Acta Geodyn. Geomater., Vol. 7, No. 3 (159), 245–251, 2010

EARTH ORIENTATION PARAMETERS BASED ON EOC-4 ASTROMETRIC CATALOG

Jan VONDRÁK *, Cyril RON and Vojtěch Štefka

Department of Galaxies and Planetary Systems, Astronomical Institute, Academy of Sciences of the Czech Republic, Boční II, 141 31 Prague, Czech Republic, phone +420 267103043, fax +420 272769023
**Corresponding author's e-mail:* vondrak@ig.cas.cz

(*Received* January 2010*, accepted* February 2010)

ABSTRACT
Recently we derived a new star catalog EOC-4 that contains not only the mean positions and linear proper motions, but also periodic changes, due to orbital motions, for double and multiple star systems. The catalog contains 4418 stars that were observed in programs monitoring Earth orientation by optical astrometry during the 20th century. 599 stars of the catalog have significant periodic components.
This catalog is now used, as a basic celestial frame, to obtain the Earth orientation parameters from optical astrometric observations of latitude/universal time/altitude in the interval 1899.7-1992.0. Polar motion is determined in 5-day steps for the whole interval studied, Universal time covers the interval 1956.0-1992.0 (i.e., after the invention of atomic clocks) also in 5-day steps, and celestial pole offsets (with respect to recent IAU2000 and IAU2006 models of nutation and precession) are modeled by second-order polynomials of time. In addition to these, a combination of Love and Shida numbers for each observing site is computed..

KEYWORDS: Earth orientation, astrometry, reference systems

1. INTRODUCTION

Since 1991 we have collected about 4.5 million individual astrometric observations of latitude / universal time / altitude variations made worldwide at 33 observatories. These observations, re-analyzed with the Hipparcos Catalogue (ESA 1997), were then used to determine the Earth Orientation Parameters (EOP) at 5-day intervals, covering the interval 1899.7 – 1992.0 (Vondrák et al., 1998; Vondrák et al., 2000; Ron and Vondrák, 2001). The analysis of the residuals revealed that a large proportion of the Hipparcos stars (mostly double or multiple systems) have rather big errors in proper motions, due to the relatively short time interval of the Hipparcos mission compared with the orbital periods of the stellar systems. These three solutions, made with gradually increasing number of observations and corrected proper motions of some Hipparcos stars, are denoted as OA97, OA99, and OA00, where OA stands for Optical Astrometry. Five EOP, describing the full orientation of the Earth in space, were solved for: two components of polar motion (fixing the position of the spin axis in the body), the angle of proper rotation around the spin axis, and two components of the celestial pole offsets (describing the misalignment of the spin axis with its position in space predicted by an accepted precession-nutation model).

The above mentioned observations, accumulated during almost a century of monitoring the Earth's orientation, contain valuable and rich astrometric material that was only seldom used to construct astrometric catalogs. Therefore we utilized them to derive star catalogs, tailored to serve as reference frames for Earth orientation studies from optical astrometry. To this end, we used the astrometric catalogs, such as ARIHIP (Wielen et al., 2001) or TYCHO-2 (Høg et al., 2000), that recently appeared as combinations of Hipparcos/Tycho positions with ground-based catalogs. These catalogs yield more accurate proper motions than the original Hipparcos Catalogue. Many of the objects observed in the programs of monitoring Earth orientation from the ground are double or multiple systems, having non-negligible periodic motions. We developed a method to obtain a star catalog, first only with improved positions and proper motions, and then also with periodic terms, reflecting orbital motions of the stars observed in these programs. To this end, we combined the astrometric observations mentioned above with the catalogs ARIHIP, TYCHO-2, *etc*… to obtain a new astrometric catalog, "tailored" for long-term Earth orientation studies. So far we developed four versions of the Earth Orientation Catalog (EOC), whose general ideas were outlined by Vondrák and Ron (2003):

