

ASTROMETRIC STAR CATALOGUES AS COMBINATION OF HIPPARCOS/TYCHO CATALOGUES WITH GROUND-BASED OBSERVATIONS

J. Vondrák

*Astronomical Institute, Academy of Sciences of the Czech Republic
Boční II, 14131 Prague 4, Czech Republic*

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SUMMARY: The successful ESA mission Hipparcos provided very precise parallaxes, positions and proper motions of many stars in optical wavelength. Therefore, it is a primary representation of International Celestial Reference System in this wavelength. However, the shortness of the mission (less than four years) causes some problems with proper motions of the stars that are double or multiple. Therefore, a combination of the positions measured by Hipparcos satellite with ground-based observations with much longer history provides a better reference frame that is more stable in time. Several examples of such combinations are presented (ACT, TYCHO-2, FK6, GC+HIP, TYC2+HIP, ARIHIP) and briefly described. The stress is put on the most recent Earth Orientation Catalogue (EOC) that uses about 4.4 million optical observations of latitude/universal time variations (made during the twentieth century at 33 observatories in Earth orientation programmes), in combination with some of the above mentioned combined catalogues. The second version of the new catalogue EOC-2 contains 4418 objects, and the precision of their proper motions is far better than that of Hipparcos Catalogue.

Key words. Astrometry – Catalogs – Reference systems

1. INTRODUCTION

The successful ESA mission Hipparcos provided very precise parallaxes, positions, proper motions and photometry of many stars in optical wavelength (ESA 1997). Two catalogues were derived from the mission – Hipparcos and Tycho. The Hipparcos Catalogue (118 218 stars with precision better than 1 mas) was linked to extragalactic International Celestial Reference System - ICRS (Ma et al. 1998) with the precision of 0.6 mas in orientation and 0.25 mas/year in rotation (Kovalevsky et al. 1997). Therefore, it has been chosen as a primary representation of the ICRS in this wavelength. Tycho Catalogue contains the positions of 1 058 332 stars

with median precision of 25 mas.

However, the shortness of the mission (less than four years) causes some problems of proper motions of the stars that are double or multiple. Therefore, a combination of the positions measured by Hipparcos satellite with ground-based observations with much longer history provides a better reference frame, more stable in time. Recently new star catalogues (combinations of Hipparcos/Tycho Catalogues with ground-based catalogues) given in International Celestial Reference System have appeared, with substantially improved proper motions. They are briefly described in the next section.

We use some of these catalogues, together with the observations of latitude and/or universal time variations gathered throughout the 20th century at

many observatories worldwide, to derive a catalogue containing almost five thousand stars. The principal purpose of the new catalogue is to form an improved reference frame for long-term Earth rotation studies, but it can be used for other purposes as well.

2. COMBINED STAR CATALOGUES

The following combined catalogues, based on Hipparcos or Tycho and ground-based catalogues, appeared recently. Because the ground-based observations have usually a very long history, their inferior precision is more than balanced by the time interval used for a competitive determination of proper motions.

2.1. ACT Reference Catalog

ACT (Urban et al. 1998) is the catalogue of positions and proper motions derived from the combination of the AC 2000 Catalog and the positions taken from Tycho Catalogue. It contains nearly one million stars. The positions and proper motions are given on the Hipparcos system for J2000.0, i.e., virtually on the ICRS. The AC 2000 Catalog (Urban et al. 1997) is the positional catalogue based on international program of photographing and measuring the astrographic plates taken at 20 observatories worldwide (Astrographic Catalogue), and compiled at the U.S. Naval Observatory. The average epoch of photographic plates used is 1907.

2.2. TYCHO-2 Catalogue

The Tycho-2 Catalogue (Høg et al. 2000) is a catalogue of positions, proper motions and magnitudes of 2.5 million stars covering the whole sky. The positions of this catalogue were derived from a new reduction of the Tycho data from the Hipparcos satellite, proper motions result from the combination with the re-analysis of additional 144 ground-based astrometric catalogues (including the Astrographic Catalogue mentioned in preceding subsection). Thus in some way, it supersedes the ACT Catalogue.

