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Using the Earth orientation parameters to link the Hipparcos and VLBI reference frames

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Abstract. One of the methods, used to link the free Hipparcos reference system to the conventional extragalactic reference system, is the indirect method using the rapidly rotating terrestrial reference system as an intermediary. We solve the Earth orientation parameters, referred to the preliminary Hipparcos reference frame H37C, from the observations made by the classical methods of optical astrometry (latitude and universal time variations) in the interval 1899.7–1992.0. These parameters are then compared with the series of the Earth orientation parameters obtained by VLBI observations (thus referred to extragalactic objects) in the interval 1980.0–1992.0, and from their differences the two angles $\varepsilon_{0x}, \varepsilon_{0y}$ (out of three) and their annual rates ω_x, ω_y are derived. The non-alignment of the terrestrial longitude systems used by optical astrometry and VLBI makes the determination of ε_{0z} impossible, and the practical tests show that its obtained rate, ω_z, is also worthless, very probably due to a mutual drift between the optical astrometry and VLBI terrestrial systems in longitude. The remaining angles $\varepsilon_{0x}, \varepsilon_{0y}$ are determined with formal standard errors of about 0.9 mas (for the mean epoch of the common observations of VLBI and optical astrometry, 1985.25) and their rates with the accuracy of 0.3 mas yr^{-1}. The necessity of referring these angles to the mean epoch of the Hipparcos catalog, 1991.25 (as required by the Hipparcos Science Team) however raises their standard errors to 1.9 mas.

Key words: astrometry – reference systems – Earth

1. Introduction

It is well known that the Hipparcos catalog is characterized by a high degree of internal consistency, but its global orientation and a slow rotation, defined by six parameters, is left free (Froeschlé & Kovalevsky 1982, Kovalevsky 1995). To determine these parameters, an external link to other objects with known positions in an existing reference frame is needed. The natural choice is the reference frame tied to extragalactic objects since it is the closest approximation of the ideal barycentric, non-rotating system. In addition, its realization as maintained by the International Earth Rotation Service (IERS) is very close to the mean equator and dynamical equinox of J2000.0 (Arias & Feissel 1990). This very system is now under consideration to be adopted by the IAU as the International Celestial Reference System (ICRS).

To link the Hipparcos catalog to this system, several methods are used, their overview being given by Lindegren & Kovalevsky (1995), the results obtained by these methods and their combination are discussed by Kovalevsky et al. (1996). Most of the methods used consist in more or less direct observations of relative positions of the Hipparcos stars with respect to extragalactic objects.

The method presented here belongs to the ones that have been considered only very recently. It qualitatively differs from all the others, mainly because it is indirect; it uses the rotating Earth as an intermediary reference system. We measure the rapidly changing orientation of the Earth with respect to Hipparcos stars (by optical astrometry) and with respect to extragalactic objects (by VLBI). The principal idea of the method and a numerical example of linking FK5 to extragalactic system has recently been published by one of us (Vondrák 1996).

2. Relation between the Earth orientation parameters and linking angles

There are five Earth orientation parameters (EOP) that are routinely calculated from the radio interferometric observations: the components of polar motion x, y (giving the position of the celestial pole in the terrestrial reference system), the celestial pole offsets $\Delta\epsilon, \Delta\psi \sin\epsilon$ (giving the displacement of the actual spin axis of the Earth from its ephemeris position in the celestial reference system in obliquity ϵ and longitude ψ) and the difference between Universal and Atomic time scales UT1-TAI (giving the angle between the actual zero meridian and its expected position, assuming the uniform angular rotation of the Earth). The accuracy is on the level of 1 milliarcsecond (mas), or better (Carter & Robertson 1993).

