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Abstract

Pulsar timing offers a comprehensive avenue for exploring diverse topics in physics and astrophysics. High-precision solar system planetary ephemeris is crucial for pulsar timing as it provides the positions and velocities of solar system planets including the Earth. However, it is inevitable that inherent inconsistencies exist in these ephemerides. Differences between various ephemerides can significantly impact pulsar timing and parameter estimations. Currently, pulsar timing highly depends on the JPL DE ephemeris, for instance, the Pulsar Timing Array data analysis predominantly utilizes DE436. In this study, we examine inconsistencies across various ephemeris series, including JPL DE, EPM, and INPOP. Notably, discrepancies emerge particularly between the current ephemeris DE436 and the earliest released ephemeris DE200, as well as the most recent ephemerides, e.g., DE440, INPOP21A, and EPM2021. Further detailed analysis of the effects of ephemeris on geometric correction procedures for the conversion of measured topocentric times of arrival is presented in this study. Our researches reveal that variations in the Roemer delays across different ephemerides lead to distinct differences. The timing residuals and the fact that these discrepancies can be readily incorporated into the subsequent pulsar parameters, leading to inconsistent fitting estimates, suggest that the influence of errors in the ephemeris on the timing process might currently be underappreciated.

Full Text

Preamble

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The Influence of Different Solar System Planetary Ephemerides on Pulsar Timing

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Abstract

Pulsar timing offers a comprehensive avenue for exploring diverse topics in physics and astrophysics. High-precision solar system planetary ephemerides are crucial for pulsar timing as they provide the positions and velocities of solar system planets including the Earth. However, inherent inconsistencies inevitably exist in these ephemerides, and differences between various ephemerides can significantly impact pulsar timing and parameter estimations. Currently, pulsar timing heavily depends on the JPL DE ephemeris; for instance, Pulsar Timing Array data analysis predominantly utilizes DE436. In this study, we examine inconsistencies across various ephemeris series, including JPL DE, EPM, and INPOP. Notably, discrepancies emerge particularly between the current ephemeris DE436 and the earliest released ephemeris DE200, as well as the most recent ephemerides such as DE440, INPOP21A, and EPM2021. We present a detailed analysis of the effects of ephemerides on geometric correction procedures for converting measured topocentric times of arrival. Our research reveals that variations in Roemer delays across different ephemerides lead to distinct differences. The timing residuals demonstrate that these discrepancies can be readily incorporated into subsequent pulsar parameter fitting, leading to inconsistent estimates. This suggests that the influence of ephemeris errors on the timing process might currently be underappreciated.

Key words: (stars:) pulsars: general – Planetary Systems – time – ephemerides

1. Introduction

High-precision solar system planetary ephemerides are extensively utilized in various fields, including planetary orbit observations, gravitational law verification, and deep space navigation. Notable examples include the series developed by the Jet Propulsion Laboratory (JPL) in the United States [**?**, **?**], the Ephemeris of Planets and the Moon (EPM) series developed by the Russian Institute of Applied Astronomy of the Russian Academy of Sciences, and the Integration Numerique Observation de Paris (INPOP) series developed by the

Paris Observatory in France [?, ?]. Solar system planetary ephemerides form the basis of pulsar timing, which plays an important role in both theoretical research and practical applications, such as detecting nanohertz gravitational waves, constraining the masses of solar system objects [?], autonomous navigation using pulsars [?], and developing a pulsar-based timescale [?]. The accuracy of pulsar timing has benefited significantly from large telescopes and has improved substantially, with timing residuals of millisecond pulsars in Pulsar Timing Array (PTA) projects mostly better than 1 s [?, ?].

Pulsar timing is particularly sensitive to planetary ephemerides because an ephemeris provides essential planetary information for the pulsar timing process, such as the masses, positions, and velocities of solar system planets [?]. Therefore, differences and errors inherent in an ephemeris have a certain impact on pulsar timing, especially for high-precision timing [?]. The difference in Roemer delay caused by different ephemerides (DE200, DE405, DE421, and DE430) was found to be greater than 1 ms [?]. Conversely, PTA data have been used to constrain the upper mass limits of unidentified asteroids in the solar system [?], and the masses of the major planets have been estimated by analyzing pulsar timing data [?]. In addition to studying the influence of ephemeris error on pulsar timing by disturbing different parameters of the JPL DE ephemeris [?], pulsar timing can be used to study reference frame rotation ties between different series of ephemerides [?].

