SOLUTION OF EARTH ORIENTATION PARAMETERS IN THE FRAME OF NEW EARTH ORIENTATION CATALOGUE

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The new Earth Orientation Catalogue was recently derived, based mostly on the ARIHIP and Tycho-2 Catalogues that were combined with ground-based optical observations of latitude and Universal Time variations in the 20th century. The solution of Earth orientation parameters, based on this new star catalogue and the new IAU model of precession-nutation, is presented.

INTRODUCTION

We produced, in the past years, several solutions of Earth Orientation Parameters (EOP) in the frame of the Hipparcos Catalogue [2] that were based on optical astrometry observations of latitude / Universal Time variations made at up to 33 observatories in the years 1899.7–1992.0. All of them were referred to the "old" IAU 1976 precession [5] and IAU 1980 nutation [14] models. Three solutions, that differed in number of instruments, slightly different criteria for correcting positions / proper motions, and also in methods of merging observations with different instruments into series, were made (where OA stands for Optical Astrometry):

- OA97 [12] that was based on observations made with 45 different instruments located at 31 observatories. 4.32 million individual observations in 48 series were used, and applied corrections to 11% of positions and / or proper motions of the observed Hipparcos stars.
- OA99 [13] that was based on observations made with 47 instruments at 33 observatories. 4.45 million observations in 39 series were used, and 20% of positions and / or proper motions of the observed stars were corrected.
- OA00 [7] that was based on observations made with 47 instruments at 33 observatories. 4.45 million observations in 41 series were used, and 20% of star positions and / or proper motions were corrected.

The reason why these corrections (mostly for double and multiple star systems) had to be applied was threefold:

Firstly, the real motions of the observed objects are not linear – the reference point that was observed (either a component or a photocenter) exhibits, in addition to the linear drift, also a small periodic motion.

Secondly, the Hipparcos mission was shorter than four years, *i.e.*, usually much shorter that the orbital periods. As a result, the linear proper motion derived from Hipparcos observations is rather a tangential motion near the epoch of the Hipparcos mission (1991.25) than the mean motion over a longer time span (decades) that is required for deriving Earth orientation parameters. So, even if the amplitude of the periodic part is negligible, the extrapolated star's position can have big error.

Thirdly, it was sometimes not quite clear which object was observed: a component of a double star or its photocenter? This reference point was often different from the object listed in the Hipparcos Catalogue, and sometimes even different for different types of instruments (visual, photographic, photoelectric). Usually, the human eye proved to be a better detector than photography or photoelectric device, capable of distinguishing much closer objects.

After these solutions were finished, several new star catalogues appeared as combination of Hipparcos / Tycho positions with ground-based catalogues with a much longer observational history. The result is the catalogues with much more reliable proper motions. The most important ones are Tycho-2 [3] (the combination of the Tycho Catalogue with additional 144 ground-based astrometric catalogues), and ARIHIP [15] (selection of the best stars from other combined catalogues FK6, GC+HIP, Tycho-2+HIP and Hipparcos itself). We decided to make use of these catalogues, and to combine them further with the rich observational material collected in Earth rotation programmes during the whole 20th century (latitude / Universal Time variations). The goal is to get a better and more stable celestial reference frame for long-period Earth rotation studies [10]. Thus, the idea of constructing the Earth Orientation Catalogue (EOC), containing all stars observed in Earth rotation programmes, appeared. A more detailed description of the combined catalogues, including EOC, can be found in [9]. Here follows an abbreviated outline of deriving the EOC.

CONSTRUCTION OF THE NEW EOC CATALOGUE

The idea is to use the observed data made by optical astrometry in Earth rotation programmes (instantaneous latitude / Universal Time / altitude difference) to improve the catalogue positions and proper motions. We have collected the data with 47 instruments located at 33 observatories, covering the interval 1899.7–2003.0. They can be divided into three groups according to the observables that they provide:

1. *10 Photographic Zenith Tubes* that measured simultaneously latitude and Universal Time (3 at Washington, DC; 2 at Richmond, Florida and Mizusawa, Japan; 1 at Mount Stromlo, Australia; Punta Indio, Argentina; Ondřejov, Czech Republic).