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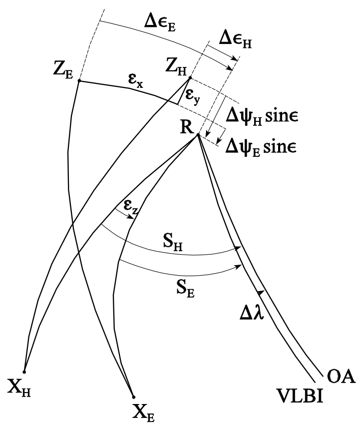

Fig. 1. Celestial pole offsets, sidereal time and orientation of the Hipparcos and extragalactic reference systems

The new reduction of optical astrometry observations proposed by Vondrák (1991) yields the same EOP at roughly 5-day intervals since the beginning of the century; the expected accuracy of the Earth orientation in the Hipparcos reference frame is, according to Vondrák et al. (1992) on the level of 10 mas during the last two decades of the solution.

The relative orientation of the two celestial reference systems (Hipparcos and extragalactic) and their mutual rotation can be described by six parameters. The transformation of a column vector given in the system of Hipparcos as $\boldsymbol{H} = (x_H, y_H, z_H)^{\mathrm{T}}$ into the extragalactic system $\boldsymbol{E} = (x_E, y_E, z_E)^{\mathrm{T}}$ is given by the formula

$$\boldsymbol{E} = \begin{bmatrix} 1 & \varepsilon_z & -\varepsilon_y \\ -\varepsilon_z & 1 & \varepsilon_x \\ \varepsilon_y & -\varepsilon_x & 1 \end{bmatrix} \boldsymbol{H}, \tag{1}$$

where we assume the orientation angles ε to be small and linearly changing with time. The six parameters defining the orientation of the Hipparcos catalog with respect to extragalactic reference system are then the values of ε at a fixed epoch t_0 ($\varepsilon_{0x} = \varepsilon_x(t_0)$, $\varepsilon_{0y} = \varepsilon_y(t_0)$, $\varepsilon_{0z} = \varepsilon_z(t_0)$) and their time derivatives ($\omega_x = \dot\varepsilon_x$, $\omega_y = \dot\varepsilon_y$, $\omega_z = \dot\varepsilon_z$). Their relation to the EOP on the celestial sphere is graphically shown in Fig. 1. The intersections of the axes X and Z of both reference systems (Extragalactic and Hipparcos) with the sphere are denoted as X_E, X_H, Z_E, Z_H, respectively, the position of the spin axis, corrected for the standard precession-nutation (Lieske 1979, Seidelmann 1982) as R, and the terrestrial zero meridians used by the two techniques are marked VLBI and OA. The small angles between R and Z_H, Z_E are measured by optical astrometry and VLBI, respectively, and expressed by means of celestial pole offsets $\Delta\epsilon_H, \Delta\psi_H \sin\epsilon$ and $\Delta\epsilon_E, \Delta\psi_E \sin\epsilon$. The observed Universal time UT1 can easily be converted into the Greenwich mean sidereal time S, using the conventional formula (Aoki et al. 1982); their values S_H, S_E as observed by the two techniques measure the angles between the respective zero meridian of a technique and the great circles RX_H, RX_E, respectively. The orientation angles between the two reference frames H and E, as also displayed in the figure, are then given in terms of the differences of EOP as

$$\begin{aligned} \varepsilon_x &= \Delta\epsilon_E - \Delta\epsilon_H \\ \varepsilon_y &= (\Delta\psi_H - \Delta\psi_E)\sin\epsilon \\ \varepsilon_z &= S_H - S_E - \Delta\lambda = 15.041(\mathrm{UT1}_H - \mathrm{UT1}_E) - \Delta\lambda. \end{aligned} \tag{2}$$

Notice that two of the five EOP, polar motion components x, y, are useless for the purpose since they are fully sensitive only to the terrestrial reference system, and almost entirely insensitive to the choice of the celestial reference system. They just measure the offsets of the axis z of the terrestrial system from the spin axis R, and as such can be used to determine the relation between the terrestrial reference systems used by the two techniques. From the third equation of (2) follows that the angle ε_z can be determined only if the misalignment of the two terrestrial reference systems in longitude, $\Delta\lambda$, is known. Unfortunately it is not the case – the origins of terrestrial longitudes of VLBI and optical astrometry are given by the adopted directions of the baselines and local verticals, respectively. The direct geodetic link between these two systems is practically impossible.

