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Polar motions with a half-Chandler period and less in their temporal variability

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Chandler and annual wobbles based on space-geodetic measurements

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Abstract. In this study, we examine the major components of polar motion, focusing on quantifying their temporal variability. In particular, by using the combined Earth orientation series SPACE99 computed by the Jet Propulsion Laboratory (JPL) from 1976 to 2000 at daily intervals, the Chandler and annual wobbles are separated by recursive band-pass filtering of the x_1- and x_2-components. Then, for the trigonometric, exponential, and elliptic forms of representation, the parameters including their uncertainties are computed at epochs using quarterly sampling. The characteristics and temporal evolution of the wobbles are presented, as well as a summary of estimates of different parameters for four epochs.

Key words: Polar motion, Chandler wobble, annual wobble, representation (trigonometric, exponential, elliptic), parameter, variability, uncertainty

1 Introduction

Variations in the Earth's rotation provide fundamental information about the geophysical processes that occur in all components of the Earth. Therefore, the study of the Earth's rotation is of great importance for understanding the dynamic interactions between the solid Earth, atmosphere, oceans and other geophysical fluids. In the rotating, terrestrial body-fixed reference frame, the variations of Earth rotation are measured by changes in length-of-day (LOD), and polar motion (PM).

The theoretical foundation of studying of PM was derived by Euler (1758), Lagrange (1788) and Poinsot (1834, 1851). Afterwards, intensive efforts at several observatories were aimed to prove its existence by resolving variations in latitude. Finally, in 1888, a real latitude variation was detected by Küstner at the Berlin Observatory. Moreover, in 1891/92, there was the discovery by Chandler that the motion of the pole consists of two superposed constituents. The first, of late referred to as Chandler wobble, has a period of about 427 days, while the second has an annual period. Within the scientific community, the problem of PM has raised considerable interest. After an effort covering 10 years, international activities in this field began in September 1899 with the establishment of the International Latitude Service (ILS) as the first permanent world-wide scientific cooperation to monitor the motion of the Earth's pole of rotation with respect to six observing sites based on continuous latitude observations. The ILS was reorganised in 1962 as the International Polar Motion Service (IPMS), and has provided valuable observations for PM over about 100 years. All ILS latitude observations have been reanalysed and combined to the PM solution within a consistent system for the period 1899.9-1979.0 by Yumi and Yokoyama (1980). Based on optical astrometry observations, a PM time series for the period 1899.7-1992.0 was obtained from a re-analysis within the Hipparcos frame by Vondrák et al. (1998). For more information on the PM time series available from mid-19th century to the present, see Höpfner (2000).

Based on optical astrometry and ILS data, a large number of polar motion studies have been made in order to derive the dominant terms of PM, including the secular drift of the Earth's pole, the Chandler and annual motions. Some pertinent examples should be noted: Wanach (1916) derived the mean parameters of the dominant motions from ILS data for the epoch 1900-1912. The radius and period variations of the Chandler motion was examined by Kimura (1917) who used the two time series of observations made at Greenwich and Pulkowa from 1825 until 1890 and the time series of the latitude variation investigations of Albrecht and Wanach. It should be noted that Kimura predicted a marked minimum in the Chandler radius to occur at around 1930. Assuming the Chandler period to be 1.2 years, Iijima (1965) separated the secular, Chandler and seasonal components from ILS data for the period 1900.0-1963.2 with a 0.1-year sampling. The results were then investigated with respect to annual changes. In particular, he found that the Chandler period varies from about 1.1 to 1.2 years and that the smaller period happens when the Chandler component has a smaller amplitude and vice versa. Based on the ILS data for 1900-1962, Proverbio et al. (1971) analysed the Chandler motion with time using Orlov's method, confirming a correlation between the amplitudes and periods. Using latitude variations observed at 20 stations (5 ILS and 15 independent stations) between 1900 to 1970 and 1900 to 1980, the properties of the Chandler wobble including amplitude, phase and ellipticity were derived by Guinot (1972, 1982). An analysis of the homogeneous ILS time series for the period 1899-1977 made by Wilson and Vicente (1980) was concerned with annual, Chandler and long-period motions of the Earth's pole.

