A COMPARISON OF THE HIGH ACCURACY PLANETARY EPHEMERIDES DE421, EPM2008, and INPOP08

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ABSTRACT. At the heart of many astronomical applications lies a planetary ephemeris. Since the 1980s the *de facto* world standard has been the Jet Propulsion Laboratory's DE (Development Ephemeris) series ephemerides. Recently, ephemerides from the Paris Observatory (Intégrateur Numérique Planétaire de l'Observatoire de Paris, or INPOP) and the Institute of Applied Astronomy in St. Petersburg (Ephemerides Planets-Moon, or EPM) have become available. These two ephemerides now provide accuracies similar to those from JPL. Here we compare the constants, initial conditions, and planetary positions produced by DE421, INPOP08, and EPM2008, the most recent ephemerides released for general use from these three groups. Ultimately, the true test of any ephemeris is how well its predictions compare with actual observations. Other considerations, such as availability, shall be discussed as well.

1. INTRODUCTION

Recently, two series of planetary ephemerides, the Ephemerides Planets-Moon (EPM) from the Institute for Applied Astronomy (Pitjeva 2009, Yagudina 2009) and the Intégrateur Numérique Planétaire de l'Observatoire de Paris (INPOP) from the Paris Observatory (Fienga et al. 2009) have become widely available. These two ephemerides provide positions and velocities with accuracies comparable to the well established Development Ephemerides (DE) from the *Jet Propulsion Laboratory*, JPL, (Standish 1998). The availability of these three high accuracy ephemerides prompts the question: How do they compare to one another? The ultimate test of any ephemeris is how well it actually predicts the future positions of the bodies included in it.

In particular, this paper is an initial comparison of the DE421, EPM2008, and INPOP08 ephemerides to the DE405 ephemerides, which is currently used in *The Astronomical Almanac*. The final report, including all comparisons and graphs, will be made available at the IAU Commission 4: Ephemerides web site[1]. There is no attempt here to determine which ephemeris is 'best'. Such a judgement is left for the user to make based on the data provided and his application of the ephemerides.

2. AVAILABILITY AND SOFTWARE

All three ephemerides, software to read them, and documentation are available on the internet. The DE421 ephemeris files are available by ftp[2] from the Solar System Dynamics group at JPL. The EPM2008 ephemeris files are available by ftp[3] from the Laboratory of Ephemeris Astronomy at the Institute for Applied Astronomy. And the INPOP08 ephemeris files are available by http[4] from the Insitut de mécanique céleste et de calcul de éphémérides. The ephemeris files are all available as ASCII text. Both EPM2008 and INPOP08 are available in binary versions as well, while JPL provides a Fortran program to convert DE421 from ASCII to binary format.

The data in all three ephemerides store their data as series Chebyshev polynomials using Barycentric Dynamical Time (TDB) as the independent variable. DE421 and INPOP08 store the coefficients for all

[1] *http://iaucom4.org/*
[2] *ftp://ssd.jpl/nasa.gov*
[3] *ftp://quasar.ipa.nw.ru/incoming/EPM2008/*
[4] *http://www.imcce.fr/inpop/calceph*

the body's positions in a single file while EPM2008 stores the velocity coefficients in individual body files.[5] Except for Uranus, Neptune, and Pluto in EPM2008, the segment length of the Chebyshev polynomials is an integer number of days.

All the ephemerides provide Barycentric Celestial Reference System (BCRS) positions of the Sun, planets, and Pluto, and geocentric equatorial positions for the Moon. Each also has a lunar rotation ephemeris. EPM2008, however, does not currently make its lunar rotation ephemeris available. The INPOP08 ephemeris includes an ephemeris of the difference between TDB and Terrestrial Time as well.

3. SUMMARY OF THE MODELS

A summary of the parameters used in modeling the three ephemerides is given in Table 1. No comprehensive summary is available for any of the ephemerides, so the data in this table is the best available estimate gathered from a variety of sources including the headers of the ephemeris files and the available papers and memos published describing them.

	DE405	DE421	EPM2008	INPOP08
Year Produced	1995	2007/08	2009	2009
Span	1600-2200	1900-2050	1800-2197	$1900-2100$ $1000-3000$
Parameters	156	228	>260	402
Main Belt Objects	300	343	301 + ring	303 + ring
Trans-Neptunian Objects	Pluto	Pluto	Pluto + 20	Pluto

Table 1: A summary of the parameters used for each of the ephemerides.

