Long-term Prediction and Accuracy Assessment of Earth Orientation Parameters Based on China' s Independent Observations: Postprint

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Date: 2025-10-10T00:00:00+00:00

Abstract

Earth' s rotation can be described using Earth Orientation Parameters (EOP). EOP serve as key parameters connecting the celestial and terrestrial reference frames, constituting important spatiotemporal datum parameters. Due to the latency inherent in observational data processing, real-time applications of EOP must be realized through prediction series, which hold significant application value in fields such as space vehicle orbit determination, guidance, and deep space exploration. An EOP combined series is constructed from the combined solution of the International Earth Rotation and Reference Systems Service and China' s independently observed rapid solution, with climate variability introduced into the fitting model to conduct 365-day long-term predictions. For the recent two-year period, prediction accuracy is statistically analyzed and compared with forecast products maintained by the United States Naval Observatory (USNO). Results indicate that the EOP prediction series generated based on China's independently observed combined series exhibits slightly lower accuracy than USNO products in the short term, yet demonstrates advantages in the medium to long term. In particular, the medium to long-term prediction accuracy for Universal Time parameters has improved by 20%–30%, reflecting technological progress in China' s independent EOP observation, solution, and forecast data service capabilities.

Full Text

Preamble

Vol. 43, No. 3

September 2025

PROGRESS IN ASTRONOMY

doi: 10.3969/j.issn.1000-8349.2025.03.08

Long-term Forecast and Accuracy Evaluation of EOP Based on China' s Autonomous Observations

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Abstract

Earth' s rotation can be intuitively described using Earth Orientation Parameters (EOP), which serve as critical spatiotemporal reference parameters linking the celestial and terrestrial reference frames. Due to inherent delays in observational data processing, real-time applications of EOP require forecast sequences, which hold significant value in spacecraft orbit determination, guidance, and deep space exploration. This study constructs a hybrid EOP sequence by combining the International Earth Rotation and Reference Systems Service (IERS) combined solution with China' s autonomously observed rapid solution. Climate variability is incorporated into the fitting model to generate 365-day long-term forecasts. Focusing on the most recent two-year period, we statistically evaluate forecast accuracy and compare it with products maintained by the United States Naval Observatory (USNO). Results demonstrate that while the short-term forecast accuracy of EOP based on China' s autonomous observations is slightly lower than USNO products, it exhibits advantages in medium- and long-term forecasts. Notably, the medium- to long-term forecast accuracy for Universal Time parameters improves by 20%-30%, reflecting China' s technological advancement in autonomous EOP observation, solution, and forecast data services.

Keywords: Earth rotation variation; Earth orientation parameters; high-accuracy prediction; rapid UT1 solution; rapid polar motion solution

1 Introduction

Earth' s rotation characterizes the coupling processes between the solid Earth and the atmosphere, oceans, mantle, and core across various spatial and temporal scales, and can be intuitively described using Earth Orientation Parameters (EOP). EOP serves as the transformation parameter between the International Celestial Reference Frame (ICRF) and International Terrestrial Reference Frame (ITRF), with critical applications in deep space exploration and satellite precision orbit determination. Earth' s rotation is extremely complex and highly time-varying, necessitating integrated observations from multiple space geodetic techniques for monitoring. Conventional space geodesy methods primarily include Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS) [1-3].

The celestial reference frame, terrestrial reference frame, and their connecting parameters (EOP) constitute the primary framework of spatial datum, serving as the reference benchmark for all ground- and space-based activities and representing key technologies for China to independently conduct space programs. Figure 1 illustrates the components of EOP and their relationship with celestial and terrestrial reference frames. As shown, EOP typically comprises three components: (1) precession and nutation, describing the motion of Earth' s rotation axis in space resulting from gravitational effects of the Sun, Moon, and planets on Earth' s equatorial bulge; (2) polar motion, representing the movement of the rotation axis relative to the Earth' s crust; and (3) variations in length of day, reflecting changes in Earth' s rotation rate. Since precession and nutation can be precisely calculated using models and length-of-day variations can be derived from Universal Time, EOP in this paper refers specifically to polar motion (including Px and Py components) and the difference between Universal Time and Coordinated Universal Time (UT1-UTC), sometimes abbreviated as UT1.

