Chandler wobble: two more large phase jumps revealed

Zinovy Malkin and Natalia Miller

Pulkovo Observatory, Pulkovskoe Ch. 65, St. Petersburg 196140, Russia

(Received August 23, 2009; Accepted November 8, 2010; Online published February 3, 2011)

Investigations of the anomalies in the Earth rotation, in particular, the polar motion components, play an important role in our understanding of the processes that drive changes in the Earth's surface, interior, atmosphere, and ocean. This paper is primarily aimed at investigation of the Chandler wobble (CW) at the whole available 163-year interval to search for the major CW amplitude and phase variations. First, the CW signal was extracted from the IERS (International Earth Rotation and Reference Systems Service) Pole coordinates time series using two digital filters: the singular spectrum analysis and Fourier transform. The CW amplitude and phase variations were examined by means of the wavelet transform and Hilbert transform. Results of our analysis have shown that, besides the well-known CW phase jump in the 1920s, two other large phase jumps have been found in the 1850s and 2000s. As in the 1920s, these phase jumps occurred contemporarily with a sharp decrease in the CW amplitude.

Key words: Earth rotation, polar motion, Chandler wobble, amplitude and phase variations, phase jumps.

1. Introduction

The Chandler wobble (CW) is one of the main components of motion of the Earth's rotation axis relative to the Earth's surface, also called Polar motion (PM). It was discovered by Seth Carlo Chandler in 1891 (Chandler, 1891a, b). The CW is one of the main eigenmodes of the Earth rotation, and investigation of its properties such as period, amplitude and phase variations is very important for the understanding of the physical processes in the Earth, including its surface, interior, atmosphere and ocean. Since the discovery of CW, numerous papers were devoted to analysis of this phenomenon. The results are summarized in Munk and MacDonald (1960) and Lambeck (1980). For the latest result see e.g. Schuh *et al.* (2001) and referenced papers.

Among other interesting CW peculiarities, a phase jump of about 180° occurred in the 1920s. Perhaps, it was for the first time detected by Orlov (1944). Detailed consideration of this CW phase jump is given e.g. in Guinot (1972) and Vondrák (1988). Also, less significant CW phase jumps can be observed, which may be in temporary coincidence with geomagnetic jerks and Free Core Nutation (FCN) phase perturbations (Gibert and Le Mouël, 2008; cf. Shirai *et al.*, 2005). However, the "main" phase jump in the 1920s remains to be most interesting feature of the CW, which, in particular, is a real test of Earth rotation theories.

It should be noted that most papers devoted to the CW studies are based chiefly on the observations of the Earth rotation obtained in the period from 1899 (start of the International Latitude Service) till the end of 1990s. Recently fulfilled study of CW based on analysis of the whole IERS (International Earth Rotation and Reference Systems Service) C01 PM time series (Miller, 2008) has shown clear evidence of two other large CW phase jumps that occurred in the beginning and the end of the C01 series. Earlier, Sekiguchi (1975) found a CW phase perturbation of about 40° in the 1850s, but he did not come to a definite conclusion due to the poor quality of the observations used.

