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Linear drift and periodic variations observed in long time series of polar motion

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Abstract. Two long time series were analysed: the C01 series of the International Earth Rotation Service and the pole series obtained by re-analysis of the classical astronomical observations using the HIPPARCOS reference frame. The linear drift of the pole was determined to be 3.31 ± 0.05 milliarcseconds/year towards 76.1 ± 0.80° west longitude. For the least-squares fit the a priori correlations between simultaneous pole coordinates x_p, y_p were taken into account, and the weighting function was calculated by estimating empirical variance components. The decadal variations of the pole path were investigated by Fourier and wavelet analysis. Using sliding windows, the periods and amplitudes of the Chandler wobble and annual wobble were determined. Typical periods in the variable Chandler wobble and annual wobble parameters were obtained from wavelet analyses.

Key words: Polar motion – Chandler wobble – Wavelet analysis

1 Introduction

Polar motion research still has a lot of unanswered questions:

Is there a long-term drift of the pole with respect to the Earth's surface?
If so, what are the main causes for this drift, which is often called 'secular polar motion'?
What are the causes of the observed decadal variations of polar motion?
Are the decadal variations stable or irregular?
Why is the amplitude of the Chandler wobble (CW) not steadily decreasing with time due to damping, and what are its excitation mechanisms?
What are the reasons for the apparent rapid variations of the CW period, also expressed as phase jumps and/or the strong CW amplitude variations, which have been reported by many from analysis of polar motion time series?

The reasons for the investigation presented in the present paper are as follows.

(1) New precise and consistent time series of polar motion exist, as will be described in the next paragraph.
(2) The wavelet analysis is a relatively new and useful technique to detect quasi-periodic, partly irregular variations in time series.
(3) Powerful computers are available which allow big matrices to be inverted in a short time. Thus, the stochastical model of the analyses can be extended and completed, as will be shown.

Starting from these prerequisites and using the tools mentioned above, an analysis was carried out to determine the linear drift and decadal variations of the pole and to investigate the CW and the annual wobble (AW). Wavelet transformation was used, which has been proven a powerful tool for investigating the time-variable Earth rotation (see e.g. Chao and Naito 1995; Gibert et al. 1998 and references therein). The goal of this investigation is to fully describe what can be seen in the polar motion data and to reveal previously unstudied effects. Further interpretations of the results might help to answer the questions given above.

2 Long time series of polar motion

Several time series of polar motion were initially analysed with respect to a linear drift. The linear model was then combined with periodical models of CW and AW. The decadal variations were investigated by Fourier analysis and wavelet analysis. Finally, the CW and AW parameters were repeatedly determined by a sliding window analysis, and their variability was analysed by wavelet transformation.

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The following long time series of polar motion were analysed.

(1a) The C01 series (1861.0–1997.0) published by the International Earth Rotation Service (IERS), here referred to as IERS C01 (1861.0–1997.0).
(1b) As regular astronomical observations by the International Latitude Service (ILS) started in 1899, we also looked at a truncated version of the above for the time interval from 1899.7 to 1992.0. This series will be called IERS C01 (1899.7–1992.0).
(2a) The pole series OA97 (1899.7–1992.0) obtained by re-analysis of optical astrometry observations referred to the HIPPARCOS catalogue as described by Vondrák (1999a). This series, based on 4.3 million observations, will be used for the determination of the linear drift, for the sliding window analyses and the wavelet analyses.
(2b) We also used a new time series recently received from Vondrák (Vondrák and Ron 2000) called OA99 (1899.7–1992.0), based on 4.5 million observations. This is more observations than in the OA97 series, although those from the Ukiah station since 1960 were neglected by Vondrák and Ron (2000) because of probable local or regional movements of that station. The OA99 series also refers to a slightly different reference frame due to proper motion corrections.

3 Linear drift and decadal variations of polar motion

3.1 Model

Our numerical model contains a purely linear part for 'secular polar motion' (offset and drift parameters a, b, c, d) and two periodical elliptical motions representing CW (parameters R_{1a}, R_{1b}, ω_1, φ_{1a}, φ_{1b}) and AW (parameters R_{2a}, R_{2b}, ω_2, φ_{2a}, φ_{2b}):

$$x_p = a \cdot t + b + R_{1a} \cos(\varphi_{1a} + \omega_1 t) + R_{2a} \cos(\varphi_{2a} + \omega_2 t) \quad (1)$$

$$y_p = c \cdot t + d + R_{1b} \sin(\varphi_{1b} + \omega_1 t) + R_{2b} \sin(\varphi_{2b} + \omega_2 t) \quad (2)$$

The semi-major and semi-minor axes of an elliptical motion correspond to the amplitude of a circular motion. If an elliptical motion of the pole for a specific frequency is detected this could allow this variation to be referred to the geographical distribution of particular geophysical fluids. All parameters were estimated simultaneously by a least-squares (LS) fit as described in the following sections.

3.2 Choice of weighting function

One important issue in LS parameter estimation is the right choice of the weight matrix **P**, i.e. the determination of an appropriate weighting function. Without considering the influence of the geometry on the results of the LS fit, the weights p_i were chosen according to three different weighting functions in our study:

(1) $p_i = 1$, which means equal weights. This simple method was used in most previous analyses [see the comprehensive tables given in McCarthy and Luzum (1996), Gross and Vondrák (1999) and Korsun and Yatskiv (1999)]. However, this approach does not take into account the fact that the precision of the measurements has increased considerably over the century.
(2) $p_i = \text{const}/\sigma_i^2$, with σ_i^2 being the variances of the 'observed' pole coordinates as given in the time series. When using this weighting function, which is usually recommended in textbooks on LS analysis, care has to be taken that a small number of observations do not influence and perhaps bias the results, whereas the other observations – although formally entered into the LS fit – are almost neglected (e.g. a difference in σ_i by a factor of 10 will cause differences of the weights by a factor of 100).
(3) $p_i = \text{const}/(\sigma_i^2 + \sigma_0^2)$, with σ_0^2 being a constant. This approach allows us to take into account the different precisions of the data but not as much as the formal errors indicate. A reasonable value for σ_0^2 can be obtained by a χ^2 test when comparing the (a posteriori) variance with the a priori variance of the observables. This procedure is called estimation of empirical variance components.

Figure 1a shows the three weighting functions for series OA97 depending on the a priori formal errors σ_i. The constant σ_0^2 was determined by a χ^2 test and set to 0.054 arcseconds^2.

