Multi-scale (time and mass) dynamics of space objects
Proceedings IAU Symposium No. 364, 2022
A. Celletti, C. Galeş, C. Beaugé, A. Lemaitre, eds.
doi:10.1017/S1743921321001447

Planetary and lunar ephemeris EPM2021 and its significance for Solar system research

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Abstract. We present an updated public version of EPM (Ephemerides of Planets and the Moon). Since the last public version, EPM2017, many improvements were made in both the observational database and the mathematical model. Latest lunar laser ranging observations have been added, as well as radio ranges of Juno spacecraft and more recent ranges of Odyssey and Mars Reconnaissance Orbiter. EPM2021 uses a new improved way to calculate radio signal delays in solar plasma and has a major update in the method of determination of asteroid masses. Also, a delay-capable multistep numerical integrator was implemented for EPM in order to properly account for tide delay in the equations of the motion of the Moon. The improved processing accuracy has allowed to refine existing estimates of the mass of the Sun and its change rate, parameters of the Earth–Moon system, masses of the Main asteroid belt and the Kuiper belt; and also to raise important questions about existing numerical models of solar wind.

Keywords. celestial mechanics; astrometry; ephemerides; solar wind; minor planets, asteroids; Moon

1. Introduction

Numerical planetary and lunar ephemeris, being in constant development since 1960s in the United States (DE), since 1980s in Russia (EPM), and since 2000s in France (INPOP), have applications not only in space exploration, but also in realization of reference frames, fundamental astronomy, and physics. Each ephemeris theory is based on a mathematical model of the Solar system; the models are being improved as more (and more precise) planetary and lunar astronomical observations are made. The observational capabilities grow simultaneously with requirements for space missions and scientific experiments. Improvement of models may involve addition of bodies previously neglected or inclusion of physical effects previously unaccounted for. Recently, INPOP19a and DE440 were released (Fienga et al. 2019, Park et al. 2021). We present EPM2021, the latest public update of the EPM ephemeris. Compared to the last public release, EPM2017, EPM2021 has improvements in both the observational database and the mathematical model.

2. Observations

Several kinds of observations are processed to determine the parameters of the dynamical model of the ephemeris. The orbit of the Moon is determined from lunar laser ranging (LLR) observations. To determine the orbits of the inner planets, radio ranging observations of orbiters and landers are used, along with some Doppler observations of Martian landers. For the outer planets, there are fewer ranges obtained (and none at all for Pluto), thus optical observations of the outer planets and their satellites are used in the solution. Recent additions to the ground optical observations database came from Pulkovo Observatory in Russia (Ershova et al. 2016, Narizhnaya et al. 2018, 2019) and Yunnan Observatory in China (Wang et al. 2017, Xie et al. 2019). Also, some observations made at the Sheshan station of the Shanghai Observatory in 2003–2009 were added (Qiao et al. 2007, 2014). The next major release of data from the Gaia space telescope (Gaia DR3), planned for 2022, is expected to contain observations of planets and natural satellites, which will hopefully fill the current lack of data for the outer planets.

Important spacecraft ranging observations that were added to EPM2021 are: 4 normal points of the Jovian orbiter Juno obtained in 2016–2017, 780 normal points of Mars Reconnaissance Orbiter (MRO) obtained in 2014–2017, and 3226 observations of Mars Odyssey obtained too in 2014–2017. The MRO and Odyssey data were kindly provided by Dr. William Folkner of NASA JPL. The Juno data is published at the NASA website (`https://ssd.jpl.nasa.gov/?eph_data`), as are older observations of Odyssey and MRO, and other radio and optical observations used in the JPL DE ephemeris. However, the post-2017 observations of Odyssey, MRO, and Juno that were used for DE440 (Park et al. 2021) are not available.

In the lunar part, there was a major update in the LLR observations at the Apache Point Observatory in NM, USA: 1211 normal points were made available recently (`https://tmurphy.physics.ucsd.edu/apollo/norm_pts.html`), covering the timespan from late 2016 to late 2020. Côte d'Azur Observatory in Grasse, France regularly provides LLR data (Chabé et al. 2020) to the NASA CDDIS (`https://cddis.nasa.gov/archive/slr/data/npt_crd`) archive via the International Laser Ranging Service (ILRS). From September 2017 to July 2021, 3789 normal points were obtained with the 1024-nm infrared laser at Grasse. The "green" (532 nm) normal points seem to have ended in November 2020; 262 normal points produced since September 2017 have been added to the EPM database. 261 normal points (2017–present) were added from the Matera observatory in Italy, also via CDDIS. Finally, the Wettzell Observatory in Germany started to provide infrared laser ranges in 2018 (Eckl et al. 2019) and has since produced 101 normal points that can be found at `ftp://edc.dgfi.tum.de/pub/slr/data/npt_crd`.

