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GAIA DPAC INPOP final release: INPOP10e

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1 Presentation of the INPOP10e ephemerides

1.1 Main facts

Since the Gaia DPAC planetary ephemeris release in 2007 (called INPOP06b in the following), much improvements have been applied for improving the orbit accuracy and the extrapolation capabilities. Two complete versions have been published: INPOP08 ([6]) and INPOP10a ([5]) and several other improved versions have been developed such as INPOP10d ([4]) or INPOP10d ([27]), meanly oriented towards the improvement of the determinations of the asteroid masses.

The integration of the differences between the TDB and TT time scales (as well as TCG-TCB) have been implemented in order to ensure the consistency between the time scales and the planetary ephemerides ([6]).

Adjustment of the mass of the sun is now performed as recommended by the IAU [2] when with INPOP06b both the astronomical unit and the mass of the sun were fixed. Estimated values of the mass of the sun, the sun oblateness (through the J_2 coefficient) and of the ratio between the mass of the Earth and the mass of the Moon (EMRAT) are given in Table 2. Masses of the planets have been updated as well (see Table 1). Their values were extracted from the best estimated values list defined by the IAU ([20]).

Sophisticated procedures have been implemented for the asteroid mass determinations. For this release (called INPOP10e), bounded values least square [19] have been associated with a-priori sigma estimators ([17]). Corrections of the solar corona perturbations over the radiometric measurements have also been applied ([27]). In total, 152 asteroid masses have been estimated. In Tables 8, 9 and 10 of the appendix, are presented and compared to values found in the recent literature, asteroid masses inducing more than 3 meters over the Earth-Mars distances during the observed time period (from 1970 to 2012).

In terms of data sample used for the ephemeris adjustment, as one can see on figure 1, since INPOP06b a big amount of crucial data have been added. For the inner planets, MEX and VEX radar tracking and VLBI data have an important impact for the quality of the Mars and Venus orbits as well as for the link between the inner planet orbits and the ICRF. Messenger flybys data of Mercury were also important for the improvement of this orbit. For the outer planets, the positions deduced from the flybys of spacecraft are also crucial for the construction of the new version. The role of the Cassini tracking and VLBI data have to be emphasized as well as the Jupiter flyby positions and the Galileo VLBI tracking data. Uranus and Neptune also benefited from the use of positions deduced from the Voyager 2 flybys.

The link to ICRF is thus maintained by the VLBI observations of spacecraft.

Moon libration parameters, Moon and Earth potential coefficients and Earth-Moon barycenter mass were also obtained by adjustment to LLR observations.

Furthermore, as part of the INPOP ephemerides, informations about the Pluto ephemeris are also given here even if not requested by DPAC.

1.2 Estimation of uncertainties

1.2.1 Comparisons to observations

The INPOP10e observational sample has 3 times more data than the INPOP06b one which ended in 2005.45. The statistical distribution of the supplementary data sets is not uniform and is mostly constituted with MEX and VEX observations (60 %). However, the two flyby points of Uranus and Neptune and the five flybys of Jupiter are of crucial importance for the accuracy of these orbits. The

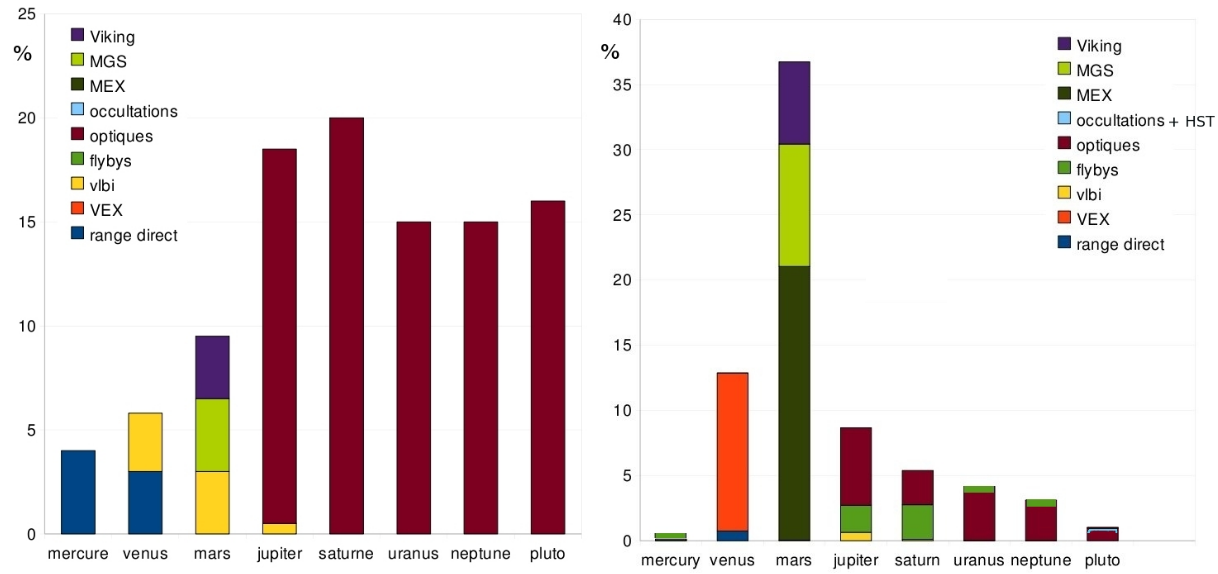

Figure 1: Data sample distribution used for the construction of INPOP06b on the left-hand side and of the last INPOP version of the right-hand side. Uranus, Neptune and Mercury flyby contributions are oversized for representation purposes.

Table 1: Fixed values of planetary masses.

Planet	INPOP10e ($M_\odot$ / M)	Ref.	INPOP06b ($M_\odot$ / M)	DE423 ($M_\odot$ / M)
Mercury	6.0236×10^6	[1]	6.0236×10^6	6.0236×10^6
Venus	4.08523719×10^5	[15]	4.0852371000×10^5	4.08523719×10^5
Mars	3.09870359×10^6	[16]	3.0987080×10^6	3.09870359×10^6
Jupiter	1.0473486440×10^3	[8]	1.0473486250×10^3	1.0473486254×10^3
Saturn	3.4979018×10^3	[10]	3.4978980×10^3	3.4979018×10^3
Uranus	2.290298×10^4	[11]	2.2902980×10^4	2.290298×10^4
Neptune	1.941226×10^4	[9]	1.941224×10^4	1.941224×10^4
Pluto	1.36566×10^8	[26]	1.352×10^8	1.35837×10^8

Table 2: TCB values of parameters obtained in the fit of INPOP10e and INPOP06b to observations.

	INPOP10e $\pm 1\sigma$	INPOP06b $\pm 1\sigma$	DE423 $\pm 1\sigma$
(EMRAT-81.3000)$\times 10^{-4}$	(5.700 $\pm$ 0.020)	5.6	(5.694 $\pm$ 0.015)
$J_2^{\odot} \times 10^{-7}$	(1.80 $\pm$ 0.25)	(1.95 $\pm$ 0.5)	1.80
$GM_\odot$ - 132712442000 [$km^3.\ s^{-2}$]	(107.89 $\pm$ 1.3)	75.72	98.68
AU - 1.49597870700 $\times 10^{11}$ [m]	0.0	-9.0	(-0.3738 $\pm$ 3)
[$M_\odot$ / M_{EMB} - 328900]	0.55223 $\pm$ 0.004	0.56140	0.55915 $\pm$ NC

three positions of Mercury deduced from the Messenger flybys play also an important role for the Mercury orbit determination even if their distribution in time was very limited (less than 2 years). The residuals given in Tables 5 and 6 confirm the improved quality of the INPOP10e orbits compared to INPOP06b. By providing measured distances between the Earth and the outer planets, the flyby data brought new information to the fit when only optical observations were used in the INPOP06b adjustment. As a result, one can notice the satisfactory INPOP06b residuals obtained for the outer planet flybys in right ascension and declination (at the level of the accuracy of the optical data used in the INPOP06b fit) but the very poor estimations in distances.

The residuals given in Tables 5 and 6 give then the limits of the present fit accuracy of planetary ephemerides especially for Uranus and Neptune geocentric distances. For these two planets the DPAC requirement ([22]) of an uncertainty in positions of few kilometers over the Gaia period will then not be reached.

For Jupiter, the expected accuracy of the ephemerides will not be better than the postfit residuals obtained by comparison to flyby positions which reach up about 2 kilometers. This could meet the DPAC requirement if no secular trend arise after the end of the fitting interval in 2001. Unfortunately, no direct accurate observation of Jupiter (such as radio or VLBI tracking of a spacecraft in its vicinity) are planned before the Gaia period. Calibration of possible Jupiter orbit degradation would only be partially possible through indirect constraints from Cassini Solstice mission, Dawn, Messenger, Mars orbiters ...

With the Cassini observations, the accuracy of the Saturn orbit has been highly improved. Residuals in geocentric distances have been decreased from several hundred kilometers to few ten meters during the Cassini period of time. This again could meet the DPAC requirement if no degradation of the orbit grows up with time. However, contrary to Jupiter, new Saturn positions would be obtained during the Cassini Solstice mission through 2017 and would then be helpful for constraining the Saturn orbit over the Gaia period.

For the inner planets, the requirements in positions will be meet with no difficulty thanks to spacecraft tracking data of Mars orbiters, VEX and Messenger missions. We note however a rapid degradation of the Mars orbit accuracy as estimated by comparison between planetary ephemerides and observed MEX distances not included in the fit of the ephemerides. Such comparisons are called extrapolation in the Table 6. The differences between estimated distances and the observed one reach up to 30 meters after 32 months and are mainly due to unmodeled perturbations of main-belt asteroids.

1.3 Lunar Laser Ranging constraints

The preliminary delivery of INPOP ephemeris for Gaia was based on the INPOP06b ephemerides and some parameters related to the Moon (initial conditions and time delays in Earth's tides) were fitted to the Earth-Moon distances deduced from DE405. Since INPOP08a, the initial conditions of the Moon orbit and angles of rotation are directly fitted to Lunar Laser Ranging observations which are laser measurements of the light time delay between a station on the Earth and one of the five reflectors on the Moon. With INPOP10e, more than 19000 data are available, from the end of 1969 to 2012. They are provided by several sites: Cerga (Grasse, France), Mc Donald (Fort Davis, Texas, USA), Haleakala (Hawaii, USA), Apollo (New Mexico, USA) and Matera (Italy). Their accuracy is estimated to reach up to 1 centimeter for the best of them and they give constraints not only on the orbital motion of the Moon around the Earth, but also its rotational motion.

About 200 parameters could have a significant effect on LLR observations: initial conditions of the Earth-Moon vector or Moon's librations, coefficients of potential, coordinates of stations, of reflectors, biases in measurements, ... But because of large correlations or better estimates obtained with other techniques, only 65 of them are regularly fitted during the INPOP construction. They have been chosen so that the ratio between the formal error (given by the least-square fit over the fitted value) is smaller than 5%. INPOP estimated values of the parameters related to the dynamical model are given in Table 12 when LLR residuals are shown in Table 11 and figure 7.

1.3.1 Uncertainty in the link to ICRF

As described previously, the tie between INPOP ephemerides and the ICRF is maintained by the use of VLBI differential observations of spacecraft relative to ICRF sources. Such methods give milliarcsecond (mas) positions of a spacecraft orbiting a planet directly in the ICRF. Combining such VLBI observations with spacecraft navigation, positions of planets can be deduced relatively to the ICRF sources. The link between modern planetary ephemerides and the ICRF is then obtained at the accuracy of the VLBI localization of the space missions. With the INPOP10e version, such tie was sustained by the addition of new VLBI tracking data of inner planets (for Mars, the number of VLBI positions came from 44 to 96, and from 18 to 46 for Venus) and of outer planets. The VLBI observations of Saturn deduced from the Cassini mission were there decisive for disentangling the ICRF link to outer planet reference frame from the VLBI Galileo positions which were the only available for outer plan ets at the time of the INPOP06b adjustment. Based on the most recent Mars and Cassini VLBI observations, the link between the INPOP10e reference frame and the ICRF is maintained with an accuracy of about 1 mas for the last 10 years.