Dickman (1981) also studied these terms using the homogeneous ILS time series from 1899.9-1979.0, with a focus on controversial PM features apparently possessed by the older ILS data. Okubo (1982) dealt with the question of whether the Chandler period varies over time. He found that a variability may be explained for an invariant period model. Chao (1983) applied the autoregressive harmonic analysis to the homogeneous 80-year-long ILS time series, again focusing on the dominant PM terms. Some of principal conclusions found in that work include how the Chandler wobble can be adequately modelled as a linear combination of four (coherent) harmonic components and that the annual wobble is relatively stationary both in amplitude and in phase. Based on BIH and ILS data, Lenhardt and Groten (1987) studied the character of the Chandler wobble. They concluded that the double peak structure in the ILS spectra does not reflect a two component wobble but could be attributed to a phase shift or other events. Using the longest astrometric PM time series that was available (from 1846 to 1988), Nastula et al. (1993) investigated amplitude variations in the Chandler and annual wobbles, including their prediction. For the Chandler, annual, semi-Chandler and semi-annual components of polar motion for the epoch 1976 to 1987, parameter average estimates including their uncertainties can be found in Höpfner (1995, 1996a). Vicente and Wilson (1997) estimated the Chandler frequency from a variety of PM time series derived from optical and space geodetic data spanning various intervals from 1846 through to the early 1990s. According to their results, its variation may not be significant. Earth rotation parameters obtained from the reanalysis in the Hipparcos frame for the epoch 1899.7 to 1992.0 by Vondrák et al. (1998) were studied with respect to longer-period polar motion, in particular the mean pole position, its drift and parameters of annual and Chandler wobbles, using a least-squares fit at running intervals of 8.5 years, the Chandler frequency to be 0.845 cycles per year; see Vondrák (1999). The same PM time series and the EOP (IERS) C01 time series computed by the International Earth Rotation Service (IERS) from 1861.0 to 1997.0 were analysed by Schuh et al. (2001). Their research considered the linear drift and decadal variations of the pole and the Chandler and annual wobbles. The amplitude, phase and period variations of both wobbles were analysed, using a least-squares fit in terms of an iterative procedure with a sliding time window of 13.76 years. From this analysis, it was seen that the PM reanalysis series is more consistent than the IERS series. For an overview of polar motion studies, see Dick et al. (2000).

Since the middle of the 1970s, the Earth Orientation Parameters (EOPs) have been measured by precise space-geodetic techniques such as VLBI (Very Long Baseline radio Interferometry), LLR (Lunar Laser Ranging), SLR (Satellite Laser Ranging) and most recently, GPS (Global Positioning System). By combining independent measurements of the Earth's orientation taken by the space-geodetic techniques, more precise PM time series are now available. Therefore, compared to earlier polar motion studies, an analysis of these data should provide more precise results. In this study, we consider the major periodic components of polar motion, in particular the Chandler and annual wobbles, with a focus on quantifying their temporal variability.

2 Data sets used in this study

The data sets used to examine the Chandler and annual motions are the combined Earth orientation series, SPACE99, as computed by the Jet Propulsion Laboratory (JPL), from MJD 43049.0 (1976 9 28.0) to 51565.0 (2000 1 22.0) at daily intervals (Gross, 2000). Using a Kalman filter, this solution is based on data from space-geodetic techniques (LLR, SLR,VLBI, and, since mid-1992, GPS). Before their combination, bias-rate corrections and uncertainty scale factors are applied to the independent series to make them consistent with each other. Moreover, the combined series is referred in bias and rate to the IERS 1999 solutions, i. e., it is consistent with the IERS combined Earth orientation series EOP(IERS) C04. For more information and in particular for the uncertainties and the differences between SPACE99 and EOP(IERS) C04, see Gross (2000).

Figure 1 shows the input data of polar motion in terms of an irregular spiral curve using the mathematical perspective in space-time view of Höpfner (1994a). The beat with a cycle of ca. six years is induced by the superposition of the two dominant oscillations, with periods of about 435 and 365 days, respectively.

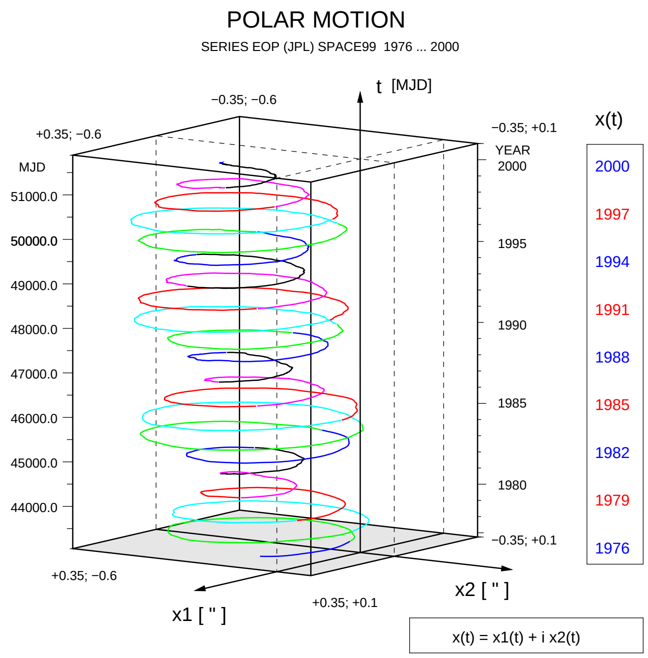

Figure 1. Polar motion as computed by JPL (Gross, 2000) using the mathematical perspective in space-time view of Höpfner (1994a). The x_1-axis points towards the Greenwich meridian and the x_2-axis towards 90^0 E longitude.

