Calculation of the Ephemeris and Clock Corrections of GLONASS and GPS Navigation Space Vehicles in Ultra-Rapid Regime on the Basis of Measurement Data

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CALCULATION OF THE EPHEMERIS AND CLOCK CORRECTIONS OF GLONASS AND GPS NAVIGATION SPACE VEHICLES IN ULTRA-RAPID REGIME ON THE BASIS OF MEASUREMENT DATA

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An algorithm and program for calculation in ultra-rapid regime of the ephemeris and time information of GLONASS and GPS navigation space vehicles are developed. The results presented here were obtained at the Main Metrological Center of the State Time and Frequency Service and Determination of the Parameters of the Earth's Rotation at the All-Russia Research Institute of Physicotechnical and Radio Measurements (VNIIFTRI). Calculations of the ephemeris and time information are performed on the basis of the data of code and phase measurements at two carrier frequencies. The measurement data are presented in the form of hourly RINEX files of observations and files of navigation messages from tracking stations in the network of the IGS international service of global navigation satellite systems (International GNSS Service). Results of test calculations of the ephemeris and clock corrections of GLONASS and GPS navigation satellites in ultra-rapid regime are presented. An analysis of the precision of the results as compared to a posteriori (final) data from other data processing and analysis centers is presented.
Keywords: *navigation space vehicles, global navigation satellite systems, ephemeris and clock corrections, centers for data analysis and processing, hourly RINEX files, International GNSS Service.*

Introduction. Ephemeris and time information from navigation space vehicles in the Global Navigation Satellite Systems (GNSS) is the basis for many applications in the field of space geodesy, performance of cadastral studies, and precise positioning of objects, both in fixed positions on the Earth's surface and travelling in near-Earth space [1]. In order to obtain ultra-rapid results, the ephemeris and time information of the navigation space vehicles in the Global Navigation Satellite Systems must often function in real time. The ephemeris and clock corrections of GNSS navigation space vehicles are calculated at data analysis and data processing Centers, both foreign Centers and Centers located in the Russian Federation, from data obtained by tracking stations incorporated into the International GNSS Service (IGS) (www.igs.org/network). Note that the ephemeris and time information obtained by different Centers may differ. Thus, in determining the spatial coordinates of space vehicles the differences (mean-square deviations) between two Centers may reach several centimeters while the clock correction, 10 ns and more. Since precise values of the coordinates of orbits and clock corrections of navigation space vehicles remain unknown, a procedure of combination is often resorted to as a way of obtaining the reference values [2–5]. Since 1993, IGS (USA) has generated ephemeris and clock corrections by means of a method of combination (ephemeris and clock corrections) for GPS satellites from the results of calculations of nine (in 2019) Centers. A similar procedure (combination of ephemeris alone) for obtaining the ephemeris and time information of GLONASS navigation space vehicles has been used since 2004 until the present day by the NOAA/NGS (USA) (https://www.ngs.noaa.gov/) within the framework of the International GLONASS Service Pilot Project (IGLOS-PP) [6]. The calculation results of eight Centers are used here. Files of ephemeris and time information are generated in ultra-rapid, rapid, and a posteriori (final) regimes and are downloaded the form of annual products to the ftp-servers of the respective Centers (Table 1).

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TABLE 1. Generation of Ephemeris and Time Information (files in SP3 format) of GNSS Navigation Space Vehicles at the Centers

