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Systematic relations between the HIPPARCOS catalogue and major (fundamental) catalogues of the 20th century (Paper II)

H. Schwan*

Astronomisches Rechen-Institut, Moenchhofstrasse 12-14, 69120 Heidelberg, Germany

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Abstract. Presented are the systematic relations between the HIPPARCOS catalogue and major catalogues of the 20th century, not yet treated in Paper I. Colour-dependent errors in the catalogues are also determined and eliminated. The derived systematic relations allow one to reduce observations given in the system of one of the analyzed catalogues to the HIPPARCOS system. The necessary software and the required input data can be downloaded from `http://www.ari.uni-heidelberg.de/fk6/sysdiff`. Other catalogues may be added from time to time.

Key words. reference systems – catalogs

1. Introduction

The present paper continues the presentation of the systematic differences between the HIPPARCOS catalogue (ESA 1997) and major astrometric catalogues of the 20th century (Paper I by Schwan 2001b). Our primary goal is to determine and present the systematic relations between the HIPPARCOS catalogue and old catalogues which were frequently used as reference systems for reducing observations of celestial objects. In particular we provide the software and input data required for the practical transformation of old observations published in one of these catalogue systems to the HIPPARCOS system.

Catalogue comparisons are presented for the AGK3R (Scott 1963), the SRS (Smith et al. 1990), the IRS and ACRS (Corbin & Urban 1990), the SAO catalogue (staff of the Smithsonian Astrophysical Observatory, 1968), the AGK3 (Dieckvoss et al. 1975), the CPC2 (de Vegt et al. 1993; Zacharias et al. 1992; Zacharias et al. 1999), the AGK2A (Kopff 1943), and the AGK2 (Schorr & Kohlschuetter 1951).

The software and numerical data required for the practical reduction of observations given in one of these catalogue systems to the HIPPARCOS system can be downloaded from the Web Site of the Astronomisches Rechen-Institut:

`http://www.ari.uni-heidelberg.de/fk6/sysdiff`

We cannot discuss here the various comparisons to the same extent as was done e.g. by Schwan (2001a) for the comparison of the FK5 catalogue (Fricke et al. 1988) with HIPPARCOS. The extensive discussion of the FK5 was justified by the fact that it has preceded the HIPPARCOS catalogue as the International Reference Frame for the positions and proper motions of celestial objects. The catalogues treated in the present paper have adopted the system of one of the fundamental catalogues analyzed in Paper I or in Schwan (2001a), namely the FK3 (Kopff 1937, 1938), FK4 (Fricke & Kopff 1963) or FK5 system. The analyzed catalogues provide extensions of those systems with respect to the star density and the magnitude range. A detailed knowledge of the construction and of the properties of these catalogues is not needed for the reduction of observations to the HIPPARCOS system with the aid of the results offered here. Therefore we restrict the discussions to merely a few remarks to help understand the comparison or to show the astrometric meaning of a catalogue. In addition a short comparison is made between those catalogues which have some logical interrelation, e.g. if they should nominally be on the same system (see Sect. 4).

For the catalogues prior to about 1970 the interested reader is referred to Eichhorn (1974), for the more recent catalogues the introductory parts of the catalogues should be consulted (see the references given for the respective catalogue). In addition much information and critical investigation can be found in the proceedings of the various relevant astrometric conferences.

2. Some general remarks concerning the catalogue comparisons

The procedure applied for determining the systematic relation between HIPPARCOS and another catalogue has been explained in detail in Paper I. A few additional

* e-mail: `schwan@ari.uni-heidelberg.de`

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remarks are added here which seem to be helpful for the interpretation of the results summarized in Table 2 (and the corresponding Table 1 in Paper I). Moreover we describe the extension of our procedure for the inclusion of colour-dependent systematic errors which exist in many photographic catalogues.

2.1. Inclusion of colour effects in the determination of the systematic differences

All comparisons are made according to the procedure outlined in Paper I, Sect. 5. The essential steps are:

1) Computation of the differences between HIPPARCOS and the catalogue under consideration at the mean epoch of the respective catalogue;
2) Elimination of the elliptic aberration (if necessary);
3) Estimation and elimination of the equinox error;
4) Transformation to the IAU (1976) system of constants;
5) Determination of a global rotation of the catalogue onto the HIPPARCOS system;
6) Determination and elimination of the regional errors, the magnitude equation and colour-dependent systematic errors;
7) Transformation to the equinox (and epoch, if proper motions are an inherent part of the catalogue) J2000.

A few of the catalogues analyzed here have made significant use of photographic observations. Since it is well known that such observations are often affected by systematic errors depending on the star's colour we have extended our method for the inclusion of such effects. Our analytical method is at present not able to model errors depending simultaneously on four parameters (α, δ, apparent magnitude m and the colour, which we denote in the following by the symbol c). Instead we determine the colour-dependent errors in a second step, after the systematic errors depending on the position on the sphere and the apparent magnitude were determined and eliminated. The residuals obtained in that first step are now analyzed in a completely analogous way with the colour index $c = B - V$ as the argument of the Hermite polynomials instead of the apparent magnitude. This second step yields a series development of the systematic errors depending on the colour and, eventually, simultaneously on α and/or δ. Since the pure α, δ-dependence was already eliminated in the first standard step no significant functions independent of the colour should occur.

The colour equation is determined as follows:

Let Δ_{res1} be a residual $\Delta\alpha*, \Delta\delta, \Delta\mu_{\alpha*}$ or $\Delta\mu_\delta$, obtained in Step 1 after eliminating the systematic errors depending on α, δ and m. Let c denote the colour index $B - V$ (e.g. in the Johnson system) of the star as given in the HIPPARCOS catalogue.

We use the Hermite polynomials for the representation of the systematic errors depending on the colour. With the same arguments as given by Schwan (1977) and Bien et al. (1978) we transform c to the normalized variable z which is given by

$$z = e_0 + e_1 \cdot c,$$

and determine e_0 and e_1 by the condition that z has the mean value 0 and the dispersion 1. This leads to the expressions

$$e_0 = - < c > /\sigma_c,$$
$$e_1 = 1/\sigma_c,$$

where $< c >$ and σ_c are the mean value and the dispersion of c, respectively. The colour effect is modelled by the series development

$$\Delta_{\text{res1}}(\alpha, \delta, c) = \sum Y_j(\alpha, \delta, c) + \Delta_{\text{res2}}.$$

Each function Y_{j} is the normalized product of a Legendre polynomial $L_{\text{n}}(x(\delta))$, a Fourier term $F_{\text{ml}}(\alpha)$ and a Hermite polynomial $H_{\text{p}}(z(c))$. We include only those functions into the development which reduce significantly the dispersion of the residuals. Δ_{res2} are the new residuals obtained after the additional elimination of the colour equation.