2. *7 Photoelectric Transit Instruments* that measured only Universal Time (3 at Pulkovo and 1 at Irkutsk, Russia; Kharkiv and Mykolaiv, Ukraine; Wuhang, China).

3. *16 Visual Zenith-Telescopes and similar instruments* that measured only latitude (7 Visual Zenith-Telescopes at International Latitude Service stations – Carloforte, Italy; Cincinnati, Ohio; Gaithersburg, Virginia; Kitab, Uzbekistan; Mizusawa, Japan; Tschardjui, Turkmenistan; Ukiah, California; 2 at Poltava, Ukraine; 1 at Belgrade, Serbia; Blagoveshchensk, Irkutsk, and Pulkovo, Russia; Józefoslaw, Poland; Floating Zenith Telescope at Mizusawa, Japan; Visual Zenith Tube at Tuorla-Turku, Finland).

4. *14 instruments for equal altitude method* that measured the differences of stars' altitude, *i.e.*, the combination of latitude and Universal Time (Danjon astrolabes at Paris, France; Santiago de Chile; Shanghai and Wuhang, China; Simeiz, Ukraine; 2 photoelectric astrolabes at Shaanxi, China; photoelectric astrolabes at Beijing, Shanghai, Yunnan, China, and Grasse, France; circumzenithals at Bratislava, Slovakia; Prague and Ondřejov, Czech Republic).

The inspection of all observations made with these instruments showed that there were 4418 different objects observed (stars, double star components, photocenters). They were identified in different recent catalogues, and their positions, proper motions, parallaxes, and radial velocities taken over from them. Not all of them were found in the best one, ARIHIP, – we also had to use less precise Tycho-2, and the rest were found in the Hipparcos and PPM Catalogues [1, 8]. ARIHIP uses three types of solution, with slightly different positions / proper motions: single-star mode, short-term prediction mode and long-term prediction mode. To construct EOC, we used a "classical" single-star mode. The statistics is as follows:

2995 objects were taken over from ARIHIP, 1248 from Tycho-2, 144 from Hipparcos, and 28 from PPM; 3 objects were found in none of the above catalogues, and therefore, their initial entries were taken over from the catalogues used at the respective observatories. These entries formed the zero version of the catalogue, so-called **EOC-0**.

The authors of ARIHIP introduced a classification of "astrometrical excellency" of each star – the number of asterisks (the larger is the number, the more reliable the position / proper motion). The stars with no asterisk are most probably double or multiple systems. There are 56% of such "non-excellent" stars in EOC-0 (including those originating from other catalogues than ARIHIP), so further improvement is still necessary and possible. Taking into account the number of observations and number of different objects observed, each of them was observed about a thousand times during long time interval, with precision of one observation of about $0.2''$. It means that proper motions can be determined with precision competing with recent catalogues, and the combination with EOC-0 should bring a significant improvement.

The positions and proper motions were first improved by means of combining EOC-0 with the observations made in local meridian (*i.e.*, with only the first three groups of instruments shown above). This version, containing only 3784 objects, was denominated **EOC-1** and described in detail in [11].

In further improvement of the catalogue we used all available observations (*i.e.*, made with all four groups of instruments mentioned above) to determine relative positions of all stars with respect to those denoted as astrometrically excellent. The strategy, assuming that the latitude / Universal Time is constant only during a night, was chosen. Consequently, the method used was practically insensitive to any change of the terrestrial coordinates of the instruments during the time. We proceeded by following these steps:

1. The instantaneous observables (*i.e.*, latitude / Universal Time / altitude difference) were transformed from original observations, using the entries from EOC-0 and the new model of precession-nutation IAU2000A [6].

