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Preliminary link of the Hipparcos and VLBI reference frames

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Abstract. We present a comparison of VLBI and Hipparcos astrometric parameters of several optically bright radio-emitting stars. The systematic discrepancies found in these preliminary data can be removed by performing a single global rotation between the extragalactic and Hipparcos reference frames. Two estimates of this rotation and its time derivative have been made by using seven and six link stars from the two Hipparcos reduction consortia FAST and NDAC, respectively. The three angles and annual rates of rotation between the two frames are determined at better than the milli-arcsec level. The angles of rotation found are relative to a VLBI extragalactic reference frame that is defined by the IERS VLBI coordinates of the extragalactic reference sources used for the differential VLBI measurement of the link stars. The post-fit residuals of the star coordinates and proper motion components after the adjustment of the global rotation indicate that the consistency between the Hipparcos and VLBI astrometric techniques is at the milli-arcsec level. This is the first cross-check between these two astrometric techniques of comparable precision. The level of agreement found is consistent with the expected accuracy of the technique, even though the astrometric parameters used are from preliminary reductions of the data for both techniques. The Hipparcos reference frame has been aligned with a *quasi-FK5* frame in the process of its construction. The magnitudes of the rotation angles found are consistent with the degree of alignment known between the VLBI and FK5 frames. This VLBI link of the Hipparcos catalog is preliminary and we describe various improvements that will be implemented before the release of the Hipparcos catalog in 1996. Comparison of the VLBI and Hipparcos trigonometric parallaxes are also discussed.

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1. Introduction

The VLBI (Very Long Baseline Interferometry) extragalactic frame is the primary celestial reference frame due to its accuracy and stability over time. For example, the internal precision of the Jet Propulsion Laboratory frame is 0.2 and 0.3 milli-arcsec for the coordinate differences $\sigma_\alpha \times \cos\delta$ and σ_δ and the agreement between this frame and the independant Goddard Space Flight Center frame is 0.4 and 0.6 milli-arcsec for the same coordinate differences (Jacobs 1994). This precision is better than the expected internal consistency of the Hipparcos optical reference frame, currently in a provisional form represented by the 30 months solutions of the Hipparcos reduction consortia FAST and NDAC. The new Hipparcos frame represents a 50−fold improvement in precision over previous optical frames (e.g. FK5). The link between the two reference frames (VLBI and Hipparcos) is important to unify the optical and radio coordinate systems for registration of images at both wavelengths, to combine radio and optical data in astrometric and geodetic studies, and to stop any residual global rotation of the Hipparcos frame for dynamical studies. Note that the Hubble Space Telescope and radio interferometers such as the Very Large Array and the Australian Telescope produce optical and radio images of comparable angular resolution (50 milli-arcsec) that could be registered at the milli-arcsec level with the Hipparcos/VLBI link. Since 1982, we have been conducting a high-accuracy VLBI astrometric program of 11 optically bright radio-emitting stars which are objects common to both frames (VLBI and Hipparcos) and which can be used to link them at the milli-arcsec level. Other techniques will also be used to achieve this link as described by Lindegren (1995).

The link between the extragalactic (VLBI) and Hipparcos frames has been studied theoretically by Froeschlé and Kovalevsky (1982) and Lindegren and Kovalevsky (1995). I t can be written in matrix form as:

$$\sigma_{vlbi} = [R(t_0)]\sigma_{hip} \quad (1)$$

$$\dot{\sigma}_{vlbi} = [R(t_0)]\dot{\sigma}_{hip} + [\dot{R}]\sigma_{hip} \quad (2)$$

where $\sigma_{vlbi}, \sigma_{hip}, \dot{\sigma}_{vlbi}$ and $\dot{\sigma}_{hip}$ are the direction unit-vector and proper motion vectors of the link stars measured by both techniques (VLBI and Hipparcos) and referred to the same epoch t_0. The direction unit-vector σ is $(\sin\alpha\cos\delta, \cos\alpha\cos\delta, \sin\delta)$ and the proper motion vector $\dot{\sigma}$ is the time derivative of σ with the 2 conventional components of the proper motion $\mu_\alpha = \dot{\alpha}$ and $\mu_\delta = \dot{\delta}$. The matrices $[R(t_0)]$ and $[\dot{R}]$ represent the fixed global rotation and residual angular velocity of the Hipparcos frame relative to the VLBI frame, respectively. In principle, the directions and proper motions of 2 link stars are sufficient to determine the 3 angles and 3 rates of rotation of these two matrices. However, our VLBI program has made several (4-12) observations of each of 11 link stars to provide redundancy. These stars, displayed on the celestial sphere in Figure 1, are the most active of the radio-emitting stars initially selected to achieve high-accuracy VLBI astrometry by Lestrade *et al* (1982) subsequently to the first list of radio stars drawn up for astrometry by Walter (1977). These link stars are mostly chromospherically active close binaries (RS CVn) and 2 are optically bright X-ray close binaries. Similar radio-emitting stars in the southern hemisphere would be useful for the link but they are not visible with the VLBI antennas we used in the northern hemisphere. A VLBI astrometric program on 3 deep southern stars is being conducted by a group from CSIRO in Australia and USNO.

