Updated IAA RAS Planetary Ephemerides-EPM2011 and Their Use in Scientific Research

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Abstract - The EPM (Ephemerides of Planets and the Moon) numerical ephemerides were first created in the 1970s in support of Russian space flight missions and since then have been constantly improved at IAA RAS. In the following work, the latest version of the planetary part of the EPM2011 numerical ephemerides is presented. The EPM2011 ephemerides are computed using an updated dynamical model, new values of the parameters, and an extended observation database that contains about 680,000 positional measurements of various types obtained from 1913 to 2011. The dynamical model takes into account mutual perturbations of the major planets, the Sun, the Moon, 301 massive asteroids, and 21 of the largest trans-Neptunian objects (TNOs), as well as perturbations from the other main-belt asteroids and other TNOs. The EPM ephemerides are computed by numerical integration of the equations of motion of celestial bodies in the parameterized post-Newtonian n-body metric in the BCRS coordinate system for the TDB time scale over a 400-year interval. The ephemerides were oriented to the ICRF system using 213 VLBI observations (taken from 1989 to 2010) of spacecraft near planets with background quasars, the coordinates of which are given in the ICRF system. The accuracy of the constructed ephemerides was verified by comparison with observations and JPL independent ephemerides DE424.

The EPM ephemerides are used in astronavigation (they form the basis of the Astronomical Yearbook and are planned to be utilized in GLONASS and LUNA-RESURS
programs) and various research, including the estimation of the solar oblateness, the parameters of the rotation of Mars, and the total mass of the asteroid main belt and TNOs, as well as the verification of general relativity, the secular variations of the Sun’s mass and the gravitational constant, and the limits on the dark matter density in the Solar System.

The EPM ephemerides, together with the corresponding time differences TT - TDB and the coordinates of seven additional objects (Ceres, Pallas, Vesta, Eris, Haumea, Makemake, and Sedna), are available at [ftp://quasar.ipa.nw.ru/incoming/EPM](ftp://quasar.ipa.nw.ru/incoming/EPM).

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**HISTORICAL INTRODUCTION**

Until the coming of the space age in the 1960s, the classic analytical theories of planetary motion developed by Le Verrier, Hill, Newcomb, and Clemens, which were fully consistent with optical observations in terms of accuracy, were being constantly refined in accordance with the development of astronomical practice.

However, the launch of the first satellites exposed the demand for a more accurate calculation of the coordinates and the speeds of planets. Deep-space experiments and the introduction of new observational techniques (lunar and planetary ranging, trajectory measurements, etc.) required the development of planetary ephemerides that would be far more accurate than the classical ones. On the other hand, it was the new observational facilities that made it possible to develop ephemerides of the new generation.

The errors of the current best ranging observations do not exceed several meters, which makes it necessary to compute the ranging correctly up to the 12th significant digit. An appropriate model of the motion of celestial bodies is required to achieve such high precision. The construction of a proper model that would take into account all the significant factors is a serious problem, and the current most feasible way to solve it is to perform numerical integration of the equations of motion of the planets and the Moon on a computer.

In the late 1960s several research groups in the United States and Russia developed numerical theories to support space flights. American groups worked at the California Institute of Technology and the Massachusetts Institute of Technology. Russian high-
precision numerical ephemerides of planets (Akim et al., 1986) were created as a result of the research carried out at the Institute of Applied Mathematics, the Institute of Radio Engineering and Electronics and the Space Flight Control Center, and the Institute of Theoretical Astronomy, where N. I. Glebova, G. I. Eroshkin, and a group led by G. A. Krasinsky developed theories independently. This work was continued at the Institute of Applied Astronomy (IAA), where a series of EPM (Ephemerides of Planets and the Moon) ephemerides was produced. In order to provide technological support for such research, a large group of developers working at the IAA under the direction of G. A. Krasinsky created a unique software system called ERA (Ephemeris Research in Astronomy) that uses a high-level language targeted at astronomical and geodynamical applications. This ensures the flexibility of the system, which is being constantly upgraded, and considerably simplifies the development of various applications. The two dynamical models of planetary motion that are being developed in the series of DE (Development Ephemeris, JPL) (Standish, 1998; 2004; Folkner, 2010; Konopliv et al., 2011) and EPM (Krasinsky et al., 1993; Pitjeva, 2001; 2005a; 2012) ephemerides are currently the most complete, have the same precision, and are faithful to modern radio observations. For the reasons of technological independence, researchers at the Institut de Mecanique Celeste et de Calcul des Ephemerides (IMCCE) have started constructing their own numerical planetary ephemerides INPOP (Fienga et al., 2008; 2011) in 2006. The history of the creation of planetary ephemerides, the EPM2004 ephemeris and the differences between the DE and EPM ephemerides are discussed in greater detail in a paper by Pitjeva (2005a). In the present work the planetary part of the latest, updated version of the EPM ephemerides (EPM2011) and its use in various scientific investigations are discussed.

EPM DYNAMICAL MODEL OF PLANETARY MOTION

Construction of high-precision planetary ephemerides that are needed for space experiments, and would guarantee the meter-level accuracy of modern observations, requires creating a proper mathematical and dynamical model of the motion of planets, which takes into account all the significant perturbing factors on the basis of general relativity (GR).
The motion of the barycenter of the Earth-Moon system is appreciably perturbed by the Moon itself. The Moon’s orbit is subject to perturbations from the asphericity of the gravitational potentials of the Earth and the Moon, which makes it necessary to characterize the positions of the equators of the Earth and the Moon with respect to an inertial coordinate system (i.e., take into account the impact of precession, nutation, and physical libration) with sufficient accuracy. The resonant behavior of the coupling between orbital and rotational motions of the Moon makes it essential to reconcile various theories in a unified dynamical model. As a consequence, modern numerical theories are built by simultaneous numerical integration of the equations of motion of all planets and the Moon’s physical libration, while also taking into account the perturbations on the figure of the Earth due to the Moon and the Sun and the perturbations on the figure of the Moon due to the Earth and the Sun. Construction of the theory of the Moon’s orbital and rotational motions and its improvement using lunar laser ranging (LLR) observations are the most difficult tasks in creating modern ephemerides of planets and the Moon. This work was carried out at the IAA under the direction of G. A. Krasinsky and is described in a series of papers (Aleshkina et al., 1997; Krasinsky, 2002; Yagudina et al., 2012). The lunar theory takes into account the effects associated with elasticity, tidal dissipation of energy, and the frictional interaction between the Moon’s liquid core and its mantle, and cites selenodynamical parameters obtained through the analysis of LLR observations made from 1970 to 2010.

