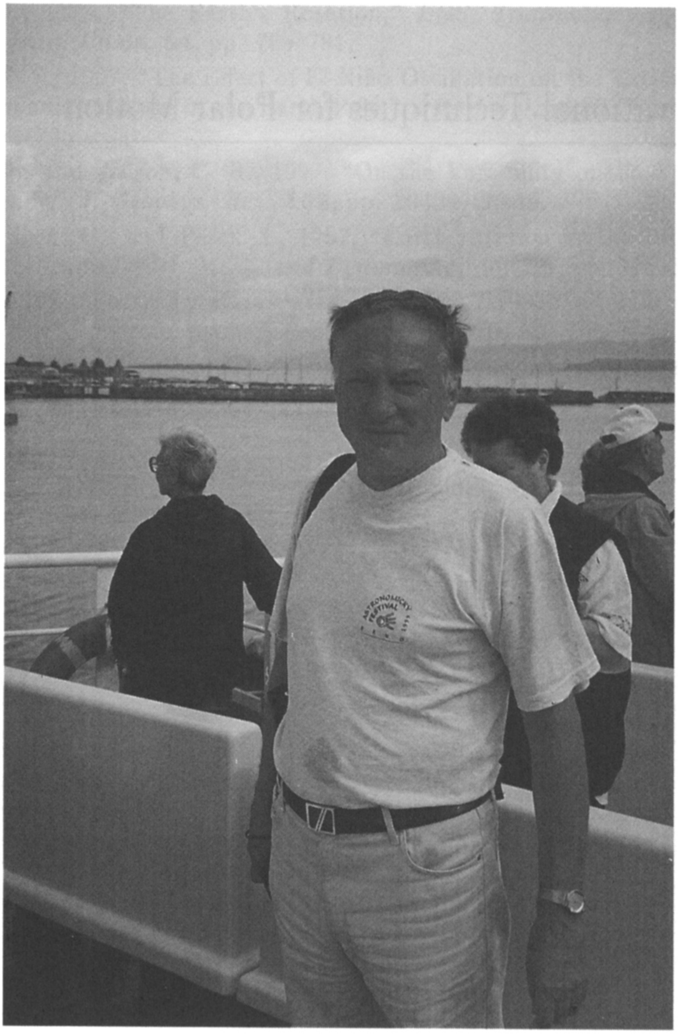
Part 3.

Observational Techniques for Polar Motion



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Survey of Observational Techniques and Hipparcos Reanalysis

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Abstract. Polar motion and Universal Time have been regularly determined since 1899 and 1956, respectively, at a number of observatories all over the world. Before the International Earth Rotation Service (IERS) was established in 1988, the classical astrometry instruments such as visual zenith-telescopes, PZTs, transit instruments, astrolabes *etc.* were used. The survey of all these instruments and the methods of observation used is described. The values of instantaneous latitude and UT0–UTC made at a set of selected observatories and based on individual star observations have been collected at the Astronomical Institute in Prague during the past years. They were recalculated using the most recent astronomical standards and the Hipparcos Catalogue, and used to determine the Earth orientation parameters (polar motion, celestial pole offsets and Universal Time). The most recent solution, based on about 4.5 million observations with 47 different instruments at 33 observatories, is described and the results of polar motion presented.

1. Introduction

Since the foundation of International Latitude Service (ILS) in 1899 millions of observations of latitude and Universal Time with different optical astrometry instruments have been made by generations of astrometrists. In 1988, Commission 19 of the International Astronomical Union set up the working group (McNally 1990) whose task was to propose the algorithms, collect the observations from a set of selected observatories and work out the new solution of Earth Orientation Parameters (EOP) using the Hipparcos Catalogue as a celestial reference frame (Vondrák 1991).