Center	Grouping of navigation space vehicles (number of Centers)	Ephemeris and time information regime	File	Regime rate	Frequency
IGS (USA)	GPS (9)	Ultra rapid	IGUwwwwd_00.SP3[*]	Real time	6 h
			IGUwwwwd_06.SP3		
			IGUwwwwd_12.SP3		
			IGUwwwwd_18.SP3		
		Rapid	IGRwwwwd.SP3	Delay 1–2 days	1 day
		Final	IGSwwwwd.SP3	Delay 2 weeks	1 day
NOAA/NGS (USA)	GLONASS (8)	Ultra rapid	IGVwwwwd_00.SP3	Real time	6 h
			IGVwwwwd_06.SP3		
			IGVwwwwd_12.SP3		
			IGVwwwwd_18.SP3		
		Rapid	–	–	–
		Final	IGLwwwwd.SP3	Delay 2–3 weeks	1 day
IAC (Russia)	GNSS	Ultra rapid	Stark_1D_yymmddhh.SP3[**]	Real time	6 h
		Rapid	Stawwwwd.SP3	Delay 1–2 days	1 day
		Final	Stawwwwd.SP3	~5 days	1 day
SHPDECC (Russia)		Ultra rapid	PMKyymmdd.SPU[**]	Real time	1 day
		Rapid	PMKyymmdd.SPR	Delay 1–2 days	1 day
		Final	PMKyymmdd.SP3	Delay 2 weeks	1 day

[*] "wwww" and "d" denote, respectively, the ordinal number and day of the week of the global positioning system (GPS); [**] "yy," "mm," "dd," and "hh" denote the last two digits of the year, the month, day of the month, and hourly shift (00/06/12/18).

Two Centers now function in the Russian Federation, the Information and Analytical Center (IAC) of Coordinate-Time and Navigation Support for GLONASS (https://www.glonass-iac.ru) and the System for High-Precision Determination of Ephemeris and Clock Corrections (SHPDECC) (www.glonass-svoevp.ru/) (cf. Table 1). At the same time, neither of these Centers generates reference values of ephemeris or time information that could serve as official data.

One of the goals of studies in this area is to create in the Russian Federation, specifically at the Main Metrological Center of the State Time and Frequency Service and Determination of the Parameters of the Earth's Rotation at the All-Russia Research Institute of Physicotechnical and Radio Measurements (VNIIFTRI), a system for metrological monitoring of the ephemeris and time information of GLONASS navigation space vehicles similar to the IGS and NOAA/NGS systems. The fact that the Main Metrological Center, as an organization incorporated into Rosstandart, may be in terms of status the highest link in the system for assurance of the uniformity of measurements in the area of ephemeris and time information in accordance with the objectives defined in All-Russia State Standard GOST R 8.000-2015, *State System for Ensuring the Uniformity of Measurements (GSI). Basic Assumptions*, may serve as a prerequisite.

One of the difficulties involved in creating in the Russian Federation a system of metrological inspection based on the technology of combination as this is implemented in IGS and NOAA/NGS (USA) is that there are not enough Centers in the Russian Federation whose results after corresponding processing could be used to obtain reference values of the ephemeris and clock corrections of GLONASS navigation space vehicles. Therefore, obtaining alternative ephemeris and time information by yet another Center – the Main Metrological Center – may create real prerequisites for the generation (also at the Main Metrological Center) of a statistically well-founded solution.