The influence of solar oblateness on planetary motion was established theoretically a long time ago, and some researchers even tried to attribute to it the anomalous motion of Mercury’s perihelion which was discovered by Le Verrier in the late 19th century. The solar oblateness causes secular variations of the orbital elements of planets, with the exception of semimajor axes and eccentricities, and has to be taken into account when constructing the model of planetary motion. The problem lies in the fact that the solar oblateness is determined indirectly from some complex astrophysical measurements that are subject to various systematic errors caused by equipment imperfection and the solar atmosphere and activity. The use of modern equipment made it possible to give a more reliable estimate $J_2 = 2 \cdot 10^{-7}$. This value is used for the construction of ephemerides starting with DE 405.
(Standish, 1998) and EPM2000 (Pitjeva, 2001). Recently, it became possible to determine the dynamical solar oblateness while processing of high-precision radar observations when constructing planetary ephemerides (see Pitjeva, 2005b).

A serious problem arises in the construction of modern high-precision planetary ephemerides due to the necessity of taking into account the perturbations caused by asteroids. The DE200 and EPM87 ephemerides considered the perturbations only from the 3-5 largest asteroids; the experiments revealed that this was impossible to attain a proper representation of high-precision observations of the Viking 1 and Viking 2 landers, i.e., a representation which would match the a priori errors (6-12 meters) of these observations. Amplitudes of the perturbations from asteroids were determined analytically by Williams (1984) considering commensurability between the orbital periods of the asteroids and Mars. The perturbations from 300 asteroids that were selected by Williams due to the significant perturbations of the orbit of Mars caused by them (Williams, 1989) are taken into account starting with the DE 403 (Standish et al., 1995) and EPM98 (Pitjeva, 1998) ephemerides. However, the masses of the majority of these asteroids are either unknown or known with insufficient accuracy, and Standish and Fienga (2002) showed that the accuracy of planetary ephemerides deteriorated substantially with time due to this factor. Direct dynamical estimates of the masses of asteroids may be obtained by analyzing their perturbations to other celestial bodies caused by them. This technique may be applied when examining spacecraft near asteroids, binary asteroids or asteroids with satellites, perturbations on the Mars and the Earth caused by asteroids and revealed through the processing of radar observations of Martian spacecraft and landers, and close encounters of asteroids. Applying the latter (classical) method requires great caution, since optical observations may produce large errors (Krasinsky et al., 2002). These techniques were used to measure the masses of several dozen asteroids, but the construction of high-precision planetary ephemerides demands taking into account the perturbations from about 300 large asteroids. If the estimates of the diameters and densities of these asteroids are available, one may also estimate their masses. The diameters of hundreds of asteroids were determined by processing the infrared data from the Infrared Astronomical Satellite (IRAS) and Midcourse Space Experiment (MSX)
satellites. When constructing the DE and EPM ephemerides, these asteroids were divided into the C (Carbonic), S (Sillicum), and M (Metallic) taxonomic types according to their spectral classes, and the estimates of their densities were derived from radar observations while improving the ephemerides. Apart from the sufficiently large asteroids, thousands of small asteroids, many of which are too small to be ever discovered from the Earth, produce a substantial cumulative effect on the orbits of the inner planets. The majority of these bodies travel within the main asteroid belt, and the distribution of their instantaneous positions in the main belt may be considered uniform. Thus, the perturbations from the small asteroids that were not considered individually in the integration may be modeled by additional perturbations from a massive ring in the plane of the ecliptic with a uniform mass distribution. Starting with EPM2004 (Pitjeva, 2005a), the two parameters characterizing the ring (its mass $M_r$ and radius $R_r$) are included in the set of parameters that are improved from observations.

Hundreds of trans-Neptunian objects (TNOs) that were discovered lately also exert influence on the motion of planets, especially the outer planets. The updated dynamical model of the EPM ephemerides includes Eris (a dwarf planet discovered in 2003, which is more massive than Pluto) and 20 of the largest TNOs into simultaneous integration. The perturbations from the other TNOs were modeled by a homogeneous TNO ring lying in the plane of the ecliptic and having a radius of 43 AU and an estimated mass (Pitjeva, 2010a).

Thus, the dynamical model created at the IAA RAS, takes into account (besides the mutual perturbations of large planets and the Moon) a number of relatively weak gravitational effects that contribute appreciably while processing modern high-precision observations:

- perturbations from 301 of the most massive asteroids;
- perturbations from other minor planets in the main asteroid belt, modeled by a homogeneous ring;
- perturbations from the 21 largest TNOs;
- perturbations from the other trans-Neptunian planets, modeled by a homogeneous ring at a mean distance of 43 AU;
• perturbations from the solar oblateness \((2 \cdot 10^{-7})\);
• relativistic perturbations from the Sun, the Moon, planets (including Pluto), and five largest asteroids.

When constructing the EPM ephemerides, the equations of motion of \(n\) bodies with masses \(m_1, \ldots, m_n\) in a non-rotating barycentric coordinate system were used. These equations take the form of

\[
\ddot{\mathbf{r}}_i = A + B + C + D + E,
\]

where \(A\) stands for the Newtonian gravitational accelerations:

\[
A = \sum_{j \neq i} \frac{\mu_j (\mathbf{r}_j - \mathbf{r}_i)}{r_{ij}^3};
\]

\(B\) stands for the relativistic terms:

\[
B = \sum_{j \neq i} \frac{\mu_j (\mathbf{r}_j - \mathbf{r}_i)}{r_{ij}^3} \left\{ -\frac{2(\beta + \gamma)}{c^2} \sum_{k \neq i} \frac{\mu_k}{r_{ik}^3} - \frac{2\beta - 1}{c^2} \sum_{k \neq j} \frac{\mu_k}{r_{jk}^3} + \gamma \left(\frac{v_i}{c}\right)^2 + \right. \\
\left. + (1 + \gamma) \left(\frac{v_j}{c}\right)^2 - \frac{2(1 + \gamma)}{c^2} \dot{\mathbf{r}}_i \cdot \dot{\mathbf{r}}_j - \frac{3}{2c^2} \left[ (\mathbf{r}_i - \mathbf{r}_j) \cdot \dot{\mathbf{r}}_j \right]^2 + \frac{1}{2c^2} (\mathbf{r}_j - \mathbf{r}_i) \cdot \ddot{\mathbf{r}}_j + \right. \\
\left. + \frac{1}{c^2} \sum_{j \neq i} \sum_{i \neq j} \frac{\mu_j}{r_{ij}^3} \left\{ \mathbf{r}_i - \mathbf{r}_j \right\} \cdot \left[ (2 + 2\gamma) \dot{\mathbf{r}}_i - (1 + 2\gamma) \dot{\mathbf{r}}_j \right] (\dot{\mathbf{r}}_i - \dot{\mathbf{r}}_j) + \frac{3 + 4\gamma}{2c^2} \sum_{j \neq i} \frac{\mu_j \ddot{\mathbf{r}}_j}{r_{ij}^3} \right\};
\]