Having the series of EOP observed by the two techniques simultaneously in a sufficiently long time interval, we can derive the angles $\varepsilon_{0x}, \varepsilon_{0y}, \varepsilon_{0z} + \Delta\lambda_0$ for a chosen epoch t_0, and their rates $\omega_x = \dot\varepsilon_x$, $\omega_y = \dot\varepsilon_y$, $\omega_z = \dot\varepsilon_z$. The value ω_z can obviously be determined only on the assumption that the longitude difference $\Delta\lambda$ is constant.

3. The new solution of EOP by optical astrometry

To use the above described method, we need the new series of EOP, referred to preliminary Hipparcos catalog. We used a subset of preliminary catalog H37C, containing approximately 90% of the stars observed in the Earth rotation programmes since the beginning of the century, provided by the Hipparcos Science Team. It is the combined final Hipparcos catalog with preliminary orientation (i.e., before the rotation into the extragalactic reference was made), containing only single stars.

We roughly followed the procedures outlined in (Vondrák 1991) and applied later by Vondrák et al. (1995). The observations made with several different types of instruments were used (visual zenith-telescope – ZT, photographic zenith tube – PZT, photoelectric transit instrument – PTI, photoelectric astrolabe – PAST, Danjon astrolabe – AST, circumzenithal – CZ, visual zenith tube – VZT, and floating zenith-telescope – FZT). These instruments measured three different quantities:

1. latitude variations $\Delta\varphi$ (ZT, PZT, VZT, FZT),
2. universal time UT0-TAI (PZT, PTI),
3. zenith distance differences δh (AST, PAST, CZ).

We used the observations made with 46 instruments at 29 observatories. Their list is given in Table 1, together with the types of the instruments, intervals covered by the observations and their coordinates. Plate tectonic motions that were removed from the observed quantities (before being used in the solution) are also

Table 1. The observatories and instruments used in the solution by optical astrometry