2. VLBI astrometric parameters of the link stars

We used the phase-referencing VLBI technique to achieve both high sensitivity with multi-hour integrations and high accuracy through measurement of the differential interferometric phase between the target star and an angularly nearby extragalactic source as a function of time. The details of this technique is described in Lestrade *et al* (1990). Practically, after differencing the target star and reference source observed phases, the VLBI visibilities of the target star are Fourier-inverted to produce a map of a patch of the sky from which the relative coordinates of the radio star can be directly measured. In this process, the optical positions and uncertainties of the radio-emitting stars provided by the Automatic Meridian Circle of Bordeaux Observatory in the FK5 frame (Réquième and Mazurier 1991) have been the most reliable source of *a priori* parameters to restrict the sky area to map for the initial search of the stellar radio source.

A total of 77 MarkIII VLBI observations (as of March 1994) have been conducted since October 1984. One to three stars were observed at each of these 77 epochs. Each observed pair, star and associated reference source, runs for about 8 hours with 4 to 7 radiotelescopes located in the continental US (Goldstone 70-m of the Deep Space Network, VLBA antennas, Haystack, Green Bank 140-foot, OVRO 130-foot, Phased-VLA, Hat Creek) and in Europe (Bonn, Medicina, Noto). The observation frequency was either 5 GHz or 8.4 GHz. All the recorded data were cross-correlated on the MarkIII Processor at Haystack Observatory. The distribution of the VLBI observations over the years is shown in Figure 2 and peaks during the Hipparcos mission (1990 January – 1993 March) to minimise the possible effect of non-linearity of the proper motions of link stars. This effect could be significant if some of the link stars were relatively short period double stars unknown as such during the planning phase. At this stage, 7 VLBI stars have been fully analysed and will be used for the preliminary link between the Hipparcos and VLBI reference frames described below but a total of 11 stars should be available for the final link in 1995.

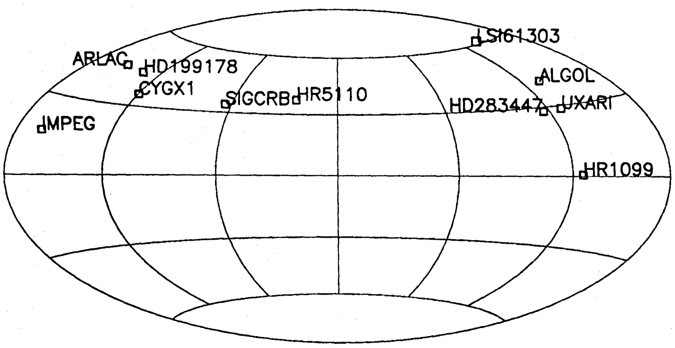

Fig. 1. Sky distribution of the VLBI link stars for Hipparcos

The result of each VLBI observation is the differential coordinates of the target star relative to the IERS coordinates of its associated reference extragalactic source at the date of observation. The angular separations between the VLBI link stars and their reference sources are between 0.5° and 5.0°. The astrometric precision of the differential measurement depends on this separation, on the signal-to-noise ratio (since these stars are weak variable radio emitters), on the u-v coverage in the image plane of the interferometer, and on weather and ionospheric fluctuations during the observations that current models cannot predict. For most of the VLBI observations, the theoretical uncertainty based on SNR and angular resolution of the interferometer alone is smaller than 0.1 milli-arcsec. But some sources of systematic errors are larger, e.g. ionosphere (at 5 GHz), troposphere, possible variation of the location of the radio emission in the close binaries and structure of the stellar and reference radio sources. A more realistic error estimate leads to a typical measurement uncertainty for an individual differential position of a link star of 0.1 to 0.5 milliarsecond (Lestrade *et al* 1990).