3 Data processing and results

In studying the Chandler and annual components of polar motion, processing the data consists of the following analysis steps:

(1) Separating the low-frequency component by low-pass filtering and the Chandler and annual wobbles by recursive band-pass filtering for the x_1- and x_2-components with one-day sampling

Compared to other analysis methods such as least-squares fit, filtering is most appropriate for separating variable signals when studying their behaviour over time. As in our previous studies, digital filters have been applied; see Höpfner (1996b) for details dealing with constructing the zero-phase digital filters. To filter out the Chandler term from the daily values of the time series, a Chandler filter analogous to the filter developed for separating the annual term was designed. The Chandler and annual filters have a cosine shape modified over four periods as weight function. In order to best separate both periodic terms from each, the procedure applied was that of successive approximation by alternate elimination of the Chandler and annual terms. The results obtained for both wobbles are represented in Figs. 2 and 3 in a similar manner as Fig. 1. In particular, the Chandler motion is described by the elliptic spiral in Fig. 2, and, for the annual motion, the same is shown in Fig. 3. It should be noted that the filtered wobbles are truncated at the beginning and the end of the analysis intervals. The Chandler motion is referred to the time interval from MJD 44004.0 (1979 5 11.0) to 50610.0 (1997 6 11.0) and the annual motion from MJD 43843.0 (1978 12 1.0) to 50771.0 (1997 11 19.0).

(2) Calculating optimal estimates for the periods of the Chandler and annual wobbles over time

For this step, we applied a method, based on the maximum, zero crossing and minimum of a periodic function, to the filtered periodic terms separately for the x_1- and x_2- components (for details about this method, see the Appendix in Höpfner (2001)). This resulted in two period time series for the Chandler and annual wobbles, one for the x_1- component and another for the x_2-component. In both cases, the differences between them were between 0 and 2 days, i. e. not significant, and we determined the final period time series as means. The standard deviations of the period means are ±0.48 and ±0.54 days. Figure 4 shows the period variability of the Chandler and annual wobbles over time.

(3) Deriving the trigonometric Fourier coefficients a_1, b_1 and a_2, b_2 of the Chandler and annual wobbles, and their uncertainties, for the x_1- and x_2-components

The expressions for the periodic terms have the trigonometric form $a_1$cos (2πt/T) + $b_1$sin (2πt/T) and $a_2$cos (2πt/T) + b_2 sin (2πt/T) for the x_1- and x_2-components respectively, where t is the time in days elapsed since 1977.0 (MJD 43144.0) and T the period of the concerned wobble in days. Using a least-squares fit, the trigonometric Fourier coefficients a_1, b_1 and a_2, b_2 and their uncertainties were derived for x_1 and x_2 from the filtered time series at running intervals of 441 days for the Chandler wobble and 375 days for the annual wobble, with quarterly sampling, taking variable periods as computed according to (2) and presented in Fig. 4.

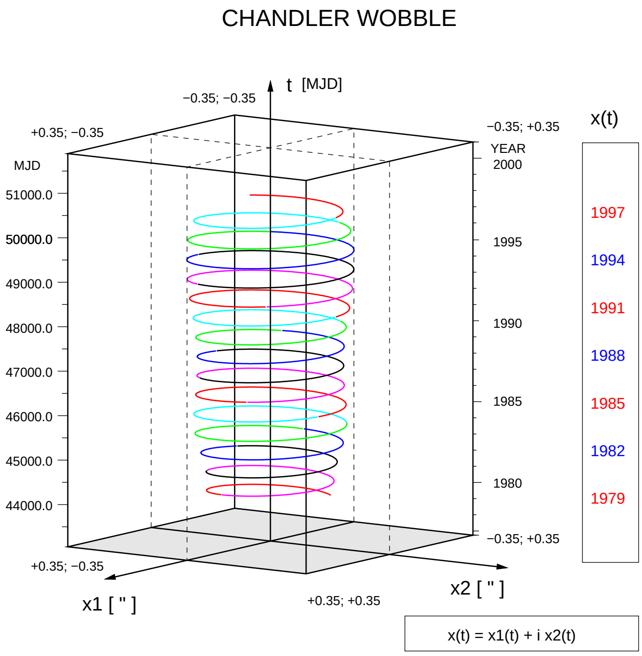

Figure 2. Chandler wobble filtered out from the series EOP (JPL) SPACE99 using the mathematical perspective in space-time view of Höpfner (1994a). The x_1-axis points towards the Greenwich meridian and the x_2-axis towards 90^0 E longitude.

