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The Earth Orientation Catalog 4*

An optical reference frame for monitoring Earth's orientation in the 20th century

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ABSTRACT

Context. The astrometric ground-based observations of latitude/universal time variations, covering the interval 1899.7–2003.0, were used in combination with Hipparcos/Tycho positions and some older ground-based catalogs to construct a family of catalogs, tailored to long-term Earth-rotation studies. These catalogs, called Earth Orientation Catalogs (EOC-1 through EOC-3) yielded more accurate proper motions than the original Hipparcos Catalogue, and its latest version, EOC-3, even periodic motions for a large portion of the stars.

Aims. It appeared that more stars than are contained in EOC-3 are double or multiple and that a better procedure can be used to improve the periodic terms, reflecting the orbital motions of the stars observed in the programs of monitoring Earth orientation.

Methods. We used about 4.5 million observations of latitude/universal time variations at 33 observatories all over the world, and combined them with the catalogs ARIHIP, TYCHO-2, etc. to obtain the Earth Orientation Catalog (EOC-4). These observations are identical to those used to construct the previous version, EOC-3. Spectral analysis of ground-based data and comparison with the USNO Sixth Catalog of Orbits of Visual Binary Stars was used to discover which of the observed objects display periodic motions. The corresponding amplitudes and phases were then estimated in one-step least-squares solution, together with positions and proper motions. Unlike in EOC-3, where annual averages were used, we use here the individual nightly observations.

Results. The fourth version of the catalog, EOC-4, contains 4418 different objects (i.e., stars, components of double stars, photocenters), out of which 599 have significant orbital motions. The catalog will eventually be used for new determination of the Earth orientation parameters during the twentieth century.

Key words. astrometry – reference systems – catalogs

1. Introduction

The nearly four-year ESA mission Hipparcos (1989–1993) has provided very precise parallaxes, positions, proper motions, and photometry for many stars in the optical wavelength. Two catalogs were derived from the mission – Hipparcos and Tycho (ESA 1997). The Hipparcos Catalogue (containing 118 218 stars with precision better than 1 mas and 1 mas per year in position and proper motion, respectively) was linked to the extragalactic International Reference System – ICRS (Ma et al. 1998) with the precision of 0.6 mas in orientation and 0.25 mas/yr in rotation (Kovalevsky et al. 1997). Therefore, it has been chosen as primary representation of the ICRS in optical wavelength. The Tycho Catalogue contains only the positions of 1 058 332 stars with a median precision of 25 mas.

The brevity of the mission (fewer than four years, usually much shorter than the typical periods of double stars) causes problems for the proper motions of the stars that are double or multiple, because the motion of the star in space is not strictly linear but it also contains a periodic term. The proper motions of the Hipparcos Catalogue then instead represent instantaneous (tangential to the real motion near the mean Hipparcos epoch) than a mean motion suitable for long-term prediction. Therefore, a combination of the positions measured by the Hipparcos satellite with ground-based observations with a much longer history provides a better reference frame that is more stable and consistent in time.

Thus, new catalogs with improved proper motions have appeared recently. They are obtained as a combination of the Hipparcos and/or Tycho catalogs with older ground-based catalogs. They are:

FK6, which is the combination of Hipparcos with the FK5 catalog (Wielen et al. 1999, 2000). It contains 878 basic stars (FK6 I) and 3272 extensions (FK6 III);
GC+HIP, which is the combination of Hipparcos with Boss' General Catalogue (Wielen et al. 2001a). It contains about 20 thousand stars;
TYC2+HIP, which is the combination of Hipparcos positions with Tycho-2 (see below) proper motions (Wielen et al. 2001b). It contains about 90 thousand stars;
ARIHIP, which is the selection of the astrometrically best stars from all the above-mentioned catalogs plus Hipparcos itself (Wielen et al. 2001c). It contains 91 thousand stars;
TYCHO-2, which is the combination of a new reduction of Tycho data with 144 different ground-based astrometric catalogs (Høg 2000), containing about 2.5 million stars.

In all their combined catalogs, Wielen et al. introduced a classification of "astrometric excellency" of each individual star. By assigning a number of asterisks (from one to three), the stars

* Table 1 (EOC4 catalog) is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/509/A3

are classified from the astrometric point of view – higher number of asterisks means a better star. The best objects are single stars, with well-determined positions and proper motions. Three different solutions of proper motions are contained in these catalogs: single-star mode (SI), long-term prediction mode (LTP), and short-term prediction mode (STP). In all our studies, only the LTP mode is used.

The principal sources of information for our subsequent work are the latter two, i.e., ARIHIP and TYCHO-2. The main idea is to further combine these (and some other) catalogs with the rich observation material obtained during the 20th century in programs of monitoring Earth orientation; hence the name Earth Orientation Catalogs.

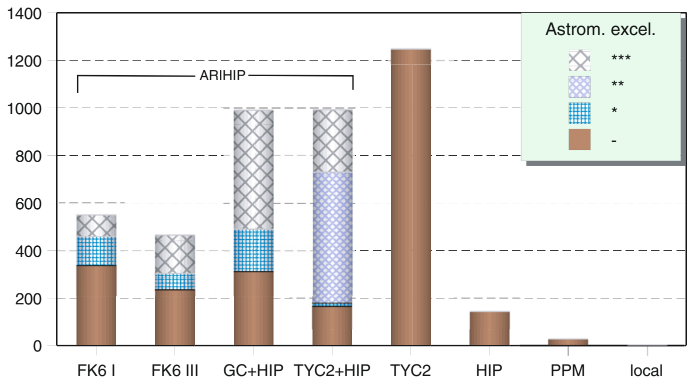

Fig. 1. Number of stars in EOC-0 taken over from original catalogs, and their "astrometric excellency".

