THE HIPPARCOS CATALOGUE: A REFERENCE FRAME FOR EARTH ORIENTATION IN 1899.7–1992.0

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ABSTRACT

The Hipparcos Catalogue is used to form a homogeneous reference frame in which a new series of the Earth Orientation Parameters (EOP) is described. Being now linked to the extragalactic objects that define the new International Celestial Reference Frame (ICRF), it provides a new possibility of referring the long series of astrometric observations to the same reference frame that is used by the modern space techniques, such as Very Long-Baseline Interferometry. The observations of latitude and universal time variations (made in 1899.7–1992.0 and 1956.0–1992.0, respectively) at thirty observatories all over the world are used to determine the EOP in ICRF at five-day intervals. The results, covering almost one century, can further be used to study such fundamental phenomena as, e.g. precession-nutation, or interactions of the rotating Earth with geophysical excitations. In addition, certain improvement of some of the Hipparcos proper motions can also be obtained from our solution.

Key words: space astrometry; Earth rotation.

1. INTRODUCTION

The Hipparcos Catalogue, being a realization of the International Celestial Reference System (ICRS) in optical wavelength (Kovalevsky et al. 1997), provides a new homogeneous celestial frame, independent of ground-based observations. It is more accurate than any other previous star catalogue and free of at least some of the known systematic errors. Therefore it provides a unique possibility of determining the Earth Orientation Parameters (EOP) from the past optical astrometry observations in the same reference system as now monitored by the Very Long-Baseline Interferometry (VLBI) and other space techniques. Since 1991, when the first proposal of the new adjustment was published (Vondrák 1991), 11 solutions were made, first with the original local star catalogues and later with the preliminary Hipparcos Catalogues H30, H37 and H37C. The number of participating instruments was gradually increasing from 7 to 46, one of the more recent solutions was used to link the H37C catalogue to extragalactic reference frame (Vondrák et al. 1997). The present paper describes the very first solution that we made with the definitive Hipparcos Catalogue.

2. THE METHOD AND DATA USED

2.1. Description of the Method

The method used being described in detail elsewhere (Vondrák 1991; Vondrák et al. 1995), we shall limit ourselves to only a short outline of the basic principles here. The ever changing (and theoretically unpredictable) orientation of the Earth in space is determined, in principle, by monitoring the motion of local verticals of at least two observatories (not on the same meridian) amongst the stars. The measured quantities that are used in this study are threefold:

1. zenith distance (or the difference of zenith distances) of the star (star pair) when it passes over the local meridian. It is converted into the instantaneous latitude of the observatory φ, provided the star's apparent declination is known;
2. time of star's transit through the local meridian. It is converted into deviation of the instantaneous universal time from the International Atomic Time UT0–TAI, provided the star's apparent right ascension and observatory's longitude are known;
3. time of star's transit through the local almucantar. It is converted into the difference of the zenith distance δh, provided the apparent star's position and geographic position of the observatory are known.

These three types of measured quantities lead to three different types of observation equations, all expressed in arcseconds:

$$\begin{aligned} v_\varphi = {} & \\ & \varphi - \varphi_0 - (1 - 0.0042\cos 2\varphi_0)(x\cos\lambda_0 - y\sin\lambda_0) + \\ & + \Delta\varepsilon\sin\alpha + \Delta\psi\sin\varepsilon\cos\alpha - (A + A_1T + B\sin 2\pi t + \\ & + C\cos 2\pi t + D\sin 4\pi t + E\cos 4\pi t) - \Lambda D_\varphi \end{aligned}$$