3.3 A priori correlations between simultaneous pole coordinates x_p, y_p

In both time series OA97 and OA99 calculated by Vondrák (1999a), and by Vondrák and Ron (2000), correlation coefficients are given between simultaneous pole coordinates $x_p(t_i)$, $y_p(t_i)$ (Fig. 1b). They are usually between 0.2 and 0.5; some of them reach 0.9 or more. It is interesting to note that with the increasing precision and intensity of astronomical measurements since late 1950s, the correlations between x_p and y_p have decreased and seldom exceed ± 0.4. The correlations also depend on the geometry of the network, i.e. the geographic distribution of the observations. Two solutions were carried out, first the 'uncorrelated' (standard) solution neglecting the correlations, and second a solution in which the given correlations between the observables were considered in the LS fit ('correlated approach'). In the latter approach the block-diagonal variance–covariance matrix has to be calculated. The inversion of this matrix requires more central processing unit (CPU) time than that of a diagonal matrix, but poses little problem.

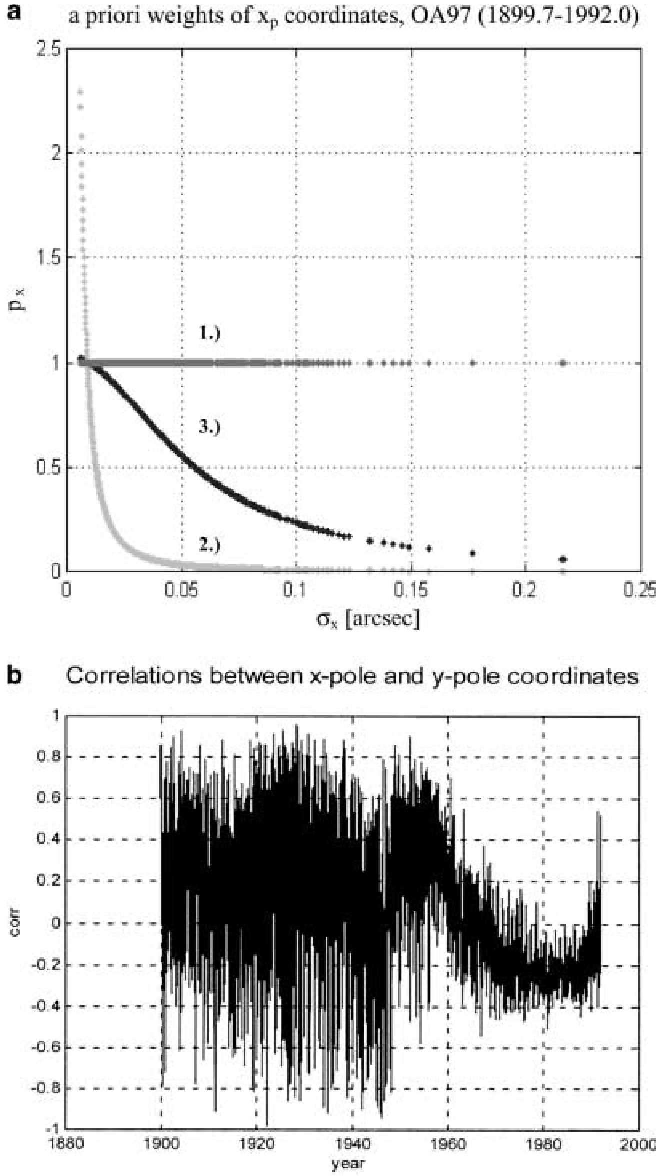

Fig. 1. **a** Three weighting functions for series OA97 (1899.7–1992.0) depending on the a priori formal errors σ_i of the x_p coordinates. The constant σ_0^2 was set to 0.054 arcseconds^2. **b** Correlation coefficients between simultaneous pole coordinates $x_p(t_i)$, $y_p(t_i)$

3.4 Determination of the linear drift of polar motion

The results of the various LS fits are summarized in Table 1. It can be seen that the choice of appropriate weights is essential; both extreme cases ($p_i = 1$, $p_i = \mathrm{const}/\sigma_i^2$) seem to be unreasonable. In particular, with approach (2) the results are biased very much towards the more precise observations from 1960 to 1980, although these data cover only a relatively short time span.

The correlated approach, with a weighting function estimated by the empirical variance component method [approach (3)], is considered as the most satisfactory. Thus, we obtained from the pole series OA97 (1899.7–1992.0) as presently the most plausible result for the linear drift of the pole in the 20th century a drift of 3.31 ± 0.05 milliarcseconds/year in the direction of 76.1 ± 0.80° west longitude. These results are discussed in more detail by Schuh et al. (2000). The LS fits also included the CW and AW parameters according to Eqs. (1) and (2). For series OA97 (1899.7–1992.0) and approach (3) we obtained the following as best-fit mean values for the 20th century:

CW period: 1.17428 ± 0.00009 years

CW amplitude:

semi-major axis $R_{1a} = 0.1217 \pm 0.0017$ arcseconds

semi-minor axis $R_{1b} = 0.1037 \pm 0.0017$ arcseconds

AW period: 1.00055 ± 0.00008 years

AW amplitude:

semi-major axis $R_{2a} = 0.0992 \pm 0.0017$ arcseconds

semi-minor axis $R_{2b} = 0.0836 \pm 0.0017$ arcseconds.

Table 1 shows that the pole drift evident in series OA99 (1899.7–1992.0) is substantially less than that evident in series OA97 (1899.7–1992.0). This could be due to the fact that for the computation of OA99 the observations from the Ukiah station were not considered by Vondrák (2000), as already mentioned in Sect. 2. Concerning the geophysical causes of linear polar motion, it is most probably caused by post-glacial rebound as described by e.g. Milne and Mitrovica (1998), where further references to this topic are given.