\(C\) stands for the terms caused by the solar oblateness (the solar quadrupole moment):

\[
C = 3J_2\mu_S R^2 \frac{R_S}{r_{iS}^5} \left\{ \frac{5}{2} \left( \frac{\mathbf{r}_i - \mathbf{r}_S}{r_{iS}} \cdot \mathbf{p} \right)^2 - \frac{1}{2} \left( \frac{\mathbf{r}_i - \mathbf{r}_S}{r_{iS}} \right)^2 - \left( \frac{\mathbf{r}_i - \mathbf{r}_S}{r_{iS}} \cdot \mathbf{p} \right) \mathbf{p} \right\};
\]

\(D\) stands for the terms caused by the asteroid and TNO rings to the inner planets:

\[
D = \frac{1}{2} \frac{M_r}{R^2} F \left( 1.5, 1.5, 2, \frac{r_i^2}{R^2} \right) \mathbf{r}_i;
\]

and \(E\) stands for the terms caused by the asteroid ring to the outer planets:

\[
E = -\frac{M_r}{r_i^3} \left[ F \left( 0.5, 0.5, 1, \frac{R_r^2}{r_i^2} \right) + \frac{1}{2} \frac{R_r^2}{r_i^2} F \left( 1.5, 1.5, 2, \frac{R_r^2}{r_i^2} \right) \right] \mathbf{r}_i.
\]
Here the following designations were introduced: $\mathbf{r}_i$, $\dot{\mathbf{r}}_i$, $\ddot{\mathbf{r}}_i$ (barycentric vectors) are the coordinate, velocity, and acceleration vectors of the $i$th body; $\mu_j = Gm_j$, where $G$ is the gravitational constant and $m_j$ is the mass of the $j$th body; $r_{ij} = |\mathbf{r}_j - \mathbf{r}_i|$; $\beta, \gamma$ are the parameters of the PPN (parameterized post-Newtonian) formalism; $v_i = |\dot{\mathbf{r}}_i|$; $c$ is the speed of light; $J_2$ is the second zonal harmonic of the Sun; $R$ is the equatorial solar radius; $\mathbf{p}$ is the unit vector pointing to the Sun’s north pole; $M_r = Gm_r$, $m_r$, $R_r$ are the masses and radii of the rings; and $F$ is the hypergeometric function.

The summation in the equation that pertains to the Newtonian gravitational accelerations ($A$) includes (besides planets, the Sun, and the Moon) 301 asteroids and 21 TNOs. The five main asteroids (Ceres, Pallas, Vesta, Iris, and Bamberg) are entered not only in $A$, but also in the equations $B$ (the relativistic terms) and $C$ (the terms caused by the solar oblateness). Thus, the equations of motion for the 16 main objects incorporate all the mutual perturbations, including relativistic ones and the perturbations due to the solar oblateness.

The variable $\ddot{\mathbf{r}}_j$, that appears in two terms in the right side of the equations stands for the barycentric acceleration of the $j$th body due to the Newtonian acceleration of other bodies.

It should be noted that only the equations of motion of planets, asteroids, TNOs, and the Moon are actually integrated. The barycentric coordinates and velocities of the Sun are derived from the following equation:

$$\sum_i \mu_i^* \mathbf{r}_i = 0,$$

where

$$\mu_i^* = \mu_i \left\{ 1 + \frac{1}{2c^2}v_i^2 - \frac{1}{2c^2} \sum_{j \neq i} \frac{\mu_j}{r_{ij}} \right\}.$$

All modern high-precision ephemerides are based on relativistic time scales and relativistic equations of motion of celestial bodies and radio and light rays. The main common feature of the DE, EPM, and INPOP series of ephemerides is the simultaneous numerical integration of the equations of motion of nine major planets, the Sun, the Moon, and the lunar physical libration carried out in the post-Newtonian approximation for GR ($\beta = \gamma = 1$) in a harmonic coordinate system ($\alpha = 0$).

Thus, the terms $A$, $B$, and $C$ are identical in all those major planetary ephemerides.
Various versions of ephemerides differ in modeling the lunar libration, reference frames in which the ephemerides are computed, adopted values of the solar oblateness and other parameters, modeling of perturbations from asteroids, and used sets of observations and estimated parameters. The main distinction of the latest EPM ephemerides (starting with EPM2008, as described in Pitjeva, 2009) from the DE and INPOP ephemerides is the inclusion of the perturbations from TNOs that are actually present in the Solar System. The inclusion of any additional objects into the simultaneous integration leads to the shift of the barycenter of the Solar System. Since TNOs are located beyond the orbit of Neptune, and there are many large objects (for example, Eris) among them, the said shift becomes significant. In the process of calculations, the barycenter remains in its place, while the coordinates of all objects involved in the integration change. Therefore, comparing the EPM ephemerides with the DE and INPOP ephemerides requires using relative (heliocentric, geocentric, etc.) coordinates of objects, but not barycentric ones. Such a comparison was carried out for DE421, EPM2008, and INPOP08 by Hilton and Hohnerk (2011). Since any observations are relative (are usually made from the Earth), the shift of the barycenter does not influence the representation of observations.

In recent years, a large number of high-precision radiometric observations of spacecraft, revolving around or passing close to planets, and optical observations of the satellites of planets carried out by both terrestrial observatories and the Hubble Space Telescope became available. This enabled the researchers to derive new masses of planets and other bodies of the Solar System. These values were adopted as the current best values of the constants of dynamical astronomy by XXVII IAU GA in 2009 (Luzum et al., 2011) and are used in updated versions of the EPM ephemerides (starting with EPM2008).

The integration in the barycentric coordinate system at the J2000.0 epoch was done using Everhart’s method over a 400-year interval (from 1800 to 2200) by a lunar and planetary integrator of the ERA-7 software system.

