EPM - HIGH ACCURACY NUMERICAL PLANETARY AND LUNAR EPHEMERIDES

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Performance of complicated experiments in space and the introduction of new astrometric methods (radar ranging, lunar laser-ranging, VLBI measurements) now require planetary ephemerides of the highest accuracy. For instance errors of ranging measurements to martian landers Viking 1,2 and Pathfinder is only about 7 meters, and there are prospect to reach submeter accuracy. There are several versions of the well-known DE ephemerides Jet Propulsion Laboratory that in some degree correspond to these requirements. Another ephemerides (EPM) of the same class of accuracy are under development in the Institute of Applied Astronomy.

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 Parameterised Post-Newtonian metric for the harmonic coordinates $\alpha=0$ and General Relativity values $\beta=\gamma=1$. The various ephemerides differ mainly in the modelling of the perturbations from asteroids, and that modelling offers serious difficulties.

On this level of accuracy the ephemeris of Mars is significantly affected by the perturbations from a large number of the minor planets. In the ephemerides DE200 the perturbations from three biggest minor planets (Ceres, Vesta, Pallas) were accounted. The experience showed that fitting of the ephemerides to the lander data mentioned above is nonetheless poor. In the more advanced DE403 and DE405 ephemerides the perturbations from additional 297 asteroids were taken into account by some simplified method and the lander dataset was successfully processed.

The last version of the EPM ephemerides was produced by simultaneous numerical integration of the equations of motion of nine planets, the Sun, the Moon, lunar physical libration and 300 asteroids over a 125-year time interval (1886–2011). For the five biggest minor planets their mutual perturbations are accounted, for the other asteroids such perturbations are neglected. Since asteroid orbits computed using mean elements obtained for a long time interval differ significantly from their true orbits, therefore, it was necessary to integrate the orbits of each of the 300 asteroids. We used the lunar-planetary integrator embedded to the program package ERA [2]. Numerical integration of the equations of motion in the barycentric coordinate frame of J2000.0 has been carried out by the Everhart method of nineteenth order.

It was shown that the asteroids with masses more than $10^{-12} M_{\odot}$ noticeably affect the orbit of Mars on the level of accuracy of measurements of ranging to the martian landers. So, an attempt was undertaken to extent the list of 300 perturbing asteroids accounted in the adopted DE405 ephemerides. Several sets of masses of perturbing asteroids estimated in different ways were tested and list of the most plausible masses for 357 asteroids was derived.

It seems plausible that there exists a large number of asteroids of the main belt which are too small to be observed from the Earth, but their summary perturbating action upon the orbit of Mars is not negligible. The perturbing effects of remaining asteroids have been modelled as being caused by a circular ring in the ecliptical plane. Mass M of the ring and its radius R are considered as solved-for parameters. The estimate $M \approx 518 \cdot 10^{-12} M_{\odot}$ is obtained with the uncertainty 10% as a sequence for the total mass of the main asteroid belt we have $M_{belt} \approx 1800 \cdot 10^{-12} M_{\odot}$. This estimate is in a good accordance with the total mass of the asteroid belt obtained by extrapolation to small masses distribution of the biggest 300 asteroids (supposing that there is no effect of the observational selection in this set). For the mean radius of the ring the estimate $R \approx 2.80$ AU with the uncertainty 3% is derived.

The ephemerides were fitted to data totaling nearly 80000 American and Russian radar observations of planets (1961–1997), ranging and Doppler measurements of the Viking and Pathfinder landaus, various measurements of spacecraft at Jupiter (1973–1997), and VLA positional measurements of Jupiter's thermal emission. Parameters of the lunar theory and the lunar physical librations were derived by processing LLR observations 13500 lunar laser ranging (1970–2000). An earlier version of this analysis is described in [1].

Reductions of measurements include relativistic corrections, effects of propagation of electromagnetic signals in the Earth troposphere and in the solar corona with simultaneous evaluation of parameters of the corona model. Great attention was given to the reduction of radar observations for the topography of Mercury, Venus and Mars. The positions of the landers are computed, taking into account the precession, nutation and seasonal terms of the Mars rotation. The rms of post-fit residuals of observations are 1.4 km for Mercury, 0.7 km for Venus and Mars, 8 m for Viking and 4 m for Pathfinder measurements.

Tables 1 – 4 gives values of different astronomical parameters (the parameters of the Mars rotation, masses of objects, relativistic parametes, the derivative of gravitational constants, the solar oblateness) obtained in the fitting process of the EPM ephemerides to radiometric observations of planets and spacecraft. The solution value of the astronomical unit $AU = (149597870691.2 \pm 0.2)$ m is in good agreement with that of DE405.

Table 1 The formal standard deviations of elements of the planets.

planet	a [m]	*sinicos*Ω [mas]	*sinisin*Ω [mas]	*Ecos*π [mas]	*esin*π [mas]	λ [mas]
Mercury	0.187	3.169	3.329	0.321	0.279	0.826
Venus	0.309	0.606	0.594	0.039	0.040	0.184
Earth	0.102	-	-	0.001	0.001	-
Mars	0.259	0.024	0.025	0.002	0.002	0.008
Jupiter	675.1	4.817	4.086	0.321	0.322	1.164

Table 2 The parameters of the Mars rotation.

$\dot{V}$ [°/day]	I_q [°]	$\dot{I}_q$ [″/year]	Ω_q [°]	$\dot{\Omega}_q$ [″/year]
350.891985129 ±0.000000011	25.1893932 ±0.0000050	-0.0036 ±0.0024	35.437724 ±0.000020	-7.5712 ±0.0050

Table 3 Sun-Jupiter and Ceres-Sun, Pallas-Sun, Vesta-Sun mass ratios and densities of C, S, M taxonomic asteroids classes.

$M_\odot/M_{Jup}$	$M_{Cer}/M_\odot$ 10^{-10}	$M_{Pal}/M_\odot$ 10^{-10}	$M_{Ves}/M_\odot$ 10^{-10}	ρ_C g/cm^3	ρ_S g/cm^3	ρ_M g/cm^3
1047.34866 ±0.00003	4.808 ±0.012	0.996 ±0.004	1.364 ±0.010	1.38 ±0.02	2.71 ±0.02	5.32 ±0.07

Table 4 Parameters of PPN formalism, $\dot{G}/G$ and the solar quadrupole moment.

$\dot{G}/G(10^{-11} yr^{-1})$	β-1	γ-1	$\Delta\pi_{Mcr}$(″cy^{-1})	$J_2(10^{-7})$
0.004 ±0.008	0.0004 ±0.0002	0.0001 ±0.0001	0.0055 ±0.0085	2.43 ±0.67

For further details of the EPM ephemerides and determination of astronomical parameters the reader is referred to the papers [3],[4].

References

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