Russain Academy of Sciences
Institute of Applied Astronomy

Communications of the IAA RAS №155

E. V. Pitjeva

EPM2002 and EPM2002C — two versions of high accuracy numerical planetary ephemerides constructed for TDB and TCB time scales

St. Petersburg
2003

UDK 521.3

Е. В. Питьева. EPM2002 and EPM2002C — две версии высокоточных численных планетных эфемерид, созданных в TDB and TCB шкалах времени.

Ключевые слова: Эфемериды больших планет, радарные и оптические наблюдения, TDB и TCB шкалы времени.

В работе представлены результаты планетной части обновленной версии EPM (**E**phemerides of **P**lanets and the **M**oon) эфемерид.

В соответствии с резолюциями МАС ICRS (International Celestial Reference System) должна рассматриваться как четырехмерная система координат с независимой переменной — координатным временем TCB, в шкале которого планетные эфемериды должны создаваться. Для сопоставления и сравнения с широко распространенными DE эфемеридами Лаборатории реактивного движения США EPM эфемериды ИПА РАН до настоящего времени строились с временной шкалой TDB (в качестве независимой переменной), близкой к T_{eph}, которая используется для построения DE эфемерид. Переход к шкале координатного времени TCB не должен был и не привел к увеличению точности эфемерид EPM2002C и улучшаемых параметров. Эти эфемериды были созданы для удобства пользователей, занимающихся обработкой наблюдений спутников Земли и VLBI данными. Для построения EPM2002C эфемерид в шкале времени TCB значения масс (GM_i) и начальные координаты были умножены на $(1 + L_B)$.

Последние версии EPM эфемерид были получены совместным численным интегрированием уравнений движения девяти планет, Солнца, Луны, лунной физической либрации и 300 астероидов на 125-летнем интервале времени (1866–2011 гг.). Точность эфемерид зависит от возмущений многих астероидов, чьи массы не известны достаточно хорошо, поэтому оценки масс 357 наиболее значительных астероидов были сделаны. Были использованы последние опубликованные диаметры, полученные из наблюдений в инфракрасной области спутника IRIS и из покрытий звезд астероидами. Возмущения от остальных астероидов учитывались использованием модели кольца, расположенного в эклиптикальной плоскости.

Обе версии EPM2002 и EPM2002C эфемерид были улучшены по набору наблюдений, содержащих более 260000 американских и российских радиотехнических наблюдений планет и космических аппаратов (1961–2002 гг.), CCD астрометрических наблюдений внешних планет и их спутников, меридианных и фотографических наблюдений XX-ого века. Была определена ориентация эфемерид EPM в международной небесной системе координат (ICRF).

E. V. Pitjeva.

EPM2002 and EPM2002C — two versions of high accuracy numerical planetary ephemerides constructed for TDB and TCB time scales.

Keywords: Ephemerides of major planets, radar and optic observations, TDB and TCB time scales.

In paper there are presented results of updating the planet part of EPM (**E**phemerides of **P**lanets and the **M**oon) ephemerides.

To be consistent with IAU resolutions ICRS (International Celestial Reference System) should be treated as four-dimensional reference frame with TCB time scale in which planetary ephemerides should be constructed. For correlation and comparison with the wide-spread JPL DEs ephemerides EPMs ephemerides of IAA have been created up to now in TDB time scale close to T_{eph} used for the DEs ephemerides. The conversion to TCB time scale could not and did not allow greater accuracy of ephemerides and adjusted parameters and was only done for convenience of users processing VLBI and Earth satellite observations. The values of masses GM_i and initial coordinates of all celestial bodies involved in integration have been multiplied by $(1 + L_B)$ for the construction of EPM2002C ephemerides in the TCB time scale.

The last versions of EPM ephemerides have been produced by simultaneous numerical integration of the equations of motion of nine planets, the Sun, the Moon, lunar physical libration and 300 asteroids over a 125-year time interval (1886–2011). The accuracy of the planetary ephemerides depends on the perturbations of many asteroids whose masses are not well known. So, estimations of masses of the most relevant 357 asteroids have been made. The latest published diameters of asteroids based on *IRAS* data and observations of occultations of stars by minor planets have been used. The perturbing effects of remaining asteroids were modelled as being caused by a circular ring in the ecliptical plane.