**OBSERVATIONAL DATA, THEIR REDUCTION, AND TT - TDB**

The observations that were used to improve the accuracy of the EPM2011 ephemerides
included 677670 positional measurements of various types (from classical meridian observations to modern radio observations of planets and spacecraft) obtained from 1913 to 2011. Optical observations dating from 1913, when an improved micrometer was installed at the United States Naval Observatory and the measurements became more accurate (\(\sim 0.5''\)), and all the available radio observations (up to the year 2011) were used. It should be noted that the accuracies of modern CCD observations approach a few hundredths of an arcsecond. A real revolution in dynamical astronomy started in 1961 when the first successful radiolocation of Venus was carried out simultaneously in the United States (at the California Institute of Technology and the Massachusetts Institute of Technology), the USSR (at the Institute of Radio Engineering and Electronics), and England (at the Jodrell Bank Observatory). The significance of astronomical radar observations stems from two factors. Firstly, they added two new types of measurements, namely, the measurement of the delay time (ranging) that could be converted to distance using the known speed of light and the measurement of the Doppler frequency shift that gives the relative radial velocity of the reflecting surface. Secondly, radar observations are highly accurate. Nowadays the relative accuracy that ranges from \(10^{-11}\) to \(10^{-12}\) has become ordinary for trajectory measurements of spacecraft. These values are five orders of magnitude better than the accuracy of classical optical measurements. However, only the terrestrial planets are fully provided by with radio observations. Fewer observations of this type are made for Jupiter and Saturn, and there exists only one three-dimensional normal point provided by Voyager 2 for Uranus (and Neptune). Therefore, optical observations still retain their significance for the outer planets. The main factors that limit the accuracy of photographic and CCD observations of planets are the brightness of planets compared to reference stars (the equalization of brightness); the distortion of photographic images due to meteorological, instrumental, and astronomical (the phase effect) causes; and the difficulty of measuring an extended object of a non-uniform density. This applies especially to bright planets (Jupiter and Saturn) with large visible disks. Positional observations of planetary satellites are not prone to any of these restrictions. Since the position of a satellites relative to the stars is determined both by the planetary motion and the satellite’s own motion around the planet, the measurements of
the positions of satellites may be used to define the planetary orbits more accurately. The astrometric photographic observations of the satellites of Jupiter and Saturn were started in the Nikolaev Observatory in 1962. In 1998, astronomers in Flagstaff began observing the satellites of the outer planets (in addition to the observations of the outer planets themselves), and all their measurements are referred to the ICRF system with the use of reference stars from the AST and TYCHO2 catalogues. Observations of satellites are also carried out at a number of other observatories. Theories of the motion of satellites are required to process such observations. Analytical theories of the motion of the satellites of Jupiter (Lieske), Saturn (Vienne and Duriez), and Uranus (Lascar and Jacobson) are incorporated in the ERA-7 software system. The drawback of these analytical theories lies in the fact that they do not provide an opportunity to correctly introduce the parameters of the satellite’s motion when improved from observations. Therefore, the researchers at the IAA RAS, construct their own numerical theories of the motion of the satellites of Mars and the outer planets (Poroshina et al., 2012). These theories are successfully used to improve the ephemerides of satellites and planets alike. Lately, the previous observations (prior to 2005) were supplemented with the new data from spacecraft, namely, measurements of ranging made using Odyssey, Mars Reconnaissance Orbiter (MRO), Mars Express (MEX), and Venus Express (VEX); VLBI observations of Odyssey and MRO; and three-dimensional normal point observations of Cassini and Messenger. These measurements were complemented by CCD observations of the outer planets and their satellites made at the Flagstaff and Table Mountain observatories. The observations used are shown on the page 12 (1 mas = 0′′.001); the numbers in the headings (57560, 58112, and 561998) indicate the number of observations.

The majority of these observations were taken from the Jet Propulsion Laboratory (JPL) database [http://iau-comm4.jpl.nasa.gov/plan-eph-data/index.html] which was created by E. M. Standish and is now maintained and expanded by W.M. Folkner. This data set was supplemented by Russian radar observations of planets made from 1961 to 1995 [http://www.ipa.nw.ru/PAGE/DEPFUND/LEA/ENG/rrr.html] and data from Venus Express and Mars Express obtained through the courtesy of A. Fienga.
Astrometric observations of planets and spacecraft

Optical observations of the outer planets and their satellites made from 1913 to 2011 (57560)

| USNO       | Observation type | Interval | A priori accuracy |
|------------|------------------|----------|------------------|
| Pulkovo    | Transits         | 1913–1994| 1" → 0".5        |
| Nikolaev   | Photoelectric transits | 1963–1998| 0".8 → 0".25     |
| Tokyo      | Photographic     | 1913–1998| 1" → 0".2        |
| Bordeaux   | CCD              | 1995–2011| 0".2 → 0".05     |
| LaPalma    |                  |          |                  |
| Flagstaff  |                  |          |                  |
| TMO        |                  |          |                  |

Radar observations of Mercury, Venus, and Mars (58112)

| Millstone  | Observation type | Interval | A priori accuracy |
|------------|------------------|----------|------------------|
| Haystack   | Ranging          | 1961–1997| 100 km → 150 m   |
| Arecibo    |                  |          |                  |
| Goldstone  |                  |          |                  |
| Crimea     |                  |          |                  |

Radio data provided by spacecraft from 1971 to 2010 (561998)

| Mariner − 9 | Observation type | Interval | A priori accuracy |
|-------------|------------------|----------|------------------|
| Pioneer − 10, −11 |                |          |                  |
| Voyager      |                  |          |                  |
| Phobos       |                  |          |                  |
| Ulysses      |                  |          |                  |
| Magellan     |                  |          |                  |
| Galileo      |                  |          |                  |
| Viking − 1, −2 |                |          |                  |
| Pathfinder   |                  |          |                  |
| MGS          |                  |          |                  |
| Odyssey      |                  |          |                  |
| MRO          |                  |          |                  |
| Cassini      |                  |          |                  |
| VEX          |                  |          |                  |
| Messenger    |                  |          |                  |
| MEX          |                  |          |                  |

The processing of observational data was done using proven and reliable techniques with due account for all the needed reductions (Pitjeva, 2005a). The following reductions were applied to radar data:
• reduction of time moments to a uniform scale;
• relativistic corrections, namely, the delay of radio signals in the gravitational field of the Sun, Jupiter, and Saturn (the Shapiro effect) and the transition from the coordinate time (the argument of ephemerides) to the proper time of the observer;
• the delay of radio signals in the Earth’s troposphere;
• the delay of radio signals in the plasma of the solar corona;
• correction for topography of the surfaces of planets (Mercury, Venus, and Mars).

The following reductions were applied to optical data:

• reduction to the ICRF system: from reference catalogues to FK4, then to the FK5 catalog, and at last to the ICRF frame;
• correction for additional phase effect;
• correction for gravitational deflection of light by the Sun.

The transition from the observing time (UTC = TAI + an integer number of seconds) to the barycentric dynamic time (TDB) of the ephemerides requires knowing the differences between the terrestrial time (TT = TAI + 32.184 s) and TDB. Until recently, these differences were computed by applying the analytical expansions for the DE405 ephemerides. However, the differences TT - TDB depend on the coordinates of all bodies that are involved in the integration of the corresponding ephemerides. Therefore, the construction of these differences by numerical integration using the corresponding ephemerides is more correct.