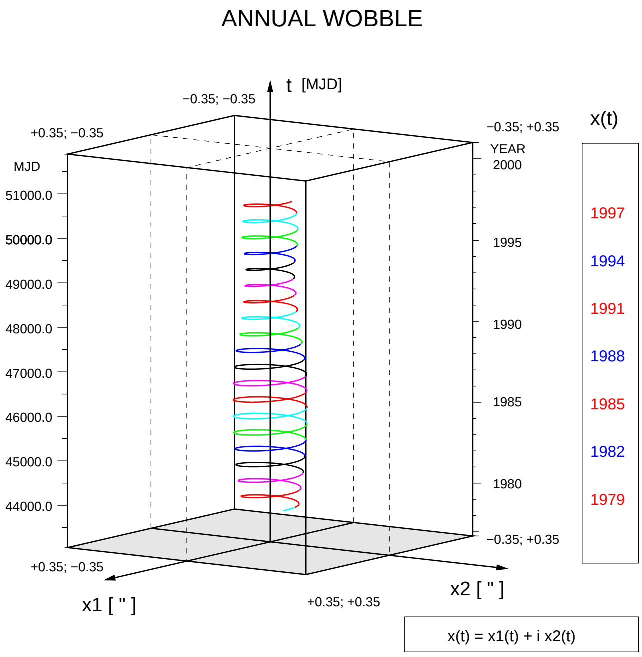

Figure 3. Annual wobble filtered out from the series EOP (JPL) SPACE99 using the mathematical perspective in space-time view of Höpfner (1994a). The x_1-axis points towards the Greenwich meridian and the x_2-axis towards 90^0 E longitude.

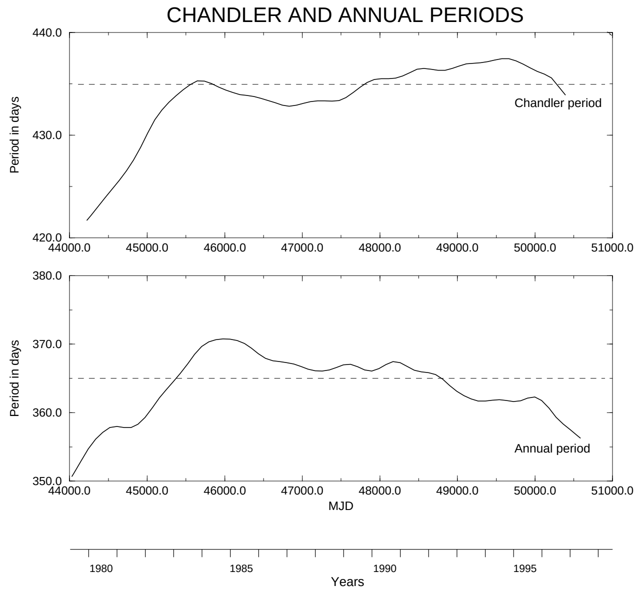

Figure 4. Variations in the periods of the main periodic components of polar motion: Chandler wobble (top) and annual wobble (bottom). The dashed lines indicate the 435-day and 365-day baselines.

(4) Computing the parameters and their uncertainties of the Chandler and annual wobbles for the trigonometric, exponential and elliptic representations

The periodic terms in (3) have the equivalent expressions for the just mentioned representations as follows:

- The trigonometric form is described by c_1 cos (2πt/T - α_1) and c_2 cos (2πt/T - α_2) for the x_1- and x_2-components, with the amplitudes c_1, c_2 and the phases α_1, α_2 of the oscillations of the real and imaginary parts. From the trigonometric Fourier coefficients a_1, b_1 and a_2, b_2, the amplitudes c_1, c_2 and the phases α_1, α_2 of the oscillations of the real and imaginary parts are computed according to the formulas

$$c_1 = \left(a_1^2 + b_1^2\right)^{\frac{1}{2}} \;\text{ and }\; c_2 = \left(a_2^2 + b_2^2\right)^{\frac{1}{2}}, \tag{1}$$

and

$$\alpha_1 = \arctan\frac{b_1}{a_1} \;\text{ and }\; \alpha_2 = \arctan\frac{b_2}{a_2}. \tag{2}$$

