PLANETARY AND LUNAR EPHEMERIDES INPOP10A

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ABSTRACT. The INPOP10a planetary and lunar ephemeris has several improvements compared to the previous INPOP solutions. No big change was brought in the dynamics but improvements were implemented in the fitting process, the data sets used in the fit and in the general features of the solution. A specific characteristic of INPOP10a is the fit of the mass of the Sun instead of the astronomical unit. Determinations of PPN parameters as well as adjustments of the Sun J_2 and of asteroid masses are also presented. As for INPOP08, INPOP10a provides to the user, positions and velocities of the planets and of the Moon and TT-TDB Chebychev polynomials at `http://www.imcce.fr/inpop`.

1. THE DATA SETS

A detailed description of the data set used for the construction of INPOP10a can be found in (Fienga et al. 2010). Several data sets have been added since INPOP08. The global distribution of the data used for the INPOP fit has changed its balance compared to INPOP06: now, more than 56% of the planetary observations are deduced from the tracking data of spacecrafts including range, VLBI angular positions and flyby normal points. The statistics of the obtained postfit residuals as well as the number of points and their distribution in time are presented in table 1.

For Mercury, two normal points deduced from the Mariner tracking data in 1974 and 1975 have been provided by JPL (Folkner 2010) and three corrections to Mercury positions have been obtained during the Messenger flybys of Mercury in 2008 and 2009. These five points change drastically our knowledge of the Mercury orbit. Until now, only direct radar ranging on the Mercury surface were available with an accuracy of about 800 meters. For Mars and Venus, like with INPOP08, tracking data of MEX and VEX missions provided by ESA (Morley 2009, Morley 2010) are used in the fit as described in Fienga et al. (2009). To the Saturn Cassini normal points provided by JPL over the 2005 to 2007 period and used in INPOP08, are added VLBI observations of the spacecraft (Jones et al. 2010) with an accuracy better than few milliarcseconds (mas). Flybys data of Jupiter, Uranus and Neptune obtained during several missions (Pioneer 10 and 11, Viking 1 and 2, Ulysses and Cassini) are also added, provided by Folkner (2009). These observations improve the estimations of the geocentric distances to the outer planets while no observation of that type were used in INPOP06 and INPOP08 adjustments. New optical data obtained from 2000 to 2008 with the Flagstaff Astrometric Scanning Transit Telescope are also added for Uranus, Neptune and Pluto. Stellar occultations (Sicardy 2009) are taken into account in INPOP10a by the use of measured offsets in topocentric (α, δ).

A detailed description of the fit procedure for the Moon orbit and libration and of the Lunar Laser Ranging observations used for the fit is presented by (Manche et al. 2010) in this volume.

2. FITTING PROCEDURE

In INPOP10a, the value of the AU is fixed to the value given in the IERS2003 convention. The GM of the Sun is fitted to the observations with the initial conditions of planets, the densities of the asteroids and the oblateness coefficient J_2 of the Sun. Values of the fitted parameters are given in table 2. (Konopliv et al. 2010) presents also a value of the GM of the Sun fitted on Mars data only when the value obtained with INPOP10a is fitted over all the available data including flyby points of Mercury. This difference explains the bigger uncertainty of (Konopliv et al. 2010) estimation. The two estimations are however consistent at 2 sigmas.

The selection of asteroids modeled in INPOP10a is based on Kuchynka et al. (2010).

Table 1: Statistics of the INPOP10a and INPOP08 postfit residuals.C.n.p stands for Cassini normal points, Mess. for Messenger mission and all the residuals in angular quantities are given in milliarcseconds.

