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ORIGINAL STUDY

An improved prediction algorithm for Earth's polar motion with considering the retrograde annual and semi-annual wobbles based on least squares and autoregressive model

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Abstract

Earth Rotation Parameters (ERP) are indispensable in the transformation between the Celestial Reference Frame and the Terrestrial Reference Frame, and significant for high-precision space navigation and positioning. As a key parameter in ERP, Polar Motion (PM) is of great importance in analyzing and understanding the dynamic interaction between solid Earth, atmosphere, ocean and other geophysical fluids. The diverse excitations, as well as complex motion mechanisms of PM, make it more difficult for its high-precision prediction. In this study, the characteristics of PM from 1962 to 2018 are firstly analyzed. The main period term of the PM is extracted and reconstructed by the Fourier Transform Band-Pass Filter, which indicates Chandler's amplitude has decayed to its lowest state in 2016 and then enters into the next growth stage. More importantly, a Retrograde Semi-annual Wobble (RSAW) is detected and confirmed for the first time. Secondly, the contributions of Retrograde Annual Wobble (RAW) and RSAW terms to PM are analyzed and compared. Results demonstrate that the magnitudes of RAW and RSAW terms to PM from 1962 to 2018 are about 3–8 mas. Finally, in view of the existence of RAW and RSAW in PM, an improved PM prediction algorithm with considering the influence of RAW and RSAW based on least squares and autoregressive model (LS + AR) is developed. The results show that the inclusion of RAW term can effectively improve the accuracy of the LS + AR model in the prediction span of 1–360 days for both components of PM. Besides, considering the RSAW term, the prediction accuracy can be further improved in the prediction spans of 50–310 days for x component of PM, and in the prediction spans of 50–180 days for y component of PM.

Keywords Polar Motion · FTBPF · Retrograde annual wobble · Retrograde Semi-annual wobble · Prediction

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1 Introduction

The Earth's rotation movement is a direct representation of external forces and internal forces of the Earth, as well as the interaction between the Earth's various spheres of the Earth's core, mantle, crust and atmosphere (Zheng and Yu 1996). The Earth rotation is not uniform and it fluctuates slightly under the influence of the celestial bodies around the Earth, the hydro-atmospheric circulation, and fluid core-mantle interaction (Bizouard et al. 2018). The changes in the Earth's rotation are often reflected by Earth Orientation Parameters (EOP), including precession-nutation, Polar Motion (PM) and the difference between Universal Time (UT1) and Universal Time Coordinated (UTC), namely UT1–UTC (Earth's rotation rate) or the LOD (Length of Day, the derivative of the UT1–UTC). As a key parameter, PM is used to describe the instantaneous movement of the Earth's rotation axis in the body relative to the Earth's surface (Zheng and Zhou 1997), and it is caused by the mass redistributions on the surface and inside the Earth. Since the twentieth century, international organizations such as the International Latitude Service (ILS) and the International Polar Motion Service (IPMS), have carried out the monitoring campaigns to improve the estimation and prediction accuracy of the PM (Ye and Huang 2000).

There are three dominant components in PM, those are secular drift with a rate of about 3.5 mas/year, Chandler Wobble (CW) with a variable amplitude ranging between 100 and 200 mas, and Annual Wobble (AW) with a nearly constant amplitude of about 100 mas (Gross 2000; Wang et al. 2016). In addition, there are other periods in PM, such as the Semi-Chandler Wobble (SCW), the Semi-Annual Wobble (SAW), the seasonal Wobble, the one-month Wobble, the half-month Wobble, the quasi-biennial Wobble and the 300-day Wobble. CW and AW are the main periodic wobble of PM, which are of great significance to study the changes and characteristics of PM. Since CW was firstly proposed by Chandler (1891), its major components and changes in period and amplitude have been extensively studied (Liu et al. 2007; Na et al. 2013; King and Watson 2014; Spada et al. 2015; Cambiotti et al. 2016). CW is an excited resonance of the Earth's rotation and freely decays as the Earth is a viscous-elastic body. Studies have shown that CW would freely decay within 68 years to the minimum rotational energy state in the absence of excitation (Gross 2000). On the one hand, some researchers consider CW as an oscillation with two close frequencies (Guo et al. 2005), On the other hand, others argue that CW is time-varying frequencies caused by the abnormal phase shift (Malkin and Miller 2010). It is generally believed that the oscillation period and amplitude of CW are time-varying, and the period varies from 1.13 to 1.20 years (Schuh et al. 2001). Although CW has been studied for more than a century, its excitation mechanism is still elusive and thus requires further in-depth exploration (Malkin and Miller 2010).

