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Investigation of Onboard Quantum Time Scale for Orbital Flight of a Space Radio Telescope (the RadioAstron Project)

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Abstract—Results of observing the operation of instrumentation of the ground–space complex of the RadioAstron project during space flight conditions of the radio observatory are presented. The technology of quality evaluation of the data received from the space radio telescope (**SRT**) is considered. The dependence of readings of the onboard frame counter on **SRT** radial velocity and distance is determined. Technology of constructing a model of the ground–space atomic clocks and onboard quantum time scale based on the results of radio astronomic observations is tested. The method of measurement of the coherent cumulative navigation delay using the onboard quantum time scale is considered. The results of observation of the effect of relativistic and kinematic time dilation onboard the **SRT** are presented.

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INTRODUCTION

The operation of the space radio telescope of the RadioAstron project is aimed at the maintenance of the functioning of the orbital arm of the radio very-long-base interferometer (VLBI). One goal of the VLBI is to study the structure of celestial sources with small angular dimensions emitting in the radio range. The base lengths reached for which interferometer response is received at the present time exceed 16 diameters of the Earth (more than 200000 km) [1, 2].

On the one hand, one can improve the resolution power of the interferometer by using receivers of higher frequencies. On the other hand, one can separate antennas at larger distances (longer bases). For radio telescopes with an interferometer operating in the centimeter wave band (in particular, at $\lambda = 1.35$ cm), the high frequency stability of reference signal generators is necessary in order to ensure a long time of coherent accumulation of information about the received signal. In turn, the long time period of coherent accumulation allows one to improve sensitivity of the radio VLBI [3].

Thus, the necessity of using hydrogen frequency standards (HFS) is caused by strong requirements of the stability of the output signal during observations in order to ensure a long time interval of coherent accumulation. These conditions should be satisfied both on the Earth and in space. Due to the causes mentioned above, the space radio telescope of the RadioAstron project is equipped with a highly stable reference signal generator, the onboard hydrogen frequency standard (OHFS). Extreme conditions of exploitation during space flight confirmed the importance of technical requirements to OHFS design.

Among the circuits of radio signals received by radio telescopes, there are some synchronized devices that should be fed with HFS output signals: generators of the network of heterodyne and reference frequencies of the radio telescope receiving channel; the generator of signals at a local time scale; generators of signals for data acquisition systems of radio astronomic observations and for radio technical measurement facilities.

For operation of those modern ground-based radio telescopes that participate in global (both ground-based and space) observations of cosmic radio sources, one needs (in addition to HFS) also a time scale constructed on the basis of signals of the above mentioned standards. The time scales are used as instruments of mutual synchronization of operation of radio telescopes. It is convenient to use them in order to measure delays in circuits of the calibrated receiving devices that record signals of radio astronomy sources. In the *SRT* of the RadioAstron project high-precision receiving equipment is installed onboard a satellite, while the ground-based tracking station at Pushchino (PRAO GTS) performs recording and storage of the signals from radio astronomical sources.

Operation of the *SRT* is coordinated via service telemetry system (STS), which includes a technical facility for generation of the onboard time scale (OTS). Signals of a temperature-controlled quartz generator having no connection with OHFS serve as a reference signal for the OTS. There is no onboard atomic clock (OAC) on the *SRT* operating from OHFS signals. The OHFS signals feed only the primary scaling circuit, the Formator, which is not synchronized either from the Earth or OTS, neither in time nor in frequency (for the majority of experiments). There is

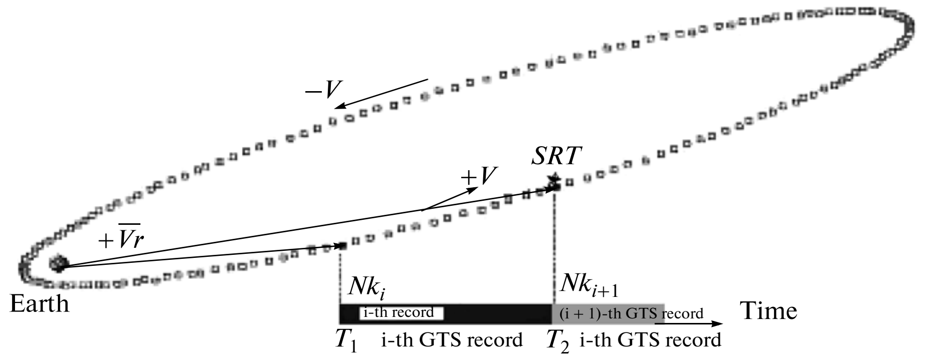

Fig. 1. Functional relationship between the **SRT** radial velocity and changes in readings of the cadre counter of the onboard Formator instrument.

