FUNDAMENTAL CONSTANTS FOR EPHEMERIS ASTRONOMY AND THE ORIENTATION OF PLANET EPHEMERIDES TO ICRF

Pitjeva E. V.

Institute of Applied Astronomy RAS
Kutuzov quay 10, 191187 St.-Petersburg, Russia
e-mail: evp@ipa.nw.ru

Recent years have yielded significant improvements to a whole set of constants for planet ephemerides. Masses of planet and Eris, the new planet-dwarf, have been determined from data of spacecraft orbiting and passing near planets or from observations of satellites of these planets. Masses of the largest asteroids, the the mass ratio of the Earth and the Moon and the value of Astronomical Unit in meters are the main parameters of planet ephemerides. They are determined to a high accuracy while improving the modern planet ephemerides DE (JPL) and EPM (IAA RAS), were proposed to the IAU WG on Numerical Standards for Fundamental Astronomy and the 27 IAU GA and adopted by GA as the current best estimates. The modern planet ephemerides are oriented to the International Celestial Reference Frame with an accuracy better than 1 mas by including into the total solution the ICRF-base VLBI measurements of spacecraft near the planets 1989-2007.

INTRODUCTION

Any calculating problem in Ephemeris Astronomy is based on knowledge of values of different constants. Since the ninetieth of the past century the International Astronomical Union has established the Working Groups (WG) for Numerical Standards of Fundamental Astronomy (NSFA) leaded by E. M. Standish and T. Fukushima. The goal of the WG is to update the IAU Current Best Estimates (CBE) and maintain them. Recent years have yielded significant improvements to a whole set of constants for ephemeris astronomy. The last Working Group for NSFA headed by Brian Luzum was established at the 26 IAU General Assembly in 2006. There is the list of Current Best Estimates determined by NSFA which was proposed to 27 IAU General Assembly and approved by it http://maia.usno.navy.mil/NSFA/CBE.html. This paper concerns description of some of them connected with ephemerides of celestial bodies.

© Pitjeva E. V., 2009
SPEED OF LIGHT – C

The speed of light in vacuum (c) is an important physical constant, now it has great importance as a pivotal constant in Einstein’s theory of special relativity, which holds that the speed of light has a special role connecting space and time in the structure of spacetime. With modern electronics, particularly oscilloscopes having time resolutions of less than one nanosecond, the speed of light has been directly measured with excellent accuracy. Then its value was fixed \( c = 2.99792458 \cdot 10^8 \text{ m/s} \), and now this value is Natural Defining Constants. In 1983 the meter was re-defined through the speed of light as “The meter is the length of the path traveled by light in vacuum during a time interval to be the distance of 1/299,792,458 of a second.”

CONSTANTS CONCERNED WITH TIME SCALES

After the brilliant explanation by Einstein the strange \((43' \text{cy})\) discrepancy between theoretical predictions and observations of the secular motion of Mercury perihelion the ephemerides of planets and other celestial bodies are to be constructed on the basis of General Relativity. In the relativistic framework the equations of motion of bodies may be given in different coordinates with corresponding time scales. Coordinate times together with 3 spatial coordinates constitute relativistic 4-dimensional reference systems; for example, Geocentric Celestial Reference System (GCRS) and Geocentric Coordinate Time (TCG), Geocentric Terrestrial Reference System (GTRS) and Terrestrial Time (TT), Barycentric Celestial Reference System (BCRS) with Barycentric Coordinate Time (TCB) or TDT (Barycentric Dynamical Time (TDT), etc. The derived or stated constants \( L_G, L_B, L_C, TDB_0 \) set ties between different time scales:

\[
TT = (1 - L_G) \cdot TCG;
\]

\[
TDB = TCB - L_B \cdot (JD_{TCB} - T_0) \cdot 86400 + TDB_0,
\]

\[
T_0 = 2443144.5003725, L_B = 1.550519768 \cdot 10^{-8}, TDB_0 = -6.55 \cdot 10^{-5} \text{s}.
\]

In ephemeris astronomy the Barycentric System Coordinates and the TDB – Barycentric Dynamical Time are used usually. \( T_{eph} \), the time of the JPL ephemeris DE’s, coincides for practical purposes with the time TDB.