3.5 Decadal periods

The long time series were subjected to a standard Fourier analysis. For the re-analysis series OA97 (1899.7–1992.0) the peaks corresponding to the main decadal periods were seen at prograde 77, 37, 26, 17 and 9 years and at retrograde 86, 28, 19, 15 and 7 years (Fig. 2). For most of these highly elliptic motions the prograde components are larger than the corresponding retrograde ones with approximately the same periods. An exception is the so-called Markowitz wobble around 30 years where the retrograde part is dominant. This can also be seen from the Morlet wavelet spectra for prograde and retrograde motions with periods shorter than 40 years (Fig. 3): the retrograde Markowitz wobble at 30 years is the only stable decadal variation whereas the prograde and retrograde motions with periods below 20 years are rather irregular. Without showing the detailed results of similar analyses of the C01 series, it should be mentioned that the IERS C01 (1861.0–1997.0) series shows even more clearly the long periods around 80 and 30 years, in spite of the poor precision of the pole coordinates measured in the 19th century. The likely causes for decadal variations of polar motion are global mass redistributions in the atmosphere, the hydrosphere and the cryosphere (see e.g. Lambeck 1980; Eubanks 1993; Jochmann 1993; Celaya et al. 1999; Jochmann 1999). Other possible causes are geomagnetic and topographic core–mantle couplings (Greiner-Mai 1993; Hide 1995) or inner-core rotation (Greiner-Mai et al. 1999).

Table 1. Linear drift of the pole determined from different data series for the three weighting functions described in Sect. 3.2; results which are considered to be the most plausible ones at present are in *italic* (see Schuh et al. 2000)

	$p_i = 1.0$		$p_i = \frac{const}{\sigma_i^2}$		$p_i = \frac{const}{\sigma_i^2+\sigma_0^2}$	
	sec p.m. (mas/year)	dir [deg]	sec p.m. (mas/year)	dir [deg]	sec p.m. (mas/year)	dir [deg]
IERS C01 (1899–1992)	4.38 ± 0.08	77.43 ± 1.06	6.02 ± 0.13	85.16 ± 1.25	4.43 ± 0.08	78.15 ± 1.00
IERS C01 (1861–1997)	3.58 ± 0.05	75.53 ± 0.85	4.49 ± 0.10	82.29 ± 1.24	4.00 ± 0.06	77.36 ± 0.77
OA97 (1899–1992) uncorrelated	3.38 ± 0.05	78.69 ± 0.80	3.80 ± 0.04	82.73 ± 0.65	3.40 ± 0.05	79.27 ± 0.76
OA97 (1899–1992) correlated	3.27 ± 0.05	75.11 ± 0.84	3.78 ± 0.04	80.59 ± 0.65	*3.31 ± 0.05*	*76.08 ± 0.80*
OA99 (1899–1992) uncorrelated	2.85 ± 0.05	73.55 ± 0.93	2.49 ± 0.04	71.54 ± 0.95	2.81 ± 0.04	73.46 ± 0.90
OA99 (1899–1992) correlated	2.85 ± 0.04	75.52 ± 0.90	2.48 ± 0.04	73.04 ± 0.96	2.81 ± 0.04	75.45 ± 0.90

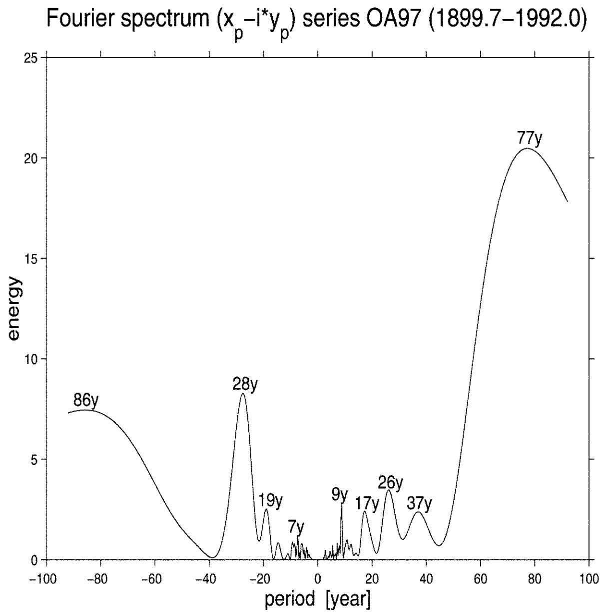

Fig. 2. Fourier spectrum of OA97 (1899.7–1992.0) for the decadal periods. The spectrum for periods between 0 and 2 years is not plotted here

4 Annual wobble (AW) and Chandler wobble (CW)

4.1 Fourier analysis and wavelet analysis

Concentrating on the AW and CW, the Fourier analysis of series OA97 (1899.7–1992.0) reveals three nearby peaks indicating a prograde CW (429, 436 and 450 days) and a large prograde annual variation (Schuh et al. 2000). A small retrograde annual variation can also be seen, i.e. the AW is a significantly elliptic motion whereas the CW is a circular motion. In Fig. 4 the corresponding wavelet spectra for the annual variations are given. Clear maxima of the weak retrograde AW occurred around 1908, 1940 and 1955. For a discussion of the retrograde AW, see also King and Agnew (1991).

4.2 Sliding window analysis of CW and AW parameters

The variations of CW and AW were investigated in the time domain by a sliding window analysis. The window size was set to 13.76 years, which corresponds to twice the beating period of the AW and a mean CW. In each window the CW and AW parameters were determined by an LS fit. As the model [Eqs. (1), (2)] is non-linear with respect to the frequencies ω_1, ω_2 and phases φ_{1a}, φ_{1b}, φ_{2a}, φ_{2b} of the CW and of the AW, the equations of observation had to be linearized first. Then, starting from good a priori values, the solutions were obtained by iterations. As the quality of the pole data usually increased with time, the window was not moved from the beginning to the end of the time series but rather in a backward direction, i.e. starting with the more precise recent observations and then moving back to the past in very short time steps. When a sufficient convergence was obtained, the iterations were stopped. Although in most of the 13.76 years' time windows the solution converged rather fast, small differences between the IERS C01 (1899.7–1992.0) and the OA97 (1899.7–1992.0) series can be seen when setting the convergence criterion rather high (i.e. where to stop the iterations). Figure 5 shows the number of iterations needed in each of the 13.76 years' windows for the two data sets. In many windows, significantly less iterations had to be carried out for the OA97 (1899.7–1992.0) series compared to the IERS C01 (1899.7–1992.0) series to achieve convergence. This is probably due to the higher consistency and homogeneity of the re-analysis series OA97 (1899.7–1992.0). It can also be seen that in the 1940s more iterations were generally needed because of the lower accuracy of the pole data during that time.