For more detail concerning the definition of the functions employed and the applied transformations reference is made to the quoted papers by Bien et al. and Schwan. One has only to read the relevant parts substituting the apparent magnitude by the colour.

We have implemented the colour equations into the software provided on the Internet. The user can choose whether or not he wants to include these effects into his reductions.

2.2. The significance level

The significance level chosen for the various comparisons depends strongly on the number of stars which could be used for the determination of systematic differences. A comparison based on many common stars is, of course, much safer than a comparison where merely a small number of stars define the system. Another parameter determining the quality of the system is the precision of the positions and/or proper motions involved. High precision data allow one to determine the system with much better accuracy than poor data. We have chosen the significance level in such a way, that a "reasonable" number of functions was included in the series developments representing the systematic relations.

2.3. The computation of the differences

As outlined formerly (see Sect. 4.1 of Paper I or Sect. 2 in Schwan 2001a) it is advantageous to make the comparison at the mean epoch of the catalogue to be compared with HIPPARCOS. This means that the positions in catalogues with given proper motions have to be transformed from the epoch adopted in the catalogue (e.g. the epoch 1950 in the case of the SAO catalogue) back to the mean catalogue epoch (e.g. 1923 for the SAO). Here the problem arises, how the catalogue postions were transformed by the authors of a catalogue from the original individual mean epoch of a star to the adopted catalogue epoch. In particular it is important to know, whether or not foreshortening effects were applied. If foreshortening effects were applied then the sources for the radial velocities and the parallaxes should be given. Since all this is in many cases not known one can merely make a guess on the basis which one of the two assumptions (with or without foreshortening) gives the smaller residuals. In determining the systematic differences this point is not so important, because wrong foreshortening effects will influence the differences for merely a few stars thus increasing the dispersion of the residuals. The foreshortening effect has, however, to be treated carefully if the observations are used individually for a star, e.g. for the determination of proper motions.

2.4. The dispersion of the residuals

In the case of proper motion differences it is mostly assumed that the dispersion of the residuals is composed as the quadratic mean value of the corresponding proper motion errors given in the two catalogues. In practice we find, however, in many cases that the dispersion of the proper motion residuals is significantly larger than expected from just the mean errors given in the two catalogues. This disturbing behaviour was also found in the comparison of the FK5 with HIPPARCOS. One explanation for that discrepancy could be that at least one of the contributing catalogues has underestimated its internal errors. Another explanation was found by Wielen (1997a) which led to the development of statistical astrometry (Wielen 1997b). In those papers it was convincingly shown that the existence of undetected binaries in the star sample has produced the excess in the dispersion of the residuals (so-called "cosmic errors"). These cosmic errors are a consequence of the fact that the HIPPARCOS satellite with its short observational period of merely a few years has measured more or less "instantaneous" proper motions whereas the FK5 gives "mean proper motions" which were derived by averaging observations over a long time interval. These proper motion measurements may differ significantly in the case of double stars. Such stars, which show up in the proper motion differences by unusually large values between the HIPPARCOS and the ground based proper motions, are also denoted as so-called "$\Delta\mu$-binaries".

In the case of the positional differences the situation is even more complicated. First the $\Delta\mu$ binaries also produce larger residuals. Another cause comes, however, from the fact that in general at least one catalogue has to be transformed to another epoch and this transformation introduces corresponding proper motion effects into the differences of the positions. In the case of a catalogue with proper motions (e.g. the SAO) we make the comparison at the mean catalogue epoch (e.g. 1923.0 for the SAO). In that case the proper motions of both, the HIPPARCOS catalogue and the catalogue to be compared (the SAO), are involved. The HIPPARCOS proper motions would be involved for the time interval $1923-1991.25 = -68.25$ years, and the SAO proper motions for the time interval between the epoch 1923.0 and a star's individual mean epoch.

In view of the high precision of the HIPPARCOS catalogue one may first be inclined to ignore the contribution of the HIPPARCOS data to the dispersion of the residuals given in Table 2. This is, however, not really true in many cases because the HIPPARCOS proper motions may significantly contribute to the dispersion of the positions and proper motions given in Table 2.

In addition it has to be noted that stars with unusually large differences between HIPPARCOS and the respective catalogue have to be eliminated from the determination of the systematic differences. This elimination is always subject to a personal judgement and the resulting dispersion depends on where the limit for elimination was chosen.

In summary: even in the comparison of a catalogue with the highly accurate HIPPARCOS catalogue it is not always legitimate to identify the dispersion of the residuals given in Table 2 with the precision of the data given in the catalogue in question.

3. The various catalogues compared with HIPPARCOS

This section presents the individual catalogue comparisons. For each catalogue we add a few short remarks concerning, for instance, its astrometric meaning or additional explanation of the comparison if it seems useful. The final results are summarized in tabular and graphical forms in Sect. 4.

3.1. The AGK3R catalogue

The AGK3R (Scott 1963, 1967) was part of the large International Reference Star Program which is described in some detail by Smith (1980). It has provided the reference system for the photographic catalogue AGK3 (Dieckvoss 1975). From 1956 through 1963 over 300 000 observations were made at various observatories for 21 499 stars north of −5 degrees in the magnitude range 6.5 to 9.5. All contributing observations were reduced to the FK4 system which was also adopted as the final AGK3R system.

The AGK3R catalogue gives no proper motions, and we had therefore to determined its systematic relation according to Paper I, Sect. 5.2, i.e. we have computed the differences HIPPARCOS – AGK3R at the individual epochs of the stars. Since the AGK3R is nominally on the FK4 system we have chosen the equinox correction E in accordance with the equinox correction of the FK4, i.e. $E(T_{\rm i}) = 0\overset{s}{.}035 + 0\overset{s}{.}085 \cdot (T_{\rm i} - 19.50)$ where $T_{\rm i}$ is the individual epoch of a star in centuries. The value $E(T_0)$ for the mean epoch $T_0 = T_{\rm E} = 1959.0$ is given in Table 2.

3.2. The AGK3 catalogue

The AGK3 project was initiated at the beginning of the 1950th with the aim of reobserving the AGK2 stars and deriving proper motions. From 1956–1963 photographic plates were taken covering the sky north of −2.5 degrees declination. Using the stars in the AGK3R catalogue as reference, mean positions were derived for more than 180 000 stars. The system adopted formally for the AGK3 catalogue is therefore that of the FK4.

The proper motions given for the AGK3 stars were derived by comparing the AGK3 positions with positions obtained from a new reduction of the AGK2 catalogue (see Sect. 3.8). This re-reduction of the AGK2 has provided an improved version of the AGK2 catalogue, which was, however, never published as a separate catalogue. It is implicitely included in the AGK3 and can easily be obtained by reducing the AGK3 positions to the corresponding AGK2 epochs with the aid of the AGK3 proper motions.