1.3.2 State-of-art uncertainties

In order to better estimate the INPOP10e uncertainties, especially for the Earth positions and velocities in the BCRS, comparisons are made over the extended period of the Gaia mission (from 2013 to 2020) and over the period of validity of the required chebychev polynomials (from August 2002 to October 2021) between INPOP10e, INPOP10d ([27]), INPOP06b and DE423 ([7]) in cartesian coordinates (Table 7). With these figures, differences in the dynamical modeling, fitting procedures and data sample can be impacted on planetary positions and velocities.

The DE423 ephemerides have been fitted on a data sets similar to the INPOP10e one. Fitting procedures differ with less asteroid masses adjusted in DE423 (63) and smoother behavior in the Mars residuals during the fitted period. INPOP10d differs from INPOP10e only by new corrections in the Messenger data and the use of very recent observations of Uranus [28] inducing modifications in the weighting schema of the adjustment. The fitting procedures are similar as well as the number of estimated parameters. As described previously, INPOP06b was fitted with a reduced sample data compared to INPOP10e and with far less estimated parameters (5 asteroid masses). Differences between INPOP10e and INPOP06b are given in order to materialize the modifications brought to the former DPAC INPOP version when differences between INPOP10e, DE423 and INPOP10d can be seen as good estimations of the state-of-art uncertainties of planetary ephemerides.

As noticed previously, the uncertainties of the positions of inner planets are below the DPAC requirements. For Jupiter, the uncertainty is about 2 km in the BCRS in the most optimistic case (INPOP10e-DE423) during the extended Gaia period and the chebychev period of validity but can also reach up to 30 km for both periods. Due to these important variations from one ephemerides to an other and to the expected lack of accurate Jupiter observations in the near future, the accuracy of the Jupiter orbit is not guaranteed to meet the DPAC requirements at the time of the Gaia mission. For Saturn, the ephemerides are about the DPAC requirements with differences up to 5 kilometers in the BCRS positions. For Uranus and Neptune, the important differences illustrate the lack of accurate estimations of distances for these objects. The DPAC recommendations about the uncertainties of the planet velocities are met for all the planets.

The specifications for the BCRS Earth velocity (2.5 mm.s^{-1}) will be met easily (see figure 3) but not for the positions. Differences in Earth BCRS positions obtained for several planetary ephemerides (see figure 2) are always bigger than 0.15 kilometer, required for the DPAC delivery. Comparisons between DE423 and DE421 which differ mainly by the data sample are equivalent to those obtained with the two consecutive INPOP versions. In the case of INPOP10e and INPOP10d, these figures can be explained up to 85 % by differences in the estimation of the mass of the sun.

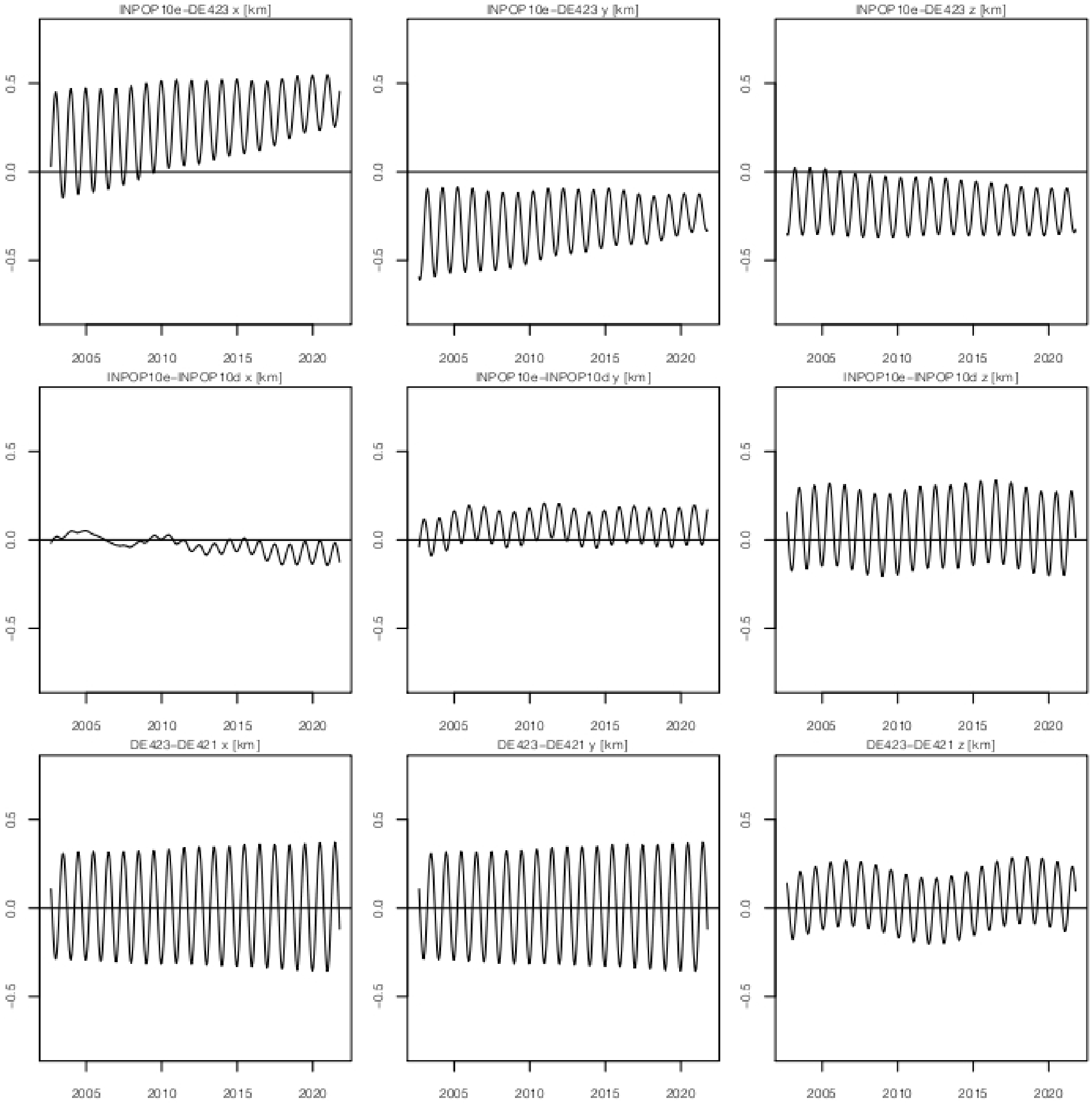

Figure 2: Differences in Earth barycentric positions in the BCRS estimated with INPOP10e, DE423, INPOP10d and DE421

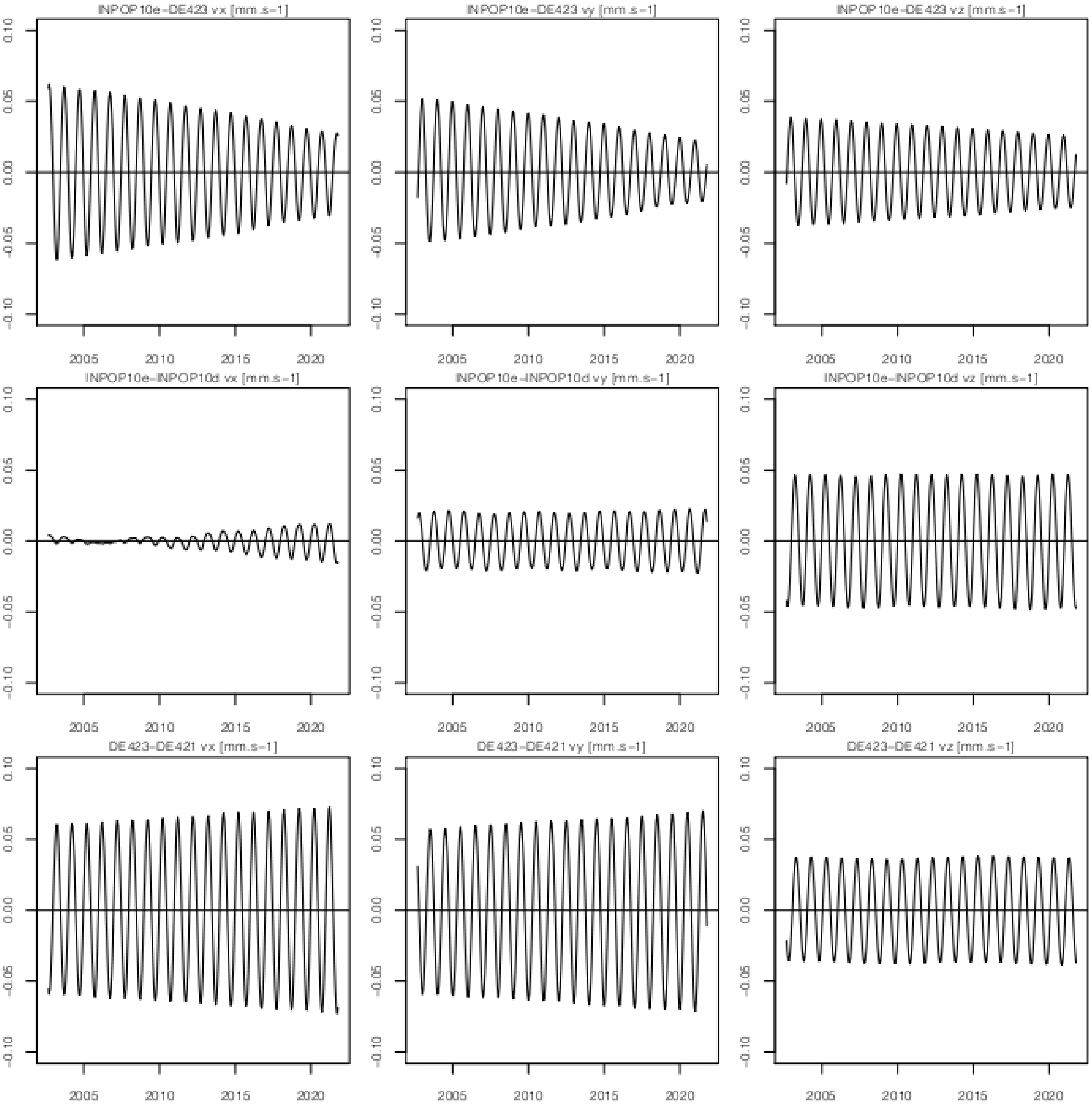

Figure 3: Differences in Earth barycentric velocities in the BCRS estimated with INPOP10e, DE423, INPOP10d and DE421

2 INPOP10e Chebychev delivery

The INPOP ephemerides are computed by numerical integration of the equations of motion of planets, the Moon and of a selection of asteroids. Values of the state vectors (containing the position and velocity vectors of the bodies, their orientations or differences on timescales) of the planets and of the Moon are thus available for discrete values of time, separated by the output stepsize. They constitute what will be called in the following, the Integrated Ephemeris (IE). To estimate the values of a state vector at any time, it is necessary to calculate an interpolation of the integrated values, usually a Chebychev representation of the IE. The whole timespan is divided into small intervals of several days (called granules), and, on each interval, a polynomial function is computed. This polynomial function is a linear combination of Chebychev polynomials. It is designed to minimize the differences with the IE and to ensure the continuity and derivability at each granule boundary.