AW is a forced motion in PM with a period of 356–376 days (Höpfner 2004), and the research on the excitation of AW has been a hotspot for many years. Yu and Zheng (2000) found that the contribution of the atmosphere to the seasonal change of PM exceeds 85%, and that to the annual change of PM can reach 95% (Yu and Zheng 2000). Zhong et al. (2002) studied the contribution of atmosphere, hydrology and ocean currents to the seasonal change of PM based on a coupled ocean–atmosphere circulation model and confirmed the importance of hydrology as an excitation source of AW (Zhong et al. 2002). Gross et al. (2003) compared the contribution of the atmosphere, winds, surface pressure and ocean currents to AW, and showed that the effects of winds and currents have nearly the same amplitude, while the effect of currents is about 2/3 of the bottom pressure variations (Gross et al. 2003). Höpfner (2004) thought that the excitations of the AW are coming from the seasonal displacement of air and water masses (Höpfner 2004).

The amplitude, frequency, and phase properties of AW and CW extracted from the observed PM are very important for studying the excitation mechanism of PM, especially for AW, which can be divided into Prograde Annual Wobble (PAW) and Retrograde Annual Wobble (RAW) (King and Agnew 2013). At present, most scholars pay attention to the PAW term while few studies are focused on RAW terms of PM. Su et al. (2014) analyzed the instantaneous amplitude, frequency and phase of RAW based on normal time–frequency transform (NTFT), and made long-term PM prediction, which shows that RAW is benefit for long-time prediction (Su et al. 2014). Wang et al. (2016) studied the variation of frequency, phase and amplitude of RAW, and proposed a Fourier basis pursuit band-pass filtering (FBPBPF), which can effectively suppress the edge effect during the acquisition of RAW (Wang et al. 2016). It can be seen that the impact of RAW on PM cannot be ignored from the above researches, especially in PM prediction. Therefore, the importance for the PM prediction is studied in this study. It is noted that a Retrograde Semi-annual Wobble (RSAW) is detected and confirmed, the contributions of RSAW terms to PM need to be analyzed and compared. Meanwhile, the measurement accuracy of PM has increased by 1–2 orders of magnitude with the improvement of observation techniques (Bizouard 2018), which provides a possibility to study its characteristics, especially the causes and effects of various excitation. Considering the characteristics of secular drift, CW and AW, researchers have developed a lot of high-precision models or algorithms in the prediction of ERP (Schuh et al. 2002; Niedzielski and Kosek 2008; Kosek et al. 2008; Kosek 2010a, b; Kalarus et al. 2010; Akyilmaz et al. 2011; Sun et al. 2015; Lei 2016; Jia et al. 2017; Dill et al. 2018). Generally, the studies can be divided into two parts: linear models and nonlinear models. In order to further improve the prediction method and theory of ERP, the IERS has successively launched Earth Orientation Parameters Prediction Comparison Campaign (EOP PCC) and Earth Orientation Parameters Combination of Prediction Pilot Project (EOPCPPP).

In order to analyze the characteristics of period and trend in PM and the influence of the main periods (such as CW and AW) on the PM prediction, firstly, the Fourier Transform Band Pass Filter (FTBPF) is used to extract and reconstruct the period and amplitude of CW and AW from Earth's PM observations since 1962. Secondly, the amplitude variation of CW and AW in PM are reanalyzed to confirm whether there is obvious RAW and RSAW in PM. Finally, an improved PM prediction algorithm with considering the influence of RAW and RSAW based on least squares and autoregressive model (LS + AR) is proposed and validated.