2. The deviations of these observables from the mean value of the night (calculated for astrometrically excellent stars only) 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 the 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 the EOC-0 catalogue was represented by three virtual observations (of both right ascension and declination) in three epochs covering one century: $t_1 = t_\circ - 90$, $t_2 = t_\circ$, $t_3 = t_\circ + 10$, where $t_\circ$ is the mean epoch of the catalogue. 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

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

that would reproduce exactly the catalogue entry if subject to linear regression. These values were then used to calculate the weights $p_i = (200/\sigma_i)^2$, if σ_i are given in milliarcseconds; all real observations (deviations calculated above) were assigned the weights 1. Then the weighted linear regression through all real and virtual observations was made to yield the combined position / proper motion. To this end, we used the following observation equations for the three types of observations (latitude φ, Universal Time UT, altitude h), 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 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 combining declination is shown in Fig. 1; the observations at all ILS stations and the Floating Zenith Telescope at Mizusawa (MZL) are combined with Tycho-2 entry for star No. 36366, represented by three virtual observations whose weights are also depicted in the figure.

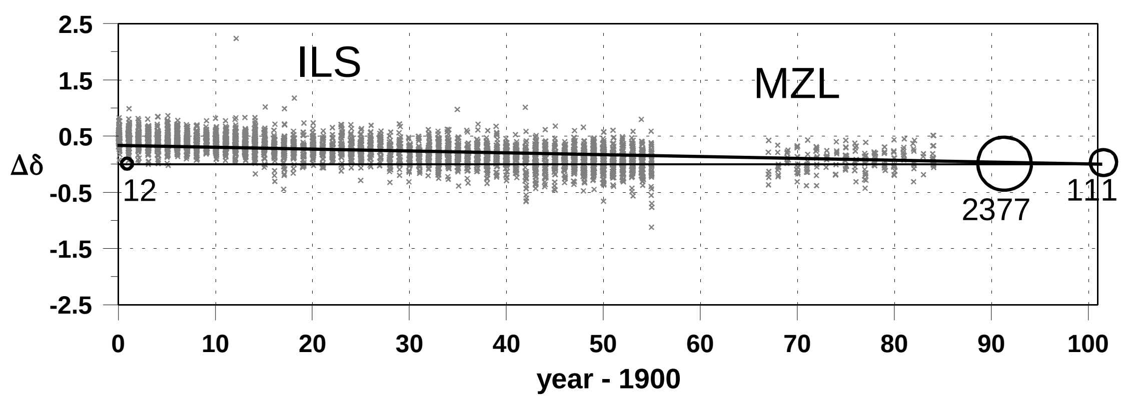

Figure 1. Tycho-2 star No. 36366: observations at all ILS stations and Mizusawa FZT (MZL, crosses), virtual observations (open circles with weights) and combined position (full line)

The combination leads to the catalogue version **EOC-2**; the comparison of its standard errors (median values) with the Hipparcos is given in Table 1. A substantial improvement, especially of proper motions, is obvious.

Table 1. Comparison of accuracy of EOC-2 with Hipparcos

Catalogue	No.	$Ep_\alpha - 1900$	σ^*_α [mas]	$\sigma^*_{\mu\alpha}$ [mas/yr]	$Ep_\delta - 1900$	σ_δ [mas]	$\sigma_{\mu\delta}$ [mas/yr]
Hipparcos	117995	91.25	0.87	0.72	91.25	1.02	0.85
EOC-2	4418	91.16	0.70	0.47	91.03	0.60	0.35

NEW SOLUTION OF EOP IN THE FRAME OF EOC-2

The new solution of EOP consists in using virtually the same data as were used to improve the catalogue, but we did not go beyond 1992.0, when the number of active observatories and number of observations decreased substantially. The series of observations with 47 instruments were merged in cases when the instruments of similar type worked at the same observatory. The steps between them were estimated and removed beforehand. Namely, we merged the observations with the following instruments into a single series: the visual zenith-telescope and FZT at Mizusawa, Japan; two PZT's at Mizusawa, Japan; two zenith-telescopes at Poltava, Ukraine; three photoelectric transit instruments at Pulkovo, Russia; two PZT's at Richmond, Florida; two PZT's at Washington, DC. On the other hand, the visual zenith-telescope at Pulkovo, Russia was treated as two different series, due to a long gap in the observations (and change of the instrument's position) during the second world war. The same holds for circumzenithal in Prague, Czech Republic, that was moved to a distant location, and was treated as two different series. Thus, the total number of series used was 42.