While the above studies are important for better understanding the relationship between planetary ephemerides and pulsar timing, several unresolved issues remain worthy of exploration. For example, although the precision of EPM and INPOP has matched that of JPL DE [?], the reference ephemerides currently used for pulsar timing research are mainly limited to the JPL DE series. Recognition of the other two types of ephemerides (EPM, INPOP) in current research is insufficient, and the potential implications of errors in a referenced ephemeris are not comprehensively understood. Furthermore, the impact of these errors on pulsar timing and subsequent parameter estimations remains ambiguous. It is worth considering whether the use of EPM and INPOP ephemerides could enhance pulsar timing studies.

In this study, we briefly compare the differences between different versions of JPL DE, EPM, and INPOP ephemerides. Key information on the three ephemerides is provided in Table 5 . We explore the impact of ephemeris inconsistencies on related pulsar timing correction terms, timing residuals, and pulsar parameter estimates using the software TEMPO2 and the Parkes Pulsar Timing Array (PPTA) dataset. Based on our results, we provide tentative recommendations for ephemeris selection in future pulsar timing procedures.

2. The Impact of Ephemeris on Pulsar Timing

Different planetary ephemerides are used for pulsar timing in different periods or contexts. To assess the impact of ephemerides on timing, we conducted a comparative analysis of their inconsistencies. Furthermore, in an effort to broaden the applicability of these ephemerides, we incorporated two additional ephemerides (EPM, INPOP) into our reference set for pulsar timing.

2.1. The Pulsar Timing Model

The measured topocentric Times of Arrival (TOAs) are transformed to the Solar System Barycenter (SSB) using the following operation, known as a timing model [**?**]:

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + \Delta_{\mathrm{C}} + \Delta_{\mathrm{A}} + \Delta_{\mathrm{E}\odot} + \Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{S}\odot} + D/f^2 + \Delta_{\mathrm{VP}} + \Delta_{\mathrm{B}}$$

where Δ_{C} denotes clock corrections, Δ_{A} signifies atmospheric propagation delay, $\Delta_{\mathrm{E}\odot}$ represents the delay due to the solar system's Einstein correction, $\Delta_{\mathrm{R}\odot}$ corresponds to the solar system's Roemer correction, $\Delta_{\mathrm{S}\odot}$ is associated with the solar system's Shapiro correction, D/f^2 stands for dispersion delay, while Δ_{VP} captures the Shklovskii effect induced by long-term proper motion and the delay resulting from the radial movement of pulsars. Additionally, Δ_{B} encompasses various delays arising from the orbital motion of binary pulsars.

Here we illustrate the terms most closely related to planetary ephemerides:

(1) **Roemer delay**: This geometric delay represents the light propagation time between the observation station and the SSB:

$$\Delta_{\mathrm{R}\odot} = -\frac{\mathbf{r} \cdot \hat{\mathbf{R}}_{\mathrm{BB}}}{c}$$

where $\mathbf{r}$ denotes the position vector of the Earth relative to the SSB, while $\hat{\mathbf{R}}_{\mathrm{BB}}$ signifies the direction vector from the observation station to the pulsar. This is the most significant time correction term, extending up to 500 s. Additionally, $\hat{\mathbf{R}}_{\mathrm{BB}}$ represents the direction vector from the SSB to the pulsar, whereas $\mu_{\parallel}$ and $\mu_{\perp}$ delineate the radial and lateral components of proper motion, respectively.

(2) **Shapiro delay**: This arises due to the gravitational influence of massive celestial bodies on the path of light propagation, also referred to as gravitational delay:

$$\Delta_{\mathrm{S}\odot} = -\frac{2GM_i}{c^3} \ln\left(\frac{|\mathbf{r}_i| + \mathbf{r}_i \cdot \hat{\mathbf{R}}_{\mathrm{BB}}}{|\mathbf{R}_{\mathrm{BB}}|}\right) + \Delta_{\mathrm{S}\odot 2}$$

where M_i and $\mathbf{r}_i$ represent the mass and position vector of the ith celestial body relative to the SSB. The term $\Delta_{\mathrm{S}\odot 2}$ represents the second-order correction. Within the solar system, the Sun and Jupiter exhibit the most pronounced Shapiro delay effects compared to all other celestial bodies.

(3) **Einstein delay**: This arises from relativistic time dilation and gravitational redshift, both caused by the motion of the observing clock relative to the SSB. TEMPO2 obtains this delay from TE405, a numerical ephemeris of the Earth used for conversion between TT and TCB based on DE405, with an error of less than 5 ns at the time [?]. Since TE405 has not been updated, it is difficult to analyze differences in Einstein delay in this study.

