A Giant Step: from Milli- to Micro-arcsecond Astrometry
Proceedings IAU Symposium No. 248, 2007
W. J. Jin, I. Platais & M. A. C. Perryman, eds.

doi:10.1017/S1743921308018565

Use of optical and radio astrometric observations of planets, satellites and spacecraft for ephemeris astronomy

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Abstract. Different types of radiometric observations of planets and spacecraft, as well as optical data used for constructing modern high-precision planet ephemerides are presented. New mass values for planets and asteroids are given. The IAA RAS EPM ephemerides (**E**phemerides of **P**lanets and the **M**oon) are the basis for the Russian "Astronomical Yearbook" and are used in the navigation program "GLONASS" and the cosmic program "Phobos-Grunt".

Keywords. astrometry, ephemerides, reference systems

Until the 1960's, classical analytical theories of planets were based entirely upon optical observations (accurate to $0''.5$). Detection of Venus radioechoes in 1961 has opened the era of astrometric radio observations. Progress in astrometric engineering and introduction of new astrometric methods resulted in a revolution in both astrometry and ephemeris astronomy.

Modern high-precision planet ephemerides are constructed by simultaneous numerical integrating the equations of motion of the nine major planets, the Sun, 300 or more biggest asteroids, the Moon, and the lunar physical libration taking into account perturbations due to the solar oblateness and the massive ring of small asteroids. The most recent planet ephemerides having about the same accuracy and being adequate to modern observations have been developed at JPL – DE414 (Standish, 2006), IAA RAS – EPM2006 (Pitjeva, 2007) and IMCCE – INPOP06 (Fienga, *et al.*, 2008). Different types of the observations of planets, their satellites and spacecraft used for improvement of planet ephemerides are presented in Table 1 (where N is a number of observations).

The significance of radar observations is conditioned by two factors. First, two new types of measurements have appeared in astrometry. They are time delay is associated with distance by the light velocity and doppler-shift which gives the radial velocity of an object. Second, radar measurements have high accuracy (on the order of one part in 10^{11}), and it surpasses the accuracy of classical optic observations by four orders. At present, radar observations of the inner planets can be carried out for any point of their orbits; however, the ranging data of a spacecraft near planets have the most accuracy that has reached 1 m. It was radar measurements that made it possible to produce ephemerides of the inner planets with the millisecond accuracy and to determine different astronomical constants.

The accuracy of the modern VLBI observations of a spacecraft near planets is 1 mas, which permits the orientation of the planet ephemerides to the International Celestial Reference Frame (ICRF), and the uncertainty of the inner planet system with respect to the ICRF to be no more than $0''.001$ or <1 km. The rotation angles between the EPM2006 ephemerides and the ICRF are (in mas): $\varepsilon_x = 1.9 \pm 0.1$, $\varepsilon_y = -0.5 \pm 0.2$, $\varepsilon_z = -1.5 \pm 0.1$.

The observations of satellites of outer planets are of great importance not only for determination of their orbits but also for determination of the orbit of the outer planets, as these are more accurate than the observations of their parent planets and practically free from the phase effect. The modern accuracy of CCD data has already reached 0.″06, which have made it possible to significantly improve the orbital elements of the outer planets, their satellites, masses of these bodies and other parameters of the outer planet systems.

Table 1. Observations used for constructing planet ephemerides

Optical observations of outer planets and their satellites 1913–2006, N = 48690

USNO, Pulkovo, Nikolaev, Tokyo, Bordeaux, LaPalma, Flagstaff, TMO

Types	Years	*A priori* accuracy
optical transit	1913–1994	1″ →0.″5
photoelectric transit	1963–1998	0.″8 →0.″25
photographic	1913–1998	1″ →0.″2
CCD	1995–2006	0.″2 →0.″06

Radar observations of Mercury, Venus, Mars, N = 58112

Millstone, Haystack, Arecibo, Goldstone, Crimea

Types	Years	*A priori* accuracy
ranging	1961–1997	100 km → 150 m

Spacecraft radiometric data obtained by DSN antennae 1971–2006, N = 305599

Mariner – 9	*Venus*
Pioneer – 10, 11	*Jupiter*
Voyager	*Jupiter*
Phobos	*Mars*
Ulysses	*Jupiter*
Magelan	*Venus*
Galileo	*Jupiter*
Viking – 1, 2	*Mars*
Pathfinder	*Mars*
MGS	*Mars*
Odyssey	*Mars*

Types	Years	*A priori* accuracy
ranging	1971–2006	6 km → 1 m
differ.range	1976–1997	1.3 → 0.1 mm/sec
radial veloc.	1992–1994	0.1 → 0.002 mm/sec
Δ VLBI	1990–2003	12 mas → 0.3 mas

