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The Bonn contribution to the extragalactic link of the Hipparcos proper motion system*

H.-J. Tucholke, P. Brosche, and M. Odenkirchen

Sternwarte der Universität Bonn, Auf dem Hügel 71, D–53121 Bonn, Germany

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Abstract. In order to calibrate the proper motions of the Hipparcos astrometry satellite, our group has measured accurate absolute proper motions of Hipparcos stars in small fields around optically bright extragalactic radio sources or bright galaxies with star-like features. In addition, we also use fields where relative proper motions are calibrated by measurements of large numbers of stars and galaxies on wide-field plates. The median internal accuracy of our relative proper motions, based on photographic plates with epoch differences up to 100 years (typically 70 years), is 1.0 milliarcsec/year (mas/a), while the calibration to an inertial system in each of the 13 fields has a median uncertainty of 1.3 mas/a.

We compute the rotation from the Hipparcos proper motions (median internal errors 0.9 mas/a) to the extragalactic reference frame represented by our absolute proper motions, using 88 stars in common. The three components of the angular velocity vector have internal errors of 0.3 mas/a. Our rotation solution has been used together with those of independent groups for the extragalactic calibration of the Hipparcos proper motion system (Kovalevsky et al. 1996). It compares favourably with the adopted mean solution.

Key words: reference systems — astrometry — quasars: general — BL Lac objects: general

1. Introduction

The proper motions of stars observed by the ESA astrometry satellite Hipparcos contain an unknown angular velocity relative to a non-rotating system. In order to provide absolute proper motions for the final Hipparcos catalogue, the proper motion system of Hipparcos had to be calibrated externally by a link to distant extragalactic sources with negligible proper motions. The problem was named, and the present solution was proposed by Brosche (1980).

Lindegren & Kovalevsky (1995) discussed the strategies of various groups for the extragalactic link of the Hipparcos proper motions. They described the method proposed to combine the different link solutions into a unique solution. Kovalevsky et al. (1996) have carried out this merging given the results of the various groups. They present the definitive extragalactic calibration of the Hipparcos proper motions, where the components of the angular velocity vector have estimated internal errors of 0.25 mas/a. The present paper describes the link project of the Sternwarte Bonn, which has earlier been called the "Small Extragalactic Link" (Brosche & Geffert 1988). An intermediate solution based on a smaller set of absolute proper motions and on preliminary Hipparcos data (Brosche et al. 1995a) is superseded by the results given below.

We have measured accurate relative proper motions, based on photographic plates with epoch differences up to 100 years, of stars from the Hipparcos Input Catalogue (Turon et al. 1992) in small (up to $1\overset{\circ}{.}5 \times 1\overset{\circ}{.}5$) fields around optically bright QSO's, BL Lac objects, and bright galaxies with well-defined optical pointlike features. The fictitious proper motions of the extragalactic objects are used to correct the proper motions of the Hipparcos stars to an inertial system. In a different approach we use relative proper motions in fields of our globular cluster program (see e.g. Tucholke et al. 1994 and references therein), where absolute proper motions of stars have been measured on Schmidt plates with respect to a large number of galaxies. In Geffert et al. (1996) the proper motions of Hipparcos stars were calibrated via measurements from plates of the Lick NPM project and additional plates from the same telescope. The data are described in Sect. 2.

The Hipparcos Science Team has provided our group with the data for the subset of Hipparcos stars which are of interest for us. They form part of the intermediary catalogue called H37Cr, which includes the final reductions for the astrometric parameters, but does not contain a number of problematic double/multiple stars, whose

Send offprint requests to: P. Brosche

* Based on observations made with the ESA Hipparcos satellite.

reduction was still pending at that time. We determine the angular velocity vector of the rotation from the H37Cr proper motion system to our extragalactically calibrated system. This procedure, the resulting vector components and a discussion of the residuals are given in Sect. 3. In Sect. 4 we discuss various sources of error. In the concluding Sect. 5 we compare our solution with the mean solution adopted for the calibration of the Hipparcos catalogue (Kovalevsky et al. 1996).

