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Preliminary link of the Hipparcos and VLBI reference frames

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Summary. We present a comparison of VLBI and Hipparcos astrometric parameters of several optically bright radio-emitting stars. The systematic discrepancies found in theme 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 t}, c two frames are determined at better than the milli-arcsec level. The angles of rotation found arc 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 p.lobs] 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. It is rather satisfactory, especially in view of the fact that the astrometric parameters used arc 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 arc 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 arc also discussed.

Key words: VLBI - Hipparcos - astrometry - reference systems

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1. Introduction

The VLBI (Very Long Baseline Interferometry) extragalactic frame is the primary celestial reference frame clue 'co its accuracy ant] 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 σ_α x cos 6 and σ_δ and the best 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 comparable to and even better than the expected internal consistency of the Hipparcos optical reference frame, currently materialised in a provisional form 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 and to stop any residual global rotation of the Hipparcos frame for dynamical studies. Note that the Hubble Space Telescope ancl 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 troth frames (VJ,1 3] and Hipparcos) and whit}) can be used to link them at the milli-arcsec level. Other techniques will also be used to achieve this link as described in Lindegren (1995).

The link between the extragalactic (VLBI) and Hipparcos frames has been studied theoretically by Froeschlé and Kc,-valev sky (1982) and can be written in matrix form as:

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

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

where o_{vlbi}, o_{hip}, $\dot{o}_{vlbi}$ and $\dot{o}_{hip}$ are the direction and proper motion vectors of the link stars measured by both techniques (VLBI and Hipparcos) and referred to the same epoch t_0. 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 but the VLBI program monitors 11 link stars for 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) after the first list of radio stars for astrometry of 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 at high declination in the southern hemisphere are 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.

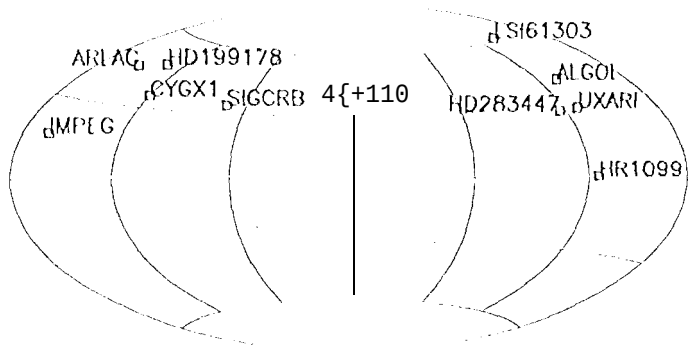

Fig. 1. Sky distribution of the VLBI link stars for Hipparcos

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 VLBI 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 December 19, 1982. Each VLBI observation of a single 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 Mark III 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.

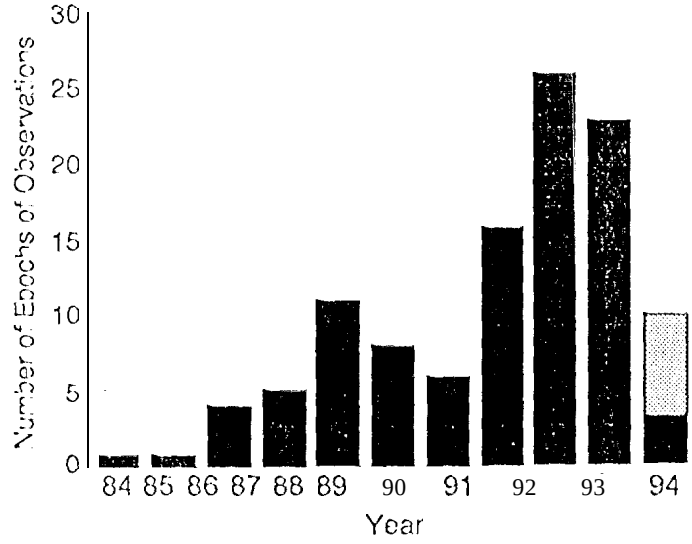

Fig. 2. Distribution of the VLBI observations over the years. For 1994, black indicates observations conducted and grey planned.

The result of each VLBI observation is the differential coordinates of the target star relative to its associated reference extragalactic source at the elate of observation. The angular separations between the 11 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 ale, ne is smaller than 0.1 milli-arc sec. But some sources of systematic errors are larger, e.g. ionosphere (at 5 GHz), troposphere, orbital motion of the c1osc binaries and structure of t}, c 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 milliarcsecond (Lestrade *et al* 1990).

