A Comparison of the High Accuracy Planetary Ephemerides DE421, EPM2008, and INPOP08

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What This Talk is About

- A Comparison of the three current, state-of-the-art planetary ephemerides: DE421, EPM2008, and INPOP08. Including:
  - Type of model
  - Both constant and solved for parameters
  - Comparison to a standard ephemeris, DE405
  - Comparison to observations

Be sure to note that this is very much of a work in progress and only some parts of these objectives have been met to date.

IMCCE announced the availability of INPOP10A on 31 Aug. 2010

What This Talk Is **NOT** About

- Any attempt to determine which ephemeris is the “best”.
- Any attempt by the authors or their institutions to endorse the adoption or use of a particular ephemeris.

Note that the authors’ hope this presentation will contribute to the continued improvement of all three ephemerides..

Availability

- DE421 is available for download from:
  - ftp://ssd.jpl.nasa.gov/pub/eph/planets/ascii/de421
- EPM2008 is available for download from:
  - ftp://quasar.ipa.nw.ru/incoming/EPM2008/
- INPOP08 is available for download from:
  - http://www.imcce.fr/inpop/

DE421: ASCII file needs to be constructed from a header file and a series of segments. The combined segments does not cover the entire period documented in the header. ASCII file needs to be converted to binary for use. The conversion may be used to cover only sub-segments of as small as 32 days. The program to do this is available at ftp://ssd.jpl.nasa.gov/pub/eph/planets/fortran.
EPM2008: ASCII and binary files are available. The binary files may be machine dependent; however, ephemeris reading software reads both binary and ASCII files.
INPOP08: Both ASCII and "universal" binary files are available covering either 200 or 2000 yr. time spans.

Features of the Ephemerides

Ephemeris	Planetary Ephemerides	Lunar Position Ephemeris	Lunar Rotation Ephemeris	Solar Ephemeris	Time Ephemeris
DE421	✓	✓	✓	✓	
EPM2008	✓	✓		✓	
INPOP08	✓	✓	✓	✓	✓

A Summary of the Models

	DE405	DE421	EPM2008	INPOP08
Vintage	1995	2007/08	2009	2009
Span	1600-2200	1900-2052	1800-2197	1000-3000 (1900-2100)
Parameters	156	228	> 260	402
Asteroids	3 & types G, S & M	67 major 276 minor	301 + Ring	303 + Ring
TNO's	Pluto	Pluto + ?	Pluto + 20	Pluto + ?

Vintage when the ephemeris was created

Parameters are the numbers given in the header file, but it's a combination of information, constants, constants evaluated before, constants estimated as part of the the solution.

Asteroids, the number (3 is Ceres, Pallas and Vesta)

Increasing complexity of models.

Asteroids in DE421

- Newtonian forces of 67 major and 276 minor asteroids with the largest perturbations on Mars iteratively included in integration of planetary orbits.
- (1) Ceres, (2) Pallas, and (4) Vesta integrated simultaneously using the DE405 positions of the Sun and planets, and mutual interactions.
- Other Asteroids integrated individually using the combined gravitational force of the Sun, planets, Ceres, Pallas, Vesta whose orbits were held fixed.
- Masses of Ceres, Pallas, Vesta and eight others are estimated in the fitting of DE421.
- Masses of the other 56 were held at their nominal values.
- The 276 minor asteroid masses were provided by their taxonomic class and estimated diameters.

Asteroids in EPM2008

- Simultaneous integration of 9 planets, 301 largest asteroids, and 21 TNOs.
- The rest of the main asteroid belt was modelled as a ring with a mass of $(0.87 \pm 0.35) \times 10^{-10}\, M_{\odot}$ at 3.13 ± 0.05 AU.

Asteroids in INPOP08

- Monte Carlo study of 24,635 asteroids gives list of 303 currently most probable perturbing asteroids
  - These asteroids are integrated independently.
- Mass of ring estimated independently to be
  - $M_{ring} = (1 \pm 0.3) \times 10^{-10} M_{\odot}$ at 3.14 AU.

