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# COMMISSION X2 — SOLAR SYSTEM EPHEMERIDES

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**TRIENNIAL REPORT 2022-2024**

## 1. Background

This document reports the progress and achievements made by the community represented by IAU Commission X-2 during the period 2022-2024. The major contributors for planetary and satellite ephemerides data are JPL-NASA (USA), IAA-RAS (Russia), IMCCE (France), and now also China. Small-body ephemeris data are rapidily evolving and a huge quantity of data are expected by new surveys such as Vera Rubin, Fly-Eye, NEO Surveyor.

## 2. Developments within the past triennium

### 2.1. *JPL planetary and satellites ephemerides*

#### 2.1.1. *Inner Planets and Moon:*

In this period the ephemerides of the inner planets and Moon have been continuously updated using Mars Orbiter data, lunar laser ranging, etc.

#### 2.1.2. *Jupiter:*

The Jupiter system ephemerides, including the barycenter, have been updated using Juno tracking data. We updated the ephemerides for the irregular satellites of Jupiter and added new discoveries as they get announced (JUP344 and JUP346).

#### 2.1.3. *Saturn:*

Saturn's Love number k2 is found primarily from the tidal effects on the satellites in Lagrange points due to tides raised on Saturn by the main satellites. We developed a model for the orientation of Saturn's pole based on a numerical integration of the rigid body rotational equations. The pole orientation is captured in the form of Fourier series. As part of our procedure for fitting the observational data, we estimated the R.A. and decl. of the pole, i.e., the constant terms in the pole series, and Saturn's axial moment of inertia. The gravity fields of the major satellites (Mimas, Enceladus, Thetys, Dione, Rhea, Titan, Iapetus) were expressed by the C20 and C22 moments of their gravity quadrupole. The orbits of the main Saturnian satellites are well known at this time (in-orbit uncertainties up to several tens of km) (SAT441)(Jacobson, (2022)). We updated the gravity field, topography, and rotation of Enceladus using Cassini data (Park, (2024)). The orbits of the irregular satellites of Saturn have been updated by the latest set of ground-based and Cassini astrometry (SAT452) (Jacobson et al., (2022). Orbital solution SAT453 contains the satellites discovered after the publication.

2.1.4. *Pluto:*

We found a fit of numerically integrated orbits for the satellites of Pluto based on the extensive set of ground-based, HST, Gaia, and spacecraft (New Horizons) astrometry (PLU060). Masses of Pluto and Charon have been determined to better than 1%. The fit shows mass sensitivity to Nix and Hydra, but the masses of Kerberos and Styx remain unconstrained.

2.1.5. *Uranus and Neptune:*

The orbits of the irregular satellites of Uranus of Neptune have been updated with new astrometry and the discovery of one new satellite of Uranus and two new satellites of Neptune (Brozović & Jacobson, (2022)). JPL has delivered new ephemerides URA117 and NEP103.

## 2.2. *IAA RAS planetary ephemerides*

The effect of solar wind on interplanetary ranging observations was studied in detail, and a model was proposed where *in situ* electron density measurements are used in the planetary ephemeris solution. This allowed to reduce the error in the determined gravitational parameter of the Sun by 12 % (Aksim & Pavlov, (2022)).

Planetary ephemeris EPM2021 was released (Pitjeva et al., (2022)). Latest lunar laser ranging observations have been added, as well as radio ranges of Juno spacecraft and more recent ranges of Odyssey and Mars Reconnaissance Orbiter. Radio signal delays processing was improved (see above); the method of determination of asteroid masses was also improved.

A study of numerical issues appearing in planetary integration routines has shown the potential of “double-double” numbers as a replacement for “extended” or quadruple-precision numbers used in modern ephemerides (Subbotin et al., (2023)).

Lunar laser ranging observations (including most recent observations made at Grasse, Wettzell, and Apache Point) were processed to show that the strong equivalence principle (SEP) is not violated above $3.5 \cdot 10^{-14}$ (Pavlov & Dolgakov, (2024)).

Another application of lunar laser ranging—determination of daily Earth orientation parameters—is becoming an increasing success due to precise and frequent data from observatories in France, Germany, and USA. As shown in (Pavlov, (2024)), for 17 nights in 2022 the ΔUT0 values were determined with $\sigma \leqslant 40$ $\mu$s, and for 15 nights, variation of latitude (VOL) values were determined with $\sigma \leqslant 1$ mas,

## 2.3. *New planetary ephemerides from China*

A completely new planetary and lunar ephemeris, PETREL19, was developed by Wei Tian (Tian, (2023)), with the underlying dynamical model simlar to the one of DE430, with a notable exception of the revisited Earth tidal model (Tian, (2022)).