$$
\begin{aligned}
v_T = {} & \\
& 15.041\cos\varphi_0\,[(\mathrm{UT0{-}TAI}) - (\mathrm{UT1{-}TAI})] - \\
& -1.0042\sin\varphi_0(x\sin\lambda_0 + y\cos\lambda_0) - \\
& -\cos\varphi_0\tan\delta(\Delta\varepsilon\cos\alpha - \Delta\psi\sin\varepsilon\sin\alpha) - \\
& -15\cos\varphi_0(A' + A'_1T + B'\sin 2\pi t + C'\cos 2\pi t + \\
& +D'\sin 4\pi t + E'\cos 4\pi t) - 15\Lambda D_\lambda\cos\varphi_0 \qquad (1) \\
v_h = {} & \\
& -\delta h + 15.041\cos\varphi_0\sin a(\mathrm{UT1{-}TAI}) + \\
& +x\,[(1 - 0.0042\cos 2\varphi_0)\cos\lambda_0\cos a\ + \\
& +\ 1.0042\sin\varphi_0\sin\lambda_0\sin a] - \\
& -y\,[(1 - 0.0042\cos 2\varphi_0)\sin\lambda_0\cos a\ - \\
& -\ 1.0042\sin\varphi_0\cos\lambda_0\sin a] + \\
& +\Delta\varepsilon(\sin q\sin\delta\cos\alpha - \cos q\sin\alpha) - \\
& -\Delta\psi\sin\varepsilon(\sin q\sin\delta\sin\alpha + \cos q\cos\alpha) + \\
& +(A + A_1T + B\sin 2\pi t + C\cos 2\pi t + D\sin 4\pi t + \\
& +E\cos 4\pi t)\cos a + 15\cos\varphi_0(A' + A'_1T + B'\sin 2\pi t + \\
& +C'\cos 2\pi t + D'\sin 4\pi t + E'\cos 4\pi t)\sin a + \\
& +\Lambda(D_\varphi\cos a + 15D_\lambda\cos\varphi_0\sin a)
\end{aligned}
$$

where φ_0, λ_0 are the adopted (constant) mean geographic coordinates of the instrument, α, δ apparent equatorial coordinates of the observed star, a, q its azimuth and paralactic angle and D_φ, D_λ theoretical tidal variations of the vertical, calculated for the rigid Earth. 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. The equations (1) are used to estimate the values of the following parameters, by the least-squares method:

1. coordinates of the pole in terrestrial reference frame x, y (for each 5-day interval);
2. universal time differences UT1–TAI (for each 5-day interval; only after 1956);
3. celestial pole offsets $\Delta\varepsilon, \Delta\psi\sin\varepsilon$ (for each 5-day interval);
4. constant, linear, annual and semi-annual deviation in latitude A, A_1, B, C, D, E (for each instrument);
5. constant, linear, annual and semi-annual deviation in universal time A', A'_1, B', C', D', E' (for each instrument);
6. rheological parameter $\Lambda = 1 + k - l$ governing the tidal variations of the local vertical (for each instrument).

The matrix of normal equations corresponding to the observation equations (1) is singular, extremely large (about 30 thousand unknown parameters) and very sparse. Therefore we apply 18 constraints, tying together the parameters $A - E, A' - E'$, to remove the singularity (fixing thus the terrestrial reference frame in which the polar motion and universal time are described):

$$
\begin{aligned}
\sum P_iA_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} &= \sum Q_iA_{1i}\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = 0 \\
\sum P_iB_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} &= \sum P_iC_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = 0 \\
\sum P_iD_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} &= \sum P_iE_i\begin{pmatrix}\sin\lambda_i\\ \cos\lambda_i\end{pmatrix} = 0 \qquad (2) \\
\sum P_iA'_i = \sum Q_iA'_{1i} &= \sum P_iB'_i = 0 \\
\sum P_iC'_i = \sum P_iD'_i &= \sum P_iE'_i = 0
\end{aligned}
$$

where P_i and Q_i are weighting factors (proportional to the weight of the instrument and to the length on the interval covered by the observations and its third power respectively). The structure of the large sparse system of normal equations being known beforehand, we use an *ad hoc* procedure to solve this specific system of normal equations (Čepek 1994) which is based on a modified Cholesky decomposition.

2.2. The Observations

We use more than four million individual observations made with 47 instruments at 30 observatories all over the world (see Figure 1).