All of the ephemerides are based on the numerical integration of a parameterized post-Newtonian gravitation model accurate to at least the second order in c^{-1}, where c is the speed of light, and fit to a set of observations similar to those described in Folkner et al. (2008). A subset of the parameters, varying between ephemerides, were adjusted using partial differential equations describing the link between the parameters and the observed values.

Probably the greatest difference in the models was the treatment of small solar system bodies not included in the ephemerides themselves. DE421 includes the Newtonian forces of the dwarf planet (1) Ceres, along with 342 main belt asteroids that had been previously determined to be the greatest perturbers of Mars. EPM2008 includes the integration of Ceres, 300 asteroids, and 21 trans-Neptunian objects (TNOs) including Pluto. In addition, the mass of the remainder of the main belt asteroids was represented by a ring with a mass, $(0.87 \pm 0.35) \times 10^{-10}\,M_\odot$, and radius, 3.13 ± 0.05 AU. INPOP08 uses Ceres and 302 independently integrated main belt asteroids determined to be the most likely to produce significant perturbations over the time span of the ephemerides. Like EPM2008, a ring at 3.147 AU with a mass of $(1.0 \pm 0.3) \times 10^{-10}\,M_\odot$ is used to represent the remaining mass of the main asteroid belt.

4. INITIAL COMPARISON

The ephemerides, DE421, EPM 2008 and INPOP08 are compared to DE405. Coordinates compared were the heliocentric range, longitude, and latitude of the planets and Pluto, while for the Moon geocentric coordinates were used, from 1900 through 2050, the period common to all the ephemerides. In general, the differences of the three ephemerides with respect to DE405 and with respect to each other increase with the increasing semimajor axis of the body. The maximum absolute differences with respect to DE405 over this time period are given in Table 2.

Fig. 1, for example, plots of differences for Jupiter and shows a significant difference for INPOP08. This is due to the fact that INPOP08 did not include the Galileo spacecraft observations for the position of Jupiter, while the others do. These observations have subsequently been included in INPOP10A[6] (Fienga 2010, private communication).

The dominant difference in the longitudes, e.g. Fig. 1, middle panel, for each of the objects is a secular trend arising from small differences in the mean motion of each of the objects. The difference in the mean motion also results in a gradual increase over time in the range differences of the planets giving those plots a "bow tie" aspect to them, Fig. 1, left panel.

[5]The relationship between the integral and derivative of the dependent variable in a Chebyshev polynomial is relatively simple. Thus, there is no penalty for storing either velocities or positions.

[6]INPOP10A became available about four weeks before prior to Journées 2010.

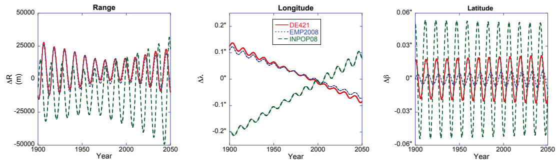

Figure 1: The difference in the heliocentric range, longitude, and latitude of Jupiter for DE421, EPM2008, and INPOP08 with respect to DE405.

Object	DE421			EPM2008			INPOP08		
	ΔR (AU)	ΔLong. ($''$)	ΔLat. ($''$)	ΔR (AU)	ΔLong. ($''$)	ΔLat. ($''$)	ΔR (AU)	ΔLong. ($''$)	ΔLat. ($''$)
Mercury	3.1×10^{-9}	0.011	0.006	2.6×10^{-9}	0.007	0.007	5.1×10^{-9}	0.016	0.009
Venus	3.9×10^{-10}	0.001	0.002	3.6×10^{-10}	0.001	0.002	4.1×10^{-10}	0.002	0.002
Earth	2.2×10^{-10}	0.001	0.002	1.8×10^{-10}	0.002	0.001	4.1×10^{-10}	0.004	0.002
Mars	3.7×10^{-9}	0.005	0.002	4.8×10^{-9}	0.008	0.001	7.7×10^{-9}	0.013	0.002
Jupiter	1.8×10^{-7}	0.137	0.022	1.8×10^{-7}	0.123	0.008	3.3×10^{-7}	0.213	0.054
Saturn	2.0×10^{-6}	0.144	0.044	2.0×10^{-6}	0.144	0.045	2.0×10^{-6}	0.142	0.048
Uranus	6.4×10^{-6}	0.249	0.050	6.4×10^{-6}	0.229	0.010	5.4×10^{-6}	0.199	0.022
Neptune	3.5×10^{-5}	0.568	0.046	4.0×10^{-5}	0.650	0.026	2.0×10^{-5}	0.337	0.056
Pluto	0.00025	1.399	0.242	0.00026	1.364	0.285	0.00010	2.166	0.538
Barycenter	6.2×10^{-9}	1.635	0.136	9.7×10^{-7}	93.104	50.396	4.4×10^{-9}	0.375	0.077
Moon*	2.4×10^{-11}	0.023	0.008	4.2×10^{-11}	0.052	0.013	4.1×10^{-11}	0.025	0.006