no possibility to make a procedure to compare frequencies. Two causes explain the difficulty of creating OAC on the *SRT*: the character of time behavior onboard satellite was not fully understood before the *SRT* flight; and there were doubts of the possibility of making distance measurements with the use of OHFS; and there was no definite technology of checking and synchronizing the OAC.

The goal of this paper is to present the results of investigations into these two problems and to describe the problems solved.

TASKS AND OBJECTS OF INVESTIGATIONS

Operation of the RadioAstron *SRT* started from inflight tests in September 2011, and these tests have demonstrated the unsatisfactory quality of PRAO GTS operation as far as concerns recording and decoding equipment.

The problem arose that there was no stable synchronization of the beginning of recording the radio astronomic signals with the rate of telemetry data transmitted from for the *SRT* board. The drawbacks of the above-mentioned equipment that were found in the course of the real *SRT* flight were not and could not be revealed at ground tests under the conditions of immobile *SRT*.

Thus, in the beginning of the space experiment the first task came into being: to find a reliable method of estimating the quality of signal records for radio astronomic observations (in what follows, VLBI observations).

One property of the *SRT* standard equipment allowed its use as a measure of quality. This property is a regular law of variation of readings of the counter of cadre numbers of the Formator onboard instrument during VLBI observations. The rate of variation of readings of the counter of cadre numbers in records made on the GTS is proportional to variations of the *SRT* radial velocity. It is convenient to make the operation of estimating the quality of records with the use of specialized devices [4]. Upon manufacturing a special instrumental monitor an empirical relationship was found between the period of variation of readings of the counter of cadre numbers of the Formator and the mean magnitude of the *SRT* radial velocity on a particular time interval. The found formula (whose meaning is clarified in Fig. 1) is presented below.

$$\mp(Nk_{i+1} - Nk_i) \approx \frac{(T_2 - T_1)(\pm V_r)}{k_{SC}\tau_{fr}c}, \quad (1)$$

where T_1 and T_2 are, respectively, the time moments (*s*) when a tracking station begins receiving the (Nk_i)th and (Nk_{i+1})th cadres of scientific data, $\pm V_r$ is the mean value (km/s) of the *SRT* radial velocity between moments T_1 and T_2, τ_{fr} is the current nominal duration (*s*) of the Formator cadre, *c* is the velocity of light in a vacuum (km/s), and k_{SC} is a correcting coefficient (approximately equal to unity). In this paper we assume:

$$k_{SC} = 1 - (F_{HFS} - F_{OHFS})/F_{HFS}, \quad (2)$$

where F_{HFS} is the real value of frequency of the reference signal at the output of the hydrogen frequency standard of the ground-based tracking station. F_{OHFS} is the real value of frequency of the reference signal at the output of the onboard hydrogen frequency standard of the Radioastron *SRT*.

One can interpret formula (1) using the following example. For instance, when the *SRT* moves away from the Earth with a radial velocity of 1250 meters per second, the periodic sequence of readings of the counter of cadre enumeration in the Formator, as recorded by the GTS, is shifted by 1 to become less for every time interval of 600 s on the time scale of the PRAO GTS. In case of approaching the Earth, after having passed through the apogee, changes occur in the opposite order. The found relationship allows one to control the quality of operation of recording and decoding equipment, to measure the *SRT* radial velocity using the records of VLBI observations (in this case, the result of measurements is synchronous and coherent with observed radio astronomic signals), and to synthesize the onboard quantum time scale (OQTS) based on the OHFS signals.