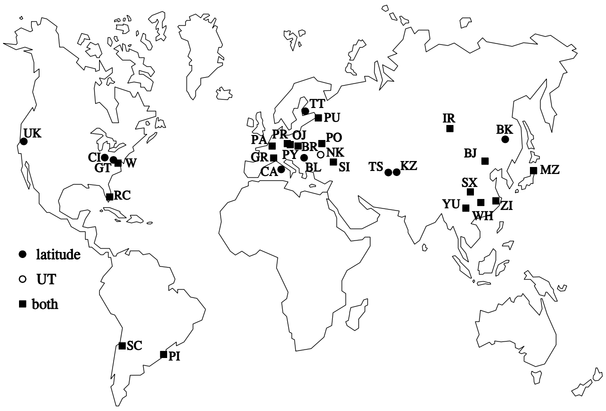

Figure 1. Geographic distribution of the observatories participating with their observations.

The observations were made available (in chronological order) by Yumi & Yokoyama (1980) for the visual zenith-telescopes of all International Latitude Service stations (CA, CI, GT, KZ, MZ, TS, UK), Chollet (1991) for the astrolabe of Paris (PA), Noël (1992) for the astrolabe of Santiago de Chile (SC), Li (1992) for the astrolabes of Shanghai (ZI), Hu (1992) for the astrolabe of Yunnan (YU), Archinal & McCarthy (1993) for the photographic zenith tubes of Richmond and Washington (RC, W), Manabe (1993) for the floating zenith-telescope and photographic zenith tubes of Mizusawa (MZ), Gorshkov & Naumov (1993) and Malkin (1995) for the transit instruments and zenith-telescopes of Pulkovo (PU), Karchevskaya & Tatarenko (1993) for the zenith-telescope and transit instrument of Irkutsk (IR), Gao (1993) for the astrolabe and transit instrument of Wuchang (WH), Wang (1994) for the astrolabes of Shaanxi (SX), Arias (1994) for the photographic zenith tube of Punta Indio (PI), Vigouroux (1994) for the astrolabe of Grasse (GR), Gorban (1994) for the zenith-telescopes of Poltava (PO), Niemi (1994) for the visual zenith tube of Tuorla-Turku (TT), Gaftonyuk &

Rykhlova (1994) for the astrolabe of Simeiz (SI), Gorshkov & Sokolova (1995) for the zenith-telescope of Blagoveschtschensk (BK), Damlianović (1995) for the zenith-telescope of Belgrade (BL), Skoupý (1995) for the circumzenithal of Pecný (PY), Hefty (1995) for the circumzenithal of Bratislava (BR), Kokaja (1995) for the transit instrument of Nikolaev (NK), and Lu (1996) for the astrolabe of Beijing (BJ). The remaining observations with the circumzenithals of Prague (PR) and photographic zenith tube of Ondřejov (OJ) were reduced by the authors.

All individual values of φ, UT0–TAI and δh submitted by the participating observatories were converted from the originally used 'local' star catalogues to the Hipparcos Catalogue. Since we found, in some cases, very large residuals having clear linear trends, we used the observations at observatories with long history to determine corrections of proper motions of corresponding stars. We applied these corrections only if the number of observations was larger than 50 and if the correction exceeded five times the standard error in its determination. These rather conservative criteria led to about 8 per cent of the observed stars requiring corrections to proper motions, with their positions fixed at the mean Hipparcos epoch, 1991.25, the formal precision of their determination ranging from ±0.2 to ±0.5 mas/yr. Additional 2 per cent of the observed stars required both positions and proper motions to be corrected. These 'suspect' stars are mostly denoted as double or multiple systems in the Hipparcos Catalogue, the corrections to proper motions reaching as much as 12 mas/yr. Nevertheless, one can expect that much greater number of binaries are present in the Hipparcos Catalogue than detected from the mission itself (see e.g. Brosche et al. 1995) which could justify even less strict criteria than used here for the selection of the stars whose proper motions/positions are corrected.