2. Earth orientation catalogs

These catalogs are primarily meant to provide a stable celestial reference frame in optical wavelength for deriving Earth orientation parameters (EOP) from optical astrometric (OA) observations. The EOC catalogs described in this section below were used to this purpose. They were preceded by solutions OA97 (Vondrák et al. 1998), OA99 (Vondrák et al. 2000), and OA00 (Ron & Vondrák 2001) that were based on the original Hipparcos Catalogue with only some of the proper motions improved. When EOC-2 became available, we prepared another solution, called OA04 (Vondrák & Ron 2005) and, finally, EOC-3 was used to prepare the solution OA07 (Vondrák et al. 2008).

2.1. Catalogs EOC-0, EOC-1, and EOC-2

The general ideas of constructing these catalogs were outlined by Vondrák & Ron (2003). The first version EOC-1 (Vondrák & Ron 2006) was based on the combination of the observations made only in local meridian with ARIHIP, TYCHO-2, and some other catalogs. Later we added the observations by the method of equal altitudes (astrolabes, circumzeniths), and constructed the version EOC-2 (Vondrák 2004). This version was based on almost 5 million individual observations of about 4.5 thousand different objects made with 47 different instruments at 33 observatories all over the world, in the interval 1899–2003. They were:

- 10 Photographic zenith tubes, measuring both latitude and universal time:
  - 3 at Washington (USA); 2 at Richmond (USA) and Mizusawa (Japan); 1 each at Mount Stromlo (Australia), Punta Indio (Argentina), and Ondřejov (Czech Rep.);
- 7 photoelectric transit instruments, measuring only universal time:
  - 3 at Pulkovo (Russia); 1 at Irkutsk (Russia), Kharkov (Ukraine), Nikolaev (Ukraine), and Wuhang (China);
- 16 visual zenith telescopes and similar instruments, measuring only latitude:
  - 7 zenith telescopes at ILS stations (Carloforte, Italy; Cincinnati, USA; Gaithersburg, USA; Kitab, Uzbekistan; Mizusawa, Japan; Tschardjui, Uzbekistan; Ukiah, USA); 2 zenith-telescopes at Poltava (Ukraine); 1 zenith-telescope at Belgrade (Serbia), Blagovestchensk (Russia), Irkutsk (Russia), Józefoslaw (Poland), and Pulkovo (Russia); floating zenith-telescope at Mizusawa (Japan); visual zenith tube at Tuorla-Turku (Finland);
- 14 instruments, measuring time of transit through local almucantar by the method of equal altitude:
  - 1 Danjon astrolabe each at Paris (France), Santiago de Chile (Chile), Shanghai (China), Simeiz (Ukraine), and Wuhang (China); 2 photoelectric astrolabes at Shaanxi (China); 1 photoelectric astrolabe at Beijing (China), Grasse (France), Shanghai (China), and Yunnan (China); 1 circumzenithal at Bratislava (Slovakia), Prague (Czech Rep.), and Ondřejov (Czech Rep.).

The observations of latitude started in 1899, but universal time observations are limited to period after 1956, when the International Atomic Time (TAI) became available.

The observed stars were identified in the following catalogs, from which the positions, proper motions, parallaxes, and radial velocities were taken:

- ARIHIP, from which 2995 entries were taken over;
- TYCHO-2, with 1248 entries;
- Hipparcos, with 144 entries;
- PPM (Röser & Bastian 1991; Bastian & Röser 1993), with only 28 objects, and
- Local catalogs (of individual observatories) that yielded the remaining 3 stars.

The harmonogram in Fig. 1 depicts a more detailed distribution of the stars according to the original catalogs where they were taken, and also to their astrometric excellency. It is clear that almost all stars (with the exception of 31 labeled "PPM" and "local") were observed by Hipparcos.

These stars formed our zero-version catalog, called EOC-0, containing 4418 different objects (stars, components of double stars, photocenters). The number of an object in EOC is equal to its HIP number, if contained in the Hipparcos Catalogue. Otherwise, a number greater than 200 000 is assigned. Whenever we met statistically significant deviation of observed positions from catalog entry, we checked the star for multiplicity, and if any double star was detected, we estimated the displacement of the reference point (very often a photocenter) and corrected the position in EOC-0. In such case, the EOC number is equal to HIP number plus 300 000. Only 44% of the stars in EOC-0 are classified as "astrometrically excellent", so there is still room for possible improvement.

The individual values of deviations of measured universal time δUT, latitude $\delta\varphi$, and altitude δh from the catalog EOC-0 were computed as follows:

- all available observations were re-computed from the original catalogs used at the observatories into the reference

frame of EOC-0, using the new IAU2000A model of nutation and IAU2006 model of precession (Mathews et al. 2002, Capitaine et al. 2003);
- to suppress the influence of relatively rapid temporal change of UT0 – TAI, we used a conventional time scale TAX whose relation to TAI (in seconds) is $\mathrm{TAX} = \mathrm{TAI} + 2.63 - 0.002047t - 0.236 \times 10^{-7}t^2 + 0.49 \times 10^{-12}t^3 - 0.17\cos(2\pi t/6000) + 0.26\sin(2\pi t/6000) - 1.32\cos(2\pi t/9000) + 0.16\sin(2\pi t/9000)$ and calculated the values UT0 – TAX;
- tacitly assuming that the latitude and/or UT0 – TAX at each observatory within one night was constant, the deviations of universal time δUT, latitude $\delta\varphi$, or altitude δh from the mean value of the same night were computed. To suppress the influence of possibly large deviations of less precisely known star positions, the mean value of the night was, however, based on only astrometrically excellent stars.

