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Highly Accurate Determination of the Coordinates and the Earth's Rotation Parameters Involving the Svetloe VLBI Observatory

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Abstract—We present the results of our processing of the first observations of extragalactic radio sources obtained with the eight-element International VLBI Network, which includes the Svetloe Russian Radio Astronomy Observatory equipped with a Mark 3A recording terminal. Our observations and their processing yielded highly accurate coordinates (in meters) of the Svetloe Observatory in the ITRF 2000 system: $X = 2730173.854 \pm 0.002$, $Y = 1562442.668 \pm 0.004$, $Z = 5529969.069 \pm 0.007$. We also show that including the Svetloe Observatory in the International Network led to an appreciable improvement in the accuracy of determining the Earth's rotation parameters (microarcseconds for the coordinates of the pole and nutation angles, microseconds for Universal Time): $X_p = -154683 \pm 77$, $Y_p = 361809 \pm 59$, UT1−UTC $= -325162.9 \pm 2.5$, $\Delta\psi = -53147 \pm 114$, $\Delta\varepsilon = -2286 \pm 47$. *© 2003 MAIK "Nauka/Interperiodica".*

Key words: *radio interferometry, International Terrestrial Reference Frame, Earth's rotation parameters.*

INTRODUCTION

The Svetloe Radio Astronomy Observatory, the first observatory of the Russian continuously operating Quasar radio-interferometric network, is located in the Priozersk District of the Leningrad Region. It was created primarily for regular VLBI observations in programs of astrometry, geodynamics, and space geodesy (Finkelstein 2001; Gubanov and Finkelstein 2001). Svetloe is a specialized radio-interferometric station equipped with all of the necessary tools for VLBI observations of extragalactic radio sources.

By the end of 2002, the observatory was equipped with the only recording terminal—a Canadian S2 terminal with video converters, designed at the Institute of Applied Astronomy, Russian Academy of Sciences. Using this terminal, we have carried out observations under several programs together with VLBI stations of China, Canada, and Australia equipped with similar terminals, as well as with the other Quasar network observatory located in the Cossack village Zelenchukskaya, Karachaevo-Cherkessian Republic. At the end of 2002, in accordance with agreement between the Russian Academy of Sciences and NASA, a Mark 3A recording terminal was installed at the observatory, and from the beginning of 2003, it was incorporated into the International VLBI Service (IVS) for Geodesy and Astrometry. A number of large and long-term international astrometric and geodynamic VLBI programs, developed together with the Institute of Applied Astronomy, Russian Academy of Sciences, are being implemented within the IVS framework.

In this paper, we report the first results of one such programs that allowed us to radically improve the three-dimensional coordinates of the Svetloe Observatory, to significantly refine its position in the IVS network, and to estimate its influence on the accuracy of determining the Earth's rotation parameters.

INSTRUMENTATION OF THE OBSERVATORY

The main element of the instrumentation at the Svetloe Observatory is a new-generation, fully steerable radio telescope (Fig. 1) with a homologous mirror (Finkelstein *et al.* 2002). The quasi-parabolic mirror of the radio telescope has a diameter of 32 m and a focal length of 11.4 m. The secondary mirror, fixed to the supports of the primary mirror near the prime focus, is a modified hyperboloid of revolution with a diameter of 4 m.

The radio telescope has two modes of motion: fast ($1.^{\circ}5$ s^{-1} in azimuth and $0.^{\circ}8$ s^{-1} in elevation) and slow ($1.'5$ s^{-1} in azimuth and $0.'8$ s^{-1} in elevation), which

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Fig. 1. The radio telescope of the Svetloe Observatory.