The data were also re-calculated, before being used in the global adjustment, to conform to the most recent astronomical constants and algorithms (McCarthy 1996). Namely we re-reduced older observations that were originally reduced with the old precession-nutation model, different algorithms and constants of annual aberration and without relativistic deflection of light in the Sun's gravitational field. The following additional corrections were applied, mostly to remove all known effects of geophysical or instrumental origin:

- plate tectonic motions after the geophysical model NUVEL-1 NNR (Argus & Gordon 1991), replaced by the values based on recent space geodetic data provided by Ma (1995) in case of observatories close to plate boundaries;
- oceanic tide-loading variations of local verticals; Schwiderski ocean-tide model is used for its long-periodic part and Le Provost model for diurnal and semi-diurnal part (Scherneck 1995);
- short-periodic zonal tide variations (periods shorter than 35 days) in UT0, using the coefficient $k/C = 0.94$ (Yoder et al. 1981); our final results are thus not UT1 but UT1R, using the standard International Earth Rotation Service (IERS) notation;
- corrections due to certain instrumental constants (micrometer value in case of visual zenith-telescopes, plate scale value in case of certain photographic zenith tubes, azimuth in case of photoelectric transit instruments);
- deformations of the apparent almucantar (in case of all instruments observing by the method of equal altitudes) that can reach as much as 0.1–0.2 arcsec (Pešek et al. 1993), including also spectral class and magnitude effects on zenith distance of the observed star. All these effects are most probably due to local refraction anomalies.

Then the data were inspected, instrument by instrument, and the outliers detected and excluded, using the norm L_1 for running monthly mean of the observed quantity; the observations with residuals exceeding 0.8 arcsec were omitted from further analysis. The mean coordinates (latitudes φ_0, longitudes λ_0) of the individual instruments were then estimated from comparison with the IERS results in the interval 1962.0–1992.0, in order to keep the results in the same terrestrial reference system.

Not all 47 observatories were active at all times; the time evolution of the number of active instruments and the density of observations per 5-day interval is depicted in Figure 2. It can be seen that the observational activity was more or less constant up to 1955, when it started to grow substantially, with the peak around 1980–1985 (MERIT campaign). After that, when it became clear that the optical astrometric technique would be completely replaced by modern space techniques, the number of astrometric instruments participating in monitoring the Earth rotation dropped substantially.

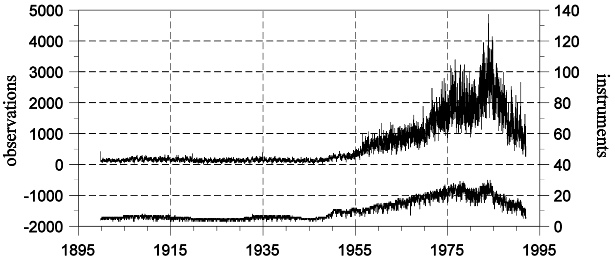

Figure 2. Number of active instruments (lower graph, right scale) and density of observations (upper graph, left scale) per five-day interval.

3. THE SOLUTION

As already mentioned, the observations of 47 different instruments are used; of these, there are 15 visual zenith-telescopes (measuring only the latitude), nine photographic zenith tubes (measuring both latitude and universal time), six photoelectric transit instruments (measuring only universal time), six photoelectric astrolabes, five Danjon astrolabes and four circumzenithals (all measuring a combination of both, by the method of equal altitudes), one visual zenith