Based on relationship (1) an express procedure of scanning scientific data records has been developed. The procedure includes the following four stages.

a) Fast content analysis of every 10-min record with signals of VLBI observations.

b) Readout of all readings of the counter of cadre numbers in the Formator onboard instrument.

c) Computation of a current magnitude of the *SRT* radial velocity.

d) Computation of a current value of the Doppler frequency shift of a received signal coherent with the results of VLBI observations.

In order to ensure prompt operation and convenience of estimating the dynamics of observations, the summary diagnostic table (SDT) is formed as a result of the express scanning procedure. In [10] the calculation formulas are considered in detail, as well as an example of SDT computing.

As a result of improvements made in recording and decoding equipment of the PRAO GTS to November 9, 2012, the rate of hardware failures was substantially (approximately by a factor of 10) reduced. Starting from this date the loss of data does not exceed 1.5%, which is quite reasonable for an operation with records of signals received from the *SRT* board. As a result of further investigations a connection was found between readings of the counter of cadre numbers in the Formator and the *SRT* distance relative to the PRAO GTS. Figure 2 illustrates the linearity of readings of the counter of cadre numbers with the distance *GTS–SRT* for an elliptic orbit of the *SRT*. One can observe a proportional relative shift of cadre enumeration values in the Formator when the period of evolving orbit of the Radioastron *SRT* changes. This fact turned out to be useful in developing the technology of OQTS synthesis based on data records of VLBI observations.

The second problem associated with the onboard time scale appeared due to necessity of immediate control of the real frequency value (RFV) of the OHFS reference signal. To solve the stated problem was difficult because of two circumstances. First, on the *SRT* board there is no adequate onboard timer operating from OHFS signals. Second, the digital data array of telemetric information on OHFS does not include information about current frequency values of the output reference signal 15 MHz. We have succeeded in approaching to the solution of the second problem by way of creating a model of an onboard atomic clock (MOAC) and synthesizing OQTS artificially on the Earth with the use of an output OHFS 15 MHz signal. The designed MOAC employs the following simple scheme: "operating clock pendulum is placed on the *SRT* board, while the clock dial, clock hands, and devices of control and synchronization are located on the Earth." The clock pendulum is connected with the clock dial and clock hands through regular 10-min records of signals of radio astronomy observations.

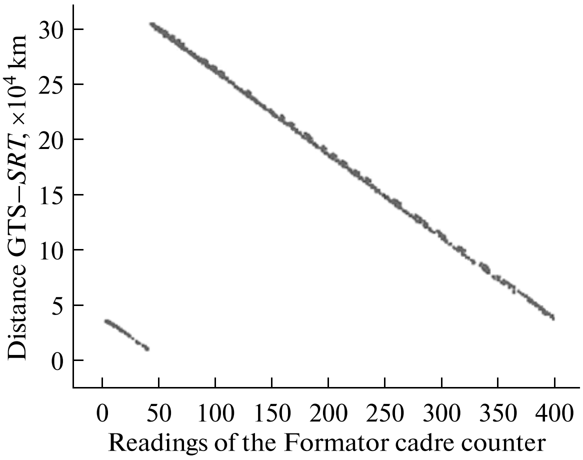

Fig. 2. The distance GTS–**SRT** versus readings of the cadre counter of the onboard Formator instrument.

The specific feature of the above 10-min records that facilitates interaction of elements of the MOAC scheme is an information quorum (synchronous presence) of signals of the three independent time scales: Time Scale of Ground Tracking Station (PRAO GTS TS), service Onboard Time Scale (OTS) of the telemetry system, and OQTS. This information quorum of the signals of three independent time scales allows one to use the methods of clock verification and synchronization developed previously at the stage of ground tests of the onboard hydrogen frequency standards [3]. In particular, the method of three generators turned out to be the most useful for the estimation of mutual delays.

The third task is a continuation of the second, and it has emerged already after creation of the MOAC. The essence of the third applied problem is to develop a method of measuring the navigation delay in order to make additional measurements of distance on the path *SRT*–PRAO GTS. We have succeeded in solving the problem practically by manufacturing additionally a hardware–software measuring complex "KORVET R." The measuring complex includes one deconvolver, one three-channel sequencer, one adjusting source of reference oscillations, three synchronometers, and one four-channel digital storage oscilloscope. The manufactured measuring complex in fact repeats the technology of measurements presented in [3] and simultaneously performs two functions: synthesizes OQTS signals and measures the navigation delay using records of signals of radio astronomy observations.

