RECENT MODELS OF THE PLANET MOTION AND FUNDAMENTAL CONSTANTS DETERMINED FROM POSITION OBSERVATIONS OF PLANETS AND SPACECRAFT

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Contents

1. Recent planet ephemerides of JPL, IAA RAS and IMCCE
2. Solution parameters of the planet ephemerides and some fundamental constants
3. New values of the planet masses
4. New mass values of Ceres, Pallas, Vesta
5. The value of the Astronomical Unit

	TDB		TCB
JPL	**DE414**	**Konopliv et al., 2006**	**Standish, XXV GA IAU, 2003**
IAA RAS	**EPM2006**	**Pitjeva, 2006**	**Pitjeva, "Celestial Mechanics-2002"**
IMCCE	**INPOP06**	**Fienga et al., 2007**	**Fienga, XXVI GA IAU, 2006**

Common for these ephemerides is:

- the simultaneous numerical integration of the equations of motion for the nine major planets, the Sun, about 300 or more biggest asteroids, the Moon and the lunar physical libration performed in the Post-Newtonian metric for General Relativity taking into account perturbations due to the solar oblateness and perturbation from the massive ring of small asteroids;

- the ephemerides have been oriented to ICRF with the accuracy better than 1 mas by including into the total solution the ICRF-base VLBI measurements of spacecraft (Magellan, Phobos, MGS, Odyssey) 1989 – 2003 near the planets.

<u>Distinction</u> between the ephemerides:

- **modeling the lunar libration (the ephemerides of the orbital and rotational motions of the Moon have been produced and improved from LLR observations by George Krasinsky);**
- **modeling perturbations from asteroids (DE414 – 342, EPM2006 – 301, INPOP06 – 300 asteroids);**
- **numerical integration for new EPM2007 also includes the largest trans-Neptunian objects;**

  for INPOP06 – Earth rotation necessary for the very long time integration in paleoclimate studies, and the additional term $\dot{\mu}_i^*$ of the Solar System Barycenter;
- **procedures of correction (for the topography of the planet surfaces and the solar corona);**
- **sets of observations (about 400000 data of different types);**
- **and sets of solution parameters (the solution of DE414 includes 225 + 34 (Moon), EPM2006 $\sim$ 230, INPOP06 – 65 parameters).**

Table 1. Radiometric observations

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
Goldstone cl.p.	τ	1990–1997	40	—	0.15–2.5 km
Crimea	τ	1980–1995	75	23	1.2–4.8 km
Mariner-10	τ	1974–1975	—	2	0.1 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
Magellan	$\alpha\delta$	1990–1994	—	18	0.″001–0.″004
Magellan	dr	1992–1994	220	—	0.002—0.1 mm/sec
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
Phobos	τ	1989	—	1	0.2 km
MGS	τ	1998–2005	138341	4930	2–7.5 m
Odyssey	τ	2002–2005	142408	3442	2-3 m
spacecraft	$\alpha\delta$	1984–2003	—	44	0.″0003–0.″006
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	1–6 km
spacecraft	$\alpha\delta$	1996–1997	—	24	0.″007–0.″012
Arecibo s 3,4	τ	1992	—	4	3–14 km

Table 2. Optical and VLA observations of the outer planets

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	1998–2006	4778	0.″2
Mountain	s 1,2,3,4	CCD	2002–2002	16	0.″5
		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 3,4,5,6,7,8,9	CCD	1998–2006	6300	0.″2
Mountain	s 3,4,5,6,7,8,9	CCD	2002–2003	628	0.″15
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	2072	0.″25
Nikolaev	p	photo	1961–1998	440	0.″2
Flagstaff	p, s 3,4	CCD	1995–2006	3262	0.″2
Mountain	p, s 3,4	CCD	1998–2003	174	0.″15
VLA,ring occ.	p	radio	1977–1985	16	0.″03–0.″2
		NEPTUNE			
USNO	p	transit	1913–1993	3804	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, s 1	CCD	1995–2006	3086	0.″2
Mountain	p, s 1	CCD	1998–2003	120	0.″15
VLA,ring occ.	p	radio	1981–1997	22	0.″03–0.″2
		PLUTO			
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	1986-1998	760	0.″25
Flagstaff	p	CCD	1995–2006	3204	0.″2
Mountain	p	CCD	2000–2003	68	0.″15

