The Pulkovo Cooperation for radar and optical observations of space objects


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Abstract

The Central Astronomical Observatory at Pulkovo (CAO) (the Pulkovo Observatory) is arranging the cooperation of optical and radio telescopes for space debris studies in two main research directions, i.e. the precise tracking of the GEO-objects for development of the dynamical control method and the barrier method study of small fragments produced by GEO-object explosions.

Radar experiments are being carried out a few times per year by using the Evpatoria RT-70 transmitter, and the receiving radio telescopes at Bear Lakes (Russia), Simeiz (Ukraine), Noto (Italy), and Urumqi (China). The data processing centers are located in Nizhnyi-Novgorod, and Noto, and integrated into the Low Frequency VLBI Network (LFVN). The adjustment of the coordinated radar VLBI measurements has been completed, and the technique of beam-track search has been tested. The program of the LFVN modernizations is in progress now.

The observatories and observation stations of the former Soviet Union around the world take an active part in the Pulkovo cooperation of optical observers (PULCOO) program with the aim to perform the routine tracking of the GEO-objects. The method of search for GEO-fragments in the barriers as predicted on the bases of the Pulkovo “LAPLACE” theory of motion has been adjusted. A program of refurbishment of the telescopes, which cooperate in the framework of the PULCOO program, is in progress.

Introduction
The satellite astrometry observations at the Pulkovo Observatory has a long history since the date, October 10, 1957, when the first photographic frame of the “Sputnik” rocket body was taken (see Figure 1) and its position determined. The list of activities in this field included optical observations, treatment of measurements, orbit determination, development of the motion theory, and compilation of a catalogue of geostationary objects.

![Figure 1](image1.jpg)

Fig. 1. The photo frame of the “Sputnik” rocket body taken on October 10, 1957, by Dr. T.P. Kiseleva using the 10-cm telescope AKD. The exposure time is 21 s.

Pulkovo Observatory has tried in recent years to realize the multiform concept of study of space objects in close collaboration with the Ballistic Center of the Keldysh Institute of Applied Mathematics and the JSC “Vympel” International Corporation.

**Radar and optical facilities for the study of space objects**

The Central Astronomical Observatory at Pulkovo (CAO) is studying space objects on the basis of optical and radar observations. The radar observations are carried out in the framework of the LFVN that includes the 70-m antenna in Evpatoria with the 6-cm transmitter facility and the international array of receiving radio telescopes (RT-64 at the Bear Lakes, RT-32 at Noto, RT-25 at Urumqi, RT-22 at Simeiz, RT-22 at Puschino (Russia), and RT-32 at Ventspils (Latvia)). More detailed information may be found in [1,2]. As a part of this work, CAO supports the radio astronomical station disposing of the 64-m antenna at the Bear Lakes (Special Research Bureau of Moscow Power Engineering Institute) near Moscow (see Figure 2).
The optical observations are made in the framework of the PULCOO [2] under participation of the optical observation stations of many observatories of the former Soviet Union and are used to control the greater part of a geostationary orbit, the telescopes used being as follows: Zeiss-400 astrograph at Ussuriysk, UAFO; Zeiss-600 astrograph at Maidanak, UBAI; Maksutov-700 astrograph at Abastumani, AAO, Zeiss-1000 astrograph at Zelenchuk, SAO; AT-64 telescope and 2.6-m ZTSh-telescope at Nauchnyi, CrAO; SR-220 at Pulkovo, CAO; RK-300 telescope at Mayaki, AOMU; Zeiss-600 astrograph at Tarija, NAOB, and others). As part of this work, CAO maintains the 22-cm optical telescope SR-220 with the wide field of view at Pulkovo (see Figure 3, it is installed on the top of the AKD telescope, with which the first satellite photograph frame in 1957 was made), and prepares the 50-cm MTM-500 telescope for observations at Kislovodsk, Northern Caucasus.

All necessary software for the CCD-frame processing, ephemeris support, and orbit determination, together with the “LAPLACE” analytical theory of uncontrolled GEO-object motion, and with a model of explosions and the space debris database, are developed in the CAO.