It is important to identify the magnitude of correction terms with different ephemerides, upon which further analysis can be conducted. The typical sizes of the above correction terms are presented by [?] and listed in Table 1 .

2.2. Inconsistency in the Solar System Planetary Ephemeris

Planetary ephemerides, which are essentially tables or databases containing timed information on the positions and motions of celestial objects, play a significant role in understanding the dynamics of our solar system. Factors such as observational data, dynamic models, and the definitions of different reference frames and coordinate systems inevitably result in inconsistencies between various ephemerides. These differences are primarily manifested in positional variances of large celestial bodies relative to the SSB.

In terms of reference frame, DE421 and DE405 utilize the International Celestial Reference Frame (ICRF) [?], achieving alignment accuracies of approximately 0.25 mas and 1 mas, respectively. In contrast, DE430 employs International Celestial Reference Frame 2 (ICRF2) [?], which has achieved an alignment accuracy of 0.2 mas. The recent versions DE440, DE441, EPM2021, and INPOP21A adopt International Celestial Reference Frame 3 (ICRF3) [?], leading to further advancements in alignment precision.

For example, in earlier versions DE405 and DE421, the positional differences of Earth and Jupiter relative to the SSB could be tens of meters and tens of kilometers, respectively [?]. In DE421 and DE430, the positional differences of Earth, Mercury, Venus, and Mars relative to the SSB could reach tens of kilometers, with differences between DE430 and DE440 reaching 100 km [?]. Likewise, the relative distances between the Moon and Earth in DE430 and INPOP19 differ by several tens of centimeters [?].

Furthermore, several ephemerides are specifically designed for distinct space missions. For instance, DE421 focuses on supporting and facilitating coordinate transformation between the lunar center inertial system and the lunar fixed system in the Gravity Recovery and Interior Laboratory (GRAIL) mission [?]. The primary objective of this mission is to elucidate the internal structure of the Moon through highly precise gravity mapping. Given that the GRAIL mission encompasses data from two lunar probes (GRAIL A and GRAIL B), DE421 may not be optimally suited for pulsar timing.

Owing to its long release time, DE200 is largely obsolete in both current and future astrometry and pulsar timing practices. Consequently, comparing time correction terms, residuals, and pulsar parameters using DE200 as a reference may offer limited value for future pulsar timing endeavors. Accordingly, we do not provide comparison results for DE200 in our research.

2.3. The Position Difference of the Earth

The SSB does not align with the center of the Sun. Instead, as the Earth orbits the Sun, the Sun in turn orbits the SSB. Therefore, the position vector of the Earth relative to the SSB can be decomposed as follows:

$$\mathbf{r}_{\text{earth}}^{\text{SSB}} = \mathbf{r}_{\text{earth}}^{\text{Sun}} + \mathbf{r}_{\text{Sun}}^{\text{SSB}}$$

where $\mathbf{r}_{\text{earth}}^{\text{Sun}}$ denotes the position vector from the Earth to the Sun's center, and $\mathbf{r}_{\text{Sun}}^{\text{SSB}}$ signifies the position vector of the solar center relative to the SSB.

We explore positional discrepancies of the Earth based on various ephemerides, employing DE436 as the reference ephemeris in our work. We compare discrepancies between the Earth's and Sun's positions relative to the SSB with those derived from DE436. Figure 1 [Figure 1: see original paper] shows the patterns of change between $\mathbf{r}_{\text{earth}}^{\text{Sun}}$, $\mathbf{r}_{\text{Sun}}^{\text{SSB}}$, and $\mathbf{r}_{\text{earth}}^{\text{SSB}}$. Meanwhile, Table 2 presents statistical analysis of the absolute values of X, Y, Z coordinate differences across various ephemerides, including maximum, mean, and rms values.

The first column presents variations in $\mathbf{r}_{\text{earth}}^{\text{Sun}}$, which are approximately annual terms. These primarily stem from perturbations in the Earth's orbit attributed to mass errors associated with the inner planets (Mercury, Venus, Mars, and Earth) [**?**]. In addition, these differences generally diminish as the three series of ephemeris versions undergo updates.