2.1 From a TDB to TCB ephemeris

The construction (integration of equations of motion, analysis of the observations and adjusment of parameters) of INPOP ephemerides is always performed using TDB time scale: the initial conditions (at January 1st 2000 12h00 TDB) and parameters are given in TDB. During the analysis of the observations used for the INPOP adjustement, the relation TT-TDB is used to link the time-scale used for the observations (UTC, TT or TAI) and the time-scale of the numerical integration (TDB).

For Gaia , the ephemeris must be distributed in TCB using the IAU definition ([24, Resolution B.3]):

$$TCB - TDB = L_B \times (TCB - T_0) \times 86400 - TDB_0 \qquad (1)$$

where $TCB - TDB$ is given in second, $L_B = 1.550519768 \times 10^{-8}$, $T_0 = 2443144.5003725$ and $TDB_0 = -6.55 \times 10^{-5} s$.

In order to obtain an ephemeris in TCB, two approaches are possible.

1. to compute an IE in TDB and then to shift all values of state vectors into TCB using expressions from [12]:

   - julian days: $JD_{TCB} = JD_{TDB} + [L_B \times (JD_{TDB} - T_0) - TDB_0] \times (1 - L_B)^{-1}$
   - positions: $\mathbf{r}_{TCB} = (1 - L_B)^{-1} \times \mathbf{r}_{TDB}$
   - velocities are unchanged: $\mathbf{V}_{TCB} = \mathbf{V}_{TDB}$
   - angles are unchanged: $\alpha_{TCB} = \alpha_{TDB}$
   - angular velocities: $\dot{\alpha}_{TCB} = (1 - L_B) \times \dot{\alpha}_{TDB}$

   The obtained ephemeris will be called $\text{I10eTCB}_{\text{TDB}}$ in this section.

2. to shift all initial conditions and parameters from TDB to TCB before the integration of the equations of motion:

   - gravitational constants: $GM_{TCB} = (1 - L_B)^{-1} \times GM_{TDB}$
   - mean equatorial radii of bodies: $R_{TCB} = (1 - L_B)^{-1} \times R_{TDB}$
   - initial positions: $\mathbf{r}_{TCB} = (1 - L_B)^{-1} \times \mathbf{r}_{TDB}$
   - initial velocities are unchanged: $\mathbf{V}_{TCB} = \mathbf{V}_{TDB}$
   - initial angles are unchanged: $\alpha_{TCB} = \alpha_{TDB}$

- initial angular velocities: $\dot{\alpha}_{TCB} = (1 - L_B) \times \dot{\alpha}_{TDB}$
- time delays (tides effects) : $\tau_{TCB} = (1 - L_B)^{-1} \times \tau_{TDB}$
- secular variation of Earth's J_2 due to post-glacial rebound: $\dot{J}_{2,TCB} = (1 - L_B) \times \dot{J}_{2,TCB}$
- other parameters (Love numbers, coefficients of potential, ...) are unchanged

The deduced ephemeris will be called $\mathrm{I10eTCB}_{\mathrm{TCB}}$ in this section.

With the comparison between $\mathrm{I10eTCB}_{\mathrm{TDB}}$ and $\mathrm{I10eTCB}_{\mathrm{TCB}}$ we can check not only the consistency of the 2 methods, but also that all parameters (physical quantities or initial conditions) related to the dynamical model have been correctly transformed from TDB to TCB. If integrations are performed using extended precision (round up error of about 10^{-19}), the differences depend on bodies but are always less than 0.01 millimeter over 30 years around J2000 (see figure 4). If quadruple precision is used (round up error of about 10^{-34}), differences are smaller than 2×10^{-17} millimeter.

The TCB Chebychev representation dedicated to Gaia is based on the IE directly integrated in TCB, $\mathrm{I10eTCB}_{\mathrm{TCB}}$.

2.2 Chebychev representations for INPOP website

When building a Chebychev representation from an IE, the choice of the granule size and the number of coefficients for the interpolation function (order) is done so that the interpolation error (see following section) is lower than a specified value. It also depends on the evolution of the interpolated parameter: a variable (like the coordinates of the Moon) facing high frequency secular variations needs a lower granule size or a higher order than a variable with lower frequency variations (like the positions of Jupiter for example).

On INPOP website (`www.imcce.fr/inpop`), among all possible values of granule sizes and orders matching the error specification, the one that minimizes the size of the ephemeris (total number of coefficients over the whole timespan) is choosen.

In order to estimate the accuracy of the representation, 2 IE have been built. For the first one, the output step size (about 0.2767 days) is equal to 5 times the integration step size (about 0.05534 days). The Chebychev representation is based on this first IE. The second one has an output step size of 51 times the same integration step size, in order to have the same evolution of the state vector (1 point over 5 is common and equal to the first integration), and to have access to output values that were not available in the first IE when building the Chebychev representation.

The accuracy of the Chebychev representation is then estimated by comparison with the second IE. The obtained results (values of maximum differences) are given in Column 4 of the Table 3 as well as the description (granule and order) of the representation (Columns 2 and 3).

2.3 Chebychev representations for Gaia delivery

2.3.1 CPU speed up

Instead of minimizing the total number of coefficients, it could be interesting to speed up the calculation, and thus to minimize the order of the polynomials. To keep the same (or better) interpolation error, it is necessary to reduce the granule size. The Chebychev construction process should not create information, that is the number of coefficients per granule should not exceed the number of outputs of the integration. With an output step size of about 0.2767 day, the order is limited to 3 for 1 day granules, 7 for 2 day granules, and so on... In order to have higher order on small granules, the output step size is changed from 5 to 2 times the integration stepsize. Its

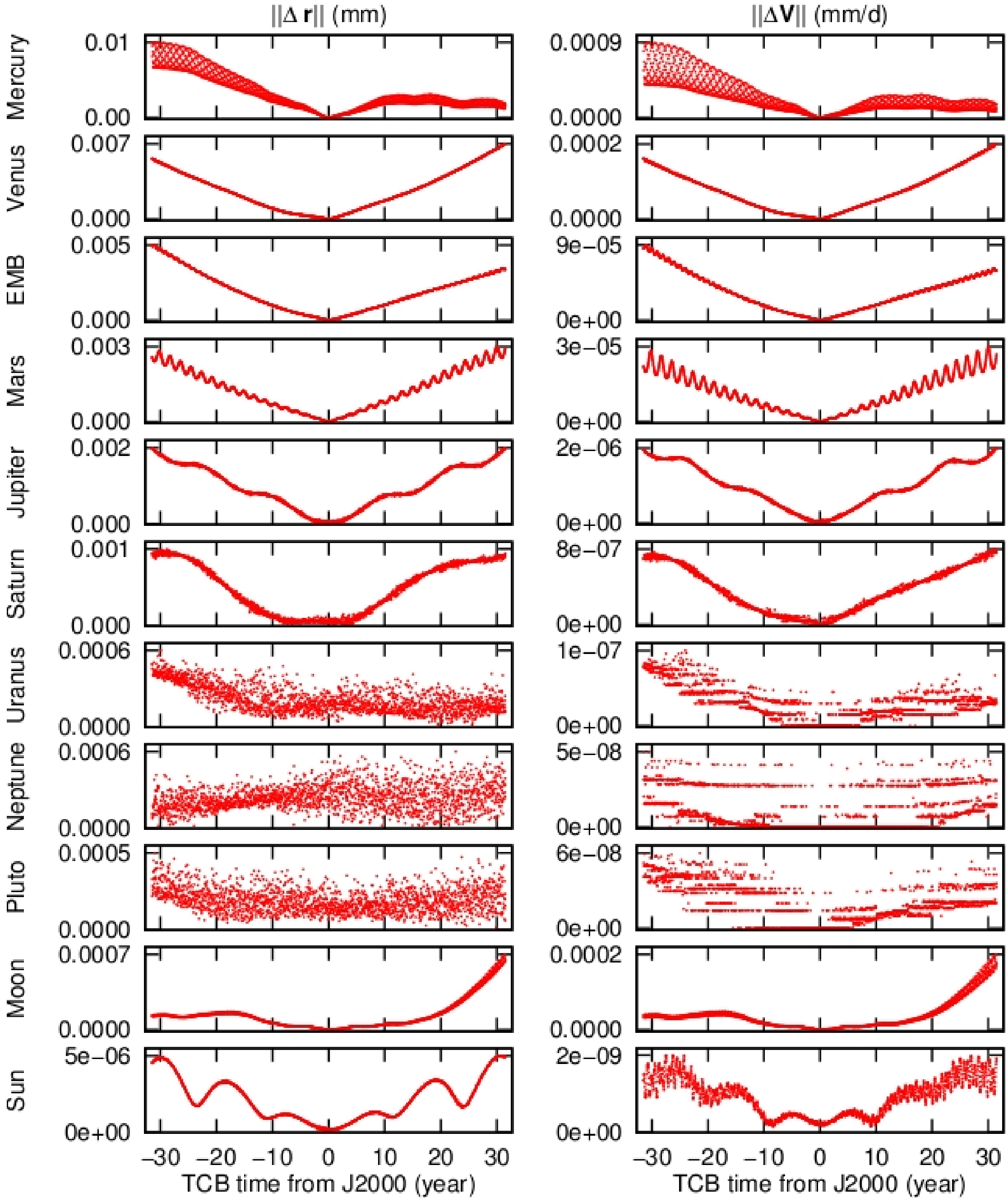

Figure 4: Differences on positions ($\Delta\mathbf{r}$ in millimeters) and velocities ($\Delta\mathbf{V}$ in millimeters per day) of bodies between an ephemeris integrated in TDB and then transformed to TCB (I10eTCB$_{\mathrm{TDB}}$), and an another one integrated directly in TCB (I10eTCB$_{\mathrm{TCB}}$). Both integrations have been performed using extended precision. If quadruple precision is used, the differences do not exceed 2×10^{-17} mm for positions and 10^{-18} mm/day for velocities.

new value of about 0.1107 day allows to compute Chebychev representations with order 9 on 1 day granules, 18 on 2 day granules, and so on...

A new set of parameters (granule size, order) is thus determined, with the constraint to keep the same (or smaller) interpolation error as on INPOP website representation, but with the lowest order. Their values are given in Columns 6 and 7 of the Table 3 and interpolation errors along time are plotted on figures 5 and 6.

As one can see on figure 5, the interpolation error does not look like numerical noise: especially for Mercury, Jupiter and Saturn. The noticeable picks correspond to the date when the planets reach their perihelion, when the variation of both position and velocity are the fastest. With the same granule size and order for the entire orbit, it is expected that the interpolation error is the highest at these periods.