2. Absolute proper motions

Within the H37Cr data we have identified 91 stars in common with our data set. 88 of them were actually used after exclusion of three outliers (see Sect. 3.1). Figure 1a shows the distribution of their internal proper motion errors, while Fig. 1b shows the internal errors of our proper motions (see below). The median error of H37Cr is 0.9 mas/a, which is typical for the average accuracy of the final Hipparcos catalogue. Not all stars from the Hipparcos Input Catalogue for which we measured absolute proper motions have data in H37Cr. The reason is that results for stars which were recognized or suspected as double/multiple should not enter into the link solutions, and were consequently not distributed to the various link groups. See Brosche et al. (1995b) for the incidence of optical doubles among Hipparcos stars and the possible danger of unresolved doubles.

In Table 1 we give an overview over the 13 link fields. Column 1 is the name of the field, bearing the name of the extragalactic object or the star cluster in the field centre, followed by the type of object. Here, QSO stands collectively for pointlike optical counterparts of extragalactic radio sources, such as QSO's, BL Lac objects or N galaxies. Columns 3 and 4 show the mean decimal right ascension and declination of the Hipparcos stars in the field. Column 5 gives the number of Hipparcos stars used for the extragalactic link. Column 6 shows the type of extragalactic calibration in each field. Here "direct" means calibration by the fictitious proper motions of the extragalactic object(s) in the field. "Schmidt" or "Lick" are given for fields where the proper motions have been calibrated by measurements of field stars with respect to galaxies from Schmidt or Lick plates, respectively. Columns 7 and 8 give the estimated errors $\sigma_{\alpha 0}$ and $\sigma_{\delta 0}$ of the extragalactic calibration. The last column gives the references, where the absolute proper motions and their extragalactic calibration have been published.

In the fields of OJ 287, 3C 273, OQ 208, 3C 371, and 3C 390.3, between 60 and 75 selected stars (all BD stars and some faint stars around the radio sources) were measured. In the remaining fields, all stars were measured, so no Hipparcos star was missed. Relative proper motions were derived by an iterative central-overlap algorithm, as described by LeCampion et al. (1992); Tucholke et al. (1994), or Odenkirchen & Brosche (1995). For most

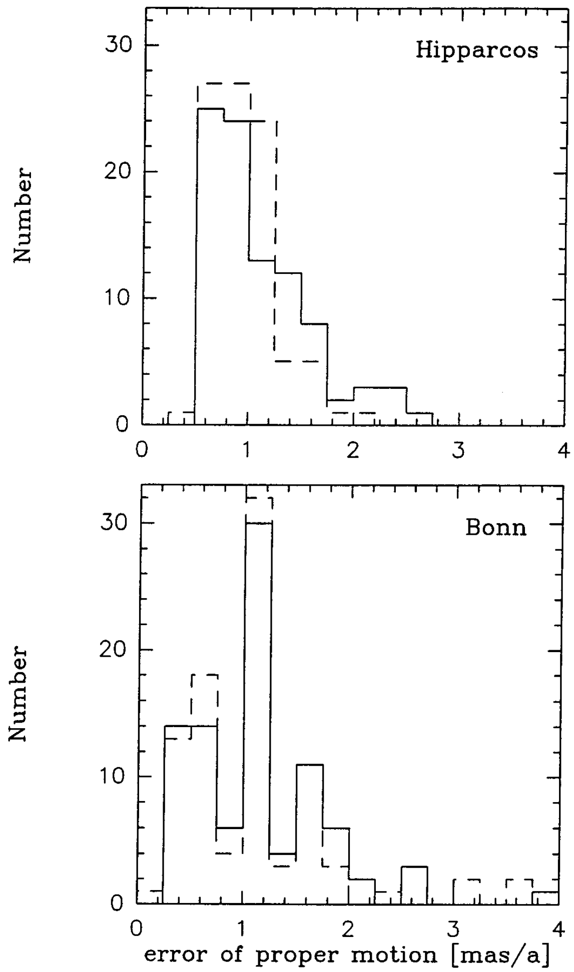

Fig. 1. Internal errors of the proper motions of 88 stars used to determine the rotation of the Hipparcos proper motions to an inertial system. The full lines show the errors in $\mu_\alpha \cos\delta$, the broken lines those in μ_δ. **a)** Hipparcos proper motions. **b)** Absolute proper motions from photographic plates determined in our link project. The errors do not contain the contribution from the extragalactic calibration in each field

fields, our proper motions and their extragalactic calibration have already been published. We now briefly describe the different data sets.