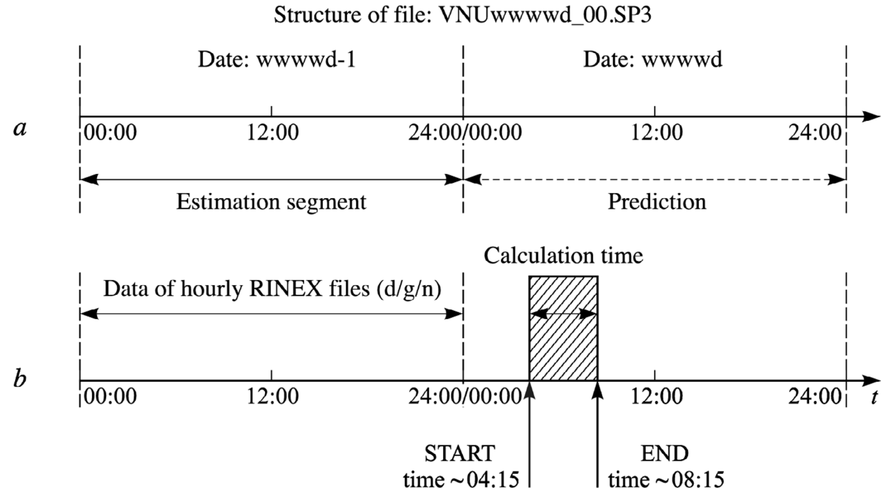

Fig. 1. Time diagram of VNUwwwwd_00.SP3 file generation in ultra-rapid regime.

Determination of ephemeris and clock corrections by GLONASS and GPS navigation space vehicles at the Main Metrological Center. The present articles discusses the basic results achieved on the development of a combined hardware-software complex for the creation of alternative ephemeris and time information of the navigation space vehicles in the Global Navigation Satellite System in an ultra-rapid regime. The results that have been achieved so far were obtained at the Main Metrological Center. Note that the application software used to generate the ephemeris and time information of the navigation space vehicles in the Global Navigation Satellite System were developed at the Main Metrological Center in rapid and a posteriori (final) regimes [7, 8].

The terms "ephemeris" and "clock corrections" used in the present article denote three-and one-dimensional time series of the spatial coordinates of the navigation space vehicles and corrections to the readings of their onboard clocks, respectively. The time series are calculated at successive times at 15-minute intervals, beginning with the start of the day. It should be noted that, in addition to these terms, the synonymous terms "orbits" and clock corrections," respecively, are often used in the scientific and technical literature.

The hardware-software complex used to calculate the ephemeris and clock corrections by the navigation space vehicles in the Global Navigation Satellite Systems in ultra-rapid regime create corresponding files at a rate of four times a day (at six-hour intervals) in accordance with existing international practice. The hardware-software complex now functions in a test regime the objective of which is to perfect the software, improve the precision characteristics of ephemeris already calculated by the navigation space vehicles, and increase the rate at which the final result is obtained. Hourly RINEX files (in d/g/n formats) containing the results of measurements of code and phase pseudo-ranges at two carrier frequencies are the initial data for the calculations. These data are obtained by stations that track the satellites in the Global Navigation Satellite Systems incorporated into the global IGS system. The total number of stations whose data are used in the calculations varies from 450 to 700. Four files in SP3 format, each of which containing data on the ephemeris and clock corrections of the satellites in the Global Navigation Satellite Systems over two days by analogy with the ultra-rapid data on ephemeris created by foreign analysis Centers IGS (USA) and NOAA/NGS (USA) (https://www.ngs.noaa.gov/) are generated within 24 hours. The first segment of each file – the estimation segment – contains ephemeris and time information obtained from the results of processing the measurement data. The second segment of the file – the prediction segment – contains ephemeris and time information obtained on the basis of prediction. In the course of several days denoted wwwwd, where wwww and d denote the GPS weeks and day, respectively, the following files are created, listed in the order they were generated: VNUwwwwd_00.SP3, VNUwwwwd_06.SP3, VNUwwwwd_12.SP3, and VNUwwwwd_18.SP3. The abbreviation VNU derives from VNIIFTRI and Ultra-rapid. The shift from in the clock from the start of the preceding days to the time, beginning with which the estimated values of the ephemeris and clock corrections are entered into the file, is indicated by underlines. For example, the first of the above files, VNUwwwwd_00.SP3, contains estimated values of the ephemeris and clock corrections of the satellites from

TABLE 2. Time Table for Generation of Files with Ultra-Rapid Ephemeris and Time information

File	Generation time	Data interval segment	
		estimation	prediction
VNUwwwwd_00.SP3	~08:15	00:00(–24)–23:59(–24)	00:00–23:59
VNUwwwwd_06.SP3	~14:15	06:00(–24)–05:59	06:00–05:59(+24)
VNUwwwwd_12.SP3	~20:15	12:00(–24)–11:59	12:00–11:59(+24)
VNUwwwwd_18.SP3	~02:15(+24)	18:00(–24)–17:59	18:00–17:59(+24)