Note the very good agreement Between EPM2008 and INPOP08 for the parameters for the main belt asteroid ring.

Summary of the Bases of the Ephemerides

- **Similar Bases**
- Basic set of observations used to construct the ephemerides
- k^2 & GM_{Sun}, c, β, γ, R_{Sun}
- EPM masses most similar to 421

- **Different Bases**
- M_E/M_M
- AU
- INPOP J_{2Sun} [DE421 differs by 9%]
- Starting epoch & initial conditions
- Masses mostly different
- Lunar Parameters

Lunar parameters are different. Not a lot of data on EPM.

Representation

	DE421 and INPOP08		EPM2008	
Body	Time Interval (days)	Degree	Time Interval (days)	Degree
Sun	16	10	2	15
Mercury	8	13	5	15
Venus	16	9	20	15
Earth-Moon	16	12	20	15
Mars	32	10	50	15
Jupiter	32	7	100	15
Saturn	32	6	300	15
Uranus	32	5	400.2740	15
Neptune	32	5	500.3425	15
Pluto	32	5	598.7705	15
Moon	4	12	4	15
Lunar Rotation	8	9		

All ephemerides are stored as Chebyshev polynomials and use the TDB rather than TCB time scale.

DE421 and INPOP08 store the coefficients for the position while EPM2008 store the coefficients for the velocity. The integral and derivative of the dependent variable with respect to the independent variable is fairly simple for Chebyshev polynomials.

DE421 and INPOP08 are stored in single files while each body in EPM2008 is stored in a separate file.

DE421 runs from JD2414922.5 (25 Sept. 1899) to JD2469808.5 (2 Jan. 2050); INPOP08 runs from JD2076569.0 (3.5 May 973) to JD2826521.0 (26 Aug. 3026); and all the EPM2008 ephemerides begin on JD2378494.5 (30 Dec. 1799). The extreme end dates for EPM2008 are JD 2523995.7 (13.2 May 2198) for Pluto and JD2524400.5 (22 June 2199) for the Sun.

Each of the EPM2008 ephemerides contains some empty series of Chebyshev polynomials at its late extreme. The final dates in the table are the actual final dates and do not include these empty series.

