EARTH ROTATION
IN THE HIPPARCOS REFERENCE FRAME

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Abstract. New determination of the Earth orientation parameters (EOP), based on optical astrometry observations since the beginning of the century, is now under preparation by the Working group established by Commission 19 of the IAU. The Hipparcos catalog is to define the celestial reference frame in which the new series of EOP are to be described. The novelties of the prepared solution are the higher resolution (5 days) and more parameters estimated from the solution (celestial pole offsets, rheological parameters of the Earth, certain instrumental constants). The mathematical model of the solution is described, and the results based on the observations made with 46 instruments at 29 observatories and a preliminary Hipparcos catalog are presented.

1. Introduction

Preparation of the new solution of EOP from optical astrometry in the Hipparcos reference frame began in 1988 when IAU Commission 19 set up a working group to this end; the project had been initiated earlier by Feissel (1986). The first proposal of the procedures to be used was described by Vondrák (1991), and the expected accuracy estimated by Vondrák *et al.*(1992). Several solutions based on the star catalogs originally used at the observatories were then worked out (Vondrák *et al.*, 1993; Vondrák and Ron, 1994; Vondrák *et al.*, 1994; Vondrák *et al.*, 1995).

Since 1995, when a cooperation with the Hipparcos Science Team has been established on the linking of the Hipparcos system to extragalactic objects, we have been able to use the preliminary versions (H30, H37, H37C)

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of the Hipparcos catalog. They were employed to work out several solutions, the last of which was used (in combination with VLBI-based EOP) to determine the linking of the preliminary Hipparcos system with respect to extragalactic objects (Vondrák *et al.*, 1996). Here we use the last two of these catalogs to calculate the new EOP.

2. The Preliminary Hipparcos Catalog H37P

The subsets of preliminary H37 and H37C catalogs were made available to us by the Hipparcos Science Team (Turon and Morin, 1995; Turon and Morin, 1996) for linking purposes, containing 9 071 and 8 841 stars, respectively. Most of the stars (8 575) are common in both sub-catalogs that are given in the same system; we merged them, retaining the positions and proper motions of H37C and taking over the additional H37 stars. Then we used the preliminary orientation of H37C with respect to extragalactic system, obtained by combining several methods (Lindegren and Kovalevsky, 1995) and provided by Kovalevsky (1996), to bring the merged catalog into the International Celestial Reference System. Internally, we call this catalog (containing 9 337 stars) H37P, and use it in all subsequent calculations.

3. The Observations and Their Corrections

The observations of individual stars made since 1900 at 29 observatories with 46 instruments are used in the new solution. The list of the participating observatories and instruments is given in Table 1, in which the different types of instruments are abbreviated as ZT (visual zenith-telescope), PZT (Photographic zenith tube), PTI (photoelectric transit instrument), AST (Danjon astrolabe), PAST (photoelectric astrolabe), CZ (circumzenithal), VZT (visual zenith tube) and FZT (floating zenith tube).

Three different observed quantities reported by the observatories (latitude, universal time, zenith distance) are corrected, before being used in the solution, to remove certain systematic effects:

1. The submitted observations were converted into the newest astronomical standards, following (McCarthy, 1992).
2. Differences in apparent places as calculated with H37P and original catalogs were applied to correct the observed quantities.
3. Plate tectonic motions as given by the geophysical model NUVEL-1 NNR (Argus and Gordon, 1991). For the sites located near the plate boundaries (Carloforte, Mizusawa, Santiago and Ukiah) the values based on space geodetic data (Ma, 1995) were used.
4. Corrections to certain instrumental constants were determined, and the observations corrected:
    - Micrometer values for ZT, VZT, FZT, together with their time- and temperature-dependent terms for each year.

TABLE 1. The observatories and instruments used in the solution.