- The exponential form is expressed as (A_+ + i B_+) exp (i 2πt/T) + (A_- + i B_-) exp (-i 2πt/T) with the exponential Fourier coefficients A_+, B_+ and A_-, B_- being circular motions of the positive and negative frequencies. Instead of (A_+ + i B_+) and (A_- + i B_-), another way to express this is $\mid C_+ \mid$ exp (i ϕ_+) and $\mid C_- \mid$ exp (i ϕ_-), with the circular motions having amplitudes $\mid C_+ \mid$, $\mid C_- \mid$ and phases ϕ_+, ϕ_-. In each case, an elliptical path results from the circular motions of the positive and negative frequencies. For the exponential Fourier coefficients A_+, B_+ and A_-, B_-, the following relationships to the trigonometric Fourier coefficients a_1, b_1 and a_2, b_2 exist:

$$A_+ = \frac{1}{2}\left(a_1 + b_2\right) \;\text{ and }\; B_+ = \frac{1}{2}\left(a_2 - b_1\right) \tag{3}$$

and

$$A_- = \frac{1}{2}\left(a_1 - b_2\right) \;\text{ and }\; B_- = \frac{1}{2}\left(a_2 + b_1\right). \tag{4}$$

The amplitudes $\mid C_+ \mid$, $\mid C_- \mid$ and the phases ϕ_+, ϕ_- of the circular motions are obtained by

$$|C_+| = |A_+ + iB_+| = \left(A_+^2 + B_+^2\right)^{\frac{1}{2}} \tag{5}$$

and

$$|C_-| = |A_- + iB_-| = \left(A_-^2 + B_-^2\right)^{\frac{1}{2}}, \tag{6}$$

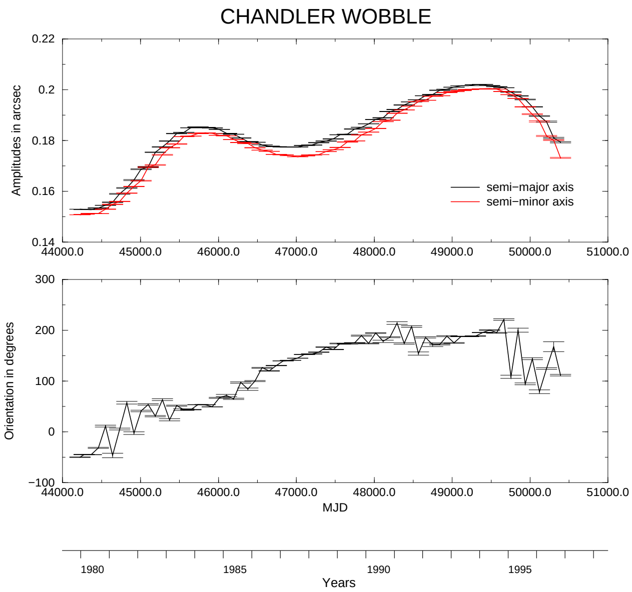

Figure 5. Variations in the semi-major and semi-minor axes (top) and direction of the major axis (bottom) of the Chandler motion. The solutions with their standard deviations are shown at quarterly sampling.

and

$$\phi_+ = \arctan \frac{B_+}{A_+} \text{ and } \phi_- = \arctan \frac{B_-}{A_-}. \tag{7}$$

- Concerning the elliptic motion, knowledge of its parameters is of particular interest in the geophysical interpretation. The major and minor semi-axes a, b of the ellipse are given by

$$a = |C_+| + |C_-| \text{ and } b = |C_+| - |C_-|, \tag{8}$$

and their directions γ_a, γ_b by

$$\gamma_a = \frac{1}{2}\left(\phi_+ + \phi_-\right) \text{ and } \gamma_b = \gamma_a + \frac{\pi}{2}. \tag{9}$$

The numerical eccentricity ϵ is a dimensionless measure for the divergence of the ellipse from the circle and is obtained by

$$\epsilon = \frac{(a^2 - b^2)^{\frac{1}{2}}}{a}. \tag{10}$$

If $\epsilon = 0$, then there is a circle; if $0 < \epsilon < 1$, then there is an ellipse. For example, the orbit of the Earth has only the numerical eccentricity ϵ = 0.0167.

