INTERNATIONAL RADAR SPACE DEBRIS RESEARCH

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ABSTRACT

The radar research of space debris objects at HEO and GEO are carried out using Evpatoria RT-70 transmitter and Low Frequency VLBI Network since 2001. Primary goal of these experiments is developing and validation of the VLBI radar method to obtain the information on trajectory parameters, attitude motion and shape for known objects. The echoes from about 50 objects were recorded on magnetic tapes or PC-disks at Bear Lakes RT-64, Noto RT-32, Urumqi RT-25 and Simeiz RT-22. The correlation processing in N. Novgorod and Noto provided measuring the Doppler shifts, angular coordinates, rotation periods and dimensions for most of studied objects. Pulkovo Cooperation of Optical Observers (PulCOO) and other optical facilities carried out positional measurements in support of radar experiments. The second goal was adjusting of so called the beam-park (fixed beam direction with respect to the rotated Earth) and beam-track (fixed beam direction with respect to the inertial frame) methods to search of uncatalogued fragments. The partial processing of beam-track experiment of July 2004 allowed to clearly detect the echoes from five catalogued GEO objects and measure the moment of signal maximum, duration of beam crossing and Doppler shift.

Key words: radar; space debris; VLBI.

1. INTRODUCTION

The fully steerable 70 m dish (Fig. 1) near Evpatoria city in Crimea of Ukraine is equipped with one from most powerful 6-cm band transmitter in Europe that was used for the deep spacecraft communications and the radar research of Mars, Venus and Mercury (Molotov E.P. et al., 2004). Since 2001 this facility was regularly used with international team of specialists from Ukraine, Russia, Italy and China for investigations of space debris at geostationary (GEO), highly-elliptical (HEO) and half-day orbits (HDO) (Molotov I.E. et al., 2004a). The researches are carried out in two main directions – coordinate and uncoordinated measurements for catalogued high-orbit space objects and searching of uncatalogued objects in beam-park and beam-track experiments. The close collaboration of Evpatoria RT-70 with Low Frequency VLBI Network (LFVN) (Molotov et al., 2003) gives the opportunity to apply the technique and apparatuses of Very Long Baseline Interferometry (VLBI) for receiving and analysis of echo-signals. The three main principles of VLBI are following: (i) simultaneous observations of space object with array of spaced dish antennas, (ii) radio signals are received and recorded to the tapes/disks together with the precise clock, all frequencies are connected to H-maser, (iii) tapes/disks from all antennas are cross-correlated to measure the time delay between arrival of wavefront to antennas and frequency of interference (fringe rate).

Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005
(ESA SP-587, August 2005)

Figure 1. 70-m antenna near Evpatoria with 200 kW continuous power transmitter at 5010 MHz, National Control and Space Facilities Test Center, National Space Agency of Ukraine.

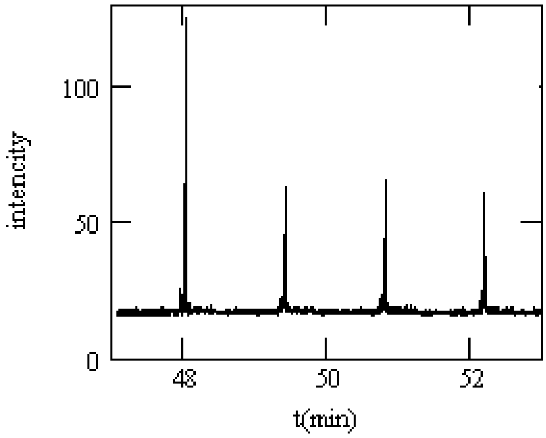

Figure 2. Recording of echo intensity of Raduga 9, estimated period of rotation is 83 s.

Such combination of the “classic” radar and VLBI techniques can results instrument for 3-D measurements (i) radar has the resolution for range and radial velocity, (ii) VLBI provides the angle and angular rate. We named such technique as VLBI radar method (VLBR). The four receiving antennas regularly participated in VLBR sessions – Bear Lakes RT-64 in Russia, Noto RT-32 in Italy, Urumqi RT-25 in China and Simeiz RT-22 in Ukraine. The equipping of fifth telescope, Ventspils RT-32 in Latvia, will be finished in this year. The Evpatoria RT-70 => LFVN radar system can obtain the measurements of Doppler shifts at four receiving points with precision of 0,003 Hz, angular position of object with accuracy of $0.01''$, range (existing linear frequency modulation of 512 kHz, 32 ms can give precision of 50 m), rotation period, orientation of rotation axis, sizes and structure of surface (Molotov et al., 2004b). In common, seven space debris experiments were arranged, see Table 1.