Planet Type of Data		INPOP08 mean ± 1σ	INPOP10a mean ± 1σ	Planet Type of Data		INPOP08 mean ± 1σ	INPOP10a mean ± 1σ
Mercury				Saturn			
Direct range [m] (462)	1965-2000	30 ± 842	7 ± 866	C.n.p. ra (31)	2004-2007	1.5 ± 4	0.7 ± 4
Mariner range [m] (2)	1974-1975	-1000 ± 305	-28 ± 85	C.n.p. de (31)	2004-2007	7.0 ± 7	6.5 ± 7
Mess. ra (3)	2008-2009	1.1 ± 0.7	0.4 ± 1.2	C.n.p. range [m]	2004-2007	0.5 ± 22	0.0 ± 17
Mess. de (3)	2008-2009	2.0 ± 1.9	1.9 ± 2.1	VLBI ra (10)	2004-2009	0.3 ± 0.7	0.0 ± 0.6
Mess. range [m] (3)	2008-2009	52 ± 619	-0.6 ± 1.9	VLBI de (10)	2004-2009	-1.2 ± 2.0	0.1 ± 0.4
Venus				Opt. ra (7824)	1914-2008	-16 ± 305	-16 ± 305
Direct range [km] (489)	1965-2000	0.5 ± 2.3	0.5 ± 2.2	Opt. de (7799)	1914-2008	-7 ± 276	-9 ± 276
VEX range [m] (22145)	2006-2010	1.6 ± 4.4	-0.2 ± 3.9	Uranus			
VLBI (22)	1990-2007	2 ± 2	2 ± 2.5	flybys ra (1)	1986	-90	-30
Mars				flybys de (1)	1986	-36	-7
MGS range [m] (10474)	1998-2008	-0.9 ± 1.6	0.5 ± 1.9	range [km] (1)	1986	1139	0.080
MEX range [m] (24262)	2006-2010	-3.5 ± 2.0	0.0 ± 1.7	Opt. ra (4145)	1914-2008	-44 ± 278	-27 ± 290
Path range [m] (90)	1997	6.8 ± 12.5	-5.0 ± 5.0	Opt. de (4130)	1914-2008	-38 ± 339	-11 ± 338
Vkg range [m] (1256)	1976-1982	-27.4 ± 19.0	-5.7 ± 35.0	Neptune			
VLBI (96)	1989-2007	0.5 ± 0.5	-0.0 ± 0.4	flybys ra (1)	1989	-88	-11
Jupiter				flybys de (1)	1989	-48	-10
flybys ra (5)	1974-2000	48.0 ± 40.0	6 ± 5	range [km] (1)	1989	2305	0.004
flybys de (5)	1974-2000	-10.0 ± 50	-13 ± 18	Opt. ra (4340)	1914-2008	-32 ± 282	2 ± 281
range [km] (5)	1974-2000	-27± 55	-0.6 ± 1.6	Opt. de (4320)	1914-2008	-36 ± 335	2 ± 330
VLBI (24)	1996-1997	4 ± 11	0.2 ± 11	Pluto			
Opt. ra (6216)	1914-2008	20 ± 304	-26 ± 304	occ. ra (13)	2005-2009	-6 ± 46	-1 ± 47
Opt. de (6082)	1914-2008	-44 ± 313	-54 ± 303	occ. de (13)	2005-2009	16 ± 30	-2 ± 19
				Opt. ra (2449)	1914-2008	353 ± 926	38 ± 629
				Opt. de (2463)	1914-2008	-22 ± 524	17 ± 536

Table 2: Values of planetary ephemerides parameters. The (F) indicates a fixed value. The equivalent value of AU deduced from the estimation of the GM⊙ in INPOP10a and (Konopliv et al. 2010) are given in the line labelled "AU from GM⊙". Only the three biggest asteroid masses fitted in INPOP10a are given in this table.

	INPOP08	INPOP10a	(Konopliv et al. 2010)
EMRAT	(81.30054 ± 0.00005)	(81.3005700 ± 0.0000010)	(81.3005694 ± 0.0000015)
$J_{2\odot}$	(1.82 ± 0.47) × 10^{-7}	(2.40 ± 0.25) × 10^{-7}	
GM⊙ [$km^3. s^{-2}$]	132712440017.98700 ± 50 (F)	132712440055 ± 1	132712440042 ± 10
AU [m]	149597870699.2 ± 0.11	149597870691.0 (F)	
AU [m] from GM⊙		149597870704.9 ± 0.3	149597870700.0 ± 3

	INPOP08	INPOP10a	(Konopliv et al. 2010)	Baer (2010)
Ceres [$10^{12} \times M_\odot$]	465.8 ± 4.5	475.836 ± 2.849	467.900 ± 3.250	475.500 ± 4.755
Pallas [$10^{12} \times M_\odot$]	107.6 ± 10.0	111.394 ± 2.808	103.440 ± 2.550	106.000 ± 1.060
Vesta [$10^{12} \times M_\odot$]	139.2 ± 15.0	133.137 ± 1.683	130.970 ± 2.060	133.070 ± 0.266

PPN parameter fixed	PPN estimated	INPOP08	INPOP10a	(Konopliv et al. 2010)
(γ -1) = 0	(β -1) × 10^{-4}	(0.75 ± 1.25)	(-0.5 ± 1.5)	
(γ -1) = (0.21 ± 0.23) × 10^{-4}	(β -1) × 10^{-4}		(-0.1 ± 1.9)	(0.4 ± 2.4)
(β -1) = 0	(γ -1) × 10^{-4}		(0.6 ± 1.0)	(1.8 ± 2.6)