Brosche et al. (1991) measured proper motions in the fields of the extragalactic radio sources 3C 273, OQ 208, 3C 371, and 3C 390.3. These proper motions were derived using the AGK3 as reference catalogue. Meanwhile the PPM catalogue (Röser & Bastian 1991) presents a better realization of the current fundamental system. Therefore the proper motions in the four fields were rederived with respect to the PPM. Improved fictitious proper motions for the four optical counterparts in the PPM system were listed in Geffert et al. (1993). Updated values for the four fields including new photographic plates are published by Geffert et al. (1996). Proper motions of Hipparcos stars

Table 1. The Bonn extragalactic link fields

Field (1)	Object type (2)	$\alpha(2000)$ [hours] (3)	$\delta(2000)$ [degrees] (4)	N (5)	Link type (6)	$\sigma_{\alpha 0}$ [mas/a] (7)	$\sigma_{\delta 0}$ [mas/a] (8)	Reference (9)
OJ 287	(QSO)	8.89755	19.8630	8	direct	1.2	2.0	Dick et al. (1993)
3C 273	(QSO)	12.46987	1.9842	4	direct	1.0	1.8	Geffert et al. (1996)
OQ 208	(QSO)	14.10333	28.9009	6	Lick	1.3	1.3	Geffert et al. (1996)
3C 345	(QSO)	16.70442	39.8119	16	direct	1.6	1.6	Tucholke (1995)
3C 371	(QSO)	18.15806	69.8753	3	direct	1.6	0.9	Geffert et al. (1996)
3C 390.3	(QSO)	18.84304	79.8301	1	direct	1.8	2.0	Geffert et al. (1996)
M 81	(Galaxy)	9.90763	69.5464	13	direct	1.0	1.0	Odenkirchen (1996)
M 51	(Galaxy)	13.52353	47.1907	7	direct	1.0	1.0	Odenkirchen & Brosche (1995)
NGC 4147	(Cluster)	12.16917	18.6686	9	Lick	1.3	1.3	Geffert et al. (1996)
M 3	(Cluster)	13.71122	28.2142	5	Schmidt	0.6	0.8	Tucholke et al. (1994)
M 12	(Cluster)	16.78825	−1.6214	5	Lick	1.3	1.3	Geffert et al. (1996)
M 92	(Cluster)	17.28506	43.0103	7	Schmidt	1.0	1.0	Tucholke et al. (1996)
M 2	(Cluster)	21.56883	−0.9712	4	Lick	1.3	1.3	Geffert et al. (1996)

$\alpha(2000)$ = mean decimal right ascension of the Hipparcos stars [hours]
$\delta(2000)$ = mean decimal declination of the Hipparcos stars [degrees]
N = number of Hipparcos stars used
Link type = Type of extragalactic calibration of the proper motions (see text)
$\sigma_{\alpha 0}$ = error in $\mu_\alpha \cos\delta$ of the extragalactic calibration [mas/a]
$\sigma_{\delta 0}$ = error in μ_δ of the extragalactic calibration [mas/a]
Reference = Reference for the absolute proper motions of the HIC stars as well as for the $\sigma_{\alpha 0}$ and $\sigma_{\delta 0}$.

in the PPM system in the field of the BL Lac object OJ 287 were given by Dick et al. (1993)[1]. Meanwhile additional plates have been taken also for OJ 287. The absolute proper motions used here stem from new reductions including this recent observational material. We mention that the B magnitudes of these sources range from 13 to 15, some of them being (violently) variable.

Odenkirchen & Brosche (1995) present absolute proper motions of stars in the field of the prominent spiral galaxy M 51. The use of bright galaxies like M 51 leads to a higher probability of finding suitable first-epoch plates, but necessitates sophisticated methods for astrometric centering of the galaxies (or parts of them), as discussed in full detail by Odenkirchen & Brosche (1995). The results in the field of the galaxy M 81 were obtained in an analogous way (Odenkirchen 1995, 1996).

Photographic plates from Schmidt telescopes show large numbers of galaxies, so that an accurate zero point for absolute proper motions can be derived even from the relatively small epoch differences (20 to 35 years) available. Tucholke et al. (1994) corrected their relative proper motions in the field of the globular cluster M 3 to absolute ones by comparison with the absolute proper motions from Schmidt plates by Scholz et al. (1993). In an analogous way, Tucholke et al. (1996) tie their relative proper motions in the field of the globular cluster M 92 to absolute proper motions from Schmidt plates by Scholz et al. (1994).

