ON THE DETERMINATION OF UT1 BY THE BIH AND THE U.S.S.R. TIME SERVICE

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ABSTRACT

The reference systems for the determination of UT1 and polar coordinates are discussed. Some arguments are given in support of the adoption of the mean pole origin (MPO) defined by the mean latitudes of the observatories. Taking into account the frequency response of the filters used by the BIH and the U.S.S.R. Time Service, the effects of the errors of the adopted nutational coefficients and tidal variations of the vertical are estimated.

1. INTRODUCTION

The following astronomical systems of terrestrial coordinates are used in the study of the Earth's rotation:
MPO - The mean pole origin defined by the mean latitudes of observatories at any moment. For determining the mean latitudes different methods may be used, such as the well-known Orlov's method.
CIO - The Conventional International Origin defined by the fixed latitudes of the ILS stations.
BIH 1968 - The reference system adopted by the BIH and referred to the epoch of 1968.
UT(SU) 1975 - The reference system adopted by the U.S.S.R. Time Service and referred to the epoch of 1975.
Some information concerning the observational data and the methods used for the determination of the above reference systems are given in Table 1. The merit of any reference system for studying the rotation of the Earth depends on:
(1) the contribution of the secular polar motion (if it exists) to the secular variations of the mean latitudes and longitudes of the stations,
(2) the stability of the periodic, nonpolar variations of the latitudes and longitudes of the observing stations,
(3) the statistical properties of the errors of astronomical observations,
(4) the methods used for preserving the reference system.
Let us consider some of these problems.

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Table 1. Astronomical reference systems of terrestrial coordinates.

Name of System	Number of Observatories	Number of Instruments		Interval of Observations	Primary Reference System
		Time	Latitude		
MPO	all	-	-	more than 1.6 yr.	instrumental
CIO	5	-	5	1900.0 - 1906.0	instrumental
BIH 1968	51	48	39	1964.0 - 1967.0	CIO
UT(SU) 1975	5	8	-	1957.0 - 1971.0 1974.0 - 1975.0	BIH 1968

2. SECULAR AND LONG-PERIOD POLAR MOTION

The existence of the secular and long-period variations of the mean longitudes and latitudes of stations has been proved by many authors. These variations may be both real and fictitious. The former are due to the motion of the Earth's rotational axis, crustal movements, and variations in the direction of gravity, etc. The latter may result from errors of astronomical observations and their reduction. Using the data of the five ILS stations, many determinations of the secular polar motion have been carried out (Yumi and Wako, 1960; Mikhailov, 1971). It has been shown that the parameters of the secular polar motion vary considerably in time and depend on the combination of the ILS stations. On the average, for the time interval from 1900 to 1968 the mean pole has been moving with respect to the CIO with the velocity $0\overset{''}{.}0030$ - $0\overset{''}{.}0040$ per year in the direction of the meridian 73° W. The observed variation, B_o, and the theoretical variation, B_t, of the mean latitudes of several stations are given in Table 2.

Table 2. Linear trends of mean latitudes.

Station	Instrument	Interval of Observations	B_o / B_t (in $0\overset{''}{.}001$ / year)
Mizusawa	VZT	1900 - 1972	-3.0 / -2.1
Mizusawa	FZT	1940 - 1972	+4.0 / -2.1
Mizusawa	PZT	1957 - 1972	-3.0 / -2.1
Tashkent	VZT, T1	1895 - 1896 1969 - 1970	-4.2 / -3.4
Washington	PZT	1915 - 1972	+3.0 / +3.0
Richmond	PZT	1949 - 1972	+0.1 / +3.0
Ukiah	VZT	1900 - 1967	+2.7 / +2.4

These trends were calculated assuming that the secular polar motion based on the data of the five ILS stations was real. This table does not explicitly confirm the reality of the secular polar motion. Moreover, Fedorov (1975) showed that the values of the linear trends of the mean latitudes of the ILS stations does not contradict the hypothesis of the random character of these trends.