This paper first describes in short the observational techniques of optical astrometry used since the end of the last century to monitor polar motion and, after the International Atomic Time was created in 1956, also Universal Time. Then the most recent analysis of the observations made with these instruments at 33 selected observatories in the interval 1899.7–1992.0 is described and the EOP with 5-day resolution are presented.

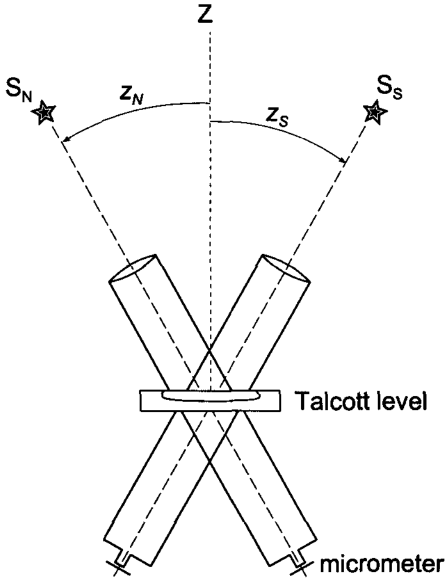

Figure 1. Principle of visual zenith-telescope.

2. Description of the Instruments and Methods of Observation

2.1. Visual Zenith-telescope, Floating Zenith-telescope, Visual Zenith Tube

Visual zenith-telescopes (ZT) are the oldest instruments used during the whole history of the ILS. They used the Horrebow-Talcott method to measure the difference of nearly equal zenith distances of two stars when passing over the local meridian on opposite sides of zenith. An optical scheme of the instrument is shown in Figure 1.

The small difference of zenith distances of two stars $\mathrm{S_S}$, $\mathrm{S_N}$ in the plane of meridian — z_S south and z_N north of zenith Z — is measured by means of a screw micrometer placed in the focal plane of the telescope that is set to two positions 180° apart. The Talcott level is fixed firmly to the telescope in order to detect the possible non-alignment of the vertical axis of the instrument with the local plumb-line. The difference of the micrometer readings D_S, D_N in both positions of the telescope are then used to calculate first the difference of zenith distances $z_S - z_N$ and then the latitude φ using the formulas

$$\begin{aligned} z_S - z_N &= (D_S - D_N)M + \text{corr.(level+refraction+curvature)} \\ \varphi &= \frac{1}{2}(\delta_S + \delta_N + z_S - z_N), \end{aligned} \qquad (1)$$

in which M is the value of micrometer screw and δ_S, δ_N denote the declinations of the stars. The corrections for the different level reading, difference of refraction and curvature of the parallel are also applied.

Similar to visual zenith-telescope are *floating zenith-telescope* (FZT) and *visual zenith tube* (VZT) that do not use Talcott levels. The telescope of the former instrument is placed in a metallic ring floating in a mercury pool in order to assure that the axis of rotation of the telescope is absolutely vertical. The telescope of the latter instrument is always pointed to the zenith and its small inclination with respect to local plumb-line is measured by means of reading the microscope micrometer relative to three plummets; typically only one star (close to the zenith) is observed in two opposite positions of the telescope. The same basic equations (1) are used to determine the latitude, with the exception of a level correction that is missing in the former and replaced by a microscope micrometer reading in the latter case.

The list of all instruments of this type used in our reanalysis is given in Table 1, in chronological order as the observatories started the observations.

Table 1. Zenith-telescopes used in the new analysis.