To combine the observations with EOC-0, we have two totally different kinds of data:

- individual observations at many different epochs in the 20th century;
- catalog entry in EOC-0, represented by the position (referred to a mean epoch t_0), proper motion, and their standard errors.

To be able to use these two different groups in a single adjustment, we converted the latter into virtual observations. They can then be used, together with all real observations, in a single regression. To do so, the catalog EOC-0 is represented by three virtual observations of right ascension and declination in three different epochs (expressed in years from 1900): $t_1 = t_0 - 90$, $t_2 = t_0$, and $t_3 = t_0 + 10$, where t_0 is the mean epoch of the catalog. Standard errors of these virtual observations, based on standard error of position σ_0 and proper motion σ_μ, are then given as $\sigma_1^2 = 9000\sigma_\mu^2$, $\sigma_2^2 = \sigma_0^2/[1 - (\sigma_0/\sigma_\mu)^2/900]$, $\sigma_3^2 = 1000\sigma_\mu^2$. From σ_i we then calculated the weights of virtual observations as $4 \times 10^4/\sigma_i^2$, provided σ's are expressed in milliarcseconds (mas). Typical values of these weights are 4, 40 000 and 40 for ARIHIP and 2, 2500 and 20 for TYCHO-2. These values are chosen so that a linear regression through the three virtual observations yields the original catalog entry exactly, including the original standard errors σ_0, σ_μ. The weights of the ground-based observations are all set equal to 1, based on the realistic assumption that their uncertainties are 200 mas.

The extremely high values of the weights of virtual observations at epoch t_0 are given by very low values of σ_0 of Hipparcos and Tycho-2 (about 2 and 4 mas, respectively), if compared with the accuracy of ground-based astrometry. Linear regression through all observations (including the virtual ones) then provides the positions and proper motions of EOC-1 and EOC-2.

2.2. Catalog EOC-3

Because the periodic character of the residuals for certain stars was evident, we decided later to construct another version of the catalog, called EOC-3 (Vondrák & Štefka 2007), containing information on the periodicity of some of the observed objects. To this end, we used the same Earth orientation observations as in preparing EOC-1 and EOC-2. It was made in two independent steps:

1. improvement of positions and proper motions (see preceding Sect. 2.1);
2. looking for periodic changes by analyzing annual averages of residuals, using spectral analysis proposed by Lomb (1976), namely the subroutine provided by Press et al. (1992), and looking for periods in Sixth Catalog of Orbits of Visual Binary Stars (Hartkopf et al. 2006). In a positive case, the residuals were used to estimate sine/cosine terms of up to two different periods and their second-order higher harmonics, i.e., up to 16 sine/cosine terms.

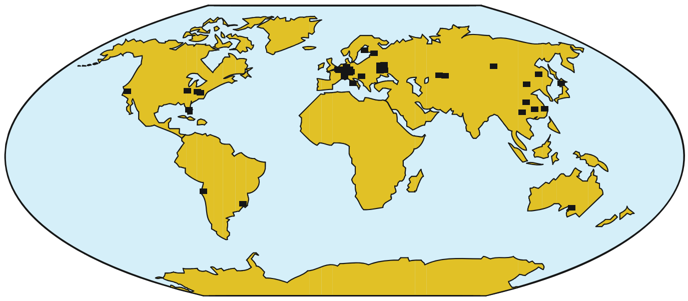

Fig. 2. Geographical distribution of contributing observatories.

Later we discovered some disadvantages of the catalog EOC-3:

- the periodic terms were based on annual averages, not individual observations, which can lead to somewhat diminished amplitudes for periods of several years or shorter;
- the periodic terms were derived independently of the positions and proper motions, which causes that the EOC-3 positions, calculated for the mean epoch of original catalogs (ARIHIP, TYCHO-2, etc.) often significantly differ from the positions in these catalogs.

Therefore, we decided to construct a new catalog EOC-4, based on the idea that positions, proper motions, and periodic terms are estimated in one-step solution, derived from a combination of individual and virtual observations. The first outline of this work and its main ideas were published by Vondrák & Štefka (2008). In the following we present a more detailed description of how we proceeded in constructing its final version.

3. Constructing the catalog EOC-4

3.1. The input data

The input data are identical to those used for constructing EOC-3; i.e., we used about 4.5 million individual observations of universal time, latitude, and altitude with 47 instruments located at 33 observatories. These values are based on star-by-star observations. The list of the instruments is given in Sect. 2.1, the geographical distribution of the observatories is depicted in Fig. 2. The asymmetric distribution of the observatories with respect to the equator is obvious – only three of them are located in southern hemisphere.

The original data, collected from the observatories, were originally referred to different star catalogs and systems of numerical constants and standards. Therefore, we first homogenized them using the most recent IAU Standards (precession-nutation, annual abberation, gravitational deflection of light, refraction, etc.). We also used a unified system of some instrumental constants such as micrometer value in case of zenith telescopes, plate scale in case of PZT's or azimuth in the case of transit instruments. These were determined from the observations themselves during the process of homogenization. For equal-altitude instruments, we also applied the time and azimuth dependent deformations of apparent local almucantarat (Pešek et al. 1993; Pešek 1995), and also color-magnitude effects. The details of how all these additional corrections were computed and applied can be found in Vondrák et al. (1998).