For each star, the differential coordinates measured at multiple epochs (the number of observations for each star is in Table 1a) were used in a weighted least-squares-fit to determine its position α, δ relative to the associated reference extragalactic source at the mid-epoch of the observing span, its

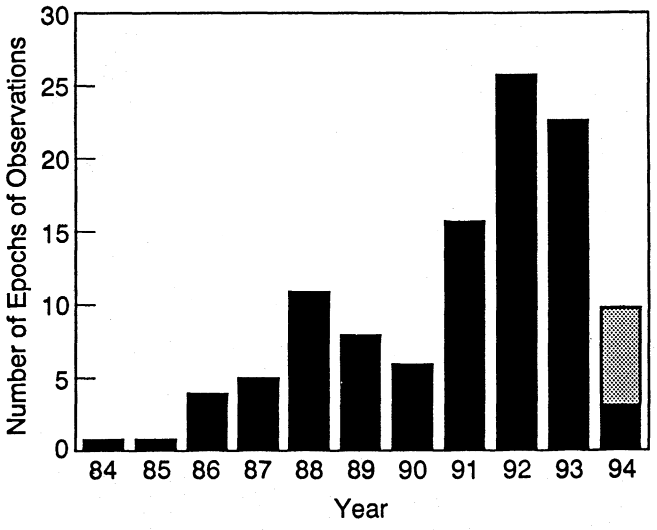

Fig. 2. Distribution of the VLBI observations over the years. For 1994, black indicates observations conducted and grey planned.

Table 1a. VLBI observations of the 7 link stars.

Star	HIP number	Number of observations	Period of observations	Separation Star-Reference
UX ARI	16042	8	88/03 - 92/03	1.1°
HR1099	16846	6	91/03 - 93/02	2.4°
HR5110	66257	8	87/05 - 92/06	4.5°
σ^2 CrB	79607	12	87/05 - 93/11	0.4°
Cyg X1	98298	9	88/03 - 93/11	1.6°
AR Lac	109303	6	89/04 - 93/09	3.7°
IM Peg	112997	4	91/12 - 93/09	0.7°

Table 1b. Formal uncertainties of the absolute positions, proper motions and trigonometric parallaxes of the 7 link stars determined by VLBI.

Star	Position Uncert. (mas)	Proper Motion Uncert. (mas/yr)	Trig. Parallax Uncert. (mas)
UX ARI	0.55	0.20	0.30
HR1099	$\sigma_\alpha = 0.30$	$\sigma_{\mu\alpha} = 0.24$	0.35
	$\sigma_\delta = 1.21$	$\sigma_{\mu\delta} = 1.20$	
HR5110	0.90	0.25	0.70
σ^2 CrB	0.20	0.04	0.08
Cyg X1	1.50	0.20	0.40
AR Lac	0.60	0.20	0.40
IM Peg	0.60	0.60	0.60

proper motion μ_α, μ_δ relative to the extragalactic background and its trigonometric parallax π. The individual differential coordinates measured and the resulting VLBI positions and proper motions will be published in detail elsewhere. However, it is relevant here to provide in Table 1b the formal uncertainties of the resulting VLBI astrometric parameters for the 7 stars which have been analysed to date. In the fitting procedure used, the *a priori* individual measurement uncertainties were slightly adjusted to achieve a value of unity for the normalized goodness of the fit ($\chi^2_{NORM} = \sum_{i=1}^{N}(\frac{r_i}{\sigma_i})^2/NdF$, where r_i are the post-fit residuals, σ_i are the *a priori* measurement uncertainties and NdF the number of degree of freedom). For each star, both VLBI coordinates and both VLBI annual proper motion components have sub-milliarcsecond formal uncertainties, except for HR1099 which is within 1° of the equator limiting the accuracy of its VLBI declination determination and Cyg X1 for which the absolute position of its reference source has only recently been determined and should improve with further observations for the final link. The most precise VLBI measurement has been achieved for σ^2 CrB with the formal uncertainties of 80 micro-arcsec in α, δ relative to the extragalactic reference source 1611+343; 40 micro-arcsec/year in μ_α, μ_δ and 80 micro-arcsec in π. The star σ^2 CrB has the smallest angular separation with its reference source (0.4°) and has been observed the most (12 epochs of observation). Note that the formal uncertainty of the absolute position of σ^2 CrB 0.2 milli-arcsec in Table 1b is larger than the relative uncertainty just quoted for the relative position of this star. This is because the uncertainty of the absolute position of the reference source 1611+343 is larger than the relative position uncertainty of the star.

Table 2. Formal uncertainties of the Hipparcos astrometric parameters for the link stars from the 30-month solutions of the two Hipparcos data reduction consortia FAST and NDAC.