Observatory	Instrument	Time interval
Cincinnati	ZT	1899.7–1916.0
Tschardjui	ZT	1899.7–1919.4[a]
Carloforte	ZT	1899.8–1943.3, 1946.5–1979.0
Gaithersburg	ZT	1899.8–1915.0, 1932.6–1979.0
Ukiah	ZT	1899.8–1960.0[b]
Mizusawa	ZT	1900.0–1979.0
	FZT	1967.0–1984.8
Pulkovo	ZT	1904.7–1941.5, 1948.7–1992.0[c]
Kitab	ZT	1930.9–1979.0
Belgrade	ZT	1949.0–1986.0
Poltava	ZT#1	1949.7–1990.4, 1950.2–1968.8[d]
	ZT#2	1967.9–1980.8
Irkutsk	ZT	1958.2–1991.0
Blagoveschtschensk	ZT	1959.0–1992.0
Jósefoslaw	ZT	1961.8–1992.0
Tuorla-Turku	VZT	1963.7–1989.1

[a] instrument moved to another location at 1909.6
[b] series truncated at 1960.0 as explained below
[c] instrument located at another place after World War II
[d] the same instrument used simultaneously in two different programs: four-group and bright stars, respectively

2.2. Photographic Zenith Tube

The *Photographic zenith tube* (PZT) was invented at the beginning of the century in the USA, first to measure the latitude, and later improved to determine also

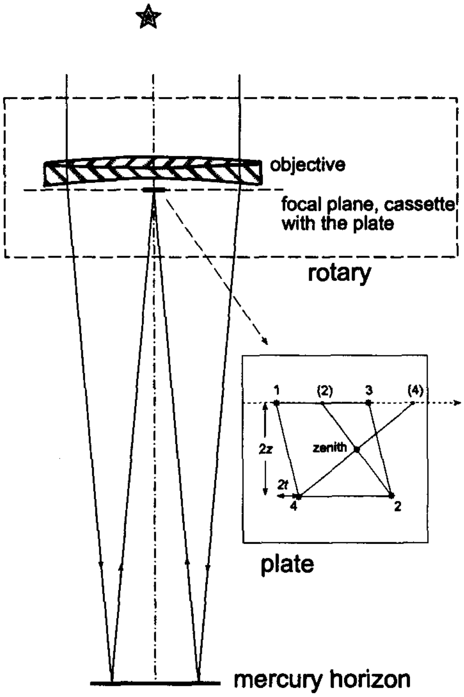

Figure 2. Principle of photographic zenith tube.

Universal Time. From the measured cartesian coordinates of four images of the same star on the plate, its zenith distance and hour angle are determined. The optical system of the instrument can be seen in Figure 2.

The telescope is pointed towards the zenith and is broken with a mercury horizon at which the light from the star is reflected to the photographic plate placed in the focal plane (intentionally coincident with the nodal plane of the objective). The plate is fixed in a cassette that is driven by a motor compensating for the apparent motion of the star across the meridian during each exposure. The upper part of the instrument (*i.e.* the objective and the cassette), so called rotary, is rotated around the vertical axis by exactly 180° between each of the four exposures made during the observation of one star. The whole cycle (consisting of four exposures and four rotations of the rotary) lasts typically about two minutes. The result is four images of the same star on the plate, forming approximately a trapezoid. The measured plate coordinates are then used to determine the zenith distance z (positive north) and hour angle t of the star at the moment UTC of the center of the cycle (plus plate scale and position of zenith on the plate), from which the latitude φ and UT0−UTC can be calculated provided the right ascension α and declination δ of the star are known:

$$\begin{aligned} \varphi &= \delta - z \\ \text{UT0–UTC} &= 0.9973...(t + \alpha - S_\circ^G - \lambda_\circ) - \text{UTC}, \end{aligned} \tag{2}$$

where S_o^G is the Greenwich sidereal time at 0^hUT and λ_o the conventional longitude. The PZTs used in our reanalysis are displayed in Table 2.

Table 2. Photographic zenith tubes used in the new analysis.

