PROGRESS REPORT OF THE IAU COMMISSION 4 WORKING GROUP ON EPHEMERIS ACCESS AND THE COMPARISON OF HIGH ACCURACY PLANETARY EPHEMERIDES

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ABSTRACT. In September 2010 IAU Commission 4, Ephemerides, organized a working group to provide a recommendation for a preferred format for solar system ephemerides. The purpose of this recommendation is to provide easy access to a wide range of solar system ephemerides for users. The working group, chaired by Hilton, includes representatives from each of the major planetary ephemeris groups and representatives from the satellite and asteroid ephemeris communities. The working group has tentatively decided to recommend the SPK format developed by the Jet Propulsion Laboratory's Navigation and Ancillary Information Facility for use with its SPICE Toolkit. Certain details, however, must still be resolved before a final recommendation is made by the working group.

An update is also provided to ongoing analysis comparing the three high accuracy planetary ephemerides, DE421, EPM2008, and INPOP10a. The principal topics of this update are: replacing the INPOP08 ephemeris with the INPOP10a ephemeris, making the comparisons with respect to DE421 rather than DE405, and comparing the $TT - TDB$ values determined in EPM2008 and INPOP10a with the Fairhead & Bretagnon (1990, A&A, **229**, 240) model used in DE421 as T_{eph}.

1. THE IAU WORKING GROUP ON EPHEMERIS ACCESS

In September 2010 IAU Commission 4, Ephemerides, organized a working group to provide a recommendation for a preferred format for solar system ephemerides. The members of the working group are J. Hilton (U.S. Naval Observatory, USNO) chair, J.-E. Arlot (Institut de mécanique céleste et de calcul des éphémérides, IMCCE), S. Bell (Her Majesty's Nautical Almanac Office), O. Bratseva (Inst. of Applied Astronomy RAS, IAA), N. Capitaine (Paris Obs.), A. Fienga (IMCCE), W. Folkner (Jet Propulsion Laboratory, JPL), M. Gastineau (IMCCE), E. Pitjeva (IAA), V. Skripnichenko (IAA), and P. Wallace (retired). The membership of the working group includes individuals from the planetary, satellite, and minor planet ephemeris producer and user communities.

The primary objective of the working group is to provide a recommended standard file format and software to give seamless access to the user community of high accuracy planetary and lunar ephemerides. These ephemerides are currently available from IAA in Russia, IMCCE in France, and JPL in the US. Not only must the file format and software be able to handle the positions and velocities of the planets, Moon and Pluto, it must be able to handle ephemerides for the orientation of the Moon and $TT - TDB$, the difference between the Terrestrial Time (TT) and Barycentric Dynamical Time (TDB) timescales.

The format should also be flexible enough to handle asteroids, satellites, and other natural solar system objects. To meet this secondary goal the file format needs to handle arbitrary coordinate origins, highly eccentric orbits, and objects with significant non-gravitational forces. For eccentric orbits and orbits with non-gravitational forces, either the time-segment length or the numerical order of the parameters representing the orbit should vary. An ephemeris with fixed order and time-segment length may be many times larger than one where these parameters are flexible because they must be devised to accurately describe that part of the ephemeris where the greatest change with time occurs. For example: a fixed order ephemeris of N II Nereid can cover with the same accuracy a time-segment at apoapsis that is approximately seven times longer than it can at periapsis. A similar comet Halley ephemeris could have a segment time-segment at apoapsis that is approximately 60 times its periapsis length.

1.1. Existing Formats

The working group started with the four formats in which the high accuracy planetary ephemerides are currently distributed: the CALCEPH format, the Export format, the IAA ephemeris format, and the Spacecraft Planet Kernel (SPK) format. Each format has its strengths and weaknesses as described below.

CALCEPH: The CALCEPH file format and software were designed for use with the Intégrateur Numérique Planétaire de l'Observatoire de Paris (INPOP) ephemerides developed at the IMCCE. Gastineau *et al.* (2011) state that the internal format of the CALCEPH ephemerides is described in Hoffman (1998). Thus, the format of a CALCEPH ephemeris file is similar to the Export format file described below. The main difference is: a CALCEPH file can accept one-dimension ephemerides. The ability to use one-dimension ephemerides allows CALCEPH to elegantly handle the $TT - TDB$ ephemeris. There is also an ASCII version of the INPOP10a ephemeris, which has a significantly different format form the binary version. One reason for the development of INPOP is for use with Gaia; giving CALCEPH a major user. It also means CALCEPH is actively being maintained. To simplify cross-platform use, the CALCEPH software can detect whether the Chebyshev coefficients are stored in big-endian or little-endian order. It is distributed as a linked in library for use with Fortran 77, 95, and 2003 and C with both single and multiple threads. CALCEPH does not currently have a wide user base, however.