About <u>230 parameters</u> for EPM2006:

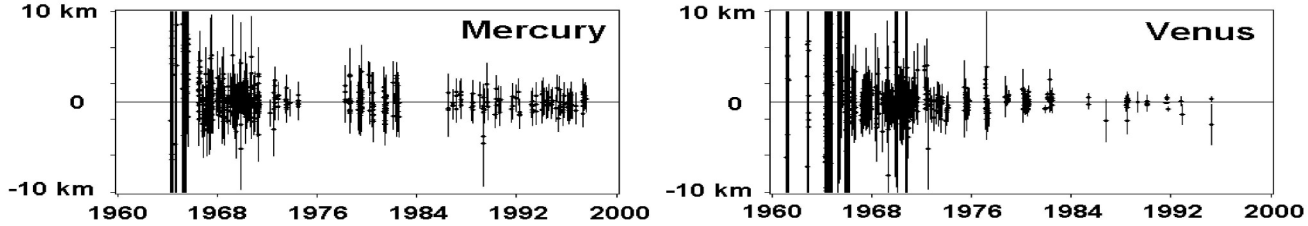
- **the orbital elements of 9 planets and 14 satellites of the outer planets;**
- **the value of the Astronomical Unit in kilometers;**
- **3 orientation angles of the ephemerides relative to ICRF;**
- **13 rotation parameters of Mars and the coordinates of 3 landers on the martian surface;**
- **masses of Jupiter and the 7 asteroids, mean densities for three taxonomic classes of asteroids (C, S, M), the mass and the radius of the asteroid ring, the ratio masses of the Earth and the Moon;**
- **the solar quadrupole moment (J_2) and 15 parameters of the solar corona for different conjunctions with the Sun;**
- **8 coefficients of Mercury's topography and the corrections to the level surfaces of Venus and Mars;**
- **5 coefficients of the phase effect correction for the outer planets;**
- **constant bias for Viking-1, Viking-2, Pathfinder, MGS and Odyssey data and some other series of observations;**
- **the relativistic parameters (β, γ, $\dot{G}/G$, $\ddot{G}/G$, $\dot{\pi}_i$).**

Table 3. Mean values and rms residuals for radiometric observations

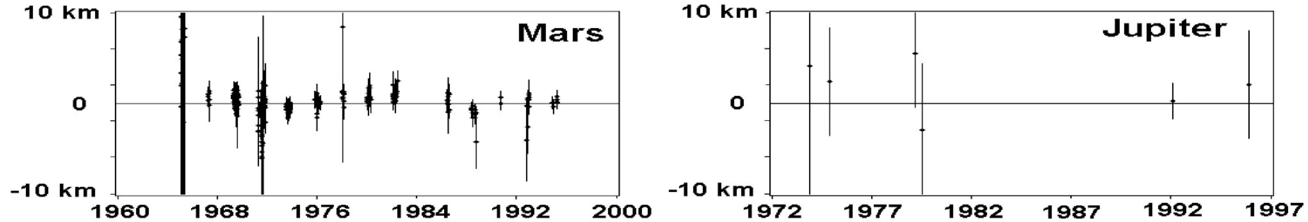
Planet	Type of data	Time interval	N	$< O - C >$	σ
MERCURY	τ [m]	1964–1997	746	0	575
VENUS	τ [m]	1961–1995	1354	-2	584
	Magellan dr [mm/s]	1992–1994	195	0	0.007
	Magellan VLBI [mas]	1990–1994	18	1	2
MARS	τ [m]	1965–1995	402	0	738
	Viking τ [m]	1976–1982	1258	0	8.8
	Viking $d\tau$ [mm/s]	1976–1978	14978	-0.02	0.89
	Pathfinder τ [m]	1997	90	0	2.8
	Pathfinder $d\tau$ [mm/s]	1997	7569	0	0.09
	MGS τ [m]	1998–2005	6429	-0.1	2.3
	Odyssey τ [m]	2002–2005	3441	-0.1	2.0
	spacecraft VLBI [mas]	1984–2003	44	0	0.8
JUPITER	spacecraft τ [m]	1973–1995	6	-538	2642
	spacecraft VLBI [mas]	1996–1997	24	-1	11