Star	Position Uncert. FAST/NDAC (mas)	Proper Motion Uncert. FAST/NDAC (mas/yr)	Trig. Parallax Uncert. FAST/NDAC (mas)
UX ARI	0.87/1.60	1.37/2.00	1.01/1.70
HR1099	1.03/1.20	1.94/1.80	1.25/1.50
HR5110	0.63/0.70	0.76/0.80	0.96/1.10
σ^2 CrB	0.94/–	1.23/–	1.07/–
Cyg X1	0.92/1.10	1.37/1.60	1.19/1.30
AR Lac	0.59/0.70	0.98/1.10	0.78/1.00
IM Peg	0.93/1.1	1.10/1.40	1.26/1.40

3. Hipparcos astrometric parameters of the link stars

The two Hipparcos reduction consortia have determined the astrometric parameters of the link stars in solutions using the first 30-months Hipparcos data as described in (Kovalevsky *et al* 1995) and (Lindegren *et al* 1995). The FAST parameters are from the FAST 30-month solution for double stars. The NDAC parameters are from the NDAC 30-month solution for double stars for UX Ari and HR1099 and from the NDAC 30-month solution for single stars for the other link stars. Table 2 below lists the formal uncertainties of the astrometric parameters.

4. Comparison of positions and proper motions: global rotation between Hipparcos and a VLBI reference frame

The analytic expansion of equations (1) and (2) have been carried out and the 4 independent equations for each link star derived. To first order with respect to the small rotation angles A_1, A_2, A_3 in radians and small rates $\dot{A}_1, \dot{A}_2, \dot{A}_3$ in radians/yr, they are :

$$\Delta\alpha = A_1 \cos\alpha \tan\delta + A_2 \sin\alpha \tan\delta - A_3 \quad (3)$$

$$\Delta\delta = -A_1 \sin\alpha + A_2 \cos\alpha \quad (4)$$

$$\Delta\mu_\alpha = \dot{A}_1 \cos\alpha \tan\delta + \dot{A}_2 \sin\alpha \tan\delta - \dot{A}_3 \quad (5)$$

$$\Delta\mu_\delta = -\dot{A}_1 \sin\alpha + \dot{A}_2 \cos\alpha \quad (6)$$

where $\Delta\alpha = \alpha_{vlbi} - \alpha_{hip}$, $\Delta\delta = \delta_{vlbi} - \delta_{hip}$, $\Delta\mu_\alpha = \mu_{\alpha,\, vlbi} - \mu_{\alpha,\, hip}$ and $\Delta\mu_\delta = \mu_{\delta,\, vlbi} - \mu_{\delta,\, hip}$. A_1, A_2, A_3 are the 3 right-handed rotation angles around the x-axis ($\alpha = 0^h$ $\delta = 0°$), y-axis ($\alpha = 6^h$ $\delta = 0°$), z-axis ($\delta = 90°$ direction) to bring the Hipparcos frame into coincidence with the VLBI reference frame and $\dot{A}_1, \dot{A}_2, \dot{A}_3$ are the 3 associated rates of rotation. With these definitions, the matrices of eqs (1) and (2) to transform the Hipparcos frame into the VLBI reference frame are :

$$[R(t_0)] = \begin{pmatrix} 1 & A_3 & -A_2 \\ -A_3 & 1 & A_1 \\ A_2 & -A_1 & 1 \end{pmatrix}$$

$$[\dot{R}] = \begin{pmatrix} 0 & \dot{A}_3 & -\dot{A}_2 \\ -\dot{A}_3 & 0 & \dot{A}_1 \\ \dot{A}_2 & -\dot{A}_1 & 0 \end{pmatrix}$$

The VLBI and Hipparcos positions are heliocentric and the 4 independent equations above (eqs 3-6) can be used directly with no parallax correction at epoch t_0. At present, the astrometric parameters are available for 7 link stars common to both the VLBI and FAST and for 6 link stars common to both the VLBI and NDAC. These astrometric parameters and eqs (3-6) have been used to determine the 3 angles of rotation A_1, A_2, A_3 and the 3 rates $\dot{A}_1, \dot{A}_2, \dot{A}_3$ of the two matrices $[R(t_0)]$ and $[\dot{R}]$ for FAST and NDAC by a weighted least-squares-fit. The fitted parameters, the correlation matrix and the post-fit residuals are in Tables 3 and 4 for FAST and NDAC, respectively. The goodness of fit (defined earlier) normalized with the number of degrees of freedom is close to unity for these two solutions. This was achieved by tweaking a few of the *a priori* measurement uncertainties, quadratic combination of the uncertainties of the two techniques, used as weights in the least-squares-fit. Table 5 shows the multiplicative factors of the modified uncertainties. No adjustment was necessary for the *a priori* measurement uncertainties of the proper motions. The formal uncertainties of A_1, A_2, A_3 and $\dot{A}_1, \dot{A}_2, \dot{A}_3$ are about 0.5 milli-arcsec and 0.5 milli-arcsec per year for FAST (Tables 3) and for NDAC (Table 4).