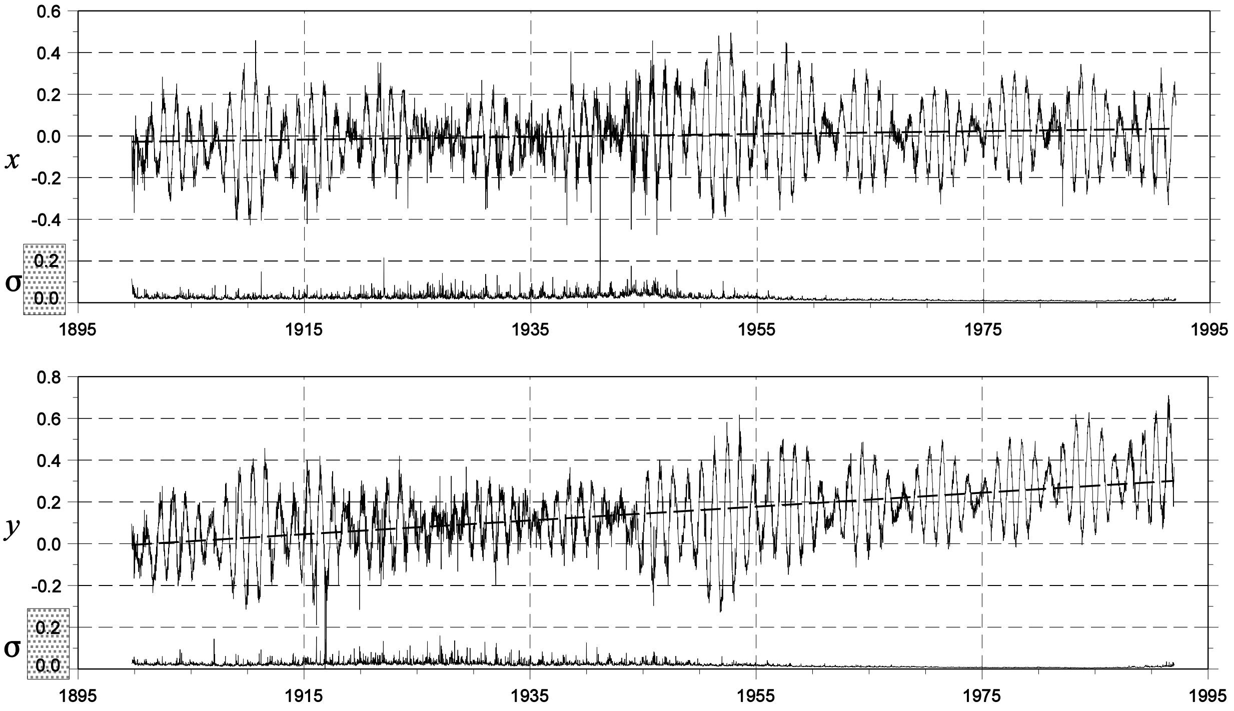

Figure 3. Polar motion at five-day intervals and its standard errors.

tube and one floating zenith-telescope (both measuring only the latitude). The solution was made in two steps:

1. In step one, all observations were used with the same weight. Then the residuals were calculated and from them the standard error σ_0 of one observation estimated. All observations with residuals exceeding $2.7\sigma_0$ were then rejected, and the weight of each instrument determined, from the dispersion of the corresponding residuals. About 1.5 per cent of all observations were thus excluded from further treatment, the weights of individual instruments range from 0.52 to 2.20.

2. In step two, we used the weights determined in step one. 4 287 092 observations were used that led to estimated 29 887 parameters. Out of these, there are 6693 values of $x, y, \Delta\varepsilon$ and $\Delta\psi \sin\varepsilon$ at five-day intervals in 1899.7–1992.0, 2630 values of UT1–TAI at five-day intervals in 1956.0–1992.0, 467 'station' parameters ($A - E, A' - E', \Lambda$) for individual instruments and 18 Lagrange multipliers, corresponding to the constraints. The standard error of unit weight (i.e. for an 'average' instrument) $\sigma_0 = 0.189$ arcsec.

The results are graphically depicted in Figures 3 – 5; they are raw data, exactly as determined from the solution (i.e. no smoothing was applied).

Polar motion (Figure 3) displays the evident secular trend in both coordinates x, y of 0.68 mas/yr and 3.32 mas/yr respectively, i.e. 3.39 mas/yr in the direction of 78.5° west meridian. The beat period between the Chandler (14 month) and annual component, of about 6–7 years is also visible. The evolution of the standard error of each five-day value is closely related to the density of observations (compare with Figure 2); it is relatively stable during the first half of the century (of the order of 30 mas), then it gradually decreases to a minimum of about 10 mas in 1980–1985 and then it increases again. Also evident is its increase in the x-component during World War II, when practically all observatories in Europe stopped observing.