We followed more or less the same procedures as in our preceding solutions, with two exceptions:

1. New IAU2000A model of precession-nutation was used, which led to much smaller values of celestial pole offsets, and consequently
2. celestial pole offsets were represented by a constant plus linear trend for both coordinates, not by five-day individual points as before, in order to decrease the number of estimated parameters, and to make the solution more robust.

The results of the solution, so-called OA04, are depicted in Figures 2 (polar motion) and 3 (Universal Time, only after 1956.0) for each five-day interval, where their mean errors σ are also shown. The latter are given in

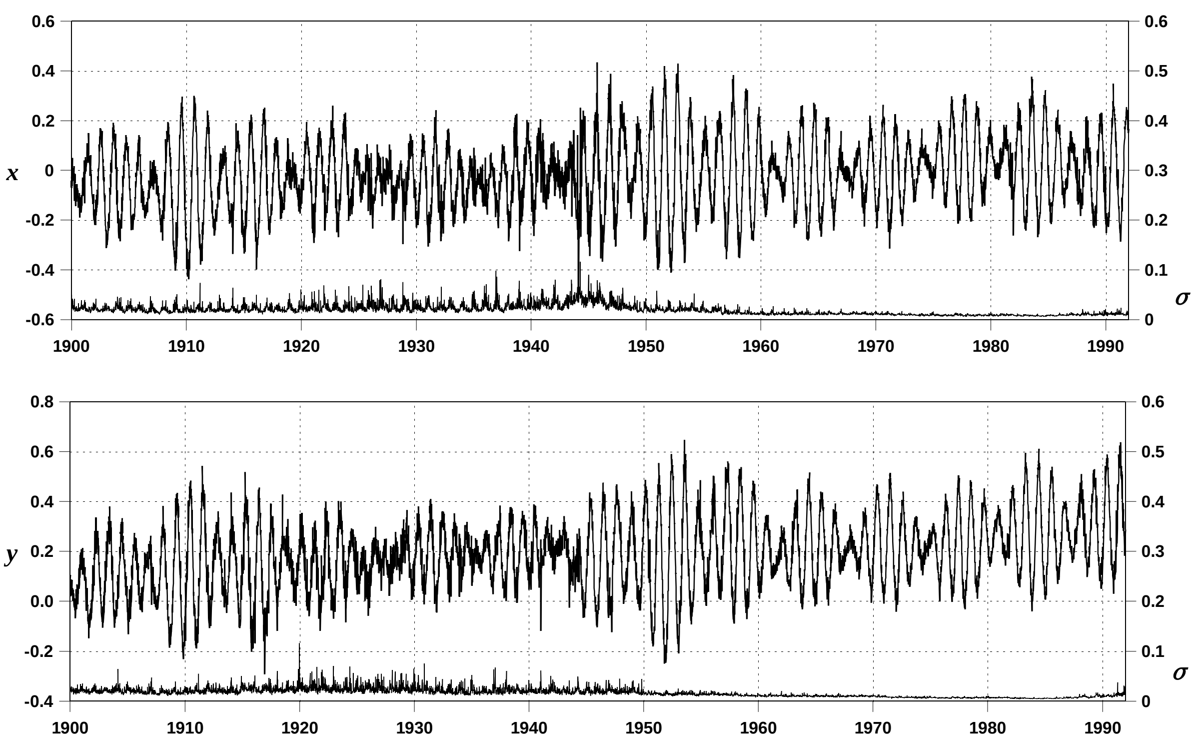

Figure 2. Polar motion of the solution OA04 (in arcseconds)