Observatory	Instrument	λ	φ
Belgrade	ZT(1949.0–1986.0)	20.5	44.8
Bratislava	CZ(1987.0–1991.9)	17.1	48.2
Blagoveschtschensk	ZT(1969.0–1992.0)	127.5	50.3
Carloforte	ZT(1899.8–1943.3,1946.5–1979.0)	8.3	39.1
Cincinnati	ZT(1899.7–1916.0)	−84.4	39.1
Gaithersburg	ZT(1899.8–1915.0,1932.6–1979.0)	−77.2	39.1
Grasse	PAST(1983.2–1992.0)	6.9	43.7
Irkutsk	ZT(1958.2–1991.0), PTI(1979.1–1992.0)	104.3	52.3
Kitab	ZT(1930.9–1979.0)	66.9	39.1
Mizusawa	ZT(1900.0–1979.0), FZT(1967.0–1984.8), PZT#1(1959.0–1975.3), #2(1974.2–1992.0)	141.1	39.1
Nikolaev	PTI(1974.4–1985.5)	32.0	47.0
Ondřejov	PZT(1973.1–1992.0)	14.8	49.9
Paris	AST(1956.5–1983.0)	2.3	48.8
Pecný	CZ(1980.0–1992.0)	14.8	49.9
Poltava	ZT#1(1949.7–1990.4), #2(1950.2–1968.8), #3(1967.9–1980.8)	34.5	49.6
Praha	CZ#1(1980.2–1985.0), #2(1985.2–1992.0)	14.7	50.1
Pulkovo	ZT#1(1904.7–1941.5), #2(1948.7–1992.0), PTI#1(1961.3–1971.4), #2(1971.2–1985.3), #3(1971.8–1992.0)	30.3	59.8
Punta Indio	PZT(1971.6–1984.5)	−57.3	−35.3
Richmond	PZT#1(1949.8–1987.5), #2(1981.9–1989.4)	−80.4	25.6
Santiago de Chile	AST(1965.9–1990.9)	−70.6	−33.4
Shanghai	AST(1962.0–1985.0), PAST(1975.7–1985.0)	121.4	31.2
Shaanxi	PAST#1(1974.0–1984.8), #2(1985.5–1992.0)	109.6	34.9
Simeiz	AST(1977.0–1991.0)	34.0	44.4
Tschardjui	ZT(1899.7–1919.4)	63.5	39.1
Tuorla-Turku	VZT(1963.7–1989.1)	22.4	60.4
Ukiah	ZT(1899.8–1979.0)	−123.2	39.1
Washington	PZT#1(1915.8–1955.3), #2(1954.3–1984.8), #3(1981.7–1992.0)	−77.1	38.9
Wuchang	AST(1964.0–1986.2), PTI(1981.9–1987.2)	114.3	30.5
Yunnan	PAST(1980.7–1991.3)	102.8	25.0

– Scale value of PZT plates. At some observatories (Richmond, Washington) two scale values were originally determined for each plate separately, in two perpendicular directions (McCarthy, 1970). The scale in the direction of the local meridian is then dependent on the adopted declinations and, consequently, if declinations are changed so must be the corresponding scale values.

- Azimuth of PTI. The azimuth of the instrument was originally determined from the observations, together with the universal time. Since it is dependent on the adopted right ascensions of the stars, the change of the star positions necessarily leads to the change of the estimated azimuth of the instrument.

5. Apparent almucantar deformations for AST, PAST, CZ. As shown by Pešek *et al.* (1993) and Pešek (1995), the apparent almucantar is deformed, most probably due to local azimuth-dependent refraction anomalies.
6. Short-periodic solid Earth tide variations in all measured UT0 after Yoder *et al.* (1981). Terms with periods less than 35 days are removed, thus converting the observed values to UT0R.
7. Ocean tide-loading variations of the local vertical in longitude/latitude. We use the values provided to us by courtesy of Scherneck (1995); Schwiderski ocean-tide model is used for long-periodic part and Le Provost model for diurnal and semi-diurnal terms.
8. Instead of TAI or UTC, we use the auxiliary 'reduced' atomic time scale TAX as a standard. The difference TAX-TAI is given by a simple conventional formula defined in (Vondrák *et al.*, 1995).
9. The observations made with the instruments with long history (ILS, Pulkovo, Belgrade, Richmond and Washington) show that there exist significant deviations in trends of the latitudes based on certain stars. Therefore we fixed the Hipparcos positions at the epoch 1991.25 and used the observations to estimate the trends; 173 star pairs and 87 stars with the largest trends were used to correct the observed latitudes.

