NUMERICAL EPHEMERIDES OF PLANETS AND THE MOON — EPM AND IMPROVEMENT OF SOME ASTRONOMICAL CONSTANTS

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ABSTRACT. The current state of the last version of the planet part of EPM (**E**phemerides of **P**lanets and the **M**oon) ephemerides whose origin dates back to the 1970s, is presented. Ephemerides of the planets and the Moon have been numerically integrated in the PPN metric over a 125-year time interval (1886–2011). The dynamical model of EPM2003 ephemerides includes mutual perturbations from the nine planets, the Sun, the five most massive asteroids, the Moon, lunar physical libration, perturbations from other 296 asteroids, as well as perturbations from the solar oblateness and the massive asteroid ring with constant mass distributions in ecliptic plane. EPM2003 ephemerides have resulted from a least squares adjustment to observational data totaling more than 280000 position observations (1913–2003) of different types. The set of different astronomical constants have been obtained from accurate radiometic observations. The angles of the rotation between EPM2003 and the ICRF are (in mas): $\varepsilon_x = 4.5 \pm 0.8$, $\varepsilon_y = -0.8 \pm 0.6$, $\varepsilon_z = -0.6 \pm 0.4$. The two versions of EPM2003 ephemerides have been constructed in TDB and TCB time scales as the independent variables of the equations.

1. DYNAMIC MODELS OF PLANETARY MOTION OF DE AND EPM EPHEMERIDES

The current state of the last version of the planet part of EPM (**E**phemerides of **P**lanets and the **M**oon) ephemerides, whose origin dates back to the 1970s, is presented. At the same time, to ensure space flights the construction of numerical planetary ephemerides was undertaken by several groups in the USA and Russia. For comparison, I'll further consider our EPM ephemerides created first at the Institute of theoretical astronomy and later at the Institute of applied astronomy as well as well-known DE ephemerides of JPL.

Common to all DE/LE and EPM ephemerides is a simultaneous numerical integration of the equations of motion of the nine major planets, the Sun, the Moon and the lunar physical libration performed in the Parameterized Post-Newtonian metric for the harmonic coordinates $\alpha = 0$ and General Relativity values $\beta = \gamma = 1$.

The various ephemerides differ slightly in

- the modelling of the lunar libration,
- the reference frames,

- the accepted value of the solar oblateness,
- the modelling of the perturbations of asteroids upon the planetary orbits,
- the sets of observations to which ephemerides are adjusted.

Some characteristics of DE118/LE62, DE200/LE200, DE403/LE403, DE405/ LE405, EPM87, EPM98, EPM2000, EPM2003 ephemerides are given in Table 1. The detailed description and comparison of DE and EPM ephemerides are given in the paper by Pitjeva (2001).

Table 1. Ephemerides DE and EPM.

Ephemeris	Interval of integration	Ref. frame	Mathematical model	Data type	number	interval
DE118	1599→2169	FK4	Integrating of	optical	44755	1911-79
(1981)			Sun,Moon,9 planets	radar	1307	1964-77
⇓		⇓	+perturbations	spacecraft	1408	1971-80
DE200		dynamic.	from 3 asteroids	LLR	2954	1970-80
		frame	(Keplerian ellipses)	total	50424	1911-80
EPM87	1700→2020	FK4	Integrating of	optical	48709	1717-80
(1987)			Sun,Moon,9 planets	radar	5344	1961-86
			+perturbations	spacecraft	–	–
			from 5 asteroids	LLR	1855	1972-80
			(Keplerian ellipses)	total	55908	1717-86
DE403	−1410→3000	ICRF	Integrating of	optical	26209	1911-95
(1995)			Sun,Moon,9 planets	radar	1341	1964-93
⇓	⇓		+perturbations	spacecraft	1935	1971-94
DE404	−3000→3000		from 300 asteroids	LLR	9555	1970-95
			(mean elements)	total	39057	1911-95
EPM98	1886→2006	DE403	Integrating of	optical	–	–
(1998)			Sun,Moon,9 planets	radar	55959	1961-95
			5 астер.+ perturb.	spacecraft	1927	1971-82
			from 295 asteroids	LLR	10000	1970-95
			(mean elements)	total	67886	1961-95
DE405	1600→2200	ICRF	Integrating of	optical	28261	1911-96
(1997)			Sun,Moon,9 planets	radar	955	1964-93
⇓			+perturbations	spacecraft	1956	1971-95
DE406	−3000→3000		from 300 asteroids	LLR	11218	1969-96
			(integrated)	total	42410	1911-96
EPM2000	1886→2011	DE405	Integrating of	optical	–	–
(2000)			Sun,Moon,	radar	58076	1961-1997
			9 planets,	spacecraft	24587	1971-1997
			300 asteroids	LLR	13500	1970-1999
				total	96163	1961-1999
EPM2003	1886→2011	ICRF	Integrating of	optical	44490	1913-2003
(2003)			Sun,Moon,	radar	58076	1961-1997
			9 planets,	spacecraft	164193	1971-2002
			301 asteroids,	LLR	14612	1970-2001
			asteroid ring	total	281371	1913-2003