Observatory	Code	Instrument	Longitude (°) (′)	Latitude (°) (′)	Plate motion in long. (s/cy)	Plate motion in lat. (″/cy)
Belgrade	BL	ZT(1949.0–1986.0)	20 31	44 48		+0.041
Bratislava	BR	CZ(1987.0–1991.9)	17 07	48 09	+0.0072	+0.044
Blagoveschtschensk	BK	ZT(1969.0–1992.0)	127 30	50 19		−0.048
Carloforte	CA	ZT(1899.8–1943.3,1946.5–1979.0)	8 19	39 08		+0.061*
Cincinnati	CI	ZT(1899.7–1916.0)	−84 25	39 08		+0.002
Gaithersburg	GT	ZT(1899.8–1915.0,1932.6–1979.0)	−77 12	39 08		+0.012
Grasse	GR	PAST(1983.2–1992.0)	6 56	43 45	+0.0063	+0.049
Irkutsk	IR	ZT(1958.2–1991.0), PTI(1979.1–1992.0)	104 20	52 17	+0.0084	−0.033
Kitab	KZ	ZT(1930.9–1979.0)	66 53	39 08		+0.001
Mizusawa	MZ	ZT(1900.0–1979.0), FZT(1967.0–1984.8), PZT#1(1959.0–1975.3), PZT#2(1974.4–1992.0)	141 08	39 08	−0.0005*	−0.045*
Nikolaev	NK	PTI(1974.4–1985.5)	31 59	46 58	+0.0078	
Ondřejov	OJ	PZT(1973.1–1992.0)	14 47	49 55	+0.0072	+0.044
Paris	PA	AST(1956.5–1983.0)	2 20	48 50	+0.0063	+0.051
Pecný	PY	CZ(1980.0–1992.0)	14 47	49 55	+0.0072	+0.044
Poltava	PO	ZT#1(1949.7–1990.4), ZT#2(1950.2–1968.8), ZT#3(1967.9–1980.8)	34 30	49 36		+0.031
Praha	PR	CZ#1(1980.2–1985.0), CZ#2(1985.2–1992.0)	14 25	50 05	+0.0072	+0.044
Pulkovo	PU	ZT#1(1904.7–1941.5), ZT#2(1948.7–1992.0), PTI#1(1961.3–1971.4), PTI#2(1971.2–1985.3), PTI#3(1971.8–1992.0)	30 20	59 46	+0.0096	+0.034
Punta Indio	PI	PZT(1971.6–1984.0)	−57 17	−35 21	−0.0005	+0.036
Richmond	RC	PZT#1(1949.8–1987.5), PZT#2(1981.9–1989.4)	−80 23	25 36	−0.0027	+0.008
Santiago de Chile	SC	AST(1965.9–1990.9)	−70 33	−33 24	+0.0045*	+0.058*
Shanghai	ZI	AST(1962.0–1985.0), PAST(1975.7–1985.0)	121 26	31 11	+0.0059	−0.045
Shaanxi	SX	PAST#1(1974.0–1984.8), PAST#2(1985.5–1992.0)	109 33	34 57	+0.0065	−0.037
Simeiz	SI	AST(1977.0–1991.0)	34 00	44 24	+0.0076	+0.031
Tschardjui	TS	ZT(1899.7–1919.4)	63 29	39 08		+0.004
Tuorla-Turku	TT	VZT(1963.7–1989.1)	22 30	60 25		+0.040
Ukiah	UK	ZT(1899.8–1979.0)	−123 13	39 08		+0.025*
Washington	W	PZT#1(1915.8–1955.3), PZT#2(1954.3–1984.8), PZT#3(1981.7–1992.0)	−77 04	38 55	−0.0044	+0.012
Wuchang	WH	AST(1964.0–1986.2), PTI(1981.9–1987.2)	114 21	30 32	+0.0060	−0.041
Yunnan	YU	PAST(1980.7–1991.3)	102 48	25 02	+0.0060	−0.032

displayed; the values based on recent space geodetic data (Ma 1995) instead of NUVEL-1 NNR model (Argus & Gordon 1991) are marked with an asterisk.

The observations were made available (in chronological order) by Yumi & Yokoyama (1980) for the ZT's of all ILS stations, Chollet (1991) for AST of Paris, Noël (1992) for AST of Santiago de Chile, Li (1992) for AST and PAST of Shanghai, Hu (1992) for Yunnan PAST, Archinal & McCarthy (1993) for Richmond and Washington PZT's, Manabe (1993) for FZT and PZT's of Mizusawa, Gorshkov & Naumov (1993) and Malkin (1995) for Pulkovo PTI's and ZT's, Karchevskaya & Tatarenko (1993) for ZT and PTI of Irkutsk, Gao (1993) for AST and PTI of Wuchang, Wang (1994) for PAST's of Shaanxi, Arias (1994) for Punta Indio PZT, Vigouroux (1994) for PAST of Grasse, Gorban (1994) for ZT's of Poltava, Niemi (1994) for VZT of Tuorla-Turku, Gaftonyuk & Rykhlova (1994) for AST of Simeiz, Gorshkov & Sokolova (1995) for ZT of Blagoveschtschensk, Damlianović (1995) for Belgrade ZT, Skoupý (1995) for CZ of Pecný, Hefty (1995) for CZ of Bratislava, and Kokaja (1995) for PTI of Nikolaev. The remaining observations were reduced by the authors.