2 Theory and method

2.1 Fourier transform band-pass filter (FTBPF)

The Fourier analysis is used to study the periodic phenomena, which is later extended to non-periodic phenomena study by Fourier transform. The essence of the Fourier series is to decompose a periodic signal into many discrete sine waves. Fourier transform has become one of the most practical and basic tools in mathematical transformation, and it can be divided into a Continuous Fourier Transform (CFT) and a Discrete Fourier Transform (DFT) according to the continuity of the time signal data. The extraction of the periodic signal in PM data with an interval of 1 day is based on a DFT. The FTBPF has already been used to extract the CW and AW from PM data (Popiński and Kosek 1995).

For a time signal $f(k)$, its DFT can be expressed as:

$$F(n)=\sum_{k=0}^{N-1} f(k)\exp\left(\frac{-2\pi ikn}{N}\right) \tag{1}$$

where N is the length of the data, $n=0,1,\ldots,N-1$, and n corresponds to the angular frequency value ω_n.

For the discrete form of a signal $f(k)$, its DFT can be inverted as:

$$f(k)=\sum_{n=0}^{N-1} F(n)\exp\left(\frac{2\pi ink}{N}\right)\Big/N \tag{2}$$

where $k=0,1,\ldots,N-1$. If the angular frequency value ω_n takes the corresponding angular frequency range $\left[\,\omega_{n1}\ \ \omega_{n2}\,\right]$, then the extracted signal by FTBPF can be written as:

$$fz(k)=\sum_{n=\omega_{n1}}^{\omega_{n2}} F(n)\exp\left(\frac{2\pi ink}{N}\right)\Big/N \tag{3}$$

where $fz(k)$ is the signal series to be extracted, the value ω_{n2} is bigger than ω_{n1}.

The Fourier analysis is widely used because it can quickly analyze the variation characteristics of observation sequences in the time domain and frequency domain. It is considered as one of the most significant contributions to numerical analysis. In the PM sequence, there are a large number of periodic characteristics, In order to find out the main periodic components and their influence in PM, the Fourier analysis provides us with a powerful tool.

2.2 LS + AR prediction model

The LS + AR model is commonly used in ERP prediction with the features of simple construction and high-accuracy. Usually, there are linear and periodic terms including Chandler wobble, annual and semi-annual periodic terms in PM. The fitting equation of LS model can be expressed as:

$$\begin{aligned} f(t) = a_0 + a_1 t + B_1\cos\left(\frac{2\pi t}{R_1}\right) + B_2\sin\left(\frac{2\pi t}{R_1}\right) + C_1\cos\left(\frac{2\pi t}{R_2}\right) \\ + C_2\sin\left(\frac{2\pi t}{R_2}\right) + D_1\cos\left(\frac{2\pi t}{R_3}\right) + D_2\sin\left(\frac{2\pi t}{R_3}\right) + \cdots \end{aligned} \tag{4}$$

where a_0 is the constant term, a_1 is the linear term, B_1, B_2, C_1, C_2, D_1, $D_2\ldots$ is the coefficients for periodic terms. In this paper, the CW, AW, RAW and RSAW are used in the LS model. R_1, R_2, $R_3\ldots$ is the corresponding periodic, t is the time of UTC.

The estimator by using the LS for the unknown coefficients can be written as:

$$\hat{\beta} = (A^T A)^{-1} A^T f \tag{5}$$

where $\hat{\beta} = \begin{bmatrix} a_0 & a_1 & B_1 & B_2 & C_1 & C_2 & D_1 & D_2 & \cdots \end{bmatrix}^T$ is the estimated parameter vector, A is the coefficient matrix, f is the observation vector of PM series. The residual series from the difference between the LS fitted series and the observations can be modelled by the AR model.

AR model is the description of the relationship between a random series $z_t (t = 1, 2, \ldots, N)$ before time t and the current time. Its expression can be written as follows:

$$z_t = \sum_{i=1}^{p} \phi_i z_{t-i} + \omega_t \tag{6}$$

where $\phi_1, \phi_2, \ldots, \phi_p$ are the autoregressive coefficients, and ω_t is the white noise with zero means, p is the model order. The above equation denoted by AR (p) is well-known as the AR model of the order p, the key to using the AR model is how to determine the order p. Usually, there are three methods for the determination of p, the final prediction error criterion, the information criterion and the delivery function criterion. In this paper, the final prediction error criterion is adopted to determine the order p.