3.2. Improving positions, proper motions and periodic terms

There are three types of observations, provided by instruments mentioned in Sect. 2.1: deviations of universal time δUT, latitude $\delta\varphi$, and altitude δh from their nightly means. The following three observation equations then correspond to them:

$$\begin{aligned} 15.041\delta \mathrm{UT}\cos\varphi &= \Delta\alpha^* + \Delta\mu^*_\alpha(t-t_0) + per_\alpha \\ \delta\varphi &= \Delta\delta + \Delta\mu_\delta(t-t_0) + per_\delta \\ \delta h &= [\Delta\alpha^* + \Delta\mu^*_\alpha(t-t_0) + per_\alpha]\sin q \\ &\quad +[\Delta\delta + \Delta\mu_\delta(t-t_0) + per_\delta]\cos q. \end{aligned} \tag{1}$$

Here $\Delta\alpha^*$, $\Delta\mu^*_\alpha$ stand for $15\Delta\alpha\cos\delta$, $15\Delta\mu_\alpha\cos\delta$, and q is the parallactic angle of the star, per_α, per_δ denote the periodic part, i.e.,

$$\begin{aligned} per_\alpha &= \sum_{i=1}^{4}[c_{i\alpha}\cos(arg_i) + s_{i\alpha}\sin(arg_i)] \\ per_\delta &= \sum_{i=1}^{4}[c_{i\delta}\cos(arg_i) + s_{i\delta}\sin(arg_i)], \end{aligned} \tag{2}$$

where arguments $arg_{i=1,2,3,4} = 2\pi t/P_1, 4\pi t/P_1, 2\pi t/P_2, 4\pi t/P_2$, for up to two admitted basic periods P_1, P_2 (corresponding to double or triple systems, respectively, and their second-order harmonics).

We found that the virtual observations of the 144 stars taken from the original Hipparcos Catalogue for distant epochs t_1, t_3 (as used in Sect. 2.1) often deviated too much from real observations. Considering the length of Hipparcos mission (less than 4 years), we chose the epochs for computing the virtual observations much closer to the mean epoch. Generally speaking, if the three epochs for virtual observations (representing catalog entry from EOC-0) are $t_1 = t_0 - \Delta_1$, $t_2 = t_0$, $t_3 = t_0 + \Delta_2$, the corresponding standard errors can be calculated from

$$\begin{aligned} \sigma_1^2 &= \Delta_1(\Delta_1+\Delta_2)\sigma_\mu^2 \\ \sigma_2^2 &= \sigma_0^2/[1-(\sigma_0/\sigma_\mu)^2/\Delta_1\Delta_2] \\ \sigma_3^2 &= \Delta_2(\Delta_1+\Delta_2)\sigma_\mu^2. \end{aligned} \tag{3}$$

This method of representing the catalog by virtual observations was found to be very robust with respect to the choice of the three epochs; large changes of the values Δ_1, Δ_2 lead to very small changes in the final combined values. Here we retain the same $\Delta_1 = 90$, $\Delta_2 = 10$ years as in EOC-3 for all stars except for the 144 from the Hipparcos Catalogue; we take $\Delta_1 = \Delta_2 = 2$ years for the Hipparcos stars, so that the virtual observations fall within the period of Hipparcos mission. The corresponding weights of the three virtual observations are then calculated as $p_i = 4\times10^4/\sigma_i^2$, assuming that the precision of optical observation is on average 200 mas. Identically with catalog EOC-3 the weights of all real observations are put equal to 1.

The first two of Eqs. (1) are always used for virtual observations (representing the catalog EOC-0) of right ascension and declination with their calculated weights, respectively. They are mixed further with any one of the three equations for real observations, according to their type. The method of weighted least squares is used to estimate the corrections $\Delta\alpha^*$, $\Delta\mu^*_\alpha$, $\Delta\delta$, $\Delta\mu_\delta$, and amplitudes of periodic cosine/sine terms c_i, s_i with periods P_1, P_2.

Most periods P_1, P_2 were taken from the preceding version EOC-3; for a detailed description of how we proceeded in finding them, see Vondrák & Štefka (2007). We inspected the stars with periodic motions again, slightly changed some values of the periods, and decided to remove star No. 62303 from the list of those with periodic motion. This star has a significant periodic motion only in right ascension, with period equal to 8.26 y, but this periodicity was confirmed neither in declination nor in the Sixth Catalog. The star is listed as double in the Hipparcos Catalogue, but with no significant change of position angle between the two components and proper motions identical for both components. Tycho-2 lists this star two times, with the same number for both components, but the proper motions are different. These facts mean that the period, if existing, must be very long.

We subjected the stars with numbers larger than 300 000 to a more detailed analysis. These stars were already positively detected as double or multiple in EOC-0 so that we could expect significant periods, but we found no significant amplitudes for a part of them so far. Spectral analysis by the Lomb method (Lomb 1976) was made to obtain their amplitude spectra. Their inspection, and comparison with the Sixth Catalog, then led to confirming periods whose amplitudes were sometimes slightly lower than the originally taken 95% significance level. Thus we found periodic terms for 14 more double/multiple stars, when compared to EOC-3. Finally, our total number of stars with periodic motions is equal to 599, out of which 14 have two different periods.

When deriving proper motions and periodic terms together in one-step solution, problems with high correlations between proper motions and periodic terms appeared, especially for periods comparable or longer than the time span covered by observations. However, we overcame these problems easily by applying loose constraints to minimize the cosine/sine terms $c_{i\alpha}$, $s_{i\alpha}$, $c_{i\delta}$, $s_{i\delta}$ of Eq. (2). It is done by adding up to 16 additional observation equations of the type

$$c_{i\alpha} = 0,\; s_{i\alpha} = 0,\; c_{i\delta} = 0,\; s_{i\delta} = 0 \tag{4}$$

with relatively low weights. We found from practical tests that the weight equal to 0.05 times the total weight of all observations ensures that the correlations for long periods disappear, but the shorter periods are not affected.

