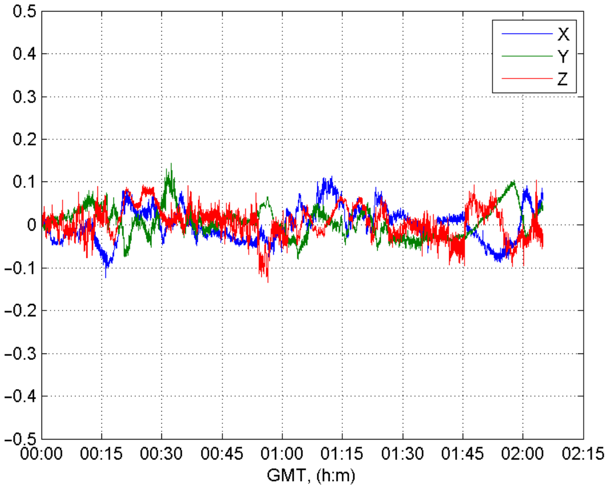


Fig. 6. The discrepancies (in meters) of the discrete fixed IF-solution relative to the reference LEOS trajectory

Fig. 2 shows the radio visibility zones of GPS satellites from the LEOS COSMIC on a time interval ~2 hours (about one LEOS circuit around the Earth) from the beginning of the day January 10, 2013.

Fig. 3 shows the geometric factors (geometric dilution of precision – DOP) of the current GPS satellite vehicles (SV) operational constellation for the selected interval of observations that characterize the deterioration of coordinate solution accuracy with respect to the accuracy of GPS-observations. Fig. 4 is an illustration of the results of the autonomous code P1-solution – discrepancies (in meters) relative to the reference LEOS trajectory.

Fig. 5, 6 show the discrepancies (in meters) of Iono-Free solutions: float PPP-solution (Fig. 5.) and discrete/integer fixed PPP-solution (Fig. 6) relative to the reference LEOS trajectory.

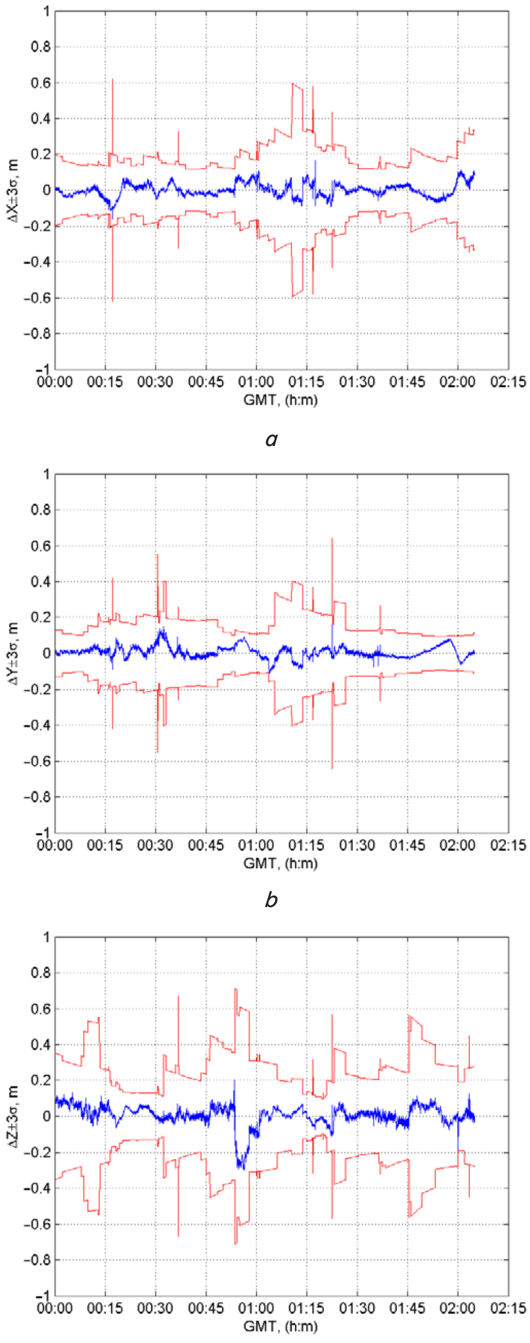
RMS of errors (a posteriori accuracy estimation) of the float solution relative to the reference trajectory made up ~0.06–0.11 m at the level of the Least Squares Method (LSM) residuals ~0.01–0.02 m. The latter indicates a good internal convergence of the solution at the level of carrier-phase measurement errors.

RMS of errors (during a posteriori accuracy estimation) of the discrete fixed-solution relative to the reference trajectory made up ~0.03–0.04 m, which is much more precise than the float solution. Limiting errors of the discrete solution lie within ~0.05–0.10 m. In both cases (float and fixed solutions) the determining of the current LEOS coordinates was performed by the geometrical method, i.e. without the use of a dynamic model of the LEOS motion. The errors in determining the divergences of GPS time scale and the on-board receiver time scale made up a few tenths of a nanosecond.