4. The Solution and the Results

We followed the algorithms outlined in (Vondrák, 1991; Vondrák *et al.*, 1995), slightly modified. The observation equations, corresponding to the three types of observed quantities (latitude $\Delta\varphi$, universal time UT0R–TAX and the difference between calculated and observed altitude δh) read

$$
\begin{aligned}
v_\varphi &= \Delta\varphi - (1 - 0.0042\cos 2\varphi)(x\cos\lambda - y\sin\lambda) + \\
&+ \Delta\varepsilon\sin\alpha + \Delta\psi\sin\varepsilon\cos\alpha - (A + A_1T + B\sin 2\pi t + \\
&+ C\cos 2\pi t + D\sin 4\pi t + E\cos 4\pi t) - \Lambda D_\varphi, \\
v_T &= 15.041\cos\varphi\,[(\mathrm{UT0R{-}TAX}) - (\mathrm{UT1R{-}TAX})] - \\
&- 1.0042\sin\varphi(x\sin\lambda + y\cos\lambda) - \\
&- \cos\varphi\tan\delta(\Delta\varepsilon\cos\alpha - \Delta\psi\sin\varepsilon\sin\alpha) - \\
&- 15\cos\varphi(A' + A_1'T + B'\sin 2\pi t + C'\cos 2\pi t + \\
&+ D'\sin 4\pi t + E'\cos 4\pi t) - 15\cos\varphi\Lambda D_\lambda, \qquad (1)
\end{aligned}
$$

$$\begin{aligned} v_h &= -\delta h + 15.041 \cos\varphi \sin a(\mathrm{UT1R{-}TAX}) + \\ &+ x\left[(1 - 0.0042\cos 2\varphi)\cos\lambda\cos a + 1.0042\sin\varphi\sin\lambda\sin a\right] - \\ &- y\left[(1 - 0.0042\cos 2\varphi)\sin\lambda\cos a - 1.0042\sin\varphi\cos\lambda\sin a\right] + \\ &+ \Delta\varepsilon(\sin q\sin\delta\cos\alpha - \cos q\sin\alpha) - \\ &- \Delta\psi\sin\varepsilon(\sin q\sin\delta\sin\alpha + \cos q\cos\alpha) + \\ &+ (A + A_1T + B\sin 2\pi t + C\cos 2\pi t + D\sin 4\pi t + E\cos 4\pi t)\cos a + \\ &+ 15\cos\varphi(A' + A_1'T + B'\sin 2\pi t + \\ &+ C'\cos 2\pi t + D'\sin 4\pi t + E'\cos 4\pi t)\sin a + \\ &+ \Lambda(D_\varphi\cos a + 15\cos\varphi D_\lambda\sin a), \end{aligned}$$

where v_φ, v_T, v_h are residuals, φ and λ denote the latitude and longitude of the instrument, α, δ the right ascension and declination of the observed star, and a, q its azimuth and parallactic angle. T is measured in centuries from the mean epoch of observation of each instrument and t in years from the beginning of the current Besselian year. D_φ, D_λ denote the theoretical rigid Earth tidal variations in latitude and longitude, respectively. Eqs. (1) are used to estimate the unknown parameters:

1. coordinates of the pole in the terrestrial reference frame x, y, celestial pole offsets $\Delta\varepsilon, \Delta\psi\sin\varepsilon$ and universal time UT1R–TAX (at 5-day intervals), where ε denotes the obliquity of the ecliptic,
2. coefficients A, A_1, B, C, D, E, describing the constant, linear, annual and semi-annual terms of the deviation of each instrument in latitude,
3. coefficients A', A_1', B', C', D', E', describing the constant, linear, annual and semi-annual terms of the deviation of each instrument in time,
4. parameter $\Lambda = 1 + k - l$, giving the ratio between the actual and rigid Earth tidal variations of the local vertical at each observatory.

