IMCCE PLANETARY EPHEMERIDES: PRESENT AND FUTURE

A. Fienga, J. Laskar, J.L. Simon, H. Manche, M. Gastineau
Observatoire de Paris, IMCCE / CNRS UMR 8028, 77 Av. Denfert Rochereau, 75014 Paris, France

ABSTRACT

We present here the new planetary ephemerides developped at the IMCCE. Two types of ephemerides are under development. 1) The analytical solution VSOP2004: Based on the previous VSOP solutions, this VSOP2004 ephemerides has its accuracy drastically improved compared to VSOP2002. An accuracy of about few meters for the inner planets is obtained. 2) The numerical integration INPOP: Developed to improve the short term ephemerides and for the prolongation of the long term astronomical solutions for the paleoclimate studies, INPOP is the first numerical ephemerides developed at the IMCCE. We present here the first-step solution fitted to spacecraft and optical observations and the lunar solution fitted to DE405.

Key words: Celestial Mechanics, Ephemerides.

1. INTRODUCTION

Because of the NASA interplanetary missions, the Jet Propulsion Laboratory was entrusted with the development and the improvement of planetary ephemerides and produced over the years many solutions combining the best theories and the most recent observational techniques, like the range measurements or VLBI tracking. We stress in particular the two last published and available solutions: DE403 (Standish et al. 1995) and DE405 (Standish 1998). Besides the JPL numerical solutions, the IMCCE developed until the early 1980's, analytical solutions of the planetary motion. New developments of numerical solutions have also begun since 2003.

Among the IMCCE analytical solutions, we can highlight the VSOP (Variations Séculaires de l'Orbite des Plantes) solutions of the eight major planet motions (Bretagnon 1982, Bretagnon & Francou 1987, Moisson & Bretagnon 2001). The goal of these solutions was to give precise ephemerides over several thousand years for the inner planets and over 1000 years for the outer planets. The relativistic time scale used in VSOP solutions is TDB. A new version of VSOP, called VSOP2004 (Fienga & Simon 2004), has been constructed by introducing the following improvements. We added the perturbations of Pluto on the outer planets taken from the TOP solution (Simon 2004). We computed the perturbations brought about by the solar J2 on the inner planets as well as the perturbations on all the planets induced by 300 main-belt asteroids (the same as in DE405) based on a simple analytical form. We fitted the integration constants by comparison to the JPL numerical integration DE405 over [1890, 2000].

Another aspect of the IMCCE planetary ephemerides evolution is the development of a new numerical solution of the planet motion called INPOP (Intégration Numérique Planétaire de l'Observatoire de Paris). This project arose from the need for accurate short term ephemerides for the analysis of Earth-based and space mission observational data, and from the necessity for short term ephemeris improvements for the prolongation of the long term astronomical solutions for the paleoclimate studies of the Earth and Mars over several millions of years. Extending the astronomical solutions from 40 Myr (Laskar et al. 2004a, b) to 60 Myr thus corresponds to a gain of two orders of magnitude on the precision of the short time ephemeris. IMCCE decided to develop a new numerical planetary ephemerides adjusted to space mission tracking observations, accurate on a very short period of time, but also very stable on a very long interval (several million years).

In a preliminary INPOP version, an Adams-Cowell integrator, based on the work of Moshier (1992), was used for test and development. At the present time, a second step of development is taking place, with a complete rewriting in C of the programs, and the use of alternate integrators, with in particular an extrapolation method that is well adapted for very high accuracy in quadruple precision. The introduction of the symplectic integration that was already used in Laskar et al. (2004a,b) will be made in a following step, after many adjustments of the planetary and lunar models are made.

Planetary perturbations are computed as described in Newhall et al. (1983) and we added the perturbations induced by the asteroids and by the Sun oblateness. Concerning the asteroids, in a preliminary version (the solution presented here), the solution is based on the same type of modelling as in DE405 (Ceres, Pallas and Vesta orbits integrated completely but separately from the main planetary integration and 297 asteroid perturbations estimated from mean orbits). Now, a new solution is built

Table 1. DE405 and INPOP Moon parameters.

	DE405	INPOP
C/MR^2	0.395295198960948	0.395295198960948
C_{20}	-2.045386×10^{-4}	-2.045318×10^{-4}
τ_{21}	1.29090×10^{-2}	1.78648×10^{-2}
τ_{22}	6.9418×10^{-3}	8.9324×10^{-3}

with a complete integration of 300 asteroid orbits included in the main planetary integration. In the near future, tests will be performed to establish a new list of perturbing minor planets. TDB is the time scale used in INPOP. The INPOP integration of the Moon takes into account, PPN interactions with all planets and asteroids included (see Newhall et al. 1983), the interaction between the figure of a non-rigid Earth and the Moon and Sun, considered as a point-mass bodies, the interaction between a non-rigid Moon and the Earth and Sun and the interaction between the figure of the Earth and those of the Moon.

