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Progress in the determination of some astronomical constants from radiometric observations of planets and spacecraft

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Abstract. Modern radiometric observations of planets, beginning in 1961, make it possible to determine and improve a broad set of astronomical constants from the value of the astronomical unit (AU) to parameters of PPN formalism. Three main factors that influence the progress in the determination of astronomical constants – 1) reductions of the observational data, 2) dynamical models of planet motion, 3) observational data themselves – are demonstrated in this paper. The reduction of the measurements included all relevant corrections, including the modeling of the topography of Mercury and Venus which reduced the rms residuals for observations by 14.5% and 23% correspondingly. The formal standard deviations of the solution elements of the planets and the AU are improved by 30–50% using the DE405 or EPM2000 ephemerides constructed in IAA (Russia) instead of DE200. It was shown that including the measurements of the Viking and Pathfinder landers, being free from the uncertainties due to planetary topography, into the observational data reduces the uncertainties of adjusted parameters by 1–2 orders. The astronomical constants obtained in the fitting process of the DE405 and EPM2000 ephemerides to data totaling more 80 000 radiometric observations of planets and spacecraft are given.

Key words. astrometry – ephemerides – solar system: minor planets – planets and satellites

1. Reductions of observations

Radiometric observations of planets began in 1961 with radar-ranging, and since then many additional techniques have come widely into astronomical practice, making it possible to determine with high accuracy various astronomical constants.

Reductions of modern observations, including relativistic corrections, the Shapiro time-delay effect near the Sun, the transition from the coordinate time of the ephemerides to the proper time of the observer, and the effects of propagation of electromagnetic signals in the Earth troposphere and in the solar corona, are well known and are described, for example, by Standish (1990).

The reduction for the topography of the radar-observable planets causes some difficulty. Large variations in the surface of a planet bring in significant systematic errors (up to 20 km for Mars), cause a large noise component of the time delay, and therefore worsen the accuracy of the determination of parameters. The correction of observations of Venus and Mars for their topography has been carried out with the help of modern hypsometric maps of the surfaces of these planets, and also by the representation of the global topography with an expansion of spherical functions of 16–18 degrees. After taking into account the topography of Venus and Mars, the systematic component of the residuals has been significantly removed and the rms residuals for the Venus observations has been decreased by 23%. Details of the topography reduction can be found in Pitjeva (1996).

The global topography of Mercury is virtually unknown, although some works based on Mercury radar altimetry have been announced (for example, Harmon et al. 1985). The topography of Mercury has been represented, as in the papers by Anderson et al. (1996) and Standish (1998), by Legendre functions to the second order. The expansion coefficients have been estimated from the 297 available ranging observations of Mercury obtained during 1966–1997, having a priori uncertainties better than 2 km (Pitjeva 2000). The adjustment to the Mercury surface has decreased the rms residuals for Mercury observations by 14.5%.

2. Dynamic models of planetary motion

The influence of dynamical models on the determination of parameters has been revealed by the use of various planetary ephemerides as the bases for the adjustment to the same set of observations. The JPL ephemerides – DE200 (Standish 1990), DE403 (Standish et al. 1995), DE405 (Standish 1998) and the similar ephemerides EPM98, EPM2000 (Pitjeva 2001), constructed at the Institute of

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Applied Astronomy of Russian Academy of Sciences, have been used with the same set of observational data.

Common to all these dynamical models is a simultaneous numerical integration of the equations of motion of the nine planets, the Sun, the Moon and lunar physical libration, performed in the Parameterized Post-Newtonian metric for the harmonic coordinates ($\alpha = 0$) and General Relativity values ($\beta = \gamma = 1$). The **E**phemerides of **P**lanets and the **M**oon (EPM2000) took into account the perturbations from 300 asteroids by numerical integration of the equations of motion of all objects, but including the mutual perturbations of only the planets, moon, sun, and the 5 most significant asteroids. Previously, EPM98 had accounted for the asteroid perturbations in a manner similar to that used for DE403.