We used the least-squares solution based on the observation equations (1) and the 18 constraints tying the 'station' parameters $A - E, A' - E'$:

$$\begin{gathered} \sum P_iA_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = \sum Q_iA_{1i}\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = \sum P_iB_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = 0, \\ \sum P_iC_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = \sum P_iD_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = \sum P_iE_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = 0, \quad (2) \\ \sum P_iA_i' = \sum Q_iA_{1i}' = \sum P_iB_i' = \sum P_iC_i' = \sum P_iD_i' = \sum P_iE_i' = 0, \end{gathered}$$

where P_i and Q_i are weighting factors. The matrix of normal equations formed on the basis of Eqs. (1) and (2) is very large but also very sparse. The procedure devised by Čepek (1994), based on a modified Cholesky decomposition, was used to solve the normal equations.

Two-step adjustment was employed with the observations covering the interval 1899.7–1992.0. In step one, we used the same weights for all

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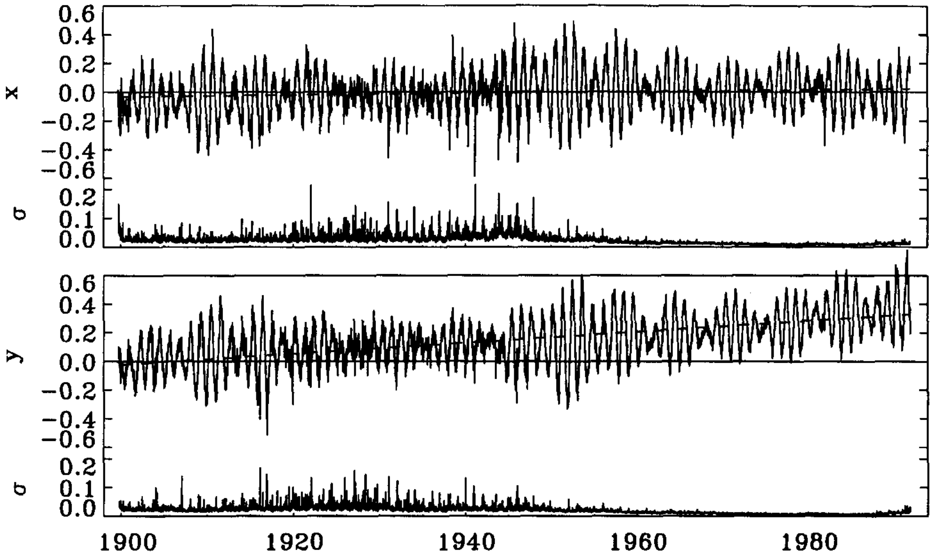

Figure 1. Polar motion components x, y.

4 078 587 observations and estimated 29 878 parameters, the standard error of one observation being $\sigma = 0\farcs216$. In step two, we calculated the different weights for each instrument (based on the dispersion of corresponding residuals) and excluded all outliers (exceeding 2.7σ). The weights ranged from 0.51 to 2.12, and 1.46% of the observations were rejected so that the number of remaining observations used for the second (and final) solution was 4 019 218. The number of estimated parameters in step two was 29 870 (i.e., 6 692 values of $x, y, \Delta\varepsilon$ and $\Delta\psi \sin\varepsilon$ in the interval 1899.7–1992.0, 2 630 values of UT1R–TAX in the interval 1956.0–1992.0, 454 station parameters and 18 Lagrange multipliers corresponding to the constraints), and $\sigma = 0\farcs193$. We then converted TAX to TAI to obtain the values UT1R–TAI that were numerically differentiated to get the length-of-day values. The results and their formal standard errors σ are graphically displayed in Figures 1–3.