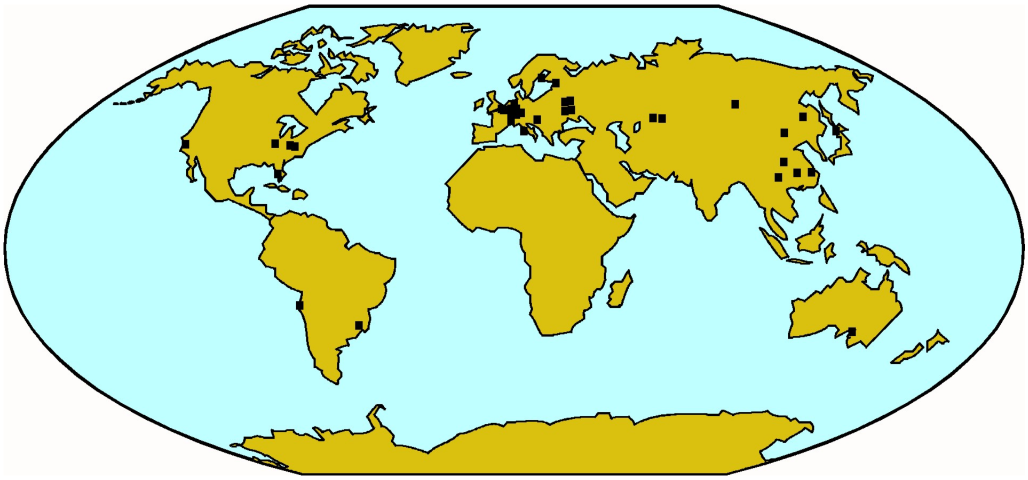

Fig. 1 Geographic distribution of the observatories whose data are used in the solution.

- EOC-1 (Ron and Vondrák, 2004; Vondrák and Ron, 2006), based only on meridian observations containing positions and linear proper motions of only 3784 stars;
- EOC-2 (Vondrák, 2004), based on all observations containing positions and linear proper motions of 4418 stars;
- EOC-3 (Vondrák and Štefka, 2007), based on all observations and containing positions and linear proper motions of 4418 stars, out of which 585 have also significant periodic motions;
- EOC-4 (Vondrák and Štefka, 2010), based on all observations and containing positions and linear proper motions of 4418 stars, out of which 599 have significant periodic motions.

The main difference between EOC-3 and EOC-4 is that the latter was constructed with an improved procedure ensuring better consistency with Hipparcos and Tycho-2 positions at their mean epochs. These catalogs were then used to derive EOP in the interval 1899.7 – 1992.0:

- Solution OA03 (Ron and Vondrák, 2004) with catalog EOC-1;
- Solution OA04 (Vondrák and Ron, 2005) with catalog EOC-2;
- Solution OA07 (Vondrák et al., 2008) with catalog EOC-3;
- Solution OA09 (this paper) with catalog EOC-4, whose preliminary results are described by Vondrák et al. (2010) and a more detailed description follows.

2. EOP SOLUTION

The values, based on about 4.5 million observations of individual stars are used. There are three different kinds:

- variations of latitude $\delta\varphi$,
- variations of universal time UT0-TAI;
- equal altitude differences δh.

We use the data observed with 47 different instruments, located at 33 observatories, whose geographic distribution is depicted in Figure. 1. Before being used in the solution, they were recalculated with the new astrometric catalog EOC-4, nutation IAU2000 (Souchay et al., 1999; Mathews et al., 2002) and precession IAU2006 (Capitaine et al., 2003). Several more corrections were applied, in order to bring all values into the homogeneous and most recent system of astronomical and instrumental constants, namely

- annual aberration;
- deflection of light in the Sun's gravitational field;
- the same model of refraction for all instruments (zenith-telescopes, astrolabes and similar);
- deformation of local almucantar for astrolabes and similar instruments (Pešek, 1995);
- unified system of instrumental constants, such as micrometer value (for ZT and similar instruments), plate scale (PZT), or azimuth (astrolabes and similar instruments);
- ocean loading effects in the local vertical (Scherneck, 1991);
- plate tectonic motions according to NUVEL-1 NNR model (Argus and Gordon 1991);
- short-periodic tidal variations of the Earth's speed of rotation (Yoder et al., 1981), so that instead of UT0 we use UT0R in the adjustment;
- unique and continuous time standard, close to UT1. To this end, we use a working standard called TAX that has a well defined, long-periodic relation to the International Atomic time (TAI), and at the same time its difference from UT1 is small during the interval studied (less than 0.2s):