Star	Nber of observation	Period of observations	Angle Star-Reference
UX ARI	8	88/03 - 92/03	1,1°
HR1099	6	91/03 - 93/02	2.4°
HR5110	8	87/05 - 92/06	4.5°
o^2 CrB	12	87/05 - 93/11	0.4°
Cyg X1	9	88/03 - 93/11	1.6°
AR Lac	6	89/04 - 93/09	3.7°
IM Peg	4	91/12 - 93/09	0.7°

Table 1a VLBI observations of the 7 link stars.

Star	Position Uncert. (mas)	Proper Motion Uncert. (mas/yr)	Trig. Parallax Uncert. (mas)
UX ARI	0.55	0.20	0.30
HR1099	σ_α = 0.30 σ_δ = 1.21	$\sigma_{\mu\alpha}$ = 0.24 $\sigma_{\mu\delta}$ = 1.20	0.35
HR5110	0.90	0.25	0.70
o^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

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

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 relative α, δ to the associated reference extragalactic source at the mid-epoch of the observing span, its 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 ($\chi^2 = \sum_{i=1}^{N} (\frac{r_i}{\sigma_i})^2$, where r_i are the post-fit residuals and σ_i are the *a priori* measurement uncertainties). 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. The most precise VLBI measurement has been achieved for o^2 CrB with the formal uncertainties of 80 micro-arcsec in 0,15 relative to the extragalactic reference source 1611+343; 40 Illicro-arcsec/year in μ_α, μ_δ anti 80 micro-arcsec in π. The star o^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 o^2 CrB is 0.2 milli-arcsec in Table 1b 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.

3. Hipparcos astrometric parameters of the link stars

The two Hipparcos reduction consortia have determined the astrometric parameters of the link stars in their 30-month solutions 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 HR 1099 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.

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
o^2 CrB	0.94/-	1.23/-	1.07/.
CygX1	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

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.

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 :

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

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

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

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

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 ($\alpha = 0^h$ $\delta = 0^\circ$), y-axis ($\alpha = 6^h$ $\delta = 00$), z-axis ($\delta = 90^\circ$ 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 (I) 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 - G) can be used directly with no parallax correction at epoch to. 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 eq. (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 used as weights in the least-squares-fit. ‘1’able 5 shows the multiplicative factors of the modified uncertainties. A'o 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),

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

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.

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, 0^2CrB, 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).

	Differences between solutions FAST(3 stars) - FAST(4 stars)
A_1	$+0.53 \sim 0.5\sigma$
A_2	0.48 - 0.50
A3	+0.08 - 0.10
$\dot{A}_1$	-11.17 - 1.00
$\dot{A}_2$	$+0.91 \sim 1.0\sigma$
$\dot{A}_3$	$+0.54 \sim 0.5\sigma$

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.

The 3 angles of rotation are consistent with the expected values since the H' 'A ST and NDAC solutions are aligned upon a *quasi-FK5* reference frame. And the FK5 itself is aligned with the VLBI reference frame within 70 milli-arcsec as 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).

The rates Of rotation are barely significant at the 0.6 milli-arcsec/yr for NDAC and only the rate A_3 is significant at the level of 3σ for FAST. 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 is inertial because any possible residual rotation of the FK5 is combined with an equally possible residual rotation 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 whether FAST or NDAC coordinates are compared 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. Various details of this procedure should account for the differences found but it was not studied.

The post-fit residuals are listed separately for $\alpha, \delta, \mu_\alpha, \mu_\delta$ and n in Tables 3 and 4. In these tables, the *a priori* measurement uncertainties used as w'ei.gilts 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 co mponents 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 crcms-check between these two astrometric techniques of comparable precision. And it is rath er satisfa ctory, especially ill view of the fact that the' astrometric parameters used are from pr eliminary reductions of the data for both techniques.

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Weighted least-square-fit solution :

  Rotation angles a  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        DEC          CosDecxPMRA       PMDE
                (mas)          (mas)          (mas/yr)        (mas/yr)
UXARI        .3,  (4.0)      0.10( 0.7)     0.15( 0.9)      -2,.60( 2.0)
HR1099       1.72( 1.1)      3.49( 3.2)    -2.26( 2.1)      1.96( 1.4)
HR5110      -0.61( 0.9)     -3.11( 3.1)     0.75( 0.8)     -0.56( 0.8)
SIGGKR       2.71( 2.0)      0.70( 1.0)     0.67( 1.2)      0.65( 1.0)
CYGX1        0.23( 1.5)      1.97( 1.8)    -0.85( 1.4)      2.10( 1.2)
ARIAC       .0,3 ['( 0.6)   -0.47( 0.8)     0.23( 1.0)     -0.84( 0.5)
IMPBS       -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
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'J'[ii,. **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 o f these stars are from the *30 month sol ution for double stars* of the reduction consortium PAS']'. The correlation matrix and post-fit residuals are given. *A* priori measurement un certainties used as weights fo r the least-squares-fit arc in parenthesis next to the cor - responding post-fit residuals. The angles of rot ation are determined relative to the VLBI extragalactic frame defined by the IERS VLBI coordinates of the reference sources of Table 7.