In the past ephemerides have been aligned onto the FK4 reference frame, then onto the dynamical equator and equinox and now ephemerides are oriented onto the **I**nternational **C**elestial **R**eference **F**rame (ICRF). Starting with DE405 a nonzero value of the solar oblateness

$J_2 = 2 \cdot 10^{-7}$ obtained from some astrophysical estimates was accepted for integrating.

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. The perturbations from 300 asteroids have been taken into account in the ephemerides DE403, DE405, and EPM ephemerides starting with EPM98. Masses of many of these asteroids are quite poorly known, and as shown by Standish and Fienga (2002), the accuracy of the planetary ephemerides deteriorates due to this factor. Masses of few most massive asteroids which more strongly affect Mars and the Earth can be estimated from observations of martian landers and spacecraft orbiting Mars. The five of 300 asteroids proved to be double and their masses are known now. The masses of Eros(433) and Mathilda(253) have been derived by perturbations of the spacecraft during the NEAR flyby. Unfortunately, the classical method of determining masses of asteroids for which close encounters occur is limited by uncertainty in masses of the large asteroids, perturbations by others, unmodeled asteroids, and a quality of observations. Perhaps, masses of many asteroids will be obtained by high accuracy observations during the GAIA mission, but it will not be soon. So at present masses of the rest of 301 asteroids have been estimated by the astrophysical method. The latest published diameters of asteroids based on infrared data of IRAS (**I**nfra **R**ed **A**stronomical **S**atellite) and MSX (**M**idcourse **S**pace **E**xperiment), as well as observations of occultations of stars by minor planets and radar observations 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. The 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 (Krasinsky et al., 2002). Two parameters that characterize the ring (its mass and radius) are included in the set of solution parameters.

Thus, the dynamical model of EPM2003 ephemerides includes the following perturbations: mutual perturbations from the nine planets, the Sun, the five most massive asteroids, the Moon, lunar physical libration, perturbations from other 296 asteroids, as well as perturbations from the massive asteroid ring and from the solar oblateness.

The lunar-planetary integrator embedded into the program package (Krasinsky and Vasilyev, 1997) ERA-7 (**ERA**: **E**phemeris **R**esearch in **A**stronomy) 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).

2. PROCESSING THE RADAR AND OPTICAL DATA

EPM2003 ephemerides have resulted from a least squares adjustment to observational data totaling more than 280000 position observations (1913–2003) of different types including radiometric observations of planets and spacecraft, CCD astrometric observations of the outer planets and their satellites, meridian transits and photographic observations. 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 Dr. Standish, the database of optical observations of Dr. 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).

Radar observations have been reduced for relativistic corrections, 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 estimated seasonal terms of the Mars rotation.

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), while the minimum impact parameter (p) was $p = 15.89R_\odot$ for the date 27.04.1998, 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:

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

where $N_e(r)$ is the electron density.

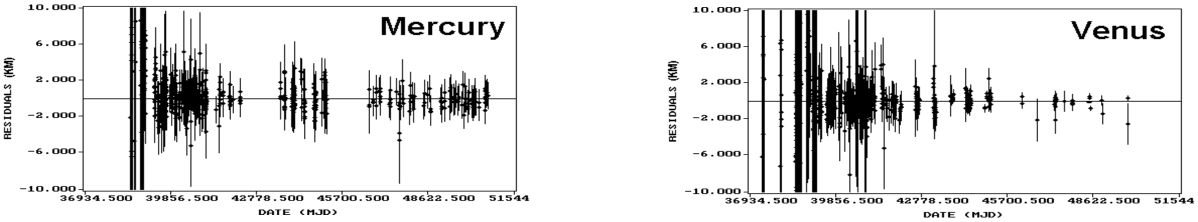

Figure 1: Ranging residuals 1960–2000 for Mercury and Venus, the scale ±10 km.