$\dot{\varpi}_{sup}$	INPOP08	INPOP10a	Pitjeva 2009	Pitjeva 2010
Mercury [$mas.cy^{-1}$]	-10 ± 30	0.2 ± 3	-3.6 ± 5	-4 ± 5
Saturn [$mas.cy^{-1}$]	-10 ± 8	0 ± 2	-6 ± 2	-10 ± 15

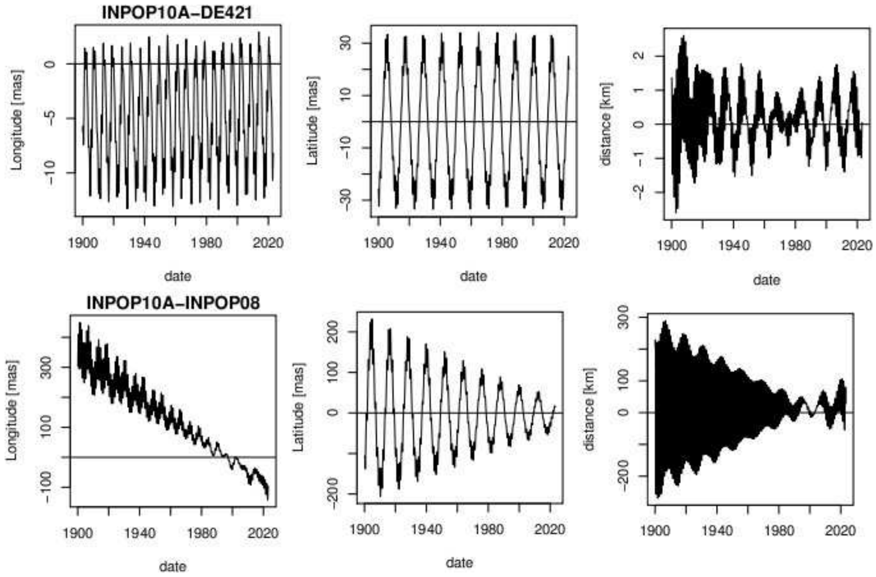

Figure 1: Comparison of Jupiter geocentric longitudes, latitudes and distances estimated with INPOP10a, DE421, INPOP08

The perturbations of 24635 asteroids have been taken into account using for most of them an averaging of their perturbations by a ring with fixed physical characteristics and for 161 of them, individual perturbations (see Kuchynka et al. 2010). Based on a study of the correlations between the asteroids, we found 30 asteroids among the most perturbing objects highly correlated with each others. In order to decrease the uncertainties on the mass estimations, we fixed 15 asteroid masses to values well determined by other methods (close encounters, binary) extracted from Baer (2010). Besides these fixed values, we estimate 146 asteroid masses using a BVLS algorithm (Lawson and Hanson, 1995) with large constraints on the densities.

We used the mass of planets provided by the IAU 2009 CBE lists (Luzum 2010).

The Moon orbit and libration are fitted over LLR observations. See in this volume (Manche et al. 2010) for more details. The final version of INPOP10a was obtained after an iterative process between planetary fit and Moon fit.

3. RESULTS AND APPLICATIONS

The table 1 gives the planetary postfit residuals obtained with INPOP08 and INPOP10a. Some of the data sets used in INPOP10a were not used in the INPOP08 adjustment: this explains some differences between the two columns of table 1. Furthermore, we obtain with INPOP10a an important improvement of the Jupiter orbit compared to INPOP08, as one can see on Figure 1. The addition of the flyby points of outer planets in the data used for the fit helps to reduce the differences between INPOP and the JPL DE ephemerides.

In Figure 2 are presented the asteroid masses obtained with INPOP10a compared to values found in the literature, ranked by their impact on the Earth-Mars distances over the 1990 to 2010 period. The major sources of comparisons are the values obtained with DE421 (Folkner et al. 2008), DE423 (Konopliv et al. 2010) and other type of estimations gathered in Baer (2010) with realistic errorbars estimated by Kuchynka (2010). It then appears clearly that the estimations for the most perturbing objects are quite consistent when the estimations of the weak perturbing objects show bigger discrepancies. For the asteroids inducing perturbations up to 10 meters, the differences in GMs are usually below 1-sigma or very close to 1-sigma except for 52 Europa. For this asteroid, which induced a maximum of 10 meters on the Earth-Mars distances, the errorbars are very large for all the determinations based on planetary ephemerides: we thus conclude to a bad determination of this mass based on the present interval of available data.