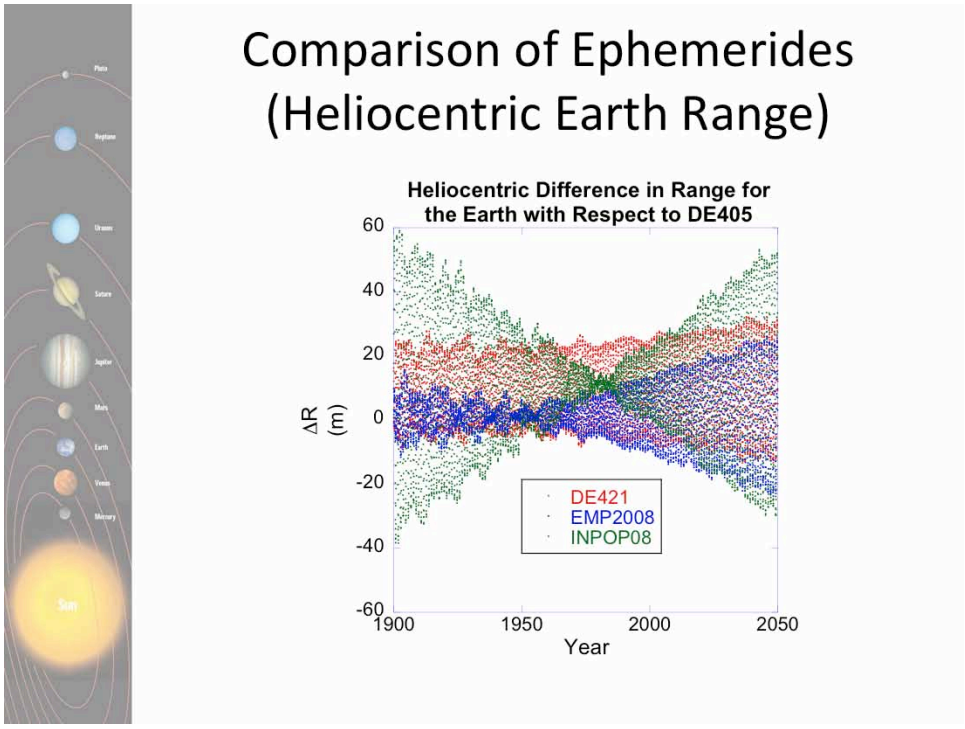
Software

- DE421 and INPOP08 are both readable using either the JPL testeph.f software available from
  - ftp://ssd.jpl.nasa.gov/pub/eph/planets/fortran
- or the CALCEPH library available from
  - http://www.imcce.fr/inpop/calceph
- EPM2008 is readable using the calc_eph.f90 module available from
  - ftp://quasar.ipa.nw.ru/incoming/EPM2008/fortran

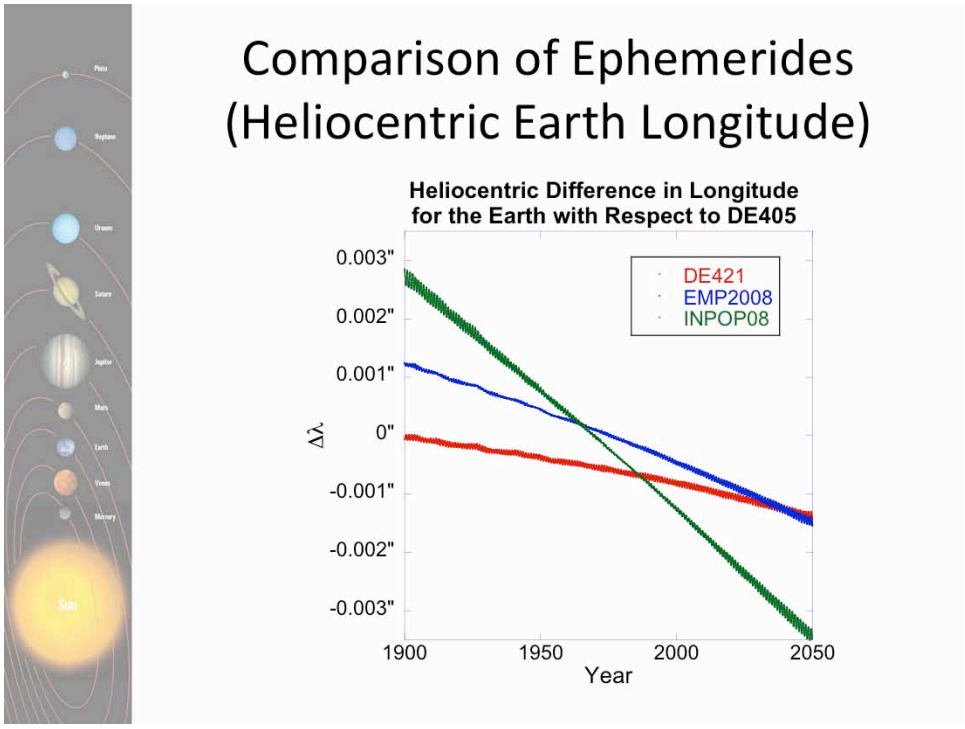
testeph.f is designed as test software that includes the ephemeris software as a part of it. It requires making a machine dependent choice of subroutine for opening the ephemeris file, which may require setting a value for file record length. C and Java versions are available from JPL.

CALCEPH is an installable library. It is designed to work with INPOP binary files in a machine independent manner. Works with C and Fortran, with an extend interface for Fortran 2003.