The following differential equation taken from the paper by Klioner (2010) was used for connection between TT and TDB:

\[
\frac{dT T - T D B}{dT D B} = \frac{L_B - L_G}{1 - L_B} + \frac{1}{1 - L_B} \left( \frac{1}{c^2} \alpha' + \frac{1}{c^4} \beta' \right),
\]

where \( L_B = 1.550519768 \times 10^{-8}, L_G = 6.969290134 \times 10^{-10} \), \( c \) is the speed of light,

\[
\alpha' = -\frac{1}{2} v_E^2 - \sum_{A \neq E} \frac{GM_A}{r_{EA}},
\]

\[
\beta' = -\frac{3}{2} v_E^2 - 2 v_A^2 + \frac{1}{2} a_A \cdot r_{EA} + \frac{1}{2} \left( \frac{v_A \cdot r_{EA}}{r_{EA}} \right)^2 + \sum_{B \neq A} \frac{GM_B}{r_{AB}},
\]
Figure 1 shows, as an example, differences in TT - TDB for the EPM2004 and EPM2008 ephemerides expressed in nanoseconds.

EPM2011 PARAMETERS AND REPRESENTATION OF OBSERVATIONS

About 270 parameters were determined in the process of improving the planetary part of the EPM2011 ephemerides:

- the orbital elements of planets and 18 satellites of the outer planets;
- the value of the astronomical unit or $GM_\odot$;
- the angles of orientation of the ephemerides with respect to the ICRF;
- parameters of the rotation of Mars and the coordinates of three Martian landers;
- the masses of 21 asteroids and the mean densities of three taxonomic classes (C, S, and M) of asteroids;
- the mass and radius of the asteroid ring and the mass of the TNO ring;
- the ratio of the Earth and Moon masses;
- the Sun’s quadrupole moment and parameters of the solar corona for different conjunctions of planets with the Sun;
- the coefficients of Mercury’s topography and corrections to the level surfaces of Venus and Mars;
- the coefficients for additional phase effect of the outer planets;
the constant shifts for the series of observations of Venus in Goldstone (1964) and Venus (1969) and Mercury (from 1986 to 1989) in Crimea, as well as the shifts (and, in certain cases, their derivatives) for all spacecraft that were interpreted as the calibration errors;

post model parameters, such as the PPN parameters \((\beta, \gamma)\), \(\pi_i, GM_\odot/GM_\odot\), \(\dot{a}_i/a_i\).
Table 2. Mean values and rms’s of the residuals of optical observations and data from spacecraft near planets (marked by *) obtained from 1913 to 2011 for \( \alpha \) and \( \delta \) expressed in mas

| Planet    | Number of observations | \(< O-C>_{\alpha}\) | \(\sigma_{\alpha}\) | \(< O-C>_{\delta}\) | \(\sigma_{\delta}\) |
|-----------|------------------------|----------------------|---------------------|---------------------|---------------------|
| Mercury*  | 6                      | 0.0                  | 0.7                 | 1.0                 | 1.8                 |
| Venus*    | 4                      | 0.3                  | 1.7                 | 1.8                 | 6.5                 |
| Jupiter   | 13364                  | 12                   | 181                 | -28                 | 194                 |
| Jupiter*  | 16                     | -1.0                 | 2.2                 | -4.9                | 7.9                 |
| Saturn    | 15056                  | -1.0                 | 160                 | -1.0                | 157                 |
| Saturn*   | 92                     | 0.1                  | 0.3                 | 0.0                 | 0.8                 |
| Uranus    | 11846                  | 3.0                  | 171                 | 0.4                 | 203                 |
| Uranus*   | 2                      | -45                  | 8.0                 | -27                 | 12                  |
| Neptune   | 11634                  | 4.9                  | 152                 | 6.4                 | 195                 |
| Neptune*  | 2                      | -12                  | 3.5                 | -13                 | 4.0                 |
| Pluto     | 5660                   | 0.4                  | 138                 | 3.0                 | 140                 |

The residuals of ranging for Odyssey, MRO, MEX, and VEX are shown in Fig. 2. In ranging the increase of the dispersion O–C is evident during solar conjunctions when the signal passes through the solar corona. The delay in the solar corona was taken into account with the improvement of the coefficients of the corona model from observations, but getting rid of the solar corona noise completely requires the two frequencies measurements. The rms errors of the residuals amount to 1.1 m (Odyssey), 1.2 m (MRO), 1.5 m (MEX), and 2.8 m (VEX).

Fig. 2. Residuals of ranging (expressed in meters) for observations made by Odyssey, Mars Reconnaissance Orbiter (MRO), Mars Express (MEX), and Venus Express (VEX).

The residuals of observations of right ascensions (or, to be more precise, \( \alpha \cos \delta \)) and declinations for the outer planets and their satellites are presented in Fig. 3.
Fig. 3. Residuals of observations of $\alpha \cos \delta$ and $\delta$ (1913-2011) for the outer planets on a scale of $\pm 5''$. 
Tables 1 and 2 show that the majority of observations that form the basis of the ephemerides are classified as radio observations, mostly ranging obtained with the use of spacecraft. These measurements allow us to obtain all the orbital elements of planets with the exception of the three angles of the Earth’s orientation, which is equivalent to the orientation of the whole system of the ephemerides (angles $\varepsilon_x$, $\varepsilon_y$, and $\varepsilon_z$). The earliest numerical planetary ephemerides (DE118 and EPM87) were referred to the FK4 catalogue system, while the DE200 ephemerides were referred to the system of the dynamical equator and equinox. At present, planetary ephemerides are oriented with respect to the international ICRF system through the use of VLBI observations of various spacecraft near planets with background quasars, the coordinates of which are given in the ICRF system. The accuracy of these observations has improved considerably from 2001 to 2010 and reached several tenths of a milliarcsecond for Saturn and Mars (Jones et al., 2011). This made it possible to significantly improve the orientation of the EPM2011 ephemerides. The angles of rotation between the EPM ephemerides and the ICRF system and their errors obtained at present and previously are presented in Table 3. Figure 4 shows the residuals of VLBI observations of various spacecraft near Mars and of Cassini near Saturn.

