COMPARISON OF THE FK5 FRAME TO HIPPARCOS*

F. Mignard, M. Frœschlé

Observatoire de la Côte d'Azur, CERGA, UMR CNRS 6527, Avenue Copernic, F06130 Grasse, France

ABSTRACT

We have compared the overall properties in position and proper motion of the FK5 to Hipparcos for the 1535 stars of the basic FK5. The analysis carried out with an expansion of the differences $\Delta\alpha\cos\delta$, $\Delta\delta$ on a basis of spherical orthogonal functions, and similarly for the proper motion, gives the global rotation and spin between the two reference frames at 1991.25. The residuals after the rotation is removed show large regional distortions up to 150 mas. We discuss the consequence of the non-zero spin in term of the rotation of the FK5 frame with respect to the kinematical frame and characterize the main features of the regional errors.

Keywords: Astrometry, Reference frames.

1. THE FK5 CATALOGUE

The compilation of the FK5 by the Astronomisches Rechen Institut provides a practical realization of a dynamical frame through the position and proper motion of carefully measured stars. This Catalogue is based on the analysis of more than 300 individual instrumental catalogues primarily observed with meridian circles, and to a lesser extent with astrolabes. It represents a revision of the FK4 and results from the determination of systematic and individual corrections to the mean positions and proper motions of the FK4, the elimination of the error in the FK4 equinox, and the introduction of the IAU (1976) system of astronomical constants (Fricke et al. 1988). From an analysis of the observations of solar system bodies and lunar occultations Fricke (1982) has derived the following correction in mas, $E(T) = (525 \pm 45) + (12.75 \pm 1.5)(T - 19.50)$, to the zero point of the right ascension. One must bear in mind that any error in the above rate propagates directly in the system of proper motion.

The 1535 bright stars (the FK5 extension to 3522 stars is not considered here because of its lesser accuracy) have an expected accuracy of 0.03 arcsec at the mean epoch of the catalogue, 1955 in right ascension and 1944 in declination. The mean error quoted for the proper motion is 0.6 mas/yr for the northern hemisphere and 1.0 mas/yr for the southern. By propagating straightforwardly the FK5 positions to the Hipparcos epoch J1991.25, this leads to an expected error of the right ascension and declination of 40 to 60 mas according to the hemisphere. One should also note that about 95 per cent of the stars of the FK5 have an Hipparcos magnitude in the range 2 to 7, that is to say brighter than the average Hipparcos star, and so their accuracies in the Hipparcos Catalogue are better than the average and always less than 1 mas.

2. THE RATIONALE BEHIND A COMPARISON

The Hipparcos Catalogue has been constructed in such a way that the reference frame materialised by the positions coincides with the International Celestial Reference System, within the measurement errors. It constitutes so far the best optical counterpart to the non-rotating kinematical reference frame defined by the coordinates of 250 extragalactic sources. With respect to the FK5, Hipparcos is virtually error free and any difference between the two catalogues at 1991.25, must originate from the FK5 only. It is then natural and scientifically important to assess the quality of the frame materialised by the FK5 with respect to Hipparcos for several reasons :

- The FK5 frame is essentially a dynamical frame as its equinox was fixed by means of observations of solar system objects. Systematic effects between Hipparcos and the FK5, variable with the time, may reveal a meaningful difference between the two frames, in addition to an error in the precession constant. However for the proper motion Fricke (1981) has used a model for the global rotation of the local standard of rest, which means that the FK5 system is not purely dynamical, like the FK4, but partly kinematical.

- The origin of the right ascension in the Hipparcos Catalogue is inherited from the ICRS and is then purely conventional. As for the latter, it is supposed to be close to the mean dynamical equinox of J2000, that is to say close to the origin of right ascension in the FK5, and it is important to assess by how much they differ.

- From the magnitude and/or the main structures of the regional differences it might be interesting to

*Based on observations made with ESA Hipparcos satellite.

go back in time in order to understand whether they result from the observational techniques used to compile the FK5, or if the methods employed to merge the different catalogues and techniques are at fault.

• The largest regional differences with wavelengths of several tens of degrees, could be represented by simple formulae to be used to correct regional or global catalogues which have been implicitly or explicitly aligned on the FK5.

3. METHOD OF ANALYSIS

The 1535 stars of the FK5 have been observed successfully by Hipparcos and their positions are known in 1991.25 with an accuracy typically 0.4 ± 0.1 mas in declination and 0.6 ± 0.2 mas in right ascension. The larger scatter in right ascension being the result of the strong dependence of the Hipparcos accuracy in right ascension with the declination, whereas the precision in declination is fairly constant over the sky, depending only on the magnitude. The corresponding figures for the proper motions are 0.7 ± 0.2 mas/yr and 0.55 ± 0.15 mas/yr with the same kind of dependence with the coordinates as the positions.

