Part 5.

Chandler and Annual Polar Motion: Observations and Excitation

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Chandler Motion Observations

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Abstract. The history of observations of the Chandler motion is presented in brief and the importance of the ninety years of the ILS data is stressed. Essential features and different empirical models of the Chandler motion are discussed.

1. Introduction

The importance of the discovery by S. C. Chandler of a 14-month latitude variation led the International Geodetic Association to organize the International Latitude Service (ILS) in 1899. It was the first permanent worldwide scientific cooperation that resulted in a host of observational data of exceptional scientific value collected by the ILS stations over about 90 years. Unfortunately, some of these stations lacked continuity in their observations, being closed from time to time for various reasons. But the ILS data is still the best available in terms of length and homogeneity.

In 1955, to meet practical requirements of time service, the Bureau International de l'Heure (BIH) began a program of polar motion determination using both latitude and time variations and more observatories than the ILS. In 1962 the ILS was succeeded by the International Polar Motion Service (IPMS) whose Central Bureau collected and reduced the data up to 1988 from several score of instruments scattered over the globe.

The advances in space science and technology made at the end of the 1960s spurred new interest in the subject of polar motion. Precise tracking of satellites, Lunar Laser Ranging (LLR) and Very Long Baseline Interferometry (VLBI) required equally precise information on the Earth's orientation. At the same time, these new techniques permitted polar motion to be observed with a precision and a resolution that were better than in customary astrometric observations. At the beginning of the 1980s the number of the optical astrometry stations which participated in the IPMS and the BIH rapidly decreased. At the same time new space geodesy observation networks were established. Therefore in 1988 the IPMS and the BIH were replaced by the new International Earth Rotation Service (IERS) whose global observing activity involves VLBI, Lunar and Satellite Laser Rangings (LLR and SLR), Global Positioning System (GPS) and Doppler Orbit Determination and Radiopositioning Integrated on Satellite (DORIS) with worldwide networks totalling up to about 150 sites. Nowadays, the IERS plays a

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key role in the coordination of the observations and their analysis. It maintains a Terrestial Reference Frame (TRF) and an extragalactic Celestial Reference Frame (CRF), and the Earth Orientation Parameters (EOP), which are pole coordinates, UT1 and Celestial Pole Offsets. The latest observations of polar motion with respect to the TRF achieved the accuracy which is by a factor of 100 higher compared with the ILS data.

2. Polar Motion Data

To provide the basis for long term studies of polar motion, the IERS brought about the homogenization of successive data sets and the possibility of their accurate appending, together with an estimation of the accuracy of older and less precise data, taking advantage of the knowledge gained from more recent and more precise data. We thus have now compiled series of pole coordinates in the form of normal values at 0.1-year or 0.05-year intervals from 1846 to the present with associated formal uncertainties. This is the well-known series EOP (IERS) 97 C01 (IERS Annual Report).

Recently the astrometric polar motion data have been reduced to the HIPPARCOS frame by Vondrák *et al.* (1998), and the pole coordinates for the period 1899.7–1992.0 have been derived. Obviously, this new set of pole coordinates substitutes for the previous one given by Fedorov *et al.* (1970), which was used for the compilation of EOP (IERS) 97 C01. So, depending on observational techniques and organizational structure of the services, one can distinguish three major epochs in the polar motion data:

- (a) the 1830.0–1899.7 epoch (before the organization of the ILS). During this period the incomplete and short series of astrometric observations made with meridian circles and transit instruments were used to determine latitude variations. These observations were analysed by Chandler (1892), Kimura (1917), Rykhlova (1970), and others for the purpose of studying 14-month variations in the polar motion. Although the accuracy of these data is considerably lower than the accuracy of the ILS data, they enable us, nevertheless, to reproduce the general character of the Chandler motion in the second half of the 19th century. One can distinguish three segments of the polar motion data for this period: the 1830.0–1846.0 as analysed by Sekiguchi (1975), the 1846.0–1890.0 segment as derived by Rykhlova (1970), and the 1890.0–1899.7 segment as derived by Fedorov *et al.* (1972). Evolution of the mean uncertainties of the pole coordinates is given in Table 0-3a of the IERS Annual Reports.