3. Dynamical model

EPM's dynamical model of the Solar system includes all planets, Pluto, the Moon, the Sun, selected asteroids, the discrete uniform 180-point asteroid annulus (Pitjeva & Pitjev 2018a), selected Trans-Neptunian objects (TNOs), and the discrete uniform 160-point TNO ring (Pitjeva & Pitjev 2018b). Sixteen bodies (the Sun, the planets, Pluto, Ceres, Pallas, Vesta, Iris, Bamberga) obey Einstein–Infeld–Hoffmann equations of motion. Other bodies, for the sake of performance, are modeled as interacting with those 16 bodies with only Newtonian forces and not interacting with each other. Apart from point-mass interactions, the model includes additional accelerations from solar oblateness and Lense–Thirring effect. Earth also gets "point mass–figure" accelerations that come from the Sun, Venus, Mars, Jupiter, and the Moon. The Moon is modeled as an elastic body with a rotating liquid core (Pavlov et al. 2016).

After EPM2017, two point masses have been added that represent Jupiter trojans, placed at L_4 and L_5 Lagrange points of Jupiter's orbit. Also, the list of asteroids was revised. In EPM2017, 301 largest asteroids were present in the dynamical model as individual point masses. In EPM2021, the number of individual asteroids is 277. The source list of asteroids was compiled by merging (with removal of duplicates) the 343 asteroids of the DE430 model (Folkner et al. 2014) and the 287 asteroids from (Kuchynka et al. 2010).

https://doi.org/10.1017/S1743921321001447 Published online by Cambridge University Press

The latter is believed to be the list of the most “non-ring-like-acting” asteroids, i.e. the ones whose cumulative effect on the inner planets cannot be modeled by a uniform ring. The resulting list contained 379 asteroids. Then, 102 asteroids whose masses were determined negative (though always within uncertainty) were excluded from the model.

4. Determination of masses of asteroids and TNOs

Of the 277 asteroids, only 17 masses are known with good accuracy because they are either binary asteroids (e.g. Kalliope) or had spacecraft orbiting them (e.g. Ceres). Masses of some other asteroids are estimated by deflections of other asteroids’ orbits on approach (e.g. Iris), though estimates may differ across works. For the remaining majority of asteroids, only a weak estimate of the mass may be obtained from the estimate of the diameter based on the infrared observations of space telescopes IRAS and WISE, and the estimate of the density based on the taxonomical class (C/S/M). In EPM2017, masses of 30 asteroids were determined purely dynamically, by the perturbations that they inflict on orbits of the inner planets, while masses of other asteroids were determined as mean densities of the three taxonomic classes. In EPM2021, following the approach proposed in (Kuchynka & Folkner 2013), all the said estimates of masses were used as *a priori* estimates in the Tikhonov regularization scheme that extends the least-squares method. All 277 masses were then determined in the planetary solution along with other parameters. As said above, 379 masses were determined initially, then 102 masses that became negative (always within uncertainty) were excluded from the model. The gravitational effect of those 102 asteroids, as well as of all the others that were not selected in the first place, is approximated with the 180-point uniform annulus, whose mass is also determined.

Similar modification was made for determination of masses of 30 TNOs and the discrete 160-point TNO ring.

5. Reductions of spacecraft ranging observations

Two improvements were made to reduce systematic errors in the residuals of Martian orbiters MRO and Odyssey who provide Earth–Mars ranges (normal points) of sub-meter accuracy. One is accounting for measurement biases that come from miscalibrations on radio observatories. Following the decision from (Kuchynka et al. 2012), two sets of biases were determined for Deep Space Network (DSN) stations: one for Mars Global Surveyor (MGS) and Odyssey spacecraft, another for the MRO spacecraft.

The second improvement concerns the delay of the radio signal due to the free electrons in the solar plasma. In EPM, from 2004 to 2017 versions, the following model was used for the electron number density:

$$N_{\mathrm{e}} = \frac{A}{r^6} + \frac{B + \dot{B}t}{r^2},$$

where r is the distance to the center of the Sun. A was fixed to the value determined in DE200, and B with its linear drift $\dot{B}$ were determined from observations, per-planet, per-year. That makes more than 50 determined parameters in the planetary solution correlate with each other, with the biases, orbits, and the mass of the Sun. In EPM2019 (unreleased), A and $\dot{B}$ were set to zero, while B was determined per-conjunction from 2002 to 2018 plus a single B prior to 2002. That makes 10 parameters. In EPM2021, there is only one determined solar plasma parameter: C, the model being

$$N_{\mathrm{e}} = C\,\frac{N_1(t)}{r^2},$$

Table 1. Statistics of spacecraft ranging residuals. Ranges that pass closer to the Sun than 60 solar radii are excluded. The third column is the number of normal points that were formed from raw spacecraft ranging observations made during the specified timespan.