Both versions of EPM2002 and EPM2002C ephemerides were fitted to data totaling more than 260000 observations including different American and Russian radiometric observations of planets and spacecraft (1961-2002), CCD astromertic observations of outer planets and their satellites, as well as meridian transits and photographic observations of XX-th century. Ephemerides EPM were oriented onto the International Celestial Reference Frame (ICRF).

Сообщения Института прикладной астрономии РАН № 155 – Санкт-Петербург, 2003. – 19 с.

Contents

1. Dynamic model of planetary motion of EPM2002 ephemerides

Significant progress has been achieved in the accuracy of positional observations, so uncertainty of modern ranging observations is only up to a few meters. On the one hand, that requires planetary ephemerides of the highest accuracy, on the other hand, these observations make it possible to construct such ephemerides and to determine with high accuracy various astronomical constants, including parameters of PPN formalism.

A serious problem in the construction of planetary ephemerides arises due to the necessity to take into account the perturbations caused by minor planets. In DE200 and our more previous versions the perturbations from only three or five biggest asteroids were accounted for. The experiment showed that the fitting of these ephemerides to the Viking lander data is poor [1]. The perturbations from 300 asteroids have been taken into account in the ephemerides DE403, DE405 and EPM2000 [1]. But masses of these asteroids are quite poorly known, and as shown by Standish and Fienga [2], the accuracy of the planetary ephemerides deteriorates due to this factor. Studies of the estimations of masses of the 357 most relevant asteroids were made in the previous paper [3]. Several tests were tried in which the total number of perturbing asteroids and their masses varied when processing the observations. The latest published diameters of asteroids based on *IRAS* data [4] and observations of occultations of stars by minor planets [5] have been used in this paper. The mean densities for C,S,M taxonomy classes have been estimated while processing the observations.

At the several meters level of accuracy the orbit of Mars is very sensitive to perturbations from many minor planets. These objects are mostly too small to be observed from the Earth, but their total mass is large enough to affect the orbits of the major planets. A major part of these celestial bodies moves in the asteroid belt and their instantaneous positions may be considered homogeneously distributed along the belt. Thus, it seems reasonable to model the perturbations from the remaining small asteroids (for which individual perturbations are not accounted for) by computing additional perturbations from a massive ring with a constant mass distribution in the ecliptic plane [6]. Two parameters that characterize the ring (its mass and radius) are included in the set of solution parameters.

Besides, as has been shown, (for example, by Brumberg [7]) the solar oblateness causes a secular trend in the planetary elements except for the semi-major axis and eccentricity with the maximum secular trend for Mercury perihelion. The solar oblateness $J_2 = 2 \cdot 10^{-7}$ obtained from some astrophysical estimates was accepted for integrating and while processing the observations the value of the solar oblateness has been improved.

Thus, the dynamical model of EPM ephemerides takes into account the following perturbations:

- mutual perturbations from major planets, the Sun, the Moon and 5 more massive asteroids for a numerical integration performed in the Parameterized

Post-Newtonian metric for the harmonic coordinates $\alpha = 0$ and General Relativity values $\beta = \gamma = 1$;
- perturbations from 295 asteroids chosen because of their strong perturbations on Mars and the Earth;
- perturbation from a massive ring with constant mass distribution in ecliptic plane;
- solar oblateness $J_2 = 2 \cdot 10^{-7}$ has been accepted.

The lunar-planetary integrator embedded into the program package ERA-7 (**ERA**: **E**phemeris **R**esearch in **A**stronomy) [8] has been used. Numerical integration of the equations of motion in the barycentric coordinate frame of J2000.0 was carried out by the Everhart method over a 125-year time interval (1886–2011). The result of this process was a set of Chebyshev polynomials for positions and velocities of all objects. The masses of planets as well as the initial positions corresponded to the ephemerides DE405 [9].

2. The conversion from the TDB to TCB time scale ephemerides

For correlation and comparison with the wide-spread JPL DEs ephemerides EPMs ephemerides were created up to now in TDB time scale, close to T_{eph} ([10]) used for the DEs ephemerides. To be consistent with IAU resolutions, ICRS should be treated as four-dimensional reference frame with TCB time scale in which planetary ephemerides should be constructed. Although the conversion to TCB time scale could not and did not allow greater accuracy of ephemerides and adjusted parameters, users processing the VLBI and Earth satellite observations must have TCB ephemerides, so the two versions of EPM ephemerides are constructed for TDB and TCB time scales.