Observatory	Instrument	Time interval
Washington	PZT#1	1915.8–1955.3
	PZT#2	1954.3–1984.8[a]
	PZT#3	1981.7–1992.0
Richmond	PZT#1	1949.8–1987.5[b]
	PZT#2	1981.9–1989.4
Mount Stromlo	PZT	1957.8–1985.7
Mizusawa	PZT#1	1959.0–1975.3
	PZT#2	1974.2–1992.0[c]
Punta Indio	PZT	1971.6–1984.5
Ondřejov	PZT	1973.1–1992.0

[a] instrument moved to another pillar at 1956.3
[b] instrument moved to another pillar at 1954.9
[c] instrument moved to another pillar at 1983.2

2.3. Equal Altitude Instruments

This section describes a group of instruments using the method of equal altitudes; from the measured time of transit of the star over the local almucantar (the small circle on the celestial sphere whose angular distance from zenith is constant) the difference δh between observed and calculated altitude of the star is determined. Provided at least three stars are observed in different azimuths, the geographic position and the (generally unknown) zenith distance can be calculated.

Danjon astrolabe (AST) is the instrument invented in Paris at the end of the last century and further improved in the fifties. Its optical scheme is shown in Figure 3.

The light coming from the star is doubled by reflections on the glass equilateral prism and mercury horizon. If it were not for the Wollaston prism, the direct and indirect image would move in opposite directions in the field of view; when the apparent altitude of the star is equal to 60° the two images are coincident. In order to observe stars in different azimuths, the instrument rotates around the vertical axis. The Wollaston prism, driven by a motor and screw along the line of sight, is used by the observer to keep the two images in coincidence for some time during which the electric contacts connected to the screw are registered.

Circumzenithal (CZ) was invented in Prague, also at the end of the last century, and further improved in the sixties. Although its optical scheme is different from the astrolabe as shown in Figure 4, it works on a similar principle.

Two images of the star are formed by reflections on a mercury horizon and two crossed mirrors. Again, both images move in opposite directions in the

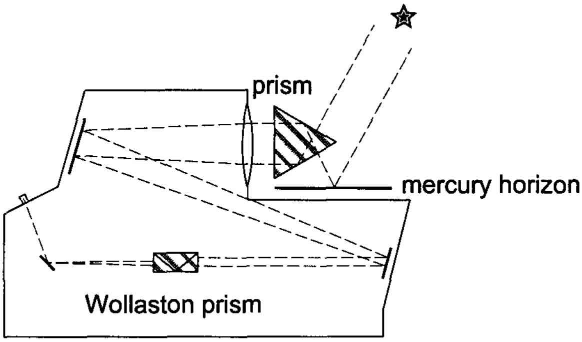

Figure 3. Optical scheme of Danjon astrolabe.

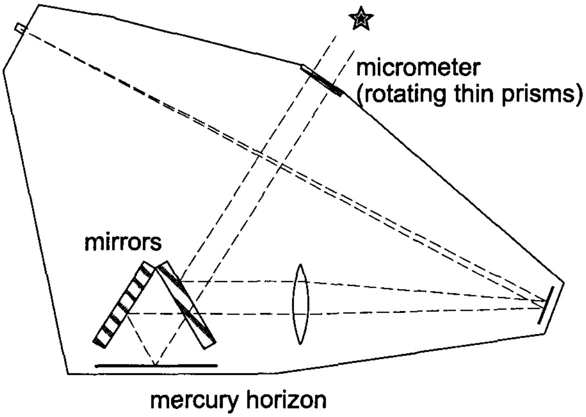

Figure 4. Optical scheme of circumzenithal.

field of view. The altitude of the star is equal to the angle between the two mirrors when both images merge. The micrometer consists of two thin glass prisms rotating in opposite directions around the optical axis; the total effect of this motion is that the light coming from the star is deflected in the vertical plane by a small angle that varies almost linearly with the angle of rotation of both prisms. The observer regulates the velocity of the motor that drives the micrometer to keep the coincidence of the two images. Electrical contacts are firmly connected to the metallic rings in which the prisms are fixed and their closing and opening times are registered.

There are also more recent instruments of this type, *photoelectric astrolabes* (PAST). They have been developed in China and France and their optical schemes are similar to the preceding two instruments. Instead of an optical micrometer and human eye, there is a grid in the focal plane and a photomultiplier to measure the time of star transit over the almucantar.