2.3. FK6 Catalogue

Parts I & III of the FK6 (Wielen et al. 1999; Wielen et al. 2000) contain 878 basic and 3272 additional fundamental stars, respectively. The catalogue results from the combination of Hipparcos and FK5 catalogues. The latter summarizes more than two centuries of ground-based observations. In addition to the classical ‘single-star (SI) mode’ solution, the catalogue provides also other solutions which take into account the fact that hidden astrometric binaries introduce sizable ‘cosmic errors’ into the Hipparcos proper motions and positions. These solutions are denoted as ‘long-term prediction (LTP) mode’ and the ‘short-term prediction (STP) mode’. The

latter two solutions are the most precise solutions for apparently single stars. The typical mean error of a FK6(I) proper motion in SI mode is 0.35 mas/year, for FK6(III) it is 0.59 mas/year. Thus the precision of proper motions is far better than that of Hipparcos.

Wielen et al. also introduced the classification of the stars according to their ‘astrometrical excellence’ by assigning a number of asterisks to each star (expressed as coefficient K_{ae}), and utilized it not only in FK6, but also in other catalogues produced at the Astronomisches Rechen-Institut at Heidelberg. The number of asterisks goes from *** ($K_{ae} = 3$, highest rank) to no asterisk at all ($K_{ae} = 0$, lowest rank). Roughly the highest rank is assigned to single stars for which errors of proper motions are smaller than 2 mas/year, lowest rank is assigned to probable binaries (with significant non-linear proper motions).

2.4. GC+HIP Catalogue

GC+HIP (Wielen et al. 2001a) contains 20 069 stars, it being a combination of Hipparcos Catalogue with Boss’ General Catalogue. The latter catalogue is based on ground-based observations covering nearly two centuries (epochs range from 1755 to 1926). As in FK6 Catalogue, GC+HIP provides also SI, LTP and STP solutions; the typical mean error of proper motion in SI mode is 0.66 mas/year. The classification of ‘astrometrical excellency’ via coefficient K_{ae} is also given.

2.5. TYC2+HIP Catalogue

TYC2+HIP (Wielen et al. 2001b) contains 89 908 stars, and represents a combination of Hipparcos with the same ground-based data as summarized in TYCHO-2 Catalogue. Thus the positions are in principle given by Hipparcos Catalogue, proper motions by Tycho-2. The same three modes as in the catalogues described above (SI, LPT, SPT) are provided; the typical mean error of proper motion in SI mode is 0.83 mas/year, still slightly better than typical Hipparcos mean errors.

2.6. ARIHIP Catalogue

ARIHIP (Wielen et al. 2001c) summarizes the preceding catalogues; it is the selection of the best stars from the catalogues FK6(I), FK6(III), GC+HIP, TYC2+HIP, and also Hipparcos itself. It contains 90 842 stars altogether. The proper motions in ARIHIP are usually more accurate than in the original Hipparcos Catalogue, and the catalogue contains additional information on how the proper motions are affected by a binary nature of the objects, through SI, LTP and STP solutions, and coefficient K_{ae} . Though smaller in number of objects listed, it is thus preferable to the Hipparcos Catalogue. This is the very catalogue that we use in the next Section.

3. EARTH ORIENTATION CATALOGUE

The existence of the new combined catalogues led to the decision of creating a new Earth Orientation Catalogue (EOC), containing only the stars observed in Earth orientation programmes (Vondrák and Ron 2003, Vondrák and Ron 2004). The main goal is to set up a new improved reference frame for long-term Earth rotation studies, by using the best catalogues available in combination with the rich observational material obtained from existing Earth orientation programmes in the 20th century (about 4.5 million individual observations).