The proper motions in the fields of the globular clusters NGC 4147, M 12 and M 2 were calibrated by field stars, whose absolute proper motions were measured from plates of the Lick NPM project and additional plates from the same telescope (Geffert et al. 1996).

In the field around the QSO 3C 345 we used Tautenburg Schmidt plates with an epoch difference of up to 23 years (Tucholke 1995). The proper motions were calibrated by about 90 carefully inspected galaxies and QSO's. This observational material results in larger individual errors, but allowed to use a higher number of Hipparcos stars due to the large field of the Schmidt telescope.

Figure 1b shows the distribution of the internal errors of the proper motions of Hipparcos stars from our measurements. The median error is 1.0 mas/a in both coordinates. Note that this number does not include the errors of the extragalactic calibration in each field, which are given in Cols. 7 and 8 of Table 1.

[1] In Dick et al. (1993) the μ_δ for HIC 43564 was incorrectly given as −15.4 mas/a. The correct figure is −1.5 mas/a.

3. Rotation of Hipparcos proper motions to the extragalactic system

A small angular velocity vector $\boldsymbol{\omega} = (\omega_1, \omega_2, \omega_3)$ leads to proper motion differences in the sense

$$\begin{aligned} \Delta\mu_\alpha \cos\delta &= -\omega_1 \cos\alpha \sin\delta \; - \; \omega_2 \sin\alpha \sin\delta \; + \; \omega_3 \cos\delta \\ \Delta\mu_\delta &= +\omega_1 \sin\alpha \qquad\qquad - \; \omega_2 \cos\alpha \end{aligned} \qquad (1)$$

(Fricke 1977; Brosche & Sinachopoulos 1987). Since we have proper motion differences $\Delta\mu_\alpha \cos\delta$, $\Delta\mu_\delta$ for each star, we are able to compute the components of $\boldsymbol{\omega}$ by least-squares adjustment. We use both components of the proper motion differences. Note that we could also derive all components from $\Delta\mu_\alpha \cos\delta$ alone, while the $\Delta\mu_\delta$ allow to find ω_1 and ω_2 only.

In order to obtain the components ω_i from a least-squares fit to Eq. (1), we can either use the proper motion differences star by star or compute average proper motion differences $\overline{\Delta\mu_\alpha \cos\delta}, \overline{\Delta\mu_\delta}$ for each field and use them in Eq. (1). It is plausible that the preference for one or the other side depends on whether or not the errors in the proper motions are correlated between neighbouring stars. In the following we discuss both strategies. In addition to the weighting by proper motion errors, discussed in the respective sections, the stars received a weight (using a simplified version of the weighting scheme of Brosche et al. 1991) depending on their positions, so that the weighted mean of their positions coincides with the field centre. This diminishes the consequences of possible systematic proper motion errors varying linearly with position on the plate.

3.1. Exclusion of outliers

Originally the number of H37Cr stars in common with our data set was 91. However, some of these stars had large differences to the rotation solution when compared to their internal errors. We excluded the most deviant stars by the following method. We built all possible pairs of stars and computed rotation solutions without these pairs. The solutions were sorted by increasing standard deviation σ. When the exclusion of a certain star led consistently to the lowest σ's in all combinations with other stars, this star was definitely omitted. This method is repeated with the new set of $N-1$ stars, until no further candidate for exclusion is found. Simulations using the actual coordinates and absolute proper motions, but an artificial rotation and a normal distribution of errors, demonstrated that this method (1) detects stars deviating from the mean solution by more than about 2.7σ, (2) isolates deviant stars clearer than simply looking at the individual $(\mathrm{O}-\mathrm{C})/\sigma_i$'s.

We excluded a total of three stars – one each in the fields of 3C 390.3, M 3, and 3C 345. All except the star in the 3C 390.3 field lie very close to the respective field border, making their astrometry somewhat doubtful. None of these stars has an a-priori probability to be an undetected astrometric binary (see Sect. 4.1) above the average. The results reported in this article are based on the remaining 88 stars.