There are slight differences among the models of the various ephemerides: the modelling of the lunar libration is different, but this has no significant effect on the parameters considered in this paper; the solar oblateness $J_2 = 2.0\ 10^{-7}$, obtained from some astrophysical estimations (Duvall et al. 1984; Brown 1989), has been taken into account; and the constructed ephemerides differ only slightly by the accuracy of interpolation for planetary coordinates by a set of Chebyshev polynomials. DE200 differs significantly from the other ephemerides in the modelling of the perturbations from asteroids: only the three most massive asteroids were taken into account in DE200, while the other ephemerides were supplemented with the modelling of perturbations from 300 asteroids upon the orbits of the planets.

The astronomical parameters have been determined by computing for each ephemeris residuals of the same observational data and then by re-computing them by adjusting a number of ephemeris parameters. The data included radar ranging of Mercury and Venus and spacecraft ranging and doppler of the Viking and Pathfinder martian landers (observations marked by a * in Table 2). Note that the uncertainties, given in this paper, are formal standard deviations; realistic error bounds may be an order of magnitude larger. The formal standard deviations are given in Table 1 for the orbital elements of Mercury, Venus, Earth and Mars: a_i, $\sin i_i \cos\Omega_i$, $\sin i_i \sin\Omega_i$, $e_i \cos\pi_i$, $e_i \sin\pi_i$, λ_i, where a – the semi-major axis, i – the inclination of the orbit, Ω – the ascending node, e – the eccentricity, π – the longitude of perihelion, λ – the mean longitude, index $_i = 1, 2, 3, 4$ – planets; also given in Table 1 are the corrections to the value of the astronomical unit (AU = 149 597 870 691.0 m) and to the Mars precession ($\dot\Omega_q = -7''\!.576/\mathrm{y}$) with their uncertainties determined by using the various ephemerides.

From Table 1 it is seen that, first, the dynamical models of the ephemerides DE403, DE405, EPM98, EPM2000 are nearly equivalent and yield virtually identical accuracy for the determination of the parameters. Secondly, the formal standard deviations of the solution parameters are improved by 30–50% using DE403, DE405, EPM98, EPM2000 ephemerides instead of DE200.

In addition, it should be noted that the DE200 ephemerides were created before many spacecraft-based determinations of the relevant parameters existed. Thus, many of the fitting parameters (e.g., planet masses, station locations) were less accurately determined for DE200 than they are known today. Consequently, part of the higher uncertainties of DE200 must be attributed to the embedded effect of these parameters. The numerical experiments have shown that the accuracy of adjusted parameters essentially depended on values of planet masses and asteroid modeling.

3. Observational data

The quality and quantity of the observational data affect the accuracy of estimated parameters. The accuracy of the first observations of time delay (τ) of planets, obtained in 1961–1962 was 200–500 μs (30–80 km); the accuracy of 1964–1969 ranging observations improved to 30 μs (5 km); the accuracy of modern ranging observations has achieved 0.5 μs (80 m). Unfortunately, such observations are corrupted by the peculiarities of the planetary relief, and some uncertainties remain in planetary ranging in spite of the corrections for topography. Therefore, the extremely precise observations of the martian Viking and Pathfinder landers, being free from the uncertainties due to the planetary topography, are of great importance.

Measurements of time delay τ of the Viking martian landers were obtained during 1976–1982. For 20 years these observations were the most accurate of all planetary position data. Observations of the new martian Pathfinder lander have now been obtained during three months of 1997. Simultaneously the observations of differenced range $d\tau$ were carried out. Similar differenced range data have been recovered from 1976–1978 measurements by the Viking-1 lander.

The observations of the martian landers have permitted the highly accurate improvement of not only the orbital elements of Earth and Mars, but also the parameters of Mars rotation; in particular, such an important parameter for understanding of Mars geophysics as the mean precession rate of Mars (Yoder & Standish 1997; Folkner et al. 1997; Pitjeva 1999).