The stellar positions and proper motions in the FK5 are given for the epoch J2000 in the FK5 system, while the Hipparcos Catalogue being an observation catalogue is referred to an epoch close to the average observation time, namely $T_0 = \mathrm{J}\,1991.25(\mathrm{TT})$. All the FK5 positions have been transported from J2000 to the epoch T_0 by using straightforwardly the FK5 proper motions. In the following these positions (rotated and transported to T_0) are denoted by α_{F}, δ_{F} while the Hipparcos positions are labelled α_{H}, δ_{H}.

3.1. Data Filtering

A certain number of the FK5 stars have been found either to be double (97 cases) or to present a non-uniform motion (95 cases), indicating the possibility that some are actually astrometric binaries. As a consequence the Hipparcos proper motion constructed on a time base shorter than the orbital period might be biased. For another 78 entries the Hipparcos solution has been constructed by adding to the standard astrometric parameters one or several orbital elements as supplementary unknowns. Therefore the astrometry refers in this case to the centre of mass, which may differ from the photocentre used in the FK5; these stars were not considered reliable enough for the comparison. Finally there were 22 solutions with residuals significantly larger than the measurement error and another 10 with an apparent motion of the photocentre ascribed to the variability of one of the components of a binary star. All these stars have been excluded from the analysis and the selection has ended up with 1233 reliable solutions. Most of the 302 removed stars have in fact a good Hipparcos solution, but because of their multiplicity they may exhibit systematic differences with the FK5 positions due to a more or less known physical origin while we expect that for the remaining 1233 single stars the differences could be accounted for as zonal errors.

3.2. Global Rotation

The Hipparcos Catalogue was referred to the ICRS after the final astrometric solution has been rotated. Nominally the ICRS was to maintain the continuity with the previous dynamical reference system realized by the FK5 Catalogue. However due to its limited accuracy, the alignment of the ICRS pole and origin of right ascension with the corresponding ones of the FK5 System at J2000 could not be achieved with consistency better than 20 mas for the pole and 80 mas for the origin of the right ascension (Arias et al. 1995). The final Hipparcos solution, ICRS(Hipparcos) and the optical reference frame defined by the FK5, J2000(FK5), differ by a pure rotation and numerous zonal differences of various wavelengths.

Both the rotation and zonal effects can be analysed globally by means of the decomposition of the vectors fields representing the positional differences:

$$X = (\alpha_{\mathrm{F}} - \alpha_{\mathrm{H}}) \cos\delta \quad (1)$$

$$Y = \delta_{\mathrm{F}} - \delta_{\mathrm{H}} \quad (2)$$

and the proper motion differences:

$$U = (\mu_{\alpha *})_{\mathrm{F}} - (\mu_{\alpha *})_{\mathrm{H}} \quad (3)$$

$$V = (\mu_{\delta})_{\mathrm{F}} - (\mu_{\delta})_{\mathrm{H}} \quad (4)$$

on a set of orthogonal vectorial harmonics (Mignard & Morando 1990). The first degree of these harmonics represents the pure rotation while the harmonics of higher degree account for the zonal differences at decreasing wavelengths with increasing degree. The value of the three angles of the global rotation and of the components of the spin vector are shown in Table 1 with their formal uncertainties.

Table 1. Global orientation and spin between the Hipparcos and FK5 Catalogues.

Orientation (mas)	Spin (mas/yr)
$\epsilon_x = -18.8 \pm 2.3$	$\omega_x = -0.10 \pm 0.10$
$\epsilon_y = -12.3 \pm 2.3$	$\omega_y = +0.43 \pm 0.10$
$\epsilon_z = +16.8 \pm 2.3$	$\omega_z = +0.88 \pm 0.10$

The global rotation has no particular physical meaning, giving only the relative orientation of the FK5 frame with respect to the ICRF, insofar as it can be represented by the Hipparcos Catalogue. The ϵ_x and ϵ_y components give the position of the FK5 pole with respect to the celestial pole of the ICRF. Although it is very different from the position of the Earth's pole at J2000 (Charlot et al. 1995), the three angles of rotation are consistent with the IAU recommendations stipulating that the direction of the Conventional Celestial Pole relative to the FK5's should be within 50 mas (Arias et al. 1995).