Solutions for Earth Orientation Parameters (EOP), based on optical observations of latitude and universal time variations were obtained at the Astronomical Institute, Academy of Sciences of the Czech Republic and Department of Geodesy, Czech Technical University in Prague. All observations made with 47 instruments at 33 observatories in the interval 1899.7-1992.0 were re-calculated to be referred to the Hipparcos Catalogue (ESA 1997, Perryman et al. 1997) and to a unique system of astronomical constants and algorithms. Namely, the IAU 1976 model of precession (Lieske et al. 1977) and IAU 1980 model of nutation (Wahr 1981, Seidelmann 1982) were used. These observations were then used in three different solutions, based on more and more data collected, and also using slightly different approach.

Thus the solutions OA97 (Vondrák et al. 1998), OA99 (Vondrák et al. 2000), and finally OA00 (Ron and Vondrák 2001) were worked out. The main differences among these solutions consisted in number of participating observatories, in the different approach to how the data acquired at the same observatory were merged, and the treatment of obviously systematic deviations of some Hipparcos stars.

As demonstrated in Fig. 1, the main problem is caused by double or multiple stars, with non-linear proper motions. Due to relatively short Hipparcos mission (less than 4 years), proper motion measured by Hipparcos reflects rather the instantaneous velocity than its mean value needed for long-term extrapolation, even if the amplitude of the periodic component is small.

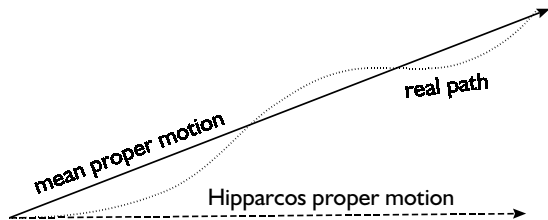


Fig. 1. Path of one of the double star components versus its mean and Hipparcos proper motion.

That is why we were forced to correct between 11% and 20% of the proper motions (and sometimes

their mean positions, too, in case that other components than the ones given in Hipparcos Catalogue were observed), before a solution was made, whenever we came upon statistically significant residuals.

3.1. The list of stars in EOC

The inventory of all optical data of Earth orientation programmes available revealed 4418 different objects (stars, photocenters of double stars) observed. In order to assure the most accurate positions and proper motions we searched for these stars first in the catalogue ARIHIP (Wielen et al. 2002) where we found 2995 objects, then in catalogue TYCHO-2 (Høg et al. 2000) with 1248 objects, in Hipparcos catalogue (ESA 1997) with 144 objects and finally in the PPM catalogue (Roeser and Bastian 1991, Bastian and Roeser 1993) with 28 objects found. Only three stars were not found in any of these catalogues, therefore their positions and proper motions were taken from the local catalogue of the instrument in question.

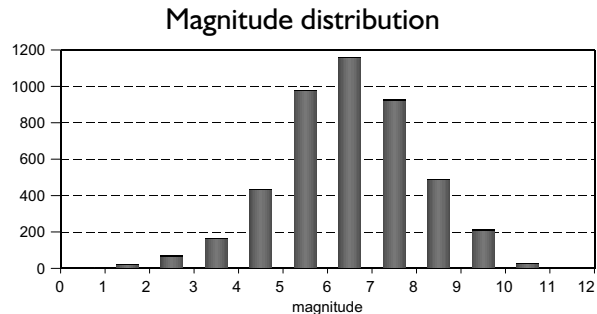


Fig. 2. Magnitude distribution of EOC stars.