2. PROCESSING AND RESULTS OF EXPERIMENTS ON CATALOGUED SPACE OBJECTS

The standard VLBI recording terminals (base band converter, 1-bit sampler, Mk-2 formatter and recorder, 2 MHz frequency bandwidth) are used to register an echo-signal in on magnetic tapes for further analysis at VLBI data processing center in N.Novgorod, Russia. Bear Lakes Mk-2 recorder can record also the echo-signal intensity (the same 2 MHz band signals after quadratic detector) in digital form (10 binary bit with period of 16 ms).

The first stage of processing includes the auto-correlation of the recorded tapes to detect the echo-signals from each object on each receiving antenna. The recording of echo intensity at Bear Lakes RT-64 allows measuring the main period of the object rotation (Fig. 2). Fourier transformation of the single impulse of an object rotation gives the one-dimensional convolution of the reflected region in wavelengths to estimate the sizes of the object. The next stage is the cross-correlation processing of the transmitted signals and received echoes for each baseline “transmitting antenna – receiving antenna” (TA-RA). As a result of spectral analysis the frequency of Doppler shift is measured (Fig. 3). The analysis of time evolution of maximum of cross-spectrum (TA-RA) also can allow to measure the rotation period (Fig. 4). Then the cross-correlation for echo-signals is obtained on baselines between each two receiving antennas to measure the fringe rate for angular coordinate determining (Fig. 5). The signal delay-time dependence in the form of a 3rd degree polynomial is calculated with respect to a preliminary trajectory model of the object, coordinates of VLBI points and cycle time. This calculation takes into consideration the near-field effect associated with the movement of the object with respect to the center and rotation of the Earth. Such a polynomial is used for the computation of the shift-time dependences, which are introduced during the correlation processing of the radar echo signals received at each VLBI point of the interferometer baseline. At final stage the measured fringe rate and other obtained data are analyzed.

For example, 17 values of Doppler shifts were obtained for the GEO-object 1982-044A, 5 on Evpatoria-Noto baseline and 12 on Evpatoria-Bear Lakes baseline at 10-minute time interval to check the consistency of the measurements. The mean-root-square error is 0.096 Hz (corresponding to 3 mm/s rate), that is three times worse than apparatus mistake (1 mm/s rate). This may be explained by the rotation of the object. The post-processing of the data on the GEO-object 1982-044A shows that the measured Doppler shifts are in good an agree-

Table 1. The list of space debris VLBR experiments.

Name	Date	Receiving radio telescopes	Processing	Received echoes from
VLBR01.1	May 23-29, 2001	Bear Lakes, Svetloe, Noto, Shanghai, Urumqi, Torun	N. Novgorod	7 GEO objects
VLBR02.1	July 23-29, 2002	Bear Lakes, Kalyazin, Noto, Shanghai, Urumqi	N. Novgorod, Noto	7 GEO, HEO, HDO objects
VLBR03.1	July 23-29, 2003	Bear Lakes, Noto, Urumqi, Simeiz	N. Novgorod, Noto	10 GEO, HEO, HDO objects, beam-park
VLBR04.1	June 21-25, 2004	Bear Lakes, Noto, Simeiz	N. Novgorod, Noto	GEO, HEO, HDO objects, beam-park
VLBR04.2	July 23-29, 2004	Bear Lakes, Noto, Simeiz	N. Novgorod, Noto	18 GEO, HEO, HDO objects, beam-park, beam-track
VLBR04.3	Sept. 29-Oct. 5 2004	Bear Lakes, Noto, Simeiz	N. Novgorod, Noto	HEO, HDO objects, beam-park, beam-track