3.2. Individual differences

We define $\Delta\mu_\alpha \cos\delta$, $\Delta\mu_\delta$ as the proper motion differences in the sense Hipparcos minus extragalactic. Each proper motion difference enters with a weight $w = (\sigma_\mathrm{B}^2 + \sigma_\mathrm{H}^2)^{-1}$ into the solution of Eq. (1), where σ_B and σ_H are the internal errors of the proper motion components from our measurements and H37Cr, respectively.

The solution of Eq. (1) leads to an angular velocity vector, which brings the H37Cr proper motions to our extragalactically calibrated system. Since H37Cr is an intermediary solution which is not generally available, the angular velocity vector $\boldsymbol{\omega}_\mathrm{A}$ given here is the difference between our solution and the mean rotation adopted for the final Hipparcos catalogue by Kovalevsky et al. (1996). The errors are the formal errors of our solution (compare also Sect. 5 and Eq. (6)):

$$\boldsymbol{\omega}_\mathrm{A} = \begin{pmatrix} +0.90 \pm 0.34 \\ -0.32 \pm 0.25 \\ +0.19 \pm 0.33 \end{pmatrix} \quad \mathrm{mas/a}, \qquad (2)$$

with a standard deviation $\sigma = 2.7$ mas/a of a single proper motion component of one star.

When we correct the H37Cr proper motions to our extragalactic system, the mean of the residual differences (O–C) to our values is zero. We define the individual normalized residuals for star i as $a_i = (\mathrm{O}-\mathrm{C})_i / \sqrt{\sigma_{\mathrm{B}i}^2 + \sigma_{\mathrm{H}i}^2}$. The χ^2 of the solution is then simply $\sum_i a_i^2$. In this case we find $\chi^2 = 244.7$ for $2 \cdot 88 - 3 = 173$ degrees of freedom, combining both proper motion components. The probability p that this χ^2 or a larger one arises by chance is smaller than $3\ 10^{-4}$, so that it is certain that either a simple rotation is not a sufficient model or the errors are underestimates.

As a numerical exercise, we test how much we would have to increase the H37Cr errors in order to achieve reasonable values of χ^2. When we replace all σ_H by $b\sigma_\mathrm{H}$ with $b = 1.42$, we have $\chi^2 = 175.3$ with a probability of 0.44. For $b = 1.29$ we arrive at $\chi^2 = 200.7$, which leads to an already acceptable $p = 0.073$. Similarly, when keeping constant the internal H37Cr errors, we would have to multiply all internal errors of our proper motions by 1.37 in order to achieve a χ^2 similar to the degrees of freedom.

The symmetric correlation matrix of the angular velocity components is

$$C = \begin{pmatrix} 1.00 & +0.11 & -0.48 \\ & 1.00 & -0.23 \\ & & 1.00 \end{pmatrix}. \qquad (3)$$

The element C_{ij} results from the covariance matrix A by $C_{ij} = A_{ij} / \sqrt{A_{ii} A_{jj}}$. These significant correlations result from the uneven distribution of the link fields over the sphere. Simulations have shown, however, that the rotation components are recovered within their internal errors in spite of the correlations.

3.3. Mean differences per field

We compute weighted average proper motion differences $\overline{\Delta\mu_\alpha \cos\delta} \pm \sigma_\alpha$ and $\overline{\Delta\mu_\delta} \pm \sigma_\delta$ for each field, using the internal proper motion errors for the weights. The field of 3C 390.3, were only one star could be used, was excluded, so that we are left with 12 fields for this solution. With these mean differences we solve Eq. (1), using the mean coordinates α and δ from Table 1 and weights $w = (\sigma_\alpha^2 + \sigma_\delta^2)^{-1}$.

The difference between the resulting rotation and the adopted rotation for the final Hipparcos catalogue (Kovalevsky et al. 1996) is

$$\boldsymbol{\omega}_\mathrm{B} = \begin{pmatrix} +1.04 \pm 0.77 \\ -0.09 \pm 0.57 \\ 0.00 \pm 0.72 \end{pmatrix} \quad \mathrm{mas/a} \qquad (4)$$

with a standard deviation $\sigma = 2.2$ mas/a of a single mean proper motion component of one field. The difference between the two versions of $\boldsymbol{\omega}$ is comfortably within the combined errors:

$$\boldsymbol{\omega}_\mathrm{A} - \boldsymbol{\omega}_\mathrm{B} = \begin{pmatrix} -0.14 \pm 0.84 \\ -0.23 \pm 0.62 \\ +0.19 \pm 0.79 \end{pmatrix} \quad \mathrm{mas/a}. \qquad (5)$$

