COMBINED ASTROMETRIC CATALOGUE EOC-2 – AN IMPROVED REFERENCE FRAME FOR LONG-TERM EARTH ROTATION STUDIES

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ABSTRACT. We collected the astrometric observations of latitude / universal time variations made worldwide at 33 observatories. These observations, referred to Hipparcos Catalogue, were then used to determine Earth Orientation Parameters (EOP) at 5-day intervals, covering the interval 1899.7-1992.0. Later on, new astrometric catalogues (such as ARIHIP or TYCHO-2) appeared as combination of Hipparcos / Tycho positions with ground-based catalogues. These catalogues yield more accurate proper motions than original Hipparcos Catalogue. Our attempt goes however even further - we use about 4.5 million observations of latitude / universal time variations, and combine them with these catalogues to obtain Earth Orientation Catalogue (EOC). The second version of the catalogue, EOC-2, contains 4418 different objects (stars, components of double stars, photocenters). The improvement of the accuracy of proper motions (especially in declination) over Hipparcos is remarkable - median formal inaccuracies attain 0.70 and 0.35 mas/year in right ascension and declination, respectively.

1. INTRODUCTION

In the past, we produced three solutions of Earth Orientation Parameters (EOP), based on optical observations of latitude / universal time / altitude variations made at 33 observatories in years 1899.7 – 1992.0. These solutions are denoted as OA97 (Vondrák et al. 1998), OA99 (Vondrák et al. 2000) and OA00 (Ron & Vondrák 2001). All these solutions were worked out in the reference frame of Hipparcos Catalogue (ESA 1997), but about 20% of positions / proper motions of Hipparcos stars had to be corrected, because of the systematic deviations in their positions extrapolated from Hipparcos epoch backwards. These corrections reflected the problems mostly connected with double and multiple star systems – real proper motions are not linear, Hipparcos mission was shorter than four years (i.e., much shorter than orbital periods of double stars), and sometimes it was not clear which component was observed by ground-based astrometry. The reference point can even be different for visual and photographic / photoelectric observations, due to better resolution of human eye!

Recently, new catalogues with improved proper motions appeared, as combination of Hipparcos and/or Tycho Catalogues with ground based catalogues. They comprise FK6, Part I and III, as combination of FK5 with Hipparcos (Wielen et al. 1999, 2000), GC+HIP as combination of Boss' General Catalogue with Hipparcos (Wielen et al. 2001a), and TYC2+HIP as combination of Tycho-2 with Hipparcos (Wielen et al. 2001b). The same authors made a selection of the preceding three catalogues and Hipparcos itself, and formed a catalogue called ARIHIP (Wielen et al. 2001c). Wielen et al. in their catalogues introduced a classification of 'astrometric excellency' by assigning a number of asterisks to each star (going from no to three asterisks, the more asterisks the better the star from astrometric point of view). Parallel to these, Høg et al. (2000) derived the catalogue TYCHO-2 as combination of Tycho Catalogue with 144 ground-based catalogues. The latter two, i.e. ARIHIP and TYCHO-2, form the basis of constructing the new Earth Orientation Catalogue (EOC) whose description follows.

2. CONSTRUCTION OF EOC

The idea is to create a new improved reference frame for long-term Earth rotation studies, by using the best available star catalogues and their combination with the rich observation material of measuring Earth orientation in 20th century. To this end, we first inspected all optical data from 47 instruments at 33 observatories, covering the interval 1899.7 – 2002.6. We found that there were 4418 different objects (stars, double star components, their photocenters) observed. They were identified in recent catalogues, and their positions, proper motions, parallaxes and radial velocities taken over from them to form zero version of the new catalogue, EOC-0. In total, 2995 objects are taken over from ARIHIP, 1248 from TYCHO-2, 144 from Hipparcos, 238 from PPM (Roeser & Bastian 1991, Bastian & Roeser 1993), and remaining three were found in none of these, so they are taken over from original 'local' catalogues used by respective observatories. However, only 44% of these stars are 'astrometrically excellent' (i.e., with at least one asterisk), so further improvement is necessary. The rich observational material of Earth orientation programmes (about 4.5 million observations made during a century), in which each object was observed in average a thousand times, makes such improvement feasible.