The data given in the AGK3 catalogue do not exactly fit into our standard procedure applied for the determination of the systematic differences. The reason is that the AGK3 gives, on one hand, mean positions valid for the individual mean epoch of a star, and on the other hand it provides derived proper motions which were, however, not used to transform the positions to some standard epoch. In the case of the AGK3 this was certainly the right procedure since it fully preserves the originally observed AGK3 positions. For catalogues with derived proper motions our software expects, however, that the positions are transformed to some standard epoch with the aid of the given proper motions. For this reason we have transformed the AGK3 positions to the average mean epoch 1959.0 using the AGK3 proper motions. The comparison was perfomed at that epoch.

After the systematic differences depending on the right ascension, declination and apparent magnitude were eliminated we looked for possible additional systematic effects depending on the colour and the position on the sphere. Significant systematic differences were found, in particular for $\Delta\delta$ with the largest efects in the zone south of 30 degrees. Merely a small linear colour effect independent of α and δ was found for the proper motions in right ascension, although larger colour effects still exist in the postional systems of the AGK3 and the AGK2 (revised version, see Sect. 3.8.2). These colour effects in position are, however, rather similar and had therefore not much influence on the determination of the proper motions.

3.3. The SRS catalogue

The SRS catalogue (Smith et al. 1990) is the southern extension of the AGK3R catalogue. The observations were made from 1961 through 1973 with epochs depending systematically on the declination zone and yielding the formal mean epoch 1968.9. Since the SRS positions hold for the stars' individual epochs and since no proper motions are given we have computed the differences HIPPARCOS–SRS at these individual epochs. Our systematic differences hold therefore formally at the average mean epoch 1968.9. The SRS was originally derived in the FK4 system with the aim of providing the reference stars for the photographic catalogue CPC2 (see Sect. 3.4). The SRS thus played the same role for the CPC2 as the AGK3R catalogue for the AGK3. The SRS stars are in the range from 6th to 10th magnitude. After the FK5 system had become available, corrections FK5–FK4 in right ascension and declination were computed and applied for each SRS star on the basis of the information given in the FK5 catalogue (Fricke et al. 1988, p. 85 ff) yielding a catalogue in the FK5/J2000 system.

Since people have used both versions of the SRS as a reference, we give the relations of both versions wrt. the HIPPARCOS system.

For the FK4-based version we have applied the equinox correction FK5 − FK4, i.e. $E(T_{\rm i}) = 0\overset{\rm s}{.}035 + 0\overset{\rm s}{.}085(T_{\rm i} - 19.50)$ at the individual epoch $T_{\rm i}$ (in centuries) of a star.

3.4. The CPC2 catalogue

The CPC2 catalogue (de Vegt et al. 1993; Zacharias et al. 1992; Zacharias et al. 1999) was a major contribution to the large project in the second half of the 20th century with the aim of constructing a dense and accurate stellar reference frame over the whole sky. In the southern sky this goal was achieved with the CPC2 catalogue which provides mean positions (and visual magnitudes) for 276 131 stars at the mean epoch 1968. The catalogue was published in the FK4/B1950 and alternatively also in the FK5/J2000 system, using the corresponding versions of the SRS catalogue as reference (see Sect. 3.3). These versions are denoted as "Release 1".

After the HIPPARCOS catalogue had become available an impoved reduction was performed by Zacharias et al. (1999) with the HIPPARCOS catalogue as reference. Since this new reduction of the CPC2 is already in the HIPPARCOS system, we restrict our subsequent analysis to Release 1 (i.e. the SRS-based version) of the catalogue. Moreover we merely derive the relation for the FK5-based version since the FK5 was already available at that time and people should have made use of that version. The CPC2 version analyzed here is nominally on the system of the FK5-based version of the SRS and one could therefore in principle use the systematic relations HIPPARCOS–SRS(FK5-based version) (see Sect. 3.3). In practice it is, however, advantageous to make a direct comparison between the catalogues under consideration.

For each HIPPARCOS star in the CPC2 catalogue the difference with respect to the HIPPARCOS data was computed at the individual epochs of the CPC2 stars. These individual epochs are widely spread and cover the range from about 1961 through 1972 with a peak near 1970. The mean epoch is 1968.0 and our systematic relations hold therefore formally for this epoch. No equinox correction was applied since the catalogue is nominally on the FK5 system.

For photographic catalogues we have to expect, in principle, systematic errors down to the size of a plate, about 4×4 squ. degrees. With our chosen limits for the highest degree of our functions ($n = 30$ and $m = 20$) we have a resolution of 3° in declination and about 9° in right ascension. But the spectrum of significant functions ceased much before the limits $n = 30, m = 20$. The significant function with the highest resolution had $n = 24$ and $m = 4$, corresponding to a scale of 4×45 squ. degrees.

No systematic errors depending on the colour were detected. There exists, however a very significant magnitude equation in declination which is correlated with the declination (functions depending simultaneously on the apparent magnitude and the declination). A small magnitude equation in right ascension was found which is independent of α and δ.

3.5. The IRS catalogue

In order to bring the AGK3R and SRS positional systems (see Sects. 3.1 and 3.3) to other epochs proper motions were determined by Corbin (Corbin & Urban 1990). There were more than 150 000 observations in 122 meridian circle catalogues which could be reduced to the FK4 system and then combined with the AGK3R and SRS positions. The resulting IRS catalogue gives mean positions and proper motions in the FK4 system for 36 027 stars. Depending on the observational histories of the stars the catalogue was subdivided in two parts, the first one giving the data for 29 163 stars with good histories of observation, the second one containing the data for 6864 stars with poor data. In the present work we have only used the stars in Part 1 of the IRS. The quality of the stars in Part 2 is too poor for significantly contributing to the definition of the system.

After the FK5 system had become available an FK5-based version of the IRS in the J2000 coordinate system was produced and provided by the USNO. Since both versions of the catalogue have probably been used by many people we have derived the systematic relations between the HIPPARCOS system and both catalogue versions.

3.6. The ACRS catalogue, AC2000, ACT and Tycho-2

The ACRS catalogue (Astrographic Catalogue Reference Stars, Corbin & Urban 1990) was constructed using all major catalogues of the 20th century. It thus resembles in many respect the PPM catalogue (Roeser & Bastian 1991 and Bastian & Roeser 1993). One major difference is that the ACRS has not yet included the positions of the Astrographic Catalogue (AC) because the authors believed that there was no sufficiently accurate and dense reference system available at that time for a safe reduction of the AC. The primary aim of the ACRS was therefore to provide such an appropriate reference frame for a new reduction of the AC. This reduction of the AC has yielded the AC2000, a catalogue of mean positions for more than 4.5 millions of stars (Urban et al. 1998a). Proper motions for the AC stars were derived at the US Naval Observatory by combining the AC2000 with the Tycho positions yielding the catalogue ACT (Urban et al. 1998b). A revised version AC2000.2 of the AC catalogue was published by Urban et al. (2002). The AC2000.2 was reduced with a completely revised version of the ACRS that included Tycho data and was much more tightly reduced to HIPPARCOS. Proper motions for about 2 million stars in the Tycho 2 catalogue (Hoeg et al. 2000) were derived using the AC2000.2, the Tycho 2 positions and the individual catalogues discussed in the revised version of the ACRS. Since all these catalogues are already on the HIPPARCOS system we merely have to discuss here the original ACRS catalogue.