[Figure 1: see original paper] EOP and its connection with celestial and terrestrial reference frames

High-precision EOP data are typically determined based on the terrestrial reference frame definition through weighted integration of multiple space geodetic datasets with specific constraints, yielding the EOP combined solution. Due to complex data processing procedures, high-precision EOP combined solutions exhibit approximately a four-week delay. Data for the most recent month are usually supplemented by polar motion from GNSS observations and Universal Time from VLBI observations, constituting the EOP rapid solution. Currently, the EOP combined solution is released by the International Earth Rotation and Reference Systems Service (IERS), while organizations providing EOP rapid solutions include the United States Naval Observatory (USNO) and the European Space Agency (ESA). China currently lacks related domestic products [4-8]. Presently, most global satellite navigation systems and space exploration missions heavily rely on EOP data released by IERS. With China' s comprehensive national strength enhancement and changing international circumstances, establishing an independent EOP observation, solution, and forecast data service system has become urgently necessary [9].

Combining EOP combined and rapid solutions enables backward extrapolation to obtain forecast data, for which high-precision EOP forecasts represent critical practical application requirements. Numerous scholars have conducted EOP forecast research in recent years. Among various forecasting methods, the model combining least squares extrapolation and auto-regressive (LS+AR) components has been recognized as the most reliable EOP forecasting model since its proposal due to its simplicity and effectiveness [10,11]. This combined method has been validated through two EOP Prediction Comparison Campaigns (EOP PCC) [12,13] and serves as the primary method for obtaining IERS Bulletin forecast data [14]. Meanwhile, extensive research demonstrates that Effective Angular Momentum (EAM) from atmospheric and oceanic fluids constitutes the primary excitation factor for Earth rotation variations, with its equatorial and axial components corresponding to excitations of the two polar motion components and rotation rate parameters, respectively. The German Research Centre for Geosciences (GFZ) releases daily EAM fundamental datasets with a one-day delay and six-day forecast sequences, providing the foundation for ultra-high-precision 1-10 day EOP forecasts [15-18]. In recent years, many studies have integrated EAM data with mathematical models for EOP forecasting, consistently demonstrating that introducing fluid excitation can effectively improve short-term forecast accuracy [19-23].

However, the aforementioned research relies on international EOP data, primarily focusing on short-term forecasts of polar motion parameters within 30 days, with limited investigation into UT1-UTC parameters and medium- to long-term EOP forecasts, and lacking forecast analysis based on autonomously observed and solved EOP data. Furthermore, EAM only improves ultra-short-term EOP forecast accuracy and has no effect on medium- to long-term forecasts. Addressing this situation, this work employs autonomously observed and solved EOP data from the most recent 30 days, combined with IERS combined solutions to form a hybrid sequence, then applies the LS+AR model for 365-day long-term EOP forecasting. Given that EAM cannot improve medium- to long-term EOP forecasts, and building upon research correlating climate change with EOP [24-30], we incorporate climate-related interannual variation periods into the fitting model and adopt newly solved geophysical parameters to enhance medium- to long-term EOP forecast accuracy.

2 Accuracy Assessment of Autonomous Rapid EOP Solutions

To meet the urgent demand for autonomous EOP determination and forecasting (particularly for Universal Time UT1) for China’ s major projects, the Shanghai Astronomical Observatory established a rapid EOP and Universal Time measurement team in early May 2022. Leveraging previously constructed VLBI stations and GNSS monitoring stations, the team initiated rapid EOP products and services using a combination of domestic autonomous observations and international joint observations. To compensate for the IERS combined solution delay, the most recent 30-day EOP observation sequence is obtained by integrating autonomous observation data (SESHAN 13-m, TIANMA 13-m, URUMQI-13-m VLBI antennas, and the Shanghai Astronomical Observatory GNSS center) with international station data.

Simple data preprocessing is required to fuse EOP combined and autonomous rapid solutions. First, GNSS rapid polar motion data at daily UTC 12h must be interpolated to daily UTC 24h to align with the IERS C04 series. Second, VLBI rapid UT1 sequence timestamps are irregular; this paper employs intensive interpolation to output daily UTC 24h point values, forming the rapid UT1 sequence. Using the first quarter of 2023 as an example, Figure 2 displays the residual sequence of autonomously observed and solved EOP relative to the IERS C04 combined solution and its accuracy statistics, with Mean Absolute Error (MAE) employed as the accuracy metric.

[Figure 2: see original paper] Residual sequence and accuracy statistics of autonomously observed EOP relative to IERS C04 combined solution

Figure 2 reveals that the residual sequence of autonomously observed and solved EOP is generally concentrated compared to high-precision post-processed combined solutions, demonstrating good accuracy stability. For comparison, this paper also statistics the accuracy of USNO rapid EOP solutions for the same period, with polar motion component MAE values of 0.033 mas and 0.028 mas, and UT1-UTC parameter MAE of 0.019 ms. These results indicate that certain accuracy gaps remain between autonomous rapid EOP solutions and USNO solutions.