## 2.4. *IMCCE planetary ephemerides*

Between 2022 and 2024, a specific effort has been put in the modeling of Kuiper Belt objects in the planetary ephemerides INPOP and to simulate possible applications of the BepiColombo mission (Fienga et al., (2022)). Updates in the selection of the objects as well the mass repartition have been explored. Machine-learning techniques have been implemented for improving constraints on alternative theories of gravitation such as the graviton (Mariani, (2023)), the dilaton, and SEP violation (Mariani, (2024)).

Modeling of the Earth-Moon tides has been also updated by the introduction of visco-elastic deformations for the Moon (Baguet et al., (2024)). Explanatory work on the definition of the new generation of selenocentric reference frames have been done together with ESA and NASA and the continuation of this work is now at the IAU Commission 4 level and IAG working groups.

Consistency with ICRF3 has also been checked as new effects related to the galactic aberration have been detected in ICRF3 and never modeled before. Furthermore, in Deram et al., (2022) INPOP19a planetary ephemerides has been used to perform the orbital adjustment of 14099 asteroids based on Gaia-DR2 observations and compare for 23 of them the resulting orbits to radar data. With this adjustement, we were able to validate the tie between the Gaia Reference Frame and the INPOP one.

### 2.5. *Small-Bodies Ephemerides*

The small-body community (both observers and data-processing centers) has made significant progress in the adoption of the ADES astrometric format. The transition is still ongoing, but major surveys like Pan-STARRS, ATLAS, and Catalina fully transitioned to the new format, the Minor Planet Center has made the data available via database replication through the Small-Body Node, and services like JPL's Scout and NEODyS's NEOScan make operational use of the information provided through ADES.

ESA's Gaia mission has completed the third data release (DR3) and focused data release (FPR). These releases include high-precision astrometry of nearly 160,000 small bodies, which has been ingested by JPL's Solar System Dynamics Group to refine the orbit solutions of the objects observed by Gaia.

JPL's Center for Near-Earth Object Studies implemented an updated impact monitoring system that replaces the previous Line-of-Variations method. The new algorithm is fully independent of previous ones and thus increases the robustness of the cross-check validations with NEODyS and ESA.

The Small Body Assessment Group's Special Action Team compiled a report on the Apophis close approach to Earth in 2029 to discuss the effects of the encounter, scientific observations and observation strategies, and hazard assessment for spacecraft contact with the asteroid.

JPL successfully supported the DART mission by providing the navigation team with accurate ephemerides of Didymos and Dimorphos to successfully execute the kinetic impact demonstration and measure the momentum enhancement factor.

JPL is also providing ephemeris support to the Psyche, Lucy, and OSIRIS-APEX missions.

Future activities include preparations for the upcoming operations of the Vera Rubin Observatory and the NEO Surveyor mission. The projected increased rate of discovery and data volume call for a corresponding scaling of computing resources and optimization of the data processing pipelines.

## 3. Conclusion and future plans

Study of dynamics of planets of Solar system, as well as the Sun and the Moon, continues to produce results of increasing theoretical and practical importance, on the level comparable to other astronomical studies made with different tools and based on different kinds of data. Some of the results are:

- Orbit of the Moon and lunar reference frame for future lunar missions and selenodesy;
- Orbits of planets and their natural satellites for future interplanetary missions;

- Improved modeling of the dynamics of Kupier Belt objects;
- Study of the physical properties of the Sun;
- General Relativity studies;
- Application of Machine Learning techniques.

Another important future (and coincidendally past) application of lunar ephemeris and lunar laser ranging is the measurement of daily corrections to the Earth rotation parameters, important for the precision tie between the terrestrial and celestial reference frames.

ESA's GAIA mission data products provided important advances for small bodies astrometric measurements, either from the high quality astrometric catalogue, now widely used by astronomers, or from direct observations of known asteroids.

The successful NASA mission DART was of paramount importance for testing deflection technologies, which can be used in case of a real threat to the planet. The pre- and post-impact observations and consequent Didymos positioning were useful for determining the outcome of the deflection test.

The major data processing systems (MPC, JPL-NASA, NEODyS and ESA-NEOCC) are getting ready for the start of operations of the Vera Rubin Telescope, which will dramatically increase the data volume for small bodies. Moreover, the adoption of the ADES format will provide more comprehensive astrometric information, which will turn into a higher quality data product such as small bodies orbits and ephemerides.

Fabrizio Bernardi
*President of the Commission*

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