4.3 Variations of CW and AW parameters

By solving for all parameters (amplitudes, phases and periods) of the CW and of the AW in the LS fit of the sliding window analyses, the model is more 'general'

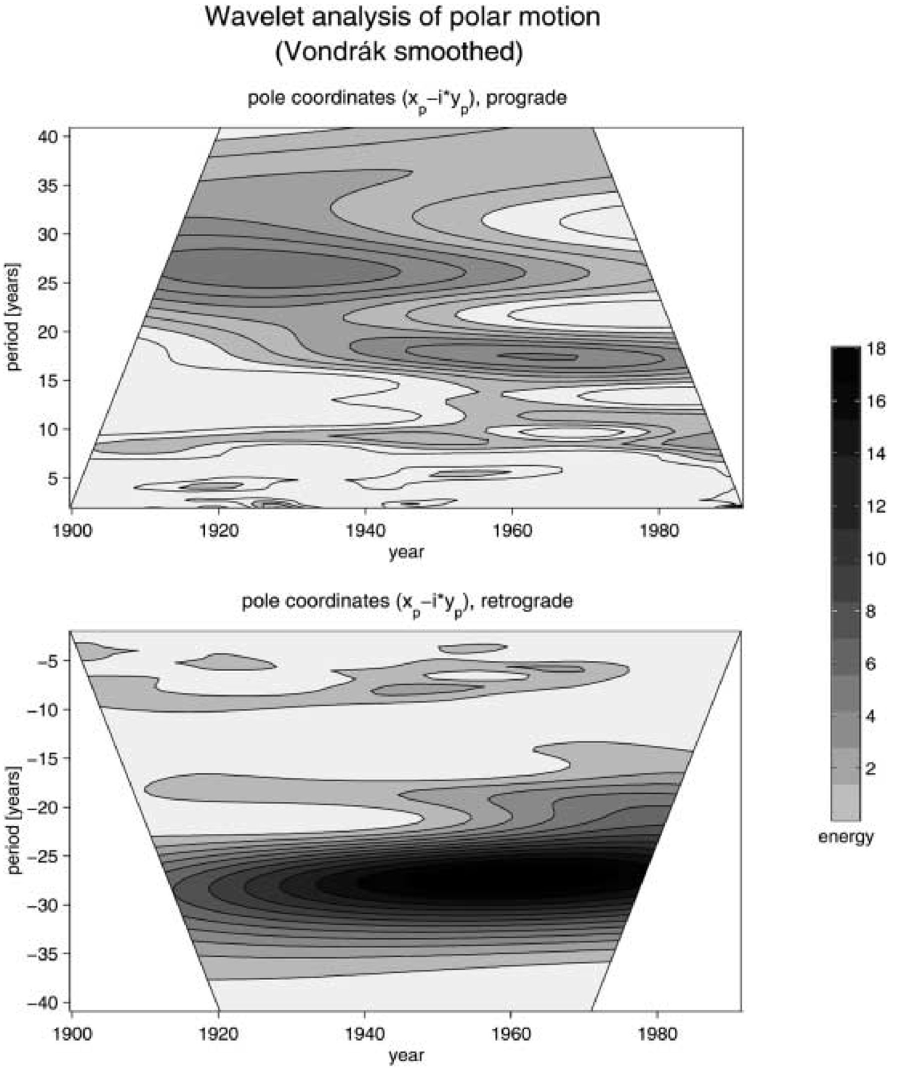

Fig. 3. Morlet wavelet spectra of OA97 (1899.7–1992.0) for decadal periods

than that in former similar analyses (see e.g. Chao 1983). This fact is described in more detail by Schuh et al. (2000). We used the same a priori weights as those empirically determined by the method described in Sect. 3.2 and entered the a priori correlations (see Sect. 3.3) into the fit. Figures 6a and b show the variations of the Chandler periods and amplitudes (semi-major and semi-minor axes) obtained for OA97 (1899.7–1992.0). The parameters of the CW change rapidly: e.g. the CW amplitude (semi-major and semi-minor axes) varies by a factor of 4 and the CW period varies between 1.13 and 1.20 years (413 and 439 days). During the time of the minimum CW amplitude (around 1930) the CW period was extremely short. The average standard deviations in the individual time windows are as follows:

for the CW and AW periods: ± 0.0007 years

for the CW and AW amplitudes (semi-major and semi-minor axes): ± 0.0023 arcseconds.

All variations of the CW parameters (and also of the AW parameters shown later) are significant at the 99% level when applying a *t* test. It can be noted that the averages of the CW semi-major and semi-minor axes taken from Fig. 6b are considerably larger than the mean values estimated in Sect. 3.4 by an LS fit of the whole time series. There, due to the rapid phase variations of the CW during the last century the CW amplitudes seem to be underestimated.

The apparent variability of the CW period is clearly revealed by analysing the data series in relatively short time windows of about 14 years. These results can be interpreted as either a second wobble nearby the CW and what we see is a beat of the two (or more) oscillations [see e.g. Chao (1983) and references therein] or – and this seems to be more likely – an excitation of the CW by a quasi-periodic force acting irregularly on the Earth. For further discussions see also Celaya et al. (1999), Vondrák (1999a, b) and Aoyama and Naito (2000).

Figures 6a and b show also the variations of the periods and amplitudes (semi-major and semi-minor axes) of the AW whose variability is smaller but faster than that of the CW parameters. While the CW is clearly circular, the AW is an elliptical motion with the semi-major axis always being 10–20% longer than the semi-minor axis.