2.3.2 Format description

The format is the same as for the files provided on INPOP website. It is described in `www.imcce.fr/inpop/fileformatascii_inpop10a.txt`.

```
Example and description of the header for the ascii ephemeris file.

Name of the ascii files :
- xxx_pos_xxx (position)
- xxx_vel_xxx (velocity)


Example of the header for the ascii ephemeris file :
-----------------------------------------------------

version :  2012.1025
Uranus     Barycenter equator position km     3           4           2       11936  0   0.0   0             2439609.00 0            2463481.00 0
             2439609.00             2439611.00   -0.27172776522534242D+10   -0.71465424613374882D+05   +0.32924640858514977D+02   +0.14008920243213652D-03

Explanation of each record (or line):
-------------------------------------

Header first record : self explanatory
---------------------

Header Second record :
----------------------
Body      values : [Sun, Mercury ...., Neptune, Moon, Libration, TT-TDB ]  "Libration" meaning "libration of the Moon"
Origin    value  : [Barycenter, Geocentric] "Barycenter" meaning "BCRS", "Geocentric" meaning "center of the Earth is the origin"
Frame     value  : [equator]    meaning ICRF
Type      values : [position, velocity, angle, ang.vel.] "ang.vel." meaning "angular velocity"
unit      values : [AU, AU/day, km, km/day, m, m/s, rd, rd/day]  "rd" meaning "radian"

dimensionality   integer      number of line per interval of time ( here this  3 is for x, y, z or vx, vy, vz, 1 for TT-TDB)

order         integer      number of coefficients for each interval and each scalar quantity
                              notice that order = degree + 1

span          real         length in days of the standard intervals of each period covered with one expansion

N_s           integer      number of standard intervals of length span in the file

0            integer       (unused, always 0)

0.0          real          (unused, always 0.0)

0            integer       (unused, always 0)

Jd_beg        days         first date of validity of the file in julian days
                           given in two doubles with integral part and then fractional part.

Jd_end        days         last date  of validity of the file  in julian days
                           given in two doubles with integral part and then fractional part.

                           notice : this is not an independent parameter, but this is useful
                           to test that the date of call is always inside this interval.

Body of the file
----------------
Each record contains :
- Jd_beg        days      first date of validity of the record
- Jd_end        days      last date of validity of the record
- the n Chebyshev coefficients (n = order) for one scalar component within an interval of length span.
There are in total in each file dimensionality*N_s records (or lines) with the coefficients.
```

Table 3: Accuracy of the Chebychev representations (INPOP website and Gaia dedicated delivery) for each body and timescale. The granule size is in days. The order is the number of coefficients in the representation, that is degree+1 of the polynomial function. The error estimate is the maximum difference between the Chebychev representation and the integration. Errors are expressed in mm for positions, in mm/day for velocities and in picosecond for TT-TDB. SSB means Solar System barycenter.

	INPOP website				Gaia dedicated delivery			
	Granule	Order	Error estimate		Granule	Order	Error estimate	
SSB-Sun vector	16	11	position	0.7	2	5	position	0.6
			velocity	0.4			velocity	0.1
SSB-Mercury vector	8	14	position	2.9	1	8	position	0.3
			velocity	2.1			velocity	0.11
SSB-Venus vector	16	10	position	17	1	6	position	0.4
			velocity	11			velocity	0.01
SSB-EMB vector	16	13	position	1.9	1	6	position	0.09
			velocity	1.8			velocity	0.003
SSB-Earth vector	4	13	position	0.09	1	9	position	0.09
			velocity	0.008			velocity	0.002
SSB-Mars vector	32	11	position	12	1	5	position	4.0
			velocity	5.9			velocity	0.08
SSB-Jupiter vector	32	8	position	2.0	4	5	position	1.3
			velocity	0.4			velocity	0.003
SSB-Saturn vector	32	7	position	3.3	1	4	position	1.7
			velocity	0.08			velocity	0.001
SSB-Uranus vector	32	6	position	8.3	2	4	position	4.8
			velocity	0.02			velocity	0.0007
SSB-Neptune vector	32	6	position	12.2	2	4	position	6.4
			velocity	0.003			velocity	0.0004
SSB-Pluto vector	32	6	position	11.8	2	4	position	6.3
			velocity	0.003			velocity	0.0005
Earth-Moon vector	4	13	position	0.5	1	9	position	0.02
			velocity	0.7			velocity	0.02
TT-TDB	4	12	time	1.5e-5	1	8	time	2.8e-6

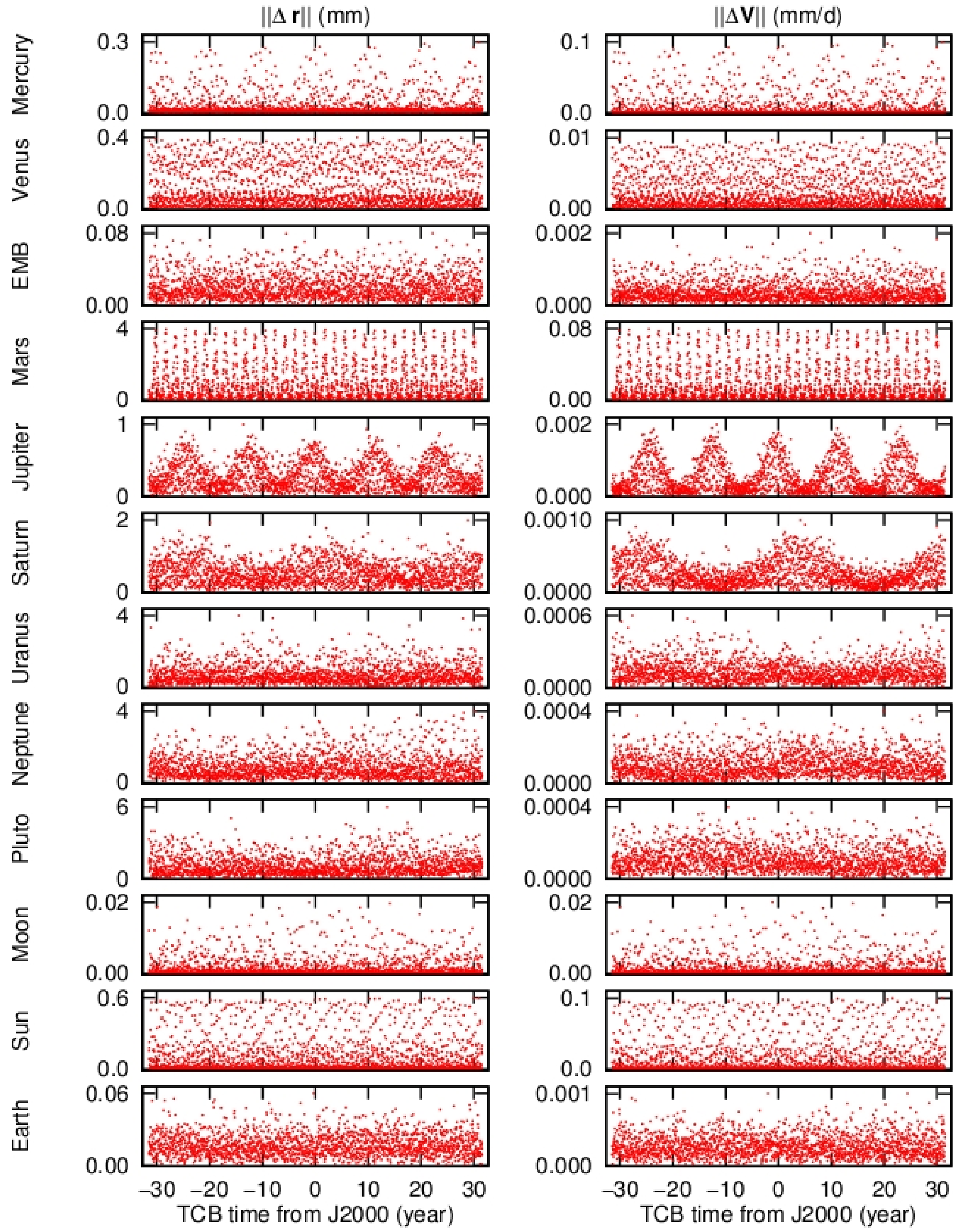

Figure 5: Interpolation error on position ($\Delta\mathbf{r}$) and velocity ($\Delta\mathbf{V}$) for all bodies: comparison between integration in TCB and its Chebychev representation (Gaia dedicated delivery).

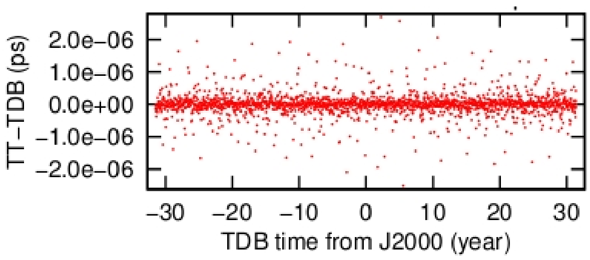

Figure 6: Interpolation error for the TT-TDB : differences between integration in TDB and its Chebychev representation (Gaia dedicated delivery).

2.3.3 Header format

The parameters related to the dynamical model of INPOP are available in "I10e_GAIA20121025_TCB_header.asc" and "I10e_GAIA20121025_TDB_header.asc", for both TCB and TDB timescales. These files are similar to those of the public delivery provided on INPOP website. The meanings and units are explained in Table 4.

The file "I10e_GAIA20121025_TCB_header2.asc" is specific to the Gaia dedicated delivery; it contains the same information as the standard file "I10e_GAIA20121025_TCB_header.asc", but a third column has been added to give values using kilometers and seconds when the second column of the file gives the values using AU and days (only the secular variation of Earth's J_2 has been kept in century^{-1}):

- GMs of all bodies (GM_AAA, MAXXXX, GM_RIN): AU^3/day^2 $\rightarrow$ km^3/s^2
- initial conditions for bodies positions (X_AAA, Y_AAA, Z_AAA): AU $\rightarrow$ km
- initial conditions for bodies velocities (XD_AAA, YD_AAA, ZD_AAA): AU/day $\rightarrow$ km/s
- angular velocities (X_LIBM, Y_LIBM, Z_LIBM, OMEGAE): rad/day $\rightarrow$ rad/s
- time delays for tides effects (TAUE0, TAUE1, TAUE22, TAUM): day $\rightarrow$ second
- the radius of the asteroid ring (RRING): AU $\rightarrow$ km

Their TCB values using the kilometer and the second are given in Table 13.

Table 4: Meaning of parameters given in header files ("I10e_GAIA20121025_TCB_header.asc" and "I10e_GAIA20121025_TDB_header.asc"), with their units.

NCONST	number of parameters given in the file
EMRAT	Earth/Moon mass ratio (no unit)
AU	astronomical unit, in kilometers
KSIZER, FVERSI, FORMAT	not relevant
VERSIO	date, month and day of construction of the ephemeris files (e.g.: 0.20121025D+04 means 20121025 = October 25th 2012)
UNITE	1: Chebychev interpolation provides positions in km and velocities in km/day
CLIGHT	velocity of light, in kilometer/second
GM_AAA	product of the gravitational constant G by the mass of the body AAA, in AU^3/day^2
JDEPOC	initial date of integration (always January 1st, 2000 at 12h00 TDB), in julian day of the ephemeris timescale
GAMMA, BETA	post-newtonian parameters γ and β (no unit)
RSUN	mean equatorial radius of the Sun, in kilometer
RMOON	mean equatorial radius of the Moon, in kilometer
REARTH	mean equatorial radius of the Earth, in kilometer
K2E0 to K2E2	Love numbers of the Earth (no unit)
TAUE0, TAUE1, TAUE22	time delays of the Earth for tides effects, in days
J2ESEC	secular variation of Earth's J_2 due to postglacial rebound (in century^{-1})
OMEGAE	angular velocity of the Earth at initial time of integrations (in radian/day)
CMR2E	ratio between the third moment of inertia of the Earth over its mass and the square of its mean equatorial radius (no unit)
SINJE	not relevant
CMR2M	ratio between the third moment of inertia of the Moon over its mass and the square of its mean equatorial radius (no unit)
K2M	Love number of the Moon (no unit)
TAUM	Moon's time delay for tides effects (day)
J2SUN	Solar J_2
ALPSUN, DELSUN	right ascension and declinaison of Solar pole
GM_RIN	product of the gravitational constant G by the mass of asteroid ring
RRING	radius of the asteroid ring, in AU
LBTCBD	value of L_B constant for the time transformation TCB-TDB
LGTCGT	value of L_G constant for the time transformation TCG-TT
DASTC0, DASTS0, DASTM0	not used (density of asteroids taxonomic classes)
DASTC1, DASTS1, DASTM1	not used (degree 1 in radius for density of asteroids taxonomic classes)
C20E to C40E	Earth's coefficients of potential (no unit)
C20M to S44M	Moon's coefficients of potential (no unit)
X_AAA, Y_AAA, Z_AAA	initial positions of body AAA (in AU)
XD_AAA, YD_AAA, ZD_AAA	initial velocities of body AAA (in AU/day)
X_LIBM, Y_LIBM, Z_LIBM	initial values of Moon's Euler angles (in radian)
XD_LIBM, YD_LIBM, ZD_LIBM	initial values of the time derivatives of Moon's Euler angles (in radian/day)
X_EARG, Y_EARG	initial coordinates of the unit vector of Earth's angular momentum (no unit)
X_RING, Y_RING	initial coordinates of the unit vector of the asteroids ring pole (no unit)
TIMESC	value is 1 for a TCB ephemeris, 0 for a TDB ephemeris
MAXXXX	GM of the asteroid number XXXX, in AU^3/day^2