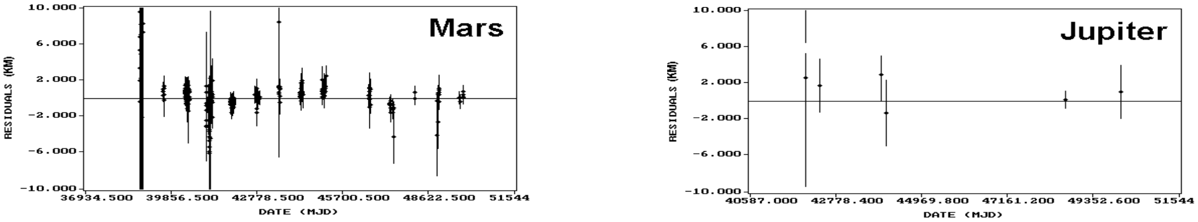

Figure 2: Ranging residuals for Mars (1960–2000) and Jupiter (1970–2000), the scale ±10 km.

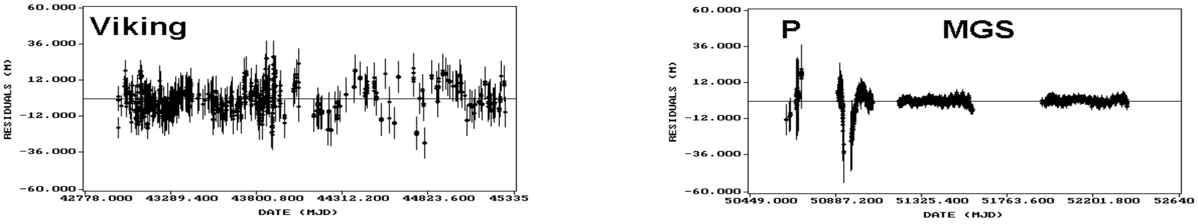

Figure 3: Ranging residuals of Viking (1976–82); Pathfinder, MGS (1997–2002), the scale ±60 m.

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 modeled with another value of the B coefficient.

The residuals of all radiometric data are shown in Fig. 1–3. The rms residuals of ranging for the Mercury are 1.4 km, for Venus and Mars are 0.7 km, for Viking and Pathfinder are 8 m, MGS (1998) are 7 m, MGS (1999–2002) are less 2 m. For the MGS observations even far away 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.