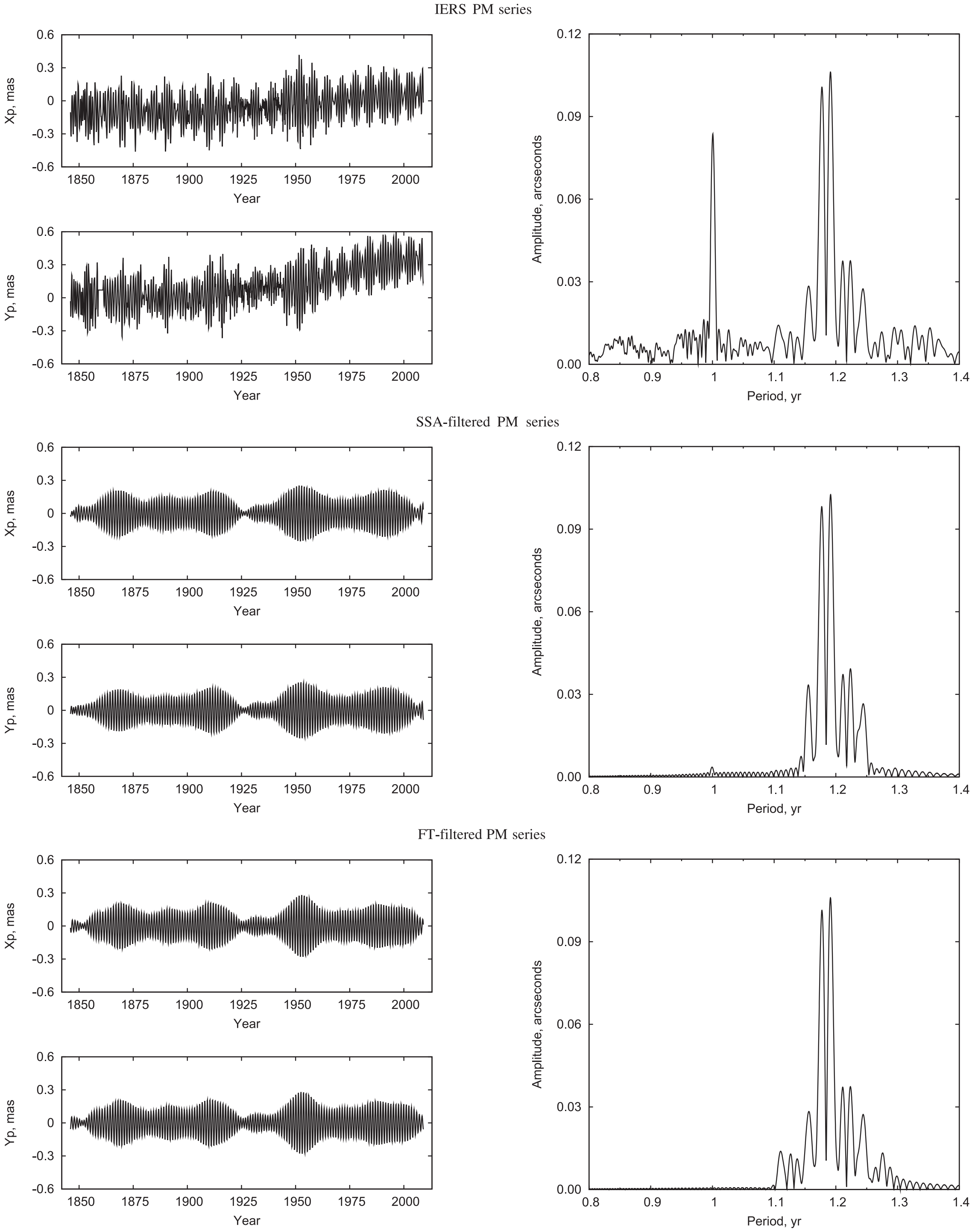
In this paper, we perform detailed investigation of the IERS Pole motion data to finally confirm that preliminary finding. Our study consists of three steps: forming the longest available IERS PM time series joining C01 and C04 series, extracting CW signal, and analyzing CW signal thus obtained. To improve reliability of the results, several methods of analysis were used, and their results corroborate the common conclusion on the two existing large CW phase jumps in the 1850s and nowadays.

2. Preliminary Data Processing

For our analysis, we used the EOP(IERS)C01 PM series that spans the period from 1846.0 through 2008.5. We extended this series up to 2009.0, merging it with the EOP(IERS)C04 series. These series are sampled at different rates: 0.1 yr (C01, 1846–1899), 0.05 yr (C01, 1890–2008), 1 d (C04). Using this data, three 163-year evenly spaced series with 0.05 yr, 0.1 yr, and 10 d step were constructed, and all the computations described below were made with all three series. No visible differences in results were found.

Our next goal was to extract the CW signal from the PM time series, removing all the regular (periodic and quasi-periodic) and non-regular (trend) PM components out of the CW frequency band. Using digital filtering enables us to cut off the PM variations with periods beyond the CW band without application of any models of annual, trend, and other signals. The following two methods were used

doi:10.5047/eps.2010.11.002


IERS PM series

SSA-filtered PM series

FT-filtered PM series

Fig. 1. Original and filtered PM series used for our analysis, and corresponding spectra. One can see that both types of digital filtering allows us to effectively suppress the annual signal. The CW signal looks similar in both filtered series. However, some differences can be seen near the ends of the interval.

for digital filtering of the PM series.

Singular spectrum analysis (SSA). This method allows us to investigate the time series structure in more detail than other digital filters. As shown in previous studies, it can be effectively used in investigations of the Earth rotation (see, e.g., Vorotkov *et al.*, 2002; Miller, 2008).

Fourier filtering. We used the bandpass Fourier transform (FT) filter with the window 1.19±0.1 cpy. Such a wide filter band was used to preserve the complicated CW structure. In the filtered PM series, the amplitude of the remaining annual signal is about 0.5 mas, i.e. 0.5% of the original value.