$$\begin{aligned}\mathrm{TAX}-\mathrm{TAI} = {} & 2.63 - 0.002047t - 0.236\times10^{-7}t^2 \\ & + 0.49\times10^{-12}t^3 - 0.17\cos\frac{2\pi t}{6000} \\ & + 0.26\sin\frac{2\pi t}{6000} - 1.32\cos\frac{2\pi t}{9000} \\ & + 0.16\sin\frac{2\pi t}{9000}, \qquad (1)\end{aligned}$$

where t runs in days from MJD=35300. The details of how these corrections are applied are described by Vondrák et al. (1998). The homogenized data were then used to determine EOP at 5-day intervals: coordinates of the pole in the terrestrial frame x, y, and Universal time differences UT1-TAX (only after 1956, when Atomic Time was introduced). For each instrument, we determine constant, linear, annual and semi-annual deviation in latitude / longitude (here symbolically denoted as dev_φ, dev_λ), and the rheological parameter (combination of Love and Shida numbers) $\Lambda = 1 + k - l$ for the tidal variations of the local vertical. For the whole interval, we determine celestial pole offsets with respect to IAU2000/2006 precession-nutation model dX, dY, represented as quadratic functions of time.

The observation equations have rather complex form, so we publish here only their simplified version, for the three kinds of observations that we have (all expressed in arcseconds):

$$\begin{aligned}\Delta\varphi = {} & x\cos\lambda - y\sin\lambda - \mathrm{d}X\cos\alpha - \mathrm{d}Y\sin\alpha \\ & + \mathrm{dev}_\varphi + \Lambda D_\varphi \qquad (2)\end{aligned}$$

$$\begin{aligned}15\cos\varphi(\mathrm{UT0R}-\mathrm{TAX}) & \\ = {} & 15\cos\varphi(\mathrm{UT1R}-\mathrm{TAX}) \\ & + \sin\varphi\,(x\sin\lambda + y\cos\lambda) \\ & + \cos\varphi\tan\delta(\mathrm{d}Y\cos\alpha - \mathrm{d}X\sin\alpha) \\ & + \mathrm{dev}_\lambda + \Lambda D_\lambda\ ,\end{aligned}$$

$$\begin{aligned}\mathrm{d}h = {} & 15\cos\varphi\sin a\,(\mathrm{UT1R}-\mathrm{TAX}) + x(\cos\lambda\cos a \\ & + \sin\varphi\sin\lambda\sin a) - y(\sin\lambda\cos a \\ & - \sin\varphi\cos\lambda\sin a) \\ & + \mathrm{d}Y(\sin q\sin\delta\cos\alpha \\ & - \cos q\sin\alpha) \\ & - \mathrm{d}X(\sin q\sin\delta\sin\alpha \\ & + \cos q\cos\alpha) + \mathrm{dev}_\varphi\cos a \\ & + \mathrm{dev}_\lambda\sin a + \Lambda(D_\varphi\cos a \\ & + D_\lambda\sin a),\end{aligned}$$

in which φ, λ are geographic coordinates of the instrument, α, δ, a and q are right ascension, declination, azimuth and parallactic angle of the observed star, and D_φ, D_λ are rigid-Earth tidal variations of the local vertical. The matrix of normal equations based on observation equations (2), is however singular. To remove the singularity and to make the system solvable, we must apply 18 additional independent constraints, tying the parameters of dev_φ, dev_λ (for details see Vondrák et al., 1998). These constraints fix the terrestrial frame, both in orientation and drift, to the one given by the adopted mean astronomical coordinates of the instruments and site motions relative to model NUVEL-1, and minimize the seasonal deviations of the solution in polar motion and universal time. On the other hand, the terrestrial frame is thus purely conventional; its origin, drift and seasonal motions depend on the selection of the site coordinates, motions of the sites with respect to NUVEL-1 and seasonal refraction anomalies at individual sites.