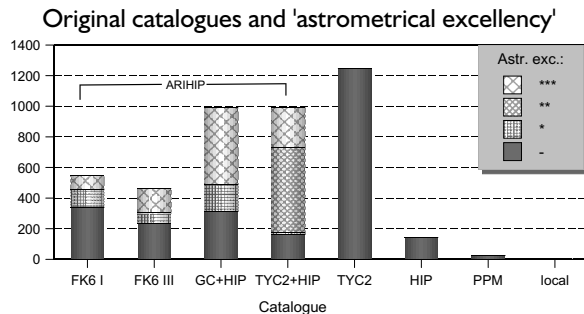


Fig. 3. Statistics of where the EOC stars come from, and their 'astrometrical excellency'.

Fig. 2 displays the magnitude distribution, Fig. 3 the statistics of the catalogues from which the stars come from. Out of these stars, less than 2000 are classified by Wielen et al. as 'astrometrically excellent' (i.e., marked with at least one asterisk). Evidently, more than 50% of EOC stars require a thorough inspection and most probably an improvement.

The entries from the above mentioned catalogues (LTP mode is used for ARIHIP) form the zero version of the catalogue EOC-0. Star numbers are assigned as follows:

- Hipparcos number is used if the star is contained in HIP and is either single or the same entry as given in original catalogue was observed.
- HIP number + 300000 for the stars that are contained in HIP but another component than given as entry in the original input catalogue is observed. In this case, the displacement of the observed component from catalogue entry is estimated from the observations; 59 such objects have been identified.
- Numbers 200001, 200002,... for the stars that are not contained in Hipparcos Catalogue; there are only 85 such stars (55 being taken over from TYCHO-2 and 30 from PPM and local catalogues).

Sometimes different components of the same catalogue entry were observed by different instruments. In general, visual instruments are less liable to observe photocenter instead of a component than photographic or photoelectric instruments; human eye seems to be a better detector of light, able to distinguish close objects (about $1 - 2''$ seems to be a limit). In these cases, we keep two different entries in the catalogue, with two different numbers (differing by 300000); the two entries in EOC-0 differ only in position, their proper motions are identical.

3.2. Further improvement of EOC

On the average, each star was observed in Earth orientation programmes about thousand times, with the precision of one observation of about 200 mas, usually in a relatively long time interval (decades). This means that the proper motions (and sometimes even positions) can be determined with a precision competing with that of ARIHIP and other similar catalogues. Thus the combination with these input catalogues will surely bring an important improvement.

We have collected the data from 47 instruments of different types. They can be divided into four groups, according to the method of observation that they use:

- 1) 10 photographic zenith tube PZT's that observe near local zenith and determine both latitude and universal time:
 - 2 at Mizusawa, Japan, covering 1959.0-1993.1;
 - 1 at Mount Stromlo, Australia, covering 1957.8-1985.7;
 - 1 at Punta Indio, Argentina, covering 1971.6-1984.5;
 - 1 at Ondřejov, Czech Republic, covering 1973.1-2002.6;
 - 2 at Richmond, Florida, USA, covering 1949.8-1989.4;
 - 3 at Washington DC, USA, covering the interval 1915.8-1992.0;
- 2) 7 photoelectric transit instruments, observing the transits of stars through local meridian and determining only universal time:
 - 1 at Irkutsk, Russia, covering 1979.1-1992.0;
 - 1 at Nikolaev, Ukraine, covering 1974.4-1992.4;

1 at Kharkov, Ukraine, covering 1973.0-1992.0; 3 at Pulkovo, Russia, covering 1959.7-1994.0; 1 at Wuhang, China, covering 1981.9-1987.2;