These gaps can be summarized as follows: (1) All three residual sequences exhibit semi-monthly variation terms, likely related to the omission of smaller variation terms in tidal models during autonomous solution [3,5,9]; (2) Polar motion residual sequences also show certain linear biases, primarily attributable to reliance on single GNSS technology for autonomous rapid data; (3) Universal Time residual sequences exhibit locally dispersed observation points, possibly related to the distribution of some participating stations. Consequently, future improvements to autonomous EOP rapid solution accuracy can focus on two aspects: (1) Increasing globally distributed stations to reduce solution errors caused by insufficient baseline lengths; (2) Improving rapid EOP integrated processing schemes to eliminate systematic biases and reduce tidal model error impacts.

3 Improving Medium- and Long-term EOP Forecasts by Incorporating Climate Variability

This work constructs a hybrid EOP observation sequence by combining the IERS combined solution (EOP C04 series) from January 1, 1962, to present with autonomously observed and solved rapid solutions. Based on this sequence, forecasts are generated using the LS+AR method. Regular terms in the EOP sequence (primarily including trend and periodic components) are forecasted through model fitting and extrapolation, while remaining residual terms are forecasted using an autoregressive model. Combining both yields 1–365 day EOP forecast sequences. The fitting and autoregressive models are expressed as follows:

$$\mathrm{rg}(\ ) = \quad + \quad +$$

$$\text{rs}(\ ) = \alpha \quad \text{rs}(\ - \ )$$

where rg and rs represent regular and residual terms, respectively; , , , , are fitting model parameters; and , α are autoregressive model parameters [29].

Research indicates that Earth Fluid Angular Momentum (EAM) significantly improves ultra-short-term EOP forecasts but has virtually no impact on medium- to long-term forecasts [20–24]. Therefore, this work does not incorporate EAM for long-term EOP forecasting. Additionally, recent studies investigating climate change signatures in Earth rotation variations confirm that EOP sequences have undergone trend changes in recent years [24,26]. Figure 3 displays EOP observation sequences from 1962 to present, with red boxes marking anomalous periods for each parameter.

[Figure 3: see original paper] EOP observation sequences from 1962–2024

Figures 3a and 3b present Px and Py observation sequences, respectively, showing that Earth polar motion sequence amplitudes decreased sharply during 2012–2021. Recent research indicates this amplitude attenuation resulted from antiphase excitation by the atmosphere and oceans, reflecting changes in ocean-atmosphere coupling patterns [26]. Figure 3c shows the UT1-UTC sequence, with breaks indicating leap seconds resulting from Earth’ s long-term rotation deceleration. The decreasing trend of the UT1-UTC sequence changed in 2020, reversing to an increasing trend. This trend reversal indicates Earth has recently entered a rotation acceleration phase, with the triple La Niña event during 2020–2023 contributing approximately 9% to this acceleration [29]. These EOP sequence variations affect medium- to long-term forecasts and must be considered.

Based on the aforementioned research on climate change indicators in EOP sequences, this work incorporates climate variability into EOP forecast models to improve medium- to long-term forecast accuracy. Specific improvements include: (1) To accurately fit complex variations in the Universal Time sequence, the model incorporates not only conventional annual, semi-annual, and 1/3-year periodic terms but also several interannual variation periods (approximately 2, 3, 6, and 7-year periods), thereby improving fitting accuracy for long-term variation terms [27–29]; (2) To accommodate recent amplitude changes in polar motion sequences, fluid excitation data are introduced to re-estimate the Chandler wobble period (approximately 432.4 days; for specific solution methods, see reference [31]). These data introductions and updates consider climate change impacts on Earth rotation variations in recent years, collectively referred to as climate variability.

Based on these improvements, 1–365 day EOP forecast data can be obtained from the hybrid observation sequence. This data file is generated monthly and uploaded to a data platform for user download. With forecast data files accumulated over two years since May 2022, accuracy evaluation becomes possible. This paper selects forecast data from May 2022 to July 2024 for comparison with corresponding EOP observation data, using MAE as the accuracy metric. MAE is expressed as:

$$= - \quad |/$$

where represents EOP observed values, represents forecast values, represents forecast span, and represents the number of points participating in forecast accuracy statistics.