In Figure 1 one can see the secular polar motion that is present in both its components, x and y, corresponding to the motion of 3.70 mas/yr in the direction of 78°.14 W. Evident is the increase of σ_x during World War II, when European observatories were closed. The standard errors dropped down in the fifties, when more observatories became active and time observations started contributing to polar motion determination; they rose again after 1988, when many optical astrometry instruments were shut down.

A similar behavior of standard errors can be seen in case of celestial pole offsets shown in Figure 2. However, these standard errors display a strong semi-annual variation, especially in the first half of the century. These va-

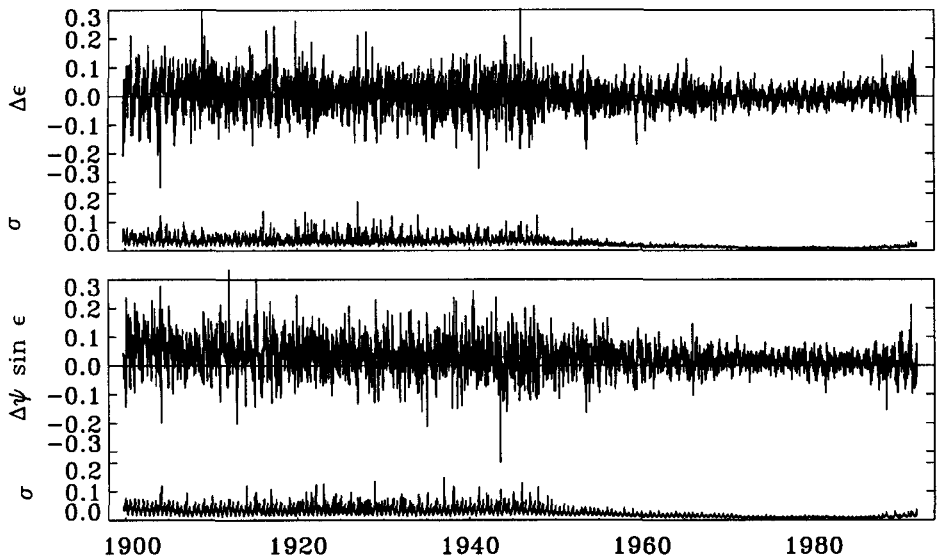

Figure 2. Celestial pole offsets $\Delta\varepsilon, \Delta\psi \sin\varepsilon$.

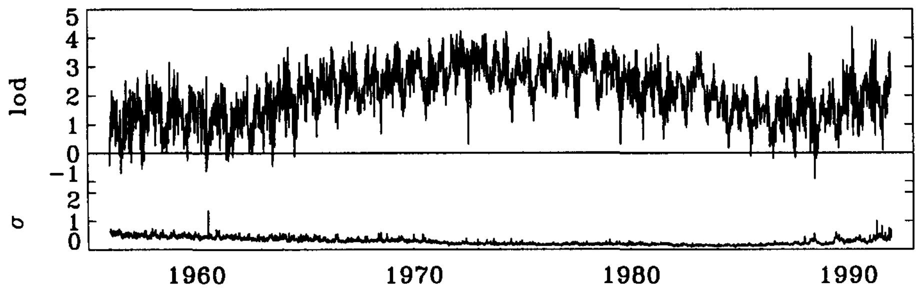

Figure 3. Length-of-day variations (in msec), with short-periodic tidal terms removed.

riations are reflecting a correlation between the two components of celestial pole offsets. The correlation becomes much smaller when longer nights of observation are used, and both latitude and universal time observations are employed. The obvious negative trend in $\Delta\psi \sin\varepsilon$ reflects the combined effect of the now well-known error in the adopted value of the precession constant and a slow residual rotation of the catalog H37P. The celestial pole offsets determined in this solution are analysed elsewhere (Bizouard *et al.*, 1996).

Figure 3 displays the observed length-of-day values, together with their standard errors. Their evolution clearly reflects the changing number of participating instruments; the minimum around 1984 coincides well with the MERIT campaign, when the observations were intensified. The closing of many instruments after 1988, when the new IERS stopped using the optical astrometry, projected into a sudden (almost stepwise) increase of standard errors to the level of the late fifties.

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