The components of the spin have a deeper physical meaning, being linked to the lack of inertiality of the FK5 frame with respect to the non–rotating extragalactic frame. The uncertainty of the time dependent correction of Equinox of 1.5 mas/yr (Fricke 1982) is fully compatible with the residual rotation rate found in this analysis. An error in the precession constant used for the FK5 is absorbed by the proper motion of the stars, thus is included in ω_z. From the analysis of Lunar ranging and radio interferometric data it has been shown that the IAU (1976) value of the precession must be corrected by -3.00 ± 0.20 mas/yr (Charlot et al. 1995, which again is of the same order of magnitude as ω. This value is very close to the result (-3.35 ± 0.05 mas/yr) of the analysis carried out from the Lunar ranging observations by Chapront & Chapront (1997) in view of tying the dynamical frames to the ICRS.

In the following analysis the positions and proper motions of the 1233 selected stars have been rotated in order to refer the FK5 Catalogue to the ICRS and then eliminate this systematic difference between Hipparcos and the FK5.

4. RESULTS OF THE COMPARISON

For each of the 1233 comparison stars each of the differences X, Y and U, V, corrected for the rotation and spin, have been computed and analysed from a statistical point of view. Results are shown in a series of diagrams as a function of the right ascension and declination in Figures 1–2 for the positions and Figures 3–4 for the components of the proper motion. A fit has been done through the data using a robust fitting technique with a moving window of 100 data points. One must recall that if the Hipparcos formal errors are to be believed, virtually all the scatter in the plots must originate from the FK5 positions.

There are several notable features in the plots of the positional differences between Hipparcos and the FK5:

• the ICRS and FK5 equators are about 60 mas apart, leading to a systematic effect in declination between the two Catalogues of the same magnitude. This effect is clearly seen in Figure 2 in the left plot with the average of $\Delta\delta \simeq -60$ mas;

• both coordinates show significant regional differences as large as ± 100 mas, an amplitude which is definitely larger than the expected accuracy of the FK5 at the Hipparcos epoch. Recent observations with meridian instruments have confirmed this effect and support the claim that these are local distortions in the FK5 rather than regional errors of Hipparcos;

• both the north and south polar regions exhibit larger discrepancies and scatters than the regions at intermediate declinations;

• the scatter in each of these diagrams is a good and robust measure of the FK5 external error at epoch J1991.25. From this analysis one gets: $\sigma_{\alpha*} \sim \sigma_\delta \sim$ 80 to 100 mas and: $\sigma_{\mu_{\alpha*}} \sim \sigma_{\mu_\delta} \sim 2.0$ to 2.5 mas/yr for the global inaccuracy, combining the random component, about 55 mas in both coordinates, and the contribution of the regional errors which amounts to about 60 mas. The random error in declination is larger in the southern hemisphere (~ 70 mas) than in the northern (~ 50 mas). As for the proper motion the random component is 1.7 mas/yr and the contribution of the zonal distortion to the standard deviation is 1.5 mas/yr, with no clear distinction with the sign of the declination. These figures are markedly larger than the expected error at epoch J1991.25 and than the quoted uncertainty for the proper motion, even if we consider only the random components. One might have expected that locally, the proper motion components would have been consistent below 1 mas/yr, which is definitely not the case. However the size of the fields used in this analysis are not very small (200 square degrees) as a result of the small number of stars, and the distortion on a very small scale cannot be separated from the truly random errors. Using this uncertainty of 2 mas/yr for the proper motion, the propagation from the mean observation epoch to J1991.25, yields precisely the observed uncertainty in the position found from the comparison with the Hipparcos. This consistency indicates that the standard errors in the position and proper motion are broadly correct and that the external accuracy, including zonal errors, of the FK5 is not as good as believed for years. This discrepancy was already pointed out a few years ago by Morrison et al. (1990) from their meridian observations;

• the regional errors in proper motion display a behaviour as a function of declination rather similar to that of the position. For example the overall shapes of the curves representing $\Delta\alpha\cos\delta$ and $\Delta\mu_\alpha\cos\delta$ as a function of the declination are rather alike. The same is true for the declination and the corresponding proper motion. Since the FK5 positions are propagated from the mean observation epoch of the FK5 to J1991.25, an error of 2 to 3 mas/yr in proper motion gives rise to a distortion in the position of about 100 to 150 mas at the same latitude. Thus, the wavy pattern in the positional differences with the declination might be simply the consequence of the zonal error in proper motion.

5. CONCLUSION

We have compared the positions and proper motions of the FK5 at 1991.25 to the Hipparcos observations of the same stars. Besides a global rotation and a spin, the differences exhibit large regional errors as large as 100 mas. They seem to originate primarily from the proper motions rather than from the positions at the mean epoch of the observations used to construct the FK5.