4 Medium- and Long-term EOP Forecast Results and Analysis

To better evaluate the accuracy of this work’ s long-term EOP forecast sequence, Bulletin A forecast data published by IERS for the same period are selected for comparison. Figure 4 displays the 1-365 day EOP forecast accuracy comparison between this work’ s results and Bulletin A from May 2022 to July 2024. Bulletin A files are provided by the United States Naval Observatory, with results marked as USNO, while this paper’ s results are marked as SHAO (Shanghai Astronomical Observatory).

[Figure 4: see original paper] Comparison of 365-day EOP forecast accuracy between SHAO and USNO

Figure 4 reveals varying performance between the two institutions across different parameters and forecast spans. For the Px parameter, SHAO demonstrates superior forecast accuracy between 50–150 days and after 320 days, while USNO achieves higher accuracy within 50 days and between 150–320 days. For the Py parameter, SHAO shows accuracy advantages between 180–260 days, with USNO performing better across other spans. For UT1-UTC parameters, USNO leads within 1-140 days, while SHAO exhibits clear advantages beyond 140 days. According to different application requirements, EOP forecasts are typically categorized as: (1) ultra-short-term (within 10 days); (2) short-term (within 90 days); (3) medium-term (within 180 days); and (4) long-term (within 365 days). For intuitive comparison, Figure 5 presents MAE comparisons across these primary spans, additionally showing short-term forecast accuracy at 30 and 60 days for the three parameters.

[Figure 5: see original paper] Comparison of EOP forecast accuracy across primary spans between SHAO and USNO

Based on the fixed-span MAE comparisons in Figure 5, several conclusions emerge: (1) At the 10-day span, USNO’ s EOP forecast accuracy is slightly higher than SHAO’ s; (2) For 30, 60, and 90-day short-term forecasts, SHAO and USNO each demonstrate advantages in Px and Py components, respectively, while USNO leads in UT1-UTC; (3) For 180-day medium-term forecasts, SHAO shows advantages in both Px and UT1-UTC components, with USNO slightly leading in Py; (4) For 365-day long-term forecasts, SHAO substantially leads in Py and UT1-UTC components, while USNO leads in Px.

In summary, USNO marginally leads in ultra-short- and short-term forecasts, primarily due to higher accuracy in its most recent 30-day rapid EOP solutions. SHAO demonstrates accuracy advantages in medium- and long-term forecasts, indicating that rapid solution accuracy for the most recent month only affects short-term forecasts within 90 days, while medium- to long-term forecast accuracy depends primarily on the forecast model. SHAO’ s medium-term forecast advantages simultaneously demonstrate that incorporating climate variability into forecast models improves accuracy. Particularly for Universal Time parameters, medium- to long-term forecast accuracy improves by approximately 20%–30%. Additionally, results show that incorporating climate variability yields less significant improvement for polar motion than for UT1-UTC. During the evaluation period (2022–2024), polar motion amplitude attenuation adjustment had completed and returned to normal amplitude phases, thus Chandler period updates had minimal impact on forecasts during this period. Meanwhile, UT1-UTC’ s complex variation trends persisted, making the introduction of relevant interannual periods effective for improving medium- to long-term forecasts.

5 Summary and Outlook

This work preprocesses autonomously observed and solved rapid EOP solutions, then combines them with EOP C04 combined solutions to form a hybrid observation sequence. Based on this sequence, climate variability is incorporated into the model for the first time to obtain real-time 1–365 day EOP forecast data through backward extrapolation, which are then uploaded to a data platform in file format to serve relevant users. Accuracy evaluation of EOP forecast data generated by SHAO and USNO reveals that each institution demonstrates advantages across different forecast spans. Analysis indicates that SHAO and USNO achieve comparable accuracy levels in rapid EOP solution and 1–365 day EOP forecasting. These results demonstrate that after years of technological accumulation, China has established comprehensive capabilities in multi-technology EOP system construction, observation and solution, data processing, and product services.

To better support application requirements for China’ s major projects and meet scientific research needs, autonomous EOP data services can be improved through: (1) Adopting multi-technology collocation strategies to eliminate station coordinate error effects and enhance VLBI, GNSS, and other station stability; (2) Combining high-resolution data to precisely analyze excitation mechanisms across EOP frequency bands, reducing solid Earth and ocean tide model errors; (3) Developing new rapid EOP data processing strategies to eliminate systematic biases from frame inconsistencies; (4) Improving existing Earth rotation theory by incorporating comprehensive geophysical excitation factors to further enhance EOP forecast accuracy; (5) Extensively surveying user requirements to provide personalized EOP data services.

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