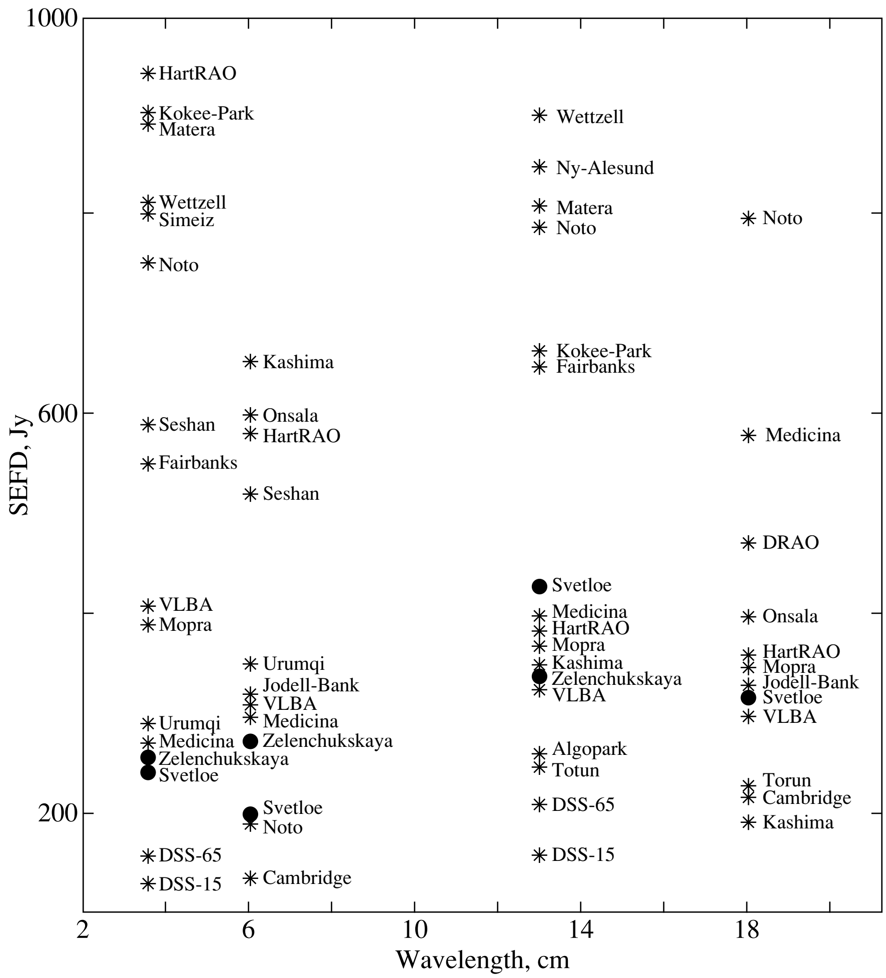

Fig. 2. SEFD values for the radio telescopes of the IVS network.

makes it possible not only to track radio sources but also to quickly repoint the antenna from one source to another. This is necessary for the carrying out of any astrometric or geodynamic program. A cable system rotates the antenna by $\pm 270°$ in azimuth from the central position northward and in the elevation range (from $-5°$ to $+90°$), which allows us to optimize various programs of observations of many radio sources located at widely differing hour angles.

The radio telescope is equipped with five low-noise cooled HEMT (High Electron Mobility Transistor) receivers for wavelengths of 1.35, 3.5, 6.0, 13, and 18/21 cm, which allow observations in two orthogonal circular polarizations to be carried out (Ipatov *et al.* 1994; Ivanov *et al.* 1997). To achieve a noise temperature of the radio telescope–radiometer system of ∼50 K, some of the input circuits of all bands are cooled down to 20 K. Closed-cycle microcryogenic systems are used to cool the low-noise devices of all bands down to 20 K. Figure 2 compares the system equivalent flux densities (SEFD) in the above bands of the Svetloe Observatory with those of other VLBI stations (including the second station of the Quasar Network, the Zelenchukskaya Observatory). This comparison shows that by this parameter, Svetloe ranks among the world's best VLBI stations.

The illumination system consists of horn feeds arranged in a circle with a diameter of 3.6 m. The working band is rapidly changed by rotating the remotely controlled secondary mirror, an asymmetric subdish, through an appropriate angle around the radio telescope axis.