Next we combine EOC-2 with the observations that can be divided into four groups, according to the type of instruments used and observable obtained:

- 10 PZT's that observe stars near local zenith and determine both latitude and universal time: 2 at Mizusawa (1959.0-1993.1), Japan; 1 at Mount Stromlo (1957.8-1985.7), Australia; 1 at Punta Indio (1971.6-1984.5), Argentina; 1 at Ondřejov (1973.1-2002.6), Czech Republic; 2 at Richmond (1949.8-1989.4) and 3 at Washington DC (1915.8-1992.0), USA;
- 7 photoelectric transit instruments (PTI), observing the transits of stars over local meridian and determining only universal time: 1 at Irkutsk (1979.1-1992.0) and 3 at Pulkovo (1959.7-1994.0), Russia; 1 at Nikolaev (1974.4-1992.4) and 1 at Kharkov (1973.0-1992.0), Ukraine; 1 at Wuhang (1981.9-1987.2), China;
- 16 visual zenith telescopes (ZT) and similar instruments (visual zenith tube - VZT, floating zenith telescope - FZT) that observe small difference of zenith distances of two stars passing over local meridian symmetrically (one in south, one in north), determining only latitude: 7 ZT's at ILS stations – Carloforte, Cincinnati, Gaithersburg, Kitab, Mizusawa, Tschardjui, Ukiah (1899.7-1979.0); 1 ZT at Belgrade (1949.0-1986.0), Yugoslavia; 1 ZT at Blagovestschensk (1959.0-1992.0), 1 ZT at Irkutsk (1958.2-1991.0) and 1 ZT's at Pulkovo (1904.7-1995.0), Russia; 1 ZT at Józefoslaw (1961.8-1996.0), Poland; 1 FZT at Mizusawa (1967.0-1984.8), Japan; 2 ZT's at Poltava (1949.7-1990.4), Ukraine; 1 VZT at Tuorla-Turku (1963.7-1989.1), Finland;
- 14 equal altitude instruments (Danjon astrolabes - AST, photoelectric astrolabes - PAST, and circumzenithals - CZ) that observe transits of stars through an almucantar, determining a combination of latitude/universal time: 1 PAST at Beijing (1979.0-1987.8), 2 PAST's at Shaanxi (1974.0-1992.0), 1 AST + 1 PAST at Shanghai (1962.0-1985.0), 1 AST at Wuhang (1964.0-1986.2) and 1 PAST at Yunnan (1980.7-1991.3), China; 1 CZ at Bratislava (1987.0-1991.9), Slovakia; 1 PAST at Grasse (1983.2-1992.0) and 1 AST at

Paris (1956.5-1983.0), France; 1 AST at Pecný (1970.0-1992.0) and 1 CZ at Prague (1980.2-1992.0), Czech Republic; 1 AST at Santiago de Chile (1965.9-1990.9), Chile; 1 AST at Simeiz (1977.0-1991.0), Ukraine.

A procedure of combining these observations with the catalogue EOC-0 was first applied to only the first three groups above, leading to first version EOC-1 (Vondrák & Ron 2003, 2004), more details on constructing EOC-2 by using all instruments are given in (Vondrák 2004).

The strategy, based on the assumption that the latitude / universal time is constant during a night, was followed; the method is insensitive to any change of the direction of the local vertical (in terrestrial frame) between successive nights. We proceeded by following these steps, for observations by all instruments:

1. All observed quantities (i.e., latitude / universal time / altitude difference) were recalculated with EOC-0 and the model of precession-nutation IAU2000A (Mathews et al. 2002).
2. The deviations of these observables from the mean value of the night (calculated only for astrometrically excellent stars) were computed, and linear regression for these differences for the same star in different epochs was made.
3. Stars with statistically significant deviations were checked for multiplicity, using the information contained in Hipparcos Catalogue. In positive case, the displacement of reference point from EOC-0 was estimated, and the respective position in EOC-0 was corrected. In this case, the procedure above (item 2) was repeated.
4. Combination of these deviations with EOC-0 was made. To this end, each entry of the star of EOC-0 was represented by three virtual observations (both for right ascension and declination) in three different epochs: $t_1 = t_\circ - 90$, $t_2 = t_\circ$, $t_3 = t_\circ + 10$, where $t_\circ$ is the mean epoch of the catalogue in years. The values of these 'observations' were implicitly set to zero, their uncertainties were then calculated from catalogue standard errors of the position $\sigma_\circ$ and proper motion σ_μ as

$$\sigma_1^2 = 9000\sigma_\mu^2, \quad \sigma_2^2 = \sigma_\circ^2 / \left[1 - (\sigma_\circ/\sigma_\mu)^2/900\right], \quad \sigma_3^2 = 1000\sigma_\mu^2. \tag{1}$$