The basic equations used to calculate the difference in altitude δh from the observed time of transit (UTC) and to relate this quantity to the instantaneous latitude and UT0 are

$$\begin{aligned}\delta h &= z_\circ - \arccos[\sin\varphi_\circ \sin\delta + \cos\varphi_\circ \cos\delta \cos(1.0027..\mathrm{UTC} + S_\circ^G + \lambda_\circ - \alpha)] \\ \delta h &= 15.041...(\mathrm{UT0{-}UTC})\cos\varphi_\circ \sin a - (\varphi - \varphi_\circ)\cos a, \qquad (3)\end{aligned}$$

in which $\varphi_\circ$ is the adopted approximate value of the latitude and a is the azimuth of the star. The list of instruments of this type used in the new analysis is given in Table 3.

Table 3. Equal altitude instruments used in the new analysis.

Observatory	Instrument	Time interval
Paris	AST	1956.5–1983.0
Shanghai	AST	1962.0–1985.0
	PAST	1975.7–1985.0
Wuhang	AST	1964.0–1986.2
Santiago de Chile	AST	1965.9–1990.9
Pecný	CZ	1970.0–1992.0
Shaanxi	PAST#1	1974.0–1984.8
	PAST#2	1985.5–1992.0
Simeiz	AST	1977.0–1991.0
Beijing	PAST	1979.0–1987.8
Prague	CZ	1980.2–1985.0,1985.2–1992.0[a]
Yunnan	PAST	1980.7–1991.3
Grasse	PAST	1983.2–1992.0
Bratislava	CZ	1987.0–1991.9

[a] instrument moved to another location

2.4. Photoelectric Transit Instrument

Photoelectric transit instrument (PTI) is used to measure the star's time of transit over the local meridian, by means of a grid and photomultiplier. The instrument, based on the classical visual transit instrument, has been developed in the former USSR and used also in China. Its optical scheme can be seen from Figure 5.

The broken telescope rotates around a horizontal axis that is fixed in the east-west direction, so that the optical axis moves in the plane of the local meridian. The observation is made in two reversed positions of the telescope (eyepiece east and west), in order to compensate for the collimation error. The observed time of the star's transit UTC is used to calculate UT0–UTC from the simplified equation

$$\mathrm{UT0{-}UTC} = 0.9973..(\alpha - S_\circ^G - \lambda_\circ) - \mathrm{UTC} + \mathrm{corr.(level{+}azimuth)} \qquad (4)$$

in which α is the right ascension of the star and $\lambda_\circ$ the conventional longitude. The small corrections for the level of the axis (measured by a level) and the non-

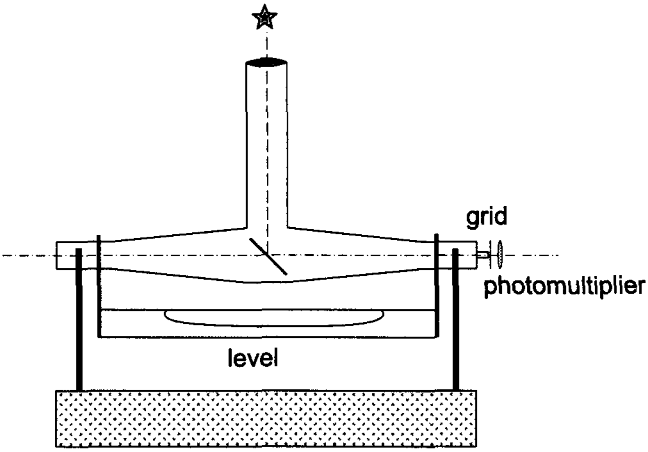

Figure 5. Optical scheme of photoelectric transit instrument.

alignment of the optical axis with the meridian (determined from observations of a group of stars) are also applied.