- (b) the 1899.7–1972.0 epoch (activities of the ILS, BIH, and IPMS). After the organization of the ILS a regular program of star observations by zenith telescopes for the purpose of determining polar motion was implemented. It is well known that the observations were not a uniform series. Originally there were six stations. Afterwards, due to various reasons, some stations ceased their operation. Moreover the changes in the catalogue of zenith stars resulted in changes of observation programs during the long history of the ILS. Therefore many suggestions were made to overcome the difficulties caused by discontinuity of operation of some stations and by changes of observation program for the ILS stations (see, for example, Yumi and Yokoyama, 1980). Recently this problem was partially solved by Vondrák *et al.* (1998), the ILS data being re-reduced in the HIPPARCOS frame. The evolution of the standard errors of the pole coordinates derived by Vondrák *et al.* (1998) from the ILS and the BIH data depends on the density of observations, *i.e.*, the numbers of instruments and observations (see Table 1). Although the ILS data are noisy they are the best available in terms of length and homogeneity for studying the long-term changes of the Chandler motion. The BIH and IPMS data are less noisy due to the incorporation of observations from several dozen of observatories.

Table 1. The mean standard errors of pole coordinates.

Date (years)	sig x (arcsec)	sig y (arcsec)
1899.7–1915.0	0.025	0.023
1915.0–1941.5	0.031	0.029
1941.5–1956.0	0.034	0.023
1956.0–1962.0	0.017	0.014
1962.0–1988.0	0.011	0.008
1988.0–1992.0	0.012	0.012

As pointed out by Vondrák *et al.* (1998), the standard errors of pole coordinates were relatively stable during the first half of the century (about 30 mas). Then they gradually decreased to a minimum of about 10 mas, and then increased again. One can use the set of pole coordinates derived by Vondrák *et al.* (1998) for the period of 1899.7–1972.0 for studying the Chandler motion features.

- (c) 1972.0 to the present. The BIH and the IERS solutions are used. The Doppler technique was introduced for the determination of polar motion in 1972. The IERS solution, based on VLBI, LLR, and SLR from 1980 to now, provides the basis for the most accurate analysis of the Chandler motion parameters. Mean uncertainties of the pole coordinates for this period are given in Table O-3a of the IERS Annual Reports.

Based on these three different sources of polar motion data, we compiled the Kiev standard series of pole coordinates to be used to study the Chandler motion. There are other combinations or compilations of polar motion data which differ from that mentioned above by the source and the span of data used in the combination, by the method of processing and interpolation, *etc.* (see, for example, Gross, 1999). It is worth noting that the essential features of the Chandler motion have much in common for various compilation sets of polar motion data.

3. Essential Features of the Chandler Motion

In practice, it is impossible to observe directly the Chandler motion of the pole. The observed polar motion contains variations in a wide range of frequencies: from a secular drift to high-frequency variations. Two extreme parts of the polar motion spectrum can be easily removed from the data by appropriate smoothing or filtering. The remaining part consists of two major spectral components:

- (1) The Chandler component whose power spectrum is a broadened peak centered at about 0.84 cpy (435-day period);
- (2) The annual component whose power spectrum is a narrow peak centered at 1.00 cpy.

The two oscillations alternately reinforce and oppose each other in a cycle of about six years (Fig. 1). Because the amplitudes of the oscillations can change, the motion is not the same during different cycles. These deviations caused difficulties in analysing two major components of polar motion because their frequencies were so close that long data series were necessary for adequate resolution. However, in order to study the characteristics of the Chandler component, short time records are desirable, since there is evidence that these characteristics change with time. Numerous authors suggested various approaches to solve this problem. For example, assuming that the amplitude and the phase of the annual component are more stable then those of the Chandler component the annual component is modelled and eliminated from the polar motion data. Another approach relies upon the use of a numerical technique for filtering the polar motion data. We assume here that the seasonal component has been properly removed from the polar motion data. The residuals, *i.e.*, the Chandler component or the Chandler wobble, are shown in Fig. 2.

In reference to numerous studies (Chandler, 1892; Kimura, 1917; Guinot, 1972, and others) let us try to summarize the essential features of this component:

1. The amplitude varies from about 50 to 300 mas. During some time span this variation looks like a beat phenomenon.
2. The revolution number counting indicates that the phase (or the period) was subject to changes, in particular between 1923 and 1940. The amplitude was extremely small during the same period.
3. Both the amplitude and the phase are subject to irregular (and sometimes proportional) changes.

The essential features of the Chandler motion were studied by numerous authors with various methods (Melchior, 1957; Colombo and Shapiro, 1968; Pedersen and Rochester, 1971; Yatskiv, 1974; Dickman, 1981; Okubo, 1982; Vondrák, 1985, and others). Some results of these studies are illustrated in Fig. 3–6. Obviously, these features appear to be too regular for a randomly excited free motion, as is supposed in the case of the well-known "damped model." This was the reason for proposing various empirical models of the Chandler motion (for review, see Munk and MacDonald, 1960; Lambeck, 1980).