The solution was made in two steps. In step one we used all available observations with the same weights. Then the outliers (exceeding 2.7σ) were rejected and the weights of all instruments estimated from the dispersion of residuals. The solution of step two, based on 3 615 067 weighted observations, led to the determination of 29 858 parameters. Out of these, there were 6 689 5-day values of $x, y, \Delta\epsilon, \Delta\psi \sin\epsilon$ in the interval 1899.7–1992.0, 2 630 5-day values of UT1-TAI in 1956.0–1992.0, 454 station parameters and 18 Lagrange multipliers. The standard error of unit weight (i.e., corresponding to an average observation of a star/star pair) was $0.190''$.

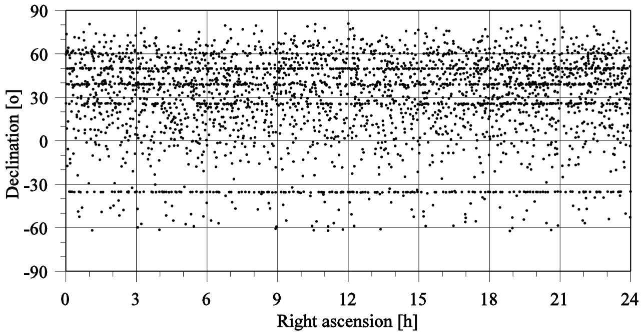

Fig. 2. Distribution of the 2 907 stars observed after 1980

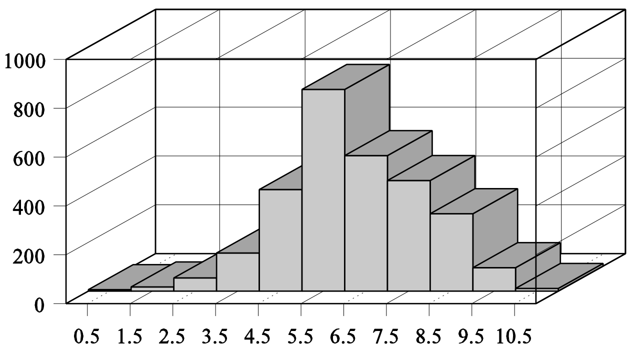

Fig. 3. Magnitude distribution of the stars observed after 1980

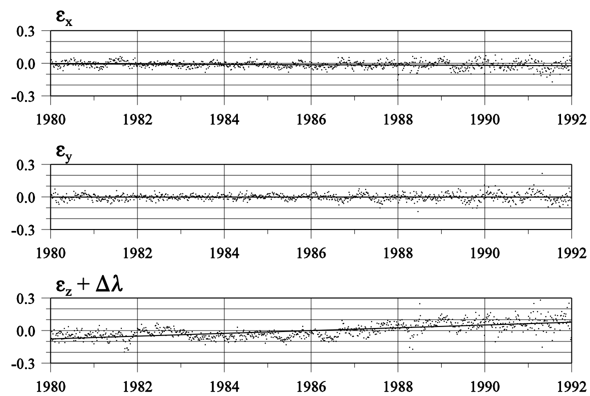

Fig. 4. Time evolution of the orientation angles of H37C with respect to ICRS (in arcseconds)

4. The linking to extragalactic reference frame

The optical astrometry results described above overlap partially with the VLBI observations. In order to get the link angles of Hipparcos we use only the last part of our solution, in the interval 1980.0–1992.0. This part is based on 1 350 807 observations of 2 907 different stars. The distribution of these stars on the celestial sphere is shown in Fig. 2 – one can see that the distribution in right ascension is rather good but there is a big asymmetry in declination, due to the geographic distribution of the observatories participating in the project. The magnitude distribution of the observed stars is displayed in Fig. 3.

The VLBI results obtained at different analysis centers and combined by the IERS are used; namely we use the solution IERS C04 that is referred to the prepared ICRS (Arias et al. 1995). According to Gambis (1995), who made the solution available, the series consists of the observed values after 1984.0 while the data before that date represent a backward extrapolation using the model of Souchay et al. (1995). Nevertheless, we made sure that the extrapolated data of C04 series fit well to rather sporadic and less precise VLBI observations made before 1984.0. The solution is given at daily intervals and is slightly smoothed so that it enables a simple linear interpolation to the irregular 5-day epochs of optical astrometry.