MASSES OF PLANETS

Masses of planets are the parameters of dynamical models of planet motions and may be determined while fitting these models to the observation data. However, masses determined more accurately from data of spacecraft orbiting and passing near planets or from observations of satellites of these planets than from position data of the parent planets. Actually, the masses of DE200 and DE405 were obtained by different people, by different methods and with different errors, so they
were choose by E. M. Standish as the most reasonable at that time. The recent years have yielded the noticeably more accurate values of planet masses those are given in Table 1.

Table 1. New and previous values of the planet masses

<table>
<thead>
<tr>
<th>Planet</th>
<th>Previous values</th>
<th>New values</th>
<th>Year</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_{E} / M_{S}</td>
<td>6.0236(3) \cdot 10^6</td>
<td>4.085237(6) \cdot 10^5</td>
<td>1987</td>
<td>Anderson et al.</td>
</tr>
<tr>
<td>M_{E} / M_{V}</td>
<td>4.085237(6) \cdot 10^5</td>
<td>4.08523719(8) \cdot 10^5</td>
<td>1999</td>
<td>Konopliv et al.</td>
</tr>
<tr>
<td>M_{E} / M_{M}</td>
<td>3.098708(9) \cdot 10^6</td>
<td>3.09870359(2) \cdot 10^6</td>
<td>2006</td>
<td>Konopliv et al.</td>
</tr>
<tr>
<td>M_{E} / M_{J}</td>
<td>1.0473466(8) \cdot 10^7</td>
<td>1.047346644(17) \cdot 10^8</td>
<td>2000</td>
<td>Jacobson et al.</td>
</tr>
<tr>
<td>M_{E} / M_{P}</td>
<td>3.4979984(1) \cdot 10^6</td>
<td>3.49799841(1) \cdot 10^6</td>
<td>2006</td>
<td>Jacobson et al.</td>
</tr>
<tr>
<td>M_{E} / M_{E}</td>
<td>2.290298(3) \cdot 10^5</td>
<td>2.290298(3) \cdot 10^5</td>
<td>1992</td>
<td>Jacobson et al.</td>
</tr>
<tr>
<td>M_{E} / M_{N}</td>
<td>1.941224(4) \cdot 10^6</td>
<td>1.941224(6) \cdot 10^6</td>
<td>2009</td>
<td>Jacobson et al.</td>
</tr>
<tr>
<td>M_{E} / M_{P}</td>
<td>1.3521(15) \cdot 10^8</td>
<td>1.3521(15) \cdot 10^8</td>
<td>2008</td>
<td>Tholen et al.</td>
</tr>
<tr>
<td>M_{E} / M_{N}, r</td>
<td>1.291(14) \cdot 10^8</td>
<td>1.291(14) \cdot 10^8</td>
<td>2007</td>
<td>Brown et al.</td>
</tr>
</tbody>
</table>

The masses of Venus and Mars were determined by Konopliv et al. from the data of spacecraft Magellan for Venus and MGS and Odyssey for Mars. The masses of Jupiter, Saturn and Neptune were obtained by Jacobson et al. from the data of spacecraft near these planets and the Earth-based observations of the satellites of these planets. The mass of Pluto was improved recently by Tholen et al. from astronomical observations of Charon and the two small Pluto’s satellites. The mass of Eris (the new planet-dwarf) was estimated by Brown and Schaller from observations made in the Keck Observatory and with the Hubble Space Telescopes from the Eris’s satellite Dysnomia.