Since the orbit of Mars is perturbed significantly by Jupiter and a number of asteroids, the observations of the martian landers contain information concerning the mass of Jupiter, elements of its orbit, as well as about the masses of the three largest asteroids: Ceres, Pallas and Vesta (Standish & Hellings 1989; Pitjeva 1997).

An electronic date base of planetary observational data used in the production of ephemerides has been created on the INTERNET: "`http://ssd.jpl.nasa.gov/iau-comm4`". All ranging observations from this data base together with Russian ranging measurements of planets obtained during 1962–1995 have been used in this paper. Thus we have over 80 000 radiometric observations of the inner planets during 36 years. For this paper, all Mars observations

Table 1. The formal standard deviations of parameters, readjusted to the same set of observations, using a selected set of parameters and DE200, DE403, EPM98, DE405, EPM2000

parameters	DE200	DE403	EPM98	DE405	EPM2000
a_1 [m]	0.430	0.306	0.309	0.305	0.308
$\sin i_1 \cos\Omega_1$ [mas]	5.451	3.886	3.917	3.874	3.909
$\sin i_1 \sin\Omega_1$ [mas]	6.010	4.284	4.318	4.272	4.310
$e_1 \cos\pi_1$ [mas]	0.537	0.383	0.386	0.382	0.385
$e_1 \sin\pi_1$ [mas]	0.460	0.328	0.331	0.327	0.330
λ_1 [mas]	1.708	1.218	1.227	1.214	1.225
a_2 [m]	1.463	1.042	1.050	1.038	1.048
$\sin i_2 \cos\Omega_2$ [mas]	2.322	1.655	1.668	1.650	1.665
$\sin i_2 \sin\Omega_2$ [mas]	2.244	1.600	1.612	1.595	1.609
$e_2 \cos\pi_2$ [mas]	0.127	0.090	0.091	0.090	0.091
$e_2 \sin\pi_2$ [mas]	0.119	0.085	0.086	0.085	0.085
λ_2 [mas]	0.990	0.706	0.711	0.704	0.710
a_3 [m]	0.180	0.109	0.104	0.103	0.103
$e_3 \cos\pi_3$ [mas]	0.001	0.001	0.001	0.001	0.001
$e_3 \sin\pi_3$ [mas]	0.001	0.001	0.001	0.001	0.001
a_4 [m]	0.518	0.291	0.271	0.270	0.270
$\sin i_4 \cos\Omega_4$ [mas]	0.033	0.024	0.024	0.024	0.024
$\sin i_4 \sin\Omega_4$ [mas]	0.040	0.026	0.026	0.026	0.026
$e_4 \cos\pi_4$ [mas]	0.002	0.002	0.002	0.002	0.002
$e_4 \sin\pi_4$ [mas]	0.003	0.002	0.002	0.002	0.002
λ_4 [mas]	0.013	0.008	0.008	0.008	0.008
scale factor [m/au]	21.354	1.408	0.310	2.010	0.206
	±0.288	±0.190	±0.186	±0.184	±0.184
$\dot{\Omega}_q$ [mas/yr]	−10.98	2.35	4.61	−3.42	−7.36
	±7.28	±5.17	±5.20	±5.15	±5.17

and, as a rule, Venus observations, carried out within a single day have been combined into normal points after the necessary reductions. The observations have been weighted in accordance with their a priori standard deviations. The orbital elements of Jupiter have been fitted to all measurements of spacecraft at Jupiter (Pioneer-10,11, Voyager-1,2, Ulysses, Galileo) and its VLA thermal emission, as well as to those of the martian landers, as indicated above. The observations used in this paper are described in Table 2. The columns contain the station or the observed object, the components measured, the time coverage, the number of observations and normal points, and the a priori uncertainties of measurements. Table 3 gives corrections (with their formal uncertainties) to parameters of the EPM2000 fitted to three different sets of observations:

- version I – only ranging observations of planets;
- version II – ranging observations of planets and Viking-1,2;
- version III – ranging of planets, of Viking and Pathfinder, differenced range observations of Viking and Pathfinder.