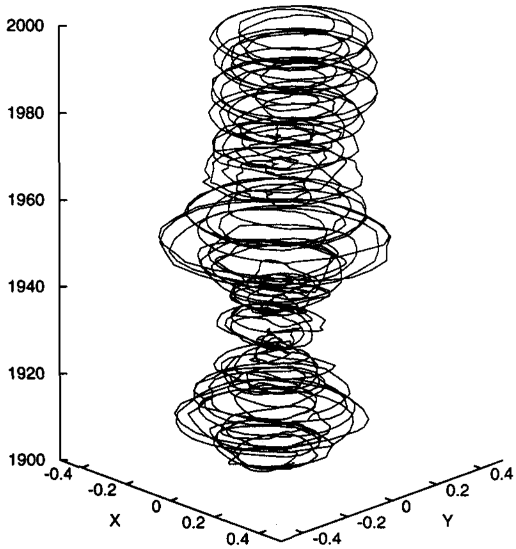

Fig.1. Polar motion after removal of the secular variation (Unit: arcsec).

Figure 1. Polar motion after removal of the secular variation (Unit: arcsec).

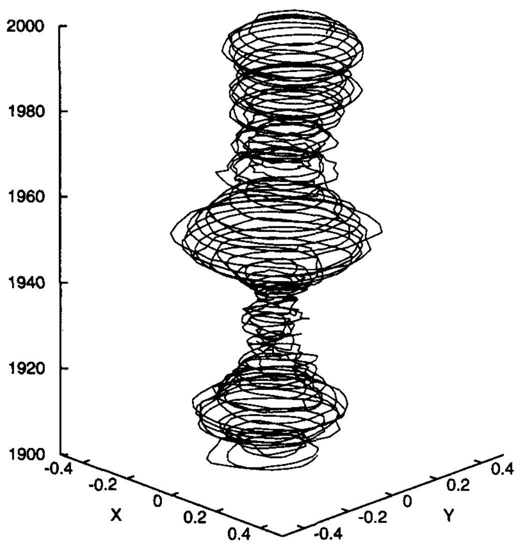

Fig.2. Polar motion after removal of the secular and seasonal variation.

Figure 2. Polar motion after removal of the secular and the seasonal variations.

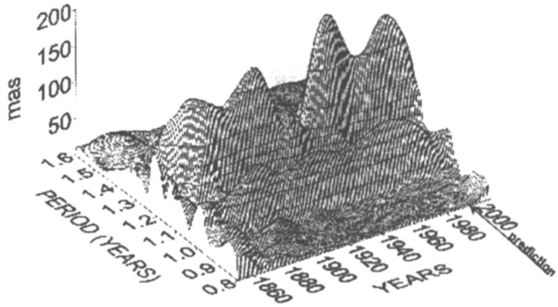

Figure 3. Amplitude spectrum of the IERS 97 C01 pole coordinates and their autocovariance prodiction (after Kołaczek and Kosek, 1998).

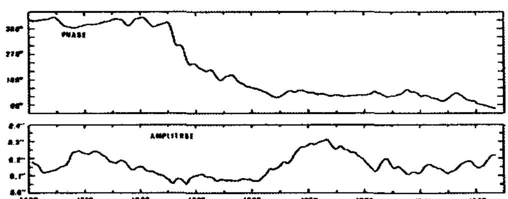

Figure 4. Phase and semi-major axis of the Chandler wobble (after Vondrák, 1985).

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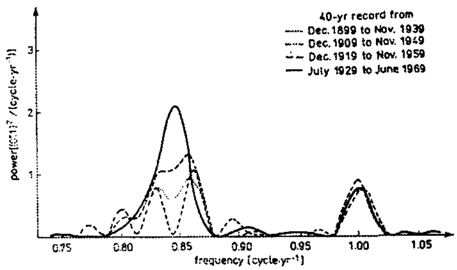

Figure 5. Power spectra of the Chandler motion for four subsets of the ILS data (after Pederson and Rochester, 1974).