Note that, for all parameters and quantities of the periodical terms, the formulas for computing their standard deviations can be found in Höpfner (1994b). Using the results of (3), we computed the parameters and their uncertainties for the trigonometric, exponential, and elliptic forms of representation for the Chandler and annual wobbles. Figure 5 shows the variation of the semi-major and semi-minor axes (top) and the direction of the major axis (bottom) of the Chandler motion. In Fig. 6, the same is shown for the annual motion. Additional information including some results of the different parameters and the related standard deviations of the Chandler and annual wobbles at four chosen epochs (Oct./Nov. 1980, Oct./Nov. 1984, Jan./Feb. 1989, Jan./Feb. 1993) are given in Table 1.

4 Discussion of the results

Before discussing the results obtained from this work, it needs to be stated that, compared to the PM time series based on optical astrometric measurements, the combined Earth orientation series SPACE99 used in this study are qualitatively better. However, the separation of two signals with similar time varying periods, in particular the Chandler and annual wobbles, requires a special effort.

Table 1. Results of the different parameters of the Chandler and annual wobbles. Note: The numbers 1 and 2 are used for the x_1- and x_2-components respectively, and the signs + and - are for positive and negative frequencies. s_0 is the standard deviation of a single estimate. The expressions for the oscillations have the form c cos(2 π t / T - α), where c is the amplitude, α the phase, t the time in days elapsed since 1977.0 (MJD 43144.0), and T the Chandler or annual period in days. Units: arcsec for s_{01}, s_{02}, a_1, b_1, a_2, b_2, c_1, c_2, A_+, A_-, B_+, B_-, $|C_+|$, $|C_-|$, a and b; degree for α_1, α_2, ϕ_+, ϕ_- and γ_a. The symbols used are defined within the text.

(a) Chandler wobble

MJD	T	s_{01}		s_{02}
44550.0	424.76	±0.0007452		±0.0013794
46011.0	434.38	±0.0008583		±0.0005646
47563.0	433.66	±0.0010998		±0.0010907
49024.0	436.74	±0.0004573		±0.0003590
MJD	a_1	b_1	a_2	b_2
44550.0	-.11534±0.00005	-.10267±0.00005	0.10125±0.00009	-.11466±0.00009
46011.0	-.18036±0.00006	-.02699±0.00006	0.02557±0.00004	-.18218±0.00004
47563.0	-.17876±0.00007	-.03529±0.00007	0.03535±0.00007	-.17372±0.00007
49024.0	-.19167±0.00003	0.06045±0.00003	-.05964±0.00002	-.19010±0.00002
MJD	c_1	α_1	c_2	α_2
44550.0	0.15441±0.00005	221.67±0.02	0.15297±0.00009	311.45±0.04
46011.0	0.18236±0.00006	188.51±0.02	0.18397±0.00004	277.99±0.01
47563.0	0.18221±0.00007	191.17±0.02	0.17728±0.00007	281.50±0.02
49024.0	0.20098±0.00003	162.50±0.01	0.19923±0.00002	252.58±0.01
MJD	A_+	B_+	A_-	B_-
44550.0	-.11500±0.00005	0.10196±0.00005	-.00034±0.00005	-.00071±0.00005
46011.0	-.18127±0.00003	0.02628±0.00003	0.00091±0.00003	-.00071±0.00003
47563.0	-.17624±0.00005	0.03532±0.00005	-.00252±0.00005	0.00003±0.00005
49024.0	-.19088±0.00002	-.06004±0.00002	-.00079±0.00002	0.00040±0.00002
MJD	$\vert C_+\vert$	ϕ_+	$\vert C_-\vert$	ϕ_-
44550.0	0.15369±0.00005	138.44±0.02	0.00079±0.00005	244.35±3.86
46011.0	0.18317±0.00003	171.75±0.01	0.00116±0.00003	322.18±1.71
47563.0	0.17974±0.00005	168.67±0.02	0.00252±0.00005	179.26±1.19
49024.0	0.20010±0.00002	197.46±0.01	0.00089±0.00002	152.77±1.27
MJD	a	b	γ_a	ϵ
44550.0	0.15448±0.00005	0.15290±0.00009	191.40±1.93	0.14266±0.00474
46011.0	0.18432±0.00004	0.18201±0.00006	246.97±0.86	0.15782±0.00236
47563.0	0.18226±0.00007	0.17723±0.00007	173.96±0.59	0.23331±0.00242
49024.0	0.20099±0.00003	0.19922±0.00002	175.12±0.63	0.13242±0.00146