In such case the catalogue entry is reproduced exactly, if the three virtual observations are subject to linear regression. The values from Eq. (1) were then used to calculate the weights $p_i = (200/\sigma_i)^2$, if σ_i are given in milliarcseconds. Real observations (deviations calculated above) were assigned the weights 1. Weighted linear regression through all real and virtual observations was then made to yield the combined position / proper motion. To this end, we used the following observation equations for the three types of observations (deviation in latitude $\delta\varphi$, universal time δUT, altitude δh), respectively:

$$\begin{aligned} v_\varphi &= \Delta\delta + \Delta\mu_\delta(t - t_\circ) - \delta\varphi \\ v_{UT} &= \Delta\alpha^* + \Delta\mu_\alpha^*(t - t_\circ) - 15.041\delta\mathrm{UT}\cos\varphi \\ v_h &= \Delta\alpha^*\sin q + \Delta\mu_\alpha^*(t - t_\circ)\sin q + \Delta\delta\cos q + \Delta\mu_\delta(t - t_\circ)\cos q - \delta h. \end{aligned} \tag{2}$$

Here $\Delta\alpha^*$, $\Delta\mu_\alpha^*$ stand for $\Delta\alpha\cos\delta$, $\Delta\mu_\alpha\cos\delta$, and q is the parallactic angle of the star. First two of Eqs (2) are used always, for virtual observations of declination and right ascension with their weights, respectively, and they are mixed with any of the three equations for real observations, according to their type.

An illustrative example of combination is given in Figs. 1 and 2. Tycho-2 double star No. 84606 was observed - universal time by four PTI's, latitude by all ILS ZT's. Since the photocenter was observed, its position as given in Tycho-2 was displaced from component A

Table 1: Comparison of accuracies of different catalogues

Catalogue	n_{stars}	Ep_α	σ^*_α	$\sigma^*_{\mu\alpha}$	Ep_δ	σ_δ	$\sigma_{\mu\delta}$
Hipparcos	117995	91.25	0.87	0.72	91.25	1.02	0.85
ARIHIP	90842	91.24	0.81	0.79	91.27	0.62	0.71
TYCHO-2	2.5 mil.	90.74	8.00	1.30	90.54	9.00	1.30
EOC-2	4418	91.16	0.70	0.47	91.03	0.60	0.35

position by a value, estimated from the observations, and the corrected position was adopted in EOC-0. This very position (and original proper motion) was then used to calculate the three virtual observations and combined with real observations.

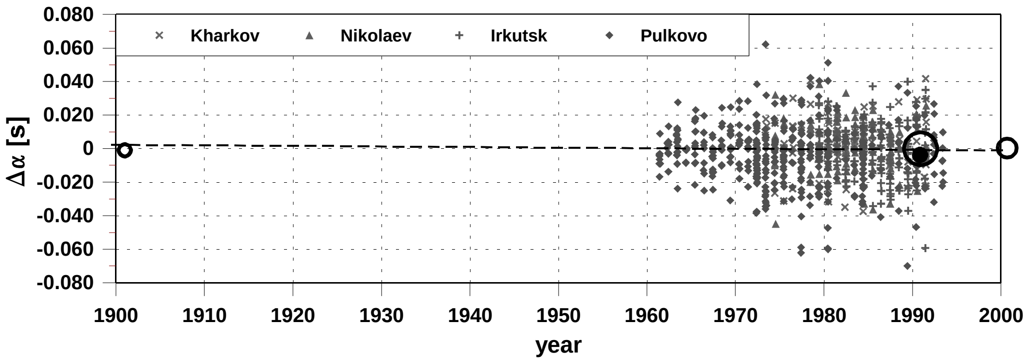

Figure 1: Combination (dashed line) of Tycho-2 right ascension of double star 84606 with PTI observations (gray markers) of its photocenter. Virtual observations (open circles) are displaced from component A (full circle).

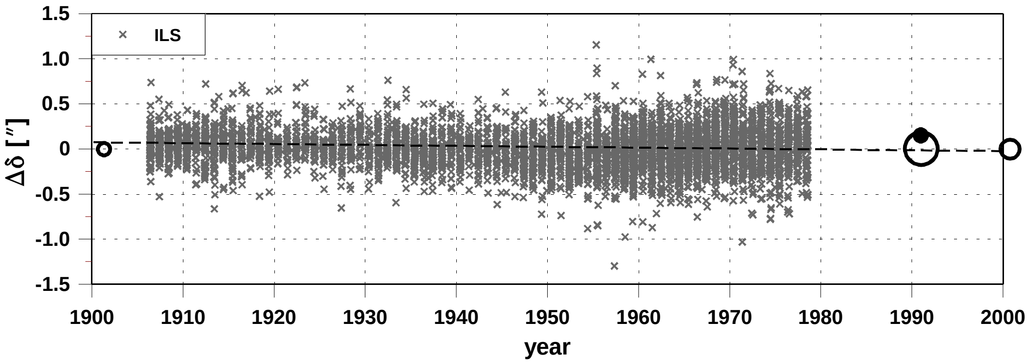

Figure 2: Combination (dashed line) of Tycho-2 declination of double star 84606 with ZT observations (gray markers) of its photocenter. Virtual observations (open circles) are displaced from component A (full circle).