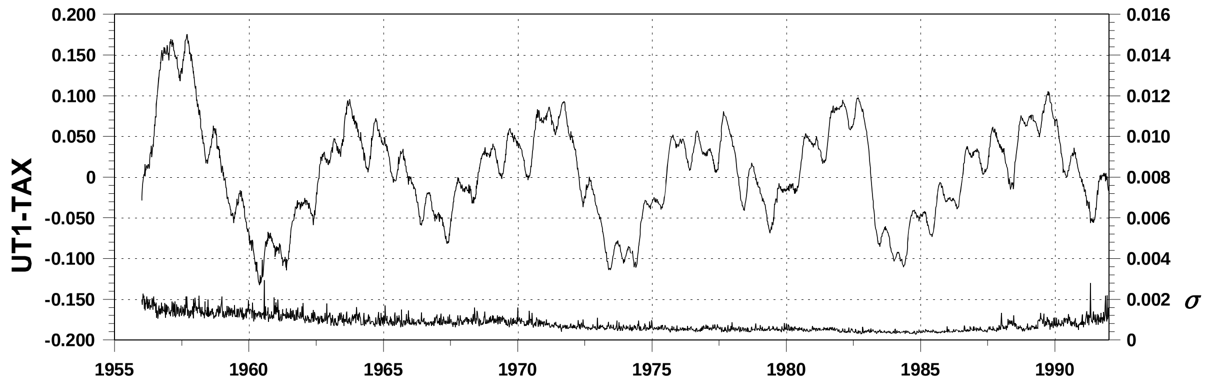

Figure 3. Reduced Universal Time variations of the solution OA04 (in seconds of time)

enlarged scales – two times larger than the results for polar motion, 25-times larger for Universal Time. Instead of UT1–TAI, the reduced values UT1–TAX (with long-periodic part removed, in order to show the variations in more detail) are depicted. The relation between TAI and TAX is given (in seconds of time) by the formula

$$\begin{aligned} \mathrm{TAX} &= \mathrm{TAI} + 2.63 - 0.002047t - 0.236 \times 10^{-7}t^2 + 0.49 \times 10^{-12}t^3 - 0.17\cos(2\pi t/6000) \\ &\quad +0.26\sin(2\pi t/6000) - 1.32\cos(2\pi t/9000) + 0.16\sin(2\pi t/9000), \end{aligned} \tag{3}$$

where t = MJD − 35300. The formula was selected so that the difference UT1–TAX never exceeds 0.2 s in the interval 1956.0–1992.0.

The resulting celestial pole offsets (in milliarcseconds) are given as

$$\Delta\psi \sin\varepsilon = -5.7_{\pm 0.32} + 28.5_{\pm 1.08}T, \quad \Delta\varepsilon = -5.5_{\pm 0.32} + 6.7_{\pm 1.07}T, \tag{4}$$

where T is given in centuries since 1956.0. These values represent a sum of a bias between ICRS and the new EOC catalogue with the correction of the new IAU precession. They are very small, and are quite comparable with the formal uncertainties of the link between the Hipparcos (to which EOC is linked) and ICRS (±0.6 mas at the epoch 1991.25 and ±25 mas/cyr in rotation, according to [4]).

CONCLUSIONS

The new star EOC catalogue (given in the ICRS) was constructed, using about 4.5 million individual observations of latitude / Universal Time / altitude difference, in combination with recent catalogues such as the ARIHIP or Tycho-2. Version EOC-2 of the catalogue, in which many double stars were detected and their positions / proper motions referred to their reference points (either double star components or photocenters) is more accurate and stable in long-periodic sense than the original catalogues based on the Hipparcos mission (Hipparcos, Tycho, ARIHIP, ...). The catalogue is used in the new solution of Earth orientation parameters from optical astrometry in the interval 1899.7–1992.0. The present solution, OA04, has a better precision of five-day values than our preceding solutions based on the Hipparcos, which is demonstrated by the statistics shown in Table 2.

Table 2. Comparison of some characteristics of the solution OA04 with OA00

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	0.87
OA04	4 538 694	16 443	0.190	17.4	15.7	0.72

Thanks to the better star catalogue, more observations (n_{obs}) could be used in the solution OA04 than before, because less observations were rejected due to large residuals. The number of estimated parameters (n_{param})

decreased, because a better precession-nutation model was used, and it became unnecessary to estimate five-day values of celestial pole offsets. Thus, the solution is made more robust. Although the mean error of one observation ($\sigma_\circ$) slightly increased, the median mean errors of the unknowns representing five-day values of pole position and Universal Time (σ_x, σ_y, $\sigma_{\rm UT1}$) decreased substantially, by almost 20%.

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