*The lunar differences are geocentric rather than heliocentric.

Table 2: The maximum heliocentric absolute differences with respect to DE405.

The dominant difference in latitude for each of the objects is a periodic component with the period of its orbital period, Fig. 1, right panel. This difference can arise from a difference in the orientation of the planetary reference system, a difference in the object's inclination, or a difference in the position of the nodes of the orbits. For all of the bodies in each of the ephemerides, the combined difference from all three of these sources is small; an indication of the basic soundness of the ephemerides.

Fig. 2 shows the EPM2008 offset in the barycenter is two orders of magnitude greater than for the other ephemerides. This offset is a result of including TNOs other than Pluto in its model. To first order, the motions of the additional TNOs are slow enough that their contribution to position to the solar system barycenter can be considered a fixed offset from the center of mass of the Sun and other solar system bodies. Moreover, Jupiter's contribution to the position of the barycenter dominates over that of the other planets. Thus, the position of the EPM2008 barycenter, which includes the TNOs, is offset with respect to the barycenters of the other ephemerides, which do not include the other TNOs. This offset gives EPM2008 a barycentric position that moves with respect to the others with a periodic motion with approximately Jupiter's sidereal period.

There is an offset of approximately $76''$ between the rotation angle around the lunar pole of rotation, between DE421 and INPOP08. The most likely reason for this difference is a difference in the rotation about the polar axis between the mean-Earth mean-lunar pole of rotation (ME) reference system and the lunar principal moments of inertia (PMI) reference system. Lunar laser observations used to determine the position and orientation of the Moon are made in the ME reference system, while the rotation angle is given in the natural system for solving the lunar rotation equation of motion, the PMI reference system. The offset rotation between these two reference systems must be solved for in determining the lunar rotation parameters. Thus, as long as the offset rotations between the two reference systems are published, the difference between the two ephemerides should be of no concern to the observer. Yagudina (2010, private communication) has stated that current lack of an offset rotation between the lunar ME and PMI reference systems is the reason that EPM2008 does not currently make its lunar rotation ephemeris available.

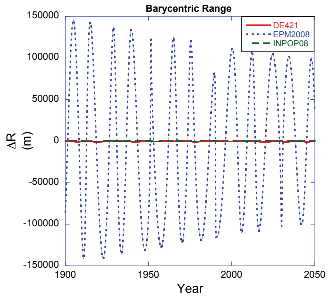

Figure 2: The difference in barycenter range of the Sun with respect to DE405.

5. DISCUSSION & FUTURE WORK

All three of the high accuracy solar system planetary ephemerides, DE421, EPM2008, and INPOP08, provide high quality models of the positions and velocities of the Sun, Moon, planets, and Pluto. Three significant differences were found: (1) A difference in the position of Jupiter in INPOP08. (2) The barycentric positions produced by EPM2008 differ. (3) A constant offset in the value of the lunar rotation angle between DE421 and INPOP08. These differences show how important it is for the user to understand what data have been used and the choice of models and parameters.

Further comparisons are planned. The first will be to replace DE405 as a standard with DE421, and INPOP08 with INPOP10A. Then, there are more quantitative numerical tests, such as determining the constant of integration, the angular momentum and energy. All the ephemeris generating groups hold some observations in reserve to check their accuracies. This check is the most important test of the ephemerides. Thus, comparison of each of the ephemerides with a uniform set of observations, including observations made after the construction of the ephemerides, is planned.

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