3.4. Search for systematics in the residuals

In Fig. 2 we display the magnitude dependence of the residuals from the rotation solution using individual data (Eq. 2). We chose the B magnitude, since most of the photographic plates were taken with a blue-sensitive emulsion. The Hipparcos Input Catalogue (Turon et al. 1992) served as source for the magnitudes. Bold symbols show the mean residuals for 13 stars each. While the naked eye cannot discern any dependence on B for single or mean residuals, weighted least-squares fits of straight lines result in moderately significant slopes of 0.17 ± 0.07 mas/a/mag in $\mu_\alpha \cos\delta$ and 0.11 ± 0.06 mas/a/mag in μ_δ. From the appearence of Fig. 2 it is far from clear whether a straight line or some other functional dependence should be applicable in this case. Accordingly, we did not apply any correction for a systematic change of the proper motions with magnitude.

We also tested for systematic dependences of the residuals in $\mu_\alpha \cos\delta$ and μ_δ on colour, right ascension, declination, or distance from the field centre. We did not detect any systematic behaviour in the respective plots. As an example, we plot in Fig. 3 the residuals as small arrows versus the projected distances from the respective field centres. No systematic pattern appears. This still holds if one plots the fields individually.

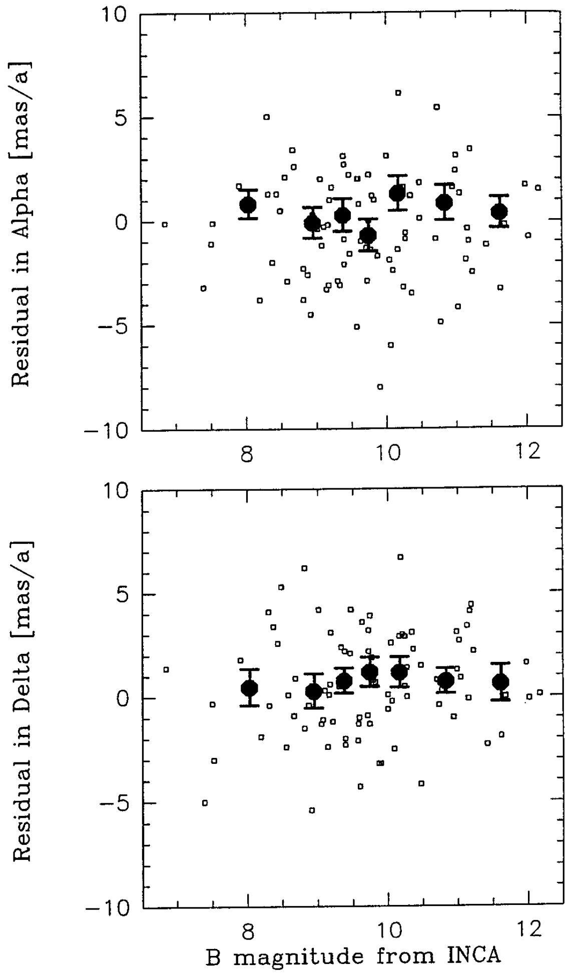

Fig. 2. The residuals in proper motion in α (upper panel) and δ (lower panel) after the rotation solution from individual stars are plotted as small symbols versus B magnitude from the Hipparcos Input Catalogue (INCA). Bold symbols are the mean residuals for 13 stars each, where the error bars are mean errors of the mean

Since the residuals are independent of position in the field, there is no need to create an average proper motion difference Hipparcos minus extragalactic for each field, in order to suppress such errors. This is the main reason for our choice of the rotation solution using individual stars (Eq. 2) instead of that from field means (Eq. 4) as our final result.

4. Discussion

4.1. Errors

The large standard deviations from the rotation solution (Eq. 2) and the larger than expected χ^2 values leave the possibilities that either the internal proper motion errors are underestimates or that a rigid rotation between the proper motion systems is not a sufficient model.