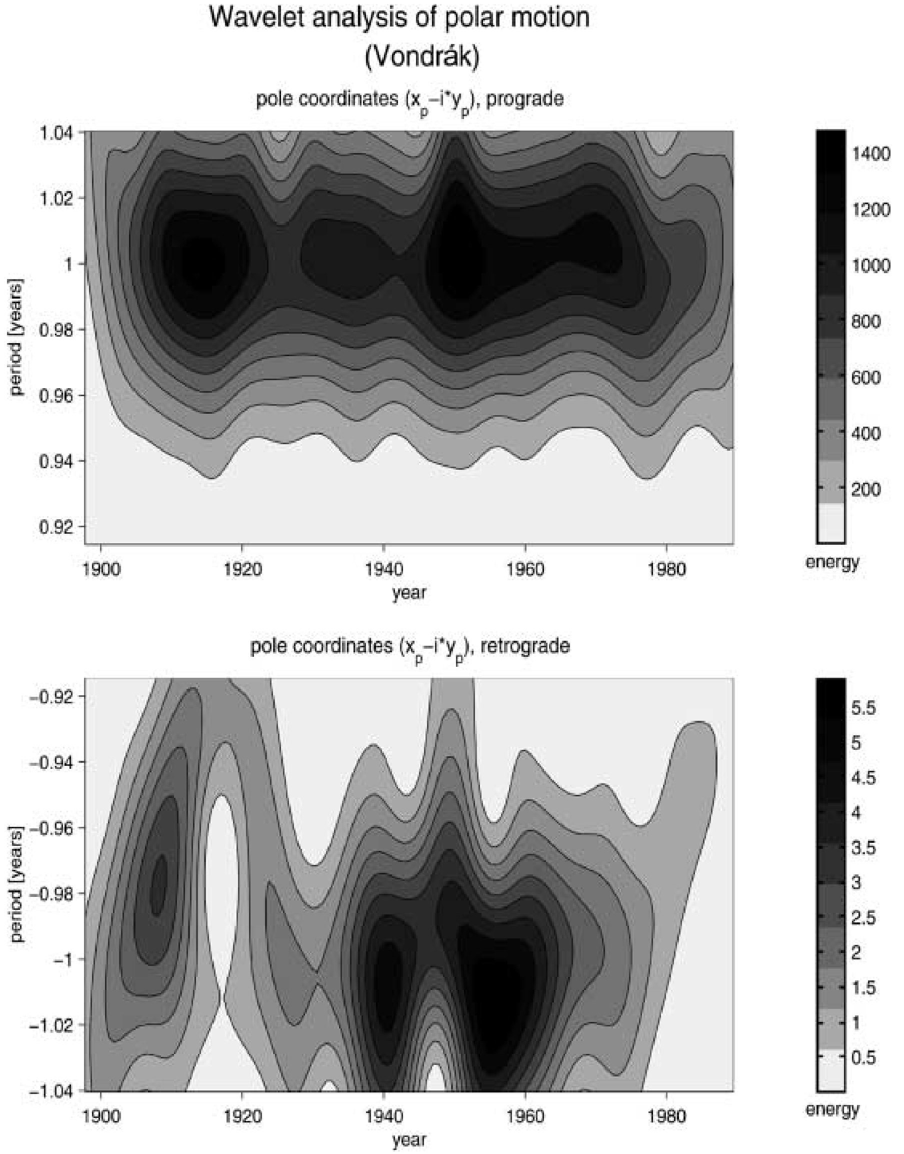

Fig. 4. Morlet wavelet spectra of OA97 (1899.7–1992.0) for AW

We also submitted the long IERS C01 (1861.0–1997.0) time series to a sliding window analysis. The results for the CW and AW amplitudes and periods are plotted in Fig. 7a and b. Despite its poorer quality in the 19th century, the series allows us to determine the CW and AW parameters from 1861 onwards (again sliding the window backwards in time). They vary in the same range as the parameters determined in the 20th century and again – when considering the standard deviations of the CW and AW parameters – their variations are significant at the 99% level when a *t* test is applied.

4.4 Wavelet analysis of CW parameters

The CW parameters estimated from the re-analysis series OA97 (1899.7–1992.0) were analysed by wavelet transform. Figures 8a and b show the wavelet spectra of the periods and amplitudes (semi-major and semi-minor axes) of the CW.

The variation of the CW period has a dominant period of approx. 50 years (Fig. 8a), smaller variations are found around 28 years, decreasing since 1940, which can be seen when amplifying the wavelet plot for periods shorter than 35 years (not shown here). For the CW amplitude a main, very stable period of approx. 40 years can be seen (Fig. 8b) and – again after amplification of the part of the plot which corresponds to shorter decadal periods (not shown here) – a small variation at approx. 20 years in the first half of the 20th century. Both periodicities appear in the CW semi-major and semi-minor axes. In principle, the main periods (40–50 years) of the CW parameters, which can also be derived from the long IERS C01 (1861.0–1997.0) time series, could be explained by a beat of two oscillations with close periods.

4.5 Wavelet analysis of AW parameters

Finally, the AW parameters obtained for OA97 (1899.7–1992.0) were analysed by wavelet transform. Figures 9a

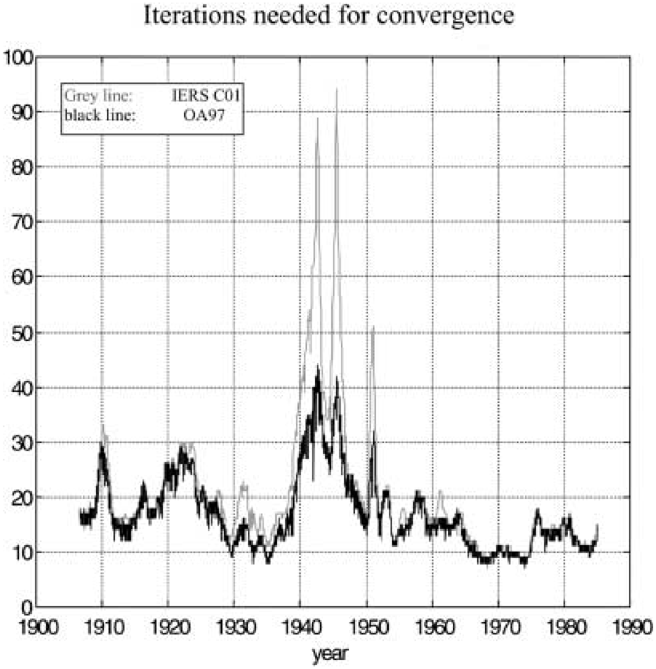

Fig. 5. Number of iterations needed to get a sufficient convergence in each of the windows of the sliding analysis

and b show the wavelet spectra of the periods and amplitudes (semi-major and semi-minor axes) of the AW. In the AW period the main periods are of 18 years (since 1940) and 5–6 years (1920–1960) (Fig. 9a). The main period of the AW amplitude (Fig. 9b) is approx. 50 years (in the AW semi-major axes). Irregular variations of the AW semi-major and semi-minor axes occurred with periods of 8–9 years (in the AW semi-major axes), approx. 18 years and 8–9 years (in the AW semi-minor axes). Interestingly, the variation at approx. 18 years appears only in the AW semi-minor axes with a maximum between 1930 and 1950 and later in the AW period (second half of the 20th century).