In order to evaluate the prediction accuracy, we use the Mean Absolute Error (MAE) standards. It can be expressed as follows:

$$E_i = P_i - O_i \tag{7}$$

$$\mathrm{MAE}_j = \frac{1}{n} \sum_{i=1}^{n} (|E_i|) \tag{8}$$

where P_i is the predicted value of the i-th prediction, O_i is the corresponding observation value, E_i is the true error (assume the observation value as true), n is the total prediction number.

3 Time series analysis of Polar Motion based on EOP 14C04

3.1 Data description

The new version of the Earth Oriented Parameter EOP 14C04 based on ITRF2014 was released by IERS on February 1, 2017. The new series has been recombined from 1984, as the space-geodetic data became available. EOP 14C04 is available at http://hpiers.obspm.fr/eoppc/eop/eopc04/. The sampling interval of the EOP 14C04 is 1 day. The time-series is collected from January 1, 1962, including PM, UT1-UTC and LOD etc. In the processing of FTBPF, the time-span of PM series is from 1962 to 2018. The optimal order p for AR model is selected as 50, which is determined by the final prediction error criterion. The PM observation data can be seen in Fig. 1.

3.2 Analysis of Periodic Change of Polar Motion

In order to analyze the amplitude variation and characterizes of CW and AW in PM data, the Fast Fourier Transform (FFT) spectrum analysis is performed on the EOP 14C04

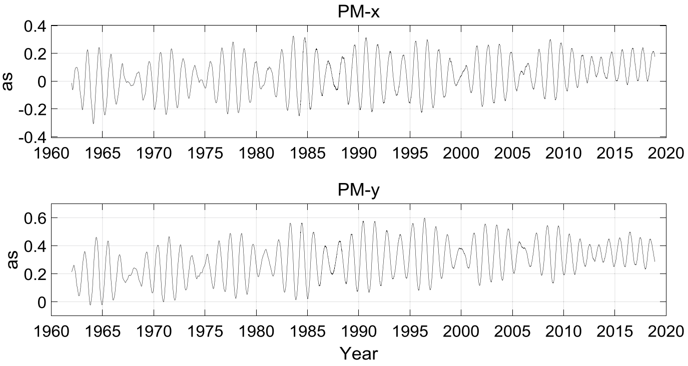

Fig. 1 Polar motion (PM-x, PM-y) observations time from 1962 to 2018

series. The linear trends of the PM series are removed based on the LS method, and the FFT spectrum can be seen in Fig. 2.

It is can be seen from Fig. 2 that CW and AW are very prominent in PM data, and the periodic range of the AW and CW in the FFT spectrum are 340–390 days, 390–500 days, respectively. The RAW can also be clearly revealed from the FFT spectrum. In order to better display the existence of RAW, both PAW and RAW are also separately displayed in Fig. 2. It can be seen from Fig. 2 that RAW and RSAW are obvious in the FFT spectrum of PM time series, though the amplitude of RAW is lower than the amplitude of PAW.

In order to analyse the contribution of CW, PAW, RAW and RSAW terms to PM, these periodic signals are reconstructed based on FTBPF filtering, and the proportions of each term in PM are compared, which are presented from Figs. 3, 4, 5 and 6.

It can be seen from Figs. 3 and 4 that the main contribution for PM is CW and PAW. CW has a variable amplitude ranging between 100–200 mas, which is consistent with the result in (Gross 2000). It should be noticed that the amplitude of CW has been reducing since 2005, and decaying to its lowest state in 2016 (the amplitude is less than 50 mas, which is much smaller than the amplitude of PAW). After that, it enters into the next growing period. This is also the key reason that the rate of PM has not changed significantly