2.3.4 Test file

The file "I10e_GAIA20121025_testfile.txt" contains information useable to check procedures:

```
! ****************************************************************
! Test file for Chebychev ephemeris (GAIA)
! Prefix of files:
! - I10e_GAIA20121025_TCB for bodies
! - I10e_GAIA20121025_TDB for TT-TDB
! ****************************************************************
! E(JD)          F(JD)      Targ. Cent. Comp.  Interpolated value
! ****************************************************************
...
 2442462  0.1779588213595691    6  12   4   -8.4153518942329858e+05
 2442463  0.0996267989500627    1  12   3    3.8117152754636796e+05
 2442464  0.0554964848464356   10   3   6   -1.2649546001249173e+03
 2442465  0.3777614887737840   10   3   1   -3.1391124391284397e+04
 2442466  0.9003576011223920    8  12   2   -3.9603608996160259e+09
 2442467  0.4846218567095611    5  12   3   -2.1467867422407676e+07
 2442468  0.3531843665112898    1  12   3   -9.2354074530971982e+06
 2442469  0.4856739048014330    1  12   3   -1.1213304751535105e+07
 2442470  0.6736968380461055   16   0   1   -1.3353984523685764e-03
...
```

It is similar to the equivalent provided on INPOP website for binary files and Calceph library, but is better adapted to the ASCII files. The header contains the names of ASCII files containing the Chebychev representation of the ephemeris, one for the bodies (TCB ephemeris) and the other for the TT-TDB (TDB ephemeris). The 5 fields of the following lines are then:

- E(JD) and F(JD) are respectively the integer and fractal part of the julian day (TCB for bodies, TDB for TT-TDB)
- target number: it is consistent with indices used in JPL routines and Calceph library. 1 to 11 stands for Mercury, Venus, Earth , Mars, Jupiter, Saturn, Uranus, Neptune, Pluto, the Moon and the Sun. 12 is not used (Solar System Barycenter). 13 stands for the Earth-Moon barycenter. 14 and 15 are not used. 16 stands for TT-TDB.
- center number: like for the target, it is consistent with indices used in JPL routines and Calceph library and depend on the target; for all bodies except the Moon, 12 is used and stands for the Solar System Barycenter. 3 is used only for the Moon and corresponds to the Earth. 0 is only used for the TT-TDB.
- component number: 1 to 3 stands for positions x, y, z, 4 to 6 for velocities Vx, Vy, Vz. If the target number is 16 (TT-TDB), only the first component is relevant.
- the interpolated value of the corresponding state vector component. Units are kilometer and kilometer per day for positions and velocities, and seconds for the TT-TDB.

2.3.5 MD5 checksums

Numerical signatures of all files (md5 checksums) are provided in "I10e_GAIA20121025_md5.txt":

```
189a8322f88c171de1c474af0c5e30b5  I10e_GAIA20121025_TCB_header2.asc
f4f419d9cc98bf9818f9c57f9eaf4209  I10e_GAIA20121025_TCB_header.asc
73fca69d9be04b8ad837fab23da71ea2  I10e_GAIA20121025_TCB_pos_Ear.asc
a8e42740245ae88054ba053381eab924  I10e_GAIA20121025_TCB_pos_EMB.asc
ef20b9fd5d07b1a7a40f21afe371707a  I10e_GAIA20121025_TCB_pos_Jup.asc
0878ffeee2803593eeecbb7b2d50fe56  I10e_GAIA20121025_TCB_pos_Mar.asc
83304142bdf394aa6375e4b6846c109a  I10e_GAIA20121025_TCB_pos_Mer.asc
ccd2f940c94e7cbb601f210aba404d0a  I10e_GAIA20121025_TCB_pos_Moo.asc
13fe14a6ea5341b5f3ce14ba6d95942a  I10e_GAIA20121025_TCB_pos_Nep.asc
36252428676a154f4c7864ddb26fbc10  I10e_GAIA20121025_TCB_pos_Plu.asc
290bcd53f682d41ea7fd12c2a3697f96  I10e_GAIA20121025_TCB_pos_Sat.asc
3e1582e4617e40a9e3275a7056033657  I10e_GAIA20121025_TCB_pos_Sun.asc
bd0f2c2df6401fc1cd96f12736b89036  I10e_GAIA20121025_TCB_pos_TCG.asc
81d7284560c2c933bde795b305b1ad58  I10e_GAIA20121025_TCB_pos_Ura.asc
bd4ce0d89839454074fbae1dd4475746  I10e_GAIA20121025_TCB_pos_Ven.asc
83473334e8f78f8391956e9a5155c6bc  I10e_GAIA20121025_TCB_vel_Ear.asc
f0a5f5a2bff9cbdef90d61b63929ec3e  I10e_GAIA20121025_TCB_vel_EMB.asc
181da619482320284db2761def1a6e30  I10e_GAIA20121025_TCB_vel_Jup.asc
87c4ae3101cac008a3a6ebcaf8b57343  I10e_GAIA20121025_TCB_vel_Mar.asc
08d2b2d8a68d67f92415fcd080fa18df  I10e_GAIA20121025_TCB_vel_Mer.asc
0fd781b7a2cc31b14ede3e4f4e866589  I10e_GAIA20121025_TCB_vel_Moo.asc
bd41d689674ee204539b2e8ad57d19a9  I10e_GAIA20121025_TCB_vel_Nep.asc
57decfd63334c2952d113ee393f7a687  I10e_GAIA20121025_TCB_vel_Plu.asc
3139aacb5212404e4b33b78fac56eb36  I10e_GAIA20121025_TCB_vel_Sat.asc
174eb725b1dededad51a783a0189e4ae  I10e_GAIA20121025_TCB_vel_Sun.asc
f6210d3bc1d8eb1bd4dd64fbf7fc05f0  I10e_GAIA20121025_TCB_vel_Ura.asc
2c5a7a55ffd2996a5e079832d3dfce80  I10e_GAIA20121025_TCB_vel_Ven.asc
df36bf2cb7e68c3111f62815a0071b33  I10e_GAIA20121025_TDB_header.asc
8a479ccf659915612b0c0336f6453147  I10e_GAIA20121025_TDB_pos_TT.asc
8605fc19a8833a57a0512fd7fc62dd77  I10e_GAIA20121025_testfile.txt
```

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Table 5: Statistics of the residuals obtained after the INPOP10e fit. For comparison, means and standard deviations of residuals obtained with INPOP10a and DE423 are given. In italic are indicated INPOP06b residuals not included in the original fit and which can be seen as INPOP06b extrapolated differences.

Type of data		Nbr	Time Interval	INPOP10e		INPOP06b		DE423	
Mercury	range [m]	462	1971.29 - 1997.60	-45.3	872.499	218.487	869.989	-117.323	879.778
Mercury Mariner	range [m]	2	1974.24 - 1976.21	-52.486	113.185	-1312.066	207.971	-86.416	52.073
Mercury flybys Mess	ra [mas]	3	2008.03 - 2009.74	0.738	1.485	-0.537	0.209	0.170	1.167
Mercury flybys Mess	de [mas]	3	2008.03 - 2009.74	2.422	2.517	1.913	2.533	1.565	2.429
Mercury flybys Mess	range [m]	3	2008.03 - 2009.74	-5.047	5.792	231.006	1466.908	22.0	14.8
Venus	VLBI [mas]	46	1990.70 - 2010.86	1.590	2.602	-0.634	2.834	2.166	2.518
Venus	range [m]	489	1965.96 - 1990.07	500.195	2234.924	2498.169	3671.999	496.861	2236.798
Venus Vex	range [m]	22145	2006.32 - 2009.78	-0.054	4.091	538.020	5246.298	1.655	4.057
Mars	VLBI [mas]	96	1989.13 - 2007.97	-0.004	0.407	-0.408	0.535	-0.319	0.457
Mars Mex	range [m]	13842	2005.17 - 2009.78	-0.503	9.859	31.752	22.173	0.945	9.611
Mars MGS	range [m]	13091	1999.31 - 2006.83	-0.341	3.926	17.171	16.583	0.746	4.052
Mars Ody	range [m]	5664	2006.95 - 2010.00	0.280	4.155	33.399	16.995	2.021	3.504
Mars Path	range [m]	90	1997.51 - 1997.73	-6.289	13.663	9.374	13.648	23.393	13.821
Mars Vkg	range [m]	1257	1976.55 - 1982.87	-1.391	39.724	-1.181	38.557	-26.153	38.993
Jupiter	VLBI [mas]	24	1996.54 - 1997.94	-0.291	11.068	-2.815	11.247	-0.069	10.958
Jupiter	ra [arcsec]	6532	1914.54 - 2008.49	-0.039	0.297	-0.044	0.296	-0.039	0.297
Jupiter	de [arcsec]	6394	1914.54 - 2008.49	-0.048	0.301	-0.045	0.302	-0.048	0.301
Jupiter flybys	ra [mas]	5	1974.92 - 2001.00	2.368	3.171	-3.834	17.955	1.919	3.529
Jupiter flybys	de [mas]	5	1974.92 - 2001.00	-10.825	11.497	-10.585	16.807	-11.117	11.706
Jupiter flybys	range [m]	5	1974.92 - 2001.00	-907.0	1646.210	37467.054	55467.239	-998.461	1556.568
Saturne	ra [arcsec]	7971	1913.87 - 2008.34	-0.006	0.293	0.022	0.286	-0.006	0.293
Saturne	de [arcsec]	7945	1913.87 - 2008.34	-0.012	0.266	-0.016	0.265	-0.012	0.266
Saturne VLBI Cass	ra [mas]	10	2004.69 - 2009.31	0.215	0.637	17.299	12.561	-0.193	0.664
Saturne VLBI Cass	de [mas]	10	2004.69 - 2009.31	0.280	0.331	8.206	7.798	0.308	0.330
Saturne Cassini	ra [mas]	31	2004.50 - 2007.00	0.790	3.879	33.123	8.024	0.314	3.876
Saturne Cassini	de [mas]	31	2004.50 - 2007.00	6.472	7.258	6.437	7.731	6.329	7.283
Saturne Cassini	range [m]	31	2004.50 - 2007.00	-0.013	18.844	214542.236	68780.508	12.277	27.375

Table 6: Statistics of the residuals obtained after the INPOP10e fit. For comparison, means and standard deviations of residuals obtained with INPOP10a and DE423 are given. In italic are indicated INPOP06b residuals not included in the original fit and which can be seen as INPOP06b extrapolated differences. The last four lines indicated as *extrap* in the first column give residuals obtained by comparisons with observations not used in the fit of the three ephemerides and computed positions. These results illustrate how the accuracy of the ephemerides can be extrapolated out from the fitting interval.