At present there is no way to resolve the problem of how much is secular polar motion and how much is due to other secular effects providing that the number of stations is limited, for example, to five. However, it is possible to solve the problem qualitatively. We have calculated the index, k, the sign of which might be used as a criterion for a decision on the reality of the secular polar motion derived from the ILS data. We let

$$k = (S_2{}^2/S_1{}^2) - 1,$$

where

$$S_1{}^2 = \frac{1}{n}\sum_{j=1}^{n} (\psi_j - \psi_{jo})^2,\quad S_2{}^2 = \frac{1}{n}\sum_{j=1}^{n} (\psi_j - \psi_{jo}) - (\Delta\psi_j - \Delta\psi_{jo})^2,$$

ψ_j is the yearly mean value of the latitude or longitude of the station, j, reckoned from an arbitrary initial value, ψ_{jo}, $\Delta\psi_j$ is the correction for secular polar motion derived from the ILS data and reckoned from an initial vaule, $\Delta\psi_{jo}$, and n is the number of stations. If the sign of k is negative it would support the reality of the secular polar motion. The results are given in Table 3. They do not support the reality of secular polar motion. We can conclude that the secular trend of the CIO relative to the MPO is, in the most part, due to the local nonpolar effects of the ILS stations.

Table 3. Values of the index, k.

	Latitude		Time	
Year	n	k	n	k
1955	10	+1.18	24	+0.20
1956	10	+0.93	25	+0.03
1957	17	+0.72	28	+0.08
1958	18	+0.79	28	+0.05
1959	21	+0.57	28	+0.01
1960	21	+0.20	32	0
1961	21	-0.14	32	0
1962	28	0	32	0
1963	28	0	32	+0.08
1964	27	0	32	+0.16
1965	26	+0.12	32	+0.01
1966	26	+0.19	-	-
1967	26	+0.26	-	-
1968	26	+0.19	-	-

If the secular polar motion does not exist, we should clear up whether there is some long-period motion with a period comparable to the interval of observation. Markowitz (1970) claimed to reveal the 24-year libration of the mean pole. Recently this problem was carefully studied by Vicente and Currie (1976). They have found a 30-year period in the polar coordinates. We have tried to find new support for this discovery, but failed. The polar coordinates have been calculated for the period 1905 - 1940 from observations of two groups of stations:

Group 1 (x_1, y_1) - Mizusawa, Carloforte, Ukiah;

Group 2 (x_2, y_2) - Pulkovo, Greenwich, Washington.
The value of (x_1, y_1) and (x_2, y_2) have been filtered and analyzed by the same method as given in the paper by Vicente and Currie (Figure 1).

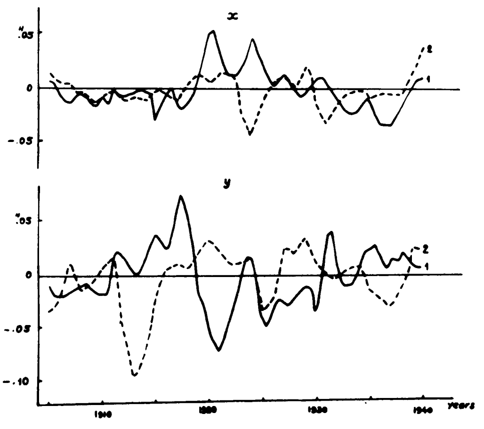

Figure 1. Long-period variations of polar coordinates derived from two groups of stations.

The significant periods found by the maximum entropy power spectrum analysis are 23.5 years and 22.0 years in x_1 and y_1, respectively, and 20.0 years and 29.5 years in x_2 and y_2, respectively. There are no correlations between the values of x_1 and x_2, y_1 and y_2. The long-period components in polar motion appear to result from local, nonpolar variations of the latitudes of some stations. We have concluded that the main contribution to these components is from the Ukiah station. Figure 2 shows the variation of the angle (S_{uk}) between the verticals of Ukiah and Kitab (Tschardjui) stations as well as the mean latitude of Ukiah (ϕ_u). There is a significant correlation between these two curves, the amplitudes of which are about 0".20. The variations of S_{uk} do not depend on polar motion (Fedorov et al., 1972). Therefore the 20 to 30-year variation of mean latitude of Ukiah is nonpolar and may contribute to variations of x_1 and y_1 with an amplitude of about 0".05. Figure 3 also gives strong support to this statement.