It is seen from Table 3 that including the Viking and Pathfinder landers into the observational data reduces the uncertainties of the adjusted parameters by 1–2 orders and their formal accuracy reaches the microarcsecond level.

4. The adjusted astronomical constants

A number of parameters have been adjusted into the fitting process of the DE405 and EPM2000 ephemerides to data totaling over 80 000 radiometric observations of planets and spacecraft.

Tables 4 and 5 give the formal standard deviations of the orbital elements of Mercury, Venus, Earth, Mars, Jupiter and the parameters of Mars rotation. The solution value of the astronomical unit is in good agreement with that of DE405:

$$\mathrm{AU}_{\mathrm{EPM2000}} = (149\,597\,870\,691.2 \pm 0.2)\ \mathrm{m},$$

$$\mathrm{AU}_{\mathrm{DE405}} \;=\; 149\,597\,870\,691\ \mathrm{m}$$

and is 1.5 m longer than its last value by Standish (2000a):

$$\mathrm{AU}_{\mathrm{Standish}} = (149\,597\,870\,689.7 \pm 0.4)\ \mathrm{m}.$$

Following formulas of Folkner et al. (1997) and considering the gravity coefficient of Mars J_2, obtained from detection of the Mars gravity field with the use of the Viking orbiter and other tracking data by Konopliv & Sjogren (1995), to

Table 2. Radiometric observations used in the ephemerides solutions

station, object	type	time interval	number of obs.	normal points	a priori accuracy
		MERCURY			
Millstone	τ	1964	5	—	50–500 μs
Haystack*	τ	1966–1971	217	—	20 μs
Arecibo*	τ	1964–1982	341	323	20–200 μs
Goldstone*	τ	1971–1997	259	138	10–20 μs
Crimea	τ	1980–1995	75	23	8–32 μs
		VENUS			
Millstone*	τ	1961–1967	135	—	10–800 μs
Haystack*	τ	1966–1971	219	—	10 μs
Arecibo*	τ	1964–1970	319	—	20–100 μs
Goldstone*	τ	1964–1990	512	—	10–40 μs
Crimea	τ	1962–1995	1139	170	1–150 μs
		MARS			
Haystack	τ	1967–1973	3801	133	0.5–80 μs
Arecibo	τ	1965–1973	1680	43	0.5-300 μs
Goldstone	τ	1969–1994	48989	149	0.5–4 μs
Crimea	τ	1971–1995	381	78	1–32 μs
Mariner-9	τ	1971–1972	643	—	0.1–1.8 μs
Viking-1*	τ	1976–1982	1161	—	0.046–0.080 μs
Viking-1*	dτ	1976–1978	14980	—	1.3–27 mm/s
Viking-2*	τ	1976–1977	80	—	0.046–0.067 μs
Pathfinder*	τ	1997	90	—	0.067–0.146 μs
Pathfinder*	dτ	1997	7576	—	0.11 mm/s
		JUPITER			
spacecraft, VLA	α	1979–1995	—	4	$0''.003$–$0''.046$
spacecraft, VLA	δ	1979–1995	—	4	$0''.005$–$0''.2$
spacecraft	τ	1973–1995	—	6	3–40 μs
spacecraft	$\alpha\delta$	1996–1997	—	23	$0''.007$–$0''.012$

Table 3. Corrections to parameters of the EPM2000, fitted to three different sets of observations