(b) Annual wobble

MJD	T	s_{01}		s_{02}
44517.0	357.82	±0.0015888		±0.00057004
45978.0	370.78	±0.0002691		±0.00017295
47530.0	366.97	±0.0010593		±0.00162090
48991.0	363.12	±0.0003175		±0.00047668
MJD	a_1	b_1	a_2	b_2
44517.0	0.00007±0.00012	-.07988±0.00012	0.07577±0.00004	0.00263±0.00004
45978.0	-.09141±0.00002	-.02622±0.00002	0.02134±0.00001	-.08470±0.00001
47530.0	-.05443±0.00008	-.05760±0.00008	0.05566±0.00012	-.04838±0.00012
48991.0	0.01538±0.00002	-.06070±0.00002	0.05369±0.00003	0.01555±0.00003
MJD	c_1	α_1	c_2	α_2
44517.0	0.07988±0.00012	270.05±0.08	0.07582±0.00004	1.99±0.03
45978.0	0.09509±0.00002	196.01±0.01	0.08735±0.00001	284.14±0.01
47530.0	0.07924±0.00008	226.62±0.06	0.07375±0.00012	319.00±0.09
48991.0	0.06262±0.00002	284.22±0.02	0.05590±0.00003	16.15±0.04
MJD	A_+	B_+	A_-	B_-
44517.0	0.00135±0.00006	0.07782±0.00006	-.00128±0.00006	-.00205±0.00006
45978.0	-.08806±0.00001	0.02378±0.00001	-.00335±0.00001	-.00244±0.00001
47530.0	-.05141±0.00007	0.05663±0.00007	-.00302±0.00007	-.00097±0.00007
48991.0	0.01546±0.00002	0.05720±0.00002	-.00008±0.00002	-.00351±0.00002
MJD	$\vert C_+\vert$	ϕ_+	$\vert C_-\vert$	ϕ_-
44517.0	0.07784±0.00006	89.01±0.05	0.00242±0.00006	238.07±1.45
45978.0	0.09121±0.00001	164.89±0.01	0.00414±0.00001	216.04±0.16
47530.0	0.07648±0.00007	132.23±0.05	0.00317±0.00007	197.74±1.28
48991.0	0.05925±0.00002	74.87±0.02	0.00351±0.00002	268.63±0.34
MJD	a	b	γ_a	ϵ
44517.0	0.08026±0.00011	0.07542±0.00005	163.54±0.71	0.34202±0.00448
45978.0	0.09535±0.00002	0.08707±0.00001	190.46±0.08	0.40775±0.00059
47530.0	0.07965±0.00008	0.07331±0.00012	164.98±0.65	0.39111±0.00432
48991.0	0.06276±0.00002	0.05574±0.00003	171.75±0.18	0.45938±0.00135

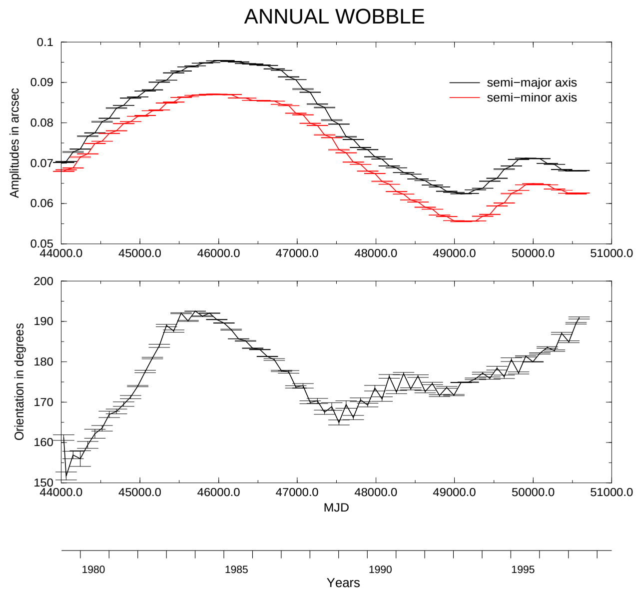

Figure 6. Variations in the semi-major and semi-minor axes (top) and direction of the major axis (bottom) of the annual motion. The solutions with their standard deviations are shown at quarterly sampling.

To derive the parameter of the Chandler and annual wobbles and the associated uncertainties in the temporal variability, we applied a 4-step procedure as described in Sect. 3. Some of our results are plotted in Figs. 2 to 6 and summarised in Table 1. As can be seen, the parameter estimates show remarkably small uncertainties. Concerning their variability over time, this is clear without the estimated uncertainties, i.e. statistically significant, and the courses appear rather steady. Therefore, it can be said that the method used to derive these solutions for the Chandler and annual wobbles yields results of high quality. However, it should be mentioned that a few of the estimates at the beginning and end of the time series may be less accurate because of an edge effect of the recursive band-pass filtering.