The values of masses GM_i and initial coordinates of all celestial bodies involved in integration for the date JD=2448800.5 were multiplied by the factor $(1 + L_B)$ for the construction of EPM2002C ephemerides in the TCB time scale in accordance with the IAU resolutions (see, for example, Brumberg and Groten [11]). Because EPM ephemerides are very close to DE405 ephemerides the value $L_B = 1.55051976772 \cdot 10^{-8}$, obtained for relationship between TCB and TDB of DE405 ephemerides ([12]), has been used. Moreover, the round-trip light time of ranging observations calculated in TCB time, should be expressed in the proper time, i.e. at first, τ_{TCB} multiplied by $(1 - L_B)$ and then translated to the proper time in the ordinary way.

By this means, the following modifications must be done for the conversion from the TDB to TCB time scale ephemerides:

- the integration epoch:
  $\mathrm{date}(TCB) = (\mathrm{date}(TDB) - 2443144.5) * L_B + \mathrm{date}(TDB)$
- positions: $x_i(TCB) = x_i(TDB) * (1 + L_B)$
- masses: $GM_i(TCB) = GM_i(TDB) * (1 + L_B)$

- the light time: $\tau_{TDB} = \tau_{TCB} * (1 - L_B)$
$$L_B = 1.55051976772 \cdot 10^{-8}$$

3. Processing the radar and optical data

Both versions of EPM2002 and EPM2002C ephemerides have been fitted to data totaling more than 260000 observations and including different American and Russian radiometric observations of planets and spacecraft (1961-2002), CCD astrometric observations of outer planets and their satellites, meridian transits and photographic observations of XX-th century. Data used for the production of ephemerides were taken from databases of the JPL website (http:/ssd.jpl.nasa.gov/iau-comm4/) created and kept by Standish, the database of optical observations of Sveshnikov and extended to include Russian radar observations of planets (on the website of IAA http://www.ipa.nw.ru/PAGE/DEPFUND/LEA/ENG/englea.htm). All the observations used are described in Tables 1,3.

Radar observations have been reduced for 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), the effects of propagation of electromagnetic signals in the Earth troposphere and in the solar corona as well as reduction for the topography for ranging of planet surfaces. Special mention should be made of the uniqueness of the extremely precise observations of the martian Viking (1976-1982), Pathfinder landers (1997) and MGS (Mars Global Surveyor) data (1998-2002) which are free from uncertainties due to planetary topography that do remain in radar ranging despite the modeling of topography. The positions of the landers are computed taking into account the precession, nutation and seasonal terms of the Mars rotation.

All the observations of ranging to Mars and, as a rule, to Venus, carried out within a single day were grouped into normal points after necessary reductions. Normal points for MGS data were obtained by grouping data of one session. It is assumed that data belong to different sessions, if the time interval between them is more than one hour. The observations were weighted in accordance with their a priori standard deviations.

The part of MGS data obtained during 1998 was carried out at superior solar conjunction unlike the later MGS data of 1999-2002. Although the frequency was high – the X-band, but the minimum impact parameter (p) was $p = 15.89R_\odot$ for the date 27.04.1998, so the effect of the solar corona delay was considerable. When these data were excluded from the fitting the residuals for them were calculated with the obtained ephemerides, their rms appeared to be as large as 150 m which value greatly exceeded the a priory errors. These residuals decreased after reduction for the solar corona with different values of parameters of the corona model for different parts of MGS observations. A simple model of the solar corona was used:

$$N_e(r) = \frac{A}{r^6} + \frac{B}{r^2},$$

Table 1. Radiometric observations used in the ephemeris solutions.