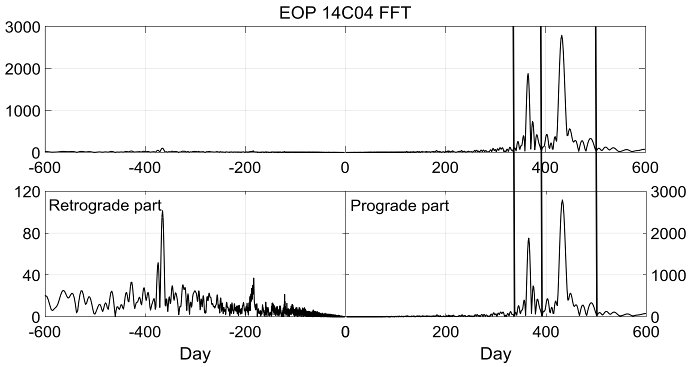

Fig. 2 FFT spectrum in prograde and retrograde part (in half bottom, the right is same as upper, but the left is shown in another scale to better display retrograde part)

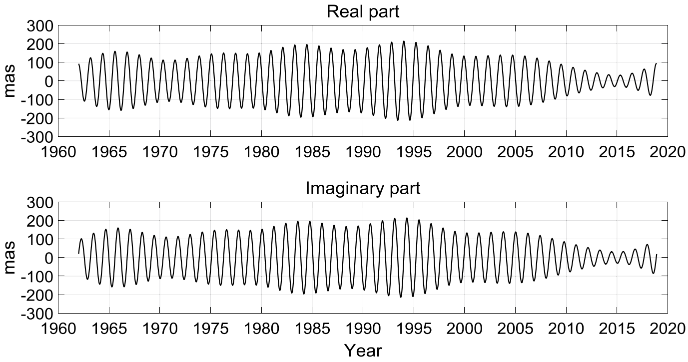

Fig. 3 Reconstruction of chandler term

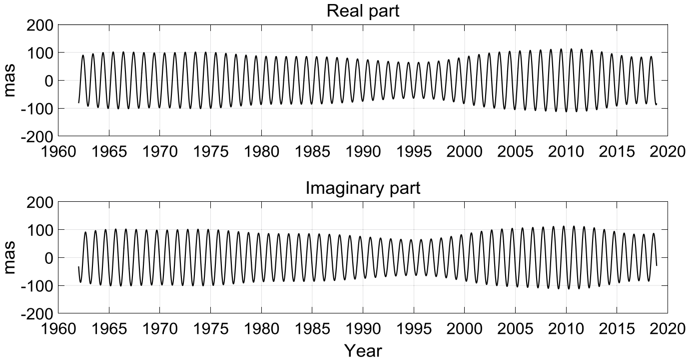

Fig. 4 Reconstruction of prograde annual term

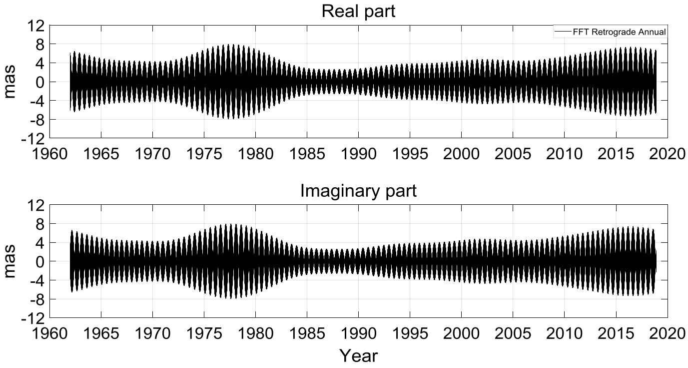

Fig. 5 Reconstruction of retrograde annual term

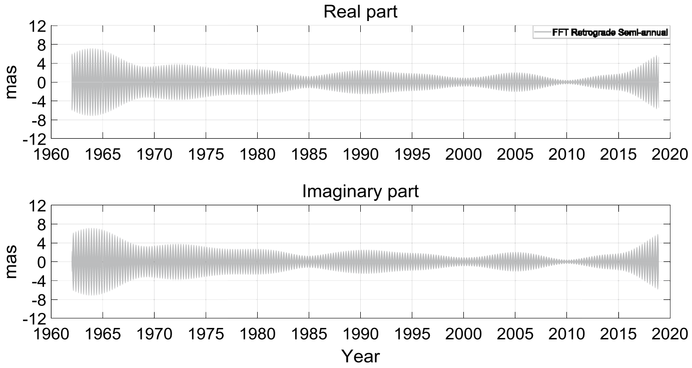

Fig. 6 Reconstruction of retrograde semi-annual term

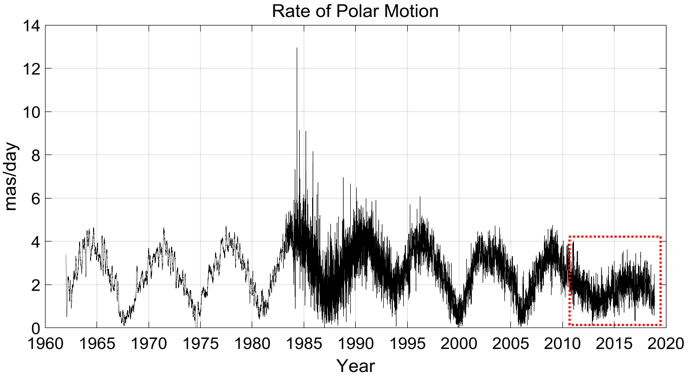

Fig. 7 Rate of polar motion in EOP 14C04

since 2010. Besides, the periodic variation of the PM rate is not obvious, which can be seen from the red box in Fig. 7. For PAW, the amplitude is maintained at 100 mas for a long time although with a slight change, which indicates that the PAW is the most stable period term in PM.

The amplitude of RAW and RSAW are shown in Figs. 5 and 6. It can be seen that the retrograde periodic terms do exist in PM time series, although the real physical mechanism or cause is still unclear. Their influences on PM are weaker than those of the prograde periodic terms with the amplitude of between 3 mas to 8 mas. However, it cannot be ignored in the high-precision prediction of PM.

4 An improved prediction algorithm of PM and its evaluation

Due to the complexity of space geodetic observation and data processing, it is difficult to obtain ERP in real-time. To meet the needs for space navigation and positioning, the high-precision prediction of ERP is urgent. In the prediction of ERP, researchers have established a lot of high-precision prediction algorithms. Overall, the LS + AR model is