Several illustrative examples of the solutions with periodic parts are depicted in Figs. 3–6. All plots are referred to the catalog EOC-0. Instead of individual observations, their annual average values and their uncertainties are displayed (small circles with abscissae). When one of the coordinates (right ascension, declination) was either not observed at all, or its observation was weak (e.g., in case of equal altitude method with parallactic angle close to either 0° or 90°), real observations are replaced by virtual observations with error bars ten times higher. Full lines represent the position in catalog EOC-4.

Figure 3 depicts the declination of star No. 518, whose period of about 107 years exceeds substantially the interval covered by 324 latitude observations, made only with Pulkovo visual zenith telescope. The photocenter of double star No. 36850, shown in Fig. 4, was observed at several observatories (Bratislava, Kharkov, Pecný, Prague and Wuhan), the total number of observations was 630. Declination of star No. 96491, depicted in Fig. 5, was observed 11468-times at all ILS stations; two different periods of about 78 and 28 years were found. Figure 6 shows the right ascension of declination of star

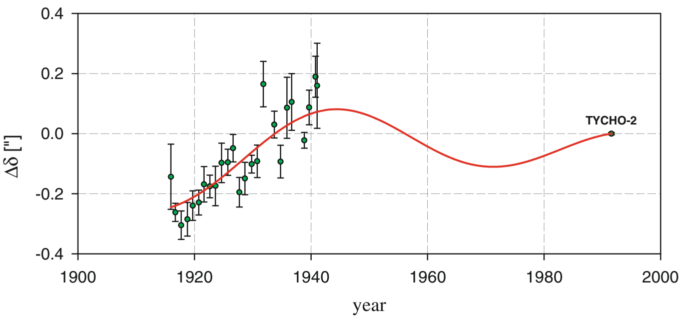

Fig. 3. Declination of the star No. 518 whose period, taken from the Sixth Catalog, is 106.70y. Position in TYCHO-2 is also shown.

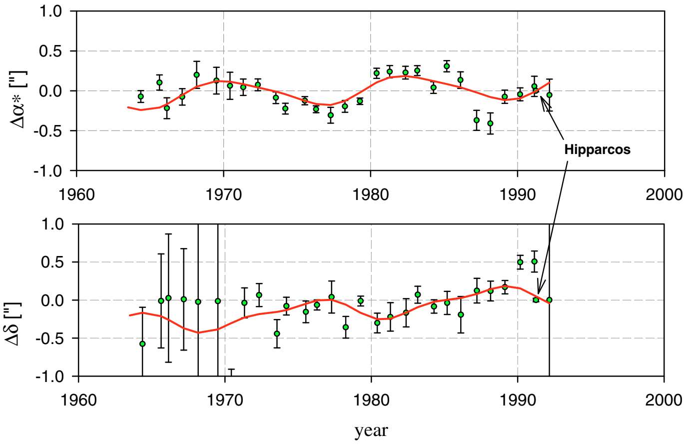

Fig. 4. Right ascension and declination of the photocenter of double star No. 36850 whose period, found by spectral analysis only, is 12.36 y. Position in Hipparcos is also shown.

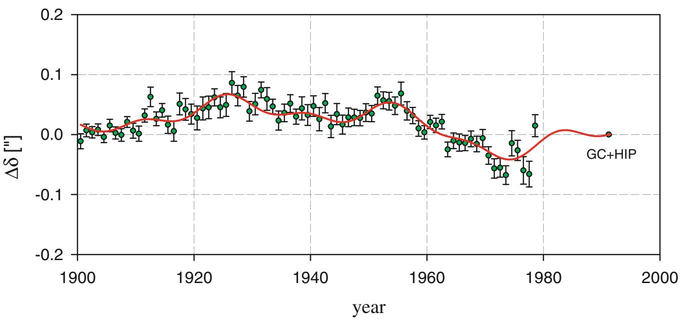

Fig. 5. Declination of the star No. 96491 whose periods, found by spectral analysis only, are 78.05 and 28.38 y. Position in GC+HIP is also shown.

No. 111841 that was observed 6752-times at many observatories (Bratislava, Mizusawa, Paris, Pecný, Prague, Shaanxi, Shanghai, Washington, Wuhan).

It is clear that including the periodic terms into the solution helps to improve the fit with the observations, and also that the position calculated for the mean epoch of the Hipparcos mission agrees well with the position measured by the satellite.

3.3. Special case – two components observed

There are several cases when two components of the same double star are observed (either by the same or different instruments). In all these cases, we found only a single period. Typically, these are either components A and B or component A

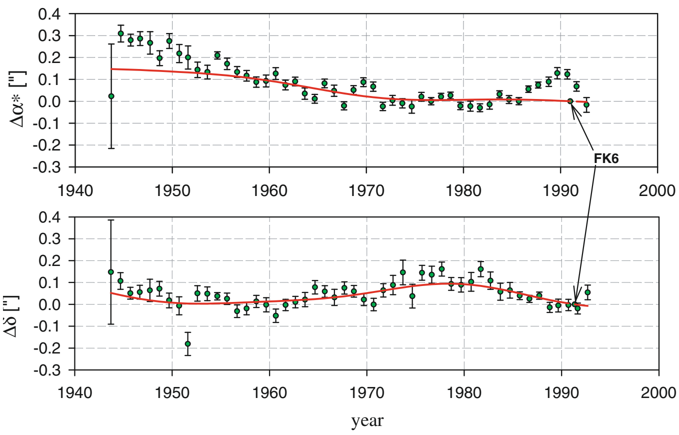

Fig. 6. Right ascension and declination of the star No. 111841 whose period, found by spectral analysis only, is 43.59 y. Position in FK6 is also shown.