5 Conclusions

Two long time series of polar motion were analysed with respect to linear drift, decadal variations, CW and AW: the C01 series published by the IERS and the series obtained by re-analysis of the optical observations within the HIPPARCOS frame (Vondrák 1999a), Vondrák and Ron (2000). The weights used in the LS fit have to be chosen carefully; all results strongly depend on the weighting function. The empirical variance component estimation method was applied to determine an appropriate weighting function. A priori correlations between simultaneous pole coordinates $x_p(t_i)$, $y_p(t_i)$ (only available for the re-analysis series) were also taken into account in the LS fit. The most reliable result at present is a linear drift of polar motion in the 20th century of 3.31 ± 0.05 milliarcseconds/year in the direction of 76.1 ± 0.80° west longitude, obtained from the re-analysis series (OA97) (1899.7–1992.0) using the correlated approach. This linear drift is considerably smaller than that derived from the IERS C01 series. The new series OA99 (1899.7–1992.0) published recently by Vondrák and Ron (2000) yields an even slower linear drift, of only 2.81 ± 0.04 milliarcseconds/year. Fourier analysis of the pole series reveals a strong prograde (and smaller retrograde) motion of the pole with a period of about 80 years. Thus it is obvious that the linear drift of the pole in the 20th century (sometimes called ‘secular polar motion’) can only be derived from a time series covering at least 90–100 years. The only stable decadal

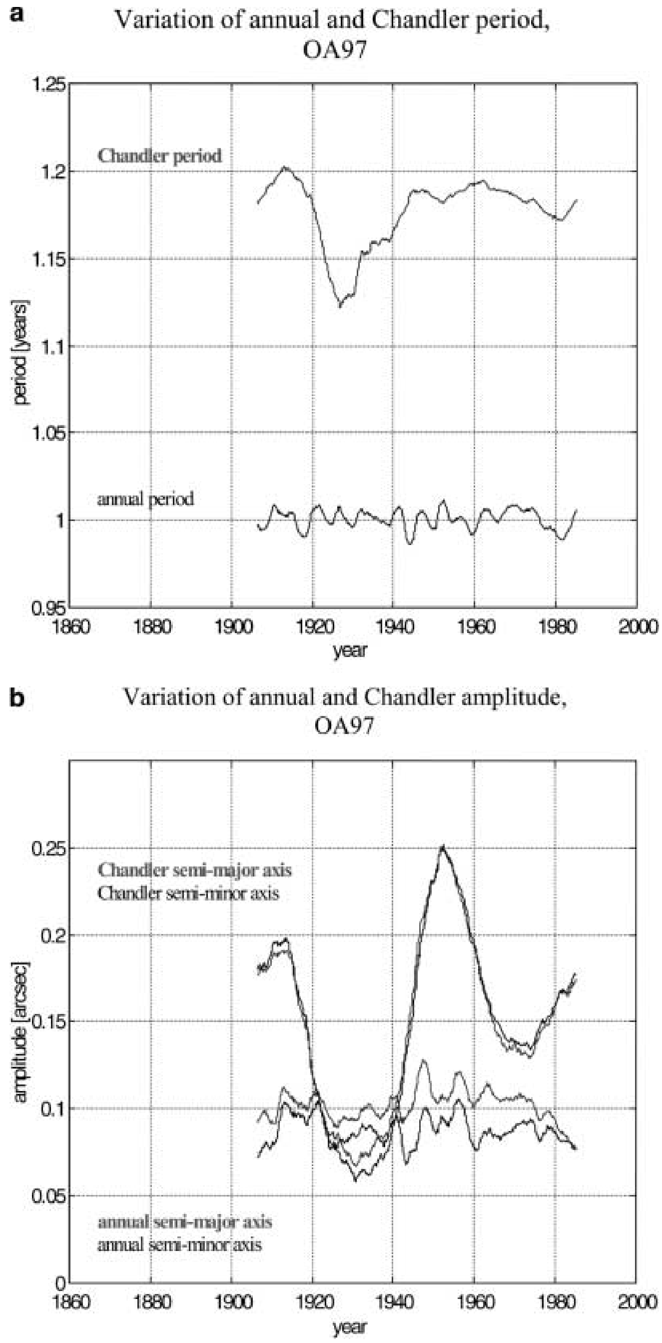

Fig. 6. **a** Apparent variation of CW and AW periods from re-analysis series OA97 (1899.7–1992.0). **b** Apparent variation of CW and AW amplitudes from re-analysis series OA97 (1899.7–1992.0)

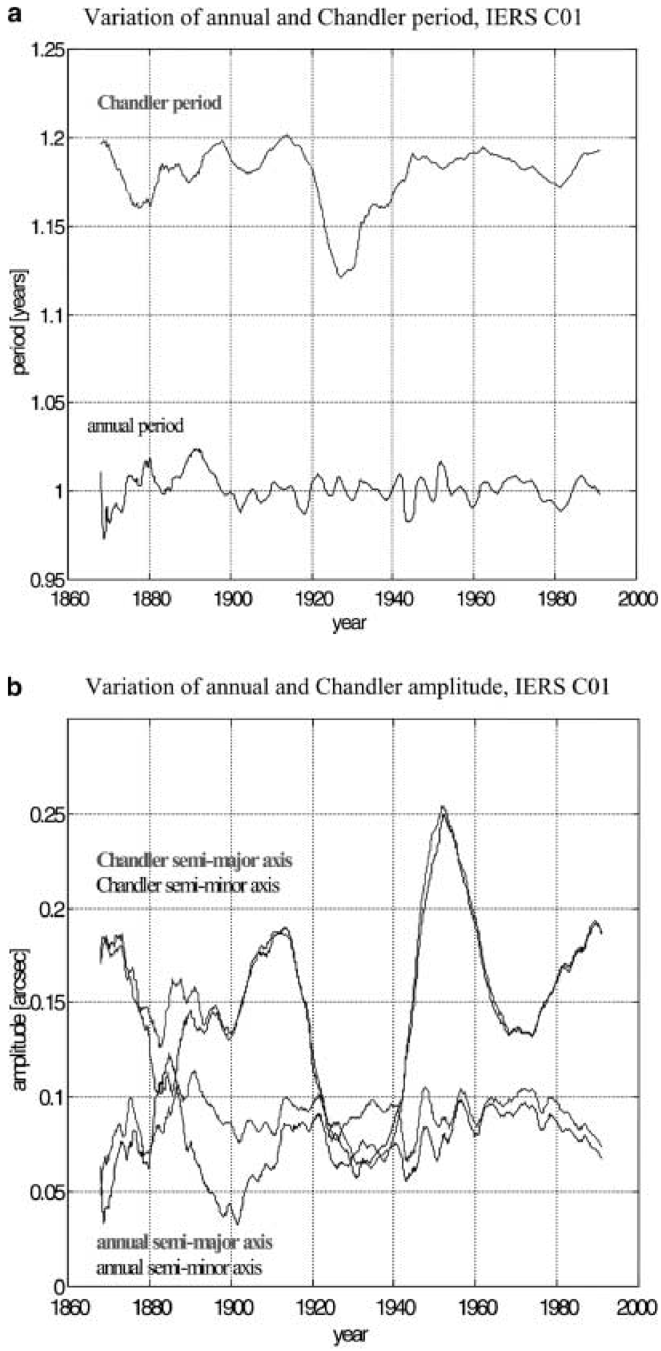

Fig. 7. a Apparent variation of CW and AW periods from series IERS C01 (1861.0–1997.0). **b** Apparent variation of CW and AW amplitudes from series IERS C01 (1861.0–1997.0)