Recent VLBI-radar results

The main directions of the work include the development of a VLBI method for the coordinated and non-coordinated measurements of catalogued high-orbit space objects and the adjustment of the beam-park and beam-track techniques for the search for non-catalogued objects. The three main VLBI principles consist in the following: (i) simultaneous observations of a space object by use of an array of spaced dish antennas, (ii) receiving the radio signals and recording them on the tapes/disks together with the precise clock readings, all frequencies being tied to an H-maser, (iii) cross-correlation of the tapes/disks received from all antennas in order to determine the time delays between the times of arrival of wavefronts to antennas, and the frequencies of interference (the fringe rates). The VLBI-radar combines both the “classic” radar and the VLBI techniques to provide an instrument for 3-D measurements: the radar resolves for range and radial velocity; the VLBI provides the angle and angular rate. The Evpatoria RT-70
included in the LFVN radar system can measure the Doppler shifts at five receiving points (with a precision of 0.003 Hz), the angular positions of objects (with a precision up to 0.01") and the information on sizes and the surface structures can be obtained. This research started in 1999, the first VLBI-radar experiment for space debris was carried out in May, 2001. The correlation processing procedure stages are described in [4], where the precision of the Doppler shift measurements has been evaluated. These data were obtained by the cross-correlations of the transmitted sounding signal recordings and the echo-signals received at radio telescopes. The VLBI-radar experiments on space debris objects moving in various orbits were carried out in 2004-2005, and the final stage of the correlation processing of radar echoes was adjusted. The fringe rate measurements were obtained by cross-correlations of echo-signals received by pairs of radio telescopes (see Figures 4, 5) on the baselines Bear Lakes-Noto-Urumqi and Bear Lakes-Noto-Simeiz.

![Figure 4](image1.png)

**Fig. 4.** The cross-spectrum of the echoes from Cosmos-1366 on the baselines Bear Lakes-Noto, Urumqi-Noto and Bear Lakes-Urumqi. The fringe rates are measured as frequencies of spectral maximums: \(-373.703\) Hz, \(-176.524\) Hz and \(-195.890\) Hz, respectively. VLBR03.1.

![Figure 5](image2.png)

**Fig. 5.** Time dependence of the cross-spectrum maxima of Cosmos-1366 on the baselines Bear Lakes-Noto (mono), Bear Lakes-Urumqi (mour) and Noto-Urumqi (nour). VLBR03.1.

The cross-spectrum maxima shifts obtained on baselines between the receiving antennas, (Fig. 6) with respect to the initial count point 22:23:11 are \(-3.35\) s for the Bear Lakes-Noto baseline, \(+1.65\) s for the Bear Lakes-Urumqi one, and \(-5.5\) s for the Noto-Urumqi one. With respect to the Bear Lakes point, the echo signals are, accordingly, ahead in Noto by 2.15 s and delayed in Urumqi by 5 s. It may be explained by the fact that the reflecting area of the Raduga 9 facility has a narrow beam directivity (about a few degrees wide) and has successively passed the receiving points during its rotation. This fact is demonstrated for the initial orbit of an object, which was reconstructed by use of optical data to evaluate the direction of the object rotation axis. The results of comparisons of precisions of the Doppler shift and fringe rate measurements are given in Table 1 below. The Doppler shift measurements were transformed into the half-
sums of the object radial velocities with respect to the sounding and receiving antennas. The fringe rate measurements were transformed into the object radial velocity differences with respect to two receiving antennas.

Table 1. The precision of the two types of VLBI-radar measurements – the Doppler shift and fringe rate – for Cosmos-1366.

<table>
<thead>
<tr>
<th>Date</th>
<th>UTC</th>
<th>Evpatoria-Bear Lakes</th>
<th>Evpatoria-Noto</th>
<th>Evpatoria-Urumqi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler shift</td>
<td>2002/07/25</td>
<td>12:44:00</td>
<td>-0.41</td>
<td>2.21</td>
</tr>
<tr>
<td></td>
<td>2002/07/25</td>
<td>12:45:00</td>
<td>-3.29</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>2002/07/25</td>
<td>12:46:00</td>
<td>4.37</td>
<td>-3.34</td>
</tr>
<tr>
<td></td>
<td>2003/07/25</td>
<td>22:23:16</td>
<td>13.2</td>
<td>78.0</td>
</tr>
</tbody>
</table>

One can see that the Doppler shift measurement precision is dozens of times worse than the fringe rate data precision whereas it should be quite the reverse. It may be explained by the insufficient current frequency resolution of the correlator. Nevertheless both types of VLBI-radar measurements may be used for the improvement of the initial orbit of an object.