and photocenter. Since they move in an elliptic orbit around the barycenter of the system, we can assume that both components have the same linear proper motion, and their periodic terms per_α, per_δ are proportional. These cases therefore require a special treatment that should ensure these two conditions to be met. We proceed in two steps:

1. the position, proper motion, and periodic terms of both components are derived independently as described above;
2. the periodic parts of both components are inspected, and an average coefficient of proportionality C is found. To this end, we use the weighted mean of the ratios of all coefficients c_i, s_i, with the weights proportional to their squares, corresponding to the component with the larger amplitude. If a_{1i} (where i runs from 1 to 8) stand for all coefficients c, s of the component with the smaller amplitude, and similarly a_{2i} for the component with the larger amplitude, we use the formula

$$C = \sum_{i=1}^{8} a_{1i}a_{2i} / \sum_{i=1}^{8} a_{2i}^2 \quad (5)$$

to compute the coefficient C that can be positive or negative, but whose absolute value is always lower than 1. Then a system of observation equations similar to (1) is solved for the two components in question mixed together, with the constraints

$$\begin{aligned} \Delta\mu^*_{\alpha 1} &= \Delta\mu^*_{\alpha 2},\ per_{\alpha 1} = C per_{\alpha 2} \\ \Delta\mu_{\delta 1} &= \Delta\mu_{\delta 2},\ per_{\delta 1} = C per_{\delta 2}. \end{aligned} \quad (6)$$

One such example is depicted in Figs. 7 and 8. Component A of double star No. 9640 was observed 770-times by six instruments of astrolabe type, with significantly better results in right ascension, due to parallactic angle $q = \pm(60° - 84°)$. In contrast to this, declination of component B was observed 310-times by only one zenith telescope. This example illustrates how the applied constraints (6) enable the periodic parts for both coordinates of both components to be derived. The coefficient $C = -0.68$ assures the proportionality of periodic terms, with the opposite phase for components A and B. The observations cover only a half of the period of about 64 years, found in the Sixth Catalog and confirmed by spectral analysis, so the full line depicts only a half of the sinusoid.

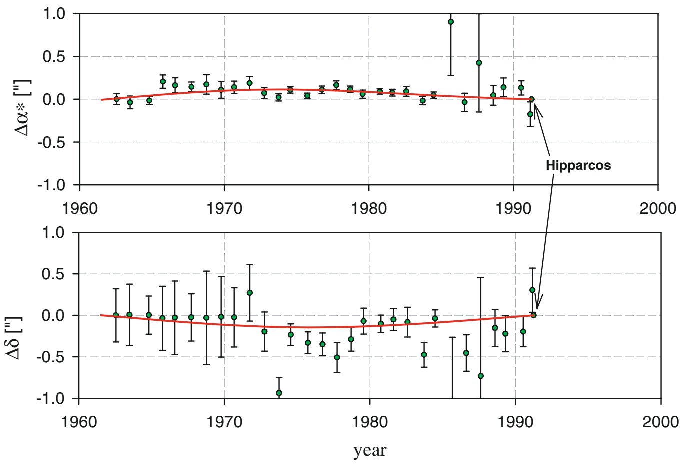

Fig. 7. Right ascension and declination of the component A of double star No. 9640 whose period, found in the Sixth Catalog and confirmed by spectral analysis, is 63.67 y. Position in Hipparcos is also shown.

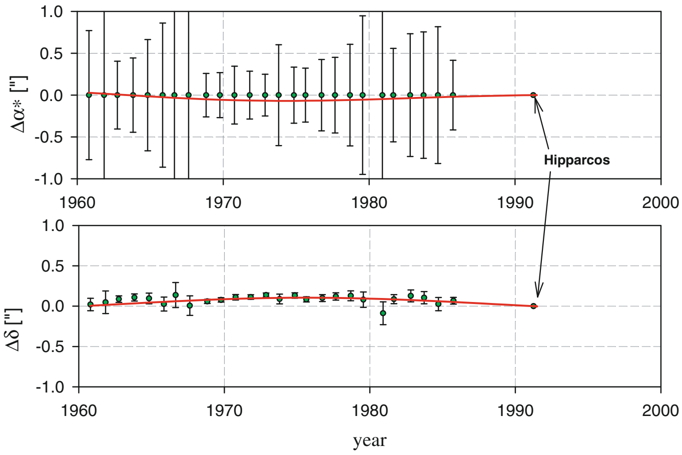

Fig. 8. Right ascension and declination of the component B of double star No. 9640 whose period, found in the Sixth Catalog and confirmed by spectral analysis, is 63.67 y. Position in Hipparcos is also shown.

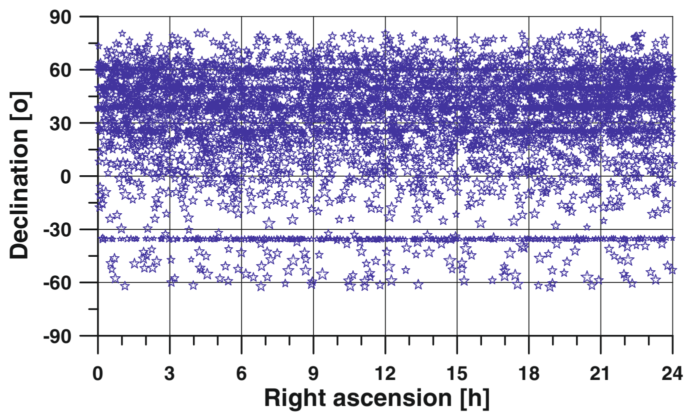

Fig. 9. Distribution of EOC-4 stars on the celestial sphere.