**Table 3. Rotation angles for orientation of the EPM ephemerides into the ICRF system**

| Observation interval | Number of observations | $\varepsilon_x$ mas | $\varepsilon_y$ mas | $\varepsilon_z$ mas |
|----------------------|-----------------------|---------------------|---------------------|---------------------|
| 1989-1994            | 20                    | 4.5 $\pm$ 0.8       | $-0.8$ $\pm$ 0.6   | $-0.6$ $\pm$ 0.4   |
| 1989-2003            | 62                    | 1.9 $\pm$ 0.1       | $-0.5$ $\pm$ 0.2   | $-1.5$ $\pm$ 0.1   |
| 1989-2007            | 118                   | $-1.528$ $\pm$ 0.062 | 1.025 $\pm$ 0.060 | 1.271 $\pm$ 0.046  |
| 1989-2010            | 213                   | $-0.000$ $\pm$ 0.042 | $-0.025$ $\pm$ 0.048 | 0.004 $\pm$ 0.028 |

The improvement of the orientation of the EPM ephemerides made it possible to reach the accuracy of the Earth’s heliocentric coordinates ($X$, $Y$, $Z$) over a 100-year interval (from 1950 to 2050) of at least 250 m and the accuracy of velocities ($\dot{X}$, $\dot{Y}$, $\dot{Z}$) of at least 0.05 mm/s (see Fig. 5). The knowledge of the Earth’s accurate heliocentric coordinates is particularly important when studying pulsars, variable stars, and exoplanets. However, the comparison of
Fig. 4. Residuals of VLBI observations of various spacecraft near Mars and of Cassini near Saturn expressed in mas.

the EPM2011 and JPL DE424 ephemerides showed that differences of heliocentric distances of the Earth, determined by ranging, for these ephemerides over the same interval are much smaller and do not exceed 6 m (see left side of Fig. 6 for the geocentric Sun).

Fig. 5. Differences EPM2011 – DE424 in heliocentric coordinates ($X, Y, Z$) and velocities ($\dot{X}, \dot{Y}, \dot{Z}$) of the Earth from 1950 to 2050.
Some parameters determined in the process of improving the DE and EPM ephemerides (Pitjeva and Standish, 2009) and adopted as the current best values for ephemeris astronomy by XXVII IAU GA in 2009 (Luzum et al., 2011) were taken as initial in EPM2011 and were then improved from all observations. Among them are such parameters as the ratio of masses of the Earth and the Moon $M_{\text{Earth}}/M_{\text{Moon}} = 81.30056763 \pm 0.00000005$ and the masses of largest asteroids (Ceres, Pallas, and Vesta) and 18 other asteroids. Table 4 gives the masses and the estimates of these masses with ones taken from papers by Konopliv et al. (2011) and Fienga et al. (2011), where they were obtained in the same way using the DE423 and INPOP10a ephemerides. All parameters obtained in the present work and mentioned in this section are given with uncertainties that correspond to $3\sigma$ (formal standard error of the least squares method). Experience shows that formal standard errors are overly optimistic. Uncertainties given by Konopliv et al. (2011) are obtained with a special method that is characterized by the fact that the uncertainties of the masses of asteroids that are not estimated are taken into account while calculating all the adjusted parameters. The uncertainties obtained in this way are probably close to the actual errors. Uncertainties specified in a paper by Fienga et al. (2011) are larger than the ones obtained here due to the large quantity (145) of the estimated masses of asteroids. The data presented in Table 4 point to the fact that the estimates of masses of asteroids largely agree with each other within the limits of their errors. The two exceptions are the masses of (52) Europa and (511) Davida for the INPOP10a ephemerides. On August 16, 2011, the Dawn spacecraft approached Vesta, one of the largest asteroids. The spacecraft studied the asteroid for a year and determined its mass to be $(130.2927 \pm 0.0005) \cdot 10^{-12}GM_\odot$ (Russel et al., 2012). This value virtually coincides with the estimate of the mass of Vesta obtained in the present work.

Special effort was given to producing an accurate estimate of the total influence of asteroids on the motion of planets, the majority of which lie in the main asteroid belt. In EPM the main belt is modeled by the motion of the 301 largest asteroids and a homogeneous material ring that represents the influence of numerous other small asteroids. Parameters $M_{\text{ring}}$ and $R_{\text{ring}}$ that characterize the ring of small asteroids were determined through the
processing of observations:

\[ M_{\text{ring}} = (1.06 \pm 1.12) \cdot 10^{-10} M_\odot, \quad R_{\text{ring}} = (3.57 \pm 0.26) \text{ AU} \]

**Table 4.** Estimates of the masses of asteroids obtained by using the observations of ranging for the EPM 2011, DE423 (Konopliv et al., 2011), and INPOP10a (Fienga et al., 2011) ephemerides and expressed in \((GM_i/GM_\odot) \times 10^{-12}\)

| Asteroid | EPM2011  | DE423    | INPOP10a |
|----------|----------|----------|----------|
| (1) Ceres| 472.17 ± 0.79 | 467.90 ± 3.25 | 475.8 ± 2.8 |
| (2) Pallas| 104.72 ± 0.92 | 103.44 ± 2.55 | 111.4 ± 2.8 |
| (3) Juno | 14.67 ± 0.25  | 12.10 ± 0.91  | 11.6 ± 1.3  |
| (4) Vesta| 129.70 ± 0.45 | 130.97 ± 2.06 | 133.1 ± 1.7 |
| (6) Hebe | 4.05 ± 0.46   | 6.73 ± 1.64   | 7.1 ± 1.2   |
| (7) Iris | 6.54 ± 0.30   | 5.53 ± 1.32   | 7.7 ± 1.1   |
| (8) Flora| 2.05 ± 0.18   | 2.01 ± 0.42   | 4.07 ± 0.63 |
| (9) Metis| 1.64 ± 0.25   | 3.28 ± 1.08   | —          |
| (10) Hygiea| 41.61 ± 1.34 | 44.97 ± 7.36  | —          |
| (14) Irene| 3.61 ± 0.28   | 1.91 ± 0.81   | —          |
| (15) Eunomia| 14.45 ± 0.55 | 14.18 ± 1.49  | 18.8 ± 1.6 |
| (16) Psyche| 12.75 ± 1.03  | 12.41 ± 3.44  | 11.2 ± 5.2 |
| (19) Fortuna| 4.36 ± 0.13  | 3.20 ± 0.53   | —          |
| (23) Thalia| 1.24 ± 0.21   | 1.11 ± 0.71   | —          |
| (29) Amphitrite| 5.39 ± 0.50 | 7.42 ± 1.49   | —          |
| (41) Daphne| 4.17 ± 0.44   | 4.24 ± 1.77   | 9.2 ± 2.6  |
| (52) Europa| 9.06 ± 1.32   | 11.17 ± 8.40  | 42.3 ± 8.0 |
| (324) Bamberga| 5.10 ± 0.14  | 5.34 ± 0.99   | 4.67 ± 0.38 |
| (511) Davida| 6.11 ± 1.74   | 8.58 ± 5.93   | 19.9 ± 4.1 |
| (532) Herculina| 7.07 ± 0.62  | 4.97 ± 2.81   | 2.89 ± 0.76 |
| (704) Interamnia| 12.22 ± 0.96 | 19.97 ± 6.57  | —          |

The total mass \(M_{\text{belt}}\) of the main belt asteroids is expressed as the sum of the masses of 301 largest asteroids and the asteroid ring and is equal to \(M_{\text{belt}} = (12.3 \pm 2.1) \cdot 10^{-10} M_\odot\) (about 3 times the mass of Ceres). The gravitational attraction of trans-Neptunian objects is modeled in much the same way by summing the influences of 21 known TNOs and an additional homogeneous ring with a radius of 43 AU that represents numerous other smaller
objects. The mass of the TNO ring \( M_{\text{TNOring}} \) was determined to be equal to \( M_{\text{TNOring}} = (501 \pm 249) \cdot 10^{-10} M_\odot \) while processing observations.

