VLBI Data are the Basis for Orientation of Planetary Ephemerides with Respect to ICRF2 and Improvement of Other Ephemeris Parameters

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The modern planetary ephemerides are based generally on ranging data of planets and spacecraft. However, the orientation of planet ephemerides with respect to ICRF has been made by the ICRF-based VLBI measurements of spacecraft near planets using the following two types of VLBI measurements: one component made by tracking stations from NASA DSN, and VLBA measurements. This paper shows a progress in accuracy of orientation angles (up to fractions of mas) as a result of adding new VLBI points (VLBA data), as well as an increase of the accuracy of measurements. Also, usage of these measurements allows us to improve planetary ephemerides. The orientation and the improvement were made within the new version of EPM2015 (Ephemerides of Planets and the Moon) at IAA RAS, available via the FTP server ftp://quasar.ipa.nw.ru/incoming/EPM/.

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1 Historical Introduction

Before the 1960s, classical analytical theories of planets (Leverrier, Hill, Newcomb and Clemence) were based entirely on optical observations having accuracy no better than $0.''5$. Progress in astrometric engineering, introduction of new astrometric methods (radar ranging, lunar laser ranging, and the international atomic time scale) changed this situation radically and resulted in a revolution in both astrometry and ephemeris astronomy. The successful radiolocation of Venus made in 1961 opened the era of astrometrical radio observations. Two new types of measurements appeared: the time delay (ranging) and the doppler shift, while the accuracy of observations increased by orders of magnitude. Then regular radar observations of the planets began, and other types of radar observations emerged, such as: differenced ranging; VLBI measurements of spacecraft and quasars; and tracking measurements of spacecraft. Radar measurements of planets and spacecraft (mainly ranging) made it possible to produce high-precision ephemerides of the inner planets and Saturn and to determine a wide range of astronomical constants.

In particular, EPM were first created in the 1970s to support of Russian space flight missions; and they are being constantly improved at IAA RAS [5].

However, ranging measurements are relative, usually between the Earth and another the celestial object. From these observations, all orbital elements can be detected with the exception of the three angles of the Earth orientation or angles of rotation of the system to a reference frame. The reference frames for classical and earlier numerical planetary ephemerides were the fundamental star catalogs. The ephemerides DE118 and EPM87 were aligned onto the FK4 reference frame by using transit measurements of the inner planets and the Sun obtained with respect to the FK4-catalog stars. The reference frame of DE200 ephemerides was the mean equator and the dynamical equinox of J2000. Since DE403 [7] and EPM1998 ephemerides, the ICRF-based VLBI measurements of spacecraft near planets have been included into the total fitting, thus the fundamental planetary ephemerides have been referenced to ICRF.

2 VLBI Observations and Orientation of Planetary Ephemerides

Two types of VLBI measurements are used currently for planetary ephemeris improvements. One of them is measuring one component of the direction to a planet relative to the radio source made by pairs of tracking stations from the NASA global Deep Space Network (DSN) and ESA. Another one is VLBA antennas with rapidly alternating scans between Cassini and a nearby reference. All data received as a result of these VLBI measurements have been combined with the trajectory data obtained from DSN stations for determination of barycenter positions of planets with respect to ICRF.

Since 1989 up to 2013 the VLBI measurements of a spacecraft with respect to the ICRF2-based radio sources were carried out by antennas of the NASA DSN and ESA stations. These measurements have been using a technique called delta differential one-way range (ΔDOR) to measure one component of the direction to a planet relative to radio sources. Those are given as one-dimensional angular correction to the DE405 ($aldel$) and as orientation of these observations (the angle θ) in the direction connecting the two radio antennas involved [1] (see http://ssd.jpl.nasa.gov/dat/planets/vlbiobs_jun2013.html):

$$\Delta\alpha = \frac{aldel}{\cos\theta}, \quad \Delta\delta = \frac{aldel}{\sin\theta}.$$

All such VLBI observations are presented in Table 1, and their residuals calculated for EPM2015 ephemerides are shown in Fig. 1. Uncertainties of observations for Jupiter obtained in 1996–1997 by using the Galileo spacecraft when the large antenna did not work, were worse than for other observations. Observations for Venus were obtained in 1990–1994 for Magellan and Venus Express in 2007–2013. The best data were obtained for Martian orbiters MGS, Odyssey, and MRO.