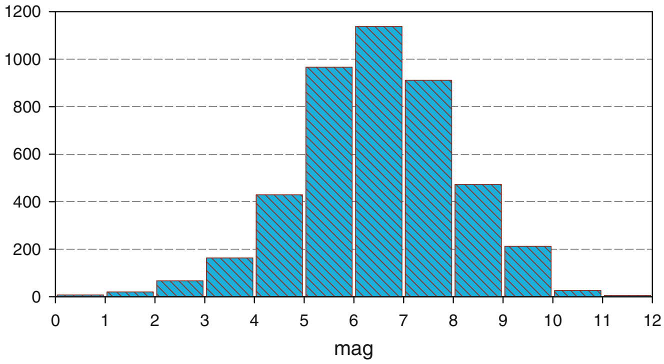

Fig. 10. Distribution of magnitudes in EOC-4.

4. Description of the catalog

The whole catalog EOC-4 is included in Table 1, which is only available in electronic form at the CDS. It contains the following information.

Column 1 contains the star number, Cols. 2 and 3 its right ascension and declination (in seconds and arcseconds, respectively), Cols. 4 and 5 give proper motions in right ascension (multiplied by cosine of declination) and declination (both in arcseconds per year), Col. 6 lists the mean epoch of right ascension, Cols. 7 and 8 rms errors in right ascension and its proper motion, Cols. 9–11 the same information for declination. Columns 12–14 list the parallax (arcseconds), radial velocity (km s^{-1}), and magnitude, Cols. 15 and 16 the two periods P_1, P_2. The next eight Cols. 17–24 contain the periodic cosine/sine terms for the two periods in right ascension, Cols. 25–32 the same information in declination, both in arseconds, as defined by Eqs. (2). Average rms errors of these periodic terms are given in Cols. 33 and 34, and the last four Cols. 35–38 give the information about the astrometric excellency, the catalog with which our combination is made, the component of double star, and the method by which the period was found. More detailed description of all information is given in ReadMe file that accompanies the catalog at the CDS.

There are 4418 entries in the catalog, out of which 599 also contain periodic terms, with periods ranging from 0.3 to 380 years. Eight of the objects with periodic behavior (i.e., four double stars) represent the cases when two components of the system were observed and their periodic terms are constrained (see Sect. 3.3). Distribution of the stars on the celestial sphere is depicted in Fig. 9, where the symbols are proportional to their magnitudes. There are evidently many fewer stars in the south, which reflects the asymmetric distribution of participating observatories. The distribution histogram of magnitudes is depicted in Fig. 10, from which it is clear that most of the stars of the catalog are in the range between 5 and 8 mag; 99.3 percent of these stars, including the brightest ones, were observed by the Hipparcos satellite.

The distributions of formal standard errors of the catalog in position and proper motion are shown in Figs. 11 and 12, respectively. They are very similar to our preceding catalogs EOC-2 and EOC-3. The median value of sigmas in right ascension is 0.75 mas, in declination 0.61 mas. Again, we see two distinct maxima (a bigger one between 0 and 1 mas and a smaller one around 3 mas) in sigmas in position (Fig. 11), reflecting the two different statistical populations with different accuracy – ARIHIP and TYCHO-2.

This feature, however, does not exist in proper motions (Fig. 12), which are improved by combining the original catalogs with ground-based observations covering several decades, and therefore less influenced by the precision of position in the original catalogs. The median values of the sigmas are 0.48 and 0.36 mas/year for proper motions in right ascension and declination, respectively. The amplitudes of periodic terms are determined with much lower accuracy, as demonstrated in Fig. 13.

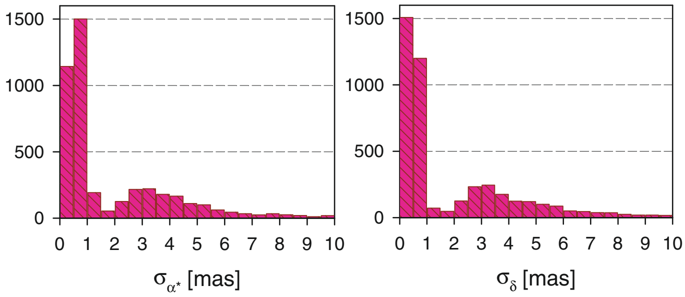

Fig. 11. Distribution of standard errors in position.

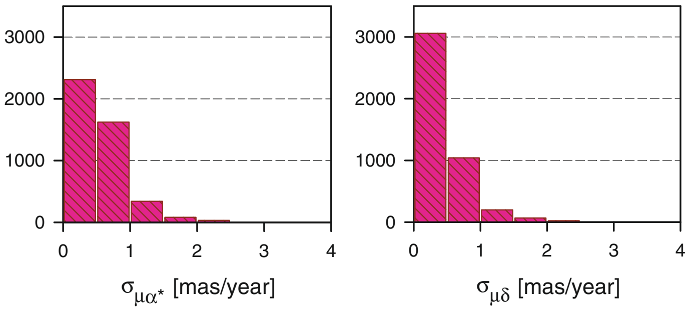

Fig. 12. Distribution of standard errors in proper motions.