The robustness of the solution has been tested by splitting the 7 FAST link stars into two independant subsets, one with 3 stars (HR1099, HR5110, AR Lac) and one with 4 stars (UX Ari, σ^2 CrB, CygX1, IM Peg). Rotation angles and rates have been solved for with these 2 subsets and compared. The differences are no more than the quadratically combined uncertainties of the 2 solutions (see Table 6).

Table 3. VLBI-FAST solution: the 3 angles (A_1 =A1, A_2 =A2, A_3 =A3) and the 3 rates of rotation (PA1= $\dot{A}_1$, PA2=$\dot{A}_2$, PA3=$\dot{A}_3$) between the Hipparcos and VLBI reference frames have been determined with 7 link stars. The Hipparcos astrometric parameters of these stars are from the *30 month solution for double stars* of the reduction consortium FAST. The correlation matrix and post-fit residuals are given. *A priori* measurement uncertainties (mas) used as weights for the least-squares-fit are in parenthesis next to the corresponding post-fit residuals (mas). The angles of rotation are determined relative to the VLBI extragalactic frame defined by the IERS VLBI coordinates of the reference sources of Table 7.

Weighted least-square-fit solution :

Rotation angles at epoch 1991 4 1 :

A1 = -26.87 +/- 0.46 mas
A2 = -12.64 +/- 0.55 mas
A3 = 22.99 +/- 0.46 mas

Rotation rates :

PA1 = 0.60 +/- 0.48 mas/yr
PA2 = 0.06 +/- 0.46 mas/yr
PA3 = 1.35 +/- 0.43 mas/yr

Correlation matrix :

	A1	A2	A3	PA1	PA2	PA3
A1	1.00	0.19	0.22	0.00	0.00	0.00
A2	0.19	1.00	-0.34	0.00	0.00	0.00
A3	0.22	-0.34	1.00	0.00	0.00	0.00
PA1	0.00	0.00	0.00	1.00	0.02	0.07
PA2	0.00	0.00	0.00	0.02	1.00	-0.23
PA3	0.00	0.00	0.00	0.07	-0.23	1.00

Post-fit residuals (a priori measurement uncertainties)

Star	CosDECxRA (mas)	DEC (mas)	CosDecxPMRA (mas/yr)	PMDE (mas/yr)
UXARI	-3.68(4.0)	0.10(0.7)	-0.19(0.9)	1.96(1.4)
HR1099	1.72(1.1)	3.49(3.2)	-2.26(2.1)	-2.40(2.0)
HR5110	-0.81(0.9)	-3.11(3.1)	0.75(0.8)	-0.56(0.8)
SIGCRB	2.71(2.0)	0.70(1.0)	-0.87(1.2)	0.85(1.0)
CYGX1	0.23(1.5)	1.97(1.8)	-0.85(1.4)	2.10(1.2)
ARLAC	-0.30(0.6)	-0.47(0.8)	0.23(1.0)	-0.84(0.8)
IMPEG	-0.34(1.1)	-0.09(1.0)	0.50(1.2)	-0.52(1.2)

Post-Fit residual coordinates : mean = 0.15 mas rms = 1.91 mas
Post-Fit residual p.m. : mean = -0.15 mas/yr rms = 1.29 mas/yr
Non-normalized goodness of fit = 22.47 Number of degrees of freedom = 22

Table 4. VLBI-NDAC solution: the 3 angles (A_1 =A1, A_2 =A2, A_3 =A3) and the 3 rates of rotation (PA1=$\dot{A}_1$, PA2=$\dot{A}_2$, PA3=$\dot{A}_3$) between the Hipparcos and VLBI reference frames have been determined with the 6 link stars. The Hipparcos astrometric parameters of these stars are from the *30 month solution for double stars* for UX Ari and HR1099 and from the *30 month solution for single stars* for the other link stars of the reduction consortium NDAC. See caption of Table 3 for complementary information.

Weighted least-square-fit solution :

Rotation angles at epoch 1991 4 1 :

A1 = -19.78 +/- 0.74 mas
A2 = -8.83 +/- 0.62 mas
A3 = 21.43 +/- 0.70 mas

Rotation rates :

PA1 = -0.89 +/- 0.61 mas/yr
PA2 = -0.32 +/- 0.60 mas/yr
PA3 = 0.60 +/- 0.54 mas/yr

Correlation matrix :

	A1	A2	A3	PA1	PA2	PA3
A1	1.00	-0.18	0.53	0.00	0.00	0.00
A2	-0.18	1.00	-0.39	0.00	0.00	0.00
A3	0.53	-0.39	1.00	0.00	0.00	0.00
PA1	0.00	0.00	0.00	1.00	-0.02	0.06
PA2	0.00	0.00	0.00	-0.02	1.00	-0.28
PA3	0.00	0.00	0.00	0.06	-0.28	1.00

Post-fit residuals (a priori measurement uncertainties)