Hereafter we will refer to filtered PM time series as CW series. Analyzed PM and CW time series and their spectra are shown in Fig. 1. We can see two main spectral peaks of about equal amplitude near the central period of about 1.19 yr, and several less intensive peaks in the CW frequency band. Discussion on its origin, and even reality, lies out of the scope of this paper. Here we can only mention that observed bifurcation of the main CW peak is most probably caused by the phase jump in 1920s as suggested in to Fedorov and Yatskiv (1965). Detailed analysis of this problem is given e.g. by Sekiguchi (1976) and Guo *et al.* (2005). According to our study, comparison of the spectral components obtained at different time intervals gave us the single main CW period $P_0 = 1.185$ yr.

3. Evaluation of the CW Parameters

The next step of our study was to estimate the CW parameters, namely, instant amplitude and phase. Let us consider a general CW model with variable amplitude $A(t)$ and phase $\Phi(t)$ which can be written as

$$\begin{aligned} X_\mathrm{p}(t) &= A(t)\cos\Phi(t)\,, \\ Y_\mathrm{p}(t) &= A(t)\sin\Phi(t)\,, \end{aligned} \tag{1}$$

where X_p and Y_p are the Pole coordinates. Mathematically (not geophysically, indeed!), we can suppose three equivalent models for the CW phase:

$$\Phi(t) = \begin{cases} \dfrac{2\pi}{P(t)}\,t + \varphi_0\,, \\[2ex] \dfrac{2\pi}{P_0}\,t + \varphi(t)\,, \\[2ex] \dfrac{2\pi}{P(t)}\,t + \varphi(t)\,, \end{cases} \tag{2}$$

where P is the CW period, and zero subscripts mean constant (time-independent) values. In other words, we can consider the following three models: with variable period and constant phase, variable phase and constant period, or variable both period and phase. Of course, this is a subject of a special geophysical consideration.

The CW amplitude time series can be easily computed as

$$A(t) = \sqrt{X_\mathrm{p}(t)^2 + Y_\mathrm{p}(t)^2}\,, \tag{3}$$

The CW amplitude variations thus obtained are shown in Fig. 2 for two CW series. We can see that both CW series show very similar behavior of the CW amplitude, with some differences near the ends of the interval. In both CW series, three deep minima of the amplitude below 0.05 mas around 1850, 1925 and 2005 are unambiguously detected.

Evaluation of the CW phase is a more complicated task. Two methods of investigation of the CW phase variations were examined. The first method was developed by Malkin (2007) for Free Core Nutation modelling. The computations are made in two steps. In the first one the wavelet analysis is applied to both CW series to get the period variations. To perform the wavelet transform (WT) we used the program WWZ developed by the American Association of Variable Star Observers[1]. Theoretical background of this method can be found in Foster (1996). Since, as discussed above, we cannot separate by a mathematical tool the phase variations from the period variations, we consider the WT output as apparent period variations $P(t)$. Then we can compute the phase variations $\Phi(t)$ as

$$\Phi(t) = \int_{t_0}^{t} \frac{2\pi}{P(t)}\,dt + \Phi_0\,, \tag{4}$$

here Φ_0 is the parameter to be adjusted.

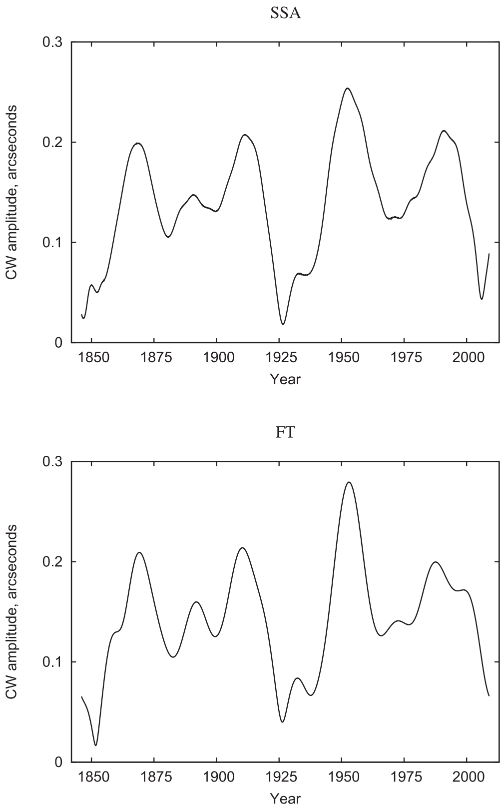


Fig. 2. The CW amplitude computed for SSA-filtered and FT-filtered CW time series. Unit: mas. One can see similar behavior of the CW amplitude obtained for both series, with some differences near the ends of the interval. However, three deep minima below 0.05 mas around 1850, 1925 and 2005 coincide in both cases.

