EXPERIMENTS ON THE DIFFERENTIAL VLBI MEASUREMENTS WITH THE FORMER RUSSIAN DEEP SPACE NETWORK

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ABSTRACT

The differential VLBI technique (delta-VLBI) is applied for measuring spacecraft position with accuracy up to 1 mas. This procedure allows to link the sky position of object with the position of close ICRF quasar on the celestial sphere. Few delta-VLBI measurements can urgently improve the knowledge of object trajectory in the times of critical maneuvers.

The Russian Deep Space Network that was based on three large antennas: 70 m in Evpatoria (Ukraine) and Ussuriysk (Far East), and 64 m in Bear Lakes (near Moscow) arranged the trial delta-VLBI experiments with help of four scientific institutions. The specialized “Orion” system for regular delta-VLBI measurements was not finally completed. The series of delta-VLBI runs was carried out from 1984 to 1993 for the Venus-15, Vega-1, 2 and Phobos-1, 2 interplanetary stations, Astron and Granat highly-apogee spacecrafts.

Since 1999 the differential VLBI radar (VLBR) method is under development using 6-cm transmitter in the Evpatoria to radio sound the space objects. The VLBR observations of space debris objects at geostationary and highly elliptical orbits, Venus and Mars planets were arranged to determine their trajectories in Radio Reference Frame and measure the variations of proper rotation.

The further development is connected with Phobos sample return mission. It is planned to adjust the delta-VLBI technique in near real time with translation of signals from antennas to correlator through Internet.

1. INTODUCTION

The delta-VLBI method is used for interplanetary spacecraft navigation in the time of the critical maneuvers, when the position of spacecraft must be measured quickly and precisely. The VLBI technique implies the joint observations of the radio telescope array of selected radio emitters (spacecraft, quasar, etc.) in the desired frequency band under a common schedule. In each radio telescope, the radio signals are received with low noise receiver and transformed into an intermediate frequency. Then base band converter filters the necessary frequency bandwidth and transforms the signals into video frequencies, which then are sampled with 1- or 2-bit quantization, formatted in any standard VLBI format (Mk-4, S2, K-4, Mk-2) and recorded on magnetic tapes or PC-disks together with precise clock using VLBI terminal. All frequency transformations are connected with atomic frequency standard. The tapes/disks from all radio telescopes of VLBI array are collected at data processing center, where the data are cross-correlated. The processing is aimed to measure the time delay of emitted wavefront arrival to receiving antennas, and frequency of interference (fringe rate), that contain the information about angular coordinates of spacecraft.

The delta-VLBI technique is used for measuring spacecraft trajectories with accuracy up to 1 mas. This procedure allows to link the sky position of object with the position of close quasars on the celestial sphere (the angular distance between close quasar and observed object must be 5^o – 10^o). During the experiment, the radio telescopes alternately observe the object and reference quasar. Each experiment contains the several cycles: 15 minutes of object observations and 10 minutes of observations of reference quasar (few close ICRF quasars are selected along trajectory of object in order to make few points of measurements). The recorded pairs (object and reference quasar signals) are processed at the correlation center to determine the relative time delay and fringe rate.

Two kind of delta-VLBI measurements of spacecraft may be applied for space navigation: wide-band, using specially formed signal (few spectral lines spaced in band of 10 – 15 MHz), and narrow-band, using the standard telemetry signal. The wide-band mode allows to measure both time delay and fringe rate. Therefore, it is in few times more precise but more complicated in realization. The narrow-band mode allows to measure the fringe rate only, but it is more cheap and easy.

Russian Deep Space Network carried out a lot of delta-VLBI experiments with help of four scientific institutions under development of specialized VLBI system “Orion” for deep space navigation purposes.