2. COMPARISONS OF VSOP2004 AND INPOP TO DE405 AND OBSERVATIONS

2.1. Comparisons to DE405

For Mercury and Venus, one notices the differences induced by the asteroid perturbation models VSOP2004 and INPOP which include 300 asteroid accelerations in the computation of the forces upon all the planets, including Mercury and Venus orbits. DE405 doesn't. Analytically and numerically, it was estimated that such an introduction induces drifts in the inclination, in the argument of perihelion and in the ascending node of the perturbed planet orbit. Over a 30-years period and compared to DE405, Mercury and Venus distances are given with an accuracy better than 20 meters with VSOP2004 and 5 meters with INPOP.

For Mars and the Earth Moon Barycentre (EMB), the DE405, VSOP2004 and INPOP orbits are computed with different models of asteroid perturbations. So the comparisons between these ephemerides include effects resulting from the different asteroid models. VSOP2004 gives heliocentric distances with an accuracy, compared to DE405 over 30 years, better than 100 meters for Mars and 10 meters for the EMB. Over 30 years, INPOP gives an heliocentric distance accuracy compared to DE405 better than 50 meters for Mars and 5 meters for the EMB. For the Earth, over 1 century, the accuracy of Solar System barycentric distances in INPOP compared to DE405 is better than 20 m and the accuracy of Solar System barycentric radial velocities versus DE405 better than 0.15 meters per day. For the Gaia mission, an accuracy of 1 km and 15 meters per day is required for the barycentric distances and radial velocities respectively.

For Saturn, Uranus, Neptune and Pluto, VSOP2004 and INPOP have a good accuracy compared to DE405 at the VLBI observations precision (few mas in longitude and latitude). For Jupiter, the differences in longitude between INPOP and DE405 are about 3.5 mas over 1 century but about only 0.2 mas over 30 years. Thus, INPOP has a very good accuracy for all the outer planets on its adjustment interval.

Table 2. Observations used to fit INPOP. Column 4 indicates from which observatory or space mission the observations were produced: UNCBP meaning USNO, Nikolaev, CAMC, Bordeaux, MPC observatories; GA is for Goldstone, Arecibo radar antennas; and MGSMO is for MGS, Mars Odyssey missions. Column 5 gives the a priori sigma for each type of observations. In many cases, this sigma is seen as the fit weight of the solution.

Planet	Type of Data	Time Interval	Sources	σ
Mercury	Radar	1972-1997	GA	1 km
Venus	Radar	1970-1990	GA	1 km
	VLBI	1991-1994	Magellan	1 mas
Mars	radar	1999-2003	MGSMO	10 m
	VLBI	2001-2003	MGSMO	1 mas
Jupiter	VLBI	1996-1997	Galileo	1 mas
	Optical	1970-2004	UNCBM	$0.5''$
Saturn	Optical	1970-2004	UNCBM	$0.5''$
Uranus	Optical	1970-2004	UNCBM	$0.5''$
Neptune	Optical	1970-2004	UNCBM	$0.5''$
Pluto	Optical	1988-2004	UNCBM	$0.5''$

VSOP and INPOP show again that their differences to DE405 are smaller than the differences between DE405 and the previous JPL solution DE403, meaning that the analytical and numerical IMCCE solutions are comparable to the JPL ephemerides.

For the Moon, over 30 years, the differences between DE405 and INPOP in geocentric longitudes and latitudes are smaller than 5×10^{-4} arcsec, and in geocentric distances, the differences are limited to 6 mm. This means that our INPOP lunar solution is quite similar the DE405/LE405 one. To obtain these results, the parameters presented in Table 1 have been refitted to DE405, as well as the initial conditions of the geocentric Moon. The value of C/MR^2 is not given in DE405. But it can be calculated from other Moon parameters C_{22}, β and γ. The DE405 value of C_{20} ($= -$J2) has no physical significance, but is then correct by a function of the mean semi-major axis. τ_{21} and τ_{22} are explicitely given by the JPL. These values have been modified to correct a quadratic trend in the INPOP Moon's longitude.

2.2. Comparison to Observations

After having built the INPOP solution we presented above, we fitted this solution to observations (see Table 2). The set of observations we used is different from the set used by JPL to fit the DE405 solution. More recent data were added, especially the VLBI and radar tracking data of MGS and Mars Odyssey space missions, and the Magellan and Galileo VLBI data. Table

Table 3. INPOP Before (Column 4) and after fit (Column 6) residuals for each type of observations. Column 3 gives the number of observations N used in the fit and in the residual computations. Column 5 gives the residuals obtained with the DE405 solution. For optical observations, the residuals are given respectively in right ascension and declination $(\alpha;\delta)$. The given uncertainties are given at 1-sigma