Table 4. **Mean values and rms residuals for optical observations α and δ in mas, 1913–2005**

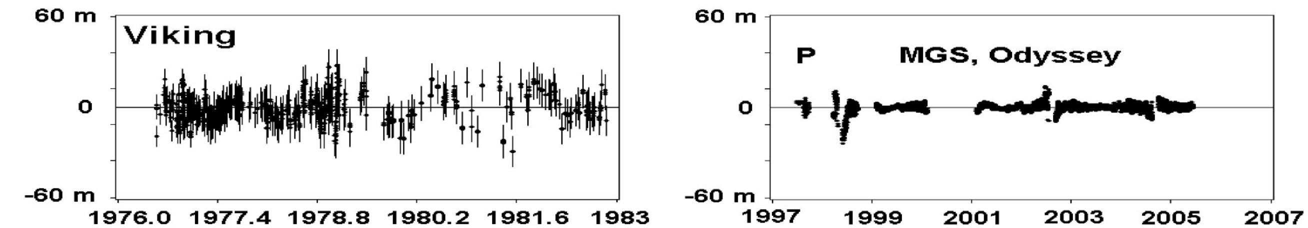
Planet	N	$< O - C >_\alpha$	σ_α	$< O - C >_\delta$	σ_δ
JUPITER	11562	3	103	-14	128
SATURN	12205	-1	192	-5	190
URANUS	10659	0	205	-5	251
NEPTUNE	9701	0	183	-1	240
PLUTO	4563	0	237	5	236



Ranging residuals for Mercury and Venus.