The procedures of the beam-park and beam-track searching are adjusted using the newly designed recording terminals for the e-VLBI named NRTV (Near Real Time VLBI). It can record the echo-signals on the PC-disks and then transfer them into the Internet for further analysis at the VLBI data processing center. The recorded signals are auto-correlated to the high frequency and time resolutions, and the obtained data are presented in the form of the “frequency vs.time” diagram. It is supposed that possible space objects will leave the tracks in the form of lines on this diagram, and the slope of the line will reflect the value of the Doppler shift of echo-signals. The beam-park mode (i.e. the fixed beam direction with respect to the rotating Earth) was used in an attempt to find the LEO objects. The beam track mode (i.e. the fixed beam direction with respect to the inertial frame) was used in an attempt to detect the GEO objects. In the beam track mode the antenna beams are slowly moving along the GEO. During VLBR04.2 in July, 2004, the GEO region around the point with coordinates RA. 12h 08m 43.0s, Dec. +00° 50' 45” has been observed. Processing the measurements in this experiment allowed to clearly detect the echoes from 6 catalogued GEO objects and to determine the time-moment of the signal maximum, the duration of the beam crossing and the Doppler shift. A sample of the “frequency vs. time” diagram is shown in figure 6.
Figure 6. The sample of the “frequency vs. time” diagram for analyzing the beam-track experiments. On the vertical axis is time from 22:12:31 through 22:16:41 of day 206, 2004. On the horizontal axis are frequencies 247802.734 through 262451.172. The two points are identified with COSMOS 1961 and TELESAT-5.

PULCOO activities

The geographic locations and apertures of the telescopes participating in the PULCOO project are presented in Figure 7. The PULCOO project was organized to improve, in the first place, the ephemerides of the objects selected as targets for the VLBI-radar experiments. Two other major research goals are the precise tracking of the GEO-objects in order to develop the dynamical control method and to search for the small fragments produced by GEO-object explosions on the basis of the barrier method [5]. About 20 thousand measurements were obtained in the past year for the GEO
and objects moving in highly-elliptical orbits. Also regular observations of the GEO fragments were carried out. The 64-cm AT-64 and 2.6-m ZTSH telescopes at Nauchnyi (CrAO) are used to search for the fragments in the barriers calculated by use of the “LAPLACE” theory. The Zeiss-600 astrograph in Nauchnyi (SAI MU), Zeiss-1000 astrograph in Zelenchuk (SAO RAS), and Zeiss-600 astrograph in Maidanak (UBAI), and Zeiss-600 astrograph in Pulkovo and transferred to the “Vympel” International Corporation and to Ballistic Center of the Keldysh Institute of Applied Mathematics as well, where the Russian Academy of Sciences Center for collection, processing, and analysis of space debris information has been established this year.

Conclusions

The Pulkovo Observatory carries out the radar and optical research of high-orbit space objects in wide cooperation with other institutes and observatories. The Low Frequency VLBI Network designed for the VLBI-radar experiments has been equipped with the new NRTV recording terminals that allow it to obtain the measurements in a quasi-real time using the Internet for transfer of the VLBI signals from the receiving antennas to a correlation center. The procedure of the correlation process was adjusted for the radar echo signals to determine the Doppler shift and fringe rate. The Pulkovo cooperation of optical observers initiated the routine observations of space objects practically along the entire geostationary ring. The “barrier” method of searching for the faint non-catalogued GEO fragments was adjusted. After completing the first modernization stage, the potentialities of the PLOO will increase. This work was supported by the National Space Agency of Ukraine under project “Interferometer”, by the grant of the Russian Ministry of Education and Science, and by the INTAS-2001-0669, INTAS 03-70-567, RFBR 05-02-16832 grants as well.

References.