The method of measuring the navigation delay using the results of radio-astronomic observations has important advantages over others in use (method of laser range finding, radio technical method of response signal etc.), since the measured quantity is within the data array processed by the correlator of the ground-space interferometer [5, 8]. The correlator executes a search for a characteristic time moment corresponding to synchronous observations of the ground-space interferometer [5, 8]. It is reasonable to suppose that the use of results of direct measurements of the navigation delay, coherent with respect to the information stream under processing, facilitates the procedure of correlator search substantially.

In the process of investigating signals received from the *SRT* board a method of measuring coherent cumulative navigation delay (CCND) was constructed. The term "cumulative" implies that the measured navigation delay includes two groups: a group of instrumental delays and a group of broadcasting delays. The resulting measured value of CCND is equal to an algebraic sum of all delays of both the groups. Using the results of performed measurements the contributions of both groups to the final values of CCND were estimated. The total instrumental component of the CCND does not exceed 30 microseconds, and it was virtually invariable over the entire time of measurement. Its onboard and ground components have been distributed approximately in equal parts: 15 μs for the Onboard Complex of Scientific Instrumentation (OCSI), including the Highly Informative Radio Complex (HIRC), and 14 μs for the PRAO GTS, including the decoder of scientific data.

The broadcasting group includes a delay of propagation of 15 GHz *SRT* signal in free space together with tropospheric, ionospheric, and other components. Its contribution to the CCND is prevailing. Over the period of one and a half year of measurements this contribution of the CCND broadcasting group varied in the range from 54 milliseconds (*SRT* perigee) up to 1.12 s (*SRT* apogee).

THE METHOD OF SYNTHESYZING THE ONBOARD QUANTUM TIME SCALE

The information quorum of signals of three independent time scales mentioned above allows one to construct the time scale operating from signals of the onboard quantum generator. The onboard quantum time scale is a solution of the problem of juxtaposing the data of the Formator cadre counter with OTS time markers and with time markers of GTS TS. Practical usage of the OQTS has been determined the main role played by it in the present study: a method of measuring the *SRT* distance relative to the PRAO GTS and an instrument for investigating relativistic effects during the *SRT* flight.

In order to solve the problem of OQTS synthesis, we have reconstructed the hardware–software complex "KORVET R," which, among other things, serves the function of synthesizer of a sequence (in what follows, sequencer) of second markers for all three time scales mentioned above.

At the present time the algorithm of operation of the complex as a whole includes four basic stages: scrolling all binary records of radio astronomic observations in the form of PDF or TCI files for one *SRT* orbit and forming a complex of relationally connected measurement tables. In the process of scrolling the records metafiles are prepared. The deconvolver, using the complex of relationally connected measurement tables, retrieves from the metafiles a combined sequence of second markers in the form of a digital array. Thus the obtained sequence of second markers comes to the input of the three-channel sequencer (synthesizer of second markers for all three time scales that are in use). All three outputs of the sequencer are connected to inputs of the multichannel digital storage oscilloscope that plays the role of a three-channel synchronometer. A similar scheme is considered in [3] in detail. Illustrations of typical oscilloscope patterns are presented in [10] together with results of operation of OQTS synthesizer. The initial setting of OQTS is an important stage of operation of OQTS deconvolver and sequencer. This stage consists of two steps: synchronization and adjustment.

The synchronization is a process of predetermination of the position of the first OQTS marker on an interval of measurements [8, 9]. The synchronization procedure is repeated if the result of measurements exceeds the specified limit of accuracy. Provisions are made for two limits of synchronization: 1 microsecond and 100 nanoseconds.

The adjustment is a procedure of the precise determination of the sequence of Formator cadre numbers in which OQTS markers are located. At the stage of adjustment, the result of measurements is represented by numbers of two pairs of adjacent bits of RDF-record between which the first and the last OQTS markers for the current record are located. In order to estimate the error of measurements several verification procedures are used: the procedure of comparison with results of orbital measurements made by the KORTEX system; the procedure of comparison with results of measurements by the PRAO GTS; the procedure of comparing the results with the orbital forecast data; and the procedure of comparing the results with data of special test sessions.