In the process of research considerable attention was paid to the development and testing of the model of GPS-observations errors and coordinate determinations, and also to the heuristic refinement of these model components. Such models, in combination with a posteriori accuracy estimation (in case of the availability of an independent source of reliable reference information) allow not only to predict the accuracy of the planned trajectory LEOS determinations but perform an important function of determining the area of searching the discrete carrier-phase solution during CPAR in order to achieve the best positioning accuracy. Detailed consideration of all significant sources and error components of all non-differential GPS observations is presented in [8, 9, 11]. At this stage of research for the float and fixed solutions the following levels (RMS) of components of IF-observations errors were specified:

- fluctuation errors and multipath ~1.6 cm;
- GPS satellite clock errors of ~4 cm;
- GPS satellites ephemeris errors ~2 cm;
- reference trajectory errors ~1.7 cm;
- systematic errors of a priori coordinates (code solution) are calculated by a separate derived empirical formula.

The use of these components during the calculation of correlation matrixes of coordinate determination errors (float and fixed solutions) showed the acceptable agreement of the obtained a priori and a posteriori accuracy estimates. This is confirmed by the results of calculations and comparison of discrepancies of the PPP-estimates of the current LEOS coordinates with respect to the reference trajectory (a posteriori accuracy estimation) and model estimates of determination errors (a priori estimation accuracy) for each of the solutions considered – the code, the code-carrier-phase float IF-solution and carrier-phase fixed IF-solution. The examples of comparison of estimates of the accuracy of the current LEOS coordinates for float IF-solution are shown in Fig. 7. The figure displays the discrepancies (in meters) of the given solution relative to the reference LEOS trajectory and the calculated (according to the proposed error model) confidence intervals (with a probability of P=0.997) of solution errors.



a

b

c

Fig. 7. Comparison of the a posteriori and a priori accuracy estimations of the LEOS coordinates determination for code-carrier-phase float IF-solution: *a* — coordinate X; *b* —coordinate Y; *c* — coordinate Z

Another important feature of PPP-solutions is their convergence/initialization [3, 5, 7, 10, 13], i. e. measuring information accumulation interval for which it is achieved the stable solution with a given accuracy level (for float IF-solution) or it is achieved the reliable carrier-phase ambiguity resolution (CPAR) in case of performing the discrete IF-solution. The examples of possible functions for the estimation of convergence of code-carrier phase and only carrier-phase-float IF-solutions are shown in Fig. 8.

Fig. 8, *a* shows the change of RMS estimates of a posteriori errors of the geocentric LEOS coordinates X, Y, Z (in case of obtaining *the code-carrier-phase* float IF-solution) as a function of the observation interval value. Fig. 8, *b* shows the change (blue line) of average (by three coordinates) value of a posteriori RMS of errors of the LEOS coordinates in case of obtaining the *carrier-phase* float IF-solution, i. e. without the use of a code P1-solution (a priori coordinates).

Following the analysis of dependencies in Fig. 8, *a*, the level of ~0.08–0.14 m of RMS errors of LEOS coordinates in case of code-carrier phase float IF-solution may be achieved in the interval of observations about ~1 hour. In the interval ~2 hours the level of coordinate errors ~0.03–0.06 m (RMS) is achieved.

The comparison of dependences in Fig. 8, *b* for code-carrier phase float IF-solution (using a code P1-solution – a priori coordinates) and for "pure" carrier-phase float IF-solution (without the use of a priori coordinates) shows the following. "Pure" IF-phase solution initially converges faster than code-carrier-phase solution, but with the increase of the interval of observation the convergence rate is significantly reduced, and at the end of a two-hour observation interval the accuracy of code-carrier-phase solution becomes about two times as high as the accuracy of IF carrier-phase solution.

Convergence (initialization interval) of the discrete IF-solution is determined by the minimal interval of accumulation of measuring information for which the reliable carrier-phase ambiguity resolution is achieved. It was established experimentally that the proposed realization of the discrete CPAR algorithm allows obtaining the reliable solution in the interval of observations not less than about 30–40 minutes. In this case the sub-decimeter accuracy level of LEOS coordinates determination is achieved.

The comparison of the achievable accuracy of the float and the discrete/integer PPP-solutions shows the following. The discrete solution makes it possible to determine the current LEOS coordinates with limit (with a probability P=0.95÷0.997) errors ~0.05–0.10 m on the observation intervals ~30–40 minutes, while the float solution provides determining the coordinates with critical errors ~0.20 m at the intervals of observation ~1.5–2 hours.