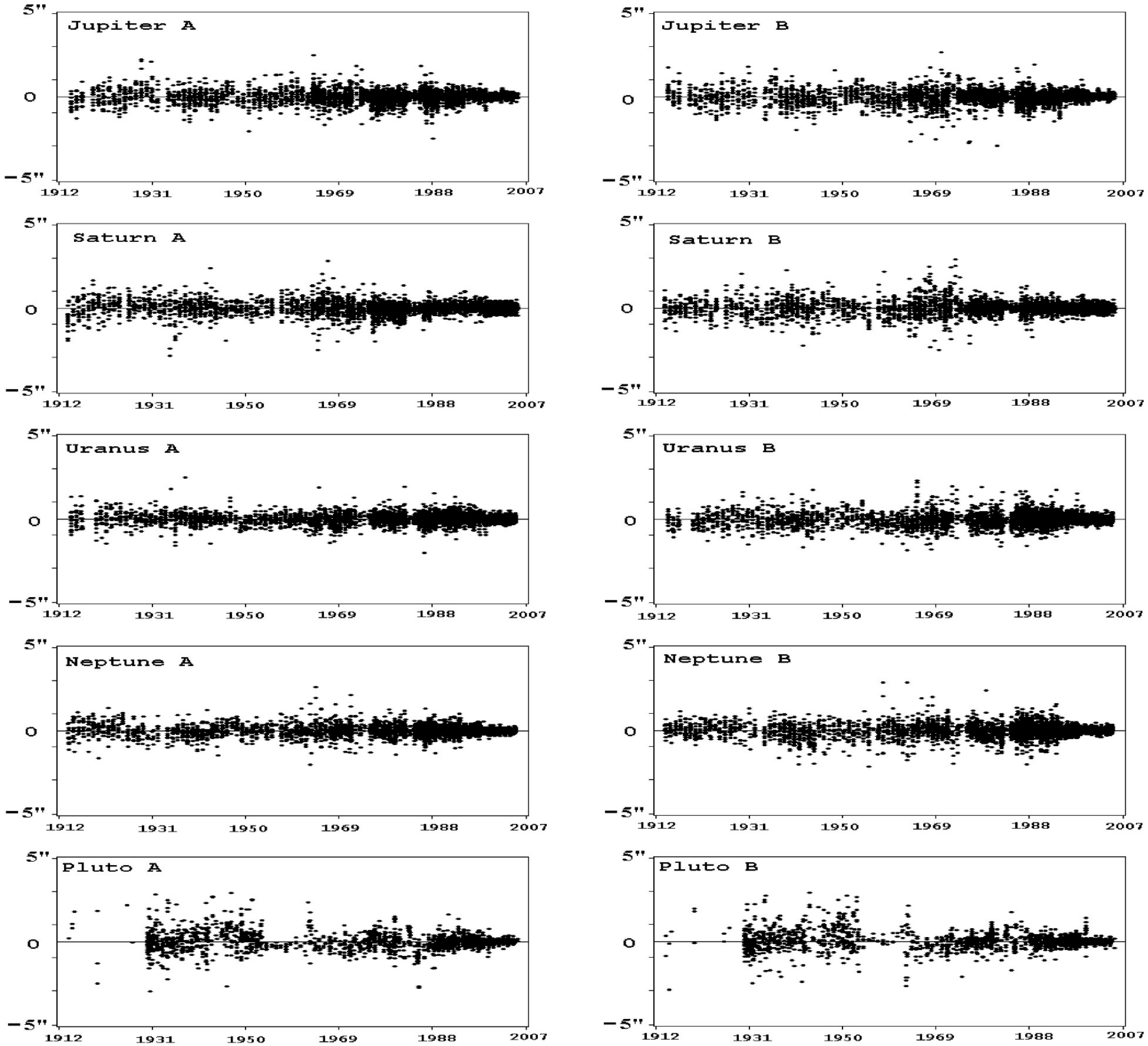


Ranging residuals for Mars and Jupiter.



Ranging residuals of Viking,
Pathfinder-P(1997), MGS(1998–2005), Odyssey(2002–2005).

The rms residuals of ranging for the Mercury and Venus are 0.58 km, for Mars are 0.7 km, for Viking are 8.8 m, for Pathfinder 2.8 m, for MGS and Odyssey 2.2 m.



Residuals of the outer planets 1913–2005
in $\alpha \cos \delta$ (A) and in δ (B), the scale $\pm 5''$.

Table 5. **New values of the planet masses proposed to NSFA**

Planet	Previous values	New values	Year	Authors
M_M/M_E	**1.23000345(5)**$\cdot 10^{-2}$	**1.23000371(4)**$\cdot 10^{-2}$	**2007**	**Standish**
$M_\odot/M_V$	**4.0852371(6)**$\cdot 10^{5}$	**4.08523719(8)**$\cdot 10^{5}$	**1999**	**Konopliv et al.**
$M_\odot/M_{Ma}$	**3.098708(9)**$\cdot 10^{6}$	**3.09870359(2)**$\cdot 10^{6}$	**2006**	**Konopliv et al.**
$M_\odot/M_J$	**1.0473486(8)**$\cdot 10^{3}$	**1.047348625(17)**$\cdot 10^{3}$	**2003**	**Jacobson**
$M_\odot/M_{Sa}$	**3.497898(18)**$\cdot 10^{3}$	**3.4979018(1)**$\cdot 10^{3}$	**2006**	**Jacobson et al.**
$M_\odot/M_P$	**1.3521(15)**$\cdot 10^{8}$	**1.36578(32)**$\cdot 10^{8}$	**2007**	**Tholen et al.**
$M_\odot/M_{Eris}$		**1.191(14)**$\cdot 10^{8}$	**2007**	**Brown et al.**