The list of PTIs used in the reanalysis is given in Table 4.

Table 4. Photoelectric transit instruments used in the new analysis.

Observatory	Instrument	Time interval
Pulkovo	PTI#1	1959.7–1971.4
	PTI#2	1971.2–1985.3
	PTI#3	1971.8–1992.0
Kharkov	PTI	1973.0–1992.0
Nikolaev	PTI	1974.4–1992.0
Irkutsk	PTI	1979.1–1992.0
Wuhang	PTI	1981.9–1987.2

3. The Solution and Results

A complete and detailed description of the previous solution have been described elsewhere (Vondrák *et al.* 1998 or Vondrák 1999) so only a short outline and the substantial changes made since then are given here. The geographic distribution of the observatories participating in the solution and listed above is displayed in Figure 6.

The Hipparcos Catalogue (ESA 1997), being a principal realization of the recently adopted International Celestial Reference System in optical wavelength (Kovalevsky *et al.* 1997), is used to monitor the celestial motions of local verticals

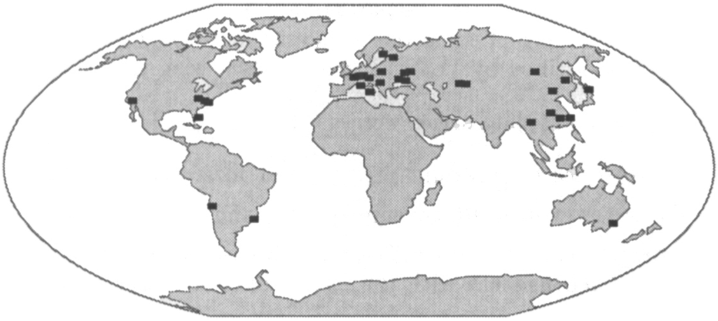

Figure 6. Geographic distribution of participating observatories.

of all participating observatories. From the above description of the instruments used it follows that we have three different types of observations:

- instantaneous latitude φ, measured by ZTs, VZT, FZT and PZTs;
- instantaneous values of Universal Time, UT0–UTC, measured by PZTs and PTIs;
- values δh (that is a combination of both φ and UT0–UTC), measured by ASTs, PASTs and CZs.

These three observables lead to three different types of observation equations. They are used, after applying all necessary corrections to account for such effects as plate tectonic motions (Argus & Gordon 1991), short-periodic tidal variations of the Earth's speed of rotation (Yoder *et al.* 1981), oceanic tidal variations of local verticals (Scherneck 1995), deformations of the apparent almucantar (Pešek 1992), color and magnitude effects (Hefty 1991) or instrumental constants, and to refer them to the Hipparcos Catalogue and the most recent system of astronomical constants and standards (McCarthy 1996) in a global least-squares adjustment to estimate the following parameters:

- coordinates of the pole x, y (for each 5-day interval);
- Universal Time UT1–UTC (for each 5-day interval, only after 1956);
- celestial pole offsets $\Delta\varepsilon, \Delta\psi$ (for each 5-day interval);
- deviations in latitude A, A_1, B, C, D, E to account for the constant, linear, annual and semiannual systematic errors (for each instrument);
- deviations in Universal Time A', A'_1, B', C', D', E' to account for the constant, linear, annual and semiannual systematic errors (for each instrument;
- rheological parameter $\Lambda = 1 + k - l$ responsible for solid-Earth tidal variations of the vertical (for each instrument).