- 3) 16 visual zenith telescopes (ZT) and similar instruments (visual zenith tube - VZT, floating zenith telescope - FZT), measuring only latitude:
 - 7 ZT's at ILS stations (Carloforte, Cincinnati, Gaithersburg, Kitab, Mizusawa, Tschardjui, Ukiah), covering 1899.7-1979.0;
 - 1 ZT at Belgrade, Yugoslavia, covering 1949.0-1986.0;
 - 1 ZT at Blagovestschensk, Russia, covering 1959.0-1992.0;
 - 1 ZT at Irkutsk, Russia, covering 1958.2-1991.0;
 - 1 ZT at Józefoslaw, Poland, covering 1961.8-1996.0;
 - 1 FZT at Mizusawa, Japan, covering 1967.0-1984.8;
 - 2 ZT's at Poltava, Ukraine, covering 1949.7-1990.4;
 - 1 ZT's at Pulkovo, Russia, covering 1904.7-1995.0;
 - 1 VZT at Tuorla-Turku, Finland, covering 1963.7-1989.1;
- 4) 14 equal altitude instruments (Danjon astrolabes - AST, photoelectric astrolabes - PAST, and circumzenithals - CZ) that observe a combination of latitude/universal time:
 - 1 PAST at Beijing, China, covering 1979.0-1987.8;
 - 1 CZ at Bratislava, Slovakia, covering 1987.0-1991.9;
 - 1 PAST at Grasse, France, covering 1983.2-1992.0;
 - 1 AST at Paris, France, covering 1956.5-1983.0;
 - 1 AST at Pecný, Czech Republic, covering 1970.0-1992.0;
 - 1 CZ at Prague, Czech Republic, covering 1980.2-1992.0;
 - 1 AST at Santiago de Chile, covering 1965.9-1990.9;
 - 2 PAST's at Shaanxi, China, covering 1974.0-1992.0;
 - 1 AST + 1 PAST at Shanghai, China, covering 1962.0-1985.0;
 - 1 AST at Simeiz, Ukraine, covering 1977.0-1991.0;
 - 1 AST at Wuhang, China, covering 1964.0-1986.2;
 - 1 PAST at Yunnan, China, covering 1980.7-1991.3.

Generally speaking, latitude observations are used to improve declinations, observations of universal time are used to improve right ascensions, observations by the method of equal altitude contribute to both coordinates.

The strategy was to determine the positions of the observed stars with respect to astrometrically excellent stars observed by the same instrument. To this end,

- all available data were re-computed into the reference frame of EOC-0, using the new IAU2000A model of precession-nutation (Mathews et al. 2002);
- the differences of latitude, universal time or altitude were computed from the mean values on the same night based on only astrometrically excellent stars;
- the differences for the same star at different epochs were subject to linear regression;
- the stars with significant deviations were checked for multiplicity, and in positive case the displacement of the reference point (very often photocenter) from the catalogue entry was estimated.