The ACRS catalogue was published as an FK4-based version referred to the equinox B1950.0 and an FK5-based version referred to J2000. We restrict our analysis to the FK5-based version because most people should have made use of that version. Moreover we have only used the stars of Part 1 of that catalogue for the determination of the systematic differences. The stars in Part 2 have a much poorer history of observation, and their accuracy is not sufficiently high to contribute to the definition of the system. The mean epochs in right ascension and declination differ less than half a year from 1950, the epoch for which the catalogue data are given and which we have therefore adopted for our catalogue comparison.

A colour equation depending linearly on $B - V$ was found in declination. The functions are coupled with the declination yielding four declination zones with significantly different values of the colour effects. The numerical values are, however, comparatively small. The largest values are found in the region south of $-60°$ increasing from about -50 mas for the colour $B - V = -0.2$ (spectral type B5) to about $+50$ mas for $B - V = +1.6$ (M5).

An investigation of the proper motion system of the ACRS (and PPM) was made by Zi Zhu (2000). Since the kinematical consequences of the systematic errors in the FK5 proper motions are a major aspect in that paper, no investigation of the system of mean positions was made. Those results were also not intended to be suitable for a practical reduction of ACRS-based observations to the HIPPARCOS system.

3.7. The AGK2A catalogue

The AGK2A catalogue (Kopff 1943) was observed at seven observatories and provided the reference stars for the photographic catalogue AGK2 north of -5 degrees. Altogether mean positions for 13 746 stars were reduced to the FK3 system from observations made mainly from 1928 through 1932 with an average mean epoch of 1930.0. There exists, therefore, no large dispersion in the AGK2A epochs. The AGK2A gives no proper motions and we had to compute the differences HIPPARCOS – AGK2A at the individual mean epochs of the stars. Since there was no change in the equinox from FK3 to FK4 we have used the equinox correction FK5–FK4. The value $E(T_0)$ at the mean epoch $T_0 = 1930.0$ is given in Table 2. This is also the "effective" epoch of our catalogue comparison.

3.8. The AGK2 catalogue

Photographic plates were taken at Hamburg and Bonn from 1928 until 1932. The coordinates for more than 181 000 stars north of −2.5 degrees were derived using the AGK2A as reference catalogue. The original plan to use the AGK1 positions as the first epoch for the derivation of proper motions was abandoned because the large systematic errors inherent in the AGK1 positions could not be determined with sufficient accuracy at that time.

A new reduction of the original AGK2 catalogue was made for deriving proper motions for the AGK3 (see Sect. 3.2). Since there may exist old observations for which the original AGK2 has been used as the reference system we have compared both versions with the HIPPARCOS catalogue.

The mean epoch of the HIPPARCOS stars in the AGK2 catalogue is 1929.9 which is therefore the formal epoch of our catalogue comparisons.

3.8.1. The printed version of the AGK2

The printed version of the AGK2 (Schorr & Kohlschuetter 1951) is on the FK3 system which has the same zero point as the FK4 system. We have therefore computed and applied the equinox correction $E(T_\mathrm{i}) = 0\overset{\mathrm{s}}{.}035 + 0\overset{\mathrm{s}}{.}085(T_\mathrm{i} - 19.50)$ at the individual epoch T_i of a star. Similarly the differences $\Delta\alpha$ and $\Delta\delta$ were computed at the individual epochs T_i.

It is well known that the Bonn zone of the printed version of the AGK2 has a large colour equation (Kohlschuetter, in AGK2, Vol. 11, p. 27ff). After the systematic errors depending on α, δ and m were determined and eliminated we have analyzed the resulting residuals for additional colour effects as described in Sect. 2.1. Large systematic errors depending linearly on the colour and coupled with the declination were detected. The largest values are found in the region south of 30°, as could be expected. The colour equation is given for this catalogue in Table 1 for the following reasons. First the effects are rather large, and second we wanted to present the results of our method in numerical form at least for one example. The colour equation in right ascension is given in Table 1a and correspondingly for the declinations in Table 1b.

3.8.2. The revised version of the AGK2

The revised version of the AGK2 is obtained from the AGK3 by applying the proper motions given in the AGK3 over the star's epoch difference between the AGK2 and AGK3 epoch. This revised AGK2 version is formally on the FK4 system (as is the AGK3), whereas the original AGK2 is on the FK3 system. Since the FK3 and FK4 equinox are the same we have applied the equinox correction FK5–FK4.

When the AGK3 became available there was no need for using the AGK2 any more. The revised version of the AGK2 was therefore probably not used as a reference system for reducing observations. We have added the comparison of the revised AGK2 mainly for reasons of completeness. It may also be of some interest to see how well the reduction of the original AGK2 into the FK4 system was achieved. This question was already discussed by Corbin (1978).

No colour equation was found in the right ascensions. In declination there still exist colour dependent systematic errors with the same structure as in the printed version. The amplitudes are, however, smaller by a factor of about 2.5. The colour effects still existing in the revised AGK2 and in the AGK3 positions (see Sect. 3.2) are very similar and therefore only slightly affect the derived AGK3 proper motions.

3.9. The SAO catalogue

With the beginning of the space age in the second half of the past century there was an urgent need for a dense reference system on the sky for accurately tracking the orbits of artificial satellites. This task was undertaken at the Smithsonian Astrophysical Observatory with the compilation of the SAO catalogue (Staff of the Smithsonian Astrophysical Observatory, 1968). If possible, the proper motions were selected from the best sources available at that time. But if necessary they were also newly derived from positions published in various observational catalogues. The reductions were primarily made in the FK3 system and then transformed to the FK4 system which became available in the course of that work.

The SAO data have thus been compiled from many different sources of basic material and it is not clear, how well the reduction to the FK4 system could be performed. One must therefore expect that the system is to some extent inhomogeneous depending on the sources from which a star's astrometric data were derived. We have not tried to trace the origin of the data for an SAO star with the aim to subdivide the SAO catalogue correspondingly in subsamples of stars with common origin. This is also justified since people have certainly not made such a subdivision in making use of the SAO as a reference system. The systematic differences determined and presented here may therefore represent an average system over possibly existing slightly different subsystems.