station, object	type	time interval	number of obs.	normal points	a priori accuracy
		MERCURY			
Millstone	τ	1964	5	—	7.5–75 km
Haystack	τ	1966–1971	217	—	3 km
Arecibo	τ	1964–1982	341	323	3–30 km
Goldstone	τ	1971–1997	259	138	1.5–3 km
Crimea	τ	1980–1995	75	23	1.2–4.8 km
		VENUS			
Millstone	τ	1961–1967	135	—	1.5–120 km
Haystack	τ	1966–1971	219	—	1.5 km
Arecibo	τ	1964–1970	319	—	3–15 km
Goldstone	τ	1964–1990	512	—	1.5–6 km
Crimea	τ	1962–1995	1139	170	0.15–22.5 km
		MARS			
Haystack	τ	1967–1973	3801	133	0.075–12 km
Arecibo	τ	1965–1973	1680	43	0.075–45 km
Goldstone	τ	1969–1994	48989	149	0.075–0.6 km
Crimea	τ	1971–1995	381	78	0.15–4.8 km
Mariner-9	τ	1971–1972	643	—	15–270 m
Viking-1	τ	1976–1982	1161	—	7–12 m
Viking-1	$d\tau$	1976–1978	14980	—	0.16–3.2 m
Viking-2	τ	1976–1977	80	—	7–10 m
Pathfinder	τ	1997	90	—	10–22 m
Pathfinder	$d\tau$	1997	7576	—	0.012 m
MGS	τ	1998–2002	139608	6211	7.5 m
		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	0.5–6 km
spacecraft	$\alpha\delta$	1996–1997	—	23	$0.''007$–$0.''012$
Arecibo s 3,4	τ	1992	—	4	3–14 km

where $N_e(r)$ is the electron density. The result was better when apart from the B coefficient, its time variation was also included. For the remaining MGS data of 1999-2002 the solar corona delay was modelled with another value of the B coefficient. The contribution of the first term is insignificant for an impact parameter more than $p = 15.89R_\odot$, and it cannot be estimated from these observations. The coefficients $B, \dot{B}$ for 1998 and B for the remaining MGS data of 1999-2002 were estimated. The rms of MGS residuals for different cases of the model of the solar corona are given in Table 2. (the MGS 1998 data were not included into the adjustment here).

Table 2. The rms of residuals of MGS data
(the 1998 part of MGS data are excluded from the adjustment).

data	B_{tot}	B_1, B_2	$B_1, \dot{B}_1, B_2$
MGS_{1998} (1)	159m	8.8m	7.0m
$\mathrm{MGS}_{99-2002}$ (2)	1.8m	1.8m	1.8m

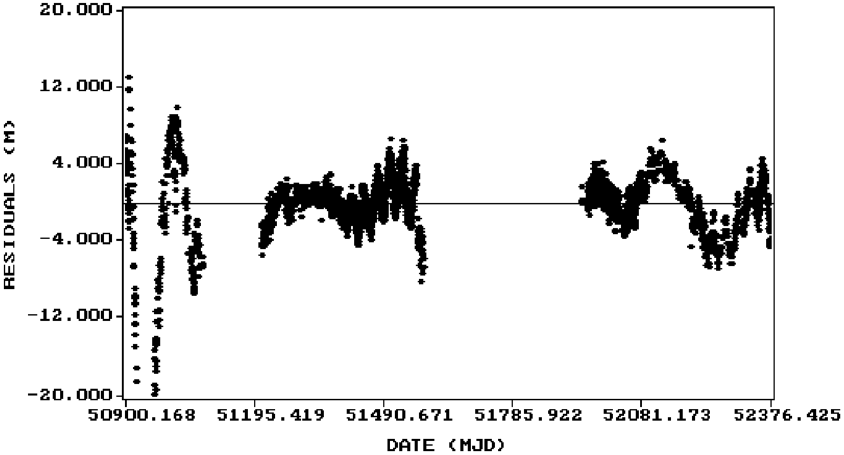

Figure 1. Residuals of MGS range, 23.03.1998–12.04.2002.

After this reduction for the solar corona, it seems that the 1998 MGS data with own weights could be used for the improvement of ephemerides. The residuals of all MGS data are shown in Fig. 1. Even for the observations far from the solar conjunction there still remains a signature at the a priory errors level. The reason for this is unclear, maybe the removal of the orbit of the MGS spacecraft was insufficiently accurate.

Optical observations used in the ephemerides solutions are described in Table 3.

The observations of satellites of Jupiter and Saturn are of great importance, as they are more accurate than the observations of their parent planets and

Table 3. Optical observations used in the ephemeris solutions.