RESULTS OF INVESTIGATIONS

The found empirical relationship (1) between the period of changing the numbers of Formator cadres and the mean value of *SRT* radial velocity on a specified time interval, which was considered above, gave the idea of possible observation onboard the *SRT* of the effect of relativistic time dilation.

Using the results of the RadioAstron project observations for the *SRT* flight lasting more than an year and a half, the time moment to begin synthesis of OQTS readings was selected as 13 h 00 min 00 s UTC on January 7, 2013. As a quantity characterizing the kinematic time dilation, we have chosen the time interval between two moments in different time scales

$$T_d = (t_{\mathrm{SRT}} - t_{\mathrm{TS}}) - (d_{\mathrm{PR}}/c), \qquad (3)$$

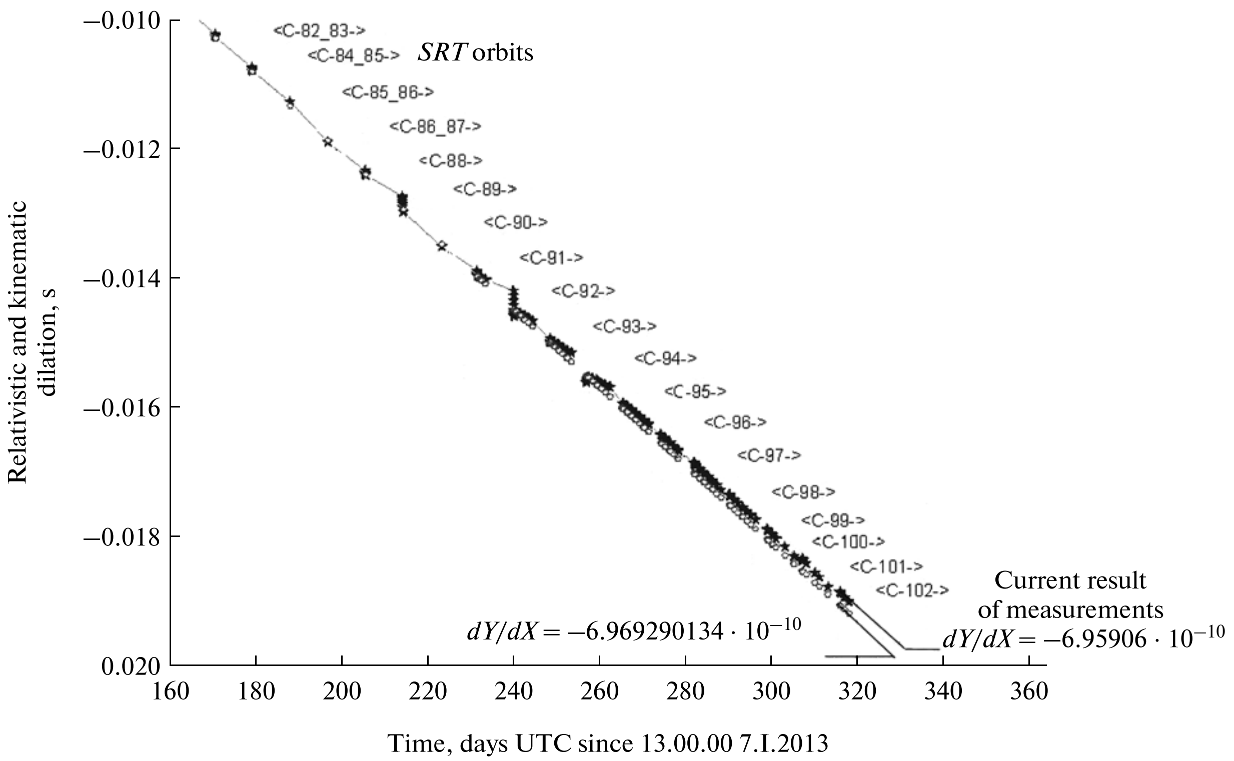

Fig. 3. Clock rate difference T_d for Time Scales (OQTS and PRAO GTS TS) as measured on the interval of radio astronomic observations in the period from January 7, 2013 up to November 19, 2013.

where T_d is the measured time interval (s), t_{SRT} is time readings according to OQTS (s), t_{TS} is time readings on GTS TS (s), and d_{PR} is the expected distance between *SRT* and GTS corresponding to t_{TS} (km).