The distribution of the mean epochs is also very inhomogeneous. If we just use the HIPPARCOS stars in the SAO catalogue then we find an average mean epoch of 1923.12 in right ascension and 1922.31 in declination. The average mean epochs for all stars are 1928.15 and 1927.79 in right ascension and declination, respectively. For our

Table 1. Colour equation in the AGK2 (printed version) for the right ascensions (left part of the table) and declinations (right part of the table). Units: [mas].

	right ascension					declination				
$B-V$	0.0	0.5	1.0	1.5	2.0	0.0	0.5	1.0	1.5	2.0
$\delta=+80^\circ$	−14	−4	+6	+16	+26	+38	+11	−16	−43	−70
$+60^\circ$	−39	−11	+16	+44	+72	+2	+4	−6	−2	−3
$+40^\circ$	+7	−5	+6	+19	+31	−22	−6	+9	+25	+41
$+20^\circ$	−90	−26	+6	+102	+166	−151	−43	+64	+171	+279
$+0^\circ$	−126	−36	+54	+143	+233	−199	−57	+85	+227	+369

catalogue comparison we have computed the differences HIPPARCOS–SAO at the rounded mean epoch 1923.0.

Since the SAO catalogue also makes use of photographic work we have looked for systematic differences depending on the spectral type. No colour dependent systematic trends were detected.

A comparison of the SAO catalogue with HIPPARCOS was made by Arias et al. (2000) with emphasize on the global orientation. A practical application of those results was, however, not intended and is hardly possible.

3.10. The PPM catalogue

In Paper I we have discusssed the PPM catalogue (Roeser & Bastian 1991; Bastian & Roeser 1993) but without looking for a colour equation. We have now analyzed the residuals obtained in that investigation for additional effects depending on the star's colour. Significant effects depending linearly on the colour and coupled with the declination were found for the differences in declination and the proper motions in right ascension.

4. Results and short discussion

Some data characterizing the catalogues and the comparisons are compiled in Table 2 which is analoguous to the corresponding table in Paper I. For the convenience of reading we repeat the meaning of the various entries.

Given are the total number $N_{\rm tot}$ of the stars in the catalogue, the number of stars used in position ($N_{\rm used,pos}$) and proper motion ($N_{\rm used,pm}$) for deriving the systematic differences, the epoch $T_{\rm C}$ of the catalogue equinox at which some of the corrections are applied in the case of catalogues with proper motions, the mean epoch T_0 at which the comparison was made, the epoch $T_{\rm E}$ for which the equinox correction holds, the rotational parameters $\epsilon_x, \epsilon_y, \epsilon_z$ in position and $\omega_x, \omega_y, \omega_z$ in proper motion at the epoch T_0, the equinox correction E at the epoch $T_{\rm E}$ and the motion of the equinox e, the number $N_{\rm sig}(\alpha)$ of significant functions included in the series development of $\Delta\alpha*$, the highest degrees $n_{\rm sig,max}(\alpha), p_{\rm sig,max}(\alpha)$ of the significant Legendre and Hermite polynomials and the highest frequency $m_{\rm sig,max}(\alpha)$ of the Fourier terms included in the development of $\Delta\alpha*$, the next four lines give correspondingly the numbers for the developments of $\Delta\delta, \Delta\mu_{\alpha*}$ and $\Delta\mu_\delta$, the line "col.equ." was not given in Paper I and is explained below, the next four lines give the dispersions $\sigma_{\rm res}(\Delta\alpha*), \sigma_{\rm res}(\Delta\delta), \sigma_{\rm res}(\Delta\mu_{\alpha*})$ and $\sigma_{\rm res}(\Delta\mu_\delta)$ of the residuals, followed by four lines with the mean quadratic deviations $\sigma_{\rm sys}(\Delta\alpha*), \sigma_{\rm sys}(\Delta\delta), \sigma_{\rm sys}(\Delta\mu_{\alpha*}), \sigma_{\rm sys}(\Delta\mu_\delta)$ of the systematic differences, and finally one finds four lines with the mean deviations $<\Delta\alpha*>, <\Delta\delta>, <\Delta\mu_{\alpha*}>$ and $<\Delta\mu_\delta>$ between the HIPPARCOS system and the system of the globally reduced catalogue (i.e. before determining the regional errors).

As a new entry we have added the column "col.equ" which gives information on the colour equation in a catalogue. A question mark indicates, that we have not looked for colour dependent effects; a plus indicates the detection of a colour equation; a minus means that we have looked for a colour equation, but no systematic effect was detected.

The number of significant functions and, even more, the highest degree of those functions, give some information on how "complicated" the systematic relations are. The more functions are included and the higher their degree, the more complicated is the system. Catalogues for which functions with $p \neq 0$ occur are affected with a magnitude equation. Functions with a plus sign in the line "col.equ" are affected by a colour equation. The values for the dispersion of the systematic differences ($\sigma_{\rm sys}(\Delta\alpha*)$ and similarly for the other components) are a measure for the typical variation of the catalogue systems.

The internal precision of a catalogue is contained in the values for $\sigma_{\rm res}(\Delta\alpha*)$ (and similar for the other components). But it is important to consider the remarks made in Sect. 2.4, describing various effects contributing to the dispersion of the residuals.

In Figs. 1–10 we give the δ-dependent parts of the systematic errors which are in many cases dominating. The catalogues are grouped according to the system which they should nominally have. The first group comprises the catalogues given in the FK5 system: these are the SRS (FK5-based version), the IRS (FK5-based version), the ACRS, the CPC2 catalogue and the Basic FK5 itself. In order to compare the positional systems of these catalogues we have transformed the systematic differences for the IRS, the ACRS and the system of the Basic FK5 to the mean epoch 1968.5 which is about the mean of the SRS and CPC2 epochs. This transformation introduces systematic

Table 2. Characteristic data in the reduction process of the various catalogues to the HIPPARCOS system.