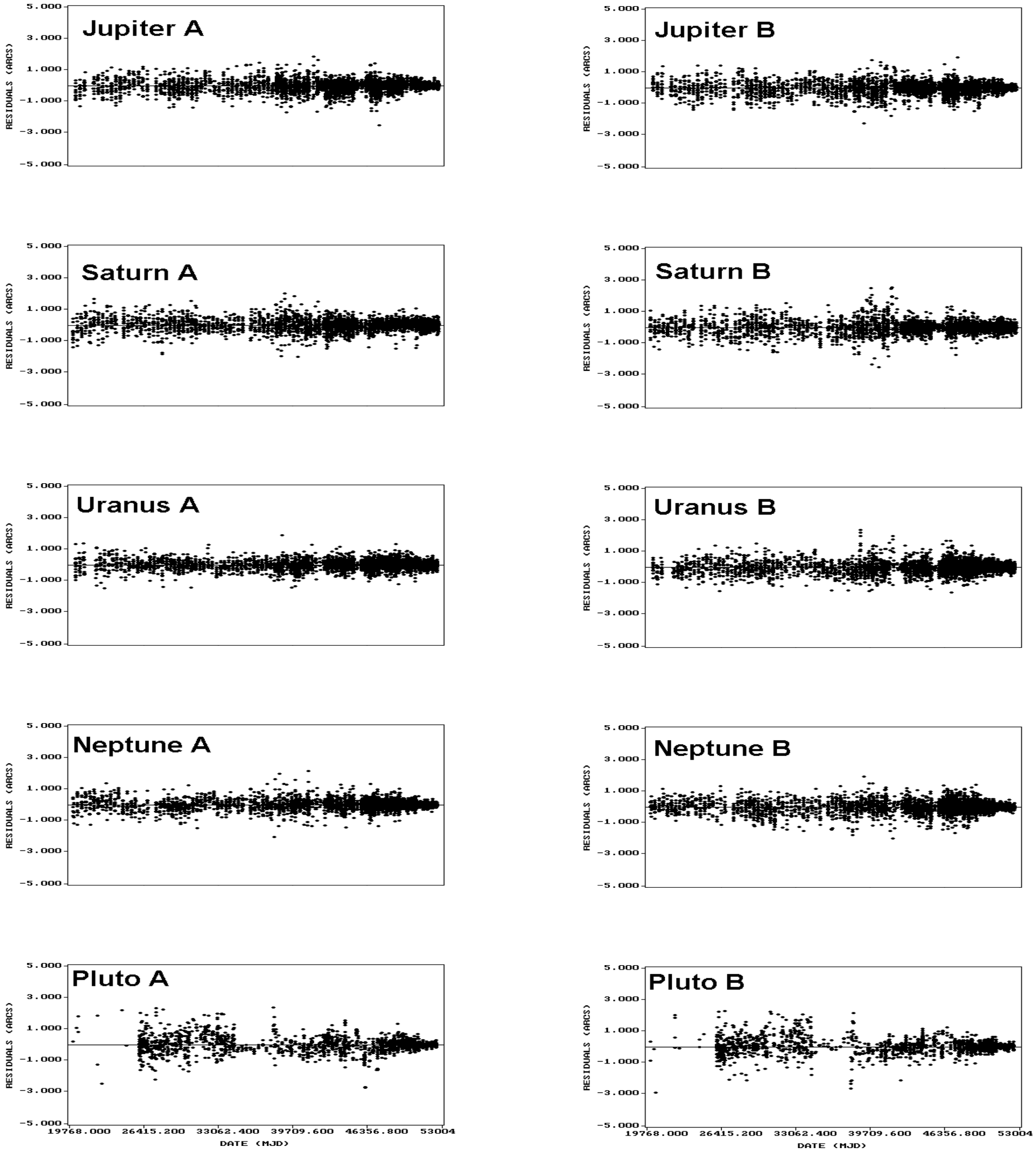

Figure 4: Residuals of the outer planets 1913–2003 in $\alpha\cos\delta$ (A) and in δ (B), the scale $\pm5''$.

The observations of satellites of Jupiter and Saturn are of great importance for optics, as they are more accurate than the observations of their parent planets and practically free from the phase effect. CCD data, obtained at Flagstaff observatory, whose observational program started in 1995 and is still being continued are the most accurate. All these 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 obtained at Nikolaev observatory during 1962–1998. They are referenced to the ICRF system by a special method which has given good results for minor planets. Combination of the satellite data from Flagstaff and Nikolaev has been successfully used to improve the planet ephemerides. Residuals of all the observations of the outer planets are shown in Fig. 4. Unfortunately, observations of Pluto are mainly photographic and have quite poor accuracy and their rms are worse.

3. ORIENTATION OF EPM2003 ONTO ICRF

Ephemerides EPM were oriented onto the **I**nternational **C**elestial **R**eference **F**rame (ICRF). The most precise optical data of the outer planets and their satellites, obtained at Flagstaff, Nikolaev, La Palma) have already been referenced to the ICRF. The remaining optical observations, referenced to different catalogues, at first were transformed to the FK4 systems by Sveshnikov. Then they were referenced to the FK5 using known formulae (see as the example Standish et al., 1995), and were finally transformed to the ICRF using the values of the three angles of the rotation between the HIPPARCOS and FK5 catalogues, J2000 in mas (Mignard, 2000):

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

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 been done by Standish (1998b) for DE405. The angles of the rotation between the EPM ephemerides and the ICRF reference frame were obtained (in mas):

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

4. RESULTS OBTAINED

The formal standard deviations of orbital elements of planets are shown in the Table 2. Note that the uncertainties, given in this paper, are formal standard deviations; realistic error bounds may be an order of magnitude larger.

