

### 3 Conventional dynamical realization of the ICRS

The planetary and lunar ephemerides are used in a number of models and analysis methods. In some cases, *e.g.* interplanetary spacecraft navigation, lunar laser ranging and pulsar timing, the accuracy of the ephemeris is critical to the quality of results and so the best ephemerides should be used. In other cases, *e.g.* to model the gravitational attraction of external bodies for nutations and tides, use of the latest released ephemerides is not critical.

Ephemerides are updated frequently with accuracy improved through the use of more data, especially spacecraft radio tracking data and increasingly accurate astronomical observations from Earth, and by improved dynamical modeling. Recent ephemerides include the DE421 <<sup>1</sup>> from the Jet Propulsion Laboratory (JPL) (Folkner *et al.*, 2008), INPOP08 from the Institut de Mécanique Céleste et de Calcul des Ephémérides (IMCCE) (Fienga *et al.*, 2009) and EPM2008 from the Institute of Applied Astronomy (IAA) (Pitjeva, 2009). These three ephemerides are expected to be of comparable quality (Folkner, 2009), *e.g.* a comparison between INPOP08 and DE421 (Fienga *et al.*, 2009) shows differences mostly comparable to the expected uncertainties. When an application is sensitive to the accuracy of the ephemeris, as discussed earlier, it is recommended that DE421 be the conventional ephemeris. This recommendation is intended to provide continuity for implementation by users as the DE series have provided the dynamical realization of the celestial reference system in previous versions of the IERS Conventions, the latest being DE405 (Standish *et al.*, 1997) in the IERS Conventions (2003).

Each of the mentioned ephemerides is integrated using the Einstein-Infeld-Hoffman equations (Einstein *et al.*, 1938) with dynamical time consistent with Barycentric Dynamical Time (TDB) as defined by Resolution 3 from IAU General Assembly XXVI (van der Hucht, 2008). Consequently the time argument of the DE421 is TDB, which is consistent, within observational uncertainties, with  $T_{eph}$  used as the time argument in previous JPL ephemerides (IERS Technical Note 32, Standish 1998). The ephemerides have been aligned with the International Celestial Reference Frame (ICRF) by means of Very Long Baseline Interferometry (VLBI) observations of spacecraft in orbit about Venus and Mars relative to extragalactic radio sources. The alignment of DE405 to the ICRF was done using the Magellan spacecraft in orbit about Venus with an accuracy of 0.001". Through the use of VLBI observations of Mars Global Surveyor, Mars Odyssey, and Mars Reconnaissance Orbiter, the later ephemerides (thus DE421) are aligned to the ICRF with an accuracy of 0.00025".

The mass parameter (GM) of the Sun is most accurately determined by fitting planetary spacecraft range data in the planetary ephemeris fitting process. From Resolution 10 from IAU General Assembly XVI (Müller and Jappel, 1977), the TDB-compatible value of the mass parameter of the Sun is related to the defined value given by Gauss' constant in units of  $\text{au}^3/\text{day}^2$  by an estimated value of the Astronomical Unit (au). The TDB-compatible value of the au estimated with DE421 is 149597870.6996262 km and is consistent with the value given in Chapter 1 (Table 1.1).

The mass parameters for the planets are most accurately estimated by means of spacecraft encounters or in orbit about them. The planetary ephemerides are also sensitive to the mass parameters of asteroids, and values have been estimated through their effect on the Earth-Mars range as measured by spacecraft and by astronomical observations of asteroid mutual encounters. Table 3.1 lists mass parameters used in the DE421 ephemeris. Each solar system body's GM is also given as a TDB-compatible value in  $\text{km}^3/\text{s}^2$  since all ratios change when the solar GM estimate changes. In this table, the GM values expressed in SI units indicate the accuracy by the number of significant digits. The values in Table 3.1 are provided directly with the DE421 ephemerides and should be considered to be an integral part of them; they will sometimes differ from a more standard set, but the differences are necessary for the optimal fitting of the data. A list of current best

<sup>1</sup> <ftp://ssd.jpl.nasa.gov/pub/eph/planets/ascii/de421>

estimates of these mass parameters has been compiled by Luzum *et al.* (2009) and is available at  $\langle^2\rangle$ .

Table 3.1: Mass parameters from DE421 expressed as ratios and as TDB-compatible values.

	$GM_{\odot}/GM_i$	$GM_i/\text{km}^3\text{s}^{-2}$
Mercury	6023597.400017	22032.090000
Venus	408523.718655	324858.592000
Earth	332946.048166	398600.436233
Moon	27068703.185436	4902.800076
Mars	3098703.590267	42828.375214
Jupiter	1047.348625	126712764.800000
Saturn	3497.901768	37940585.200000
Uranus	22902.981613	5794548.600000
Neptune	19412.237346	6836535.000000
Pluto	135836683.767599	977.000000
$GM_{\oplus}/GM_i$		
Earth-Moon mass ratio	81.3005690699	

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<sup>2</sup><http://maia.usno.navy.mil/NSFA/CBE.html>

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