S/X-band receivers (3.5/13 cm) with a common feed (Fig. 3) are used to implement astrometric, geodynamic, and geodesic programs with efficient suppression of ionospheric effects. The working intermediate frequency ranges of these cryoelectronic radiometers are 130–480 MHz and 130–890 MHz for the 13- and 3.5-cm bands, respectively. The noise temperature at the cryostat flange is 15 K, and the total noise temperature of the radio telescope–radiometer system does not exceed 50 K in the S-band and 70 K in the X-band for elevations larger than 20° (Fig. 4).

The signal from the radiometer outputs is fed through the phase-stable coaxial lines connecting the focal cabin of the radio telescope with the technical building to the input of a 14-channel Mark 3A recording terminal. The coaxial lines include amplifiers to adjust the nonuniformity of the transmission coefficient. The frequencies are converted to the video band by synchronized local oscillators with frequencies of 2020 and 8080 MHz for 13 and 3.5 cm, respectively.

The Mark 3A recording terminal performs the following functions: amplification and separation of the intermediate-frequency signal, conversion of the signal to the video frequency, clipping the output signals at a zero level and feeding the clipped signals to the recording system, measurement of the power of the received intermediate-frequency signal, and phase control. Information is recorded on magnetic tape by a Honeywell 24-track tape recorder; one tape records an 18–24-hour observational session, depending on the time required for repointing the telescope from one source to another.

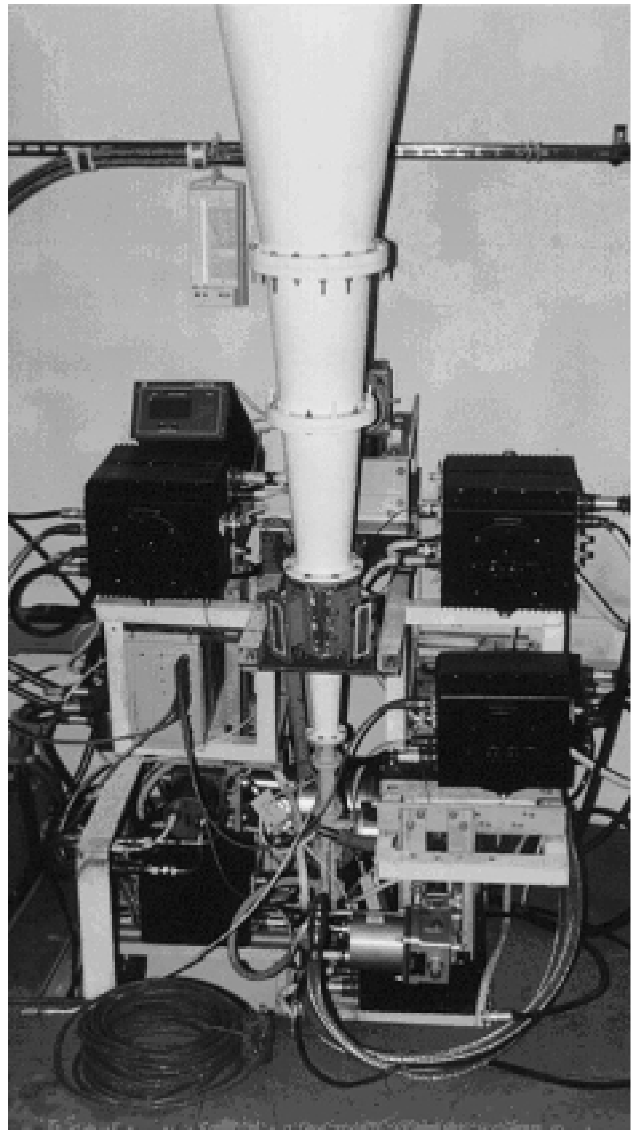

Fig. 3. S/X-band (3.5/13 cm) receivers of the Svetloe Observatory.

The Svetloe VLBI station has a high-quality time–frequency synchronization system (Vytnov *et al.* 1997). It includes four hydrogen maser frequency standards with long-term stability not worse than $(3–5) \times 10^{-15}$; one of the standards is always operational, while any other standard can be activated within one hour and can reach nominal technical parameters within another 24 hours. Comparison and time referencing relative to Moscow time and Coordinated Universal Time is made with an rms error of (30–50) ns by using the receivers of the GPS and GLONASS satellite navigation systems.