Table 3: Angles of rotation deduced from adjustment of rotation matrices following equations 1 and 2. The angles are given in mas and the uncertainties are the formal 1-sigma deduced from the least squares. [1] stands for (Folkner et al. 1994) and [2] for (Standish 1998)

	θ	η	ζ
	mas	mas	mas
DE405 → ICRF	6 ± 5	15 ± 11	-4 ± 6
INPOP08 → ICRF	4 ± 5	15 ± 11	-2.5 ± 6
INPOP10a → ICRF	4 ± 5	15 ± 11	-3.0 ± 6
DE200 → ICRF	6 ± 5	28 ± 11	9 ± 6
DE200 → ICRF [1]	2 ± 2	12 ± 3	6 ± 3
DE200 → DE405 [2]	1 ± 2	14 ± 3	10 ± 3

Table 2 gives the obtained values for the mass of the Sun, the Sun J_2, the Earth-Moon mass ratio and the three biggest asteroid masses and the interval of sensitivity of data to modifications of PPN β with γ equal to 1 or with γ equal to the value obtained by the Cassini experiment (Bertotti et al. 2000), and of PPN γ with β equal to 1. The results obtained for both modified parameters are presented on Figure 3. Supplementary advances in the Mercury and Saturn perihelia have also been tested. These results were obtained based on the method presented in Fienga et al. (2010). We computed several fits for different values of the PPN parameters (β, γ or both) or supplementary advances in perihelia with a simultaneous fit of initial conditions of planets, mass of the Sun and asteroid densities. The given intervals correspond to values of parameters inducing changes in the postfit residuals below 5% compared to INPOP10a postfit residuals. For the advances of perihelia, the estimations based on INPOP10a show the clear incompatibility of a significant supplementary advance in Mercury or Saturn orbits and the observations used in the INPOP10a adjustment. This conclusion is due to the densification of very accurate Cassini observations around Saturn and to the Mercury flybys points used in INPOP10a. As one can see in table 2, the obtained PPN intervals are compatible with each other with a better accuracy of INPOP10a due to the use of Messenger normal points. On the plots of the Figure 3, are plotted the PPN (β,γ) zones for which postfit residuals have been estimated. On the left hand side, each square is a planetary solution fitted to observations as INPOP10a but built with the corresponding values of (β, γ). In the center, the red area limits the region of (β, γ) for which all the postfit residuals have variations to INPOP10a residuals smaller than 5 %. In the gray zone, all but the Mercury flyby residuals have residuals smaller than 5 %. Then limits with specific denominations are given in order to specify which observations have their residuals modified by more than 5 % from their INPOP10a values. The right hand side plot is a zoomed and densified representation of the left hand plot. As it appears clearly on Figure 3, each type of data used in the fit gives indeed different limits for the (β, γ) variations. These limits reflect more the weighting of the data than the real sensitivity of these data to (β, γ). However, it is interesting to note the strong constraint brought by the Mercury flybys data on the right hand side plot. In the dark read area, the possible variations acceptable for all the residuals including the Mercury points are compatible with the best estimations found in the literature and obtained with different methods (LLR, Cassini experiment, VLBI astrometry).

In this volume will be presented in details the method implemented to use millisecond pulsar observations, radio timing and VLBI, for reference frame ties. Based on radio timing data obtained at the NRT (Desvignes 2010) and VLBI astrometry extracted from (Chatterjee et al. 2009) and (Deller et al. 2009), rotation matrices between the JPL DE200, DE405, INPOP08 and INPOP10a frames and the ICRF were estimated and presented in table 3. These estimations are consistent with values obtained for DE200 (Folkner et al. 1994) and DE405 (Standish 1998). The uncertainties are indeed important and are induced by a lack of sources with a mas-level accuracy. Only four pulsars observed by the NRT have at the present time the mas level astrometry for both techniques, VLBI and radio timing. Thanks to new VLBI observations of millisecond pulsars planned for next months for the FERMI mission follow-up, the sample should be increased rapidly.