TABLE 3. Root-Mean-Square Errors, ns, and Clock Corrections of GPS Navigation Space Vehicles Estimated by Different Centers

Interval	Center								
	COD	EMX	ESA	GFZ	GRG	MIT	PMK	**VNF**	**VNP**
1	0.692	1.095	1.406	0.353	0.165	2.246	3.771	**0.294**	–
2	0.701	1.550	0.872	0.379	0.166	2.306	3.543	**0.410**	**1.930**
3	0.636	1.294	1.157	0.376	0.167	2.255	3.897	**0.467**	**1.854**
4	0.636	0.764	1.289	0.389	0.151	2.305	3.894	**0.625**	**1.709**

00:00 to 23.59 of the previous day (wwwwd-1) and the predicted values of these quantities from 00:00 to 23.59 of the current day, which is represented schematically in Fig. 1*a*.

RINEX clock files in d/g/n formats are downloaded from the ftp servers of the international databases: Information and Analytical Center of Coordinate-Time and Navigation Support for GLONASS at the Central Research Institute of Machine Building (TsNIIMash) (IAC), Russia; Earth Observing System Data and Information System (EOSDIS), USA; Center for Orbit Determination in Europe, Bern, Switzerland. Experience has demonstrated that RINEX clock files arrive at the servers of the international databases roughly after a four-hour delay, whence they are downloaded in automatic regime to the database of the Main Metrological Center. Launching of the program for calculation of ephemeris and clock corrections of the navigation space vehicles in the Global Navigation Satellite Systems occurs automatically following verification of the required number of downloaded files. A file with ultra-rapid ephemeris and time information of the navigation space vehicles is created in the Global Navigation Satellite Systems after approximately four hours of calculations. The time diagram of VNUwwwwd_00.SP3 file generation is shown in Fig. 1*b*. The time table of the generation of each of the four types of files as well as the time intervals which the data contained in these files refer to are presented in Table 2.

Results of calculations. Test calculations were performed to monitor the precision of calculations of the ephemeris and clock corrections by the navigation space vehicles of the Global Navigation Satellite Systems according to a technique developed at the Main Metrological Center. Some of these calculations over four successive days (selected randomly), beginning on 05.30.2018 and ending on 06.03.2018 are presented next. Files of ultra-rapid data corresponding to the six-hour shift VNU20033_06.SP3, VNU20034_06.SP3, VNU20035_06.SP3, and VNU20036_06.SP3 were used for the analysis.

Estimation of the precision of the ephemeris of the GPS and GLONASS navigation space vehicles calculated by the Main Metrological Center was performed by comparing them (coordinates of the satellites) with the a posteriori (final) ephemeris obtained by the foreign Centers (IGS and NOAA/NGS). The estimated and predicted values of the ephemeris and clock corrections were compared separately.

The values of the root-mean-square errors of the estimated (VNF) ephemeris of the navigation space vehicles proved to be not more than 2 cm for GPS and not more than 5 cm for GLONASS. The values of the root-mean-square errors of the predicted (VNP) ephemeris of the navigation space vehicles proved to be approximately 6 cm for GPS and ~10 cm for GLONASS. Calculations of the root-mean-square errors for each of the systems were performed for all the navigation space vehicles together.