Table 2. 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	0.205	3.472	3.630	0.350	0.304	0.901
Venus	0.338	0.662	0.652	0.042	0.044	0.202
Earth	0.169	—	—	0.001	0.001	—
Mars	0.783	0.004	0.009	0.001	0.001	0.004
Jupiter	627	2.471	2.246	0.322	0.372	1.108
Saturn	4425	3.498	4.299	4.068	3.242	3.675
Uranus	41030	4.156	6.602	5.355	3.470	9.610
Neptune	516808	4.286	9.107	15.626	19.617	38.857
Pluto	3821864	7.716	15.567	92.264	37.804	91.196

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. The value of the astronomical unit has been obtained:

$$\mathrm{AU}=149597870693.3 \pm 0.1 \text{ m}.$$

The parameters of Mars rotation, masses of Ceres, Pallas, Vesta, Iris, Bamberga, Juno, densities of C,S,M classes of asteroids, the estimation of the total mass of the main asteroid belt, the solar quadrupole moment, parameters of PPN formalism β and γ have been estimated in the fitting process to all the observations. Table 3 – 6 demonstrates some of these values.

Table 3. The parameters of the Mars rotation.

$\dot{V}$ [^{o}/day]	I_q [^{o}]	$\dot{I}_q$ [$''$/year]	Ω_q [^{o}]	$\dot{\Omega}_q$ [$''$/year]
350.891985294	25.1893930	-0.0002	35.437685	-7.5844
± 0.000000012	±0.0000053	±0.0007	± 0.000021	± 0.0015

The value of precession constant for Mars is close to the recent value obtained from the data of the Viking, Pathfider landers and MGS radio tracking (Yoder et al., 2003):

$$\dot{\Omega}_q = [-7.''597 \pm 0.''025(10\sigma)]/\text{year}$$

Table 4. Masses of Ceres, Pallas, Juno, Vesta, Iris, Bamberga.
in $(\mathrm{GM}_i/\mathrm{GM}_\odot)\cdot 10^{-10}$

(1)Ceres	(2)Pallas	(3)Juno	(4)Vesta	(7)Iris	(324)Bamberga
4.749	1.036	0.142	1.358	0.052	0.051
±0.007	±0.003	±0.003	±0.001	±0.001	±0.001

Table 5. The solar quadrupole moment, the radius and the mass of the asteroid ring, the total mass of the main asteroid belt.

J_2 10^{-7}	R_{ring} AU	M_{ring} $10^{-10}\mathrm{M}_\odot$	M_{belt} $10^{-10}\mathrm{M}_\odot$
2.5±0.3	3.07±0.07	3.38±0.35	15.1±2.0

Table 6. Progress in the determination of the parameters of PPN formalism and $\dot{G}/G$.

year	β	γ	$\dot{G}/G(10^{-11}\mathrm{yr}^{-1})$
1985	0.76±0.12	0.87±0.06	4.1 ±0.8
1994	1.014±0.070	1.006±0.037	0.28 ±0.32
2003	1.0002±0.0001	0.9999±0.0001	0.003 ±0.008

Along with the planetary ephemerides the improved ephemerides of the orbital and rotational motions of the Moon have been fitted by processing the 1979-2001 LLR observations by Krasinsky (2002) where the last version of this theory accounting for a number of subtle selenodynamical effects is described.

For further details regarding the masses of asteroids, the full set of used observations and etc. the reader is referred to the paper (Pitjeva, 2003).

5. THE CONVERSION FROM THE TDB TO TCB TIME SCALE EPHEMERIDES

For correlation and comparison with the wide-spread JPL DEs ephemerides the EPMs ephemerides were created up to now in TDB time scale, close to T_{eph} (Standish, 1998a) 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.

In accordance with the recommendations of literature (see, for example, Brumberg and Groten, 2001) 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 EPM2003 ephemerides in the TCB time scale. 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 (IERS Conversions, 1996) has been used.

Thus, 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: $GM_i(TCB) = GM_i(TDB) * (1 + L_B)$
  $L_B = 1.55051976772 \cdot 10^{-8}$

This version involves the same numerical values in terms of TCB and TDB for the unit of length (AU) in km and for any velocities including the speed of light. At the XXV IAU General Assembly, Dr. Standish proposed another, more complicated version of conversion to TCB ephemerides retaining the same numerical value in SI units for the heliocentric constant $GM_\odot$ in terms of TDB and TCB. This situation is rather confusing. In any case, some official recommendation should be adopted (see Brumberg and Simon, 2004).

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