Export Format: The Export format was developed by the Solar System Dynamics group at JPL in the 1970s. Since then it has become widely used in the planetary astronomy community. It handles planetary and lunar orbits, lunar orientation, and Earth nutation ephemerides. It evaluates the ephemerides using fixed order Chebyshev polynomials (Newhall 1989). The coefficients for the Chebyshev polynomials are stored in a binary file. The ephemeris reading software, called *testeph.f*, does not detect whether the binary is in big-endian or little-endian order, so the files are distributed in ASCII format and converted to binary by the user with an auxiliary program. The Export format is built around the expectation that the reading software has some *a priori* knowledge of the contents of the ephemeris, such as the reference system and center of each ephemeris. It also assumes that all ephemerides are three dimensional. It packs all of the bodies in the ephemeris into sub-ephemerides with a common time-segment length, making it difficult to use with bodies on highly eccentric orbits. The software is available only in single thread Fortran 77 and has been essentially static for decades. Only minor revisions have been made as necessary. JPL also makes unsupported C and Java versions, written by third parties, available.

IAA Ephemeris Format: The IAA ephemeris format was developed at the IAA for use with its planetary ephemerides at about the same time the Export format was developed. It has been widely available only for the last few years, so it is not well known. It currently handles planetary and lunar orbits and $TT - TDB$ ephemerides. There are plans to include lunar orientation ephemerides in the near future (Yagudina 2011, private communication). Like CALCEPH and the Export format it stores the ephemerides using Chebyshev polynomials of the velocities of the bodies relying on a fixed order for the ephemeris of each planet where the center and reference systems are assumed. Also like the Export format, it assumes all the ephemerides are three-dimensional. However, rather than using a single file, the ephemeris for each body is stored in a separate file. These files can be either in binary or ASCII text format, whichever format is used depends on an initializing function called before starting evaluation. The initializing function stores the entire ephemeris in memory, which allows for fast evaluation, but at the cost of a significant initial delay. The reading software, called *calc_eph* is available in single thread C, Fortran 90, Java, and Pascal. It is actively being maintained by the IAA.

SPK Format: The SPK format is a specialization of the Double precision Array File (DAF) format developed by the Navigation and Ancillary Information Facility (NAIF) at JPL. It was developed for use in the SPICE Toolkit to support spacecraft missions originating at JPL. As such, it has become widely used and is the *de facto* standard in the aerospace community. The SPICE Toolkit is actively maintained by NAIF. The SPK format was developed to handle the position ephemerides of an arbitrary number of solar system bodies each with a specified reference system, center, and three dimensions. The ephemeris can be stored in several different ways including Chebyshev polynomials with fixed or variable time-length segments and as osculating orbital elements. The data in SPK files are stored in binary format, and the SPICE Toolkit is designed to be platform independent. The SPK format was not designed to handle orientation ephemerides, but they may be introduced by including an 'Object ID Number' for each orientation ephemeris. Alternatively, a different specialization of the DAF format called the Planetary

Constants Kernel (PCK) does handle orientation ephemerides. However, the PCK format cannot be used in an SPK file, so this option would require separate files for position and orientation ephemerides. The DAF, and hence the SPK, format is quite complex because it was designed to handle numerous other types of data as well as ephemerides. The SPICE Toolkit is available only in single thread Fortran 77 and may not be optimized for users who want to use it only for ephemeris access.

1.2. Current Status

The working group has tentatively elected to recommend the SPK format subject to meeting the following requirements:

1. There must be a readily available, detailed specification of the appropriate parts of the SPK format for use with ephemeris files,
2. there must be Object ID Numbers added to the SPK format to allow the storage of lunar orientation and $TT - TDB$ ephemerides,
3. a data type must be developed in the SPK format for storage of the IAA ephemerides using the current format of Chebyshev polynomials in their ephemerides,
4. stand alone ephemeris reading software must be made available, and
5. the names and values of the parameters used in the construction of the ephemerides are to be stored in the Comment Area.

The sense of the working group is that it was preferable to store the ephemerides in a single file. Thus, an Object ID Number must be assigned to the current lunar orientation ephemeris. At this time no other solar system object's orientation ephemeris requires an Object ID Number[1].