The second column indicates differences in $\mathbf{r}_{\text{Sun}}^{\text{SSB}}$, which arise from alterations in the solar system's mass distribution attributed to mass errors from larger planets (Jupiter, Saturn, Uranus, and Neptune), as well as other unidentified celestial bodies [**?**]. Theoretically, given a sufficiently long data span, these differences should appear as periodic terms. However, they currently behave like long-term drifts, with significant discrepancies between different versions. Notably, differences with respect to DE440, EPM2021, and INPOP21A can reach up to an order of 10 km, due to the inclusion of over 30 newly discovered Kuiper Belt objects (KBOs) in the models of these three latest ephemerides [**?**].

The final column represents the difference of $\mathbf{r}_{\text{earth}}^{\text{SSB}}$, which is the vector sum of the previous two columns. These differences are approximately superposed by the annual term and long-term drift. According to a pulsar timing model, these two types of positional differences can lead to expected annual and long-term terms in the associated corrections, resulting in different timing residuals and pulsar parameter fitting results.

3. Pulsar Timing Analysis Based on the PPTA Data Set

3.1. The Data Set and Software

We utilize the PPTA-DR2 datasets in our study. The PPTA is one of the most significant timing arrays in the world, based on observations with the Parkes 64 m radio telescope dating back to early 2005. Its primary goals include direct detection of gravitational waves [?], establishment of a pulsar-based timescale [?], and enhancement of planetary ephemerides [?]. The project has gathered 18 years of observation data on dozens of pulsars. We use eight pulsars within PPTA-DR2 for our investigation, including binary and single pulsars with different periods, residual levels, noise types, and positions. Figure 2 [Figure 2: see original paper] and Table 3 show basic information about these pulsars derived from the TEMPO2 software.

The TEMPO2 software, released in 2006, is widely used for pulsar timing and analysis. It calculates barycentric TOAs, forms timing residuals, and carries out pulsar parameter fitting. TEMPO2 complies with the IAU2000 resolution and utilizes the ICRS reference frame and TCB time standard, accounting for all known interference factors above 1 ns [?, ?, ?]. We employ only the weighted least squares (WLS) approach in TEMPO2 for pulsar parameter estimation. Furthermore, since TEMPO2 supports only the JPL DE series ephemerides by default, we made necessary modifications to adapt the TEMPO2 program for other ephemerides.

3.2. Analysis of Shapiro Delay Differences

The Shapiro delays of the Sun and major planets can be derived from TEMPO2. Discrepancies in Shapiro delays with different ephemerides can be identified by comparison with those derived from DE436. We demonstrate differences in Shapiro delay of the Sun and Jupiter for PSRs J0437−4715 and J0613−0200 in Figure 3 [Figure 3: see original paper], which show both annual terms and long-term drifts with amplitudes less than 10^{-7} ms. Given current timing precision, these differences are negligible. Other pulsars demonstrate similar results, which are omitted here.

3.3. Analysis of Roemer Delay Differences

As per Equation (2), inconsistencies in the Earth's position due to different ephemerides can lead to inconsistencies in Roemer delays, which in turn influence both timing residuals and pulsar parameters. To more clearly understand this effect, we calculate pre-fit Roemer delay corrections with a given ephemeris, then recalculate post-fit Roemer delay corrections after fitting RA, DEC, PMRA, and PMDEC. Differences in Roemer delay are obtained by comparing the pre-fit and post-fit Roemer delays with those obtained using DE436. Figure 4 [Figure 4: see original paper] shows Roemer delay differences for PSRs J0437−4715 and J0613−0200, revealing several key findings.

First, before parameter fitting, annual terms and long-term drifts appear in the Roemer delay differences with different amplitudes and systematic biases, primarily attributable to discrepancies in $\mathbf{r}_{\mathrm{earth}}^{\mathrm{Sun}}$ and $\mathbf{r}_{\mathrm{Sun}}^{\mathrm{SSB}}$, respectively. Notably, these differences are particularly pronounced for data derived from DE200, DE440, EPM2011, EPM2015, EPM2017, EPM2021, INPOP19A, and INPOP21A.

Second, the long-term drifts of the Roemer delay difference show no clear change after pulsar parameters are fitted. This suggests that long-term drifts do not influence positional and proper motion parameters. Instead, these parameters predominantly absorb the annual terms, leaving only long-term drifts.

3.4. Analysis of Residual Differences

We also obtain differences between pre-fit and post-fit timing residuals after fitting for RA, DEC, F0, F1, PMRA, and PMDEC, as shown in Figure 5 [Figure 5: see original paper]. The rms values of residual differences are displayed in Figure 6 [Figure 6: see original paper].