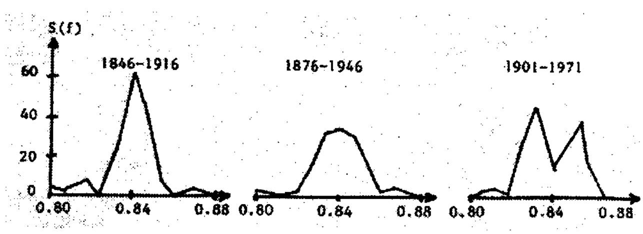

Figure 6. Power spectra of the Chandler motion for three subsets of polar motion data provided by Fedorov *et al.*, (1972) (after Yatskiv, 1974).

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4. Empirical Models of the Chandler Motion

Let us distinguish three different types of empirical models of the Chandler motion, namely (a) "damped model," which is described by the first-order differential equation (see Brzeziński, 1992; Vondrák, 1992)

$$\imath \frac{\dot{\vec{p}}}{2\pi f_c} + \vec{p} = \chi,$$

where $\vec{p} = p_1 + \imath p_2$ is the terrestrial orientation of the Celestial Ephemeris Pole (CEP); $\chi = \chi_1 + \imath\chi_2$ is the input excitation process; $f_c = f_0(1 + \imath/2Q)$ is a complex Chandler frequency, Q being the resonance quality factor

$$Q = \pi f_0 \alpha^{-1},$$

where $1/\alpha$ is damping time. For this model the frequency response function is

$$(f) = \frac{1 - f/f_0 + (1/(2Q))^2 - \imath f/(2Qf_0)}{(1 - f/f_0)^2 + (1 + (2Q))^2}.$$

The "damped model" was used to determine two basic parameters, the frequency f_0 and Q, by minimizing the functional

$$\int_{f_1}^{f_2} [|G(t)|S_\chi(f) - S_p(f)]^2 df,$$

or by means of the methods of time series analysis (Munk and MacDonald, 1960; Ooe, 1978; Wilson and Vicente, 1990, and others). According to these defermi-nations, the "time-averaged" estimate of the Chandler period is about 435 days, which is quantitatively well explained by the elastic-gravitational normal mode theory and the equilibrium pole tide hypothesis (Lambeck, 1980). As reported by various authors, the "instantaneous" estimates of the Chandler period range from 407 to 452 days depending on the time span of the data analysed.

Contrary to the agreement on the "time-averaged" estimate of the Chandler period there is no consensus about the Chandler wobble Q (sometimes denoted by Q_w). The estimates range from 25 to 1000, they are derived with large uncertainties. Many authors think that the most probable value of Q_w is about 60. The problem is that $Q_w < 100$ is too small as compared with the Q derived from seismic and tide observations or calculated on the basis of the modern Earth model (see Anderson and Minster, 1979; Eubanks, 1993). One can propose several explanations for the small value of Q_w (Yatskiv, 1997). One problem should be resolved in advance, however, to take advantage of the Q_w derived from time series analysis of polar motion data, namely the significance of the variable Chandler period hypothesis has to be tested.

(b) "time-variable model" defined by the following equations

$$\imath \frac{\dot{\vec{p}}}{2\pi f_c(t)} + \vec{p} = \chi,$$

$$\vec{p} = \vec{A}(t) exp\Big(-\imath 2\pi \int_0^t f_c(\tau) d\tau\Big),$$

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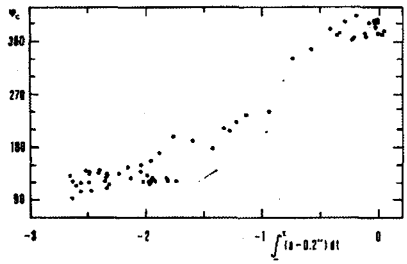

Figure 7. Correlation between integrated polar motion total amplitude (a) and observed value of the Chandler wobble phase (ϕ_c) (after, Vondrák, 1985).

$$\vec{A}(t) = -\imath 2\pi \int_0^t f_c(\tau)\chi(\tau) exp\Big(-\imath 2\pi \int_0^\tau f_c(s)ds\Big) d\tau.$$

Various models of the "time-dependent" Chandler frequency have been proposed. Carter (1981) suggested that the Chandler motion may be frequency modulated as a linear function of the polar motion amplitude. Earlier Sekiguchi (1976) stated that the Chandler frequency does not fluctuate periodically but seems to have a tendency to take one of a set of discrete values among which 0.845 and 0.820 are predominant. Vondrák (1990) derived the following relation between the wobble amplitude A and the frequency f_0 (see Fig. 7)

$$f_0 = 0.816 + 0.0037/A \text{ cpy.},$$

where A is expressed in arcsec.