Type of data		Nbr	Time Interval	INPOP10e		INPOP06b		DE423	
Uranus	ra [arcsec]	13016	1914.52 - 2011.74	0.007	0.205	-0.074	0.217	-0.008	0.220
Uranus	de [arcsec]	13008	1914.52 - 2011.74	-0.006	0.234	-0.027	0.247	-0.013	0.249
Uranus flybys	ra [arcsec]	1	1986.07 - 1986.07	-0.021	0.000	-0.087	0.000	-0.022	0.000
Uranus flybys	de [arcsec]	1	1986.07 - 1986.07	-0.028	0.000	-0.035	0.000	-0.055	0.000
Uranus flybys	range [m]	1	1986.07 - 1986.07	19.738	0.000	1196925.516	0.000	22.014	0.000
Neptune	ra [arcsec]	5395	1913.99 - 2007.88	0.000	0.258	-0.013	0.261	0.020	0.255
Neptune	de [arcsec]	5375	1913.99 - 2007.88	-0.000	0.299	-0.028	0.303	-0.010	0.306
Neptune flybys	ra [arcsec]	1	1989.65 - 1989.65	-0.012	0.000	-0.091	0.000	-0.010	0.000
Neptune flybys	de [arcsec]	1	1989.65 - 1989.65	-0.005	0.000	-0.044	0.000	-0.018	0.000
Neptune flybys	range [m]	1	1989.65 - 1989.65	69.582	0.000	-2333073.041	0.000	-121.987	0.000
Pluto	ra [arcsec]	2458	1914.06 - 2008.49	0.034	0.654	0.005	0.601	0.072	0.609
Pluto	de [arcsec]	2462	1914.06 - 2008.49	0.007	0.539	-0.024	0.519	-0.011	0.521
Pluto Occ	ra [arcsec]	13	2005.44 - 2009.64	0.003	0.047	-0.052	0.045	-0.054	0.044
Pluto Occ	de [arcsec]	13	2005.44 - 2009.64	-0.006	0.018	0.032	0.032	0.006	0.028
Pluto HST	ra [arcsec]	5	1998.19 - 1998.20	-0.033	0.043	-0.042	0.044	-0.030	0.043
Pluto HST	de [arcsec]	5	1998.19 - 1998.20	0.028	0.048	-0.033	0.048	-0.028	0.048
Venus Vex	range [m]	2825	2009.78 - 2011.45	7.605	32.821	-526.584	5846.331	12.488	32.680
Mars Mex	range [m]	57229	2009.78 - 2012.43	-2.95	30.14	29.581	42.313	1.508	30.902

Table 7: Maximum differences between INPOP10e, INPOP10d and INPOP06b and DE423 over the Gaia period, from 2013 to 2020 in geocentric cartesian coordinates and barycentric Earth coordinates and over the period of validity of the chebychev, from 2002.67 to 2021.76 in BCRS cartesian coordinates..

Planets	INPOP10e - INPOP10d		INPOP10e - DE423		INPOP10e - INPOP06b	
	XYZ	VxVyVz	XYZ	VxVyVz	XYZ	VxVyVz
	km	mm.s^{-1}	km	mm.s^{-1}	km	mm.s^{-1}
Gaia Period	2013-2020		2013-2020		2013-2020	
Mercury-Earth	1.2	0.9	0.80	0.6	1.0	0.8
Venus-Earth	0.4	0.1	0.35	0.1	1.4	0.4
Moon-Earth	0.0048	0.0145	0.0044	0.0123	0.017	0.0486
Mars-Earth	0.5	0.1	0.5	0.1	0.8	0.1
Jupiter-Earth	30.2	0.5	2.3	0.06	45.7	0.7
Saturn-Earth	3.3	0.07	4.5	0.06	212.5	1.8
Uranus-Earth	2923.0	7.0	1073.0	2.0	870	0.9
Neptune-Earth	983	1.7	2129	3.5	3101	5.6
Pluton-Earth	4853.4	6.9	38969	61.5	48422	78.8
Earth-SSB	0.34	0.048	0.54 (1)	0.045	1.13	0.044
Chebychev Period	2002.67-2021.76		2002.67-2021.76		2002.67-2021.76	
Mercury-SSB	0.9	0.9	0.85	0.75	3.6	2.8
Venus-SSB	0.3	0.05	0.56	0.08	10.6	3.3
Moon-Earth	0.0054	0.0147	0.0053	0.0147	0.0165	0.0469
Mars-SSB	0.4	0.04	0.82	0.055	1.33	0.1
Jupiter-SSB	29.9	0.5	2.35	0.04	167.8	2.2
Saturn-SSB	3.1	0.02	5.5	0.03	597.0	2.2
Uranus-SSB	3335	7.0	1073	1.9	1371	2.5
Neptune-SSB	1087.5	1.9	2247	3.9	5548.0	9.8
Pluton-SSB	4446	6.1	42989.1	67.0	51854	81.8
Earth-SSB	0.34	0.048	0.61 (2)	0.062	1.58	0.126

(1) 0.37 km for DE423-DE421, 1.1 km for INPOP10a-INPOP10d
(2) 0.38 km for DE423-DE421, 1.1 km for INPOP10a-INPOP10d

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A Asteroid masses obtained with INPOP10e

Table 8: Asteroid masses obtained with INPOP10 and and compared with values found in the recent literature. The last column gives the impact of each asteroid on the Earth-Mars distances over the 1970 to 2010 period. In this table are given only the masses of the asteroids inducing an impact greater than 3 meters. The uncertainties are given at 1 published sigma. The masses presented here are the most significant determinations (with S/N bigger than 1.8) done with INPOP10. Z11 stands for [29], B11 for [3], K11 for [14] and K12 for [18]

IAU designation number	INPOP10e 10^{12} x $M_\odot$	%	Z11 10^{12} x $M_\odot$	B11 10^{12} x $M_\odot$	K11 10^{12} x $M_\odot$	Others 10^{12} x $M_\odot$	K12 10^{12} x $M_\odot$	Impact m
4	130.274 $\pm$ 0.85	0.65	130.270$\pm$ 0.71	130.000$\pm$ 0.53	130.970$\pm$ 2.06	130.27167 $\pm$ 0.0003 [25]	130.508 $\pm$ 0.82	1198.95
1	467.267 $\pm$ 1.85	0.40	473.485$\pm$ 1.33	475.700$\pm$ 0.70	467.900$\pm$ 3.25		473.053 $\pm$ 2.87	793.74
2	102.654 $\pm$ 1.60	1.56	103.374$\pm$ 6.92	101.000$\pm$ 6.50	103.440$\pm$ 2.55		101.724 $\pm$ 2.11	146.27
324	4.769 $\pm$ 0.43	9.13	5.422$\pm$ 1.00		5.340$\pm$ 0.99		5.124 $\pm$ 0.38	93.54
10	43.997 $\pm$ 3.23	7.20	41.286$\pm$ 1.47	43.580$\pm$ 0.74	44.970$\pm$ 7.76		52.821 $\pm$ 4.22	77.00
19	4.892 $\pm$ 0.51	10.62	5.090$\pm$ 0.47	4.180$\pm$ 0.36	3.200$\pm$ 0.53		3.918 $\pm$ 0.45	59.07
3	11.793 $\pm$ 0.62	5.25	15.574$\pm$ 1.63	14.400$\pm$ 2.30	12.100$\pm$ 0.91		13.488 $\pm$ 0.83	55.64
704	19.217 $\pm$ 2.37	12.32	15.738$\pm$ 2.61	19.650$\pm$ 0.89	19.970$\pm$ 6.57		19.817 $\pm$ 3.467	34.49
532	11.552 $\pm$ 1.18	9.21	8.794$\pm$ 2.18	16.800$\pm$ 2.80	4.970$\pm$ 2.81		6.481 $\pm$ 1.36	32.71
9	4.202 $\pm$ 0.67	15.24	4.524$\pm$ 0.67	5.700$\pm$ 1.10	3.280$\pm$ 1.08		3.467 $\pm$ 0.68	29.61
7	6.302 $\pm$ 0.61	9.68	8.434$\pm$ 0.80	8.120$\pm$ 0.46	5.530$\pm$ 1.32		7.459 $\pm$ 0.83	27.82
29	7.227 $\pm$ 1.04	14.36	5.552$\pm$ 0.82	7.630$\pm$ 0.31	7.420$\pm$ 1.49		5.199 $\pm$ 1.20	26.67
31	13.234 $\pm$ 1.98	14.95	13.512$\pm$ 4.57	29.200$\pm$ 9.90			11.001 $\pm$ 3.69	23.47
13	4.713 $\pm$ 0.78	31.97	3.054 $\pm$ 1.61	8.0 $\pm$ 2.2			6.18 $\pm$ 1.66	22.04
15	15.839 $\pm$ 0.95	6.00	16.178$\pm$ 0.40	15.597$\pm$ 0.10	14.180$\pm$ 1.49		13.111 $\pm$ 1.43	21.55
6	7.084 $\pm$ 0.84	11.81	7.733$\pm$ 1.22	6.400$\pm$ 0.67	6.730$\pm$ 1.64		4.219 $\pm$ 0.98	21.15
139	2.130 $\pm$ 0.88	36.52	3.015 $\pm$ 1.6					16.7
747	0.723 $\pm$ 0.64	64.12	2.639$\pm$ 2.25					15.94
105	3.046 $\pm$ 0.64	20.42						15.20
20	2.897 $\pm$ 1.05	48.27	3.032 $\pm$ 0.57	1.680 $\pm$ 0.35				14.8
8	3.357 $\pm$ 0.39	11.72	3.693$\pm$ 0.66	3.330$\pm$ 0.42	2.010$\pm$ 0.42		2.185 $\pm$ 0.38	12.66
405	1.378 $\pm$ 0.33	21.52						11.38
511	18.250 $\pm$ 2.87	15.70	13.143$\pm$ 3.03	18.960$\pm$ 0.90	8.580$\pm$ 5.93		14.844 $\pm$ 4.2	10.25
52	10.682 $\pm$ 2.58	24.20	13.957$\pm$ 1.63	11.390$\pm$ 0.79	11.170$\pm$ 8.40		16.728 $\pm$ 4.1	9.84
16	12.613 $\pm$ 2.20	17.41	12.279$\pm$ 0.81	11.400$\pm$ 0.42	12.410$\pm$ 3.44		8.891 $\pm$ 2.11	9.70

Table 9:

IAU designation number	INPOP10e 10^{12} x $M_{\odot}$	%	Z11 10^{12} x $M_{\odot}$	B11 10^{12} x $M_{\odot}$	K11 10^{12} x $M_{\odot}$	Others 10^{12} x $M_{\odot}$	K12 10^{12} x $M_{\odot}$	Impact m
419	1.649 ± 0.44	22.92						9.59
78	2.562 ± 0.57	17.75						9.39
23	1.545 ± 0.34	20.12					0.829 ± 0.30	9.07
488	5.157 ± 1.81	29.04	1.099 ± 0.34					8.61
409	0.001 ± 0.001	49.38	6.211 ± 1.63					7.57
94	15.032 ± 3.44	30.80						7.47
111	4.489 ± 1.18	26.27						6.98
109	0.161 ± 0.25	135.81						6.86
63	0.003 ± 0.00	61.13						6.45
12	0.524 ± 0.30	62.86	0.825± 1.18					6.16
469	0.004 ± 0.00	46.73						6.11
356	4.173 ± 0.58	14.03						5.76
88	7.088 ± 1.42	22.27	5.65 ± 1.66					5.74
128	6.859 ± 1.58	29.02	4.213 ± 1.078					5.63
194	5.601 ± 0.64	10.66						5.14
51	0.009 ± 0.00	46.49	1.687± 0.81					5.11
156	3.263 ± 0.44	13.60						5.10
516	0.350 ± 0.14	20.20						5.05
451	14.984 ± 3.60	24.03	5.604± 3.22	10.200± 3.40				4.74
313	1.022 ± 0.89	124.30						4.70
107	3.413 ± 1.51	44.19	8.846± 4.37			5.630± 0.10 [21]		4.63
65	4.210 ± 0.86	16.29	7.652± 1.73	5.300± 0.96				4.54
21	0.867 ± 0.79	91.18		1.31 ± 0.44		0.8547 ± 0.0085 [23]		4.53
694	0.000 ± 0.00	156.17						4.19
134	1.014 ± 0.37	29.71						4.17
54	8.392 ± 1.08	12.91	1.480± 1.58					4.09