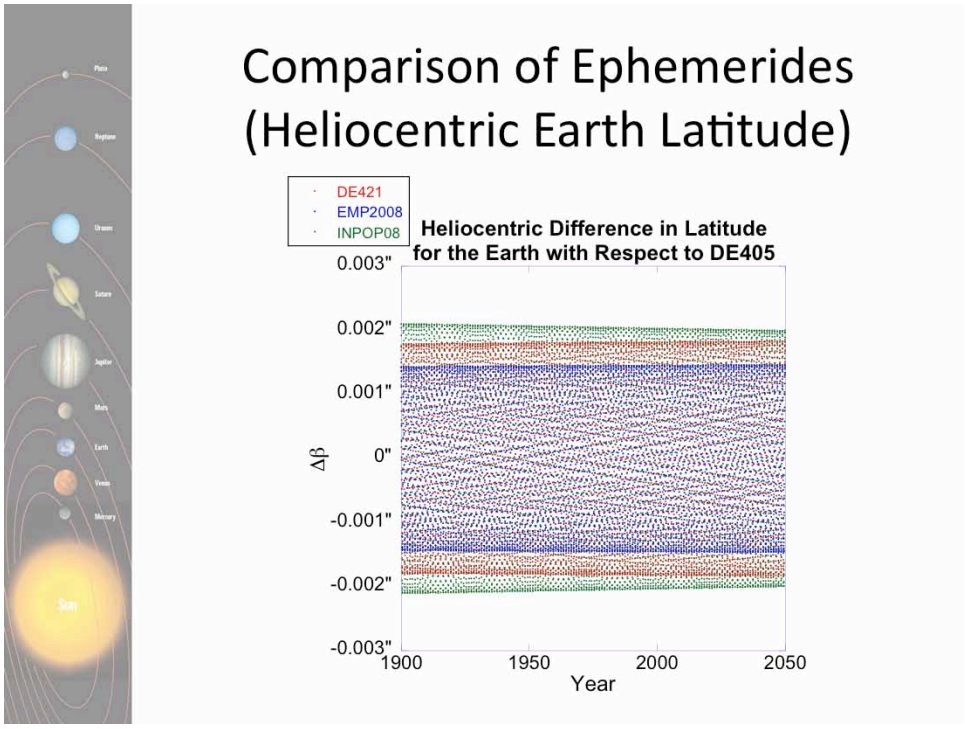
calc_eph.f90 is also available in C (calc_epm.c), Pascal (calc_eph.pas), and Java (Calc_eph.java) versions. Unlike the others, calc_eph reads the entire EPM2008 into memory. This makes for a much larger executable and requires a significant amount of start up time, but it also significantly reduces the time to retrieve a position. Testing indicates that the break even point is at about 10,000-20,000 positions.



Comparisons are made with respect to DE405 as a standard.
Comparison of INPOP08 with DE421 gives approximately the same shape and size distribution as comparison with DE405.
Comparison of EPM2008 with DE421 gives somewhat smaller residuals than comparison to DE405.
EPM2008 – INPOP08 residuals show that EPM2008 ranges are intermediate to those of DE421 and INPOP08.



Comparison of INPOP08 to DE421 shows a small improvement in the residuals. Again, EPM2008 longitudes are intermediate to those of DE421 and INPOP08.



The dominant periodicity in latitude for each of the planets is its orbital period. The reason is the differences are only showing three things. 1. Changes in the orientation of the planetary reference system. 2. Changes in the planet's inclination. 3. Changes in the position of the nodes of the orbits. That the size of these changes are all small is a testament to the basic soundness of all three ephemerides.
Comparison to DE421 reduces the residuals with EPM2008 and INPOP08 by a factor of about five.
The DE421 latitudes are intermediate to those of EPM2008 and INPOP08.
Similar plots are available for all the planets, Pluto, the Sun, the Moon, and the rotation of the Moon. Examples are available in the poster area.