commonly used in ERP prediction with the advantages of simple construction and high-accuracy. In the LS + AR model, the basic principle is to fit a certain length of PM data by using the least-squares algorithm, describing the trend term and inherent periodic terms. However, only CW, AW, Semi-annual Wobble (SAW), trend term and linear term are often included in LS + AR model.

In the previous linear models of PM prediction, all of the fitting period terms are PAW and PSAW, which are the largest terms of wobble amplitude. The RAW and RSAW are usually neglected. A possible reason is that there exist few studies on the retrograde wobble of PM, and the reasons and physical mechanisms of RAW or RSAW are still unclear. However, they do exist and need to be taken into account in the prediction. Based on this idea, an improved prediction algorithm considering the RAW and RSAW based on LS + AR model are proposed to illustrate whether the inclusion of the retrograde wobble terms has any contribution to the accuracy of PM prediction.

As described above, RAW and RSAW amplitude is about 3–8 mas, and relatively lower than the prograde wobbles. In PM prediction, the greatest influence on the prediction error is the fitting accuracy of the existing PM series (Sun 2013). Therefore, how to further improve the fitting accuracy is one of the main tasks to improve PM prediction. In order to verify the proposed algorithm, the following cases of computation are designed for analysis and comparison.

Case 1: LS + AR model including CW, PAW and PSAW terms.

Case 2: LS + AR model including CW, PAW, PSAW and RAW terms.

Case 3: LS + AR model including CW, PAW, PSAW, RAW and RSAW terms.

Case 4: LS + AR model including CW, PAW, PSAW and RSAW terms.