The second method we used to evaluate the phase variations is the Hilbert transform (HT). For this work we used the function `hilbert` from the MATLAB Signal Processing Toolbox.

Thus we computed the CW phase variations for two methods of the PM series filtering and two methods of the CW phase evaluation. The results of the computation of the CW phase variations after removing the linear trend corresponding to P_0 are shown in Fig. 3. One can see similar behavior of the CW phase obtained in all four variants, with some differences near the ends of the interval. However, substantial phase jumps in the 1850s and 2000s are clearly visible in all the cases, and their epochs are contemporary with the minima of the CW amplitude as shown in Fig. 2. So, we can conclude that the well-known event in the 1920s of the simultaneous deep minimum of the CW amplitude and the large phase jump may be not unique.

4. Conclusion

In this paper, we have investigated the whole 163-year PM series available from the IERS with the main goal to

---

[1] http://www.aavso.org/.

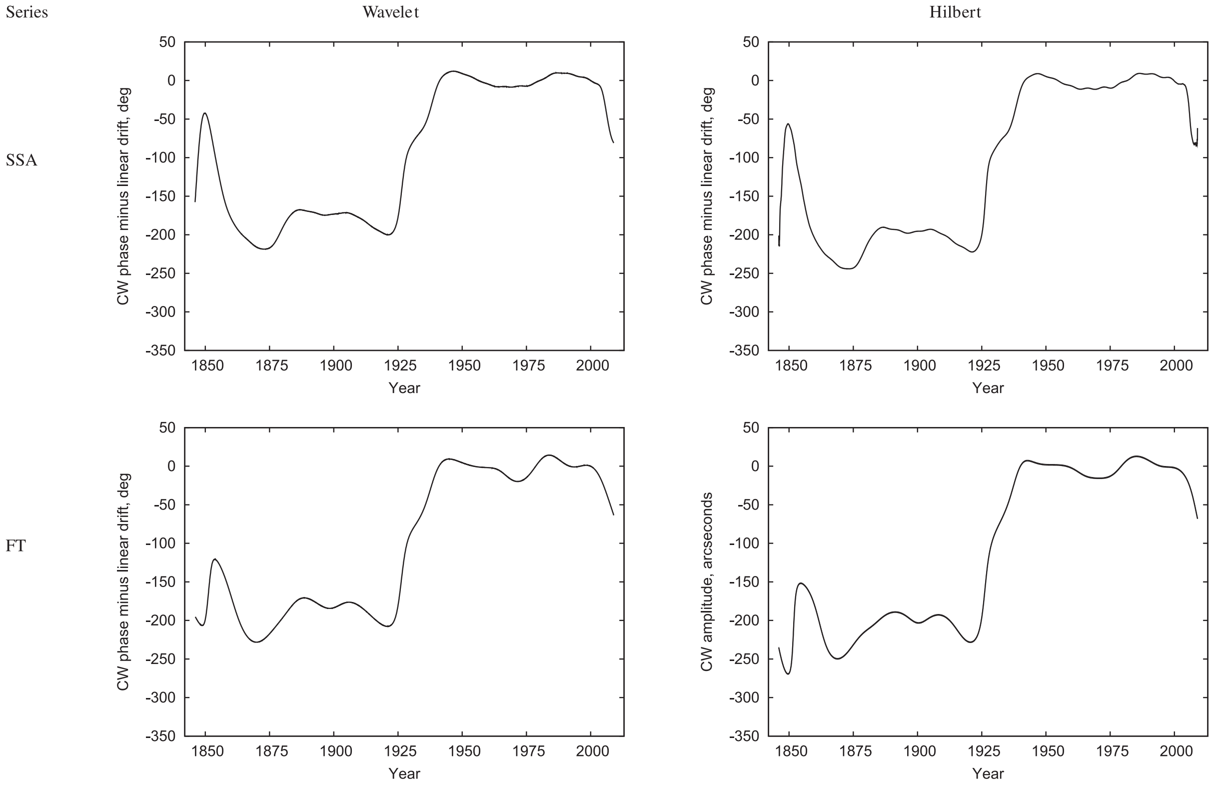


Fig. 3. The CW phase variations computed for SSA-filtered and FT-filtered CW series using WT and GT (see Section 3 for details). Unit: degrees. One can see similar behavior of the CW phase obtained in all four variants, with some differences near the ends of the interval. Three large phase jumps in 1850s, 1920s and 2000s are clearly visible in all the cases.

reveal and evaluate the major CW phase jumps. To improve the reliability of the results we used several analysis methods. To extract the CW signal from this series SSA-based and FT-based digital filters were applied. The two CW series thus obtained were used to investigate the CW amplitude and phase variations. While computation of the CW amplitude is straightforward, computation of the CW phase is not such an unambiguous procedure. Two methods, WT and HT, have been applied to evaluate the CW phase variations.