The data from the following instruments were used in the present solution:

- *10 Photographic Zenith Tubes* (PZT), measuring $\delta\varphi$, UT0–UTC: 3 at Washington; 2 at Richmond and Mizusawa; 1 at Mount Stromlo, Punta Indio, and Ondřejov;
- *7 Photoelectric Transit Instruments* (PTI), measuring only UT0–UTC: 3 at Pulkovo; 1 at Irkutsk, Kharkov, Nikolaev, and Wuhan;
- *16 visual Zenith Telescopes* (ZT), *Floating Zenith Telescopes* (FZT) *and Visual Zenith Tubes* (VZT), measuring only $\delta\varphi$: 7 ZT at International Latitude Service stations; 2 ZT at Poltava, 1 ZT at Belgrade, Blagoveschtchensk, Irkutsk, Jósefoslaw, and Pulkovo; FZT at Mizusawa; VZT at Tuorla-Turku;
- *14 instruments for equal altitude observations – Danjon Astrolabes* (AST), *Photoelectric Astrolabes* (PAST), *Circumzenithals* (CZ), measuring δh: 1 AST at Paris, Santiago de Chile, Shanghai, Simeiz, and Wuhan; 2 PAST at Shaanxi, 1 PAST at Beijing, Grasse, Shanghai, and Yunnan; 1 CZ at Bratislava, Prague, and Pecný.

If compared with our preceding solution OA07 (Vondrák et al., 2008), the differences are the following:

1. The celestial reference frame is realized by the catalog EOC-4;
2. More strict criteria are applied to exclude outliers:
   - deviations larger than 0.7" (instead of 0.8") from the monthly average for each instrument are excluded;
   - residuals larger than $2.5\sigma_o$ (instead of $2.7\,\sigma_o$) are excluded, where σ_o is the standard error of one observation, computed from all residuals after adjustment.

2.7 per cent of observations were excluded, with final σ_o=0.184" (instead of 0.190" for OA07).

3. DISCUSSION OF THE RESULTS

Polar motion in 5-day intervals is depicted in Figure 2, each coordinate separately as function of time, together with its smoothed path that was calculated by using the method of Vondrák (1977) with the coefficient of smoothing equal to 0.1 day^{-6}. This choice ensures that all periods shorter than 4 years are completely suppressed while periods

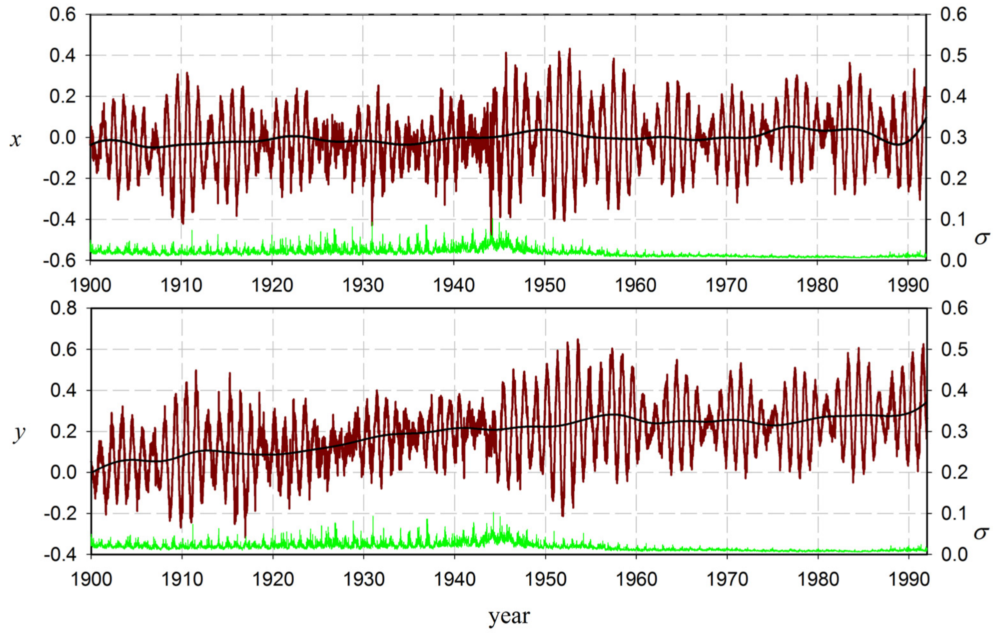

Fig. 2 Polar motion, its smoothed path and standard errors.