In the prediction of PM based on LS + AR model, to better reveal the influence of the retrograde parts on the prediction accuracy, the basic sequence length of the above 4 cases is chosen as 10-year from January 1, 2000, to December 31, 2009. The prediction accuracy statistic is from January 1, 2010, to November 11, 2018, with prediction span of 360 days base on moving window per day. For the period of prograde wobble, the value of the CW is 435 days, the PAW is 365.24 days and the PSAW is 182.62, they are same both in PM x and y components. But for the retrograde wobble, the RAW is 365.20 days and the RSAW is 183.50 days in PM-x component; the RAW is 365.24 days and RSAW is 184 days in PM-y component; it is a little bit different. All the above

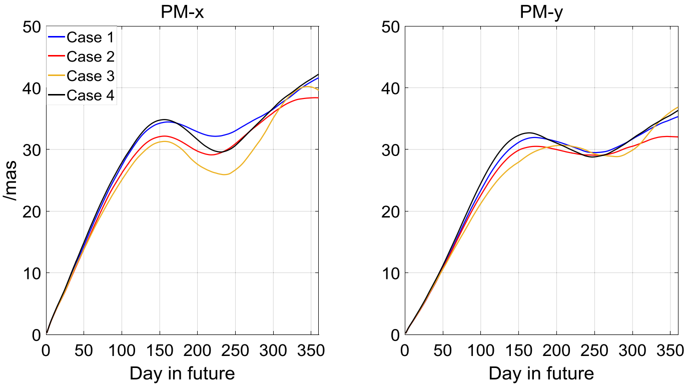

Fig. 8 MAE of different prediction intervals for polar motion in 4 cases

Table 1 MAE for polar motion prediction based on 4 cases

Day in future	PM-x				PM-y			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
1	0.2469	0.2466	0.2464	0.2475	0.1992	0.1991	0.1995	0.2003
2	0.6007	0.5992	0.5996	0.6035	0.4393	0.4389	0.4397	0.4418
3	0.9693	0.9648	0.9686	0.9754	0.6869	0.6866	0.6878	0.6921
4	1.3257	1.3189	1.3234	1.3378	0.9194	0.9184	0.9233	0.9307
5	1.6666	1.6571	1.6620	1.6880	1.1360	1.1339	1.1416	1.1537
6	1.9972	1.9836	1.9926	2.0247	1.3378	1.3343	1.3463	1.3625
7	2.3011	2.2819	2.2958	2.3369	1.5222	1.5181	1.5317	1.5567
8	2.5936	2.5693	2.5877	2.6399	1.7075	1.7030	1.7158	1.7519
9	2.8797	2.8495	2.8739	2.9382	1.8895	1.8845	1.9016	1.9454
10	3.1637	3.1271	3.1581	3.2307	2.0703	2.0652	2.0900	2.1394
20	5.8167	5.6822	5.7261	6.0028	3.9952	3.9821	4.0469	4.1935
30	8.5761	8.3178	8.3997	8.9117	6.1077	6.1194	6.2107	6.4242
60	17.2989	16.6263	16.3283	17.8514	13.3479	13.1312	12.7931	13.8151
90	25.1058	24.1567	23.0878	25.6577	21.0738	20.4350	19.2393	21.9733
120	31.2672	29.5398	28.5164	31.6712	27.4844	26.3789	24.6871	28.8138
150	34.2481	32.0835	31.2162	34.7552	31.1626	29.8861	27.9590	32.3035
180	33.9582	31.1828	29.9552	33.6612	31.8363	30.4624	30.0963	32.1501
240	32.4980	30.0460	25.9834	29.8718	29.6134	29.1147	29.8215	28.8990
300	36.5582	35.9711	35.0913	36.7167	31.6983	30.5270	29.8903	31.7736
360	41.6291	38.3823	39.5961	42.2176	35.3182	32.0379	36.8618	36.3257

period values used in LS + AR model are obtained by FFT Spectrum based on PM series. The prediction results are shown in Fig. 8 and Table 1.

It can be seen from Fig. 8 and Table 1 that the prediction accuracy of 4 cases is quite different. The prediction accuracy of case 2 is higher than that of case 1 in all the prediction spans of 1-360 days, which indicates that the inclusion of the RAW term in LS + AR model can effectively improve the prediction accuracy, especially for x component of PM. This can also be seen from the true errors of prediction in 4 cases in Figs. 9 and 10.