	AGK3R	SRS (FK4)	SRS (FK5)	IRS (FK4)	IRS (FK5)	CPC2	ACRS Pt. I	AGK3	SAO	AGK2A	AGK2 prt.	AGK2 rev.
$N_{\rm tot}$	21 499	20 488	20 488	29 163	29 163	276 131	250 052	181 581	258 997	13 747	183 233	181 581
$N_{\rm used,pos}$	19 366	18 128	18 138	26 103	25 997	49 138	83 119	47 342	85 454	8 360	47 347	46 959
$N_{\rm used,pm}$	—	—	—	26 128	26 126	—	82 700	47 280	85 052	—	—	—
$T_{\rm C}$	1950.0	1950.0	1950.0	1950.0	2000.0	2000.0	2000.0	1950.0	1950.0	1950.0	1950.0	1950.0
T_0	1959.0	1968.9	1968.9	1946.0	1946.0	1968.0	1950.0	1959.0	1923.0	1930.0	1929.9	1929.9
$T_{\rm E}$	1959.0	1968.9	1968.9	1950.0	—	1968.0	—	1950.0	1950.0	1930.0	1929.9	1929.9
$\epsilon_x(T_0)$ [mas]	–14.40	–16.48	–9.12	–4.77	+2.00	+8.18	+0.05	–12.55	–5.34	–1.65	–7.19	–1.40
$\epsilon_y(T_0)$ [mas]	–58.28	–41.62	–28.13	–51.15	–41.79	–25.78	–41.84	–56.35	–83.20	–41.60	–41.79	–45.19
$\epsilon_z(T_0)$ [mas]	– 9.24	+10.99	+23.69	–16.77	–10.51	+23.17	–3.27	–0.63	–76.27	–44.92	–33.16	–36.62
ω_x [mas/yr]	—	—	—	–0.53	–0.50	—	–0.40	–0.38	–0.10	—	—	—
ω_y [mas/yr]	—	—	—	+0.04	+0.54	—	+0.46	–0.37	+0.05	—	—	—
ω_z [mas/yr]	—	—	—	+0.89	+0.79	—	+0.02	+1.06	+0.14	—	—	—
$E(T_{\rm E})$ [s]	+0.043	+0.051	—	+0.035	—	—	—	+0.035	+0.035	+0.018	+0.018	+0.018
e [s/cy]	—	—	—	+0.085	—	—	—	+0.085	+0.085	—	—	—
$N_{\rm sig}(\alpha)$	28	45	36	29	22	31	29	22	24	22	25	21
$n_{\rm sig,max}(\alpha)$	12	21	21	26	26	20	26	18	39	19	20	20
$m_{\rm sig,max}(\alpha)$	5	4	4	4	3	4	2	8	5	6	14	6
$p_{\rm sig,max}(\alpha)$	1	0	0	2	2	0	2	1	0	0	2	2
$N_{\rm sig}(\delta)$	22	17	14	15	18	16	23	26	26	18	24	18
$n_{\rm sig,max}(\delta)$	19	24	24	23	33	15	31	24	39	20	20	26
$m_{\rm sig,max}(\delta)$	5	3	2	3	3	2	2	9	2	5	17	7
$p_{\rm sig,max}(\delta)$	0	0	0	1	1	1	1	0	1	0	2	1
$N_{\rm sig}(\mu_\alpha)$	—	—	—	23	24	—	43	19	30	—	—	—
$n_{\rm sig,max}(\mu_\alpha)$	—	—	—	21	21	—	28	8	32	—	—	—
$m_{\rm sig,max}(\mu_\alpha)$	—	—	—	3	3	—	4	6	3	—	—	—
$p_{\rm sig,max}(\mu_\alpha)$	—	—	—	2	2	—	2	2	2	—	—	—
$N_{\rm sig}(\mu_\delta)$	—	—	—	13	13	—	20	23	14	—	—	—
$n_{\rm sig,max}(\mu_\delta)$	—	—	—	32	32	—	47	24	21	—	—	—
$m_{\rm sig,max}(\mu_\delta)$	—	—	—	2	1	—	3	8	2	—	—	—
$p_{\rm sig,max}(\mu_\delta)$	—	—	—	0	0	—	0	1	0	—	—	—
col.equ.	?	?	?	?	?	–	+	+	–	?	+	+
$\sigma_{\rm res}(\Delta\alpha)$ [mas]	100.04	91.84	92.63	121.57	119.64	91.93	116.71	214.54	281.05	177.39	203.02	205.21
$\sigma_{\rm res}(\Delta\delta)$ [mas]	139.15	118.39	119.05	127.41	125.58	94.99	115.16	196.90	263.25	241.64	229.61	217.32
$\sigma_{\rm res}(\Delta\mu_\alpha)$ [mas/yr]	—	—	—	5.60	5.59	—	5.33	9.57	13.36	—	—	—
$\sigma_{\rm res}(\Delta\mu_\delta)$ [mas/yr]	—	—	—	5.71	5.69	—	5.22	9.67	12.59	—	—	—
$\sigma_{\rm sys}(\Delta\alpha)$ [mas]	47.23	131.92	56.64	57.99	34.27	58.87	40.80	43.69	86.54	70.33	81.53	59.86
$\sigma_{\rm sys}(\Delta\delta)$ [mas]	51.35	88.92	74.63	52.98	58.95	80.35	57.77	41.75	64.59	50.96	59.85	52.62
$\sigma_{\rm sys}(\Delta\mu_\alpha)$ [mas/yr]	—	—	—	2.11	1.87	—	2.52	2.40	3.17	—	—	—
$\sigma_{\rm sys}(\Delta\mu_\delta)$ [mas/yr]	—	—	—	1.27	1.40	—	1.62	2.44	2.40	—	—	—
$< \Delta_\alpha >$ [mas]	+3.20	–27.56	–0.48	–6.33	+0.79	+3.34	–0.43	+5.89	+3.01	–0.14	+8.39	–1.18
$< \Delta_\delta >$ [mas]	+31.09	+71.98	+61.55	+39.88	+45.29	+59.38	+39.19	+16.11	+16.92	+14.87	+18.22	+9.37
$< \Delta_{\mu_\alpha} >$ [mas/yr]	—	—	—	+0.01	+0.21	—	+0.33	+0.14	+0.03	—	—	—
$< \Delta_{\mu_\delta} >$ [mas/yr]	—	—	—	+0.58	+0.42	—	+0.41	0.00	+0.89	—	—	—

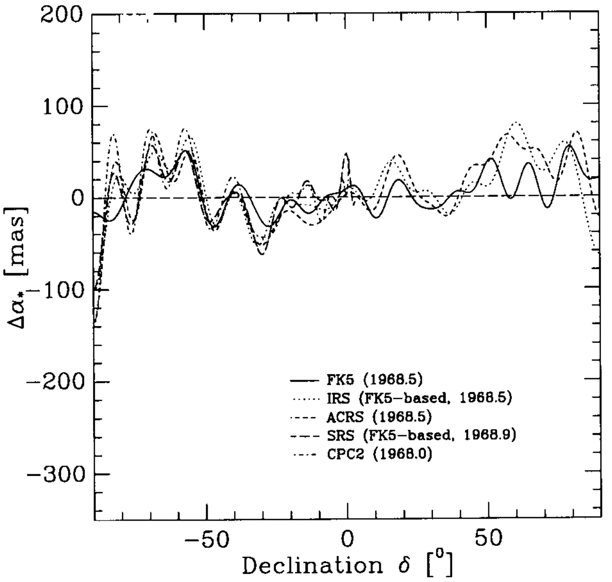

Fig. 1. Systematic differences $\Delta\alpha*$ [mas] as a function of δ between HIPPARCOS and catalogues published in the FK5 system. The epoch for which the various differences hold are given in brackets.