The root-mean-square errors of the clock corrections for the different Centers as well as for the estimation segment of the files of ultra-rapid data (VNF) and the prediction segment (VNP) (given in bold-faced) are presented in Table 3. A comparison was performed with the a posteriori (final) data of the IGS clock corrections over four successive daily intervals, beginning at 06:00 05.30.2018 and ending at 05:59 06.03.2018. For example, interval 1 begins at 06:00 05.30.2018 and ends at 05:59 05.31.2018 Similar data for the clock corrections of GLONASS are presented in Table 4. A comparison to reference values was also performed. The following abbreviations are used in Tables 3 and 4: IGS – International Service of the Global Navigation Satellite Systems (USA); COD – Center for Orbit Determination in Europe (Astronomical Institute of Bern, Switzerland); GFZ – Center of Geodetic Studies (Potsdam, Germany); GRG – National Center of Space Research (France); EMX – Ministry of Natural Resources of Canada (Canada); ESA – European Space Agency (Germany); IAC – Information Analysis Center of GLONASS (TsNIImash, Russia); IGL – Center for Data Processing and Analysis – NOAA/NGS (USA); MIT – Massachusetts Institute of Technology (USA); PMK – System for High-Precision Determination of Ephemeris and Clock Corrections (SHPDECC) (Russia); BRD – data of navigation messages; and VNF and VNP – estimation and prediction segments of data of Main Metrological Center of the State Time and Frequency Service (VNIIFTRI, Russia).

If the ephemeris of the GLONASS navigation space vehicles are generated by NOAA/NGS by joint processing of the data of eight Centers, and therefore may be adopted as reference values, the clock corrections written to the file IGLwwwwd. SP3 will differ from the analogous values transmitted in the navigation messages by only the shift. Therefore, the clock corrections from IGL, like the corrections of their navigation messages, cannot be adopted as reference values, and in the case of GLONASS, construction of the reference time series $\delta^i_{k,\mathrm{Ref}}$ is performed in accordance with the method described in [3] by means of the following formulas:

$$\delta^i_{k,\mathrm{Ref}} = \sum_{j=1,\ldots,N} \delta^i_{k,j}\sigma_j^{-2} \Big/ \sum_{j=1,\ldots,N} \sigma_j^{-2};$$

$$\sigma_j = \sqrt{\frac{1}{N_{\mathrm{Sat}}K} \sum_{j=1,\ldots,N_{\mathrm{Sat}}} \sum_{k=1,\ldots,K} \left(\delta^i_{k,j} - \bar{\delta}^i_k\right)^2};$$

$$\bar{\delta}^i_k = \frac{1}{N} \sum_{j=1,\ldots,N} \delta^i_{k,j},$$

where k is the ordinal number of the epoch; i and j – indices of the satellite and the Center, respectively; N – number of Centers; $\delta^i_{k,j}$ – clock corrections of ith satellite estimated by jth Center in epoch k; σ_j – sigma of jth Center; N_{Sat} – number of satellites; and K – number of epochs.

The clock corrections for the navigation space vehicles of the GLONASS system with system ordinal number PRN = R03 (the ordinal number of the navigation space vehicle is selected randomly), estimated by different Centers in the period from 06:00 05.31.2018 to 05:59 06.01.2018, are presented in Fig. 2. Reference data REF obtained as the root-mean-square results of the ESA, GRG, IAC, PMK, and VNF Centers are also presented in Fig. 2. No other data are used in generating the reference values.

Since the clock corrections $\delta^i_{\mathrm{VNF},k}$ of the Main Metrological Center (VNF) were calculated in the GPS time scale, these values were reduced to the GLONASS time scale for the purpose of comparison with the results of the other Centers. The procedure used in reduction of the clock corrections $\delta^i_{j,k}$ of the jth Center to the GLONASS time scale is based on the following transformation:

$$\delta^{*i}_{j,k} = \delta^i_{j,k} - \Delta T - d\Delta t_k, \quad k = 1, \ldots, K,$$

where $\delta^{*i}_{j,k}$ are the clock corrections reduced to the system time scale; $\Delta t_k = t_k - t_1$, time interval between the kth and first epoch; and ΔT and d, parameters of the shift and drift, respectively, which are to be determined.