Figure 5 shows clear annual terms and long-term drifts in timing residuals before fitting pulsar parameters. After fitting for astrometric and rotational parameters, these patterns are significantly reduced, indicating that the two components of Earth's position difference have independent effects on timing residuals. Furthermore, the influence of ephemeris on pulsar timing is reflected in both timing residuals and pulsar parameter estimates. According to the rms values of residual differences shown in Figure 6, variations exist across different ephemerides, suggesting that the impact of ephemeris on pulsar timing is universal.

3.5. Analysis of Pulsar Parameters

To assess the impact of various ephemerides on pulsar parameters, we fitted RA, DEC, F0, F1, PMRA, and PMDEC. Table 4 shows fitted parameters for PSR J0437−4715. Some parameters are displayed with only their decimal parts for clarity, with their corresponding common part given under the parameter name. We find that discrepancies can be larger than the formal uncertainties when using different ephemerides, indicating that the ephemeris exerts significant influence on pulsar parameters. The results for positional and proper motion parameters exhibit significant differences when comparing DE200 and DE405 with DE436. Additionally, discrepancies appear in results associated with DE414, DE418, DE421, EPM2011, EPM2015, EPM2017, and INPOP06C, INPOP08A. Meanwhile, attention should be paid to discrepancies in F0 and F1 for high-precision timing and applications.

4. Evaluation and Suggestion

Ephemeris errors can influence delay terms and residuals, which in turn affect estimation of pulsar parameters. Therefore, these parameters can serve as good indicators of overall ephemeris performance. We use the Rank Sum Ratio (RSR) method [?] to assess ephemerides as follows.

First, we take 21 ephemerides as evaluation objects and calculate the deviation of six parameters. The final parameter deviation matrix is constructed as:

$$P = \begin{bmatrix} \Delta\mathrm{RA}_{\mathrm{J0437}} & \Delta\mathrm{DEC}_{\mathrm{J0437}} & \cdots & \Delta\mathrm{PMDEC}_{\mathrm{J0437}} \\ \Delta\mathrm{RA}_{\mathrm{J0613}} & \Delta\mathrm{DEC}_{\mathrm{J0613}} & \cdots & \Delta\mathrm{PMDEC}_{\mathrm{J0613}} \\ \vdots & \vdots & \ddots & \vdots \\ \Delta\mathrm{RA}_{\mathrm{J2145}} & \Delta\mathrm{DEC}_{\mathrm{J2145}} & \cdots & \Delta\mathrm{PMDEC}_{\mathrm{J2145}} \end{bmatrix}$$

For example, the RAJ deviation is expressed as $\Delta\mathrm{RAJ}_i = |\mathrm{RAJ}_i - \mathrm{RAJ}_{\mathrm{DE436}}|$.

Second, we sort each column of data in matrix P in descending order (since parameter difference is a low-quality indicator), using an element's order number as its rank. This yields the rank matrix R, which has the same 21×6 structure as P, where 21 rows symbolize the 21 evaluation subjects (ephemerides) and six columns represent the six evaluation indicators (parameters).

Third, we calculate the RSR value for each ephemeris for a given pulsar:

$$\mathrm{RSR}_i = \frac{1}{n \times m} \sum_{j=1}^{m} R_{ij}$$

where R_{ij} represents the rank of the element in matrix P situated at row i and column j. Ephemeris performance is gauged by RSR, which ranges between $1/n$ and 1, with higher RSR indicating better performance compared to DE436.

Table 5 displays RSR values of parameter deviations across eight pulsars for different ephemerides. The final column serves as comprehensive indicators, derived by summing the RSR values of the eight pulsars using a weighting factor proportional to the reciprocal of each pulsar's rms value [?].

Figure 7 [Figure 7: see original paper] shows the effectiveness of various ephemerides in pulsar timing compared to DE436. The green dotted lines divide the figure into three parts: ephemerides situated in the top position provide better support for pulsar timing, those in the middle maintain comparable performance, while those at the bottom are not recommended.

As affirmed in Table 5 and Figure 7, there are significant differences in DE200, DE405, INPOP06B, INPOP06C, and INPOP08A. The comprehensive evaluation indicators of several ephemerides, including DE430, DE435, DE436, DE438, and INPOP17A, are relatively close. The recently released DE440, EPM2021, and INPOP21A show differences compared with previous ephemerides.