2. DELTA-VLBI EXPERIMENTS OF FORMER RUSSIAN DEEP SPACE NETWORK

The Russian Deep Space Network was based on three large full steerable antennas: two of 70 m in diameter (RT-70) in Evpatoria, Crimea of Ukraine (erected in 1978) and Ussuriysk, Far East of Russia (erected in 1985) and one of 64 m in diameter in Bear Lakes near Moscow (erected in 1979) [1]. The antennas have quasi-parabolic axially symmetrical Gregory mirror system with subreflector of 7 m (at RT-70) and 6 m (at RT-64) in diameter, which are programmably moved for compensation of gravitational deformations. RT-70s have the beam-guide rotating system for six feeds; the effective area is about 2600 m^2 at 5 cm wavelength (main mirror can operate up to 8 mm). RT-64 has multi-bands feedhorn system, the effective area is about 2000 m^2 at 18 cm wavelength (main mirror can operate up to 1.35 cm). The antennas are equipped with transmitter facility for 6-cm band (200 kW in Evpatoria, 50 kW in Ussuriysk).

These antennas were used for control of the Russian deep space missions and high-apogee satellites (Mars, Phobos, Venus, Vega, Astron, Granat etc.). Moreover, the Ussuriysk RT-70 was used for receiving of the telemetry information of Voyager spacecrafts in 1991; the Evpatoria RT-70 was operating as planetary radar. Another activity included VLBI observations for space navigation and radio astronomy. The interferometer baselines are 6900 km between Evpatoria and Ussuriysk, 6130 km between Bear Lakes and Ussuriysk and 1240 km between Bear Lakes and Evpatoria.

First successful Russian delta-VLBI measurements were carried out with interplanetary spacecrafts Vega-1, 2 in April 1985, April 1986 and October 1986 (10 hours each run) [2]. The trial experiments were arranged at 32 cm wavelength using Evpatoria RT-70 and RT-25 near Bear Lakes. The quasar (3C454.3, 3C368, 3C273, 3C84) signals were recorded at 1 MHz band and telemetry signals at 1.5 kHz that allowed to realize the narrow-band delay-VLBI mode only. The processing was conducted with NIRFI-1 correlator of Radio physical research institute in N. Novgorod.

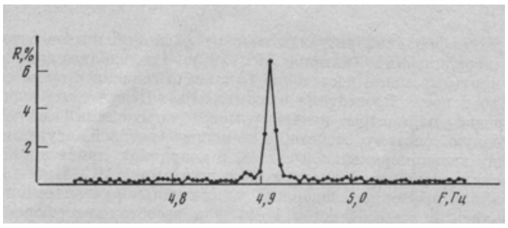

Fig. 1. VLBI fringe for Vega-1 telemetry signal. Recording duration is 186 s; frequency resolution is 0,0054 Hz.1985. R, vertical axis, is coefficient of cross-correlation in %; F, horizontal axis, is frequency of interference in Hz

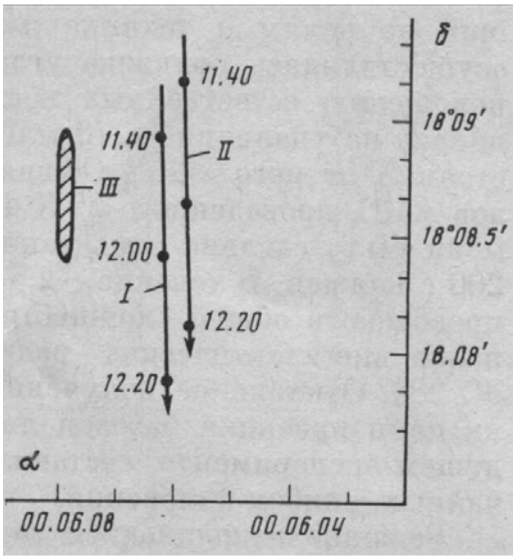

Fig. 2. Sky trajectory of Vega-2 in April 10, 1985: I – delta-VLBI measurements; II- averaged long row standard trajectory measurements; III – calculated ellipse of fluctuation errors of delta-VLBI measurements

Some results are presented in Fig. 1, 2. The obtained precision of first run measurement was not too high (1.3” for right ascension and 18” for declination) due to relatively little used baseline (1240 km) and unfavourable mutual geometry of interferometer and spacecraft in period of observations.