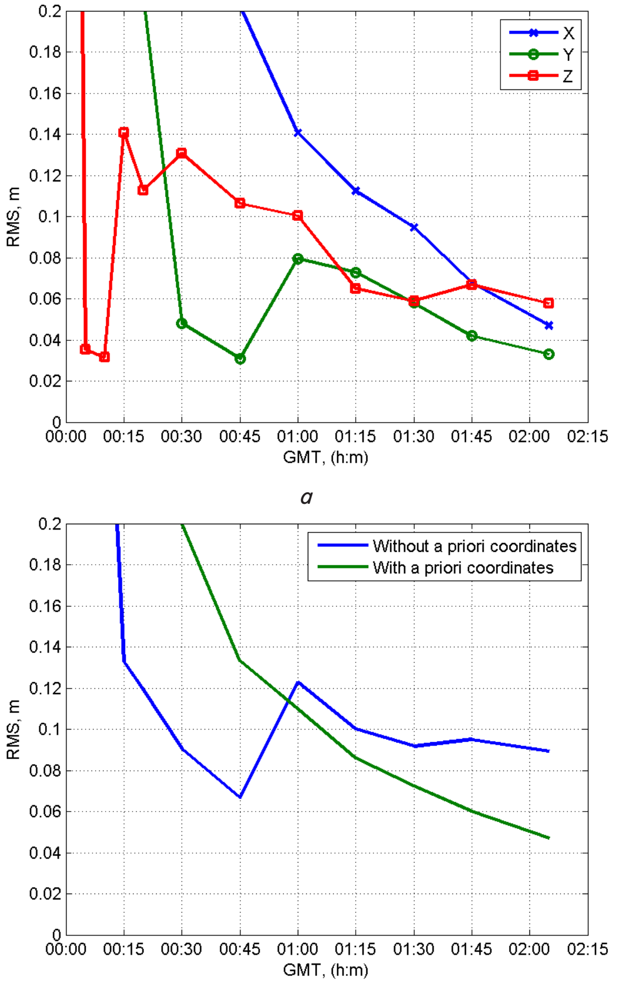
Directions of further researches

Further researches are planned to be performed in the following directions:

– adaptation of the developed PPP methods and algorithms for functioning in conditions of multi-system (GPS, GLONASS, BeiDou, Galileo) with a view to improving the reliability and accuracy of the trajectory determinations;

– adaptation of the developed methods and algorithms for the precision PPP positioning of the ground/near ground users;

– adaptation of the developed methods and PPP algorithms for functioning in real time.



a

b

Fig. 8. The assessment of convergence of code-carrier-phase and carrier-phase float IF-solutions: *a* — the change of RMS estimates of a posteriori errors of the LEOS coordinates as a function of observation interval value; *b* — the change of average (by three coordinates) values of a posteriori RMS errors of the LEOS coordinates for code-carrier phase (green line) and only carrier-phase (blue line) float IF-solutions

6. Conclusions

1. A new realization of the PPP-method for LEOS trajectory determinations is developed, the original algorithmic and software means for processing and analysis of on-board code and carrier-phase LEOS GPS-observations for precision positioning by the kinematic method without the use of dynamic models of LEOS motion is created. The obtained methodological and algorithmic solutions have a number of positive distinctive features in relation to the analogues. In particular, it is proposed to use:

– as a preliminary a priori solution a single-frequency code P1-solutions with compensation of ionospheric delays which are preliminarily estimated by code and carrier-phase geometry-free observations;

– a new realization of a discrete algorithm for carrier-phase ambiguity resolution which implies stage-by-stage reparametrization of the system of observation equations according to the author's method and allows the best use of the information of the entire sample of observations; at the same time it is proposed to search the discrete semi-cycle (not cycle) solution;

– the original model of carrier-phase IF-observations which allows improving the conditioning of the equation system, the reliability of solutions and principle ability to work without the use of code observations.

2. The developed experimental software-algorithmic means (prototype) include the modules of preliminary GPS-observations processing adapted to conditions of high LEOS dynamics, the modules of the carrier-phase ambiguity resolution, LEOS positioning using the results of carrier-phase measurements and accuracy estimation of trajectory determinations.

3. On the basis of comparison of GPS-observations processing results with the LEOS COSMIC reference coordinates it is shown the achievement of the accuracy of the positioning at the level of ~0.05–0.10 m while implementing the discrete/integer method of carrier-phase ambiguity resolution in the observation intervals of 30–40 minutes and more. In case of the float solution the level of limit errors of the LEOS coordinates determination ~0.10–0.20 m is achieved at the range of observations ~2 hours.

4. The components of the observational errors model are described, a priori and a posteriori accuracy estimates of LEOS-positioning are performed. Use of the proposed error model showed the acceptable agreement of the obtained a posteriori and a priori accuracy estimates. This was confirmed by the results of calculations and the analysis of their results.

5. The performed development at its industrial implementation may be used for high-precision coordinate-timing support of the up-to-date satellite technologies for the purpose of detecting contaminations, studying of erosion processes, supporting of scientific and applied projects in such areas as geodesy, geophysics, climatology, orbitography, meteorology. The research results may be used in solving the tasks of LEOS maneuvering, rendezvous and docking.

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