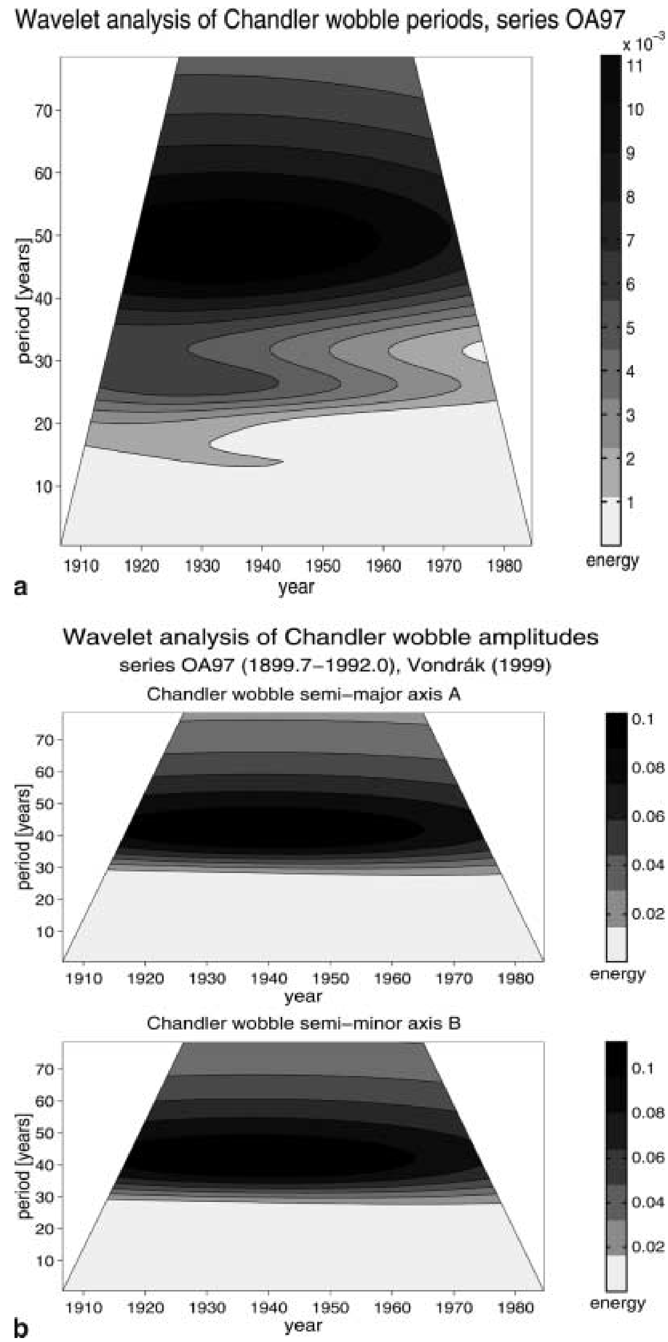

Fig. 8. a Morlet wavelet spectrum of CW periods which were determined in the OA97 (1899.7–1992.0) series. **b** Morlet wavelet spectra of CW amplitudes which were determined in the OA97 (1899.7–1992.0) series

variation of the pole is the retrograde motion around 30 years, the so-called Markowitz wobble of which the origin is still unclear (Celaya et al. 1999). All other 'decadal' variations which appear as peaks in the Fourier spectrum are rather unstable in period and amplitude, as shown by their wavelet spectra.

From a sliding window analysis it can be seen that the new time series OA97 obtained by re-analysis is more consistent than the IERS C01 series, probably due to the consistent and more comprehensive treatment of the astronomical observations by Vondrák (1999a), e.g. by considering plate motions of the observing sites. Both the CW and – to a lesser extent – the AW are rather unstable, as has already been found by many other authors (see e.g. Chao 1983; Gibert et al. 1998; Vondrák 1999a and references therein). The CW seems to be modulated with other nearby periodic variations or excited by irregular driving forces (see e.g. Aoyama and Naito in press). Obviously, a rapid variability of the CW parameters can hardly be detected if the time series is analysed in relatively long time windows, e.g. 31 years