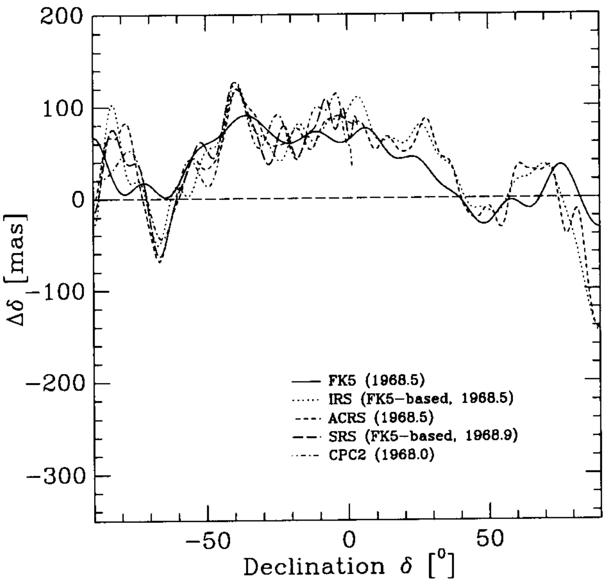

Fig. 2. Systematic differences $\Delta\delta$ [mas] as a function of δ between HIPPARCOS and catalogues published in the FK5 system. The epoch for which the various differences hold are given in brackets.

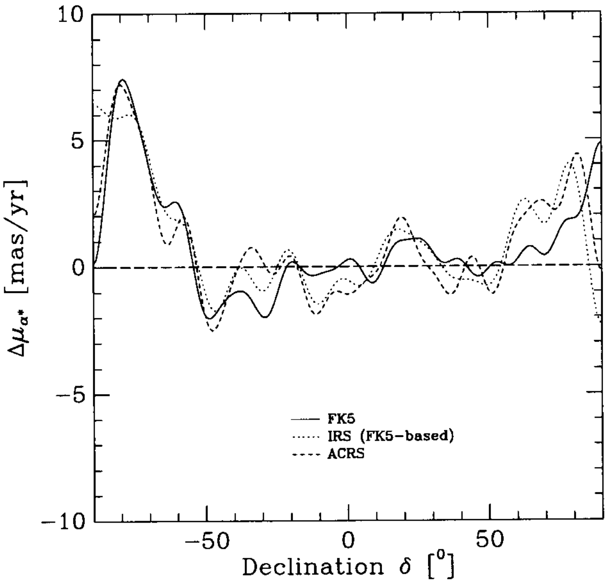

Fig. 3. Systematic proper motion differences $\Delta\mu_{\alpha*}$ [mas/yr] as a function of δ between HIPPARCOS and catalogues published in the FK5 system.

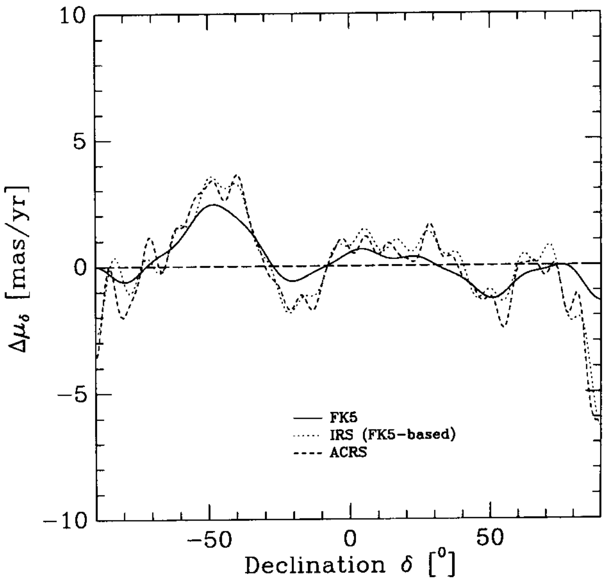

Fig. 4. Systematic proper motion differences $\Delta\mu_{\delta}$ [mas/yr] as a function of δ between HIPPARCOS and catalogues published in the FK5 system.

proper motion effects over the respective epoch differences, typically about 20 years.

The second group includes the catalogues based on the FK4 system, namely the AGK3R, the SRS (FK4-based version), the IRS (FK4-based version), the SAO, the AGK3 and the AGK2 (revised version). In the comparison of the positional systems we have transformed the systems of the FK4, the IRS and the AGK3 to the epoch 1965.0 which is about the mean epoch of the SRS and the AGK3R. Since the AGK2 epoch (1930) and the SAO epoch (1923) are more than 30 years earlier we have omitted those catalogues from the comparison of positions.

The last group comprises the catalogues which have adopted the FK3 system, namely the AGK2 (printed version) and the AGK2A. Their positional systems are compared with the FK3 system which was computed at the epoch 1930.

As might be expected, there are large deviations between the SAO system and the FK4 system, which is the nominal system of the SAO. If we omit the SAO, then we

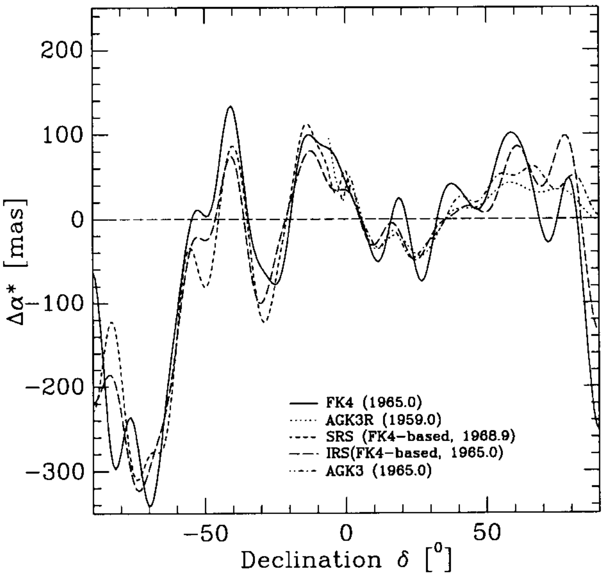

Fig. 5. Systematic differences $\Delta\alpha*$ [mas] as a function of δ between HIPPARCOS and catalogues published in the FK4 system. The epoch for which the various differences hold are given in brackets.

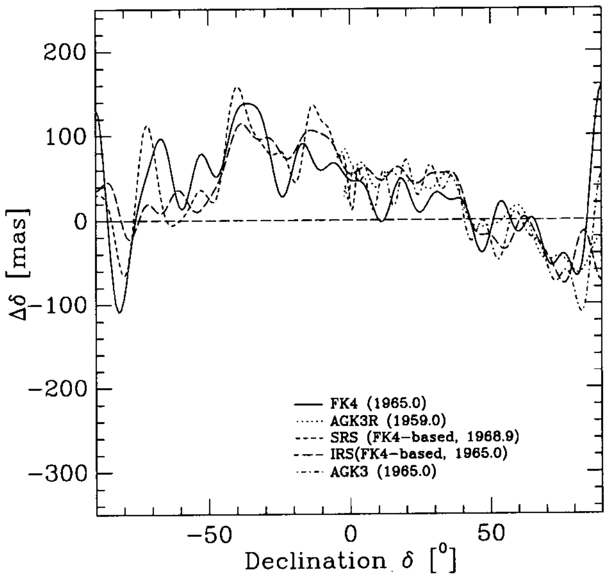

Fig. 6. Systematic differences $\Delta\delta$ [mas] as a function of δ between HIPPARCOS and catalogues published in the FK4 system. The epoch for which the various differences hold are given in brackets.