As next step, all three antennas participated in international delta-VLBI campaign on tracking of balloons in atmosphere of Venus at 18 cm wavelengths in June of 1985 using Mk-2 videocassette recording terminals with 2 MHz band [3]. The balloon signal was in the form of two spectral lines spaced at 6.5 MHz. The movement of both balloons was measured with error of 0.5 m/s.

The next delta-VLBI runs (two runs of 10 hours each) were carried out in April 1987 for highly-apogee spacecraft Astron at 32 cm wavelength on Bear Lakes-Ussuriysk baseline [4]. The obtained precision of the delta-VLBI measurement was about 0.25”.

Then the measurements were fulfilled for interplanetary spacecraft Phobos-1, 2 at 18 cm wavelength on Evpatoria-Bear Lakes-Ussuriysk baselines (6 runs, 3 of 12 hours in December 1988, and 3 of 12 hours in January 1989) [5]. The using of specially formed spacecraft signals (two spectral lines in 14 MHz band) allowed to obtain the precision of 0.05”.

Last delta-VLBI run (narrow-band) was arranged in November 26-30, 1992 for highly-apogee spacecraft Granat at 5 cm wavelength on the Evpatoria-Ussuriysk baseline [6]. The obtained precision was about 0.01”.

The specialized delta-VLBI "Orion" project of Russian Deep Space Network would be finished to time of Mars-96 mission. It was designed as two-channel system based on Mk-2 recording terminals with synthesizing the wide frequency band. The four-station Mk-2 correlator NIRFI-2 was elaborated in N. Novgorod. Unfortunately, the "Orion" project was not finally completed, but the models of devices were planned for using in delta-VLBI measurements in Mars-96.

3. CURRENT STATUS

All three antennas were temporarily stopped due to cessation of financing from the Russian Aviation and Space Agency after the loss of the Mars-96. The operations of the Evpatoria RT-70 and the Bear Lakes RT-64 were renewed for radio astronomy research purposes. Evpatoria RT-70 is property of the National Space Agency of Ukraine; Institute of Radio Astronomy in Kharkov is responsible for the scientific program forming. Special Research Bureau of Moscow Power Engineering Institute and Central Astronomical Observatory at Pulkovo, Russian Academy of Science, arranged the Bear Lakes Radio Astronomy Station on base of the RT-64. Both antennas are carried radio astronomy observations under Low Frequency VLBI Network (LFVN) project [7]. Unfortunately, there was no any Russian scientific interplanetary or highly-apogee mission after Mars-96. Therefore, it was decided to try to continue the delta-VLBI works as a part of development of VLBI radar (VLBR) method [8].

VLBR technique joins the "classic" radar and differential VLBI measurements (the sounding of investigated objects with radar signals and the VLBI receiving of reflected echo-signals with array of radio telescopes). Such a combination can provide new scientific instrument for the precise measuring the movement parameters of the Solar system bodies, and obtaining the data on the object sizes and structure of surface. The goals of this research are studying the short-periodic variation of proper rotation of the Earth group planets, determining their trajectories in Radio Reference Frame coordinate system; researching the asteroids crossing the Earth orbit, improving their trajectory knowledge; investigating the space debris population at geostationary and high-elliptic orbits including statistical measurements of cm-sized objects. In these experiments, the radar system of the Evpatoria RT-70 provided the sounding of space targets (Earth group planets, near-Earth asteroids and space debris objects) with help of the 200 kW transmitter of continuous power at 5010 MHz. The reflected echo-signals were received with Bear Lakes RT-64, Noto RT-32, Urumqi RT-25, and Simeiz RT-22 using the Mk-2 and recording terminals. In common, the 9 VLBR experiments were carried out since 1999 (VLBR99.1 in June 1999, VLBR00.2 in August 2000, VLBR01.1 in May and VLBR01.2 in December 2001, VLBR02.1 in July 2002, VLBR03.1 in July 2003, VLBR04.1 in June, VLBR04.2 in July, and VLBR04.3 in September-October 2004). The echoes of Mars, Venus and 60 orbital objects were detected. The rows of the high precise Doppler shifts were measured for a number of objects in Bear Lakes, Noto and Urumqi [9]. Rotation period and the sizes of reflecting area were estimated. Recently, the VLBI fringes were obtained for the group of space debris objects. The obtained data are processed by NIRFI-3 correlator of Mk-2 format in N. Novgorod (see Fig. 3).