18 additional constraints tying the parameters $A - E, A' - E'$ have to be applied since the matrix of normal equations without them would be singular. We used the procedures described by Vondrák *et al.* (1998) with the following changes:

- slightly different data series were used:
  - new series from Mount Stromlo and Józefoslaw,
  - more data from Blagoveschtschensk and Kharkov,
  - data from Ukiah after 1960.0 are discarded since this part was found to be inconsistent with the results of other observatories;
- prior to global adjustment, results of different instruments of the same type working at the same observatory have been merged into a single series, the steps in data (if not reported by the observatory) being estimated from overlapping series or from comparison with previous solutions, and removed from the data:
  - Mizusawa ZT+FZT (1900.0–1984.8),
  - Poltava ZT#1+#2 (1949.7–1990.4),
  - Pulkovo ZT (1904.7–1992.0), PTI#1+#2+#3 (1959.7–1992.0),
  - Richmond PZT#1+#2 (1949.8–1989.4),
  - Shanghai AST+PAST (1962.0–1985.0),
  - Washington PZT#1+#2+#3 (1915.8–1992.0);
- corrections of Hipparcos proper motions of more stars (assumed double or multiple) were estimated from the trends found in the residuals (about 20% in contrast to 10% in the previous solution).

The solution, based on 4 450 197 individual star/star pair observations made with 47 different instruments located at 33 observatories, yielded 29 813 estimated parameters. These comprise 6693 5-day values of $x, y, \Delta\varepsilon, \Delta\psi$, 2 630 5-day values of UT1–UTC, 393 station parameters and 18 Lagrange multipliers for the constraints. The average standard error of one observation is $0\farcs188$. Although we obtained all five EOP, only the results of polar motion are presented and further discussed here; the celestial pole offsets obtained in the present solution are analyzed by Yaya *et al.* (2000).

Before being displayed in Figure 7, polar motion was subject to filtering (Vondrák 1977) with the coefficient of smoothing $\varepsilon = 0.18 \times 10^{-6}$ day^{-6} that yields *a posteriori* standard errors (*i.e.*, those calculated from the dispersion of individual values around the smoothed curve) in average two times larger than their *a priori* values (the ones calculated from the dispersion of residuals of the solution in 5-day intervals). The transfer function of the applied filter is equal to 0.5 for a period of 84 days.

The smoothed polar motion curve is displayed as a three-dimensional plot from which the beat period (of about 6 years) between the annual and Chandler term is clearly seen. Less visible but also present are longer periods, including the trend (often referred to as secular polar motion). In order to see these variations more clearly, we applied a stronger smoothing to the polar motion series, this

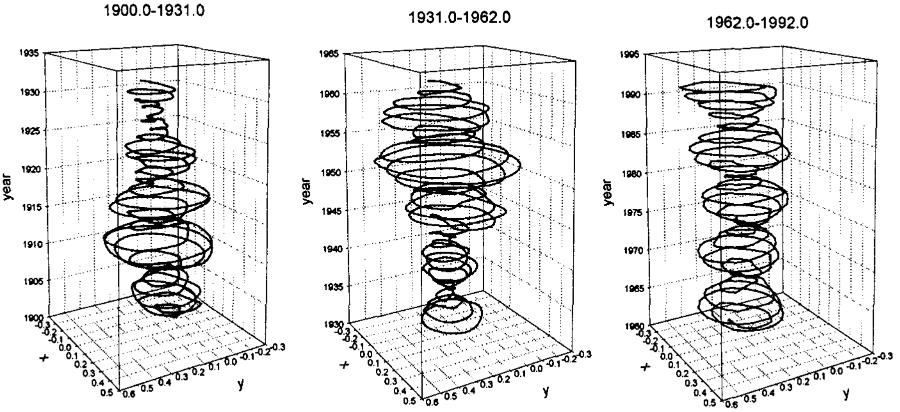

Figure 7. Polar motion in three dimensions (time running upwards), smoothed with $\varepsilon = 0.18 \times 10^{-6}$ day^{-6}.