The values of the parameters ΔT and d are found by solving the following variational problem of minimization of the functional:

$$\sum_{j=1,\ldots,N_{\mathrm{Sat}}} \sum_{k=1,\ldots,K} \left|\delta^i_{j,k} - \Delta T - d\Delta t_k - \delta^i_{\mathrm{BRD},k}\right| \xrightarrow[\Delta T,\, d]{} \min, \quad (1)$$

TABLE 4. Root-Mean-Square Errors, ns, and Clock Corrections of GLONASS Navigation Space Vehicles Esimated by Different Centers

Interval	Center					
	ESA	GRG	IAC	PMK	**VNF**	**VNP**
1	3.418	1.524	2.544	7.381	**0.675**	–
2	3.315	1.768	2.480	6.977	**0.614**	**5.663**
3	3.491	2.072	2.231	6.946	**0.609**	**4.405**
4	4.053	2.297	1.392	6.564	**0.975**	**6.468**

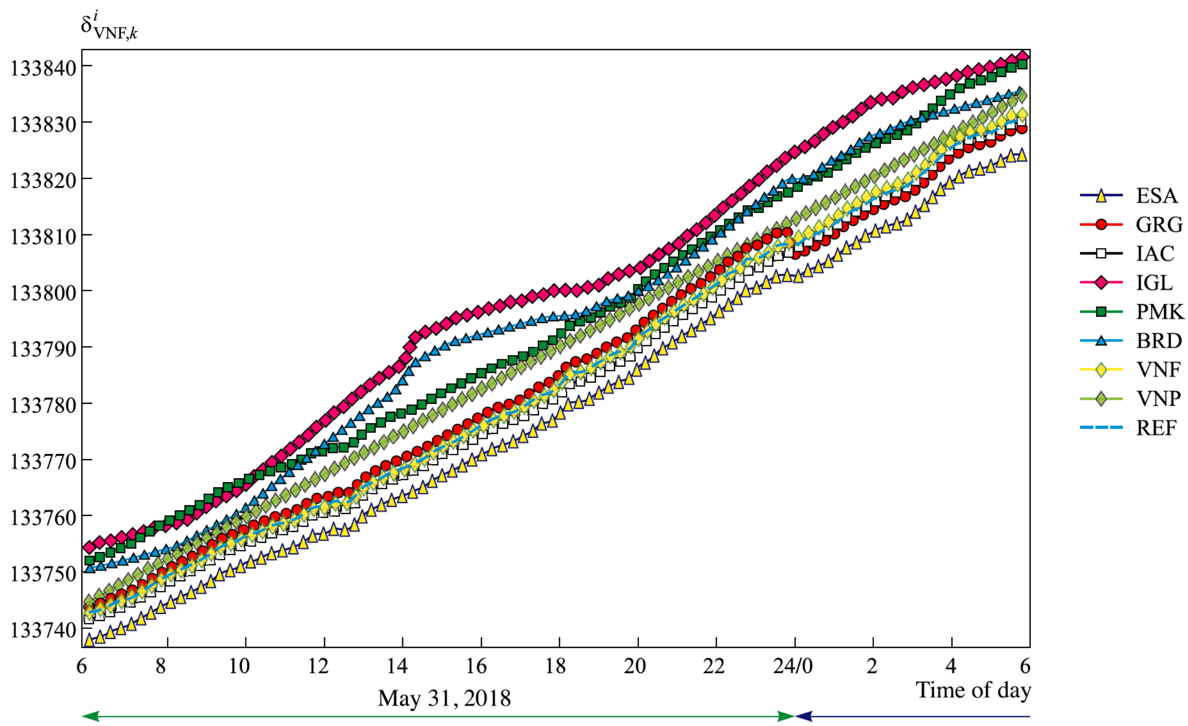

Fig. 2. Clock corrections of GLONASS navigation space vehicles (PRN = R03), obtained in ultra-rapid regime at the Main Metrological Center: VNF – estimation segment, VNP – prediction derived from preceding days. Comparison of estimated values of clock corrections with similar a posteriori (final) values of other analysis Centers.

where $\delta^i_{\mathrm{BRD},k}$ are the clock corrections obtained from the navigation messages (BRD) of the GLONASS navigation space vehicles.