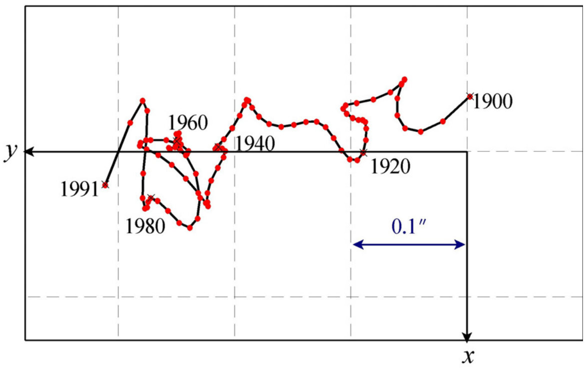

Fig. 3 Motion of the mean pole.

longer than 20 years pass completely through the filter. The standard errors σ of individual values are shown in the lower plot (notice that the scale is two times enlarged). The long-periodic pole path is separately drawn again in Figure 3, this time coordinate x against y, and time is depicted each year as full circles. The prevailing secular tendency towards Greenland is evident; spectral analysis of the rest, made by Fast Fourier Transform (Press et al., 1992) is shown in Figure 4. Although the dominant peaks are at period of about 78 years, so called Markowitz wobble with period 28 years is also evident.

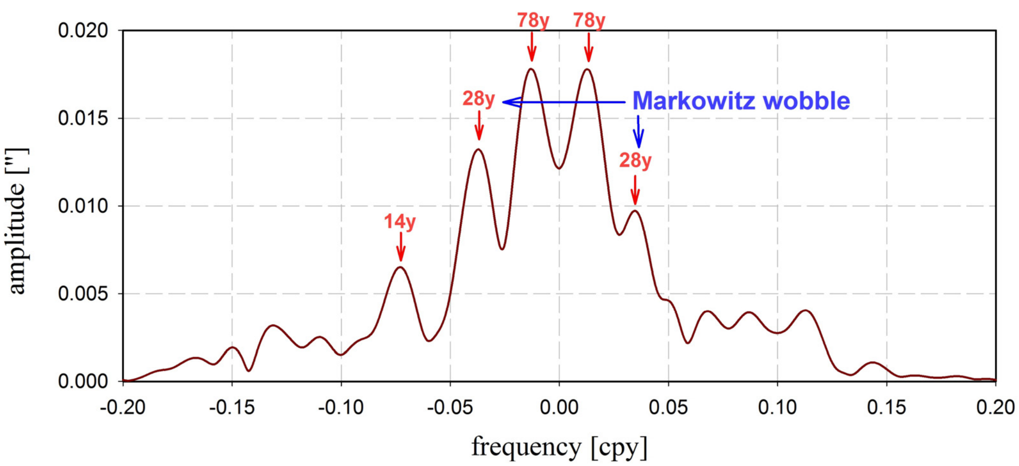

Fig. 4 Amplitude spectrum of the motion of the mean pole.

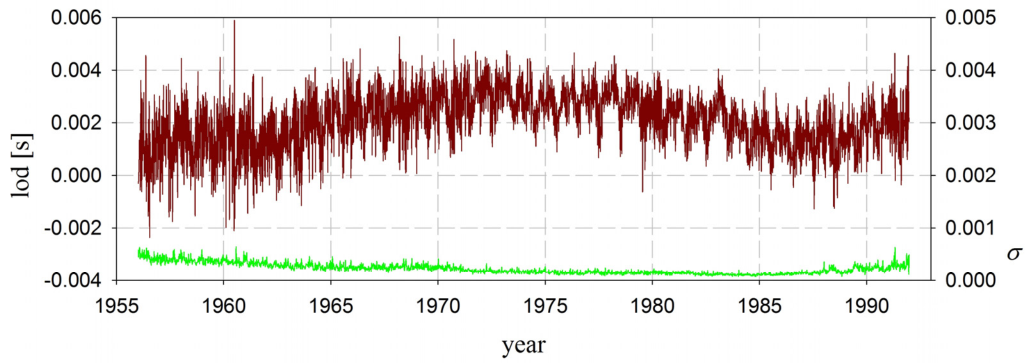

Fig. 5 Length-of-day changes.