Table 10:

IAU designation number	INPOP10e 10^{12} x $M_\odot$	%	Z11 10^{12} x $M_\odot$	B11 10^{12} x $M_\odot$	K11 10^{12} x $M_\odot$	Others 10^{12} x $M_\odot$	K12 10^{12} x $M_\odot$	Impact m
106	3.87 $\pm$ 0.41	29.90	1.769 $\pm$ 1.319					3.90
173	6.743 $\pm$ 1.50	22.32	0.669$\pm$ 0.61					3.81
22	8.374 $\pm$ 0.65	9.04	6.592$\pm$ 1.93			4.07$\pm$ 0.1 [21]		3.76
444	5.329 $\pm$ 1.84	28.26	5.608$\pm$ 1.34					3.73
185	4.407 $\pm$ 1.26	22.55	3.463 $\pm$ 3.1					3.65
46	3.525 $\pm$ 0.74	21.07						3.56
37	2.343 $\pm$ 0.60	26.36						3.55
53	2.007 $\pm$ 0.90	48.25						3.55
164	0.001 $\pm$ 0.00	65.12						3.43
410	3.476 $\pm$ 0.66	19.05						3.39
85	2.190 $\pm$ 0.81	45.02	1.755$\pm$ 1.33					3.38
1021	0.551 $\pm$ 0.94	197.24						3.25
56	2.676 $\pm$ 0.61	22.86						3.22
34	1.452 $\pm$ 0.61	59.17						3.15
17	3.686 $\pm$ 0.92	24.98						3.03
404	0.628 $\pm$ 0.59	130.64						3.01
200	0.574 $\pm$ 0.07	12.98						3.00

Table 11: Means and standard deviations (both expressed in centimeters) of LLR residuals for INPOP10e ephemeris. Na is the total number of observations available, Nk is the number kept in fitting process, Nr is the number that have been rejected according to the 3σ criterion (Na is always Nk+Nr).

Station	Period	Mean	Std. dev.	Na	Nk	Nr
Cerga	1987-1995	-0.45	6.35	3460	3415	45
Cerga	1995-2012	0.05	4.01	5143	5058	85
Cerga	1984-1986	7.10	15.89	1187	1158	28
Mc Donald	1969-1986	0.20	31.25	3604	3487	117
MLRS1	1982-1985	-7.10	73.41	418	405	13
MLRS1	1985-1988	0.24	7.35	174	163	11
MLRS2	1988-1996	-0.41	4.71	1192	1148	44
MLRS2	1996-2012	0.18	5.58	2498	1972	526
Haleakala	1984-1990	-0.40	8.09	770	733	37
Apollo	2006-2010	0.07	5.22	942	935	7
Matera	2003-2012	-0.30	29.50	33	26	7

B Earth and Moon parameters fitted with LLR observations

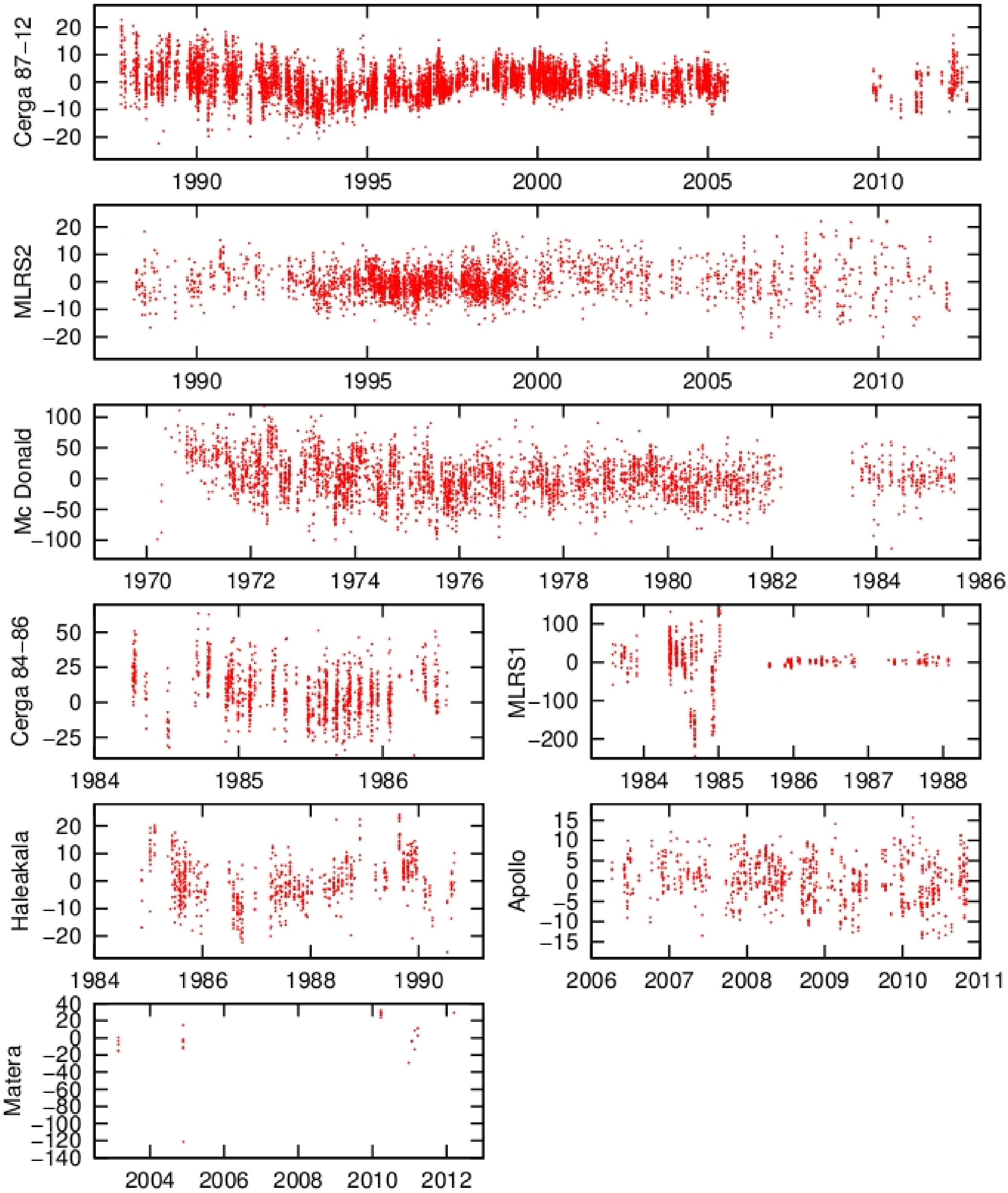

Figure 7: Postfit LLR resdiduals with INPOP10e for each station, expressed in centimeters.

Table 12: Values (TCB) of dynamical parameters fitted to LLR observations. GM_{EMB} is the sum of Earth's and Moon's masses, multiplied by the gravitationnal constant and is expressed in km^3/s^2. C_{nmE} are the Earth's coefficients of potential (without unit). τ_{21E} and τ_{22E} are time delays of the Earth used for tides effects and expressed in days. C_{nmM} and S_{nmM} are the Moon's coefficients of potential (without unit). $(C/MR^2)_M$ is the ratio between the third moment of inertia of the Moon, divided by its mass and the square of the mean equatorial radius (without unit). k_{2M} and τ_M are the Love number (without unit) and the time delay (in day) of the Moon. Formal errors at 1σ are given if the parameter is fitted. One can note that the real uncertainty on the parameter is generally much higher than this value provided by the least-square fit. Fixed values come from Lunar gravity model LP150Q [13] and Earth's ones from EGM96 (cddis.nasa.gov/926/egm96).

Name	Value	Formal error (1σ)
GM_{EMB}	$4.035032510 \times 10^{5}$	$\pm 3.3 \times 10^{-4}$
C_{20E}	$-1.0826222 \times 10^{-3}$	$\pm 1.0 \times 10^{-9}$
C_{30E}	2.875×10^{-6}	$\pm 3.9 \times 10^{-8}$
C_{40E}	$1.6196215913670001 \times 10^{-6}$	
τ_{21E}	1.1841×10^{-2}	$\pm 8.8 \times 10^{-5}$
τ_{22E}	7.0163×10^{-3}	$\pm 7.2 \times 10^{-6}$
C_{20M}	-2.03443×10^{-4}	$\pm 2.7 \times 10^{-8}$
C_{22M}	2.23971×10^{-5}	$\pm 2.6 \times 10^{-9}$
C_{30M}	-8.396×10^{-6}	$\pm 2.3 \times 10^{-8}$
C_{31M}	3.191×10^{-5}	$\pm 3.7 \times 10^{-7}$
C_{32M}	$4.8452131769807101 \times 10^{-6}$	
C_{33M}	1.7279×10^{-6}	$\pm 6.2 \times 10^{-9}$
C_{40M}	$9.6422863508400007 \times 10^{-6}$	
C_{41M}	$-5.6926874002713197 \times 10^{-6}$	
C_{42M}	$-1.5861997682583101 \times 10^{-6}$	
C_{43M}	$-8.1204110561427604 \times 10^{-8}$	
C_{44M}	$-1.2739414703200301 \times 10^{-7}$	
S_{31M}	3.167×10^{-6}	$\pm 8.5 \times 10^{-8}$
S_{32M}	1.68722×10^{-6}	$\pm 5.7 \times 10^{-10}$
S_{33M}	$-2.4855254931699199 \times 10^{-7}$	
S_{41M}	$1.5743934836970999 \times 10^{-6}$	
S_{42M}	$-1.5173124037059000 \times 10^{-6}$	
S_{43M}	$-8.0279066452763596 \times 10^{-7}$	
S_{44M}	$8.3147478750240001 \times 10^{-8}$	
$(C/MR^2)_M$	3.93129×10^{-1}	$\pm 4.6 \times 10^{-5}$
k_{2M}	2.656×10^{-2}	$\pm 1.7 \times 10^{-4}$
τ_M	1.881×10^{-1}	$\pm 1.2 \times 10^{-3}$

Table 13: List of all parameters involved in the dynamical model. Their meanings are explained in Table 4. The values reported here are from the third column of file "I10e_GAIA20121025_TCB_header2.asc", where units are given in kilometers and seconds.