The total TNO mass \( M_{\text{TNO}} \) that includes the masses of Pluto, the 21 largest TNOs, and the TNO ring is equal to \( M_{\text{TNO}} = 790 \cdot 10^{-10} M_\odot \), (about 164 times the mass of Ceres or 2 times the mass of the Moon).

**ACCURACY OF EPHEMERIDES AND COMPARISON BETWEEN THE EPM2011 AND DE424 EPHEMERIDES**

Firstly, the accuracy of the constructed ephemerides may be estimated from the representation of observations, i.e., from comparison of the observable values (O) with the computed values (C) of observations. Tables 1–3 and Figures 2–4 present the residuals, their mean values, and their errors (\( \sigma \)) that do not exceed their a priori errors. Secondly, the accuracy of ephemerides may be evaluated by comparing them with other ephemerides constructed by independent research teams. Starting from the 1970s, the EPM ephemerides computed at the IAA RAS, were regularly compared with the DE ephemerides created at JPL. In a paper by Pitjeva (2005a), the differences in heliocentric distances of planets for the EPM2004 and DE410 ephemerides over a 40-year interval (from 1970 to 2010) are presented. In the present work, the differences in three coordinates over a 100-year interval are presented in Figures 6 and 7. These coordinates – geocentric distances (\( D \)), right ascensions (\( \alpha \)), and declinations (\( \delta \)) – fully characterize the accuracy of the ephemerides determined by comparing the EPM2011 and DE424 ephemerides.

Since the coordinates of the inner planets were obtained through high-precision radio observations, the differences calculated for them are much smaller for all the coordinates (\( D, \alpha, \delta \)) than the differences for the outer planets (the geocentric position of the Sun may be viewed as the heliocentric position of the Earth with an opposite sign). The fact that the difference in Mercury distances is slightly larger than the one given in a paper by Pitjeva (2005a) is explained by the use of new Messenger data, so far inaccessible to us, in DE424. The differences in distances (over the interval considered in the 2005 paper) for all the other planets have become less. In the case of Mars, the differences remain minor over
Fig. 6. Differences EPM2011–DE424 in geocentric distances ($D$), right ascensions ($\alpha$), and declinations ($\delta$) of Mercury, Venus, the Sun, and Mars over a 100-year interval (from 1950 to 2050).

an interval which is somewhat wider than the one covered by observations. More precisely, the differences in distance, $\alpha$, and $\delta$ do not exceed 150 m, 0.7 mas, and 0.5 mas, respectively, over a 58-year interval (from 1970 to 2028).

The availability of some radio observations of Jupiter and particularly Saturn (studied by the Cassini spacecraft) allowed us to reconstruct their orbits with an accuracy greater than that achievable for the other outer planets’ orbits defined virtually only by optical observations. There exists only one three-dimensional point ($D, \alpha, \delta$) provided by Voyager - 2 for Uranus and Neptune. Besides that, not even one period of orbital rotation of Neptune
and Pluto is covered with more or less accurate observations. The uncertainty of the Pluto’s distance, which was specified by Folkner in his talk at XXVIII IAU GA, changes from 1100 to 3000 km over a 18-year interval (from 2000 to 2018). These values are roughly correspondent to the uncertainty obtained in the present work (3300 km) by comparing the EPM2011 and DE424 ephemerides (see left bottom part of Fig. 7).

**Fig. 7.** Differences EPM2011–DE424 in geocentric distances ($D$), right ascensions ($\alpha$), and declinations ($\delta$) of the outer planets over a 100-year interval (from 1950 to 2050).
In a paper by Fienga et al. (2011) the differences in geocentric distances, right ascensions, and declinations of planets over a 120-year interval (from 1900 to 2020) are also shown for the INPOP10a and DE421 ephemerides. The comparison of results on the common interval (1950–2020) shows that all the differences in $D$, $\alpha$, $\delta$ for the EPM2011 and DE424 ephemerides are lower than the corresponding differences for the INPOP10a and DE421 ephemerides. This may be attributed to the use of the new version of the EPM ephemerides. Specifically, the INPOP10a ephemerides included the observations of the outer planets that were carried out not later than 2008, whereas the EPM2011 ephemerides include data up to the year 2011. The sole exception is the distance for Jupiter in the EPM2011 and DE424 ephemerides. The distances for Jupiter are determined for the most part by a few radar observations carried out from 1974 to 2000. All 7 such observations, weighted according to their accuracy, are used in the EPM2011 ephemerides, while the other ephemerides include only the five most accurate ones.

It is interesting to look at the comparison of the same values given in a paper by Standish (2004) for the DE200 and DE409 ephemerides over a 50-year interval (from 1970 to 2020). It can be seen that all the differences are at least an order of magnitude larger. This leads to the conclusion that modern ephemerides have made great progress in terms of accuracy compared to DE200 (1982).

The comparison with modern observations and the DE ephemerides verifies that the planetary part of the EPM ephemerides is sufficiently accurate.

THE USE OF THE EPM EPHEMERIDES IN SCIENTIFIC RESEARCH

The potential to construct and maintain fundamental ephemerides of the major planets, the Sun, and the Moon may be viewed as one of the characteristics of a technologically mature state. The reason for this lies in the fact that these ephemerides have various practical applications. Specifically, they serve as an important element of terrestrial - , marine - , and space-based navigational systems. Nowadays the DE/LE series of ephemerides that are developed in the United States and serve, first and foremost, to support the American space research program are adopted as the international standard of fundamental ephemerides. The
high accuracy of these ephemerides is preconditioned by the fact that enormous high-quality sets of observational data obtained using terrestrial observatories and spacecraft are utilized in creating the DE/LE ephemerides. However, the use of the American DE/LE ephemerides may present some difficulties. Among them are the problems with licensing (the IAU did not issue recommendations for the use of any DE ephemerides except DE200), openness (not all the algorithms are described in detail), possible delays (the access to new versions of the DE/LE ephemerides may remain restricted for a certain period of time), and reliability. Since domestic ephemerides are not subject to these problems, the IAA RAS, developed its own EPM ephemerides and uses them when preparing the Astronomical Yearbook (starting from 2006), the Nautical Astronomical Yearbook, and the Nautical Astronomical Almanac. Besides that, it is planned to use these ephemerides in GLONASS and LUNA-RESURS programs.