parameters	version I	version II	version III
a_3 [m]	-2.438 ± 3.565	-2.155 ± 0.201	-1.877 ± 0.084
$e_3\cos\pi_3$ [mas]	-0.372 ± 0.095	-0.006 ± 0.002	-0.012 ± 0.001
$e_3\sin\pi_3$ [mas]	-0.346 ± 0.098	-0.005 ± 0.002	-0.005 ± 0.001
a_4 [m]	1.860 ± 9.640	-4.323 ± 0.587	-5.063 ± 0.224
$\sin i_4\cos\Omega_4$ [mas]	1.385 ± 1.218	-0.146 ± 0.030	-0.263 ± 0.023
$\sin i_4\sin\Omega_4$ [mas]	-7.086 ± 1.289	-0.002 ± 0.034	0.233 ± 0.021
$e_4\cos\pi_4$ [mas]	0.133 ± 0.088	-0.018 ± 0.002	-0.002 ± 0.001
$e_4\sin\pi_4$ [mas]	-0.403 ± 0.109	-0.022 ± 0.003	-0.015 ± 0.001
λ_4 [mas]	-2.265 ± 0.324	-0.183 ± 0.013	-0.035 ± 0.008
scale factor [m/au]	-307.634 ± 69.324	1.022 ± 0.686	0.710 ± 0.188
$\dot{\Omega}_q$ [mas/yr]	—	-672.28 ± 134.27	4.97 ± 5.28

be equal to 0.0019586, the corresponding normalized polar moment of inertia of Mars was determined as

$$C/MR^2 = 0.3664 \pm 0.0013 \ (5\sigma),$$

which practically coincides with the value by Folkner et al. (1997):

$$C/MR^2 = 0.3662 \pm 0.0017 \ (5\sigma).$$

With ranging observations of high accuracy covering the time interval of over 30 years one may estimate the time

Table 4. The formal standard deviations of elements of the planets

planet	theory	a [m]	$\sin i \cos\Omega$ [mas]	$\sin i \sin\Omega$ [mas]	$e\cos\pi$ [mas]	$e\sin\pi$ [mas]	λ [mas]
Mercury	DE405	0.186	3.156	3.316	0.320	0.277	0.823
	EPM2000	0.187	3.169	3.329	0.321	0.279	0.826
Venus	DE405	0.307	0.604	0.592	0.039	0.040	0.183
	EPM2000	0.309	0.606	0.594	0.039	0.040	0.184
Earth	DE405	0.083	—	—	0.001	0.001	—
	EPM2000	0.084	—	—	0.001	0.001	—
Mars	DE405	0.219	0.023	0.020	0.001	0.001	0.007
	EPM2000	0.224	0.023	0.021	0.001	0.001	0.008
Jupiter	DE405	672.4	4.798	4.070	0.319	0.321	1.160
	EPM2000	675.1	4.817	4.086	0.321	0.322	1.164

Table 5. The parameters of Mars rotation

theory	$\dot V$ [°/day]	I_q [°]	$\dot I_q$ [″/y]	Ω_q [°]	$\dot\Omega_q$ [″/y]
DE405	350.891985144	25.1893949	−0.0028	35.437715	−7.5741
	±0.000000011	±0.0000050	±0.0024	±0.000020	±0.0050
EPM2000	350.891985129	25.1893932	−0.0036	35.437724	−7.5712
	±0.000000011	±0.0000050	±0.0024	±0.000020	±0.0050

Table 6. Parameters of PPN formalism, $\dot G/G$ and the solar quadrupole moment

theory	$\dot G/G (10^{-11}\ \mathrm{yr}^{-1})$	$\beta - 1$	$\gamma - 1$	$\Delta\dot\pi_{\mathrm{Mer}}(''\mathrm{cy}^{-1})$	$J_2(10^{-7})$
DE405	0.001 ± 0.008	0.0001 ± 0.0001	0.0004 ± 0.0001	0.0058 ± 0.0086	2.46 ± 0.68
EPM2000	0.004 ± 0.008	0.0004 ± 0.0002	0.0001 ± 0.0001	0.0055 ± 0.0085	2.43 ± 0.67

derivative of the gravitational constant ($\dot G/G$), characterizing the fundamental properties of our physical time-space, and representing a test of the PPN parameters. The results for these, given in the first three columns of Table 6, show no significant departure from their standard values.