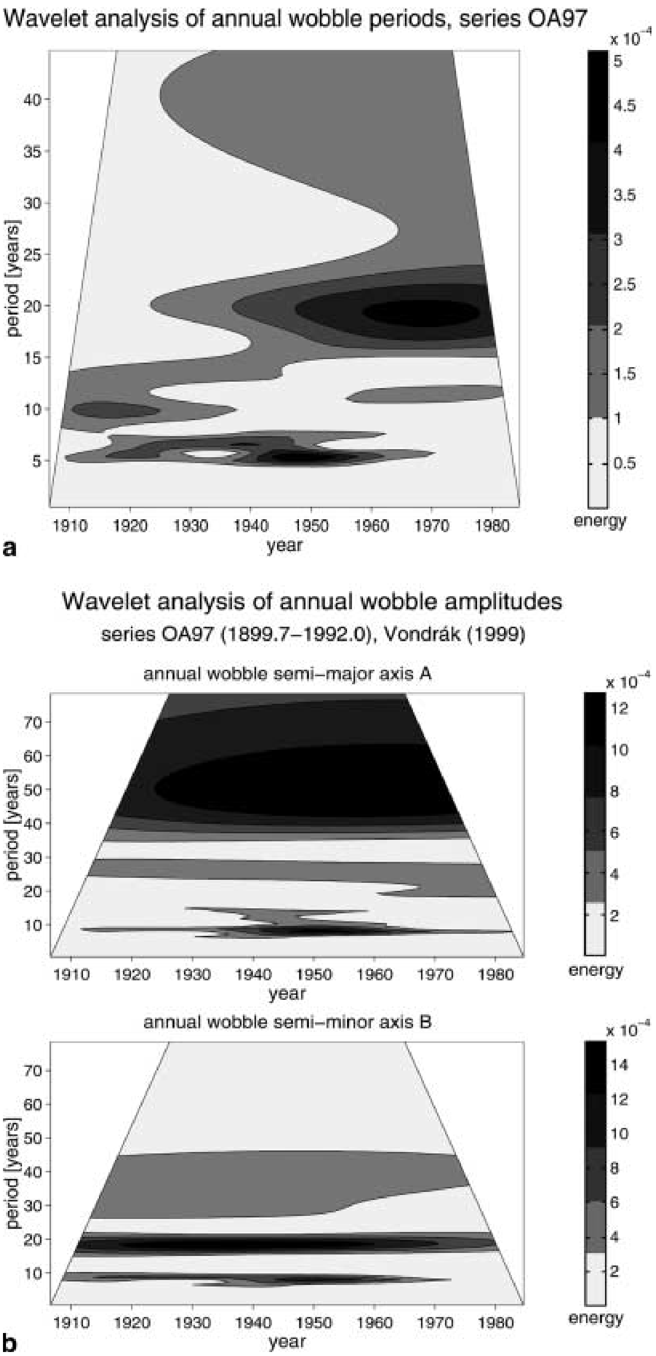

Fig. 9. **a** Morlet wavelet spectrum of AW periods which were determined in the OA97 (1899.7–1992.0) series. **b** Morlet wavelet spectra of AW amplitudes which were determined in the OA97 (1899.7–1992.0) series

(Vicente and Wilson 1997). Taking the mean values for the CW periods and amplitudes in the three time intervals 1900–1930, 1931–1961, 1962–1992 from Fig. 6a, we can see that these averaged results do not differ very much. Wavelet analyses of the CW and AW parameters allow the detection of time-variable quasi-periodic variations. The CW amplitudes and periods show strong variations with a period of 40–50 years. The wavelet analyses also reveal rapid, partly irregular variations of the AW amplitudes at approx. 50, approx. 18 (semi-minor axes only) and 8–9 years, and of the AW periods at approx. 18 and 5–6 years. The different periods in the two axes of the elliptical annual motion show that there are regionally different driving forces depending on the distribution of the continents and the oceans. This could be the key for referring the observed decadal variations of polar motion to possible atmospheric or oceanic causes, and the results presented here may form the basis for further investigations.

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References

Aoyama Y, Naito I (in press) Atmospheric variations excite the Chandler wobble, 1983–1998. J Geophys Res

Celaya MA, Wahr JM, Bryan FO (1999) Climate-driven polar motion. J Geophys Res 104(B6): 12 813–12 829

Chao BF (1983) Autoregressive harmonic analysis of the Earth's polar motion using homogeneous ILS data. J Geophys Res 88: 10 299–10 307

Chao BF, Naito I (1995) Wavelet analysis provides a new tool for studying Earth's rotation. EOS Trans Am Geophys Union 76: 161–165

Eubanks TM (1993) Variation in the orientation of the Earth, contributions of space geodesy to geodynamics: Earth dynamics. In: Smith DE, Turcotte DL (eds) AGU geodynamics series 24, pp 1–54. American Geophysical Union, Washington, D.C.

Gibert D, Holschneider M, Le Mouël J-L (1998) Wavelet analysis of the Chandler wobble. J Geophys Res 103: 27 069–27 089

Greiner-Mai H (1993) Decade variations of the Earth's rotation and geomagnetic core-mantle coupling. J Geomag Geoelectr 45: 1333–1345

Greiner-Mai H, Jochmann H, Barthelmes F (1999) Influence of possible inner-core motions on the polar motion and the gravity field. Phys Earth Planet Int 117: 81–93

Gross RS, Vondrák J (1999) Astrometric and space-geodetic observations of polar wander. Geophys Res Lett 26(14): 2085–2088

Jochmann H (1993) Earth rotation and global change. Adv Space Res 13(11): (11)271–(11)280

Jochmann H (1999) The influence of continental water storage on the annual wobble of polar motion, estimated by inverse solution. J Geodynam 27: 147–160

Hide R (1995) The topographique torque on a bounding surface of a rotating gravitating fluid and the excitation by core motions of decadal fluctuations in the Earth's rotation. Geophys Res Lett 22(8): 961–964

King NE, Agnew DC (1991) How large is the retrograde annual wobble? Geophys Res Lett 18: 1735–1738

Korsun AA, Yatskiv YS (1999) Comments on slow latitude variations and secular motion of the Earth's pole. In: Capitaine N (ed) Journées 1998, Systèmes de Référence Spatio-Temporels, Paris, September 1998. Obs de Paris, Paris UMR 8630/CNRS, pp 223–227

Lambeck K (1980) The Earth's variable rotation. Cambridge University Press, New York

McCarthy DD, Luzum BJ (1996) Path of the mean rotational pole from 1899 to 1994. Geophys J Int 125: 623–629

Milne GA, Mitrovica JX (1998) Postglacial sea-level change on a rotating Earth. Geophys J Int 133: 1–19

Schuh H, Richter B, Nagel S (2000) Analysis of long time series of polar motion. In: Dick S, McCarthy D, Luzum B (eds) Polar Motion: historical and scientific problems, IAU Colloquium 178

Cagliari, September 1999. Astronomical Society of the Pacific, San Francisco, 208, pp 321–331

Vicente RO, Wilson CR (1997) On the variability of the Chandler frequency. J Geophys Res 102(B9): 20 439–20 445

Vondrák J (1999a) Earth rotation parameters 1899.7–1992.0 after reanalysis within the HIPPARCOS frame. Surv Geophys 20: 169–195

Vondrák J (1999b) Secular and long-periodic polar motion as derived from combination of astrometric and space geodetic observations. In: Capitaine N (ed) Journeés 1998 Systèmes de Référence Spatio-Temporels, Paris, September 1998. Obs de Paris, Paris UMR 8630/CNRS, pp 195–201

Vondrák J, Ron C (2000) Survey of observational techniques and HIPPARCOS reanalysis. In: Dick S, McCarthy D, Luzum B (eds) Polar Motion: historical and scientific problems, IAU Colloquium 178 Cagliari, September 1999. Astronomical Society of the Pacific, San Francisco, 208, pp 239–250