The geocentric gravitational constant \((G M_{E})\) was obtained by Ries et al. (1992) from laser data of satellites (SLR) and is given for the three time scales (TCB, TT, TDB):

\[
3.986004418(8) \cdot 10^{14} m^3/s^2 \ (TCB \ - \ compatible),
\]
\[
3.986004415(8) \cdot 10^{14} m^3/s^2 \ (TT \ - \ compatible),
\]
\[
3.986004352(8) \cdot 10^{14} m^3/s^2 \ (TDB \ - \ compatible).
\]

DE AND EPM EPHEMERIDES

A part of ephemeris constants, namely, the masses of the three largest asteroids, the Moon-Earth mass ratio, the values of astronomical unit in meters and Heliocentric gravitational constant \(- G M_{E}\) were obtained while fitting the constructed planet ephemerides – DE (JPL) and EPM (IAA RAS) to the all modern set of about 550,000 observable data (1913–2008). There is a brief description of these ephemerides and a process.
of obtaining ephemeris constants; the more detailed one is given in the paper [3].

To ensure space flights in 1960-1970's numerical planetary ephemerides were coming into construction by several groups in the USA and Russia. The ephemerides of the two independent groups — JPL and IAA RAS, having about the same accuracy, continue to be improved since that time ([7, 1, 3, 4]). Common to these ephemerides is the simultaneous numerical integration of the equations of motion of the nine major planets, the Sun, 300 or more biggest asteroids, the Moon, and the lunar physical libration performed in the Parameterized Post-Newtonian metric for General Relativity taking into account perturbations due to the solar oblateness, the gravity fields of the moon and earth, and a massive ring of small asteroids.

The dynamical models of a planet part of different versions for these ephemerides differ slightly by:

- the modeling of the perturbations from asteroids and trans-neptunian objects (the dynamical models include perturbations from 300–343 largest asteroids, the 21 largest TNO, the massive ring of small asteroids and the ring of other TNO);
- sets of observations to which ephemerides are adjusted;
- sets of solution parameters.

Observations to which ephemerides have been fitted include many thousands of measurements of different types. They are classical and modern optical observations of the outer planets and their satellites (since 1911), ranging to planets, the martian landers and different spacecraft, including the data of Mariner-9, Viking, Pathfinder, MGS, Odyssey, MRO, Venus Express (1961–2008), a number of spacecraft Jupiter and Saturn data (mainly Cassini, 1998 – 2007), differenced range, doppler measurements, as well as the ICRF-base VLBI measurements of spacecraft near the planets (1989-2007).

The significance of the high precise radiometric observations of planets beginning in 1961 (afterwards spacecraft) and continuing with the increasing accuracy should be stressed. It has been these observations that have made it possible to determine and improve a broad set of astronomical constants.

The basic flow of the ephemeris creation and parameter determination process is that of a least-squares iteration which can be reduced to the following:

- Numerical integration of the equations of motion for the major planets, Moon, and Sun and variational equations for producing the partial derivatives.
- Computing the model observations "C" (e.g. time delays) from the produced ephemerides for the time of each observation "O", calculating the residuals (O-C) and the partial derivatives.
• Obtaining the values of the parameters being determined, and deriving the residuals of the observations after the improvement by the least-squares adjustment; for that, observations are weighted in accordance with their a priori accuracy.

Several hundreds of parameters are determined simultaneously while improving the planetary part of the ephemerides. In addition to the orbital elements of all the planets and the main satellites of the outer planets, this set includes masses of celestial bodies, parameters of surface topography of planets and rotation of Mars, the coefficients of the solar corona and the solar oblateness, parameters of the orientation of planet ephemerides to the ICRF, etc. The value of Astronomical Unit, masses of Ceres, Pallas, Vesta and the Earth-Moon mass ratio are significant parameters of the DE and EPM ephemerides.

THE MASSES OF CERES, PALLAS, VESTA

The largest asteroids are massive enough to significantly affect the orbits of other bodies in the Solar System. Direct dynamical determinations of their masses come from their perturbations upon other solar system bodies.

In the classical example, the perturbed body is some other asteroid, and the accuracy of the mass determination depends upon the geometry of a close encounter and upon the accuracy and extent of the observation data; in this case a conventional ground based astrometry is used. Accurate mass determinations in this method may be obtained only for cases when very close encounters are provided with useful data before and after the encounter.