Storage of the $TT - TDB$ ephemeris as an SPK file also requires the assignment of an Object ID Number. Since the $TT - TDB$ ephemeris is one-dimensional and a PCK ephemeris is expecting three dimensions, there is waste of storage space. That waste, however, is small. Based on the size of the binary $TT - TDB$ ephemeris of IAA's EPM2008, the excess storage is approximately 600 kB for a span of 100 years.

NAIF has agreed to produce both the specification and stand alone ephemeris reading software and will add a new type to handle the IAA style Chebyshev polynomials and required Object ID Numbers for including the lunar orientation and $TT - TDB$ within the SPK ephemeris format.

The Comment Area of an SPK file already will accept any number of records consisting of printable ASCII characters. Thus, meeting the fifth requirement is a matter of discipline on the part of the ephemeris makers.

2. COMPARISON OF THE DE421, EPM2008, AND INPOP10A EPHEMERIDES

This comparison is an extension of the report made at Journées 2010 (Hilton & Hohenkerk 2011). The principle differences between this and the previous report are:

1. The comparisons are made with respect to DE421 rather than DE405,
2. INPOP10a has replaced INPOP08 in the comparisons, and
3. ephemerides of $TT - TDB$ in EPM2008 and INPOP10a are compared to Fairhead & Bretagnon (1990), which is used for $TT - T_{eph}$ in the JPL ephemerides.

2.1. Range, Longitude, and Latitude

The differences between the ephemerides in range, longitude, and latitude are more likely the result of either the inclusion of an important new data set such as the introduction of Galileo observations into INPOP10a or decisions on the part of the ephemeris maker to resolve difficulties such as highly correlated parameters. Ultimately, the one true test of an ephemeris is how well it predicts observations that were not used in its construction.

DE421 has replaced DE405 as the basis for comparison not because DE421 is considered superior to the other ephemerides, but because it is the direct descendent of DE405. The differences between DE421, EPM2008, and INPOP10a are small enough that, if DE405 was used as the basis for comparison the differences with DE405 would tend to dominate over the differences between these three ephemerides.

[1] The Earth's orientation is complex and available from the International Earth Rotation and Reference Frames Service at http://www.iers.org. The orientations of other solar system bodies are poorly known and may be represented as quickly evaluated theories (Archinal et al. 2011).

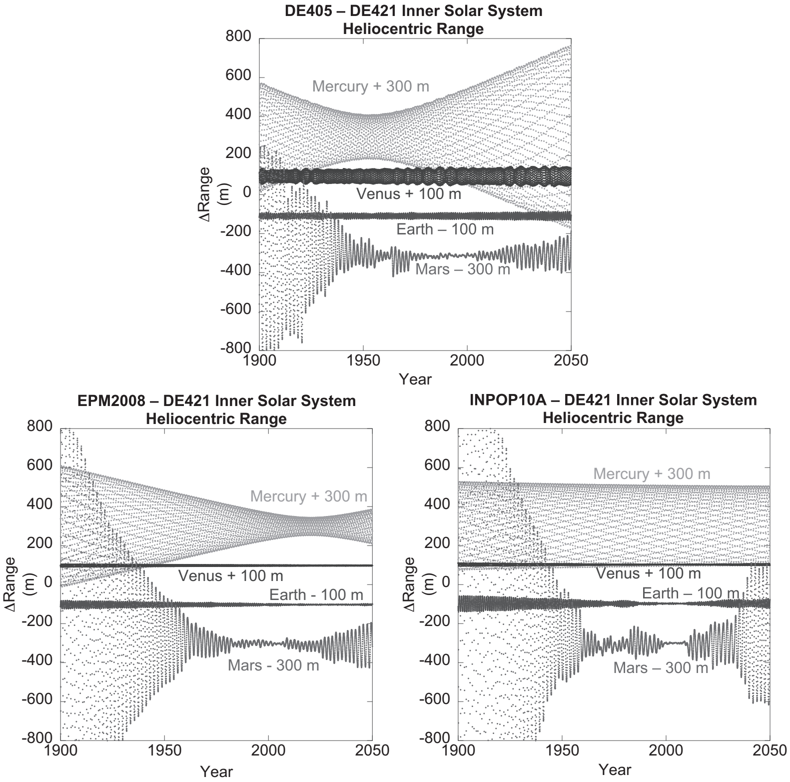

Figure 1: The differences in the heliocentric ranges of the inner solar system planets with respect to DE421.