3. ON THE PRESERVATION OF THE REFERENCE SYSTEM BY THE BIH AND THE U.S.S.R. TIME SERVICE

To preserve the reference system the BIH uses fixed corrections to the data of the individual instruments to account for the local variations of latitude and longitude in the form of a constant, an annual and a semi-annual term:

$$R_j = a_j + b_j \sin 2\pi\theta + c_j \cos 2\pi\theta + d_j \sin 4\pi\theta + e_j \cos 4\pi\theta, \quad (1)$$

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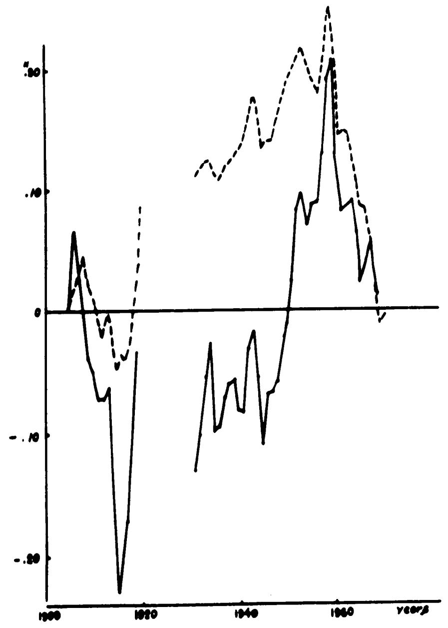

Figure 2. Variations of angle between the verticals of Ukiah and the Tschardjui-Kitab stations (solid line) and the mean latitude of Ukiah (dashed line).

where a_j, b_j, c_j, d_j, and e_j are the coefficients to be determined, and θ is the frequency of one cycle per year. It is assumed that R_j represents well enough the nonpolar variations of latitude and longitude of the stations. Clear tests are possible to check this assumption. We have calculated the angles between the verticals of several stations, S_o and S_c, based on the observational data as well as the coefficients given by the BIH, respectively.

Let D_o and D_c be the dispersions of the observed values S_o, and calculated values, S_c, respectively. In all cases we found $D_o >> D_c$. Power spectrum analysis of S_o showed the existence of many periodic components besides the annual and semi-annual components. For example, we show in Figure 4 the power spectrum of variations of the angle between the verticals of Mizusawa and Paris from 1968 to 1976. The significant periods are 6.0, 1.0, 0.6, 0.5, and 0.4 years. The dispersion, $D_o = 2.095\ (0\rlap{.}''1)^2$, is twice as large as D_c.

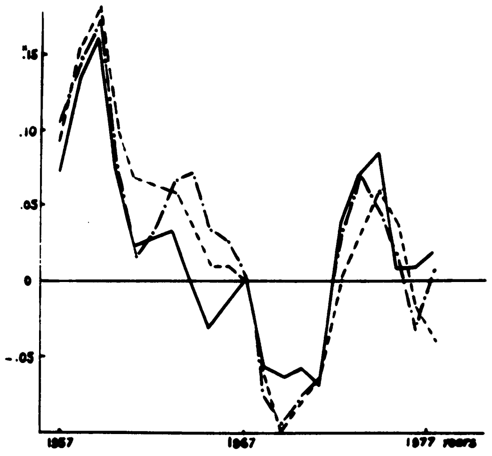

Figure 3. Variations of the angle between the verticals of stations and their mean latitudes. Solid line (S_{uk}) is the angle between the verticals of Ukiah and Kitab VZTs. Dashed line (S_{um}) is the angle between the verticals of Ukiah and mean observatory (Pulkovo, Kazan, Poltava, Kitab zenith telescopes). Dashed line with solid circles (ϕ_u) is the mean latitude of Ukiah with the opposite sign.

Therefore in our opinion the method for preserving the reference system by the BIH could be improved by using the statistical prediction of residuals, R_j, in the form,

$$R_{jt} = \sum_k p_{jk} R_{jt-k}, \tag{2}$$

instead of the representation (1). The terms, p_{jk}, in (2) are the coefficients of the prediction error filter. In the computation process of the U.S.S.R. Time Service for preserving the reference system the following condition is used:

$$\sum_j \lambda_j^2 (\delta_j - \delta_j')^2 = \text{minimum}. \tag{3}$$

The terms, δ_j and δ_j', are the systematic errors of time observations by the instrument, j, for two successive intervals of time. This condition corresponds to the assumption that the values of δ_j can be described by the Markov random process. This is not the case, and the use of (2) would be preferable.