The standard Very Large Baseline Array technique with rapidly alternating scans between Cassini and angularly nearby ICRF2 reference sources has been used. Multi-epoch (2004–2014) VLBA observations of Cassini were obtained with high accu-

Table 1

△DOR VLBI observations of spacecraft near the planet

Spacecraft	Planet	Time interval	Number of points	A priori accuracy (mas)
Phobos	Mars	1989	2	3.3–6.2
Magellan	Venus	1990–1994	18	1–4
Galileo	Jupiter	1996–1997	24	7–15
MGS	Mars	2001–2003	15	0.6–6.1
Odyssey	Mars	2002–2013	111	0.18–1.5
MRO	Mars	2006–2013	76	0.19–0.45
VEX	Venus	2007–2013	54	1.5–5.0

racy [2]. The residuals of VLBA Saturn positions for EPM2015 ephemerides, obtained from Cassini data, are presented in Fig. 2.

All these △DOR VLBI and VLBA data were used to determine the rotation angles for the orientation of EPM ephemerides onto ICRF2 (see Table 2). The orientation of the system of planets of EPM ephemerides has been provided by including the ICRF-based VLBI measurements of different spacecraft in the adjustment. The angles of rotation between the EPM ephemerides and the ICRF2 system and their formal standard errors obtained at present (the last line is for EPM2015) and previously are presented in Table 2. You can see that the orientation of EPM has been improved considerably as a result of new VLBI type points (VLBA data) added, and accuracy of measurements increased.

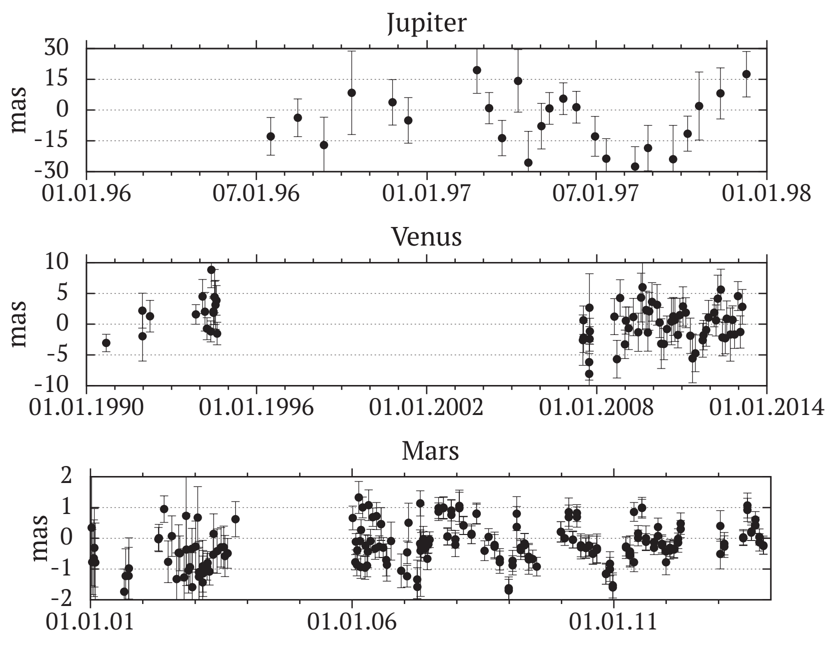

Fig. 1. The △DOR VLBI residuals for spacecraft near Jupiter, Venus and Mars, for EPM2015

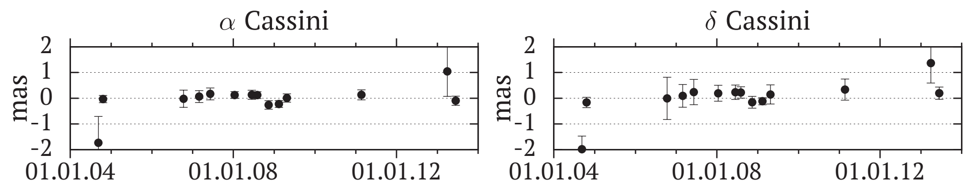

Fig. 2. The residuals of VLBA Saturn positions for EPM2015 ephemerides

The VLBI measurements of spacecraft near the planets are used also to improve ephemerides of these planets, particularly, of Jupiter. Of course, the new Juno spacecraft is orbiting Jupiter, and the new ranging and VLBI data will be available. However, there is a lack of accurate radar data currently available. The orbit of Jupiter is determined using astrometric orbit data about Jupiter and its four Galilean satellites, as well as 24 Galileo VLBI data and 23 radar measurements for Pioneer–10, 11, Voyager–1, 2, Ulysses and Cassini — (1972–2000). Table 3 shows the progress in formal accuracy of orbital elements of Jupiter for EPM2015 determined from different sets of observations: 1) only optic, 2) optic and VLBI, 3) optic, VLBI, and other radar data.