Irrespective of the proposed model of the Chandler frequency variation the problem is how to separate in (4) the effects of fluctuations of f(t) from those of $\chi(t)$. Okubo (1982) re-examined the observational grounds of the variable period hypothesis and did not find any evidence for it. He proved this conclusion by the analysis of simulation data. It seems that a nonstationary, nonisotropic excitation could be responsible for "instantaneous" changes in the Chandler frequency (Okamoto and Sasao, 1976).

The irregularity of the pole path suggests that the excitation itself is not random noise. The examination of the variation of the Chandler motion for the period 1846–1998 reveals that its amplitude underwent non-random (sometimes even periodical) variations with time (see Fig. 8–9). This was the reason for suggesting the so-called "multi-component model" of the Chandler motion.

(c)multi-component model of the Chandler motion defined by the equation

$$p(t) = \sum_j A_j exp \imath 2\pi f_i t.$$

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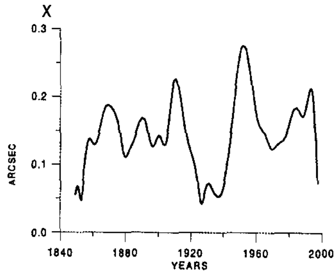

Figure 8. The envelope of the Chandler oscillation, X coordinate (after Kołaczek and Kosek, 1998).

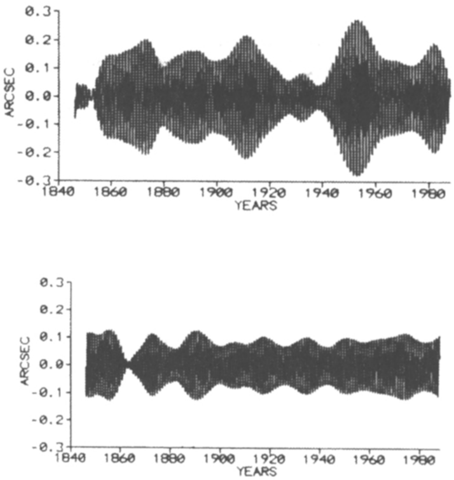

Figure 9. X components of the Chandler wobble and the seasonal variation obtained by the FT filter with widths of pass bands 1.08–1.31 and 0.93–1.09 respectively (after Nastula *et al.*, 1993).

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In the opinion of some authors, including Chandler himself, Kimura, Berg, Nicolini, and others, as well as Colombo and Shapiro (1968), Gaposchkin (1972) Dickman (1981) and Chao (1983), there exist two or even more free nutations with close periods of about 406, 426, 435 and 452 days. They could result in periodic variation in the amplitude of the Chandler motion with periods of about 11, 16, 22 and 40 years detected by Rykhlova (1970), Pejovic (1985), Nastula *et al.* (1993), and others.

On the other hand, Yatskiv *et al.* (1973) showed that the two-component model of the Chandler motion was not appropriate for describing the polar motion from 1846 through 1971. Lenhardt and Groten (1985) concluded from the comparison of the spectra of the ILS and the BIH data that multiple Chandler spectral peaks usually obtained from the ILS data are a misleading result caused by irregularities of the polar motion in the period 1925–1940. Recently, Vicente and Wilson (1997) estimated the Chandler frequency from a variety of polar motion time series which span over various time periods from 1846 through the early 1990s. They showed that estimates of the Chandler frequency vary, depending upon which time series is analysed, but the variation is not significant when associated intervals of confidence are considered.

Referring to Munk and MacDonald (1960), we conclude that "the difference in the interpretation as characterised by the damped and time-variable (or multi-component) models centers on the meaning of "period" and the methods whereby this is obtained from the record." The choice of appropriate model to describe the Chandler motion remains uncertain due to the lack of knowledge on the exitation process. At least the observed stability of the annual wobble argues against the hypothesis of large (about 4%) variation of the Chandler frequency (see Fig. 8).

5. Conclusion

Although the study of the Chandler motion has a long history extending over one century, the full interpretation of this phenomenon is not yet a resolved problem. One can suppose that the observations of polar motion were not precise enough in the past years to explain the Chandler motion essential features. It is much more likely that new approaches which employ observation of the polar motion excitation process should provide a better solution of the problem. In addition, the analyses so far seem to have been based on the assumptions of linear approximation of the equation of the Earth rotation and the observed Chandler component being a free motion. In reality, this component could be a more complicated manifestation of the energy balance between excitation and dissipation of the Earth's variable rotation.

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