Planet	Type of Data	N	Before fit INPOP	DE405	After fit INPOP
Mercury	Radar	247	− 449.5±928 m	−548.0±974 m	−95.6±784 m
Venus	Radar	212	−688.0±2009 m	−6604.0±7291 m	−460.0±1914 m
	VLBI	18	1.1±3 mas	1.6±3 mas	1.0±3 mas
Mars	Radar	5241	−42.8±137 m	−38.1±348 m	−0.2±22 m
	VLBI	44	−1.7±1 mas	−1.0±0.8 mas	−1.6±1.5 mas
Jupiter	VLBI	24	−1.2±10 mas	−1.0±10 mas	1.0±10 mas
	Optical	3147	(−83±253; −31±169) mas	(−82±250; −28±163) mas	(−11±255; −31±169) mas
Saturn	Optical	3757	(−46±197; −35±162) mas	(−42±188; −40±153) mas	(−3±187; −3±160) mas
Uranus	Optical	1815	(16±203; 21±250) mas	(17±204; 23±250) mas	(0.4±202; 1±250) mas
Neptune	Optical	2072	(5±176; 29±224) mas	(5±176; 30±223) mas	(0.2±175; 0.2±223) mas
Pluto	Optical	1024	(−7±170); −18±169) mas	(−7±170; −19±170) mas	(0.1±170; −0.3±169) mas

3 gives the accuracy obtained by our solution directly compared to the observations before and after the fit of the planet initial conditions, the masses of the 3 big asteroids (Ceres, Pallas, Vesta) and the three main taxonomic density classes. The asteroid related fitted values are (0.1392±0.05) × 10^{-12}, (0.2725±0.02) × 10^{-13} and (0.3773±0.03) × 10^{-13} AU^3/day^2 for the mass of Ceres, Vesta and Pallas respectively. The obtained densities are in g/cm^3 for the C class, 1.5±1.0, for the S class 2.3±1.0 and for the M class 5.01±0.2. These values are quite close to the published one (Standish 1995, 1998, 2004).

Based on Table 3, one can see that for Mercury and Venus, the INPOP fitted solution gives better results than DE405. The residuals between radar and VLBI observations and INPOP are greatly decreased compared to those obtained with DE405. This is due to a better modelling of the asteroid perturbations over these two planets. In DE405, no perturbation induced by asteroids is taken into account in the Venus and Mercury solutions of motion. In our solution, such perturbations are included. One can also see the big decrease of the outer planet residuals. This could be explained by the fact that several observations used in our fit were not implemented in the DE405 fit (Standish 1998). For Mars, the VLBI residuals are not improved by the INPOP fit. Furthermore, despite an important postfit improvement, the MGS and Mars Odyssey postfit residuals still face persistant systematic effect. These two points can be directly explained by the mis-modelling of the asteroid perturbations on the Mars orbit, even if the INPOP modelling is a improvement compared to the one used in DE405.

3. PROSPECTIVES

We have seen that VSOP2004 shows differences to DE405 smaller than the differences between DE405 and the previous JPL solution DE403, meaning that the analytical IMCCE solution is comparable to the JPL ephemerides.

Regarding the analytical solution, improvements by iteration of the last VSOP2004 solution would give an increase of the solution accuracy of about a factor 2 in the comparisons to DE405. A fit of VSOP2004 to INPOP will be done as soon as INPOP will been entirely fitted to observations.

For INPOP, several improvements are planned:

1. The dynamical model of the Moon has to be improved, especially the libration part. Fit to LLR data will be initiated.
2. We plan to introduce the symplectic integrator developed by Laskar & Robutel (2001) in order to initiate the construction of very long and stable ephemerides.
3. Finally, the INPOP fit to observations will continue. Investigations related to more developed models of asteroid perturbations will be done. Following Standish (2004), the MGS and Odyssey data were strongly perturbed by a set of 20 asteroids. Fit of the 20 asteroid masses was attended but despite improvements of the postfit residuals, discrepancies in the mass determinations arose, showing that no consistent solution can be built based of these data sets. This type of parameter fit has to be tested with INPOP. Until now, a list of 300 asteroids was selected by Williams (1984) and used as the main perturber list of the Mars orbit. Tests will be performed to renew this list if necessary. New sets of recent Mars spacecraft observations are necessary to obtain new information related to asteroid perturbations. Do these new data present the same systematic effect as the MGS and Odyssey data sets? Is it possible by combinations of all these data sets to obtain a consistent solution?

More generally, we plan to develop INPOP as a general framework for the analysis of all dynamical effects in the Solar System, for both orbital and rotational evolution of the planets and main satellites, with comparison and adjustment to Earth based and space mission data.

As for the requirements set by the Gaia mission, upgrades in the dynamical and relativistic models of both numerical and analytical solutions are possible. At the present time, VSOP2004 and INPOP are computed with the TDB time scale for historical reasons. It should not be a major problem for us to introduce another relativistic time scale (mainly TCB) in order to achieve a relativistic consistency between the ephemerides of the Gaia satellite and the data reduction procedure.

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