All the methods used gave very similar results, with some differences at the ends of the interval. These discrepancies can be explained by different edge effects of the methods used, but they can hardly discredit the final conclusion that can be made from this study about existence of two epochs of deep CW amplitude decrease around 1850 and 2005, which are also accompanied by a large phase jump, like the well-known event in the 1920s. Thus, the latter seems to be not unique anymore.

Unfortunately, both periods of the phase disturbances found in this paper are located at the edges of the interval covered by the IERS EOP series. As for the end of the interval, the next decade will allow us to quantify the phase jump in the beginning of the 21st century more accurately. On the other hand, a supplement study seems to be extremely important to try improve our knowledge of the PM in the 19th century, including an extension of the PM series in the past. As investigated in detail by Sekiguchi (1975), there are several latitude series obtained in the first half of 19th century, which can be used to extend the IERS C01 PM series back to the 1830s. However, most of the observations are of rather poor quality to be used directly in the computation of an extended PM series. Clearly, this material is worth revisiting and reprocessing using HIPPARCOS and later GAIA star positions and proper motions. An attentive and critical look into processing of the historical observations also could improve our knowledge of the latitude variations in 19th, and maybe even 18th, century.

Acknowledgments. This research has made use of the IERS PM series available at `http://www.iers.org`.

References

Chandler, S. C., On the variation of the latitude, I, *Astron. J.*, **11**, 59–61, 1891a.

Chandler, S. C., On the variation of the latitude, II, *Astron. J.*, **11**, 65–70, 1891b.

Fedorov, E. P. and Ya. S. Yatskiv, The cause of the apparent “bifurcation” of the free nutation period, *Soviet Astron.*, **8**, 608–611, 1965.

Foster, G., Wavelets for period analysis of unevenly sampled time series, *Astron. J.*, **112**, 1709–1729, 1996.

Gibert, D. and J.-L. Le Mouël, Inversion of polar motion data: Chandler wobble, phase jumps, and geomagnetic jerks, *J. Geophys. Res.*, **113**, B10405, 2008.

Guinot, B., The Chandlerian Wobble from 1900 to 1970, *Astron. Astrophys.*, **19**, 207–214, 1972.

Guo, J. Y., H. Greiner-Mai, L. Ballani, H. Jochmann, and C. K. Shum, On the double-peak spectrum of the Chandler wobble, *J. Geod.*, **78**, 654–659, 2005.

Lambeck, K., *The Earth’s Variable Rotation: Geophysical causes and consequences*, Cambridge Univ. Press, 1980.

Malkin, Z. M., Empiric models of the Earth’s free core nutation, *Sol. Syst. Res.*, **41**, 492–497, 2007.

Miller, N., On variations of the amplitude and phase of the Chandler wobble, *Izvestiya Vysshikh Uchebnykh Zavedeniy: Geodeziya i Aerofotos'emka*, No. 5, 48, 2008 (in Russian).

Munk, W. H. and G. J. F. MacDonald, *The Rotation of the Earth*, Cambridge Univ. Press, 1960.

Orlov, A., On triaxiality of the Earth, *Doklady AN SSSR*, **43**, 343–345, 1944 (in Russian).

Schuh, H., S. Nagel, and T. Seitz, Linear drift and periodic variations observed in long time series in polar motion, *J. Geod.*, **74**, 701, 2001.

Sekiguchi, N., On the latitude variations of the interval between 1830 and 1860, *J. Geod. Soc. Jpn.*, **21**, 131–141, 1975.

Sekiguchi, N., An interpretation of the multiple-peak spectra of the polar wobble of the Earth, *Publ. Astron. Soc. Jpn.*, **28**, 277, 1976.

Shirai, T., T. Fukushima, and Z. Malkin, Detection of phase disturbances of free core nutation of the Earth and their concurrence with geomagnetic jerks, *Earth Planets Space*, **57**, 151, 2005.

Vondrák, J., Is Chandler frequency constant, in *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics, Proc. IAU Symp. 128*, edited by A. K. Babcock and G. A. Willis, 359, 1988.

Vorotkov, M. V., V. L. Gorshkov, N. O. Miller, and E. Ya. Prudnikova, The investigation of the main components in the polar motion of the Earth, *Izvestiya GAO v Pulkove*, No. 216, 406–414, 2002 (in Russian).

Z. Malkin (e-mail: malkin@gao.spb.ru) and N. Miller