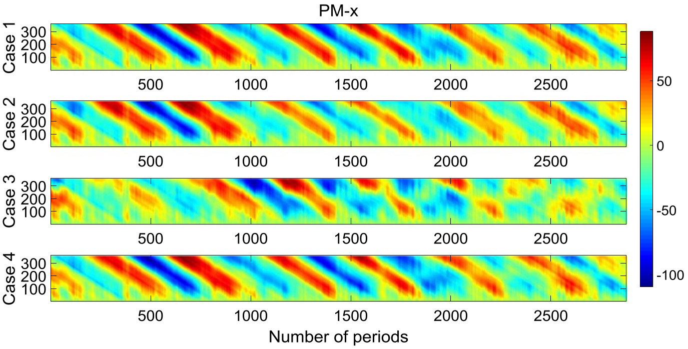

Fig. 9 Prediction errors (in mas) for 4 cases of polar motion x

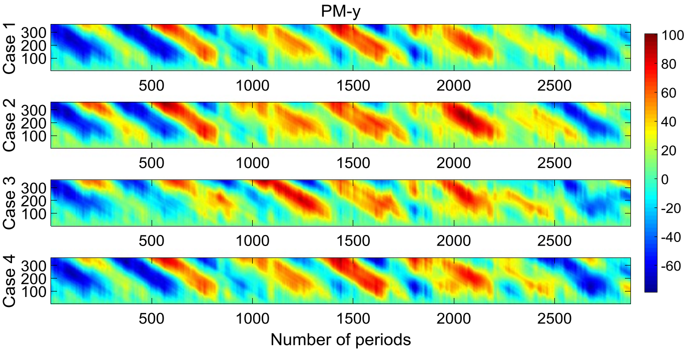

Fig. 10 Prediction errors (in mas) for 4 cases of polar motion y

The prediction accuracy of case 3 is higher than that of case 2 in the prediction spans of 50–310 days in PM-x component, and it is slightly lower than that of case 2 in the prediction spans of 1–49 days. The prediction accuracy of case 3 is higher than that of case 1 in all the prediction spans of 1–360 days for PM-x component. For PM-y component, the prediction accuracy of case 3 is slightly lower than those of case 1 and case 2 in the prediction spans of 1-49 days, but has better performance in the prediction spans of 50-180 days. Therefore, RSAW part is recommended to be added into LS fitting when using LS + AR model for PM-y prediction in the span of 50–180 days. The prediction accuracy of case 4 in PM-x and PM-y component is lower than those of case 2, and there is no obvious advantage over case 1 when including RSAW only. It shows that the RSAW part has a lower impact on prediction accuracy than RAW part for PM prediction, and RSAW part needs to be combined with the RAW term.

In summary, the inclusion of RAW term can effectively improve the accuracy of the LS + AR model in all the prediction spans of 1–360 days, which is strongly recommended to be applied in PM prediction. For RSAW term, the prediction accuracy can be further improved in the prediction spans of 50–310 days for x component of PM, and in the prediction spans of 50–180 days for y component of PM.

5 Conclusion

In this study, The FTBPF is used to extract and reconstruct the main period terms contained in the PM to reanalyze the characteristics of PM from 1962 to 2018. It confirms that the existence of RAW and RSAW in PM time series. Then, the contributions of RAW and RSAW to PM are then analyzed and compared, which shows that the contribution of RAW and RSAW terms to PM from 1962 to 2018 is about 3–8 mas. Drawing on these findings, an improved prediction algorithm by including the influence of RAW and RSAW is proposed and tested based on the new released EOP 14C04 product. The results show that the inclusion of RAW term can effectively improve the accuracy of the LS + AR model in all the prediction spans of 1–360 days, which is strongly recommended to be applied in PM prediction. For RSAW term, the prediction accuracy can be further improved in the prediction spans of 50–310 days for x component of PM and in the prediction spans of 50–180 days for y component of PM.

The further work may focus on the complement of the RAW and RSAW in other prediction algorithms such as LS + MAR (Multi-Autoregression), LS + ARIMA (Autoregressive Integrated Moving Average) et al.

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