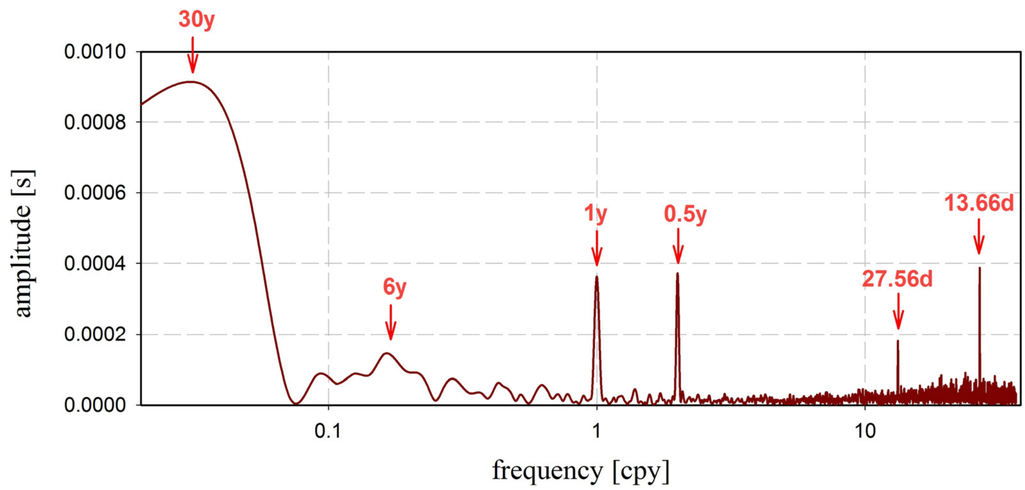

Fig. 6 Amplitude spectrum of length-of-day.

Table 1 Celestial pole offsets [mas].

	T^0	T	T^2
dX	−7.5	29.0	28.9
dY	−6.1	9.0	−0.9
$\sigma_{X,Y}$	0.4	1.1	3.4

Universal time from the adjustment is given in the form UT1R-TAX which must be then converted, replacing TAX by TAI (Eq. (1)) and adding back the originally removed short-periodic tidal terms, to UT1-TAI. Instead of these values, we plot in Figure 5 the values of the excess of length-of-day over nominal 24 hours, calculated from UT1-TAI as its negative time derivative. To show the details of the evidently periodic character of this plot, we computed the amplitude spectrum, again using Fast Fourier Transform. The result, containing several distinct peaks, is depicted in Figure 6. The very flat peak on the left (with period about 30 years) represents the well known decadal variations, most probably due to core-mantle coupling. Then there are several peaks (with periods from 6 to 0.5 years) that are caused by atmospheric and ocean excitations, and finally the peaks between 1 year and 13 days that are due to zonal tidal deformations of the Earth.

Celestial pole offsets are, since the introduction of the IAU2000 model of nutation, very small and consequently modeled as quadratic functions of time, instead of 5-day values that we produced in the past. They are given (in milliarcseconds) in Table 1, in which T is given in centuries since 1956.0.

Rheological parameter Λ is computed for each of the 33 observatories. Figure 7 shows the individual values and their error bars, ranged by increasing longitudes, from −180° to +180°. Thus the values for different continents (shown in bottom) can be easily separated. It does not seem that there are systematic differences among the continents, the values do not differ significantly from the theoretical value of the parameter, which is around 1.2. The differences however exceed sometimes the formal errors significantly. An example of big differences is the close stations Prague, Pecný and Ondřejov, for which we have no explanation.