The EPM ephemerides lie at the basis of much scientific research. For six years (1976–1982) the Viking 1 and Viking 2 landers were observed from California, Madrid, and Canberra, while the Pathfinder lander was observed for three months in 1997. These unique observations made it possible to define more precisely the rotation of Mars when constructing the EPM ephemerides. The determination of the more precise values of the parameters of rotation of Mars is important for understanding its geophysics. Firstly, the comparison of the observed and the calculated precessions of Mars coupled with the oblateness coefficient of Mars makes it possible to calculate the normalized polar moment of inertia that allows researchers to evaluate the density variations within the planet. Secondly, the comparison of the determined amplitudes of short-period nutation terms with the theoretical predictions enables exploration of the question of the distinctions between Mars and a rigid body. The observations of Martian landers (on the basis of the EPM ephemerides) made it possible to determine the coordinates of all the three landers and define all parameters of rotation of Mars (precession, nutation, and seasonal rotation terms governed by melting and condensation of carbonic acid at the polar caps) and the polar moment of inertia, corresponding to the speed of precession of Mars (Pitjjeva, 1999), more precisely. The parameters of rotation of Mars and their accuracies were found to be close to the corresponding values taken from a paper by Yoder and Standish (1997).
Asteroids exert a significant influence on the motion of planets (especially Mars); therefore, the masses of the largest asteroids (in the present work we examined the 21 largest ones) and the total mass of the main asteroid belt may be estimated from radio observations. Hundreds of trans-Neptunian objects, which also exert influence on the motions of planets, were discovered recently; their total mass may also be estimated, as was already done by Pitjeva (2010a). The knowledge of such characteristics is important not only for devising a more precise description of the forces acting in the Solar System, but also for understanding the general dynamics of the Solar System and the processes associated with its formation.

The passage of photons and motion of planets in the gravitational filed of the Sun allow us to view the Solar System as a sufficiently convenient laboratory for testing gravity theories. Modern radar observations of planets and spacecraft, that have meter-level accuracy, make it possible to explore relativistic effects, estimate the value of the heliocentric gravitational constant \( GM_\odot \) (the Sun’s mass) and its possible variation, and estimate the solar oblateness. The comparison of the results of determination of additional motion of the perihelia of planets, which is not modeled by Newtonian interaction and GR, the PPN parameters \( \beta, \gamma \), the quadrupole moment of the Sun, and \( GM_\odot \), that were cited in previous works (Krasinsky et al., 1986; Pitjeva, 1993; 2005b; 2010b) and obtained in the present work:

\[
\beta - 1 = -0.00002 \pm 0.00003, \quad \gamma - 1 = +0.00004 \pm 0.00006, \quad J_2 = (2.0 \pm 0.2) \cdot 10^{-7},
\]

shows that, firstly, the uncertainties of these parameters did decrease significantly (at least by an order of magnitude). This substantial progress may be attributed to the increase in accuracy of the dynamical models of motion and the methods of reduction of observations and to the improvement of observational data (i.e., boost in precision and widening of the observational time interval). Secondly, the reduction of the uncertainties of these parameters constrains the possible values of relativistic parameters and imposes increasingly tight restrictions on the gravity theories that are competing with GR.

For the first time, the variation of the heliocentric gravitational constant

\[
GM_\odot/GM_\odot = (-5.0 \pm 4.1) \cdot 10^{-14}
\]

per year (3\( \sigma \)) has been deduced through the analysis of various types (mostly radio) of
Positional observations of planets and spacecraft. The value obtained, coupled with the known upper limits on the possible variation of the Sun’s mass, allow us to place tighter restrictions on the variation of the gravitational constant and infer that its annual value falls in the interval

\[-4.2 \cdot 10^{-14} < \dot{G}/G < +7.5 \cdot 10^{-14}\]

with a probability of 95%. The $GM_\odot$ variation is seemingly associated not with the variation of $G$, but with the variation of the Sun’s mass. Therefore, the variation of $M_\odot$, is reflective of the balance between the mass lost through radiation and solar wind and the material falling onto the Sun (Pitjeva and Pitjev, 2012).

Besides that, the search for and the estimation of a possible gravitational influence of dark matter in the Solar System on the motion of planets has been carried out on the basis of the EPM2011 planetary theory by studying the additional motion of the perihelia of planets and the estimates of the heliocentric gravitational constant obtained through the analysis of observations of certain planets. The estimates obtained of the density and mass of dark matter at different distances from the Sun are, as a rule, exceeded by their errors ($\sigma$). This points to the fact that the density of dark matter $\rho_{dm}$ (if any) is very low and resides well below the errors of determination of such parameters achievable nowadays. It was found that $\rho_{dm}$ at the distance of the orbits of Saturn, Mars, and the Earth should be lower than $1.1 \cdot 10^{-20}$ g/cm$^3$, $1.4 \cdot 10^{-20}$ g/cm$^3$, and $1.4 \cdot 10^{-19}$ g/cm$^3$, respectively. The possibility of dark matter concentrating at the center of the Solar System was also considered, and it was found that the mass of dark matter located in the sphere inside the Saturn’s orbit would still not exceed $1.7 \cdot 10^{-10} M_\odot$ (Pitjev and Pitjeva, 2013).

CONCLUSIONS

The EPM series of high-precision ephemerides of planets and the Moon that is faithful to modern observations and comparable in terms of accuracy with the latest versions of the well-known DE ephemerides (JPL) was created at the IAA RAS. The use of a more accurate dynamical model of planetary motion and a large number of additional high-precision observations allows us to assert that the latest versions (EPM2004–EPM2011)
of the EPM ephemerides are more accurate than the DE405 ephemerides, which are adopted as an international standard. The EPM ephemerides have the following advantages over the DE ones while using EPM for Russian astronavigation:

- They are constructed using independent and constantly updated software.
- They are promptly updated and improved according to incoming new data.
- The clients (GLONASS programs) may request additional needed data in any format.

Convenient access procedures (Bratseva et al., 2010) for external users were recently devised at the IAA RAS. The users may access the EPM ephemerides of planets and the Moon together with the corresponding differences TT−TDB, as well as the ephemerides, computed simultaneously with the EPM ones, of seven additional objects (Ceres, Pallas, Vesta, Eris, Haumea, Makemake, and Sedna) that are provisionally called dwarf planets. The EPM ephemerides are available at [ftp://quasar.ipa.nw.ru/incoming/EPM/].

The constructed EPM ephemerides used in practice form the basis of the Astronomical Yearbook, and are needed to fulfill the GLONASS Federal Program and to carry out space experiments in the Solar System. They also help us to solve some of the problems of fundamental astrometry, including the determination of the dynamical structure of the Solar System and a number of astronomical constants.

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