Table 2. New mass values of planets and asteroids proposed to WG NSFA

Planet	Previous values	New values	Year	Authors
M_M/M_E	$1.23000345(5)\cdot10^{-2}$	$1.23000371(4)\cdot10^{-2}$	2006	Standish
$M_\odot/M_V$	$4.0852371(6)\cdot10^{5}$	$4.08523719(8)\cdot10^{5}$	1999	Konopliv, *et al.*
$M_\odot/M_{Ma}$	$3.098708(9)\cdot10^{6}$	$3.09870359(2)\cdot10^{6}$	2006	Konopliv, *et al.*
$M_\odot/M_J$	$1.0473486(8)\cdot10^{3}$	$1.047348625(17)\cdot10^{3}$	2003	Jacobson
$M_\odot/M_{Sa}$	$3.497898(18)\cdot10^{3}$	$3.4979018(1)\cdot10^{3}$	2006	Jacobson, *et al.*
$M_\odot/M_P$	$1.3521(15)\cdot10^{8}$	$1.36564(28)\cdot10^{8}$	2008	Tholen, *et al.*
$M_\odot/M_{Eris}$		$1.191(14)\cdot10^{8}$	2007	Brown & Schaller
$M_{Ceres}/M_\odot$	$4.39(4)\cdot10^{-10}$	$4.72(3)\cdot10^{-10}$	2007	Pitjeva & Standish
$M_{Pallas}/M_\odot$	$1.59(5)\cdot10^{-10}$	$1.03(2)\cdot10^{-10}$	2007	Pitjeva & Standish
$M_{Vesta}/M_\odot$	$1.69(11)\cdot10^{-10}$	$1.35(2)\cdot10^{-10}$	2007	Pitjeva & Standish

Masses of bodies are the fundamental constants for ephemeris astronomy. Resent research have modified most of the planet masses due to high-precission observations of

https://doi.org/10.1017/S1743921308018565 Published online by Cambridge University Press

spacecraft orbiting or passing near the planets as well as data of planet satellites. As for masses of the largest asteroids, many new, significantly more accurate mass estimates have been obtained recently from close encounters with other asteroids and from their perturbations onto Mars. In collaboration with Dr. Standish, we have chosen the best estimates of masses for planets and asteroids (Table 2) and offered them to the IAU WG NSFA (see http://maia.usno.navy.mil/NSFA/CBE.html).

More than 400000 data-points presented in Table 1 were used for construction of the EPM2006 ephemerides, and about 230 parameters of these ephemerides were determined. The detailed description of all the data used, plots of the observersion residuals, a range of astronomical constants obtained from the adjustment of the EPM2006 (namely, the value of Astronomical Unit, the rotation parameters of Mars, masses of the bodies, parameters of topography of planet surfaces, the solar oblateness, PPN-parameters, the variability of the gravitational constant, and others) are given in papers (Pitjeva 2005a; Pitjeva 2005b; Pitjeva 2007). Formal standard deviations of orbital elements of planets of the EPM2006 ephemerides are shown in Table 3.

Table 3. The formal standard deviations of elements of the planet orbits

Planet	a [m]	$\sin i \cos\Omega$ [mas]	$\sin i \sin\Omega$ [mas]	$e\cos\pi$ [mas]	$e\sin\pi$ [mas]	λ [mas]
Mercury	0.333	1.392	1.347	0.105	0.084	0.343
Venus	0.219	0.056	0.030	0.004	0.003	0.031
Earth	0.138	—	—	0.001	0.001	—
Mars	0.267	0.003	0.002	0.001	0.001	0.002
Jupiter	615	2.419	2.166	0.313	0.362	1.467
Saturn	4256	3.061	4.117	3.900	2.959	3.501
Uranus	40294	4.440	6.276	5.057	3.635	7.509
Neptune	463307	4.411	8.520	13.115	18.740	24.484
Pluto	3412734	6.790	15.662	80.870	38.847	43.554

As seen from Table 3, the uncertainties obtained for the inner planets are significantly smaller than the uncertainties for Saturn, Uranus, Neptune, Pluto. Jupiter occupies the intermediate state between the inner and the outer planets due to the availability of a number of spacecraft Jupiter data.

The EPM ephemerides which have been the basis for the Russian "Astronomical Yearbook" since 2006 and have been used in the navigation program "GLONASS" and the cosmic program "Phobos-Grunt", are available to outside users via ftp://quasar.ipa.nw.ru/incoming/EPM2004 (anonymous).

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