INPOP, A MILLION YEAR EPHEMERIS

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ABSTRACT. In the INPOP ephemeris, we integrate the Earth spin evolution at the same time as the planetary orbits. This allows to extend the ephemeris over extended time span. We present here some of the preliminary results obtained over 1 Myr.

1. MOTIVATION

The reasons for extending the planetary ephemerides over several Myr arise from the correlation that is established between the variation of insolation daily received on Earth and its climatic response that is recorded in various forms in the ice caps or in the sediments (Imbrie and Imbrie, 1979). Since several decades, our group has been involved in the construction of reference solutions for paleoclimate computations .The various solutions La93, La2004, La2010 (resp. Laskar et al., 1993, 2004, 2011) that have been constructed correspond to increasing accuracy. In La93, the equations of motion and of precession were averaged. In La2004, the equations of motion were no longer averaged, and the initial conditions were obtained by a fit to DE406 over its range ($[-5000, +1000]$ yr from the present) (Standish, 1998). The length of validity of La2004 was estimated to be around 40 Myr (Laskar et al., 2004), but in order to extend further the length of validity of this long term solution, it was necessary to extend also the duration of the short time ephemeris of reference.

This was in fact one of the motivation for the construction of the INPOP ephemerides. The goal was to obtain a full scale planetary ephemeris that could be extended over at least 1 Myr, and that could then be used as a target solution for the less accurate long time ephemeris. We have thus removed in INPOP all constraints that would limit the time validity of the solution. In particular, we have not used an external polynomial formula for precession, but we have integrated the precession equations of the Earth together with its orbital elements (Fienga et al., 2008). The numerical integrator has also been specifically designed in order to reduce the roundoff error during long time integrations.

2. INPOP NUMERICAL ERRORS OVER 1 MYR

The estimate of the error in Longitude in INPOP08 (Fienga et al., 2009) is obtained by integrating INPOP one way and back over 1 Myr. Each way is about 3 months of CPU time. The results are displayed in Table 1 (left) with the differences over 10, 100, and 1000 kyr. This error that comes from the numerical integration as well as from some instability of the system can be compared to the difference of the integration of INPOP06 and INPOP08 over the same time intervals (Table 1, right). It can be observed in Table 1 that over 10 kyr, the numerical error is much smaller than the model difference (INPOP06-INPOP08). This is still true over 100 kyr.

Over 1 Myr, the situation is more involved. Indeed, for the outer planets, the numerical error (Table 1) is much smaller than the model error (Table 2), and this is also the case for the Moon. This is also the case in a lesser extent for the inner planets, except for Mars where the numerical error is larger than the model error.

This is probably due to some instability resulting from the asteroidal motions. In that case, in both computations on INPOP06 and INPOP08, this instability is present and induces a large amplification of the initial differences of model. It is then understandable that the final difference over one way and back

	Differences in INPOP08 one way and back			Differences INPOP06 − INPOP08		
	10 kyr	100 kyr	1 Myr	10 kyr	100 kyr	1 Myr
Mercury	$< 1E - 6$	0.004452	0.543	0.7	6	39
Venus	0.000107	0.117994	75.552	0.2	4	699
EMB	0.007642	0.834716	375.493	0.2	8	952
Mars	0.003620	20.916387	3905.538	0.4	42	694
Jupiter	$< 1E - 6$	0.000514	1.214	32.6	326	3304
Saturn	$< 1E - 6$	0.000116	0.466	8.1	80	769
Uranus	$< 1E - 6$	0.000102	0.669	16.0	162	1718
Neptune	$< 1E - 6$	0.000111	0.028	7.1	75	735
Pluto	$< 1E - 6$	0.000124	0.030	94.8	378	5129
Moon	0.005105	0.779816	290.251	96.1	12678	1245609

Table 1: Maximum difference in longitude (in arcsec) in INPOP08 over 10 kyr, 100 ky and 1 Myr after one way and back (left) and differences in longitude (in arcsec) between INPOP06 and INPOP08 over 10 kyr, 100 ky and 1 Myr (right). EMB is the Earth-Moon barycenter

in INPOP08, or between INPOP06 and INPOP08 are in the same range. Because of these suspected instabilities, the errors in Table 1 are somewhat larger than what could be extrapolated from Table 1 of (Fienga et al., 2008). This is largely because the step size adopted for the long integrations is here 0.09375 days, about twice larger than the step size of 0.0553409090... days retained for the short time INPOP ephemerides. Although in most cases, the model error is still much larger than the numerical error, for a better consistency, we should adopt in further computation the same step size of 0.0553409090... days for short term and long term ephemerides. The price to pay will be to double the integration time.

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3. REFERENCES

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