5. The VLBI extragalactic reference frame used in the analysis

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 J} 'L, NAVNET network of USNO and CDP/DOSE network o f NASA. The terminology and concep ts used hereafter, **reference system, reference frame, realisation,** are borrowed from Kovalev sky and Mueller (1981 , 1989). Various VLBI groups are perfecting realisations of the VLBI extra galactic reference **syst em** (Sovers 1991 , Ma *et al* 1990, Eubanks *et al* 1991, John ston *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 P ropulsion] aboratory 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 beca use of arbitrary choice of orig ins in the modelling

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Weighted least-square fit solution

  Rotation angles at epoch 1991  4  1 :

  A1  =  -19.78 +/-  0.74 mas
  A2  =   -8.63 +/-  0.62 mas
  A3  =   21.43 +/-  [l.-/u mas

  Rotation rates :

  1/,1 -   -0.89 +/-  0.61 mas/yr
  PA2 -    0.32 +/-  0.( 0 mas/yr
  PA3 =    ['. <[1 +/-  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 -0.18
PA3  0.00  0.00  0.00  0.06 -0.28  1.00

      Post-fit residuals (a priori measurement uncertainties)
Star          CosDECxRA        DEC          CosDecxPMRA       PMDE
                (mas)          (mas)          (mas/yr)        (mas/yr)
UXARI       -4.12( 4.0)     -3.21( 3.0)     0.78( 1.6)      -1.03( 2.0)
HR1099       2.56( 2.4)      2.56( 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        1.46( 1.5)      3.02( 1.9)     0.14( 1.6)       1.23( 1.3)
ARIAC       -0.18( 0.8)     -0.75( 0.9)    -1.27( 1.1)       0.21( 1.0)
IMPBS        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
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Tab. 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. The correlation matrix and post-fit residuals are given. *A priori* measurement uncertainties used as weights for the least-squares-fit are in parenthesis next to the corresponding post-fit residuals. 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.

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 fra me is likely to be the most stable and dense frame. In the analysis presen ted here, the absolute VLBI position of each lin k star is determined by adding the measured differential coordinates to the IERS VLBI coordinates of its associated extrag alactic reference source. Most of these coordinates are adop ted from the IERS Annual Report for 1991 (published in 1992 by the Observatoire de Paris) and are listed in 'J'able 7, However, one source (1955- I 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 set of coordinates of Tab le 7 which define the VLBI extragalactic reference frame to which Hipparcos might be linked at this stage by using eqs (I) and (2). The rotation angles and rates are also specific to th e 30-month solutions provided by the two Hipparcos con sortia FAST an d NDAC. These solution s will be superseded by other solutions including the 37 month data set of the complet e Hipparcos mission for t}, c release of the catalog.

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)	-12°75615.49912 ***(0.32)***
0336 - 019	033930.937774 (0.18)	***-01 4635.80336*** (0.18)
1315-1346	131736.494214 (0.18)	-13425 15.93266 (0.24)
1611.1343	161341.064256 (0.18)	+34]2 47.90889 (0.19)
1955+335	19 57 40.54994 (1.20)	+33 38 27.9458 (1.20)
2200-1420	?2. 0243.291377 (0.14)	-142 16 39.97995 (0.17)
2251+158	2253 57,747{144 (0,18)	+ 160853,56114 (0.17)

Table 7: IERS VLBI coordinates (2000) 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).

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.

Name	π FAST - VLBI (mas)	π NDAC - VLBI (mas)
UX Ari	-10.08±1,04	- 0.50± 1.73
HR1099	-12.47±1.30	-10.85±1.59
HR5110	- 0.34,1 1,20	-10.04±1.32
o^2 CrB	-13.41 ± 1.07	
Cyg X1	-11.30 ± 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	-10.75	
rms	1.01	
mean (110 o^2 CrB)	+0.31	- 0.12
rms (110 o^2 CrB)	0.89	0.68

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.

The differences are close to 10, except for HR1099 (20) and o^2 CrB (30) of FAST. Note that HR1099 and 0^2 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.

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 1.8G-year orbit in the link and VLBI observations of 1 ,S1 61303 are being reduced.

The positions of the extragalactic reference sources 1955+355 (for Cyg X1), as well as 0241-I 622 (for 1,S1 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 DSAT) 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 link stars 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 la), the optimal epoch to minimise the covariance between the VLBI astrometric parameters of each link star is the mid-date of the 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 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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