Parameter	TCB value	Parameter	TCB value
NCONST	300	EMRAT	8.1300569999999990E+01
AU	1.4959787070000000E+08	KSIZER	1.2674000000000000E+04
VERSIO	2.0121025000000000E+03	FVERSI	0.0000000000000000E+00
FORMAT	1.2000000000000000E+01	UNITE	1.0000000000000000E+00
CLIGHT	2.9979245800000000E+05	GM_Mer	2.2032080834196266E+04
GM_Ven	3.2485859679756965E+05	GM_EMB	4.0350325101102696E+05
GM_Mar	4.2828375886337897E+04	GM_Jup	1.2671276453465731E+08
GM_Sat	3.7940585442640103E+07	GM_Ura	5.7945490985393422E+06
GM_Nep	6.8365271283644792E+06	GM_Plu	9.7178245029026607E+02
GM_Sun	1.3271244210789468E+11	JDEPOC	2.4515450001302520E+06
GAMMA	1.0000000000000000E+00	BETA	1.0000000000000000E+00
RSUN	6.9600001079161780E+05	RMOON	1.7380000269480340E+03
REARTH	6.3781366988942700E+03	K2E0	3.0190000000000000E-01
K2E1	2.9830347600000000E-01	K2E2	3.0102280700000000E-01
TAUE0	0.0000000000000000E+00	TAUE1	1.0230896740921182E+03
TAU22	6.0620574903603324E+02	J2ESEC	-2.9999999534844070E-09
OMEGAE	7.2921148869343165E-05	CMR2E	3.3069473570759190E-01
SINJE	0.0000000000000000E+00	CMR2M	3.9312860551746940E-01
K2M	2.6555608496793040E-02	TAUM	1.6249961946084906E+04
J2SUN	1.8000000000000000E-07	ALPSUN	2.8613000000000000E+02
DELSUN	6.3870000000000000E+01	GM_RIN	8.9697172580075506E+00
RRING	4.7089041809711838E+08	LBTCBD	1.5505197680000000E-08
LGTCGT	6.9692901340000000E-10	DASTS0	1.9439775571904770E+15
DASTC0	1.5450157642909970E+15	DASTM0	4.9801812284779520E+15
DASTS1	0.0000000000000000E+00	DASTC1	0.0000000000000000E+00
DASTM1	0.0000000000000000E+00	C20E	-1.0826222418469980E-03
C30E	2.8754659866043640E-06	C40E	1.6196215913670000E-06
C20M	-2.0344254329313390E-04	C22M	2.2397094582018420E-05
C30M	-8.3958582836938660E-06	C31M	3.1905765630132850E-05
C32M	4.8452131769807100E-06	C33M	1.7279405283975110E-06
C40M	9.6422863508400010E-06	C41M	-5.6926874002713200E-06
C42M	-1.5861997682583100E-06	C43M	-8.1204110561427600E-08
C44M	-1.2739414703200300E-07	S31M	3.1667826837339010E-06
S32M	1.6872187440907630E-06	S33M	-2.4855254931699200E-07
S41M	1.5743934836971000E-06	S42M	-1.5173124037059000E-06
S43M	-8.0279066452763600E-07	S44M	8.3147478750240000E-08
X_Mer	-2.0529325266054358E+07	Y_Mer	-6.0323958930597402E+07
Z_Mer	-3.0130851490243722E+07	XD_Mer	3.7004304358324021E+01
YD_Mer	-8.5413765587325461E+00	ZD_Mer	-8.3983727564575190E+00

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Parameter	TCB value	Parameter	TCB value
X_Ven	-1.0852409434542368E+08	Y_Ven	-7.3185194772851523E+06
Z_Ven	3.5481098301246529E+06	XD_Ven	1.3912185752362318E+00
YD_Ven	-3.2029519960883768E+01	ZD_Ven	-1.4497086693078913E+01
X_EMB	-2.7570175827204783E+07	Y_EMB	1.3235818801260263E+08
Z_EMB	5.7417717286309540E+07	XD_EMB	-2.9777128219310370E+01
YD_EMB	-5.0378471513874201E+00	ZD_EMB	-2.1843063465080892E+00
X_Mar	2.0698054526012605E+08	Y_Mar	-1.8637173289553743E+05
Z_Mar	-5.6672395083821304E+06	XD_Mar	1.1719850254223476E+00
YD_Mar	2.3906708192756096E+01	ZD_Mar	1.0933920636698740E+01
X_Jup	5.9749999351886487E+08	Y_Jup	4.0899037079009789E+08
Z_Jup	1.6075626855566302E+08	XD_Jup	-7.9005251330469966E+00
YD_Jup	1.0171796337199497E+01	ZD_Jup	4.5524676266214543E+00
X_Sat	9.5731754122370982E+08	Y_Sat	9.2331968310432553E+08
Z_Sat	3.4016278928249651E+08	XD_Sat	-7.4227094238070617E+00
YD_Sat	6.0974748170611122E+00	ZD_Sat	2.8376822905856387E+00
X_Ura	2.1579074252299013E+09	Y_Ura	-1.8713073612369001E+09
Z_Ura	-8.5010648379274738E+08	XD_Ura	4.6463362699671311E+00
YD_Ura	4.2511518097656591E+00	ZD_Ura	1.7961722221753826E+00
X_Nep	2.5139788766292534E+09	Y_Nep	-3.4381702612616005E+09
Z_Nep	-1.4698508627177601E+09	XD_Nep	4.4752140066315089E+00
YD_Nep	2.8771046238056903E+00	ZD_Nep	1.0662022389257737E+00
X_Plu	-1.4784023801796694E+09	Y_Plu	-4.1859854620746431E+09
Z_Plu	-8.6088140668386734E+08	XD_Plu	5.2534692198743658E+00
YD_Plu	-1.9641133388779723E+00	ZD_Plu	-2.1957761310907893E+00
X_Sun	-1.0675986179690361E+06	Y_Sun	-3.9599071144502360E+05
Z_Sun	-1.3807722869382665E+05	XD_Sun	9.3125722208232259E-03
YD_Sun	-1.1701510834189825E-02	ZD_Sun	-5.2512542822993830E-03
X_Moo	-2.9160839182218991E+05	Y_Moo	-2.6671683909792342E+05
Z_Moo	-7.6102487997847551E+04	XD_Moo	6.4353139142214544E-01
YD_Moo	-6.6608769103816179E-01	ZD_Moo	-3.0132570639749812E-01
X_LIBM	-5.4148703672666460E-02	Y_LIBM	4.2485611537325400E-01
Z_LIBM	7.1860260596884200E-01	XD_LIB	-1.3493983762120855E-09
YD_LIB	5.2433641564954329E-10	ZD_LIB	2.6631902621517801E-06
X_EARG	-2.7074571861759760E-05	Y_EARG	-2.8021155724807860E-05
X_RING	4.4962774262460000E-03	Y_RING	-3.9925503064592640E-01
TIMESC	1.0000000000000000E+00	MA0001	6.2012183942528424E+01
MA0002	1.3623519829068890E+01	MA0004	1.7288981939943643E+01
MA0007	8.3629208510440045E-01	MA0324	6.3292657018921916E-01
MA0003	1.5650376033611046E+00	MA0006	9.4013859632630392E-01
MA0008	4.4557515312994311E-01	MA0009	5.5771967924306043E-01
MA0010	5.8390041443806942E+00	MA0011	5.0048256226049659E-01
MA0012	6.9482386231968743E-02	MA0013	6.2548618644966814E-01
MA0015	2.1020267614940908E+00	MA0016	1.6739220218687143E+00
MA0017	4.8917509952675314E-01	MA0019	6.4925120044129536E-01

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Parameter	TCB value	Parameter	TCB value
MA0020	3.8450306541675405E-01	MA0021	1.1503721169099258E-01
MA0022	1.1112751634270688E+00	MA0023	2.0499213757716350E-01
MA0025	1.0366196678124742E-01	MA0026	2.0834242686152021E-01
MA0029	9.5914046612273829E-01	MA0031	1.7562517866270844E+00
MA0033	2.8960743674231371E-01	MA0034	1.9273254973801043E-01
MA0036	2.8796815326611863E-01	MA0037	3.1097050608961496E-01
MA0044	8.6199506289667369E-02	MA0046	4.6782985130525501E-01
MA0051	1.1850701657405470E-03	MA0052	1.4176132635840477E+00
MA0053	2.6631974354533383E-01	MA0054	1.1137607808140526E+00
MA0055	7.2565502740078572E-02	MA0056	3.5510132170245995E-01
MA0061	4.1297923333635481E-02	MA0062	2.1232338569167156E-01
MA0063	4.5857887479153409E-04	MA0065	5.5875034960511505E-01
MA0067	4.7960213071519098E-02	MA0070	2.7708718966786977E-01
MA0075	4.2715759272180014E-02	MA0078	3.4003238496349275E-01
MA0080	1.1784221437378468E-01	MA0085	2.9069348822079921E-01
MA0088	9.4067567843322686E-01	MA0093	5.0039749795125099E-01
MA0094	1.9949958990308891E+00	MA0097	6.1873651052720873E-03
MA0105	4.0425884340051349E-01	MA0106	5.1363068033089909E-01
MA0107	4.5300167118439338E-01	MA0109	2.1334036970797297E-02
MA0111	5.9580019641313164E-01	MA0112	9.1960926871076182E-02
MA0117	8.0437920943187535E-01	MA0120	2.0019174836054612E-01
MA0121	2.0870018202750789E+00	MA0126	2.2017513093567594E-02
MA0128	9.1024212903081403E-01	MA0132	1.9253478609675224E-02
MA0134	1.3455129358325896E-01	MA0135	1.2167072819223389E-01
MA0139	2.8269837868259146E-01	MA0141	5.5025545915405372E-01
MA0156	4.3257295425004338E-01	MA0164	1.9354802800126524E-04
MA0168	7.9887495652663520E-01	MA0171	3.8845612002754132E-01
MA0172	5.9473568787444170E-02	MA0173	8.9487138876601169E-01
MA0179	1.1462526623299404E-01	MA0185	5.8481152014919857E-01
MA0187	1.1232253601955329E-02	MA0194	7.4333048018458558E-01
MA0200	7.6156064781390989E-02	MA0204	2.8036593061651349E-02
MA0209	1.0005158700123589E+00	MA0210	1.5915077609293019E-01
MA0211	7.1779392920251495E-01	MA0212	3.1495425151492568E-01
MA0217	7.1074477882268519E-02	MA0234	2.0492014129900656E-02
MA0247	5.9420762173954988E-01	MA0250	1.2408181646515154E-01
MA0253	8.4021633178130689E-02	MA0266	3.1756085199183359E-01
MA0304	7.6417754608396754E-02	MA0308	5.1288139004370237E-01
MA0313	1.3568618932908774E-01	MA0322	8.6933740062976092E-02
MA0335	1.7274312784818519E-01	MA0336	8.1456992030180322E-02
MA0346	2.9556035531795921E-01	MA0350	4.0527274829271404E-01
MA0356	5.5379028002660302E-01	MA0381	4.2872473963951996E-01
MA0387	2.4837629612901233E-01	MA0388	3.2080410583920493E-01
MA0404	8.3335002699994498E-02	MA0405	1.8291269394614956E-01
MA0409	1.4485207257722231E-04	MA0410	4.6130313447746402E-01

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Parameter	TCB value	Parameter	TCB value
MA0419	2.1890666809971171E-01	MA0420	6.8901048902653517E-01
MA0442	7.2696133676778005E-02	MA0444	7.0727216281452998E-01
MA0445	1.6203293575514471E-01	MA0451	1.9885686160983940E+00
MA0455	1.4702122822900926E-01	MA0469	5.2207383300069518E-04
MA0481	1.1562903987899216E-01	MA0488	6.8444731733902975E-01
MA0503	1.3326002607937273E-01	MA0505	2.6643963557510253E-01
MA0511	2.4220172669698834E+00	MA0516	4.6419532383144023E-02
MA0532	1.5330914367975048E+00	MA0568	1.6092033080277343E-01
MA0569	9.4974536474941890E-02	MA0583	1.3306434325297209E-01
MA0584	3.8506494714933351E-02	MA0591	1.5125998853963997E-03
MA0593	1.0449214411384314E-01	MA0595	3.1721169220784351E-01
MA0599	6.6785968807632837E-02	MA0602	2.5659694460527005E-01
MA0618	5.1050504107617303E-04	MA0626	2.5001067131733257E-01
MA0667	7.8762291169638787E-02	MA0675	7.0108090353291874E-01
MA0690	5.9712951363080558E-01	MA0694	2.8164391089152121E-06
MA0704	2.5503367929164442E+00	MA0718	4.0557482554503969E-02
MA0735	1.0038522798255245E-01	MA0739	3.0413247983619973E-01
MA0747	9.6009858605925993E-02	MA0751	3.2994347243673572E-01
MA0752	6.0508535365628238E-02	MA0790	8.6438330145248565E-01
MA0791	2.7128482223705064E-01	MA0804	1.3669667630778690E-01
MA0814	3.2159462197573080E-01	MA0914	5.7331462009755974E-02
MA0949	8.0964451809677679E-02	MA1013	7.9531899440686213E-03
MA1021	7.3151076468356530E-02	MA1036	7.7604237885203139E-03
MA1694	5.1974702708939662E-03		