Star	CosDECxRA (mas)	DEC (mas)	CosDecxPMRA (mas/yr)	PMDE (mas/yr)
UXARI	-4.12(4.0)	-3.21(3.0)	0.78(1.6)	-1.03(2.0)
HR1099	2.56(2.4)	2.54(1.6)	-0.45(2.2)	-1.83(1.9)
HR5110	-2.52(1.6)	-2.19(1.7)	0.36(0.8)	-0.18(0.9)
CYGX1	1.48(1.5)	3.02(1.9)	0.14(1.6)	1.23(1.3)
ARLAC	-0.18(0.8)	-0.75(0.9)	-1.27(1.1)	0.21(1.0)
IMPEG	0.73(1.2)	-0.59(0.9)	0.40(1.3)	-1.57(1.5)

Post-Fit residual coordinates : mean = -0.27 mas rms = 2.30 mas
Post-Fit residual p.m. : mean = -0.27 mas/yr rms = 0.93 mas/yr
Non-normalized goodness of fit = 20.35 Number of degrees of freedom = 18

Table 5. Multiplicative factors to make the normalized goodness of fit unity in solving for the link parameters. σ_0 is the *a priori* measurement uncertainty combined from Hipparcos and VLBI initial uncertainties.

Name	FAST	NDAC	
UX Ari	σ_α = 4 mas	σ_α = 4 mas	σ_δ = 3 mas
	$\sigma_\alpha = 4\sigma_0$	$\sigma_\alpha = 2.5\sigma_0$	$\sigma_\delta = 2\sigma_0$
HR1099	σ_δ = 3 mas	σ_α = 2.4 mas	
	$\sigma_\delta = 2\sigma_0$	$\sigma_\alpha = 2\sigma_0$	
HR5110	σ_δ = 3 mas	$\sigma_{\alpha,\delta}$ = 1.6 mas	
	$\sigma_\delta = 3\sigma_0$	$\sigma_{\alpha,\delta} = 2\sigma_0$	
σ^2 CrB	σ_α = 2 mas		
	$\sigma_\alpha = 2\sigma_0$		

Table 6. Differences between the angles and rates of rotation determined after splitting the 7 FAST/VLBI link stars into 2 independent subsets of 3 and 4 stars. The symbol σ is the quadratically combined uncertainties of the 2 solutions.

	Differences between solutions FAST(3 stars) − FAST(4 stars) (mas)
A_1	+0.53 $\sim 0.5\sigma$
A_2	−0.48 $\sim 0.5\sigma$
A_3	+0.08 $\sim 0.1\sigma$
$\dot{A}_1$	+1.17 $\sim 1.0\sigma$
$\dot{A}_2$	+0.91 $\sim 1.0\sigma$
$\dot{A}_3$	+0.54 $\sim 0.5\sigma$

The 3 angles of rotation are consistent with the expected values since the FAST and NDAC solutions are aligned upon a *quasi-FK5* reference frame and the FK5 is aligned with the VLBI reference frame to within 70 milli-arcsec. This VLBI/FK5 alignment was estimated by early less precise VLBI positions and Bordeaux FK5 optical positions of 7 stars (Lestrade *et al* 1988), and, recently, by comparing the VLBI and FK5 optical positions of the supernova SN1993J (Eubanks 1994). This degree of alignment stems from the original method adopted to fix the arbitrary origin of the VLBI right-ascensions with the lunar occultation position of the radio quasar 3C273 (Hazard *et al* 1971). In the original analysis, this position is referred to the lunar ephemeris reference frame whose dynamical equinox is by construction close to the mean equinox of the stellar catalog FK4, and subsequently FK5. An effort of directly linking the VLBI extragalactic reference frame to the FK5 has also been conducted by photographic plates of 28 radio quasars (Ma *et al* 1990).

For NDAC, the rates of rotation are consistent with the uncertainty of about 0.6 mas/yr with the largest value being about 1.5σ. For FAST, the measured rates are also consistent with the uncertainty of about 0.5 mas/yr, although the $\dot{A}_3$ rate reaches 3σ. This means that the procedure used in the Hipparcos data reduction to stop the rotation of the Hipparcos sphere is efficient. In spite of this result, it is difficult to discuss to which degree the FK5 frame itself is inertial because any possible residual rotation rate of the FK5 is combined with an equally possible residual rotation rate induced by the procedure used to transform the Hipparcos frames to FK5.

The values found for A_1, A_2, A_3 and $\dot{A}_1, \dot{A}_2, \dot{A}_3$ are different for the comparison of the FAST or NDAC coordinates to the VLBI coordinates of the link stars. This is expected because each consortium has aligned the Hipparcos coordinate reference frame upon the FK5 by using its own independant procedure. These different procedures should account for the differences found but it was not studied.