Fortunately, the masses of Ceres, Pallas, and Vesta, as well as a few other asteroids which affect Mars and the Earth most strongly may also be estimated from analysis of the highly accurate ranging data of the spacecraft orbiting Mars or landed upon its surface using high precision ephemerides.

The comparison of the 21 recent values of the masses of Ceres, Pallas and Vesta, obtained by different authors from close encounters with other asteroids and from their perturbations upon the orbit of Mars, has been made. This list includes the 9 values obtained by the last method while fitting DE and EPM ephemerides (see paper [5]). In selecting the representative values of Ceres, Pallas, Vesta masses for the proposal to the NSFA WG we with collaboration with E. M. Standish preferred the estimations obtained from their perturbations upon the orbit of Mars, as the classical method based on their perturbations upon other asteroids often gets inexact results, as noted above. As experience shows, the formal accuracy of determining the parameters by LS is overly optimistic. The actual accuracy could be an order of magnitude lower due to the deviation of the distribution of observations from the Gaussian law and due to the systematic errors in the observations, often of an unknown
nature. The actual accuracies of the parameters were estimated by comparing the values obtained in different test LS solutions that differed by the sets of observations, their weights, and the sets of parameters included in the solution, as well as by comparing parameter values and ephemerides produced by independent groups. The following mean representative values of Ceres, Pallas, and Vesta masses and their realistic uncertainties set out in Table 2.

Table 2. Masses of Ceres, Pallas and Vesta proposed to NSFA and approved by the 27 IAU GA

<table>
<thead>
<tr>
<th>Object</th>
<th>Previous values</th>
<th>Adopted new values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{Ceres}}/M_\odot$</td>
<td>4.39(4)$\times 10^{-10}$</td>
<td>4.72(3)$\times 10^{-10}$</td>
</tr>
<tr>
<td>$M_{\text{Pallas}}/M_\odot$</td>
<td>1.59(5)$\times 10^{-10}$</td>
<td>1.03(3)$\times 10^{-10}$</td>
</tr>
<tr>
<td>$M_{\text{Vesta}}/M_\odot$</td>
<td>1.69(11)$\times 10^{-10}$</td>
<td>1.35(3)$\times 10^{-10}$</td>
</tr>
</tbody>
</table>

THE EARTH-MOON MASS RATIO

The ratio of the masses of the Earth and the Moon was obtained by Standish while fitting the DE414 to all the data ([7]): $M_{\text{Earth}}/M_{\text{Moon}} = 81.300568$. This value is nearly identical to the new value obtained recently by Folkner et al. ([1]) for the DE421 ephemeris: $M_{\text{Earth}}/M_{\text{Moon}} = 81.3005691 \pm 0.0000005$; and the value for the EPM2008 ephemeris by Pijeva ([3]): $M_{\text{Earth}}/M_{\text{Moon}} = 81.3005676 \pm 0.0000001$, where for the two last values the formal uncertainties are indicated. A realistic uncertainty may be more than what estimations obtained in different solutions show. Therefore we proposed the following value of the Earth-Moon mass ratio

$$M_{\text{Earth}}/M_{\text{Moon}} = 81.300568 \pm 0.000003$$

or the Moon-Earth mass ratio, as it is customary in the NSFA WG

$$M_{\text{Moon}}/M_{\text{Earth}} = 0.0123000371(4).$$

THE VALUE OF THE ASTRONOMICAL UNIT

Since the beginning Venus radar echoes in 1961 the value of the Astronomical Unit, which fixes the scale distance in the Solar system, has been determined exclusively from ranging data of planets and spacecraft. The $AU$ value is one of basic parameters of JPL (DExxx) and IAA RAS (EPMxxxx) ephemerides.