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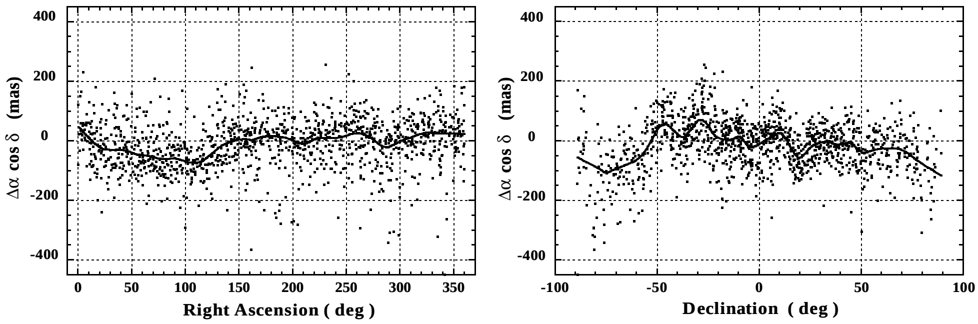

Figure 1. Difference in right ascension between the FK5 and the Hipparcos Catalogue at 1991.25 in the sense FK5-Hip. The solid line is a robust smoothing of the data.

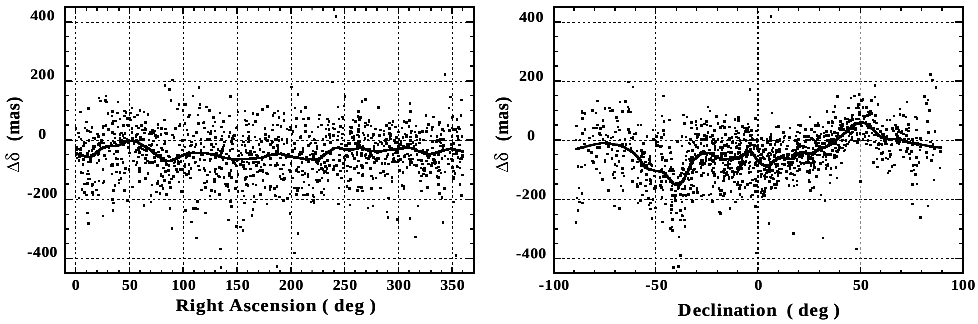

Figure 2. Difference in declination between the FK5 and the Hipparcos Catalogue at 1991.25 in the sense FK5-Hip. The solid line is a robust smoothing of the data.

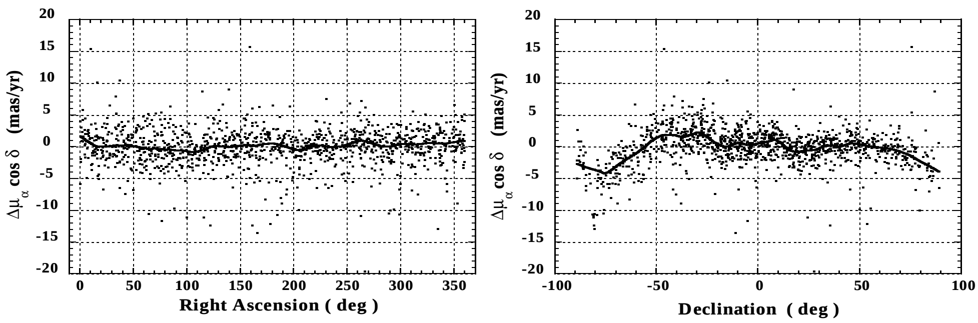

Figure 3. Difference in proper motion in right ascension between the FK5 and the Hipparcos Catalogue at 1991.25 in the sense FK5-Hip. The solid line is a robust smoothing of the data.

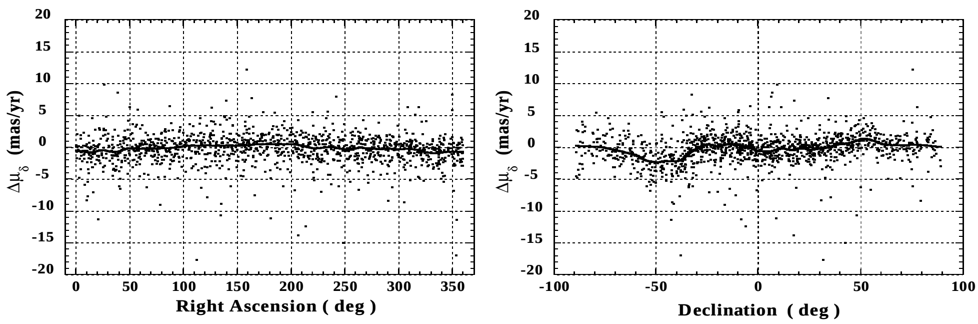

Figure 4. Difference in proper motion in declination between the FK5 and the Hipparcos Catalogue at 1991.25 in the sense FK5-Hip. The solid line is a robust smoothing of the data.