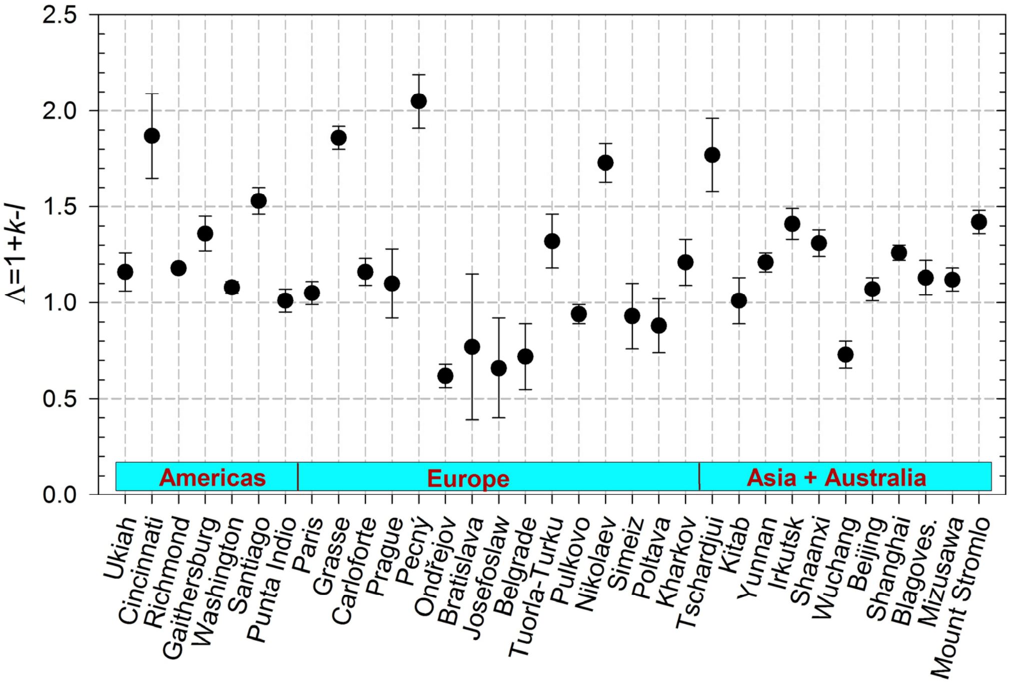

Fig. 7 Rheological factor Λ, computed for each observatory.

4. CONCLUSIONS

The present solution OA09 is based on 4505442 individual astrometric observations made at 33 observatories all over the world and the recent star catalog EOC-4; it covers the interval 1899.7 – 1992.0. This new solution yields slightly better results than the ones based on previous versions of EOC – the average standard error of one observation is now 0.184", compared to the one obtained in OA07 (0.190"). The solution is meant to be used for studying long-term Earth rotation changes during almost whole 20th century. Some preliminary studies have been already done in this paper (see preceding section). The secular motion of the pole and Markowitz wobble are confirmed again, as well as all dominant variations of length-of-day due to core-mantle coupling, luni-solar tidal forces, and atmospheric excitation. One must be aware of possible small deviations of the terrestrial reference frame used here, already mentioned in Section 2. The frame has an arbitrary origin and can exhibit small drift and seasonal motion with respect to an ideal one. To find and remove these systematic errors, a thorough comparison of this solution with independently measured EOP by space techniques is necessary, in the interval of common observations. This problem will be treated in our next study.

ACKNOWLEDGMENTS

This work was supported by the project LC506 "Recent dynamics of the Earth," financed by the Ministry of Education, Youth and Sports of the Czech Republic, and also by the grant No. 205/08/0908 awarded by the Grant Agency of the Czech Republic. We express our thanks also to the referees, I. Pešek and D.D. McCarthy, whose comments helped improve the text significantly.

REFERENCES

Argus, D.F. and Gordon, R.G.: 1991, Non-net-rotation model of current plate velocities incorporating plate model NUVEL-1. Geophys. Res. Lett. 18, 2039–2042.

Capitaine, N., Wallace, P., and Chapront, J.: 2003, Expressions for IAU 2000 precession quantities. Astron. Astrophys. 412, 567–586.

ESA: 1997, The Hipparcos and Tycho Catalogues. ESA SP-1200.

Høg, E., Fabricius, C., Makarov, V. V. et al.: 2000, The Tycho-2 Catalogue of the 2.5 million brightest stars. Astron. Astrophys. 355, L27–L30.

Mathews, P.M., Herring, T.A., and Buffet, B.A.: 2002, Modeling of nutation and precession: New nutation series for nonrigid Earth and insights into the Earth's interior. J. Geophys. Res. 107, doi: 10.1029/2001JB000390.

Pešek, I.: 1995, Systematic deformations of the apparent almucantar in homogenization astrolabe data for new solution of Earth orientation parameters from optical astrometry. Acta Polytechnica 35, 5–17.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P.: 1992, Numerical Recipes in Fortran, The art of scientific computing, 2nd edition, Cambridge University Press.

Ron, C. and Vondrák, J.: 2001, On the celestial pole offsets from optical astrometry in 1899–1992. In: N.