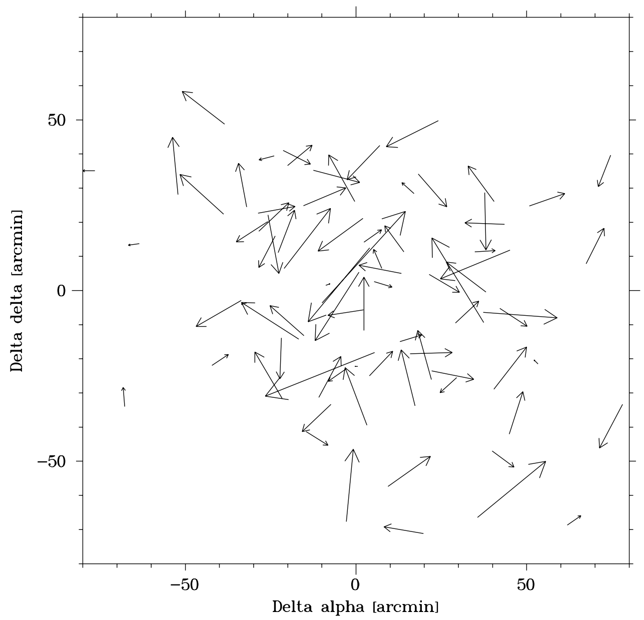

Fig. 3. Residuals from the rotation solution using individual stars, plotted at the locations of the stars relative to the field centre, combined for all 13 fields. Coordinates are given in arc minutes relative to the field centre. No systematic trends of the residuals with position in the fields can be discerned

Additionally, the proper motion measurement of some stars may be corrupted by the presence of unrecognized optical companions. We now look at these possible causes in turn.

In Sect. 3 we found that we can bring the χ^2 into agreement with the number of degrees of freedom if we multiply either the H37Cr errors or our errors by factors between 1.2 and 1.4. Comparing the standard deviation of the rotation solution Eq. (2) (2.7 mas/a) to the quadratically added median internal errors (Bonn proper motions 1.0 mas/a, Hipparcos proper motions 0.9 mas/a, zero point in each field 1.3 mas/a), we find an enhancement factor of 1.44. For comparison, Hering et al. (1994) determined the rotation from the proper motion system of a preliminary Hipparcos catalogue to an inertial one using VLA radio astrometry of 22 radio stars. They found a-posteriori errors of the rotation angles which are a factor 1.8 larger than the a-priori errors expected from the internal errors of the proper motions.

The model (1) is strictly applicable only if both proper motion systems are regarded as rigid spheres. However, there is the possibility of systematic field-to-field differences, in analogy to the well-known zonal errors in classical astrometry.

Each of our fields has its own systematic zero-point error. In the cases of the extragalactic objects the zero point is defined by a single proper motion (or a handful of proper motions in the fields of M 51 and M 81), and fully depends on the error of this proper motion. In the fields with calibration via Schmidt plate astrometry the zero point is defined by a large number of galaxies, so systematic errors from individual galaxies should be averaged out to a certain extent. Internal errors of the field zero points range from 0.6 to 2.0 mas/a (Table 1). One should keep in mind, however, that these values could be underestimates, especially for fields calibrated by a single extragalactic source.

Brosche et al. (1995b)[2] discuss the influence of double stars on the proper motion measurements in a photographic extragalactic link of Hipparcos. They add companions with a given distribution of separation and magnitude difference to a subset of the link stars and separate the resulting systems into different classes according to their influence on proper motion measurements. 16% of the systems turned out to be of a dangerous class: they are not recognizable as double either by Hipparcos or from the ground, but their period is in a range where ground-based proper motion measurements (with epoch differences of $70-90$ years) average over more than one half of an orbit, while the orbital motion is seen by Hipparcos (epoch difference 3.5 years) as part of the proper motion. The mean orbital motion of these stars is 9.2 ± 9.0 mas/a. Some of these stars may be present among our link stars, populating the high end of the a_i-distribution and contributing to the larger than expected standard deviations from the rotation solutions.

One of the stars used by us in the field of M 81 shows a highly significant deviation between the photographically measured proper motion and the proper motion determined by Hipparcos ($|\Delta\mu|$ = 8 mas/a; Odenkirchen 1996). According to Bernstein (1996, private communication) this star has an unexpectedly large χ^2 in the Hipparcos reduction without yielding a double star solution. This could be an example for the dangerous cases discussed above. A rotation solution without this star differs from our adopted solution at a 0.03 mas/a level.