The Inner Solar System Figure 1 shows the differences in range for the inner solar system planets with respect to DE421. The differences for EPM2008 and INPOP10a for Venus and the Earth are visibly smaller than those for DE405 – DE421.

The distinctive "bowtie" shapes of the DE405 and EPM2008 differences in the range of Mercury are probably the result of a small difference in the mean motion of Mercury in these ephemerides compared to DE421. To account for the size of the differences would require a change in Mercury's mean semimajor axis of 0.6 m for DE405 and 0.4 m for EPM2008. Equivalently, a change in the combined Sun-Mercury mass of 3 parts in 10^{11} for DE405 and 2 parts 10^{11} for EPM2008 would also account for the differences.

The apparently constant envelope for the differences for INPOP10a compared to DE421 is possibly caused by a slight rotation of the ellipse of Mercury's orbit. A rotation of 4 mas, approximately 1.1 km along track, would account for the differences. There is also a small change in the amplitude of the differences with time as in the DE405 and EPM2008 differences. A change of 17 cm in the mean semimajor axis, or 9 parts in 10^{13} in the combined Sun-Mercury mass would account for the rate of change in the differences.

Thus, even such apparently large differences are the result of minute changes in the models used by the different ephemeris makers.

Jupiter and Saturn Figure 2 shows the most dramatic differences between the ephemerides are for Jupiter and Saturn. The differences in the more recent ephemerides with respect to DE405 are so great that the scale for the DE405 – DE421 differences is two orders of magnitude greater than the one used for the EPM2008 – DE421 and INPOP10a – DE421 differences.

The improvement of these two ephemerides are the result of recent spacecraft data. DE405 includes both Galileo and Ulysses data, but is pre-Cassini. Thus, the DE405 – DE421 differences for Jupiter are smaller than those for Saturn. Similarly, INPOP10a's Jupiter ephemeris is superior to that of INPOP08 (Hilton & Hohenkerk 2011) because one of the differences between INPOP08 and INPOP10a is the inclusion Galileo data.

The change with time in the range of Jupiter between EPM2008 and DE421 can be explained by a

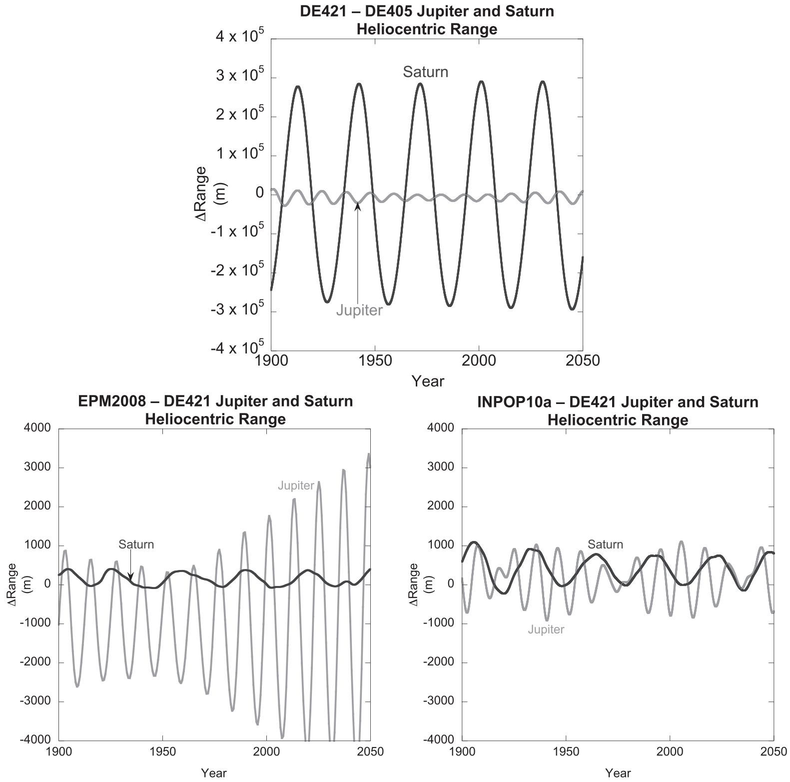

Figure 2: The differences in the heliocentric ranges of Jupiter and Saturn with respect to DE421.

difference in its semimajor axis of approximately 1100 m between the two ephemerides. The approximate mean difference measured from Figure 2 is 900 m. The uncertainty in both the required change in the semimajor axis and the measured offset are on the order of tens to hundreds of meters. Again, a small difference in this one parameter may be responsible for the difference.