station, object	planet satellite	type	time interval	number of obs.	a priori accuracy
		JUPITER			
USNO	p	transit	1913–1994	4388	0.″5
Tokyo	p	ph-e transit	1963–1988	568	0.″5–0.″8
La Palma	s 3,4	ph-e transit	1986–1997	1316	0.″25
Nikolaev	s 1,2,3,4	photo	1962–1998	2628	0.″2
Flagstaff	s 1,2,3,4	CCD	1998–2002	1874	0.″2
		SATURN			
USNO	p	transit	1913–1982	3054	0.″5
Tokyo	p	ph-e transit	1963–1988	506	0.″5–0.″8
Bordeaux	s 6,8	ph-e transit	1987–1993	238	0.″25
La Palma	s 5,6,7,8	ph-e transit	1987–1997	1460	0.″25
Nikolaev	s 3,4,5,6,8	photo	1973–1997	1264	0.″2
Flagstaff	s 3,4,5,6,7,8	CCD	1998–2002	1308	0.″2
VLA	p	radio	1984	8	0.″03–0.″06
		URANUS			
USNO	p	transit	1913–1993	4244	0.″5
Tokyo	p	ph-e transit	1963–1988	366	0.″5–0.″8
Bordeaux	p	ph-e transit	1985–1992	330	0.″25
Bordeaux	p	CCD	1997	34	0.″2
La Palma	p, s 4	ph-e transit	1984–1997	2060	0.″25
Nikolaev	p	photo	1961–1998	440	0.″2
Flagstaff	p, s 3,4	CCD	1995–2002	1786	0.″2
VLA,ring occ.	p	radio	1977–1985	16	0.″03–0.″2
		NEPTUNE			
USNO	p	transit	1913–1993	3806	0.″5
Tokyo	p	ph-e transit	1963–1988	320	0.″5–0.″8
Bordeaux	p	ph-e transit	1985–1993	366	0.″25
Bordeaux	p	CCD	1997	28	0.″2
La Palma	p	ph-e transit	1984–1998	2212	0.″25
Nikolaev	p	photo	1961–1998	436	0.″2
Flagstaff	p	CCD	1995–2002	928	0.″2
VLA,ring occ.	p	radio	1981–1997	22	0.″03–0.″2

PLUTO

station, object	planet satellite	type	time interval	number of obs.	a priori accuracy
Different stat.	p	photo	1914–1967	1164	0.″5–1″
Different stat.	p	photo	1969–1988	674	0.″5–1″
Different stat.	p	photo	1989–1995	82	0.″5–1″
Pulkovo	p	photo	1930–1993	416	0.″5
Tokyo	p	photo	1994	24	0.″3
Bordeaux	p	ph-e transit	1996	12	0.″3
Bordeaux	p	CCD	1995–1997	64	0.″2
La Palma	p	ph-e transit	19896-1998	760	0.″25
Flagstaff	p	CCD	1995–2002	910	0.″2

practically free from the phase effect. CCD data, obtained at Flagstaff observatory [13], whose observational program started in 1995 and is still being continued are the most accurate. All the positions are referenced to ICRF, using reference stars taken from ACT or Tycho-2 catalogues. Another group of high accuracy data is photographic observations of satellites of Jupiter, Saturn, as well as Uranus and Neptune planets were obtained at Nikolaev observatory during 1962–1998 [14]. They are referenced to the ICRF system by a special method which has given good results for minor planets [15]. Combination of the satellite data from Flagstaff and Nikolaev can be successfully used to improve the planet ephemerides.

Table 4. The corrections to the orbital elements of Jupiter for two versions of the fitting with (I) and without (II) the elements of satellites.

	a [m]	$\sin i\cos\Omega$ [mas]	$\sin i\sin\Omega$ [mas]	$e\cos\pi$ [mas]	$e\sin\pi$ [mas]	λ [mas]
version I	3422	−23.90	14.26	−1.32	0.58	8.11
	±644	±2.53	±2.29	±0.33	±0.38	±1.14
version II	2938	−23.77	15.22	0.22	0.23	5.73
	±676	±2.69	±2.43	±0.34	±0.39	±1.19

Up to now, ephemerides of satellites have been computed by using analytical theories of Lieske (Jupiter), Vienn and Duriez (Saturn), Lascar and Jacobson (Uranus) included into the program package ERA-7. At present in IAA numerical theories of satellites of the outer planets are in progress in guidance by Krasinsky. But if a theory of satellite motion is quite accurate, corrections to elements of a planet obtained depend but little on the inclusion or the exclusion of elements of satellites into solution parameters. For example, Table 4 gives the corrections to orbital elements of Jupiter for these two versions of the fitting.

Residuals of all the observations of Jupiter are shown in Fig. 2, 3.