The post-fit residuals are listed separately for α, δ, μ_α, μ_δ and π in Tables 3 and 4. In these tables, the *a priori* measurement uncertainties used as weights in the fit are also given in parentheses next to the corresponding post-fit residuals. The correlation coefficient matrices in Tables 3 and 4 show that all the rotation parameters are well separated. The post-fit residuals of the coordinates and proper motion components after the adjustment of the global rotation indicate that the consistency between the Hipparcos and VLBI techniques is at the milli-arcsec level. This is the first cross-check between these two astrometric techniques of comparable precision. The agreement is satisfaying, especially in view of the fact that the astrometric parameters used are from preliminary reductions of the data for both techniques.

5. The VLBI extragalactic reference frame used in the analysis

The terminology and concepts used hereafter, reference system, reference frame, realisation, are borrowed from Kovalevsky and Mueller (1981, 1989). The effort to determine the VLBI coordinates of the reference extragalactic sources associated with the link stars has been conducted with the Deep Space Network of JPL, the NAVNET network of USNO and the CDP/DOSE network of NASA. Various VLBI groups affiliated with these VLBI networks are perfecting realisations of the VLBI extragalactic reference system(Sovers 1991, Ma *et al* 1990, Eubanks *et al* 1991, Johnston *et al* 1994). The resulting VLBI extragalactic reference frames are consistent at the 0.5 milli-arcsec level after removing a global rotation between the two independant reference frames determined by the Jet Propulsion Laboratory and Goddard Space Flight Center as mentioned in the introduction (Jacobs 1994). The global orientation of each realisation is usually different by 1 − 5 milli-arcsec because of arbitrary choice of origins in the modelling of the data. The International Earth Rotation Service (IERS) has maintained a fixed orientation for the IERS VLBI extragalactic reference frame over the last few years in combining the realisations produced by the various VLBI groups (Arias, Feissel and Lestrade 1991). The IERS extragalatic reference frame is likely to be the most stable and dense frame. In the analysis presented here, the absolute VLBI position of each link star is determined by adding the measured differential coordinates to the IERS VLBI coordinates of its associated extragalactic reference source. Most of these coordinates are adopted from the IERS Annual Report for 1991 (published in 1992 by the Observatoire de Paris) and are listed in Table 7. However, one source (1955+335) has only recently been measured accurately by the USNO VLBI network NAVNET and has been subsequently rotated to the IERS celestial frame.

The angles of rotation A_1, A_2, A_3 in Tables 3 and 4 are directly related to the IERS celestial reference frame through the coordinates of the reference extragalactic radio sources of Table 7. Hence, the Hipparcos coordinates of any star can be transformed to the IERS reference frame by using eqs (1) and (2) and the rotation angles and rates of Tables 3 and 4. The rotation angles and rates are also specific to the 30-month solutions provided by the two Hipparcos consortia FAST and NDAC. These solutions will be superseded by other solutions including the 37 month data set of the complete Hipparcos mission for the release of the catalog.

Table 7. IERS VLBI coordinates (J2000) and uncertainties ($\pm\sigma_\alpha \cos\delta$ and $\pm\sigma_\delta$) of the extragalactic reference sources used in the analysis. Most of these coordinates are from the IERS Annual Report for 1991 (published in 1992 by the Observatory of Paris).

Name	Right Asc. ($\pm\sigma_\alpha \cos\delta$) h m s (mas)	Declination ($\pm\sigma_\delta$) ° ′ ″ (mas)
0326+278	03 29 57.669412 (0.42)	+27 56 15.49912 (0.32)
0336 − 019	03 39 30.937774 (0.18)	−01 46 35.80336 (0.18)
1315+346	13 17 36.494214 (0.18)	+34 25 15.93266 (0.24)
1611+343	16 13 41.064256 (0.18)	+34 12 47.90889 (0.19)
1955+335	19 57 40.54994 (1.20)	+33 38 27.9458 (1.20)
2200+420	22 02 43.291377 (0.14)	+42 16 39.97995 (0.17)
2251+158	22 53 57.747944 (0.18)	+16 08 53.56114 (0.17)

6. Comparison of trigonometric parallaxes determined by VLBI and Hipparcos

A trigonometric parallax is invariant with respect to coordinate systems and the Hipparcos and VLBI values can be directly compared. Table 8 shows the differences between VLBI and FAST as well as between VLBI and NDAC.

The differences are close to 1σ, except for HR1099 (2σ) and σ^2 CrB (3σ) of FAST. Note that HR1099 and σ^2 CrB are double stars in the field of the Hipparcos telescope and note also that the VLBI parallax of IM Peg has been determined with only 4 VLBI epochs of observations while the other stars have 6 VLBI epochs or more. Two additional VLBI observations of IM Peg are planned in 1994.