5. Summary

In this paper, we follow the steps of pulsar timing and analyze differences in Earth's position across different ephemerides. We also examine discrepancies in correction terms and residuals, focusing on pulsar parameters to conduct a comprehensive analysis of ephemeris performance in pulsar timing. However, a more in-depth understanding of the relationship between ephemerides and pulsar timing is still required. This may include exploring the impact of ephemeris errors on gravitational wave detection, as well as the dependence of the pulsar timescale on ephemeris. Discussion of these issues will improve our understanding of the relationship between pulsar timing and ephemerides, thereby advancing related research. Considering the continuity and consistency of pulsar timing, it is necessary to pay attention to differences caused by ephemerides in future timing studies.

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Appendix

The JPL DE, INPOP, and EPM series represent the most accurate and widely used ephemerides, embodying the highest level of human knowledge in the field of solar system planetary ephemerides. Table A1 displays key information for main versions of these ephemerides.

Table A1 A Brief List of Notable Update Events in Some Ephemerides

Ver (Rel)	Span	Important update information
DE200 (1981)	1599–2201	Incorporated all available observational data from the period, serving as a cornerstone for preparation of the U.S. Almanac spanning 1984–2003.
DE405 (1995)	1899–2050	Included in the IERS in 2003, with accuracy of 1 mas; frequently employed for calculating visual positions of celestial bodies [?].
DE414 (2005)	1899–2051	Added space exploration data from Mars Odyssey (ODY) probe in 2001 and Mars Global Surveyor (MGS) in 2003.
DE418 (2007)	1899–2053	Reference frame precisely aligned with ICRF using multiple VLBI measurements, achieving accuracy of 0.25 mas [?].

Ver (Rel)	Span	Important update information
DE421 (2008)	1550–2650	Through calculation of asteroid perturbations on inner planetary orbits, accuracy of lunar orbit reached sub-meter level.
DE430 (2013)	1549–2650	Achieved alignment accuracy of 0.2 mas to ICRF2; Mercury orbit enhanced through MESSENGER probe [?].
DE435 (2016)	1549–2650	High-precision data with long time spans from Cassini and New Horizons improved accuracy of Saturnian orbit.
DE436 (2016)	1549–2650	Various types of observation data further integrated; orbital precision improved for all planets [?].
DE438 (2018)	1549–2650	Important updates made to Saturn orbit; Jupiter orbit updated to support Juno Navigation Group tasks.
DE440 (2020)	1550–2440	Addition of approximately 30 KBOs notably enhanced precision of Jupiter and Saturn orbit calculations [?].
DE441 (2020)	BC13200–17191	Used to analyze data beyond time coverage of DE440, slightly sacrificing some short-term accuracy but greatly increasing time span [?].
EPM2011 (2011)	1787–2214	Used data from ODY, MRO, Cassini, ExoMars, and MEX; served as foundational basis for Russian Astronomical Almanac [?].
EPM2015 (2015)	1787–2214	Used total of 120,000 data points from different types of observations; about 300 parameters determined [?].
EPM2017 (2017)	1787–2214	Used total of over 800,000 data points from different types of observations; employed more efficient model [?].
EPM2021 (2021)	1787–2214	Considered tidal delay of the Moon; improved parameters of Sun and Earth-Moon system; improved KBO mass estimates [?].
INPOP06B (2008)	1000–3000	Used around 45,000 observations including MEX, VEX, ODY, and MGS; accounted for perturbation effects of more than 300 asteroids [?].
INPOP06C (2008)	1000–3000	Used same fitting dataset as INPOP06B but improved modeling of asteroid-induced orbital perturbations [?].
INPOP08A (2009)	1000–3000	Provided positions, velocities, and rotation angles for planets; performed conversion between TT and TDB [?].

Ver (Rel)	Span	Important update information
INPOP10A (2011)	1000–3000	Changes in dynamic modeling including fitting process, datasets, and fitting parameters [?].
INPOP13C (2013)	1000–3000	Reconfirmed parameterized post-Newtonian (PPN) parameters for testing Einstein's general theory of relativity.
INPOP17A (2017)	1000–3000	Asteroid orbits fitted based on nearly 2 million observations from Gaia mission.
INPOP19A (2019)	1000–3000	Used data from Juno, Cassini, MEX, MESSENGER, and Gaia DR2; updated planetary masses and changed some model algorithms [?].
INPOP21A (2021)	1000–3000	Utilized roughly 1.55 billion observations; new Bayesian procedure used to calculate masses of 343 main-belt asteroids [?].

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