Celestial pole offsets, shown in Figure 4, reflect the deviations of the spin axis of the Earth from the adopted precession-nutation model (here it is the IAU 1976 precession and the IAU 1980 nutation). There is an obvious trend in $\Delta\psi \sin\varepsilon$ of about -0.60 ± 0.01 mas/yr and almost invisible trend in $\Delta\varepsilon$ (-0.10 ± 0.01 mas/yr). The Hipparcos Catalogue being given virtually in the same reference system as the positions of the radiosources observed by VLBI, these trends should correspond to the error in the precession constant, detected from VLBI observations. However, the value that we obtain here for $\Delta\psi \sin\varepsilon$ is much smaller than that derived recently from VLBI observations by Souchay et al. (1995): -1.28 ± 0.01 mas/yr or the one adopted in the IERS Conventions (McCarthy 1996): -1.19 mas/yr (both latter values being multiplied by $\sin\varepsilon$ to be comparable with our result). One can only speculate whether the difference might be due to a residual rotation of the Hipparcos Catalogue with respect to the extragalactic reference frame (which is improbable, due to its declared link with the precision of ±0.25 mas/yr), or a result of another effect.

Also visible are quasi-periodic changes in both components, corresponding to the errors in nutation; from their analysis, one can determine the corrections of long-periodic terms of nutation. These are not correlated with the trend, due to the long history of optical astrometry observations, which is certainly an advantage compared with much more precise but

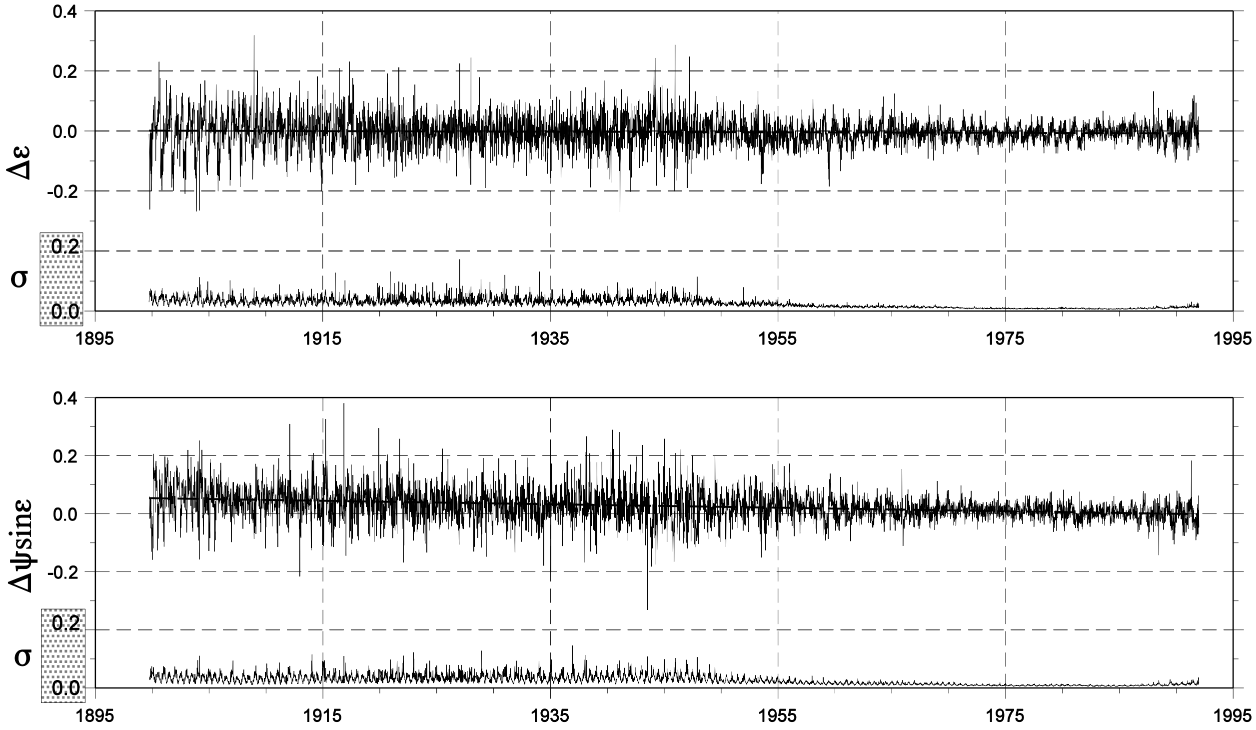

Figure 4. Celestial pole offsets at five-day intervals and their standard errors.