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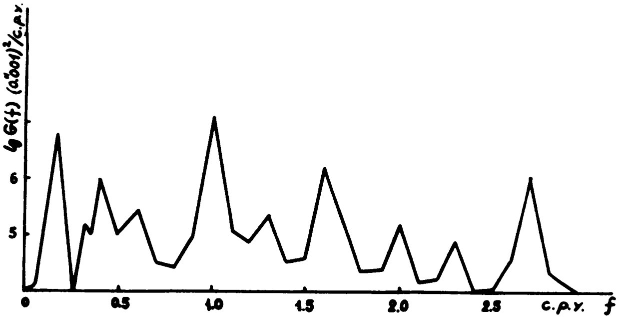

Figure 4. Power spectrum of S_0 for Mizusawa and Paris stations.

4. SYSTEMATIC ERRORS OF TIME OBSERVATIONS

4.1. Correction for the errors of nutation coefficients and the forced diurnal motion of the pole

Currently nutation is computed from a theory of the rotation of the Earth as a rigid body and only the coefficient of the principal term is determined from observations. If the values of the coefficients in obliquity, a_i, and in longitude, b_i, are in error, the values of the clock correction will contain errors depending on both the right ascension, α, and declination, δ, of the star as well as the coordinates of the perturbing bodies such as the longitude of the lunar node, Ω. These errors can be represented by

$$\Delta u_i = \tfrac{1}{2}(\Delta a_i + \Delta b_i)\cos(\theta_i t + \beta_i - \alpha)\tan\delta + \tfrac{1}{2}(\Delta a_i - \Delta b_i)\cos(\theta_i t + \beta_i + \alpha)\tan\delta \qquad (4)$$

where θ_i and β_i are the frequency and the phase of the corresponding nutation terms, and Δa_i and Δb_i are the corrections to the adopted nutation coefficients. Variations of longitude due to the effect of the forced diurnal motion of the pole are of the same form as (4). For this reason there is no possibility of deriving these effects separately from the observational data.

The BIH makes the corrections for the forced diurnal motion of the pole predicted by the theory of the rotation of the rigid Earth with a multiplication factor of 0.76. The U.S.S.R. Time Service does not make such corrections. This is not a part of the reduction of observations because, in this case, the choice of the method of reduction defines the axis to which the ephemeris of the forced nutation refers. From our point of view the best choice of the reference axis would be the mean axis of figure of the Earth's mantle. A new set of nutation coefficients which would refer to this axis may be calculated on the basis of Molodenskij's theory of the rotation of the Earth. For example, the largest nutation coefficients adopted by the IAU and calculated by Molodenskij are given in Table 4. We have calcualted the amplitudes of the corresponding variations of time assuming the nutation coefficients given by Molodenskij are real and that tan δ = 1.0. These variations are shown in Table 5 for three cases:

I - the amplitudes of variations of time due to the errors of nutation terms and including the effect of forced diurnal motion of the pole computed for a rigid Earth,

II - the same as I but a deformable Earth was assumed for the derivation of the effects of forced diurnal motion,

III - the same as I without any corrections for forced diurnal motion.

Table 4. Values of nutation coefficients.

Argument	Adopted by IAU		Calculated by Molodenskij	
	$\Delta\varepsilon$	$-\Delta\psi \sin \varepsilon$	$\Delta\varepsilon$	$-\Delta\psi \sin \varepsilon$
☊	9.″210	6.″858	9.″203	6.″841
2☉	0.552	0.507	0.572	0.523
2☾	0.088	0.081	0.097	0.090

Table 5. Effect of the errors of nutation terms in time observations.

Argument	Aliasing Period (days)	Amplitudes of variations (ms)		
		I	II	III
☊ + α	385	0.33	0.33	0.33
☊ - α	346	0.73	0.74	0.80
2☉ - α	365	1.00	1.05	1.20
2☉ + α	122	0.13	0.13	0.13
2☾ - α	14.2	0.20	0.30	0.60
2☾ + α	13.2	0.00	0.00	0.00

4.2. Correction for the tidal variation of the vertical

Tidal variations in the direction of the vertical may be a cause of periodic variations in the observed longitude. These may be expressed in the form,

$$\Delta u_2 = \Lambda \frac{1}{g\rho \cos^2\phi} \frac{\partial V}{\partial \lambda}, \tag{5}$$

where $\Lambda = 1 + k - \ell$ is the combination of Love and Shida numbers depending on the mechanical properties of the Earth, and ρ is the radius of the Earth, g is the acceleration of gravity, and V is the potential of the tide-producing force. The latter can be represented by the sum of periodic terms. These effects are shown in Table 6. The U.S.S.R. Time Service does not apply corrections for these effects. The BIH makes these corrections assuming that Λ = 1.20.