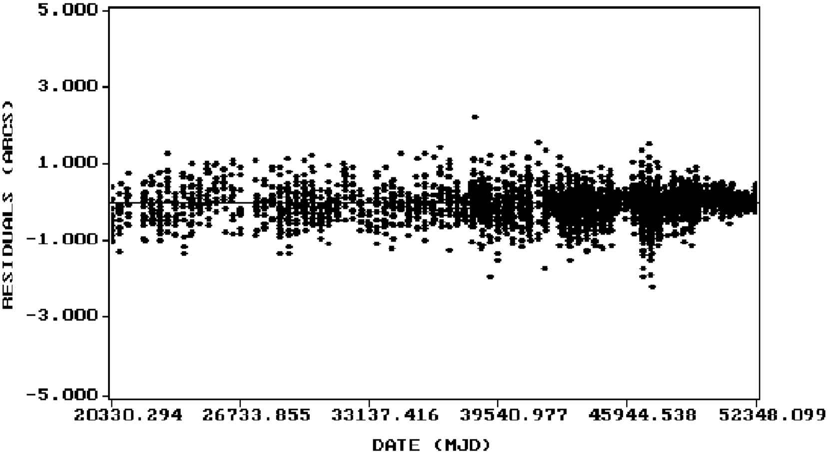

Figure 2. Residuals of Jupiter in right ascension, 1913 —2002.

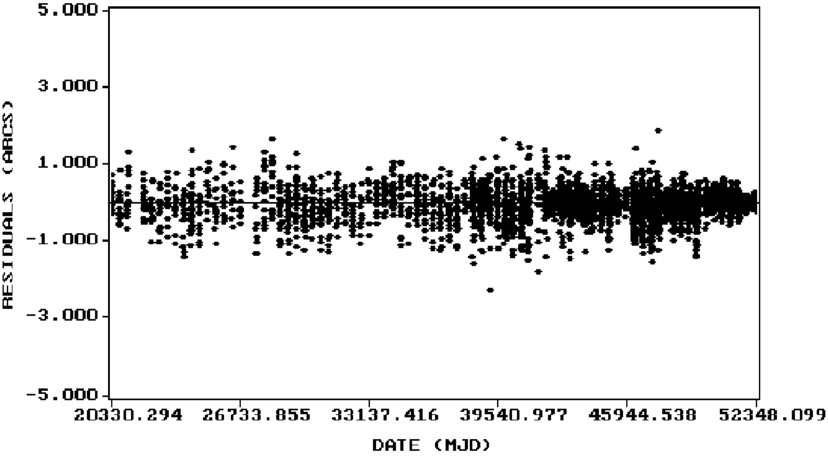

Figure 3. Residuals of Jupiter in declination, 1913 —2002.

Unfortunately, observations of Pluto are mainly photographic and have quite poor accuracy. For the Pluto–Charon system the barycenter of this system calculated differs slightly from the center of light observed. But correction for this effects has not decreased the Pluto residuals. It seems that the difference between these systems should be estimated from high accuracy observations. Residuals of all the observations of Pluto are given in Fig. 4, 5.

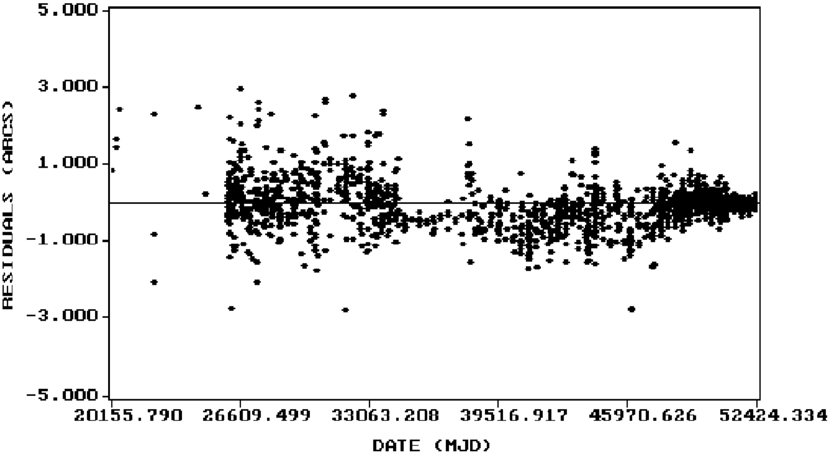

Figure 4. Residuals of Pluto in right ascension, 1913 —2002.

4. Results obtained

The formal standard deviations of orbital elements of planets are shown in the Table 5.