The mass of (15) Eunomia by
A.Vitagliano, R.M.Stoss; O.Kochetova; I.Baer, S.R.Chesley:
$(1.64 \pm 0.06) \cdot 10^{-11} M_{\odot}$

Table 6. **Masses of Ceres, Pallas and Vesta in** $10^{-11} M_{\odot}$

Ceres	Pallas	Vesta	Year	Authours
5.0 ± 0.2	1.4± 0.2	1.5 ± 0.3	1989	Standish & Hellings
4.796 ± 0.085			1992	Sitarski & Todororovic
4.62 ± 0.07		1.396 ± 0.043	1995	Sitarski & Todororovic
4.64	1.05	1.34	1995	Standish et al.
4.35 ± 0.05	1.60 ± 0.04	1.52 ± 0.09	1997	Hilton
4.759 ± 0.023			1998	Viateau & Rapaport
4.70	1.00	1.30	1998	Standish
4.39 ± 0.04	1.59 ± 0.05	1.69 ± 0.11	1999	Hilton
4.70 ± 0.04	1.21 ± 0.26	1.36 ± 0.05	2000	Michalak
	1.17 ± 0.03		2001	Goffin
		1.306 ± 0.016	2001	Viateau & Rapaport
4.76 ± 0.02	1.08 ± 0.04	1.35 ± 0.02	2000	Standish
4.81 ± 0.01	1.00 ± 0.01	1.36 ± 0.01	2001	Pitjeva
4.69 ± 0.01	1.05 ± 0.01	1.36 ± 0.01	2003	Standish
4.753 ± 0.007	1.027 ± 0.003	1.344 ± 0.001	2005	Pitjeva
4.699 ± 0.028	1.026 ± 0.028	1.358 ± 0.016	2006	Standish, Konopliv et al.
4.736 ± 0.026			2007	Kovacevic & Kuzmanovski
4.75 ± 0.03	1.06 ± 0.13	1.34 ± 0.01	2007	Baer & Chesley

Table 7. **Masses of Ceres, Pallas and Vesta proposed to NSFA**

Object	Previous values	New values
$M_{Ceres}/M_{\odot}$	$\mathbf{4.39(4)}\cdot 10^{-10}$	$\mathbf{4.72(3)}\cdot 10^{-10}$
$M_{Pallas}/M_{\odot}$	$\mathbf{1.59(5)}\cdot 10^{-10}$	$\mathbf{1.03(2)}\cdot 10^{-10}$
$M_{Vesta}/M_{\odot}$	$\mathbf{1.69(11)}\cdot 10^{-10}$	$\mathbf{1.35(2)}\cdot 10^{-10}$

The value of the Astronomical Unit

DE405: 149597870691/299792458=499.0047838061
Standish, 2005: 149597870698/299792458=499.0047838295
Pitjeva, 2005: 149597870696/299792458=499.0047838228
For NSFA: $\tau_A = $ **499.004783826(10) [SI seconds]**
for the TDB coordinate system

$$\mathrm{TDB} = K^{-1}\,\mathrm{TCB}\,, \qquad K = (1 - L_B)^{-1}$$

To distinguish between TDB and TCB values let us mark TCB values by *, with SI units used.

$$a^* = Ka\,, \qquad v^* = v\,, \qquad (GM_S)^* = K(GM_S).$$

a) Brumberg and Simon, Fukushima:

$M_S^* = KM_S\,, \qquad A^* = KA\,, \qquad \chi^* = \chi,$ **where 1AU=χ^*km**

all the formulae are valid both in SI and AS units

b) Standish:

$$M_S^* = M_S = 1\,, \qquad A^* = A = 1\,, \qquad \chi^* = K^{1/3}\,\chi$$

$$a^* = K^{2/3}\,a\ [\mathrm{AU}], \qquad v^* = K^{-1/3}\,v\ [\mathrm{AU/day}]$$

I think that the constant τ_A should be followed by "the TDB coordinate system".