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Table 6. Effects of the tidal variation of the vertical in time observations.

Tide	Aliasing Period (days)	Amplitude of Variations (ms)
K_1	365	0.73
P_1	183	0.24
K_1	183	0.16
M_1	14.8	1.26
O_1	14.2	0.52
N_1	10.3	0.24

4.3. Correction for errors in the polar coordinates

This correction is of the form

$$\Delta u_3 = (\Delta x \sin\lambda - \Delta y \cos\lambda) \tan\phi, \tag{6}$$

where Δx and Δy are the corrections to the polar coordinates. The motions of the CIO and the BIH 1968 reference systems relative to the MPO are caused mainly by the local effects at the stations participating in the ILS and the BIH. We have calculated the effects of these motions in time observations assuming that the MPO system is adopted as the standard. These are shown in Table 7.

Table 7. Effects of the instability of the reference systems in time observations (ms).

Component	CIO	BIH 1968
Linear trend	0.18/yr	--
22 to 30-yr. periodicity	2.40	--
10 to 12-yr. periodicity	1.20	--
Random	±0.60	±0.71

5. ON THE FREQUENCY RESPONSE OF THE FILTERS USED BY THE BIH AND THE U.S.S.R. TIME SERVICE

The systematic errors of time observations in the form (4) do not vanish in the determination of UT1 by the BIH and the U.S.S.R. Time Service because the observations are made approximately at the same local time and because the mean value of tan ϕ for the participating observatories is 0.9 for the BIH and 1.3 for the U.S.S.R. Time Service. However, these errors are considerably reduced due to the following procedure for filtering individual observations:

1) computation of the daily mean values,
2) computation of the normal values, for example, 5-day mean values,
3) averaging the results of all participating observatories,
4) smoothing of the resultant determinations of UT1.

We can only find the approximate frequency responses of these filters because of the variety of programs of time observations and because of the variation in the weights of the normal values. Assuming the duration of observations during the day is five hours, the amplifying factors for the diurnal and semidiurnal variations will be 0.92 and 0.74 respectively. To estimate the amplifying factors of the other filters we have used the information given by Belotserkovskij and Kaufman (1979) and the BIH reports. The amplifying factors resulting from all of the filters mentioned above are given in Table 8. Use of Tables 5 through 8 allows us to estimate the different effects in UT1 which do not represent irregularities in the rotation of the Earth, but only defects in the processing and reduction of observations.

Table 8. Amplifying factors.

Component	Aliasing Period (days)	Series of Data			
		BIH		UT U.S.S.R.	
		unsmoothed	smoothed	unsmoothed	smoothed
Semi-diurnal	10.3	0.49	0.01	0.70	0.0
	14.8	0.61	0.05	0.74	0.0
	183	0.74	0.74	0.74	0.70
Diurnal	14.2	0.66	0.05	1.20	0.0
	122	0.82	0.82	1.20	1.02
	183	0.83	0.83	1.20	1.14
	346	0.83	0.83	1.20	1.20
	365	0.83	0.83	1.20	1.20
	385	0.83	0.83	1.20	1.20
Long-period	365 and longer	0.90	0.90	1.30	1.30

6. CONCLUSIONS

1. The existence of secular and long-period variations among the origins of the CIO, BIH and MPO systems does not support the reality of secular and long-period polar motion. These might be explained by local effects at the participating stations (in particular, the Ukiah VZT). For practical use in astronomy and geodesy the MPO is preferable.

2. The methods for preserving the reference systems by the BIH and the U.S.S.R. Time Service would be more effective if statistical predictions of the residuals for each station and instrument were applied.

3. Taking into account the frequency response to the filters used by the BIH and the U.S.S.R. Time Service, and since the shortest period in the tidal variations in the rate of the Earth's rotation is about 9 days it is advisable to compute UT1 for every day.

4. To reduce systematic errors in the determination of UT1 and to provide a comparison of results given by the BIH and the U.S.S.R. Time

Service it is necessary to apply a unified set of corrections for variations in the directions of the verticals.

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