The parameters of Mars rotation, masses of Ceres, Pallas, Vesta, densities of C,S,M classes of asteroids, the solar quadrupole moment, parameters of PPN formalism β and γ have been estimated in the fitting process to all the observations. Table 6 demonstrates some of these values obtained for the three versions of EPM ephemerides, which differ by slightly varying values of 297 asteroid diameters.

- EPM2002: DE405 asteroid diameters, selected by G.Williams [16] and based mainly on the first version of *IRAS* estimates [17].
- EPMT1: The latest values of asteroid diameters based on *IRAS* data [4] and observations of occultations of stars by minor planets [5].
- EPMT2: The recent values of asteroid diameters by Tedesco *et al.*[4] with the corrected diameter scale: $D_r = (1.035 \pm 0.001)D + (0.616 \pm 0.054)$ km. As

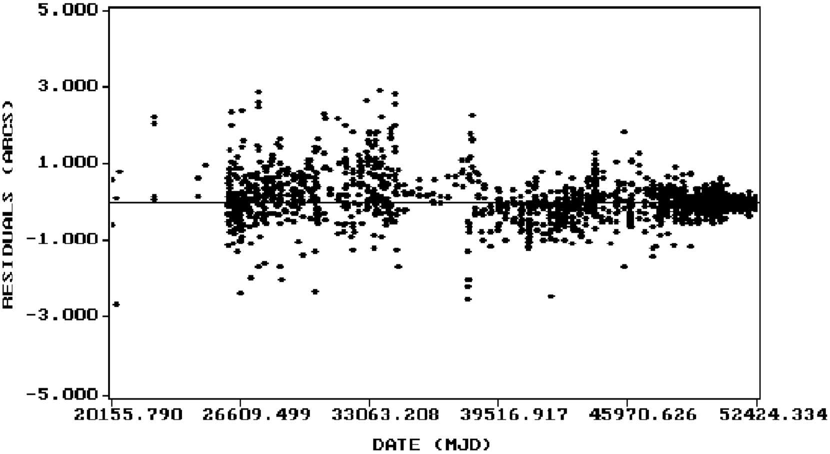

Figure 5. Residuals of Pluto in declination, 1913 —2002.

our investigation has shown ([3],[6]), the scale of asteroid diameters of the first version of *IRAS* is better than one of the later *IRAS* versions.

Variations of the estimated parameters indicate real errors of adjusted parameters due to uncertainty of asteroid diameters.

Table 5. The formal standard deviations of elements of the planets.

planet	a [m]	$\sin i \cos\Omega$ [mas]	$\sin i \sin\Omega$ [mas]	$e \cos\pi$ [mas]	$e \sin\pi$ [mas]	λ [mas]
Mercury	0.211	3.596	3.760	0.363	0.315	0.933
Venus	0.347	0.685	0.676	0.044	0.046	0.209
Earth	0.146	—	—	0.001	0.001	—
Mars	0.635	0.004	0.008	0.001	0.001	0.002
Jupiter	655	2.572	2.313	0.334	0.385	1.153
Saturn	4730	3.839	4.436	4.306	3.308	3.896
Uranus	44000	4.312	7.097	5.638	3.644	10.447
Neptune	561000	4.447	9.754	17.339	20.790	42.985
Pluto	40014000	8.207	16.090	97.219	38.599	97.513

Table 6. The adjusted parameters.

theory	$M_{\mathrm{Cer}}/M_\odot$ 10^{-10}	$M_{\mathrm{Pal}}/M_\odot$ 10^{-10}	$M_{\mathrm{Ves}}/M_\odot$ 10^{-10}	ρ_C g/cm3	ρ_S g/cm3	ρ_M g/cm3
EPM2002	4.77	1.02	1.36	1.23	2.75	5.30
	±0.01	±0.01	±0.01	±0.02	±0.02	±0.05
EPMT1	4.87	1.12	1.40	1.46	3.12	2.93
	±0.01	±0.01	±0.01	±0.02	±0.02	±0.05
EPMT2	4.88	1.10	1.41	1.22	2.83	3.92
	±0.01	±0.01	±0.01	±0.02	±0.02	±0.05

theory	ΔAU m	$\beta-1$	$\gamma-1$	J_2 10^{-7}	R_{ring} AU	M_{ring} $10^{-10}M_\odot$	M_{belt} $10^{-10}M_\odot$
EPM2002	2.89	−0.0002	0.0000	2.51	2.97	3.7	15.5
	±0.13	±0.0001	±0.0001	±0.50	±0.07	±0.04	±2.0
EPMT1	2.67	0.0003	−0.0002	2.07	2.92	3.2	14.3
	±0.12	±0.0001	±0.0001	±0.50	±0.06	±0.04	±2.0
EPMT2	2.66	0.0001	−0.0001	2.36	2.90	2.8	14.5
	±0.12	±0.0001	±0.0001	±0.50	±0.06	±0.04	±2.0