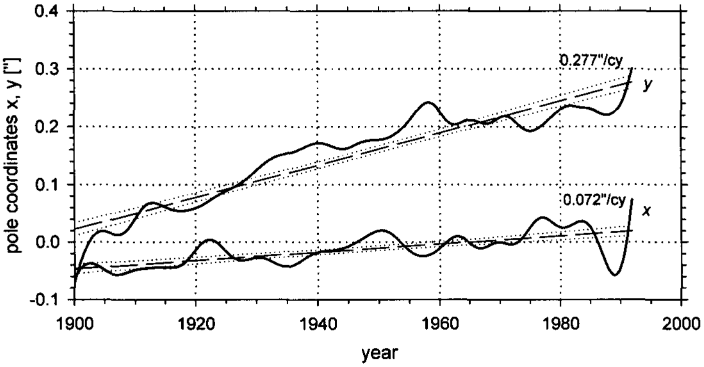

Figure 8. Long-periodic part of polar motion, obtained by smoothing the original series with $\varepsilon = 1 \times 10^{-16}$ day^{-6}.

time with $\varepsilon = 1 \times 10^{-16}$ day^{-6} (transfer function equal to 0.5 for the period of 8 years). The result is depicted, this time for each component separately, in Figure 8. The linear regression gives the trends in x and y equal to 0.72 mas and 2.77 mas per year, respectively. These trends are also displayed in the figure, with their formal 95% confidence level (dotted lines). They correspond to the trend of 2.86 mas per year towards 75.4°W which is substantially smaller than the preferred value 3.51 mas per year towards 79.2°W derived recently by Gross & Vondrák (1999) from our previous solution.

4. Discussion and Conclusions

We have worked out and presented the new EOP solution from optical astrometry observations, based on more observations and slightly different procedures from the preceding one. The terrestrial reference frame involved is hopefully more rigid than before, thanks to the merged data from more instruments of the same type located at the same observatory. The trend in polar motion found from this solution, 2.86 mas per year toward 75.4°W, is now by about 10–20 per cent smaller than the previous estimations, very probably reflecting the fact that the observations at Ukiah after 1960 (with abnormally positive trend) have been eliminated from the new solution.

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References

Argus, D.F., & Gordon, R.G. 1991, *Geophys. Res. Lett.* **18**, 2039.

ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200.

Gross, R.S., & Vondrák, J. 1999, *Geophys. Res. Lett.*, **26**, 2085.

Hefty, J. 1991, in Journées 1991 Systèmes de Référence Spatio-Temporels, N. Capitaine, Observatoire de Paris, 1991, 217.

Kovalevsky, J., Lindegren, L., Perryman M.A.C., Hemenway, P.D., Johnston, K.J., Kislyuk, V.S., Lestrade, J.F., Morrison, L.V., Platais, I., Röser, S., Schilbach, E., Tucholke, H.-J., de Vegt, C., Vondrák, J., Arias, F., Gontier, A.M., Arenou, F., Brosche, P., Florkowski, D.R., Garrington, S.T., Preston, R.A., Ron, C., Rybka, S.P., Scholz, R.-D., Zacharias, N., 1997, *A&A*, **323**, 620.

McCarthy, D.D. 1996, IERS Conventions, IERS Technical Note, 21.

McNally, D. (ed.) 1990, Transactions of the IAU XXB, Kluwer, 198.

Pešek, I. 1992, A&A, 262, 621.

Scherneck, H.-G. 1995, priv. comm.

Vondrák, J. 1977, *Bull. Astron. Inst. Czechosl.*, **28**, 84.

Vondrák, J. 1991, *Bull. Astron. Inst. Czechosl.*, **42**, 283.

Vondrák, J. 1999, *Surveys in Geophysics*, **20**, 169.

Vondrák, J., Pešek, I., Ron, C., & Čepek, A. 1998, *Publications of the Astronomical Institute, Acad. Sci. Czech R.*, **87**, 1.

Yaya, P., Bizouard, C. & Ron, C. 2000, this volume.

Yoder, C.F., Williams, J.G., & Parke, M.E. 1981, *J. Geophys. Res.*, **86**, 881.