In a second solution, we set $\beta = 1$, $\gamma = 1$, and $\dot G/G = 0$, and then we solved for a correction to the motion of Mercury's perihelion by using the partial derivative, $\frac{\partial\tau}{\partial\dot\pi} = \frac{\partial\tau}{\partial\pi} * (t - t_0)$, where τ is the measured round-trip light-time of a ranging measurement. Then, from the linear combination (see, for example, Brumberg 1972),

$$\dot\pi_1 = 42''.98[(2 + 2\gamma - \beta)/3 + 0.296 J_2\ 10^4]$$

we determined the corrected value for J_2 as shown in the last column of Table 6.

A test ephemeris, EPMTEST, was constructed to examine the validity of the fitting process and the estimation of the solar oblateness. The EPMTEST ephemeris differs from EPM2000 by only the zero solar oblateness (the $J_2 = 2.0\ 10^{-7}$ solar quadrupole moment is used for EPM2000). The secular trend of the Mercury perihelion and the corresponding solar quadrupole moment together with other parameters have been obtained into the fitting process of EPMTEST to all ranging observations. The resulting dynamical value of the solar quadrupole moment:

$$J_{2\mathrm{test}} = (2.36 \pm 0.65)\ 10^{-7}$$

agrees remarkably with the values from Table 6 and coincides on the level of an accuracy with the astrophysical value obtained by Pijpers (1998) from helioseismic measurements:

$$J_{2\mathrm{Pijpers}} = (2.18 \pm 0.06)\ 10^{-7}.$$

Tables 7 and 8 present estimates of the masses of Jupiter, Ceres, Pallas, Vesta and densities of the three major taxonomic asteroids classes (C, S, M) accepted for DE405, obtained by the author using the ephemerides DE405 and EPM2000 and obtained by Standish (2000a) from most recent ephemeris solution, fit to all relevant existing observational data. It is seen that the recent estimates of the masses of Ceres, Pallas, Vesta and the densities of taxonomic classes of asteroids are close to each other and agree well with the values $(1.29 \pm 0.03)\ \mathrm{g/cm}^3$ for carbonaceous asteroid 253 Mathilde (Yeomans et al. 1997) and $(2.67 \pm 0.03)\ \mathrm{g/cm}^3$ for asteroid Eros of S class (Yeomans et al. 1999), determined from tracking data during the NEAR flyby.

Table 7. Sun-Jupiter and Ceres-Sun, Pallas-Sun, Vesta-Sun mass ratios

theory, author	$M_\odot/M_{\rm Jup}$	$M_{\rm Cer}/M_\odot$ 10^{-10}	$M_{\rm Pal}/M_\odot$ 10^{-10}	$M_{\rm Ves}/M_\odot$ 10^{-10}
DE405	1047.34860	4.70	1.00	1.30
$\rm Pitjeva_{DE}$	1047.34856 ± 0.00003	4.71 ± 0.01	1.00 ± 0.01	1.31 ± 0.01
$\rm Pitjeva_{EPM}$	1047.34866 ± 0.00003	4.81 ± 0.01	1.00 ± 0.01	1.36 ± 0.01
$\rm Standish_{2000}$		4.76 ± 0.01	1.08 ± 0.01	1.35 ± 0.01

Table 8. The densities of the C, S, M taxonomic asteroid classes (in g/cm^3)

theory, author	ρ_C	ρ_S	ρ_M
DE405	1.8	2.4	5.0
$\rm Pitjeva_{DE}$	1.36 ± 0.03	2.67 ± 0.03	—
$\rm Pitjeva_{EPM}$	1.36 ± 0.03	2.67 ± 0.03	—
$\rm Standish_{2000}$	1.29 ± 0.06	2.71 ± 0.04	5.29 ± 0.53

5. Conclusions

Thus, the considerable progress in the determination of the parameters of planetary ephemerides using radiometric observations is due to the improvement of reduction techniques and dynamical models and also to the improvement of quality and increase of quantity of observational data. Further improvement of the accuracy of planetary parameters will depend on additional precise observations (it is desirable to obtain measurements of landers) and on the significant progress in the determination of asteroid masses, which, as was shown in the paper by Standish (2000b), restricts the accuracy of the planetary ephemerides.

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