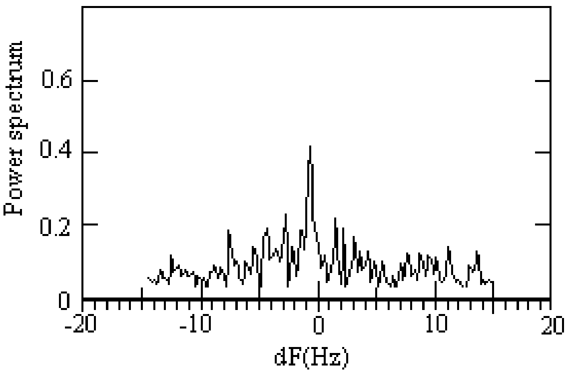

Figure 3. The TA-RA cross-spectrum Evpatoria-Urumqi baseline, for Raduga-9. Doppler shift evaluated as frequency of spectral maximum is 1574.147 Hz, frequency resolution is 0.234 Hz, VLBR03.1.

ment with the orbit calculated from optical observations. The obtained radial rate measurements have been jointly treated with optical observations, fulfilled over interval since July 2002 up to July 2003. For the comparison, the orbits of 1982-044A were calculated separately from the optical data and from optical and radar data. The table 2 shows the results of the posterior precision estimate of the orbital elements for both cases demonstrating that involving of radar data provides the noticeable improvement of the orbit precision. The discrepancies of measured and calculated values of optical and radar data are presented in Figure 6.

The shifts of cross-spectrum maximums, obtained on baselines between receiving antnnas, (Fig. 7) in respect of beginning point of count 22:23:11 are −3.35 s

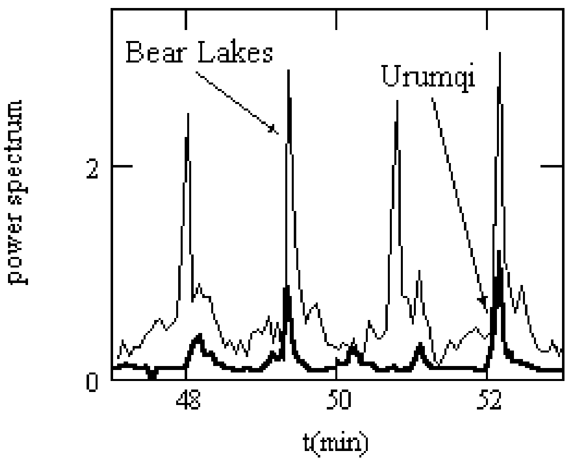

Figure 4. Dependence of spectral maximum on time (TA-RA cross-spectra for Raduga-9 on Evpatoria-Bear Lakes and Evpatoria-Urumqi baselines), time resolution is 4.26 s, real period of rotation is 166 s.

Table 2. The posterior precision estimate of orbital elements obtained with use of optical data only and of both optical and VLBI radar data.

Parameter	Error of determination	
	The optical data	The optical and VLBI radar data
Period (s)	0.00039	0.00016
Eccentricity	0.000001289	0.00000011
Inclination (degree)	0.0000397	0.0000385
Longitude of node (degree)	0.0001523	0.0001443
Argument of perigee (degree)	0.3186443	0.0553811
Time of perigee (s)	0.08468	0.03756