The Chandler wobble is found to show a period variation between 422 and 438 days with a estimated standard deviation of only ± 0.48 days (top of Fig. 4), while its amplitude mean varies from 0.15” to 0.20” (top of Fig. 5). Concerning a possible elliptic motion, note that the semi-major axis a only differs by 0.001” to 0.006” from the semi-minor axis b, resulting in the numerical eccentricity ϵ ranging between 0.10 to 0.23. Therefore, the Chandler wobble has a quasi-circular prograde (i.e. counter-clockwise) motion. Comparing the changes in amplitude with those in period, we notice that both are similar in their time dependence, i.e., there is a correlation between the amplitudes and periods over this analysis interval, as found in previous polar motion studies covering the last century over different time periods (e.g. Iijima, 1965; Proverbio et al., 1971; Vondrák, 1999). From the direction of the major axis of the Chandler wobble plotted in the bottom panel of Fig. 5, a distortion in the quasi-circular Chandler ellipse occurs between about 0^0 and 200^0, and is likely to be prograde (retrograde) if the amplitude increases (decreases).

A significant change in the period of the annual wobble, from 350 to 371 days with an uncertainty of ± 0.54 days, can be seen (bottom of Fig.4). Since the semi-major axis of the annual wobble is always visibly larger than the semi-minor axis (top of Fig. 6), there exists a significantly elliptic annual motion that is prograde, similar to the Chandler wobble. For the annual wobble, the semi-major axis a varies between 0.063” and 0.096”, and the semi-minor axis b between 0.056” and 0.087”, with the differences between both axes over this time interval reaching a minimum of 0.002” and a maximum of 0.009”. The numerical eccentricity ϵ of the annual motion ellipse ranges from 0.26 to 0.49. Comparing the annual period curve (bottom of Fig. 4) with the semi-axis curves (top of Fig. 6) reveals the shorter (longer) periods of the elliptic annual motion are probably associated with smaller (larger) semi-axes. The direction of the major axis of the annual wobble ellipse (bottom of Fig. 6) shows considerably less change than the Chandler wobble ellipse (bottom of Fig. 5), its variability over time being around 155^0 and 195^0 for the analysis interval.

Recent studies are referred to following analysis intervals: From 1848 to1988 by Nastula et al. (1993), from 1976 to 1987 by Höpfner (1995, 1996a), from 1899.7 to 1992.0 by Vondrák (1999) and from 1861.0 to 1992.0 by Schuh et al. (2001). While it should be appropriate to use these results as a comparison with ours, there are either no or only relatively short common intervals, making such comparisons difficult. However, we can say that the average results of the Chandler and annual wobbles obtained by Höpfner (1995, 1996a) conform to the estimates in this work. In Vondrák (1999), the parameter estimates plotted over the time interval 1904-1988 are the semi-major and semi-minor axes and phase of the Chandler and annual wobbles, and in addition the orientation of the annual wobble ellipse. Note that the adopted Chandler frequency is 0.845 cycles per year, i.e., a Chandler period of 432.25 days, and the time t is elapsed in days since 1900.0. Considering the estimates that cover the same time interval as ours (1980-1988), there is agreement between our and their results for the semi-axes of the Chandler and annual wobbles. Also, estimates for the direction of the major axis of annual motion are similar. For the phases, we notice that they refer to different time counting and period lengths. The common interval of our parameter estimates and those by Schuh et al. (2001) is shorter (1980-1985), with the time t in that work elapsed since 1945.0 compared to 1977.0 here. We find a similarity in the magnitude and time evolution of the Chandler and annual periods with our over the common interval. The same can be said for the amplitudes of the Chandler wobble, whereas the amplitudes of the annual wobble computed by Schuh et al. (2001) are similar to our in magnitude, but differ in their temporal course.

The time series EOP(IERS) C04 is a combined EOP solution available since 1962 at 1-day intervals from IERS. For the uncertainty of a daily value, see for example, IERS (2000), where it is shown that the uncertainty decreases by replacing the classical method for measuring polar motion by space-geodetic techniques. This was done over 6 periods, ranging from 30 milliarcseconds at the beginning of the series to 0.2 milliarcseconds at its end. That time series could be processed in a similar manner as described here, after which, a comparison may be made of the parameter estimates of the Chandler and annual wobbles with this work's results, revealing the significant differences between the JPL and IERS systems. Note that compared to the combined Earth orientation series SPACE99 used in this study, EOP(IERS) C04 is nearly 15 years longer. Therefore, the parameter estimates in terms of a time series in the IERS system are earlier, which would also be of special interest.

5 Concluding remark

Concentrating on the Chandler and annual wobbles of polar motion, the main results of our study are the characteristics and time evolution of both periodic components from 1980 to 1998 relative to the JPL system being important for geophysical interpretations, including prediction, model development and validation.

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