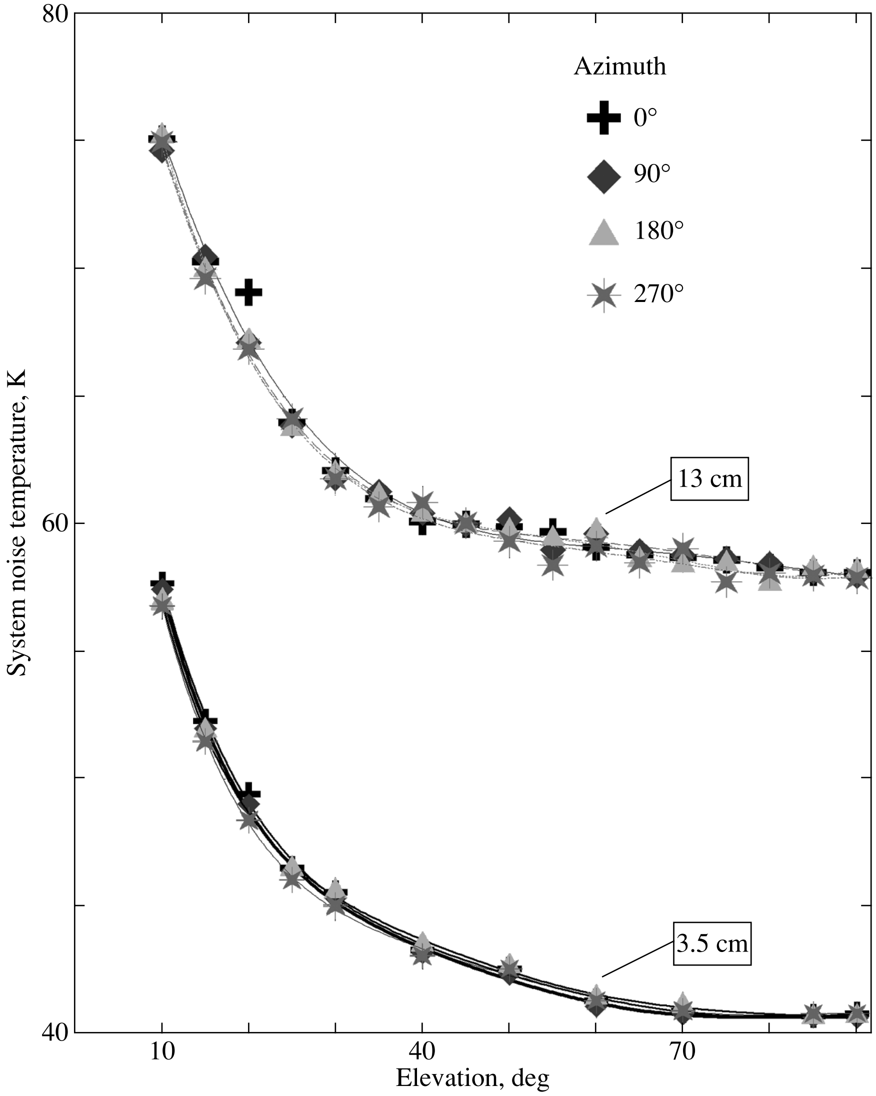

Fig. 4. Noise temperature of the radio telescope—radiometer system at the Svetloe Observatory.

The phase calibration of the system, which uses a picosecond pulse generator, consists of two main units: a pulse generator of harmonics based on a semiconductor diode and a square signal shaper with a frequency of 1 MHz from a harmonic signal with a frequency of 5 MHz fed from the hydrogen oscillator of the station. The delay in the propagation of the 5-MHz reference signal in the cable system is measured by means of a phase comparator, using the direct and delayed signals from the phase calibration oscillator fed into its comparison inputs.