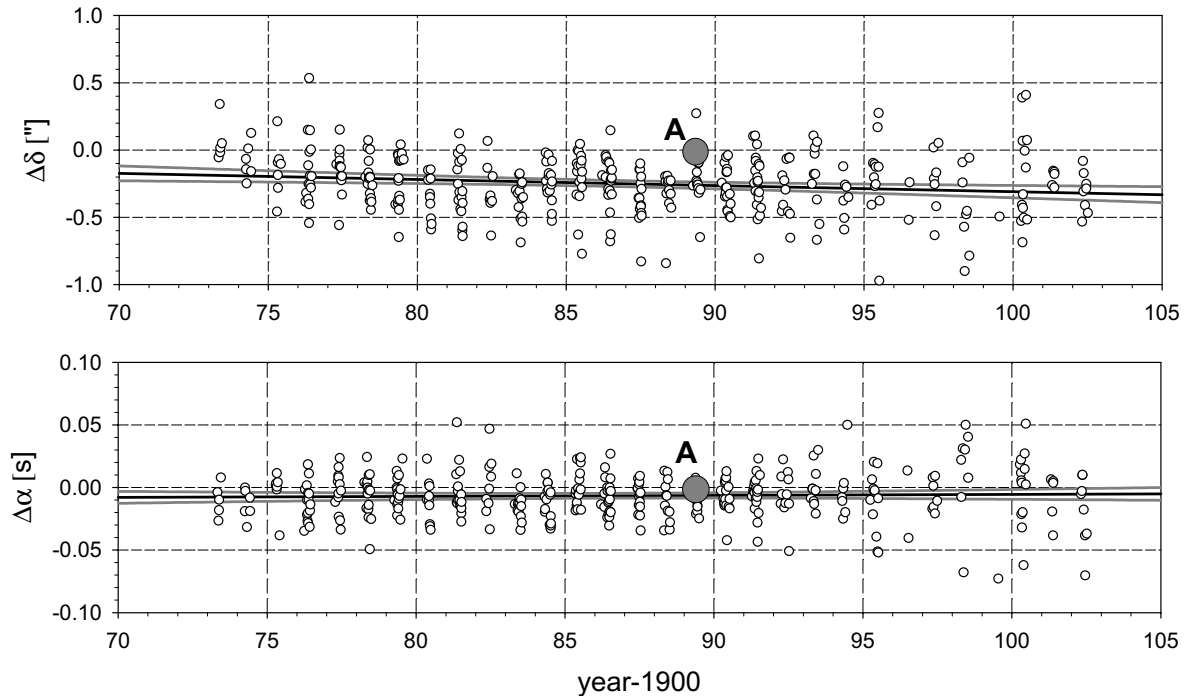


Fig. 4. Example of linear regression: observations with Ondřejov PZT (open circles) of double star 83885; position in Tycho-2 is referred to component A (gray circle), photocenter was observed.

An illustrative example of linear regression through observed positions is displayed in Fig. 4. The star with HIP number 83885 is a double star, with its two components $3.45''$ apart. Linear regression is depicted as black line, 95% confidence interval as gray lines. The observations with Ondřejov PZT (open circles) obviously refer to its photocenter, not to the component A (larger gray circle) whose entry is taken over from Tycho-2. Consequently, the position in EOC-0 was corrected and the number of the object changed to 383885.

3.3. Version EOC-1

The first step in developing the new catalogue, leading to version EOC-1, was to use only the instruments observing in local meridian, i.e. the first three groups mentioned above. The observations of latitude are closely related to declination, universal time to right ascension. Version EOC-1 is described in detail by Vondrák and Ron (2004), so only an abbreviated description is given here.

In principle, there was no problem for groups of instruments 1 and 2 listed in Subsection 3.2 that give the individual corrections of right ascension and declination separately, for each star. This was not the case for the instruments of group 3 that observed star pairs. For these instruments we obtained a mean difference of declinations of two stars, and we faced a problem of how to separate them. We chose to create, from each such series, two new series (one for each of the two stars) by using the weighting proportional to their squared *rms* error taken from the

input catalogue and calculated for the centre of the interval covered by observations.

Another question then arose of how to combine a catalogue entry with the series of observed corrections. We created three virtual observations (for the epochs t_1 , t_2 , t_3) of the same star from the information given in EOC-0: the mean epoch t_o , *rms* error of the position at this epoch σ_o , and *rms* error of proper motion σ_μ . We chose the solution in which a weighted linear regression through these three points returns exactly the same values t_o , σ_o and σ_μ as given in the input catalogue. Generally, if the central epoch is identified with the one of the input catalogue ($t_2 = t_o$) and $t_2 - t_1 = \Delta_1$, $t_3 - t_2 = \Delta_2$, this is achieved by

$$\begin{aligned} \sigma_1^2 &= \sigma_\mu^2 \Delta_1 (\Delta_1 + \Delta_2) \\ \sigma_2^2 &= \sigma_o^2 \sigma_\mu^2 / (\sigma_\mu^2 - \sigma_o^2 / \Delta_1 \Delta_2) \\ \sigma_3^2 &= \sigma_\mu^2 \Delta_2 (\Delta_1 + \Delta_2). \end{aligned} \quad (1)$$