Table 8. Comparison between the VLBI and Hipparcos trigonometric parallaxes. The uncertainties quoted are the square root of the quadratic sum of the Hipparcos and VLBI uncertainties.

Name	π FAST − VLBI (mas)	π NDAC − VLBI (mas)
UX Ari	+0.08 ± 1.04	−0.50 ± 1.73
HR1099	+2.47 ± 1.30	+0.85 ± 1.59
HR5110	−0.34 ± 1.20	+0.04 ± 1.32
σ^2 CrB	+3.41 ± 1.07	–
Cyg X1	+1.30 ± 1.25	+0.99 ± 1.36
AR Lac	−0.01 ± 0.90	−0.15 ± 1.08
IM Peg	−1.64 ± 1.40	−1.95 ± 1.43
mean	+0.75	
rms	1.01	
mean (no σ^2 CrB)	+0.31	−0.12
rms (no σ^2 CrB)	0.89	0.68

7. Future improvements of the link:

Before the release of the final Hipparcos catalog in 1996, several improvements of the preliminary VLBI link presented in this paper will be made. First, there will be new solutions from the Hipparcos reduction consortia with the complete 37 month data set of the mission. Second, VLBI observations and analysis will be completed.

There will be 4 additional link stars. VLBI observations of HD199178 and HD283447 are being completed in 1994, the multiple system Algol needs special treatment to account for its 1.86-year orbit in the link, and VLBI observations of LSI 61303 are being reduced.

The positions of the extragalactic reference sources 1955+355 (for Cyg X1), 0241+622 (for LSI 61303), 0405+305 (for HD283447) and 2100+468 (for HD199178), might improve to the sub-milliarcsecond level, similar to the other reference extragalactic sources, with enough VLBI observations of the DSN, NAVNET and NASA networks.

Various improvements of the model of the interferometric phase in the software SPRINT used to determine the differential coordinates of the VLBI link stars relative to their reference sources will be implemented. This will improve the troposphere, ionosphere and source structure corrections. A global re-reduction of all the VLBI data will be carried out with this improved software and full consistency between the IERS terrestrial, earth orientation and celestial systems will also be achieved.

Equations (1) and (2) and their analytic form (eqs 3-6) will be modified to include the more general case where the epochs of the VLBI coordinates of the different link stars are not identical. Since VLBI observations for each star are unevenly distributed between 1987 and 1994 (see Table 1a), the optimal epoch to minimise the covariance between the VLBI astrometric parameters of each link star is the mid-date of the VLBI observation span which does not usually coincide with the epoch of the Hipparcos coordinates at 1991.25. Projecting the VLBI coordinates to 1991.25 with proper motion as in the present analysis increases the VLBI coordinate uncertainties. For instance, there are 2 years between the mid-date of the VLBI observation span of HR5110 and 1991.25 and this increases the VLBI coordinate uncertainty of this star by 20%.

It is expected that all these improvements will not drastically modify the values of the rotation angles and rates but that the consistency between the Hipparcos and VLBI astrometric results will improve. An important issue however is the adoption of a "conventional" VLBI extragalactic reference frame to which the 3 rotation angles are related. The IERS VLBI extragalactic reference frame adopted in this analysis has the advantage of being consistent with the IERS terrestrial reference frame and the IERS earth orientation parameter series that must be used in the most demanding applications. The IERS VLBI frame of the Annual Report for 1991 (published in 1992) used in the analysis is not expected to differ significantly in global orientation from more recent realisations of the IERS VLBI extragalactic frame. The changes from year to year are rather the densification of the IERS catalog and improvements of coordinates of individual sources.

The present link between the Hipparcos optical reference frame and the VLBI frame is complementary to the link between the dynamical reference frame of the planetary ephemerides and the VLBI frame recently determined at the 3 milli-arcsec level by Folkner *et al* (1994). The combination of the two links yields straightforwardly a high-precision link between the Hipparcos and planetary reference frames.

The Hipparcos Input Catalog consortium INCA has drawn up a list of about 300 radio-emitting stars of various types that have been observed by the satellite. The selection criteria of this list are summarised in Argue (1988). Walter, Hering and de Vegt (1990) have compiled optical and radio information on 186 radio-emitting stars observed by Hipparcos. In addition, Wendker (1987) is keeping current a compilation of radio-emitting stars with more than 800 entries now. Note that the large radio source sizes ($0.1''$) of a fraction of these stars (thermal) are not suitable for VLBI. Nevertheless, the VLBI astrometric program could be extended to monitor 50 or more link stars that should improve the link between Hipparcos and the extragalactic background by a factor of ~ 3 in precision.

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