The control system of meteorological parameters (atmospheric pressure, wind direction and strength, temperature, and humidity) is a high-precision soft-hardware automated measurement system. The sampling rate of the measurements by this system for automatic writing to a log file of the observational session is regulated over a wide range by a control program in the Windows 98 environment.

All of the systems of the radio telescope were combined into a single complex using a central computer with special-purpose software that allows observations to be carried out in a completely automated mode. The central computer not only controls the process of observations proper but also writes the results of the commands performed by the equipment of the radio telescope and the operational information (meteorological and metrological information, operator's comments, etc.) to a log file together with the results of the observations, which considerably facilitates antenna control and the data correlation process.

The Mark IV Field System, Version 9.5.17 (FS), which is the international standard for VLBI (Himwich 1996, 2000) and is installed on radio telescopes

Fig. 5. Locations of the IVS network observing stations involved in the experiment.

with various control systems, forms the basis for this software. Although FS provides a ready-to-use interface to the various recording systems (Mark 3–5, VLBA, S2, K4), it does not contain modules for controlling the antenna and specific equipment of the radio telescope. Therefore, it was supplemented with a station-oriented interface for controlling the antenna, a receiving complex, and a radiometric recording system. The software for this interface was developed in the Linux environment using specific commands in the SNAP language (used in standard FS) and completely integrated into the FS environment for observations in both VLBI and single-dish mode (Mikhailov 2000).

OBSERVATIONS AND RESULTS

At the beginning of December 2002, the Mark 3A VLBI terminal was installed at the Svetloe Observatory. On December 12, we performed, in cooperation with NASA experts, test VLBI observations of the radio sources 0552+398, 0923+392 and 1606+106 in the S/X bands together with the 20-m radio telescope in Wettzel (Germany) and the 20-m radio telescope in Ny-Alesund (Norway). The successful correlation processing carried out at the Max Planck Institut für Radioastronomie in Bonn (Germany) allowed us to reconcile and refine several technical parameters of the instruments important for subsequent joint observations.

The first regular VLBI observations at the Svetloe Observatory were carried out from $18^h29^m50^s$ UT March 6, 2003, through $15^h52^m53^s$ UT March 7, 2003, under a program for determining the Earth's rotation parameters (experiment R4061) within the intercontinental VLBI network. The latter consists of eight globally distributed stations (Fig. 5) that formed 28 interferometric baselines with lengths of from 990 km (Wettzell–Matera) to 11064 km (Kokee–Fortaleza). The size of the network was 82° in latitude and 170° in longitude. Table 1 lists the stations, their locations, and the distribution of scans.

The total number of program radio sources was 36; 29 of them were observed at the Svetloe Observatory. The total number of planned scans at the Svetloe Observatory was 132; for technical reasons, we completed only 116 of them. Each of the radio sources was observed on the network, on average, nine times with durations from 1.5 to 12.5 min; thus the total number of scans was 1398. The tapes were processed on the correlator at the US Naval Observatory, Washington, D.C.; 2373 radiointerferometric delays were processed, 2060 of which were used in the analysis.

The mean error of a single observation (radiointerferometric delay obtained on a single baseline) was 18.4 ps (5.5 mm), and while mean error of the ionospheric correction from the S/X-band observations was 8.7 ps (2.6 mm). In the correlation processing, we simultaneously determined the fringe rate with a mean error of 20.8 fs s^{-1}.

The secondary processing of the observations was performed in order to improve the coordinates of the Svetloe radio telescope and to calculate the Earth's rotation parameters for the epoch of the observations.