For the TCB coordinate system one from the above two variants a) or b) should be chosen.

Table 4. The formal standard deviations of elements of the planet orbits

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

Planet	a	$\sin i \cos \Omega$	$\sin i \sin \Omega$	$e \cos \pi$	$e \sin \pi$	λ
	[м]	[mas]	[mas]	[mas]	[mas]	[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	839	4.895	4.219	0.399	0.415	2.021
+ s 1 — 4	616	2.419	2.166	0.313	0.362	1.467
Saturn	10518	14.873	14.676	7.677	7.334	16.658
+ s 3 — 9	4256	3.061	4.117	3.900	2.959	3.501
Uranus	42030	4.455	6.454	5.349	3.665	7.982
+ s 3,4	40294	4.440	6.276	5.057	3.635	7.509
Neptune	489930	4.564	8.958	14.015	19.644	26.123
+ s 1	463307	4.411	8.520	13.115	18.740	24.484
Pluto	3412734	6.790	15.662	80.870	38.847	43.554

The value of the Astronomical Unit and its the formal deviation:

$$\mathbf{AU} = 149597870695.3 \pm 0.1 \ \mathbf{m}.$$

Table 5. Large trans–Neptunian objects

Name	a [AU]	e	i [^{o}]	D [km]	$GM_i/GM_\odot$ [10^{-10}]
Pluto+Charon	39.48	0.25	17.14	2390	73.96
2003 UB_{313}	67.67	0.44	44.18	2755	99.09
Sedna (90377)	523.45	0.85	11.93	1700	19.41
2003 EL_{61}	43.34	0.19	28.19	1617	21.15
2005 FY_9	45.74	0.15	29.00	1500	15.99
Quaoar (50000)	43.09	0.04	8.00	1260	9.48
2002 TC_{302} (84522)	55.49	0.30	35.05	1200	8.19
Varuna (20000)	43.16	0.06	17.15	1040	2.96
Orcus (90482)	39.39	0.22	20.52	900	3.45
Ixion (28978)	39.31	0.25	19.70	890	3.34
1996 TO_{66} (19308)	43.60	0.12	27.33	850	2.91
2002 UX_{25} (55637)	42.85	0.14	19.41	840	2.80
2002 TX_{300} (55636)	43.60	0.13	25.83	810	2.51
2002 AW_{197} (55565)	47.51	0.13	24.31	790	2.34
Chaos (19521)	46.13	0.11	12.00	740	1.92
1999 TC_{36} (47171)	39.63	0.23	8.42	740	1.92
2003 AZ_{84}	39.71	0.17	13.54	730	1.84
2002 MS_4	41.65	0.15	17.69	730	1.84
1995 SM_{55} (24835)	42.15	0.11	26.96	700	1.63
2004 GV_9 (90568)	41.90	0.08	22.03	700	1.63

The total shift of the barycenter of the solar system due to the 19 largest trans-Neptunian objects is 6140 m within the lifetime of GAIA (2011-2020).

For the time interval 1913–2020 the differences of positions of planets for two ephemerides (standart and with the addition of trans–Neptunian objects) are the order of magnitude less than the formal standard deviations of elements of the planet.

It wasn't found the difference of residuals for these ephemerides after adjusting them to the present set of observational data.

TDB and TCB time-base ephemerides

The the version of the EPM ephemerides was constructed in TCB time scale, however the conversion to TCB time scale could not and did not allow greater accuracy of ephemerides and adjusted parameters.

There are different versions of conversion to TCB ephemerides proposed by Brumberg and Standish.
The first 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.
The second version retains the same numerical value in SI units for the heliocentric constant $GM_{\odot}$ in terms of TDB and TCB.

This situation is rather confusing, especially for different users. In any case, some official recommendation should be adopted before recommending the TCB time ephemerides for public.

The EPM ephemerides has been the base for the Russian "Astronomical Yearbook" since 2006.

the EPM ephemerides are available to outside users:
ftp://quasar.ipa.nw.ru/incoming/EPM2004