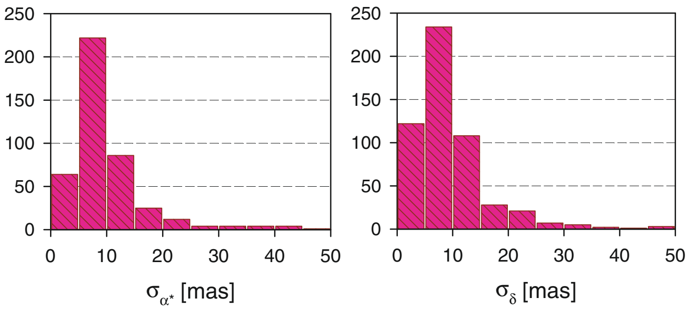

Fig. 13. Distribution of standard errors in amplitudes of periodic terms.

The corresponding median values are 7.90 and 7.59 mas, respectively.

Generally speaking, declinations are better determined than right ascensions for all parameters computed in this study (i.e., positions, proper motions, and amplitudes of periodic terms). The difference is most obvious in proper motions (compare left and right parts of Fig. 12). This is evidently caused by a longer history of observing declinations (since 1899) in contrast to right ascensions (since 1956).

5. Conclusions

An improved procedure is used to construct the new Earth Orientation Catalog EOC-4, assuring a better consistency with the positions measured by Hipparcos satellite at its mean epoch. More stars with quasi-periodic motions were detected than in EOC-3; 585 such objects with a single period and 14 with two periods are now contained in EOC-4. Similar to its predecessors EOC-1, EOC-2, and EOC-3, the catalog is "tailored" for the purpose of being used as a realization of celestial reference system in optical wavelength for long-term Earth rotation study. It can be expected that nonlinear representation of proper motions (by a linear plus periodic terms) should yield a better approximation for calculating the apparent positions of the stars. The catalog EOC-4 has recently been used to prepare a new solution of the Earth orientation parameters in the last century from optical astrometry.

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References

Bastian, U., & Röser, S. 1993, Positions and Proper Motions – South, Astron. Rechen-Inst., Heidelberg
Capitaine, N., Wallace, P. T., & Chapront, J. 2003, A&A, 412, 567
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Hartkopf, W. I., & Mason, B. D. 2006, The Sixth Catalog of Orbits of Visual Binary Stars, US Naval Observatory
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000, A&A, 355, L27
Kovalevsky, J., Lindegren, L., Perryman, M. A. C., et al. 1997, A&A, 323, 620
Lomb, N. R. 1976, Ap&SS, 39, 447
Ma, C., Arias E. F., Eubanks, M., et al. 1998, AJ, 116, 516
Mathews, P. M., Herring, T. A., & Buffet, B.A. 2002, J. Geophys. Res., 107 (B4), DOI: 10.1029/2001JB000390
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in C, The Art of Scientific Computing, 2nd Ed. (Cambridge Univ. Press)
Pešek, I. 1995, Acta Polytechnica, 35, 5
Pešek, I., Vondrák, J., Chollet, F., & Nöel, F. 1993, A&A, 274, 621
Röser, S., & Bastian, U. 1991, Positions and Proper Motions – North, Astron. Rechen-Inst., Heidelberg
Ron, C., & Vondrák, J. 2001, in Journées 2000 Systèmes de référence spatio-temporels, ed. N. Capitaine (Observatoire de Paris), 201
Vondrák, J. 2004, Serb. Astron. J., 168, 1
Vondrák, J., & Ron, C. 2003, in Journées 2002 Systèmes de référence spatio-temporels, ed. N. Capitaine, & M. Stavinschi (Observatoire de Paris), 49
Vondrák, J., & Ron, C. 2005, Kinematics and physics of celestial bodies, Suppl. No. 5, 305
Vondrák, J., & Ron, C. 2006, in Proc. IAU XXV Joint Discussion 16, The ICRS Maintenance and Future Realizations, ed. R. Gaume, D. McCarthy, & J. Souchay (US Naval Observatory), 112
Vondrák, J., & Štefka, V. 2007, A&A, 463, 783
Vondrák, J., & Štefka, V. 2008, in Exploring the Solar System and the Universe, ed. V. Mioc, C. Dumitrache, N. A. Popescu, AIP Conf. Proc., 1043, 147
Vondrák, J., Pešek, I., Ron, C., & Čepek, A. 1998, Publ. Astron. Inst. Acad. Sci. Czech R., 87, 1
Vondrák, J., Ron, C., & Pešek, I. 2000, in Polar motion: Historical and Scientific Problems, ed. S. Dick, D. D. McCarthy, & B. Luzum, Proc. IAU Coll., 178, ASP Conf. Ser., 208, 206
Vondrák, J., Ron, C., & Štefka, V. 2008, in A Giant Step: from Milli- to Micro-arcsecond Astrometry, ed. W. J. Jin, I. Platais, & M. Perryman (Cambridge Univ. Press), Proc. IAU Symp., 248, 89
Wielen, R., Schwan, H., Dettbarn C., et al. 1999, Veröff. Astron. Rechen-Inst. Heidelberg, 35, Kommissions-Verlag G. Braun, Karlsruhe
Wielen, R., Schwan, H., Dettbarn, C., et al. 2000, Veröff. Astron. Rechen-Inst. Heidelberg, 37, Kommissions-Verlag G. Braun, Karlsruhe
Wielen, R., Schwan, H., Dettbarn, C., et al. 2001a, Veröff. Astron. Rechen-Inst. Heidelberg, 38, Kommissions-Verlag G. Braun, Karlsruhe
Wielen, R., Schwan, H., Dettbarn, C., et al. 2001b, Veröff. Astron. Rechen-Inst. Heidelberg, 39, Kommissions-Verlag G. Braun, Karlsruhe
Wielen, R., Schwan, H., Dettbarn, C., et al. 2001c, Veröff. Astron. Rechen-Inst. Heidelberg, 40, Kommissions-Verlag G. Braun, Karlsruhe