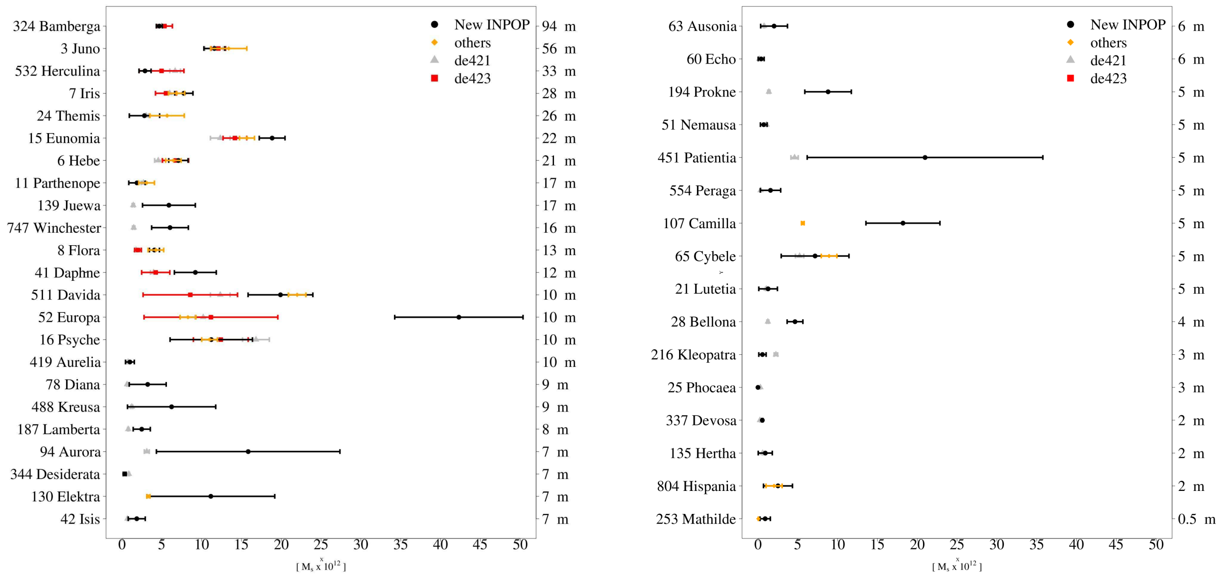

Figure 2: Comparisons of the first 23 asteroid masses given in 10^{12} solar mass (x-axis) estimated by different authors and ranked by their impact on the Earth-Mars distances over 1990 to 2010 (y-axis). The mass estimations of the 3 biggest asteroids and perturbers Ceres, Pallas and Vesta are given in table 2. "others" stands for estimations gathered by Baer (2010).

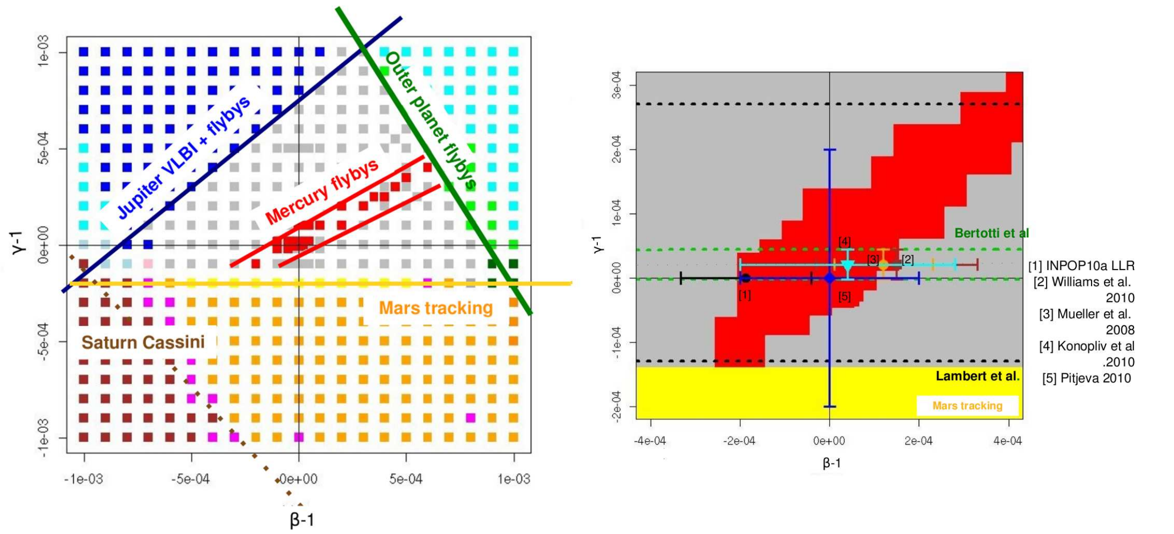

Figure 3: Variations of postfit residuals obtained for different values of PPN β (x-axis) and γ (y-axis). References on the right hand side plot label values of (β, γ) obtained in the literature.

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