Fig. 3. NIRFI-3 correlator of Mk-2 format in Radio Physical Research Institute, N. Novgorod, Russia

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 (see Fig. 4).

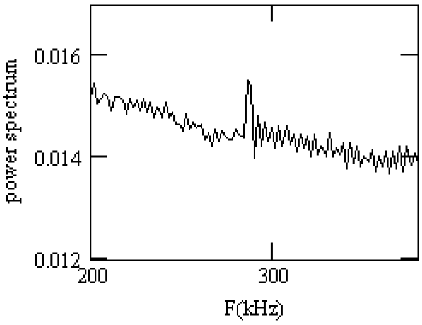

Fig.4. Autocorrelation spectrum of echo-signals of Venus received in Bear Lakes. VLBR04.2

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 (see Fig. 5).

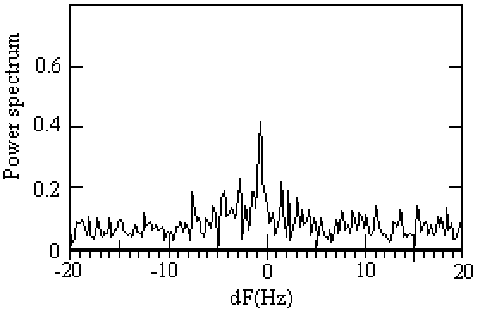

Fig. 5. The TA-RA cross-spectrum Evpatoria-Urumqi baseline, for Raduga-9. Doppler shift evaluated as frequency of spectral maximum is 1574.147 Hz, frequency resolution is 0.234 Hz, VLBR03.1

Recording of echo intensity at Bear Lakes RT-64 allows to evaluate the main period of the object rotation. Fourier transformation of the single impulse of an object echo gives the one-dimensional convolution of the reflected region in wavelengths to estimate the size of the object. While the record of intensity is not performed at other receiving sites, it is tracked the time evolution of maximum of cross-spectrum (TA-RA), that is equivalent to echo intensity changing (see Fig. 6). The time dependence of spectral maximum on baseline Evpatoria – Bear Lakes shows the period of rotation as 83 s, while spectrum Evpatoria-Urumqi demonstrates two time longer period. This means that Raduga 9 has symmetric elements (i.e. solar batteries) that are visible from Bear Lakes and Urumqi under different angles.

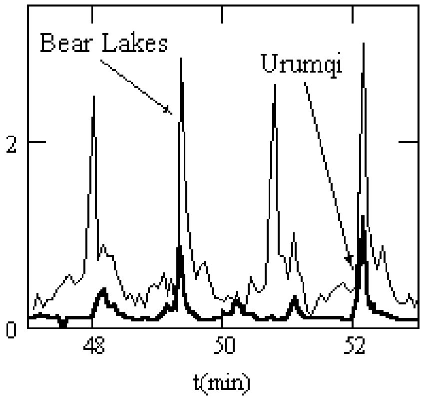

Fig. 6. Dependence of spectral maximum on time (TA-RA cross-spectra for Raduga-9 on Evpatoria-Bear Lakes and Evpatoria-Urumqi baselines), time resolution is 4.26 s, real period of rotation is 166 s

Then the cross-correlation for echo-signals is obtained on baselines between receiving antennas (see Fig. 7). The signal delay-time dependence in the form of a 3^{rd} degree polynomial is calculated with respect to a preliminary trajectory model of the object, coordinates of receiving antenna and time. This calculation takes into consideration the near-field effect, the movement of the object 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 into the radar echo signals received at antennas of interferometer baseline.