The ratio (d_{PR}/c) corresponds to the expected delay of propagation on the distance between *SRT* and PRAO GTS. The physical meaning of the ratio considered in formula (3) consists in making spatial correction of a value of quantity T_d to the point with coordinates of PRAO GTS. Notice that there exists a solution of the problem of OQTS calibration: when performing it the difference ($t_{SRT} - t_{TS}$) can be used as a result of direct measurements of the CCND quantity discussed above. In solving the problem of OQTS calibration, the function presented in Fig. 2 is used. As a standard for estimating the relativistic time dilation we use in this study the norm recommended by the International Astronomical Union [6, 7], which is defined by the relationship

$$dTT/dTCG = 1 - L_G, \qquad (4)$$

where $L_G = 6.969290134 \cdot 10^{-10}$ the determining constant; *TT* is the terrestrial time, $TT = TAI + 32.184$ s; and *TCG* is the geocentric coordinate time.

Figure 3 presents results of calculating by (4) theoretical values of the relativistic time dilation on the Earth's surface and results of measuring the kinematic time dilation onboard the *SRT* with the use of relation (3). It is reasonable to use the results of CCND measurements for estimating a deviation of the measured *SRT* distance from predicted values. It is convenient to take the relation $T_d = 0$ as a reference point for comparison ("Norm"). This equality means that there is an agreement between predicted and observed values of the *SRT* distance. The theoretical deviation of CCND value from a predicted navigation delay value is caused in the first place by errors of synchronization of the onboard and ground quantum time scales, as well as by difficulties in prediction of current instrumental delays. In more detail the results of observations and measurements are considered in [10].

CONCLUSIONS

1. The loss of reliability of the data of radio astronomic observations (transmitted from the *SRT* board and received by the GTS at Pushchino) is about 1.5% of the total information volume received since January 7, 2013 to June 27, 2013, is equal to $13.2 \cdot 10^{12}$ bytes.

2. In the course of investigations the effect of relativistic time dilation (presumed in the special relativity theory) was confirmed onboard the *SRT*. The minimum value of measured quantity is $-6.95906 \cdot 10^{-10}$, which corresponds OQTS delay relative to the geocentric coordinate time by a value of 0.021946091616 seconds per year (60.126 microseconds per day). The obtained dependence is close to the value of the deter-

mining constant: $-6.969290134 \cdot 10^{-10}$. The current deviation equals:

$$6.95906 \cdot 10^{-10} - 6.969290134 \cdot 10^{-10}$$

$$= -0.010230134 \cdot 10^{-10} = -1.02 \cdot 10^{-12}.$$

3. The rate difference between the model of onboard atomic clock and ground-based atomic clock turned out to be +50 microseconds over 341 days (from January 31, 2012 up to January 7, 2013). This corresponds to a change of frequency of the OHFS reference signal relative to frequency of the PRAO GTS reference signal equal to $-1.697 \cdot 10^{-12}$. The relative change of frequency of the OHFS reference signal observed in the period from January 7, 2012 to November 10, 2013 was equal to $-6.126 \cdot 10^{-12}$. Comparing the obtained results one can note that the effect of relativistic and kinematic time dilation onboard the *SRT* is less by approximately factor of 6 than the relative change of reference frequencies of PRAO GTS HFS and *SRT* OHFS.

4. The deviation of the results of measurements (using CCND) of the *SRT* distance from predicted values did not exceed 30 km (in absolute value) over the interval of 180-days of observations in the period from January 7, 2013 to July 10, 2013.

5. The found dependence between changing numbers of cadres in Formator and the value of distance between *SRT* and GTS (it is presented in Fig. 2) allows the development of alternative methods of measuring the distance, radial velocity, and acceleration of the *SRT* of the RadioAstron project.

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Translated by A. Lidvansky

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