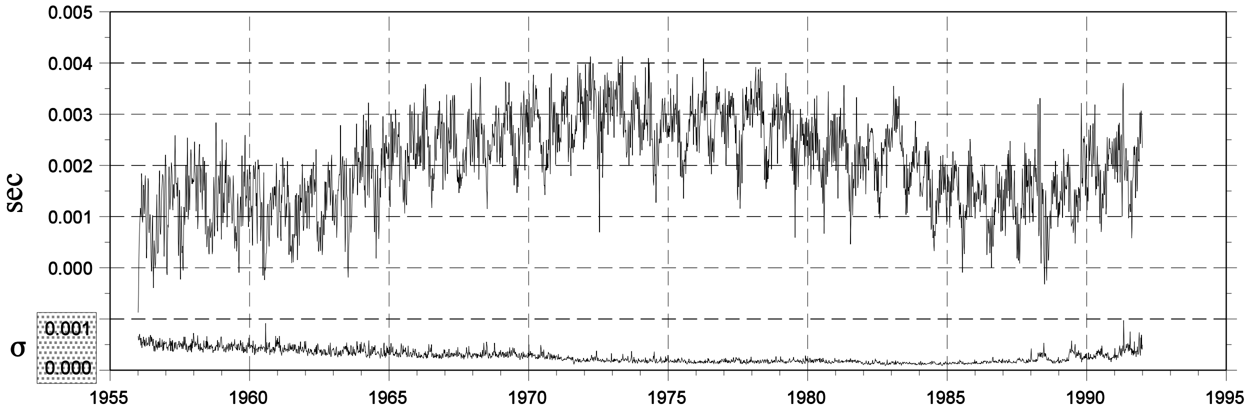

Figure 5. Excess of the length-of-day over the nominal value of 86400 sec at five-day intervals and its standard error. The short-periodic tidal variations (P<35 days) are removed.

shorter VLBI observations. As expected by Vondrák et al. (1992), the standard errors are on average of the same order of magnitude as those in polar motion, but they display a significant semi-annual character. A more detailed inspection reveals that there is a phase shift between both components of celestial pole offsets of about ninety degrees. This is a consequence of the observations covering only a part of the local night and being centered around local midnight. The error ellipses are thus rather elongated, with their minor axes pointing always towards the Sun and therefore slowly rotating (with annual period) with respect to the celestial reference system. The situation is much improved (i.e. the error ellipses are less elongated) after 1956, when both latitude and time observations are combined.

The original 5-day values of UT1R–TAI resulting from our solution were converted into the length-of-day (LODR, according to standard IERS notation) changes (that are just the first derivatives of UT1R–TAI), for a more intuitive graphical representation. Since we removed the theoretical short-periodic tidal variations from the input data UT0–TAI, the LODR changes obtained from the solution do not contain them either. From the graph one can see a slight growth in LODR during the interval in question (corresponding to a slow deceleration of the speed of Earth's rotation, mostly due to tidal friction). Probably the most impressive feature of the graph is the long-term quasi-periodical variation ('decadal variation') of so far unknown origin, but often speculatively ascribed to the core-mantle interaction. The annual and semi-annual periodic variations due to the interaction of the rotating Earth with the atmosphere are also well visible. The standard errors slowly decrease from the original 0.5 msec to about 0.1 msec around 1985, but afterwards it increases again to nearly its original value, mostly due to the decreasing number of participating observatories and density of observations (compare with Figure 2).

4. CONCLUSIONS

This paper presents the very first solution of the Earth Orientation Parameters in the definitive Hipparcos reference frame, based on optical astrometry observations since the beginning of the century; almost all expected observations (more than four million) have been used. It has been demonstrated that the ground-based astrometric observations with sufficiently long history can lead to an improvement of some of the Hipparcos proper motions, especially of double or multiple stars, with the formal precision higher than that of the Hipparcos catalogue. The new solution provides the series of EOP appropriate for further analyses such as studying long-periodic polar motion, length-of-day changes, or for determining long-periodic nutation terms. Namely we confirmed the secular motion of the pole, and found the correction of the presently adopted precession constant much smaller than obtained from VLBI observations. The solution is available upon request from the authors for further independent studies of the EOP behaviour in the past nine decades.

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