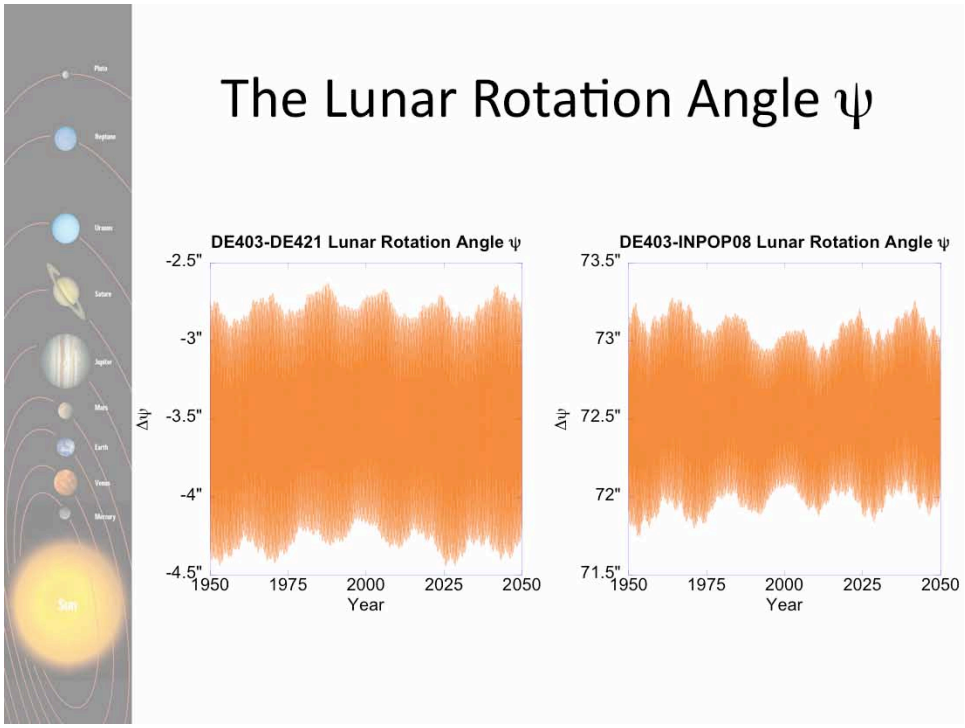
Maximum Absolute Heliocentric Differences with Respect to DE405

Body	DE421			EMP2008			INPOP08		
	Range	Longitude	Latitude	Range	Longitude	Latitude	Range	Longitude	Latitude
	(AU)	(″)	(″)	(AU)	(″)	(″)	(AU)	(″)	(″)
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
Moon (Geocentric)	2.4×10^{-11}	0.023	0.008	4.2×10^{-11}	0.052	0.013	4.1×10^{-11}	0.025	0.006
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

Maximum differences for the period of 1900 through 2050, the span of DE421, the shortest of the ephemerides.

No analysis has been done. There are both secular and periodic differences evident in the plots that have a significant effect on these values. For example, a slight difference in mean motion can mean a fairly large difference in range or longitude at the extreme ends of the time span.

Angular positions of the barycenter with respect to the heliocenter are large because of the short distance between them.



The comparison here is to DE403 rather than DE405 because DE403 has a known offset between the principal moments of inertia (PMI) rather than the Mean Earh-Mean pole of rotation (MEMP) as the reference systems, while DE405 does not. However, DE403 only is available from 1950 through 2050.

Here the range of the differences is much more important than the rather large offset. The offset is an artifact of the use of the PMI rather than the MEMP as the reference system. The orientation of the PMI is a part of the solution.

Future Work

- Filling in the tables of the parameters used in modeling the ephemerides
- Examination of the constants of integration, the total angular momentum vector and energy.
- Fourier transform of differences.
- Compute numerical statistics of the differences in the ephemerides
- Comparison of predictions from ephemerides with observations *not* used in their formation
- Construct an extended summary to be made available online, possibly at the IAU Commission 4 web site.

Fourier transform to look for periods as a clue for how the different parameters affect the different ephemerides.

Comparison with observations are easiest for the outer solar system, but difficult for the inner solar system because: 1. Extremely high accuracy of the observations means that conversion from a prediction to an observable requires inclusion of many other parameters in the model. 2. Most, if not all, of the high accuracy observations have already been used in the construction of the ephemerides