Capitaine (ed.) Journées 2000 Systèmes de référence spatio-temporels, Observatoire de Paris, 201–202.

Ron, C. and Vondrák, J.: 2004, Earth orientation parameters in 1899-1992 based on the new Earth Orientation Catalogue. In: A. Finkelstein and N. Capitaine (eds.) Journées 2003 Systèmes de référence spatio-temporels, Inst. App. Astron. St. Petersburg, 144–149.

Scherneck, H.-G.: 1991, A parametrized solid Earth tide model and ocean tide loading effects for global geodetic baseline measurements. Geophys. J. Int. 106, 677–694.

Souchay, J., Loysel, B., Kinoshita, H., and Folgueira, M.: 1999, Corrections and new development in rigid Earth nutation theory III. Final tables "REN-2000" including crossed-nutation and spin-orbit coupling effects. Astron. Astrophys. Suppl. Ser. 135, 111–131.

Vondrák, J.: 1977, Problem of smoothing observational data II, Bull. Astron. Inst. Czechosl. 28, 84–89.

Vondrák, J. 2004, Astrometric star catalogues as combination of Hipparcos/Tycho catalogues with ground-based observations. Serb. Astron. J. 168, 1-8.

Vondrák, J. and Ron, C.: 2003, An improved optical reference frame for long-term Earth rotation studies. In: N. Capitaine and M. Stavinschi (eds.) Journées 2002 Systèmes de référence spatio-temporels, Observatoire de Paris, 49–55.

Vondrák, J. and Ron, C.: 2005, Solution of Earth Orientation Parameters in the frame of new Earth Orientation Catalogue. Kinematika i fizika nebesnykh tel, Suppl. Ser. 5, 305–310.

Vondrák, J. and Ron, C.: 2006, Earth Orientation Catalogue - an improved reference frame. In: R. Gaume, D.D. McCarthy, and J. Souchay (eds.) Proc. IAU XXVth GA Joint Discussion 16: The ICRS maintenance and future realizations, USNO Washington, 112–119.

Vondrák, J. and Štefka, V.: 2007, Combined astrometric catalogue EOC-3. An improved reference frame for long-term Earth rotation studies. Astron. Astrophys. 463, 783–788.

Vondrák, J. and Štefka, V.: 2010, The Earth Orientation Catalog 4. An optical reference frame for monitoring Earth's orientation in the 20th century. Astron. Astrophys. 509, A3(2010), doi: 10.1051/0004-6361/200912472

Vondrák, J., Pešek, I., Ron, C., and Čepek, A.: 1998, Earth orientation parameters 1899.7–1992.0 in the ICRS based on the HIPPARCOS reference frame. Publ. Astron. Inst. Acad. Sci. Czech R. 87, 1–56.

Vondrák, J., Ron, C., and Pešek, I.: 2000, Survey of observational techniques and Hipparcos reanalysis. In: S. Dick, D.D. McCarthy, and B. Luzum (eds.) Polar motion: Historical and Scientific Problems, Proc. IAU Coll. 178, ASP Conf. Series 208, 239–250.

Vondrák, J., Ron, C., and Štefka, V.: 2008, Solution of Earth orientation parameters in 20th century based on optical astrometry and new catalog EOC-3. In: W.J. Jin, I. Platais, and M. Perryman (eds.) A Giant Step: from Milli- to Micro-arcsecond Astrometry, Proc. IAU Symp. 248, Cambridge Univ. Press, 89–92.

Vondrák J., Ron C., Štefka V.: 2010, New solution of Earth orientation parameters in 20th century. In: I. Corbett (ed.) Highlights of Astronomy, Cambridge Univ. Press 2010, submitted

Wielen, R., Schwan, H., Dettbarn, C. et al.: 2001, Astrometric catalogue ARIHIP containing stellar data selected from the combination catalogues FK6, GC+HIP, TYC2+HIP and from the HIPPARCOS Catalogue. Veröff. Astron. Rechen-Inst. Heidelberg, 40, Kommissions-Verlag G.Braun, Karlsruhe.

Yoder, C. F., Williams, J. G., and Parke, M. E.: 1981, Tidal variations of Earth rotation. J. Geophys. Res. 86, 881–891.