Analysis of time evolution of spectral maximums of echo from Cosmos-1366 on Bear Lakes – Noto – Urumqi baselines allows to get new information about proper movement of investigated object (see Fig. 8). There are the shifts of cross-spectrum maximums at different baselines: –3.35 s for Bear Lakes-Noto, +1.65 s for Bear Lakes-Urumqi and –5.5 s for Noto-Urumqi baselines. Accordingly Bear Lakes site, the echo signals ahead in Noto at 2.15 s and delayed in Urumqi at 5 s. It may be explained that scattering pattern of Cosmos-1366 is narrow (few degrees) and radiation maximum

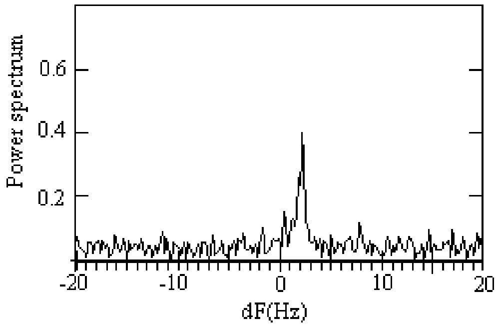

Fig. 7. The cross-spectrum of echo from Cosmos-1366, at baseline Bear Lakes-Urumqi, frequency resolution is 0.234 Hz, VLBR03.1

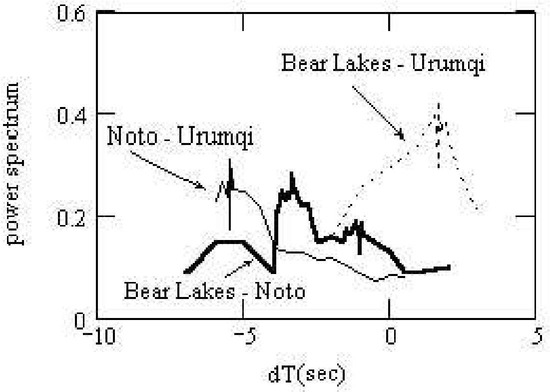

Fig. 8. Time dependence of cross-spectrums maximums of Cosmos-1366 at baselines Bear Lakes – Noto, Bear Lakes – Urumqi and Noto– Urumqi

successively passed the receiving antennas during rotation. This fact allows to evaluate the direction of object rotation axis.

At final stage the measured fringe rate is analysed and relative (echo - reference quasar) fringe rate value is calculated.

4. CONCLUSION

The VLBI team that carried out a major part of the delta-VLBI observations of former Russian Deep Space Network still exists and elaborated third generation of correlator. The antennas are placed now in two countries (Russia and Ukraine), but continue joint VLBI activities under LFVN project. The absence of current Russian interplanetary or highly-apogee missions promotes the development of new VLBR method. Combining the delta-VLBI and radar techniques allows to determine both planet and interplanetary spacecraft positions in the same Radio Reference Frame. The further works are connected with Phobos sample return mission. Russian Space Agency already started the limited financing for the verification and rehabilitation of the 70-m antenna constructions, mechanisms and apparatuses in Ussuriysk.

Recently both the Evpatoria RT-70 and the Bear Lakes RT-64 were equipped with S/X band receivers that can open a possibility of their collaboration with European Space Agency. The new elaborations of VLBI apparatuses that were made under LFVN project may be proposed for equipping of new European Deep Space Stations. The two-channel PC-disk based recording terminals of 48 MHz band were installed in the Evpatoria RT-70, the Bear Lakes RT-64 and some other LFVN antennas, and tested during few VLBR experiments [10]. These terminals can translate the VLBI signals in Internet to correlation centre to realize the near real time delta-VLBI measurements. Fig. 9 demonstrates first results of near real time VLBR.

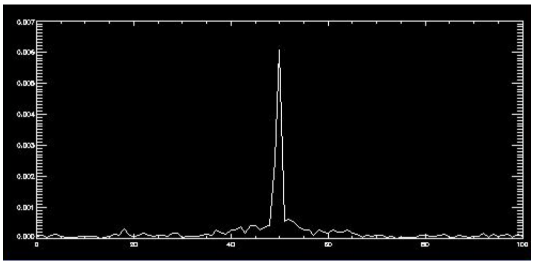

Fig.9. First TA-RA cross-spectrum on Evpatoria-Noto baseline, for geostationary object. Both signals (sounding and received echo) were translated to correlator in Noto using Internet, VLBR04.2

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