By choosing an asymmetric distribution of the epochs covering one century, $\Delta_1 = 90$ years, $\Delta_2 = 10$ years, we arrived at equations

$$\begin{aligned} \sigma_1 &= 94.87 \sigma_\mu \\ \sigma_2 &= \sigma_o / \sqrt{1 - (\sigma_o / \sigma_\mu)^2 / 900} \\ \sigma_3 &= 31.62 \sigma_\mu. \end{aligned} \quad (2)$$

The values of σ_i (in mas) were used to compute the weights of the three virtual observations (each of these ‘observed’ values being set to zero) as $p_i = (200/\sigma_i)^2$. They were combined with real observations of the same star whose weights were all put equal to 1, under the assumption that their accuracy was 200 mas. The linear regression through all these points then yielded the corrections of EOC-0 positions and proper motions, to form EOC-1. This very version was later used to derive Earth Orientation Parameters only from meridian instruments OA03 (Ron and Vondrák 2004).

3.4. Version EOC-2

Much more difficult is the treatment of observations performed by the method of equal altitudes (group of instruments 4 in Subsection 3.2). In this case it is a complicated task to separate correction to declination from that to right ascension. The observed quantity, the difference of altitude δh , is a combination of differences of both coordinates. Fig. 5 shows the situation on the celestial sphere. In nautical triangle PZS φ , δ , z , t , A and q denote the latitude, declination, zenith distance, hour angle, azimuth and parallactic angle, respectively.

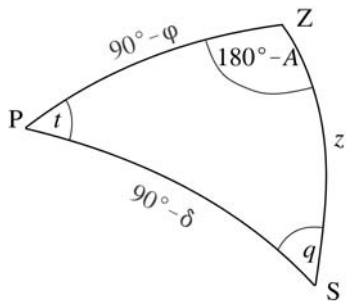


Fig. 5. Nautical triangle - P, Z and S are celestial pole, zenith and star, respectively.

The differentiation of the sine-cosine and sine relations for this spherical triangle yields the difference in altitude (or in zenith distance, with opposite sign) in terms of differences in right ascension $\Delta\alpha^* = 15\Delta\alpha \cos \delta$ and declination $\Delta\delta$:

$$\delta h = \Delta\alpha^* \sin q + \Delta\delta \cos q, \quad (3)$$

where the parallactic angle can be computed from the equations

$$\begin{aligned} \sin q &= \cos \varphi \sin A / \cos \delta \\ \cos q &= (\sin \varphi - \cos z \sin \delta) / \sin z \cos \delta. \end{aligned} \quad (4)$$

In principle, each star can be observed in both east and west transits. Then the parallactic angle is the same in absolute value but with opposite signs ($\sin q$ is positive for west transit, negative for east transit). Eq. (3) could be then used to separate correction of declination and right ascension. However, this is often not the case – at some observatories only one transit is observed. Then it is not possible to derive separately correction of right ascension and declination from the observations by the method of equal altitudes alone.

Fortunately, we still have a possibility of combining these observations by different equal altitude instruments located at other parallels, and/or by instruments measuring in local meridian, provided the same star was observed at several observatories. Another possibility is offered by applying the same approach that we used in version EOC-1, i.e., using the original catalogue entries in form of three virtual observations. This method assures that we always arrive to a result, no matter where and if the star was (or was not) observed. We used namely this method, by forming the observation equations for the three different quantities observed (universal time, latitude and altitude) for the same object:

$$\begin{aligned} v_{\alpha,i} &= \Delta\alpha^* + \Delta\mu_\alpha^*(t_i - t_o) - 15.041\Delta UT_i \cos \varphi \\ v_{\varphi,i} &= \Delta\delta + \Delta\mu_\delta(t_i - t_o) - \Delta\varphi_i \\ v_{\delta h,i} &= \Delta\alpha^* \sin q + \Delta\mu_\alpha^* \sin q(t_i - t_o) + \\ &+ \Delta\delta \cos q + \Delta\mu_\delta \cos q(t_i - t_o) - \delta h_i, \end{aligned} \quad (5)$$