When improving the coordinates, we used the conventional and GPS measurements on the local geodesic network of the observatory (Kazarinov and Malkin, 1997) as *a priori* data. The geocentric coordinates of the radio telescope (the point of intersection of the axes) obtained using the OCCAM/GROSS

Table 1. Stations involved in the experiment

Station	Location	Distance from Svetloe, km	Number of scans
Algonquin Park	Canada	6256	192
Fortaleza	Brazil	8428	104
Gilmore Creek	USA, Alaska	5854	219
Kokee Park	USA, Hawaii	9561	168
Matera	Italy	2374	183
Ny-Alesund	Norway, Spitsbergen	2133	199
Svetloe	Russia	–	132
Wettzell	Germany	1655	201

Table 2. Coordinates of the Svetloe station determined in the experiment

Processing center	X, m	Y, m	Z, m
Institute of Applied Astronomy	$2\,730\,173.854 \pm 0.002$	$1\,562\,442.668 \pm 0.004$	$5\,529\,969.069 \pm 0.007$
GSFC	$2\,730\,173.851 \pm 0.003$	$1\,562\,442.664 \pm 0.002$	$5\,529\,969.063 \pm 0.006$

Table 3. Baseline lengths determined in the experiment

Baseline Svetloe	Number of observations	Length, m	Error, m
Algonquin Park	57	6 255 567.630	0.005
Fortaleza	31	8 428 008.668	0.010
Gilmore Creek	62	5 853 689.130	0.005
Kokee Park	35	9 561 115.418	0.008
Matera	75	2 373 640.095	0.003
Ny-Alesund	67	2 133 122.998	0.003
Wettzell	73	1 654 774.855	0.002

Table 4. The Earth's rotation parameters as determined from experimental data

Number of stations	X_p, μas	Y_p, μas	UT1–UTC, ms	$\Delta\psi$, μas	$\Delta\varepsilon$, μas	σ_0, ps	C_{max}
8 (all stations)	$-154\,683 \pm 77$	$361\,809 \pm 59$	$-325\,162.9 \pm 2.5$	$-53\,147 \pm 114$	-2286 ± 47	17	0.63
7 (without Svetloe)	$-154\,724 \pm 84$	$361\,833 \pm 64$	$-325\,159.3 \pm 2.9$	$-53\,097 \pm 122$	-2292 ± 50	20	0.66

Note: X_p, Y_p are the coordinates of the pole; UN1–UTC is the Universal Time; $\Delta\psi$, $\Delta\varepsilon$ are the nutation angles; σ_0 is the error of the unit weight; and C_{max} is the maximum correlation between the Earth's rotation parameters.

package developed at the Institute of Applied Astronomy, Russian Academy of Sciences (Titov and Zarraoa 1997; Malkin *et al.* 2000) are presented in Table 2. For comparison, this table also gives the coordinates obtained at the leading western VLBI processing center—the NASA Goddard Space Flight Center (Petrov 2003). Table 3 lists the baselines between the Svetloe radio telescope and other radio telescopes of the VLBI network, determined from the experimental results.

The coordinates were obtained in the International Terrestrial Reference Frame ITRF 2000 for the epoch 2003.18 (March 7, 2003) relative to the reference stations included in this system. The coordinates of the Gilmore Creek station were corrected for the displacement of the station during a strong earthquake in Alaska in November 2002, when the station was displaced by 6 cm.

The coordinates and velocities of the reference stations in the ITRF 2000 catalog contain errors for this network at a level of 2 mm (for the epoch 1997.0) and 0.3 mm yr^{-1}, respectively. Therefore, the processing was performed with different sets of reference stations. The errors of the coordinates and the baselines listed in Tables 2 and 3 correspond to the discrepancy between the results obtained in different processing variants.

In general, the results of the determination of the coordinates for the Svetloe Observatory and the network baselines show a high degree of accuracy in the observations and processing.

The main goal of the IVS program under discussion was to determine the Earth's rotation parameters. For this reason, we estimated the coordinates of the pole X_p, Y_p, the Universal Time UT1−UTC, and the nutation angles $\Delta\psi$ and $\Delta\varepsilon$ from the VLBI observations with and without the Svetloe Observatory (Table 4).

We see from our results that even the first inclusion of the Svetloe Observatory in the IVS network significantly improved the accuracy of the results.

Twenty sessions of the R4 program have been scheduled for 2003, which will allow us to further improve the accuracy of determining the Earth's rotation parameters. Five sessions of the T2 program planned for the same period, aimed at improving the coordinates of the network stations, will allow us to begin the determination of the tectonic motions of the Svetloe Observatory.

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