2.2. $TT - TDB$

The independent argument for the ephemerides is Barycentric Dynamical Time (TDB), the coordinate time for the barycentric reference system. The realization of this time scale is called T_{eph} in the JPL ephemerides. The value of $TT - T_{eph}$ is determined using the algorithm of Fairhead & Bretagnon (1990), henceforth $F\&B$. Both EPM2008 and INPOP10a determine $TT-TDB$ from the ephemerides themselves using an iterative process. Figure 3 shows the difference in $TT - TDB$ for these two ephemerides with respect to $F\&B$. The points are the differences at 10 day intervals and the lines are five year running averages.

Determination of $TT - TDB$ in both EPM2008 and INPOP10a include the masses and orbits of minor planets not used in $F\&B$. Over a long enough time period there should be no mean difference in the value of $TT - TDB$. However, the orbits of these bodies are non-commensurate, so the timescale over which the differences average out is expected to be orders of magnitude longer than to their orbital periods (2-10 yr for main belt objects and $>$ 170 yr for trans-Neptune objects, TNOs). As a result, the gravitational potential at the barycenter is different than for $F\&B$. And the mean rate of TDB determined using the ephemerides will be somewhat different. Over the period of comparison, the mean difference is approximately linear. The mean slope, determined from a least-squares fit to the five year running average, is 0.12 ns yr^{-1} for EPM2008 and 0.03 ns yr^{-1} for INPOP 10a. The steeper slope for EPM2008 is explained by the inclusion of 20 large TNOs other than Pluto in its model. Hilton & Hohenkerk (2011) give another demonstration of the effect of including the TNOs in EPM2008 on the position heliocenter of with respect to the barycenter. The relatively short periods of approximately 300 main belt objects cause a pseudo-random motion of the heliocenter about its short-term mean position. This motion about the mean position is apparent in the points at 10 day intervals which form envelopes approximately 10 ns wide around the mean slope of each difference. At the current epoch there is an approximately 3-4 ns

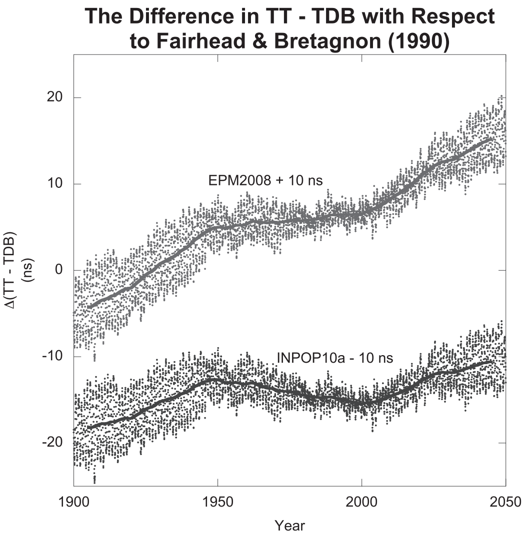

Figure 3: The differences in $TT - TDB$ in EPM2008 and INPOP10a with respect to Fairhead & Bretagnon.

offset between the $F\&B$ value for $TT - TDB$ and those of EPM2008 and INPOP10a.

3. DISCUSSION

The IAU Working Group on Ephemeris Access has tentatively agreed to standardize on SPICE Toolkit's SPK format. NAIF, the group at JPL that maintains the SPICE Toolkit, will assign body identification numbers for $TT - TDB$ and the lunar orientation angles so they may be included in SPK format files. A specification of that format for the fixed length Chebyshev polynomial formats is currently being written. A type to handle the IAA's velocity based Chebyshev polynomials and stand alone SPK file format reading software will be taken care of next. Other details, such as whether to include the SPK Type 14 (Chebyshev polynomials with unequal time steps) for highly eccentric orbits or to develop a type for planetary theories, will be taken up at a later date.

The comparison of the DE421, EPM2008, and INPOP10a is continuing using DE421 as the basis for comparison to remove the larger differences between DE405 and these three ephemerides. The inclusion of Galileo observations in INPOP10a makes this ephemeris a significant improvement over INPOP08. $TT - TDB$ for INPOP10a and particularly EPM2008 show both short term variations and secular slopes compared to the Fairhead & Bretagnon (1990) algorithm used for the same purpose for the JPL ephemerides. These differences are attributed to the inclusion of main belt asteroids and, in EPM2008, 20 trans-Neptunian objects other than Pluto in the determination of $TT - TDB$.

4. REFERENCES

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