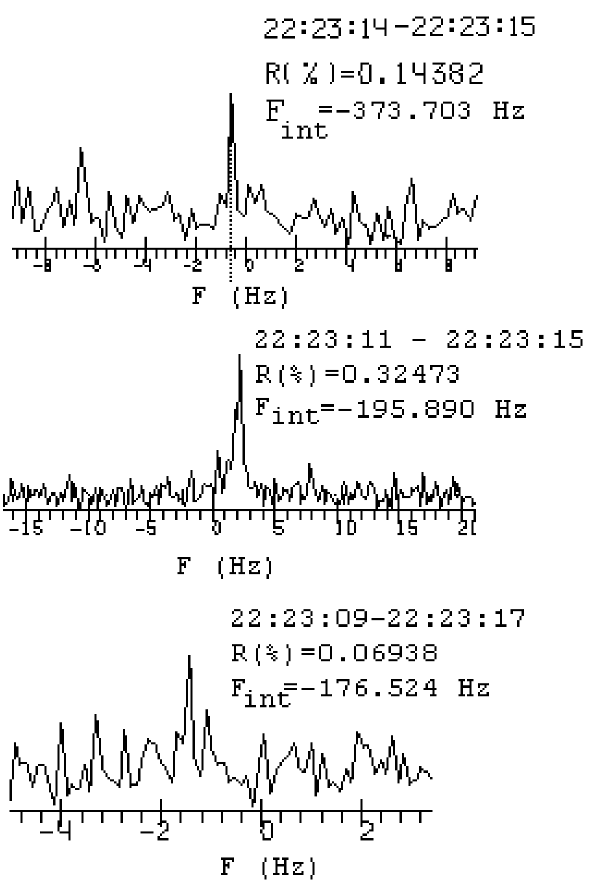

Figure 5. The cross-spectrum of echo from Cosmos-1366, at baseline Bear Lakes-Noto, Urumqi-Noto and Bear Lakes-Urumqi. Fringe rates are measured as frequency of spectral maximums: −373.703 Hz, −176.524 Hz and −195.890 Hz respectively. VLBR03.1.

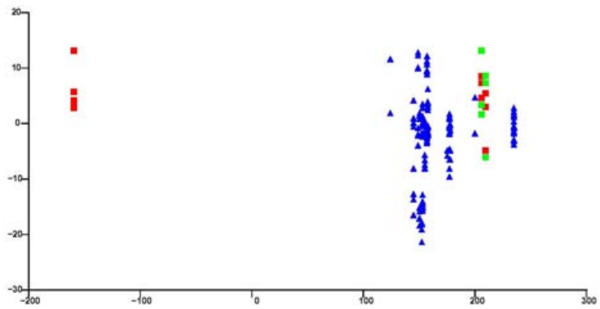

Figure 6. The representation of the observations by calculations (O-C) since January 1, 2003. The deviations of optical data (in arc seconds) are designated by triangles, but the measured radial rates (mm/s) are noted by squares.

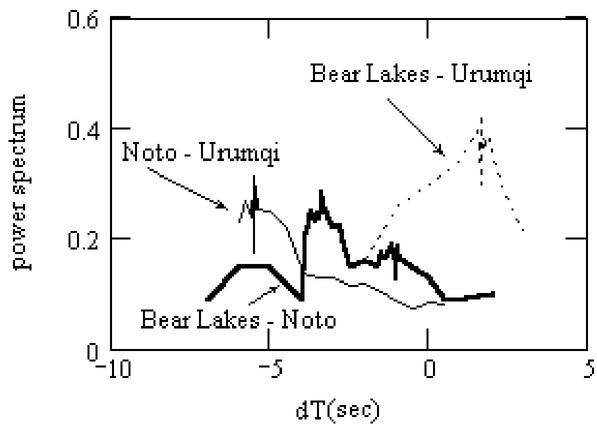

Figure 7. Time dependence of cross-spectrums maximums of Cosmos-1366 at baselines Bear Lakes-Noto, Bear Lakes-Urumqi and Noto-Urumqi.

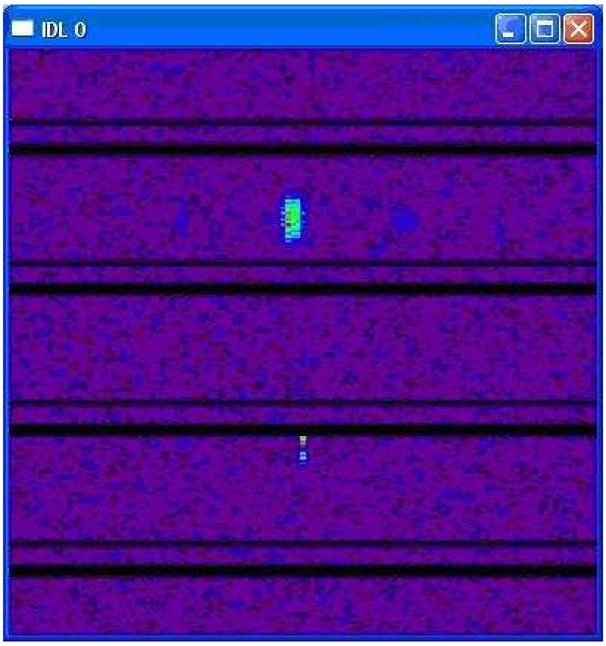

Figure 8. The sample of frequency-time diagram for analyzing the beam-track experiments. The vertical axis is time from 22:12:31 to 22:16:41 of day 206, 2004. The horizontal line is frequencies 247802.734 262451.172. The two points are identified with COSMOS 1961 and TELESAT-5.