Wielen (1995), in comparing preliminary Hipparcos data with the FK5, agrees that undetected astrometric binaries are a major disturbing effect in the comparison of astrometric catalogues.

We conclude that the order of magnitude of the accuracies found here can be explained by known sources of error.

4.2. Source structure

We mention the effects of (variable) structure of the optical counterparts of compact extragalactic radio sources on their positional accuracy, although they are probably too small to influence the present comparison.

[2] The 33 stars available to us at that time were used. A new computation with the final sample of Hipparcos stars leads to almost identical results for the fraction of problematic cases and the mean expected proper motions.

Deep imaging reveals the underlying galaxy of some quasars and sometimes even optical jets (see e.g. Benítez et al. 1996 for OJ 287). This component is very faint compared to the dominant core and probably of no relevance for our photographic plates, which have limiting magnitudes $\leq 17^{\rm m}$. In addition, effects due to colour differences between core and host galaxy are minimized, since we used only plates taken in a blue spectral range for quasar astrometry. Schramm (1988) and Galas (1990) investigated the effect of quasar host galaxies on the position of the quasars and found it to be too small to influence the accuracy of an extragalactic link using these sources.

Takahashi & Kurihara (1993) found systematic changes of the radio positions of five extragalactic radio sources measured in the CDP VLBI project. These are caused by systematic changes in the source structure due to phenomena like outward motion of knots in jets. Over epoch differences of ≤ 5 years these changes are seen as apparent proper motions of up to 0.26 mas/a. Since the changes in source structure persist over time scales of less than 10 years, our proper motions based on epoch differences of typically 70 years are hardly affected by this phenomenon.

The radio observations are not of direct relevance to the present comparison, since we measure the positions of the optical counterparts of the extragalactic objects. However, the effect of variable source structure on the position of quasars should be larger in the radio than in the optical spectral range, since the jet emissions have radio-optical spectral indices of $\alpha = -0.5... -0.8$ ($S(\nu) \propto \nu^\alpha$) (Begelman et al. 1984), while the compact cores, generally used in radio-optical link work, have flatter spectral indices ($\alpha > -0.4$) (Bridle & Perley 1984). Therefore, the contribution of the jet to the total emission is larger in the radio than in the optical domain, making the optical positions less prone to effects of source structure. The apparent proper motions found by Takahashi & Kurihara (1993) are thus upper limits to the effects expected in optical astrometry.

5. Comparison with the adopted Hipparcos calibration

The angular velocity solution from individual stars (Eq. 2) was made available to the Link Subgroup of the Hipparcos Science Team as our best estimate of the extragalactic calibration of the Hipparcos proper motion system.

Kovalevsky et al. (1996), according to the precepts of Lindegren & Kovalevsky (1995), have combined the corresponding solutions from the different link groups into one unique solution, which has been applied in the production of the final Hipparcos catalogue. The standard deviations of the components of the time-dependent rotation are 0.25 mas/a. They result from a compromise between formal errors and the root mean square of adjusted, weighted errors of the various link groups.

The difference of the adopted calibration for Hipparcos and our preferred solution is

$$\boldsymbol{\omega}_{\rm A} = \begin{pmatrix} +0.90 \pm 0.42 \\ -0.32 \pm 0.35 \\ +0.19 \pm 0.41 \end{pmatrix} \quad {\rm mas/a}, \qquad (6)$$

where the errors result from the combination of our internal errors and the 0.25 mas/a-error for the mean solution. The 2σ-difference in ω_1 may result from the uneven distribution of our link fields on the sphere. One should note that the probability for the true value to lie inside a 1σ-interval in a one-dimensional case belongs to a $\sqrt{3}\sigma_i$-ellipsoid in case of the three-dimensional $\boldsymbol{\omega}$-vector. The difference vector of Eq. (6) has the length 0.97 mas/a. If we approximate all its three errors by one and the same value 0.40 mas/a, the $\sqrt{3}$-fold is 0.68 mas/a, and the ratio $0.97/0.68 = 1.43$ tells us that the occurrence of the difference vector corresponds to a 1.4σ error in a one-dimensional case (probability of surpassing is still 15%). Regarding this, our solution compares favourably with the mean solution.

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