The accuracy of EOC-2 is compared with those of the catalogues Hipparcos, ARIHIP, and Tycho-2 in Table 1, in which median values are displayed. The improved accuracy, especially of proper motions in declination, is evident from the table.

The values from Table 1 are used to calculate the time evolution of accuracies of these catalogues over the twentieth century, shown in Fig. 3. The differences amongst the catalogues grow backwards, towards the beginning of the twentieth century. The ever growing superiority of EOC-2 with respect to the remaining three catalogues is obvious.

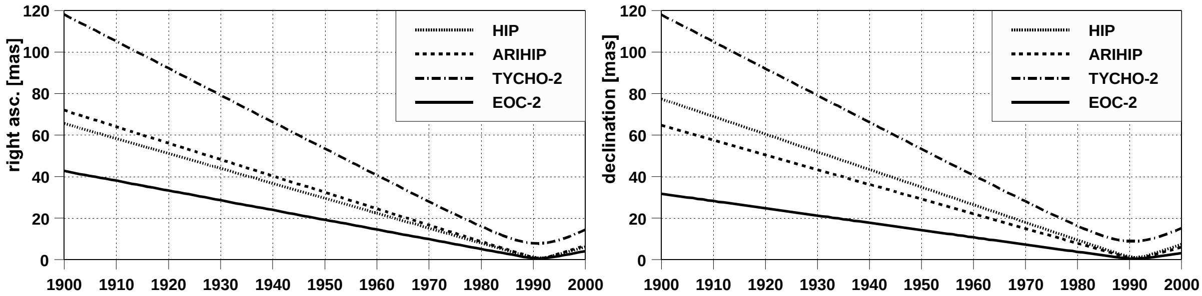

Figure 3: Comparison of accuracies of different catalogues - evolution in time.

3. SOLUTIONS OF EOP BASED ON EOC-2, CONCLUSIONS

The catalogue EOC-2 was used in 2004 to produce new solutions of Earth Orientation Parameters. There were two of them, denoted OA04 and OA04a, both calculated by a method more or less identical with our preceding solutions. They cover the same interval, i.e., 1899.7 – 1992.0, the main differences from the preceding solutions are characterized by the following:

- OA04 uses all 47 instruments merged into 42 series (instruments of the same or similar type, working at the same observatory, were treated as a single instrument). IAU2000A model of precession-nuation was used, and consequently celestial pole offsets were represented by a constant plus linear term, instead of 5-day values used formerly.
- OA04a merged the same observations into only 40 series. IAU2000A model of nutation plus P03 model of precession (Capitaine et al. 2003) were used, celestial pole offsets were represented by a constant, linear and quadratic terms. This solution is described in more detail and used to test precession models by Ron et al. (2005).

These two solutions are supposedly more robust than our preceding solutions, mainly because of the different treatment of celestial pole offsets – the replacement of 5-day points by two or three 'global' parameters for each component decreases the number of parameters estimated from the adjustment by about 45%. Also, the number of observations increased since a better EOC-2 catalogue was used as the celestial reference frame – less observations were rejected due to their large residuals, especially at the beginning of the solution. This is demonstrated in Table 2 that displays a comparison of some statistical data of the last three solutions.

Table 2: Comparison of accuracies of solutions OA00, OA04, OA04a

Solution	$n_{obs.}$	$n_{param.}$	$\sigma_\circ$ [″]	σ_x [mas]	σ_y [mas]	σ_{UT1} [ms]
OA00	4 447 400	29 809	0.188	20.5	18.3	0.78
OA04	4 538 694	16 443	0.190	17.4	15.7	0.72
OA04a	4 541 385	16 444	0.191	17.4	15.9	0.72

The uncertainties shown in the table are median values, and they confirm a higher accuracy of the last two solutions in 5-day values of all three EOP components (σ_x, σ_y and σ_{UT1}), in spite of a slightly larger average uncertainty of a single observation ($\sigma_\circ$).

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