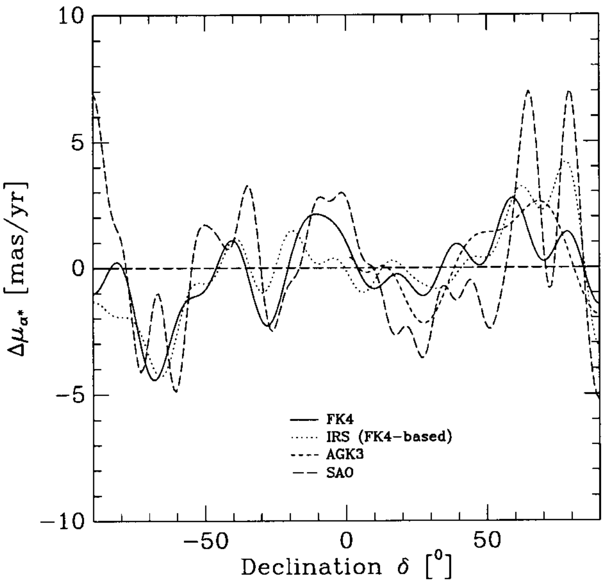

Fig. 7. Systematic proper motion differences $\Delta\mu_{\alpha*}$ [mas/yr] as a function of δ between HIPPARCOS and catalogues published in the FK4 system.

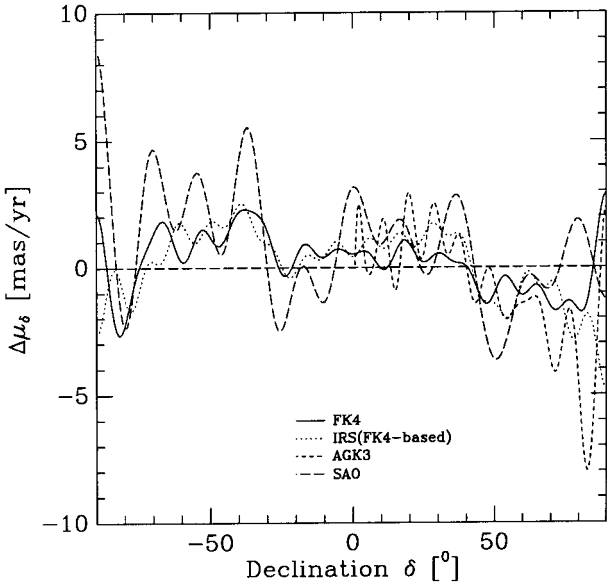

Fig. 8. Systematic proper motion differences $\Delta\mu_\delta$ [mas/yr] as a function of δ between HIPPARCOS and catalogues published in the FK4 system.

find acceptable agreement between the various catalogue systems and the system they should nominally have. A few exceptions occur, however, primarily in the polar regions.

5. Final remarks

The systematic relations between the HIPPARCOS catalogue and the following catalogues of the 20th century not treated in Paper I were derived: the AGK3R and AGK3, the SRS (FK4-based version and FK5-based version), the CPC2, the IRS (FK4-based version and FK5-based version), the ACRS, the AGK2A, the AGK2 (printed version and revised version) and the SAO catalogue. These relations include the transition to the IAU (1976) system, a global rotation of the catalogue onto the HIPPARCOS system and the determination of regional errors depending on the right ascension, declination and the apparent magnitude. In the case of catalogues including photographic observation we have extended our method to include colour equations. The derived relations allow one to transform positions and proper motions given in one of these catalogue systems to the HIPPARCOS system.

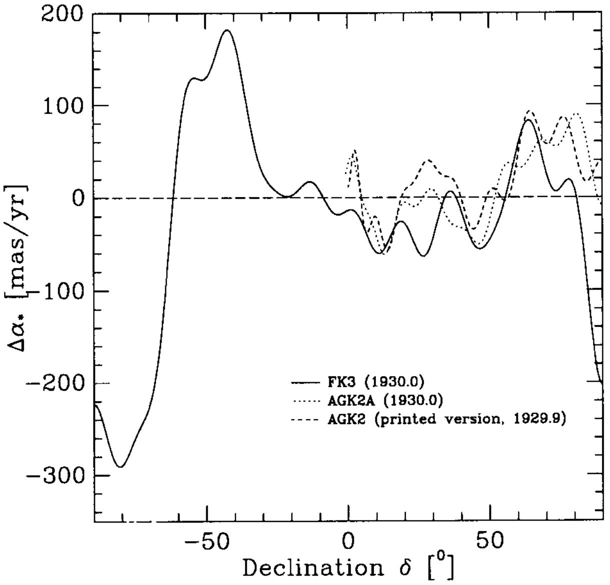

Fig. 9. Systematic differences $\Delta\alpha*$ [mas] as a function of δ between HIPPARCOS and catalogues published in the FK3 system. The epoch for which the various differences hold are given in brackets.

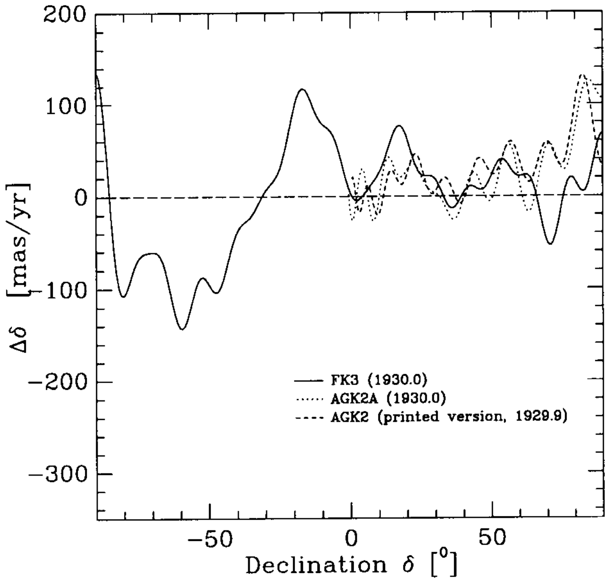

Fig. 10. Systematic differences $\Delta\delta$ [mas] as a function of δ between HIPPARCOS and catalogues published in the FK3 system. The epoch for which the various differences hold are given in brackets.

We provide software (FORTRAN programs and the required input data) via the Internet for performing the described reductions. The computer program made available via the Internet was applied for the transformation of the catalogues to the HIPPARCOS system. An analysis of the differences between these reduced catalogues and the HIPPARCOS catalogue has shown no significant systematic trends.

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