The differences between our new optical astrometry solution and IERS C04 (877 values) are then used to calculate the link angles at different epochs using Eqs. (2). Their time evolution is displayed in Fig. 4. It can be seen from the figure that the third component, ε_z, is determined less accurately than the first two, ε_x and ε_y. It is caused partially by the geographic distribution of the observatories (time is determined with the same accuracy as latitude only by instruments located near the equator), partly by larger systematic errors in measured universal time. The trends in two of the three components are obvious. The trend is especially large in the third component; it is improbably high and, in addition, it differs substantially from the results of other groups working on the same problem by different methods. This leads us to the inevitable conclusion that the value $\Delta\lambda$ is not constant, in contrast to our original expectations. This can be caused, e.g., by a secular change of the directions of local verticals at some of the observatories with respect to VLBI baselines. Systematic instrumental errors are also not ruled out. Thus we can determine, by this indirect method, only four of the six parameters needed, i.e., $\varepsilon_{0x}, \varepsilon_{0y}$, (for an epoch t_0) and ω_x, ω_y.

The individual values of $\varepsilon_{xi}, \varepsilon_{yi}$ (corresponding to epochs t_i) are not determined quite independently, being the result of a preceding least-squares estimation. The inspection of the full variance-covariance matrix shows that the only significant correlations exist between ε_{xi} and ε_{yj} for $i = j$ (i.e., for the values referred to the same epoch) while all the other correlations (like ε_{xi} and ε_{xj} or ε_{yi} and ε_{yj} for $i \neq j$) are quite negligible. In agreement with our previous expectations (Vondrák et al. 1992), these correlations vary with semi-annual period, typically within the range ± 0.1, only exceptionally reaching as much as 0.25. We take namely these correlations into account when calculating full (i.e., not diagonal) weight matrix, used for the subsequent least-squares estimation. Linear regression is used to estimate the values of orientation angles ε_0 at an epoch t_0 and their rates ω, using the weights of individual points and correlations coming from the optical astrometry solution.

An analysis of the results shows that the most accurately determined values of ε_0 are achieved for the mean epoch of common observations of optical astrometry with VLBI, i.e., t_0 = 1985.25 (σ_ε = 0.88). In this case, the angles ε_0 and rotations ω are practically de-correlated, the rotations ω being independent of the choice of the epoch t_0. Nevertheless, the requirements

Table 2. Results of linking (in mas and mas per year), and their correlation matrix. The basic epoch is that of Hipparcos (t_0 = 1991.25), the results are referred to the final orientation of Hipparcos catalog

Results			Correlations			
			ε_{0x}	ε_{0x}	ω_x	ω_y
ε_{0x}	−3.5	± 1.9	1.000	0.002	0.889	0.008
ε_{0y}	+5.8	± 1.9	0.002	1.000	0.005	0.885
ω_x	−0.96	± 0.28	0.889	0.005	1.000	0.006
ω_y	−0.32	± 0.28	0.008	0.885	0.006	1.000

imposed by the Hipparcos Science Team lead us to use the mean epoch of Hipparcos, t_0 = 1991.25. The results, referred to the final combined link of Kovalevsky et al. (1996) are shown in Table 2; we do not display the orientation of H37C since it is only one of the several intermediary catalogs used in the process of producing the final Hipparcos catalog and it is not available to general astronomical community. Their standard errors and correlation matrix are also shown.

Unfortunately, there is a lack of optical astrometry observations after 1991, what leads to rather large difference between the mean epoch of Hipparcos and that of common observations of VLBI with optical astrometry. Relatively high correlations between $(\varepsilon_{0x}, \omega_x)$ and $(\varepsilon_{0y}, \omega_y)$ and big values of standard errors in $\varepsilon_{0x}, \varepsilon_{0y}$ are due namely to this difference.

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