3 EPM2015 and its applications

The EPM ephemerides were started in the seventies of the past century; they have been developed at IAA RAS since then. These ephemerides are based upon relativistic equations of motion of celestial bodies and light rays and upon relativistic time scales. Several versions of EPM ephemerides (EPM2004, EPM2008, EPM2011, EPM2015) are available: iaaras.ru/en/dept/ephemeris/epm. Our latest EPM2015 version has been constructed recently and is available too. The EPM2015 ephemerides have been fitted to about 800000 observations of different types made from 1913 to 2014 (from classical meridian observations to the modern planetary and spacecraft ranging and VLBI).

The dynamical model of the EPM2015 planet part includes mutual perturbations between the planets (including Pluto), the Sun, the Moon; perturbations from the large 301 asteroids and 30 TNO upon the planets, the Sun, and the Moon; perturbation from the massive two-dimensional asteroid annulus of small asteroids;

Table 2

The rotation angles for the orientation of EPM onto ICRF2

Interval	Number of observ.	ϵ_x, mas	ϵ_y, mas	ϵ_z, mas
1989–1994	20	2.0 ± 1.5	0.1 ± 1.0	-0.1 ± 0.8
1989–2003	62	0.4 ± 0.2	-0.3 ± 0.3	-0.7 ± 0.2
1989–2007	123	0.294 ± 0.099	0.083 ± 0.140	0.089 ± 0.073
1989–2010	222	-0.000 ± 0.072	-0.005 ± 0.089	0.004 ± 0.051
1989–2014	296	0.002 ± 0.064	0.001 ± 0.062	0.000 ± 0.036

Table 3

The formal standard deviations of planetary orbital elements adjusted in EPM2015 (Jupiter: O – optic, + VLBI, + other radar observations)

Planet	a, m	$\sin i \cdot \cos\Omega$, mas	$\sin i \cdot \sin\Omega$, mas	$e \cdot \cos\pi$, mas	$e \cdot \sin\pi$, mas	λ, mas
Mercury	0.0008	0.00121	0.00138	0.00024	0.00011	0.0289
Venus	0.0050	0.00551	0.00383	0.00017	0.00019	0.00350
Earth	0.0028	—	—	0.00004	0.00004	—
Mars	0.0076	0.00103	0.00109	0.00005	0.00007	0.00026
Jupiter-O	2828	17.099	18.366	9.491	8.396	28.176
+24 VLBI	760.0	2.747	2.555	2.173	1.757	2.114
+23 radar	745.0	2.718	2.533	0.329	0.242	2.077
Saturn	10.268	0.1269	0.0897	0.0020	0.0007	0.0236
Uranus	49734	5.531	5.002	4.280	3.514	4.390
Neptune	444853	4.534	7.821	8.724	22.244	19.428
Pluto	1221411	1.155	5.672	27.319	19.279	9.342

perturbation from a massive ring of TNO with the radius of 43 au; relativistic perturbations; and perturbations due to the solar oblateness.

A new model of lunar orbital and rotational motion has been created by Pavlov et al. [3] based on DE430 [8] and combination of up-to-date astronomical, geodynamical, and geo- and selenophysical models. The Moon is considered an elastic body having a rotating liquid core. The following equations are included in the model: perturbations of the orbit of the Moon in the gravitational potential of the Earth; torque due to the gravitational potential of the Moon; perturbations of the orbit of the Moon due to lunar and solar tides on the Earth; distortion of the Moon figure as a result of its rotation and Earth gravity; and the torque due to the interaction between the lunar crust and the liquid core.

The formal standard deviations of planetary orbital elements adjusted in EPM2015 show (see Table 3) that accuracy of the inner planets and Saturn is very high.

EPM ephemerides are used currently for astronavigation on the Earth and in space. They are the basis for the Russian Astronomical and Nautical Astronomical Yearbooks, and also serve for the purposes of GLONASS. Also, they are used for estimating such various fundamental constants as restriction on the mass and density of dark matter in the Solar system; decreasing the heliocentric gravitational constant; limitation of a possible change of the gravitational constant G; values of relativistic PPN parameters [4]; asteroid masses; and the total masses of the asteroid main belt and TNO [6].

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