A functional of form (1), which is an analog of the L_1 norm, is more stable in the presence of approximate measurements (outliers) in the time series $\delta^i_{\mathrm{BRD},k}$ by comparison with a functional that constitutes a root-mean-square deviation. Nevertheless, approximate measurements in the navigation data may have a negative effect on the precision of the estimated parameters. The following procedure is used to eliminate outliers from the time series $\delta^i_{\mathrm{BRD},k}$. The procedure consists of two steps. On the first step, the component of the drift is subtracted from the series $\delta^i_{\mathrm{BRD},k}$ for each ith navigation space vehicle:

$$\hat{\delta}^i_{\mathrm{BRD},k} = \delta^i_{\mathrm{BRD},k} - \bar{d}^i_{\mathrm{BRD}}\left(t_k - t_1\right),$$

where $\bar{d}^i_{\mathrm{BRD}}$ is the mean value of the drift calculated from values of $\delta^i_{\mathrm{BRD},k}$ of the drift at times t_k from the file of navigation messages.

An algorithm borrowed from [9] is used on the second step of the procedure for identifying outliers to the time series $\hat{d}^i_{\mathrm{BRD},k}$. Next, all the outliers that have been found are preliminarily eliminated from the series $\delta^i_{\mathrm{BRD},k}$ in order to determine parameters ΔT and d, which minimize functional (1).

TABLE 5. Established Root-Mean-Square Errors in Determination of Ephemeris and Clock Corrections of the GLONASS and GPS Navigation Space Vehicles in Ultra-Rapid Regime

Parameter	Segment of data interval	
	estimation	prediction
GPS satellite ephemeris, m	~0.017	<0.06
GLONASS satellite ephemeris, m	~0.045	<0.1
GPS clock corrections, ns	<1.0	~3.0
GLONASS clock corrections, ns	<1.0	~5.0

Due to possible jumps in the series $\delta^i_{j,k}$ from one day to the next, the procedure used in reduction of the time scale of the jth Center to the GLONASS system time scale may be used only on daily time intervals from 0:00 to 23.59. In turn, through adjustment of the time scale of the jth Center to the system time scale, jumps in the values of the clock corrections of this Center from one day to the next may be eliminated. For example, in order to eliminate jumps in the series of clock corrections of the European Space Agency (ESA) from one day to the next, which may reach several dozen nanoseconds, the procedure of reduction to the GLONASS system time scale described above is applied to the clock corrections of this Center.

Conclusion. A combined hardware-software complex for obtaining the ephemeris and time information of the space vehicles of the Global Navigation Satellite Systems in ultra-rapid regime was developed. The values of the root-mean-square errors of the ephemeris of the GPS navigation space vehicles estimated in ultra-rapid regime proved to be no more than 2 cm, while the ephemeris of the GLONASS navigation space vehicles were on the order of 4–5 cm. The values of the root-mean-square errors of the ephemeris of the navigation space vehicles predicted in ultra-rapid regime proved to be roughly 6 cm and 10 cm for all the navigation space vehicles in the GPS and GLONASS systems, respectively. These and other results of the test calculations are reflected in Table 5.

Software modules created by the Bern DLP for Processing GNSS Measurements (Bernese Software, version 5.2) [10], some of which were adapted to multisequencing, Bernese Processing Engine (BPE), and BPE methods, by means of which processing may be performed on multiprocessor computer systems in a concurrent regime, were used in the calculations. A number of newly developed programs and scripts were implemented in BPE. The FORTRAN-90, Delphi XE7, and Perl 6.0 programming languages were used in writing the software programs and scripts.

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