Spacecraft	Timespan	NPs	wrms
MGS	1999–2006	5590	91.5 cm
Odyssey	2002–2017	7988	56.3 cm
MRO	2006–2017	1924	60.2 cm
Mars Express	2005–2015	2888	2.46 m
Venus Express	2006–2013	1294	6.06 m
Cassini	2004–2014	161	17.2 m
MESSENGER	2011–2014	1141	60.9 cm
Juno	2016–2017	4	3.58 m

Table 2. Statistics of LLR residuals. Rejected observations are not counted. The third column is the number of normal points that were formed from raw LLR observations made during the specified timespan.

Station	Timespan	NPs	wrms, cm
McDonald, TX, USA	1969–1985	3554	21.4
Nauchny, Crimea, USSR	1982–1984	25	11.6
MLRS1, TX, USA	1983–1988	585	8.8
MLRS2, TX, USA	1988–2013	3280	3.6
Haleakala, HI, USA	1984–1990	747	5.2
Grasse, France (Ruby laser)	1984–1986	1109	16.8
Grasse, France (YAG)	1987–2005	8277	2.3
Grasse, France (MeO green)	2009–2020	2000	1.52
Grasse, France (infrared)	2015–2021	6179	1.15
Matera, Italy	2003–2021	358	3.43
Apache Point, NM, USA	2006–2020	3782	1.44
Wettzell, Germany	2018–2020	101	1.25
Total	**1969–2021**	**29997**	$\chi^2 = 1.358$

where the function $N_1(t)$ is equal to the smoothed *in situ* measurements of the electron density near Earth obtained from the NASA/GSFC's OMNI dataset (https://spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni). The reference value of C is 1; *a priori* error estimate of this value was obtained from the formal errors provided in the OMNI dataset. Taking advantage of this estimate with the Tikhonov regularization has allowed to improve the accuracy of determination of the Sun's mass by more than 10%. The usage of time-varying electron density linked to *in situ* measurements has allowed to reduce the systematic errors in the ranging residuals.

6. Technical improvements

Versions of EPM since EPM2015 are made with the ERA-8 software (Pavlov, Skripnichenko 2015). Up to EPM2017, a single-step integrator was used (Avdyushev 2010). Another integrator was subsequently developed that allows to integrate differential equations that contain a time delay. Such a modification was needed to account for the tide delay in the equations of the motion of the Moon (Pavlov et al. 2016). The new integrator, called ABMD (Aksim & Pavlov 2020), is an extension of the multistep Adams–Bashforth–Moulton scheme and has allowed to improve the performance of numerical integration of orbits.

7. Residuals and determined parameters in the EPM2021 solution

Weighted root-mean-squares (wrms) of ranging residuals (one-way) of planetary orbiters are listed in Table 1. The wrms of the LLR residuals (one-way) are listed in Table 2. The values and uncertainties of selected parameters are given in Table 3.

https://doi.org/10.1017/S1743921321001447 Published online by Cambridge University Press

Table 3. Selected parameters determined in EPM2021.

Parameter	**Value and 3σ**
$GM_{\odot}$	132712440043.17 ± 0.49 km^3/s^2
$J_{2\odot}$	$(2.252 \pm 0.024) \cdot 10^{-7}$
Asteroid belt mass	$(4.13 \pm 0.09) \cdot 10^{-4} M_{\oplus}$
Kuiper belt mass	$(1.74 \pm 0.42) \cdot 10^{-2} M_{\oplus}$
Earth–Moon GM	403503.23649 ± 0.00025 km^3/s^2
Lunar J_2	$(2.0321 \pm 0.0005) \cdot 10^{-4}$
Lunar tidal delay τ	(0.094 ± 0.002) days
Lunar $(C - A)/B$	$(631.022 \pm 0.001) \cdot 10^{-6}$
Lunar $(B - A)/C$	$(227.739 \pm 0.001) \cdot 10^{-6}$
Oblateness of lunar fluid core f_c	$(0.258 \pm 0.006) \cdot 10^{-3}$

8. Other results and future plans

Several scientific results have appeared during the development of EPM2021. Aside from the already mentioned determined masses of the asteroid belt and the Kuiper belt, they are:

• The Earth–Moon very-long-baseline Interferometry (VLBI) observations were modeled in order to estimate the astrometric outcome (Kurdubov et al. 2019).

• A two-delay model was proposed for the equations of lunar rotation (Pavlov 2019).

• A lunar reference frame was built with a decimeter accuracy; also, the potential of the modern LLR to determine the Earth orientation parameters was shown (Pavlov 2020).

• The change rate of the mass of the Sun has been estimated (Pitjeva et al. 2021).

Future plans include: using Gaia's observations of satellites of the outer planets (when observations are released); improving the models of the lunar core and lunar solid body tides; further tests of general relativity from planetary and lunar observations; application of the EPM model of the Solar system to pulsar timing.

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