The values for DE405 ([6]) and EPM2000 ([2]) $AU = 149597870691$m coincide due to the similarity of the dynamical models and sets of observations used in these ephemerides. At present (DE414 [7], DE421 [1] and EPM2008 [3]) the $AU$ values differ by 3 m, giving, therefore, a rough estimate of the uncertainty involved with this parameter. We
proposed to the NSFA WG the value \( AU = 149597870700(3) \) m which is consistent with the value of the heliocentric gravitational constant \( GM_\odot = 1.32712440041(10) \times 10^{20} \text{[m}^3\text{s}^{-2}] \) (TDB-compatible) proposed to the NSFA WG by Folkner ([11]). The TCB-compatible value is \( GM_\odot = 1.3271244099(10) \times 10^{20} \text{[m}^3\text{s}^{-2}] \).

The value \( GM_\odot \) in the physical system of units \([m^3 s^{-2}]\) may be estimated from fitting ephemerides to observations. However, up to the present, this value has been calculated from an entirely equivalent process – that of adjusting the \( AU \) value, obtained in meters while fitting planet ephemerides, by using the relation,

\[
GM_\odot [m^3 s^{-2}] = k^2 \cdot AU [m] / 86400 [s]^2,
\]

where \( k = 0.01720209895 \) is Gaussian gravitational constant.

This equation effectively defines the Astronomical Unit, and is used for the transition between the physical system of units – SI and the astronomical system of units.

All of the main ephemerides of JPL and IAA RAS have been constructed in the TDB time scale. It is noted here that the \( AU \) in meters has the same numerical value for ephemerides built in the TDB or the TCB time scale, if one uses the ordinary conversion between TDB and TCB proposed by Irwin and Fukushima, Brumberg and Groten, Brumberg and Simon.

**ORIENTATION OF PLANET EPHEMERIDES ONTO ICRF**

The reference frames of classical and more earlier numerical planet ephemerides were fundamental star catalogs. The ephemerides DE118, EPM87 were aligned onto the FK4 reference frame by transit measurements of the inner planets and the Sun obtained respect to the FK4-catalog stars. The reference frames of DE200 ephemerides have been

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Number of obs.</th>
<th>( \varepsilon_x )</th>
<th>( \varepsilon_y )</th>
<th>( \varepsilon_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989–1994</td>
<td>20</td>
<td>4.5±0.8</td>
<td>-0.8±0.6</td>
<td>-0.6±0.4</td>
</tr>
<tr>
<td>1989–2003</td>
<td>62</td>
<td>1.9±0.1</td>
<td>-0.5±0.2</td>
<td>-1.5±0.1</td>
</tr>
<tr>
<td>1989–2007</td>
<td>118</td>
<td>-1.53±0.06</td>
<td>1.02±0.06</td>
<td>1.27±0.05</td>
</tr>
</tbody>
</table>

the mean equator and dynamical of J2000. The determination of the dynamical equinox from an integrated long ephemeris, covering a 1400 years interval, was done by performing a least-squares fit to the motion of the instantaneous node of the Earth-Moon barycenter about the Sun by E. M. Standish.
At present the fundamental planetary ephemerides (since DE403 and EPM98) have been referenced to the the International Celestial Reference Frame (ICRF) by including in the adjustment the ICRF-base VLBI measurements of spacecraft near to planets.

EPM2008 have been oriented to ICRF by including into the total solution the 118 ICRF-base VLBI measurements of spacecraft (Magellan, Phobos, MGS, Odyssey, VEX, and MRO) 1989–2007 near Venus and Mars. Several solutions for recent and previous data are given in Table 3. The significant increasing of an accuracy for the solution with including more VLBI data is seen in this table.

CONCLUSIONS

The all values described in this paper and the others concerning the parameters of the Earth rotation (http://maia.usno.navy.mil/NSFA/CBE.html) were discussed in the NSFA WG and proposed to 27 IAU General Assembly for confirmation. The 27 IAU General Assembly passed the resolution adopting the list of Current Best Estimates as the IAU (2009) System of Astronomical Constants.

Acknowledgments. The work described in this paper was carried out and supported at the Institute of Applied Astronomy of Russian Academy of Sciences.