for Bear Lakes-Noto, +1.65 s for Bear Lakes-Urumqi and −5.5 s for Noto-Urumqi baselines. Accordingly in respect of Bear Lakes point, the echo signals ahead in Noto on 2.15 s and delayed in Urumqi on 5 s. It may be explained that reflected area of Raduga 9 has narrow beam of directivity (about few degrees) and it successively passed the receiving points during rotation. This fact to evaluate the direction of object rotation axis.

3. BEAM-PARK AND BEAM-TRACK EXPERIMENTS

The newly designed recording terminals for e-VLBI named NRTV (Near Real Time VLBI) are used to register an echo-signals in 2 MHz frequency bandwidth on PC-disks for further analysis at VLBI data processing center in Noto, Italy. The recorded signals are autocorrelated with high frequency and time resolutions and obtained data are presented in the form of frequency-time diagram. It is supposed that possible space objects will rest the tracks in the form of lines at this diagram. The inclination of the line will be reflecting the value of Doppler shift of echo-signals.

In our experiments for searching the uncatalogued fragments we worked in beam-park and beam-track modes. Beam-park (fixed beam direction with respect to the rotated Earth) mode was used in attempt to fix LEO objects. Beam track (fixed beam direction with respect to the inertial frame) mode was used in attempt to detect GEO objects. In the time of beam-track, the antenna beams are slowly moving along GEO. During VLBR04.2, in July 2004, we observed the GEO region around of point with coordinates RA 12 08 43.0, Dec +00 50 45. The processing of this experiment allowed to clearly detect the echoes from five catalogued GEO objects and measure the moment of signal maximum, duration of beam crossing and Doppler shift (Table 3. The sample of frequency-time diagram is shown at Fig. 8.

Table 3. Autocorrelation of beam-park for observed GEO objects.

Object	T_{detect} hh:mm:ss	Duration sec	F_{Dopp} kHz
Cosmos 1961	22:13:45	4.4	1.12695
ANIK C3	22:15:28	11.5	0.76074
Cosmos 1897	22:29:40	7.8	1.37109
STTW-1	22:52:19	10.0	1.61523
GORIZONT 17	23:01:38	25.9	1.52161

4. CONCLUSION AND OUTLOOK

So, adjusting the VLBR method is close to be finished soonest. The new elaborated technique already may be used for routine work. During 2005 we suppose to concentrate our efforts on learning the VLBR in near-real time using the Internet and NRTV-terminals. Five NRTV-terminals were produced at Italy in 2003/04, installed and tested at antennas of VLBR cooperation. Three-station NRTV correlator is developed in Noto, Italy. During the VLBR sessions of 2004, the part of VLBI data from Evpatoria, Bear Lakes and Simeiz was sent to Noto and analyzed in near real-time. There is an intention to create new correlator for NRTV standard in Russia.

Important goal of future plans will be developing the technique of "classic" VLBI for evaluation of the size and form of space objects. The using length of baseline (6000 km) and frequency (5010 MHz) can allow to obtain the spatial resolution for GEO of about 40 cm.

Next VLBI radar session, VLBR05.1 is scheduled for July 22-27, 2005. In beam-track part of this experiment we plan to observe few from the eight GEO-fragments that were discovered recently with optical telescopes in Nauchniy, Crimea. In beam-park part, we suppose to observe few catalogued small LEO objects for calibration.

It is planned that in second half of year, sixth antenna, RT-32 in Ventspils, Latvia will join to our VLBR cooperation. With this goal, the 6-cm "warm" receiver will be installed in it in May.

ACKNOWLEDGEMENTS

This research was supported by INTAS 2001-0669 and "Interferometer" project of National Space Agency of Ukraine. We thank the staff at the radio observatories Bear Lakes, Evpatoria, Noto, Urumqi, Simeiz that participated in the experiments and the optical observatories Pulkovo, Nauchny, Mayaki observations of that allowed improving the ephemerides of space objects. We thank James Dick and Phil Herridge for their continuing support and tremendous help with collecting of optical measurements by PIMS for studied objects.

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