Ephemerides EPM were oriented onto the International Celestial Reference Frame (ICRF). The most precise optical data of the outer planets and their satellites, obtained at Flagstaff, Nikolaev, La Palma) have already been referred to the ICRF. The remaining optical observations, referenced to different catalogues, at first have been transformed to the FK4 systems by Sveshnikov [18-19]. Then they were referenced to the FK5 using known formulae (see as the example [20]), and were finally transformed to the ICRF using the values of the three angles of the rotation between the HIPPARCOS and FK5 catalogues, J2000 [21] in mas:

$$\varepsilon_x = -19.9,\ \ \varepsilon_y = -9.1,\ \ \varepsilon_z = 22.9.$$

Orbits of the four inner planets (with the exception of angles of the orientation) are determined entirely by the ranging observations of planets and spacecraft. The system of these planets was oriented to the ICRF by the including the ICRF-base VLBI measurements of spacecraft (Magellan in orbit about Venus and Phobos on its approach to Mars) in the adjustment, in the same way that has done by Standish [9] for DE405. The angles of the rotation between the EPM ephemerides and the ICRF reference frame were obtained (in mas):

$$\varepsilon_x = 4.5 \pm 0.8,\ \ \varepsilon_y = -0.8 \pm 0.6,\ \ \varepsilon_z = -0.6 \pm 0.4.$$

For EPM2002 and EPM2002C ephemerides the rms residuals of all observations are identical: the weight unit errors are 0.686 for TCB and 0.685 for TDB time scale ephemerides. The formal standard deviations of all the solution parameters and their values (except orbital elements of the planets) or corrections to the initial orbital elements of planets coincide within formal uncertainties, as

Table 7. The corrections to the first twelve parameters of adjusted sets with their formal standard deviations for TCB (1 column) and TDB (2 column) time scale ephemerides.

a_3[m]		$e_3\cos\pi_3$[mas]		$e_3\sin\pi_3$		a_4[m]	
−1.752	−2.320	−0.0012	−0.0012	0.006	0.007	−5.716	−6.143
±0.387	±0.387	±0.001	±0.001	±0.001	±0.001	±1.172	±1.171

$\sin i_4\cos\Omega_4$[mas]		$\sin i_4\sin\Omega_4$[mas]		$e_4\cos\pi_4$[mas]		$e_4\sin\pi_4$[mas]	
26.696	29.795	−5.299	−5.617	0.032	0.033	0.051	0.055
±2.003	±2.000	±0.838	±0.837	±0.002	±0.002	±0.003	±0.003

λ_4[mas]		L_{Vik1}[$''$]		PX_{Vik1}[m]		PY_{Vik1}[m]	
0.745	0.785	−2.643	−2.581	0.333	0.294	72.553	71.859
±0.064	±0.063	±0.296	±0.296	±0.154	±0.153	±4.910	±4.904

is bound to be. For example, the corrections to the first twelve parameters with their formal standard deviations are shown in the Table 7.

Along with the planetary ephemerides improved ephemerides of the orbital and rotational motions of the Moon have been fitted by processing the 1979-2001 LLR observations by Krasinsky [22] where the last version of this theory accounting for a number of subtle selenodynamical effects is described.

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EPM2002 and EPM2002C — two versions of high accuracy numerical planetary ephemerides constructed for TDB and TCB time scales.

Оригинал-макет подготовлен с помощью системы LaTeX

Подписано к печати 8.08.2003 Формат 60 × 90/16. Офсетная печать. Печ.л. 1.2
Уч.-изд.л. 1.2 Тираж 150 Заказ 319 бесплатно

Отпечатано в типографии ПИЯФ РАН
(188350 Ленинградская обл., г. Гатчина, Орлова роща).

Институт прикладной астрономии РАН, 197110, С.-Петербург, Ждановская ул., 8.