in which t_i is the epoch of observation, and UT_i , $\Delta\delta_i$, δh_i denote the individual observed quantities. Now we can form the observation Eqs. (5) for real observations of the same object observed by all instruments (with all weights equal to 1), and we add to them the three virtual observations for catalogue entry for the same object, with weights based on Eqs. (2). Classical least-squares procedure via normal equations then provides all four unknowns $\Delta\alpha^*$, $\Delta\mu_\alpha^*$, $\Delta\delta$ and $\Delta\mu_\delta$, and also the estimate of their mean errors. By adding these values to EOC-0 positions and proper motions we arrive at the final catalogue EOC-2.

The comparison of some characteristics of different versions of EOC is given in Table 1, where median values of the epochs and mean errors are displayed; the values of σ are given in mas. Comparison of EOC-0, EOC-1, and EOC-2 demonstrates the improvement of proper motions brought about by the combination, especially if compared with the values of the original Hipparcos Catalogue.

Table 1. Comparison of the catalogues EOC-0, EOC-1, and EOC-2 (σ in mas).

Catalogue	n	Ep_α	σ_α^*	$\sigma_{\mu\alpha}^*$	Ep_δ	σ_δ	$\sigma_{\mu\delta}$
EOC-0	4418	91.25	0.69	0.60	91.26	0.55	0.57
EOC-1	3784	91.18	0.68	0.52	91.10	0.50	0.32
EOC-2	4418	91.16	0.70	0.47	91.03	0.60	0.35

4. CONCLUSIONS

We produced two versions of Earth Orientation Catalogue, EOC-1 from only the observations with the instruments observing in local meridian (i.e., PZT's, ZT's and PTI's), and EOC-2 in which all observations available are combined with the best input catalogues resulting from combination of Hipparcos and/or Tycho Catalogues with ground-based observations (ARIHIP etc...). Substantial improvement in proper motions is achieved, as demonstrated in Table 1. This is true especially for proper motions in declination where the improvement is really substantial, due to very long series of latitude observations. It is planned to use the EOC-2 catalogue to produce another solution of Earth Orientation Parameters in near future.

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АСТРОМЕТРИЈСКИ ЗВЕЗДАНИ КАТАЛОЗИ КАО КОМБИНАЦИЈА
ХИПАРКОС/ТИХО КАТАЛОГА СА ЗЕМАЉСКИМ ПОСМАТРАЊИМА

Ј. Вондрак

*Astronomical Institute, Academy of Sciences of the Czech Republic
Boční II, 14131 Prague 4, Czech Republic*

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Успешна ЕСА мисија Хипаркос (Hipparcos) обезбедила је веома прецизне паралаксе, позиције и сопствена кретања многих звезда у оптичком подручју таласних дужина. Зато је примарно представљање ICRS (International Celestial Reference System) на овим таласним дужинама. Међутим, кратко трајање ове мисије (мање од 4 године) узрокује неке проблеме код сопствених кретања двоструких и вишеструких звезда.

Зато, комбиновање позиција које је мерио Хипаркос сателит са земаљским посматрањима која имају много дужу историју обезбеђује бољи референтни систем који има већу временску стабилност. Неколико приме-

ра оваквих комбинација је представљено (АСТ, TYCHO-2, FK6, GC+HIP, TZC2+HIP, ARHIP) и укратко су описани. Нагласак је стављен на најновији EARTH ORIENTATION CATALOGUE (ЕОС) који користи око 4.4 милиона оптичких посматрања промене географске ширине и светског времена (поправка часовника) (која су добијена током XX века на 33 опсерваторије у оквиру програма Земљине оријентације), у комбинацији са неким од претходно поменутих комбинованих каталога. Друга верзија новог каталога ЕОС-2 садржи 4418 објеката, и прецизност његових сопствених кретања је много боља него Хипаркос каталога.