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PRELIMINARY LINK BETWEEN THE HIPPARCOS 37-MONTH FAST SOLUTION AND A VLBI EXTRAGALACTIC REFERENCE FRAME

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ABSTRACT

Results of the VLBI astrometric program of 12 radio emitting stars are presented and used to provide a preliminary link of the Hipparcos 37 month FAST solution to a VLBI extragalactic reference frame. The formal precisions of this link are 0.5 milliarcsecond in global rotation and 0.5 milliarcsecond per year in residual rate of rotation

1. INTRODUCTION

The VLBI (Very Long Baseline Interferometry) extragalactic frame is the primary celestial reference frame due to its accuracy and stability. The link between the VLBI and

Hipparcos reference frames 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. Since 1982, we have been conducting a high-accuracy VLBI astrometric program of 11 optically bright radio-emitting stars in the Northern Sky which are objects common to both frames (VLBI and Hipparcos) and which can be used to link them at the milli-arcsec level. Since 1991, a similar VLBI astrometric program on 3 southern stars has been conducted by a group from CSIRO in Australia and USNO. These stars are displayed on the celestial sphere in Figure 1 and are among the most active of the non-thermal radio-emitting stars.

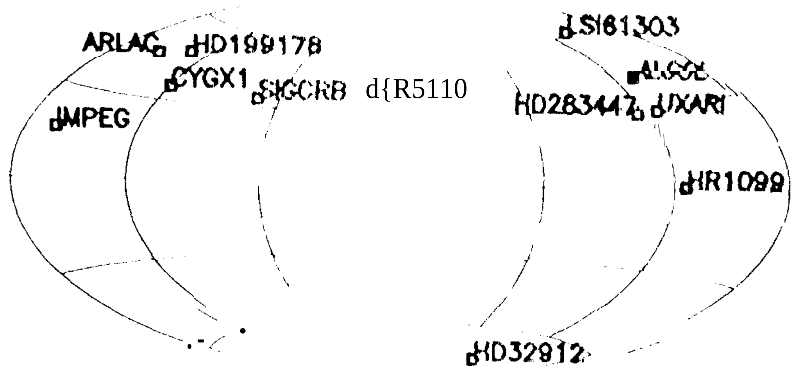

Figure 1 :Sky distribution of the VLBI link stars for Hipparcos

The link between the extragalactic (VLBI) and Hipparcos frames has been studied theoretically by Froeschlé and Kovalevsky (1982) and Lindegren and Kovalevsky (1995). It 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. For redundancy, the VLBI program in the Northern Hemisphere monitors 11 link stars and the VLBI program in the Southern Hemisphere provides at this stage useful data for one link star at declination 75° which improves considerably the geometry of the link.

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).

In the Northern Hemisphere, a total of 89 MarkIII VLBI observations have been conducted from October 1984 to December 94 with 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, Onsala, Cambridge, Jodrell Bank). 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 the link stars. This effect could be significant if some of the link stars were double stars with no known orbital parameters and exhibiting an acceleration.

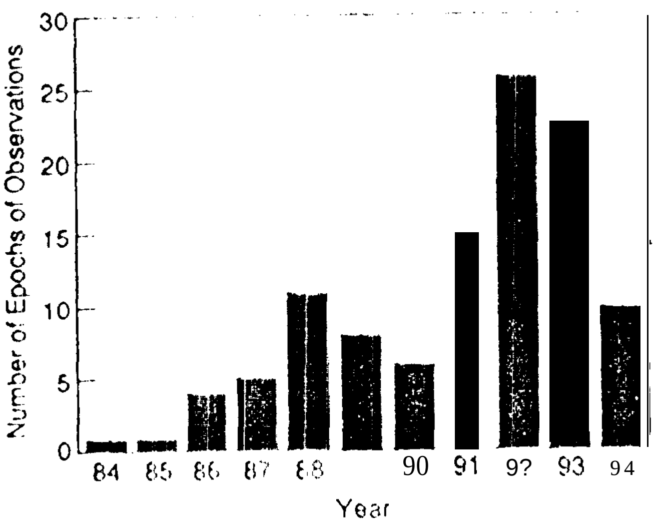

Figure 2 Distribution of the VLBI observations over the years.

For each star, the differential VLBI coordinates measured at multiple epochs (the number of observations is in Table 1a) were used in a weighted least-squares-fit to determine its position α, δ relative to the associated reference quasar 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. As of October 1995 11 link stars in the Northern Hemisphere and one in the Southern Hemisphere have high-precision VLBI astrometric parameters and are used for the link presented below. Details of the VLBI observations for each star are in Table 1a and the astrometric precisions for the VLBI positions, proper motoins and trigonometric parallaxes are in Table 1b. VLBI coordinates and VLBI annual proper motion components have generally submilliarcsecond formal uncertainties, except for α and δ of LSI61303 and Cyg X1 because the IERS coordinates of their reference quasars have the relatively large uncertainties $\sigma_\alpha \times \cos\delta$ and σ_δ of 1,5 mas. 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 aTcsec/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 quasar (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 uncertainty just quoted for the relative position of this star. This is because of the uncertainty of tile absolute position of the reference source 1611+343,

Table 1a : VLBI observations of the 12 link stars.

Star	HIP number	Number of observations	Period of observations	Separation Star-Reference
LSI61303	12469	8	89/09 - 94/09	0.6°
Algol	14576	13	84/10 - 94/11	1.0°
UX ARI	16042	9	88/03 - 94/05	1.1°
HR1099	16846	8	91/03 - 94/05	2.4°
HD283447	19762	7	92/11 - 94/08	3.4°
HD32918	23106	4	92/03 - 94/10	3.2°
HR5110	66257	15	87/05 - 94/05	4.5°
σ^2 CrB	79607	14	87/05 - 94/11	0.4°
HD199178	103144	5	92/09 - 94/05	2.9°
Cyg X1	98298	9	88/03 - 93/11	1.6°
AR Lac	109303	7	89/04 - 94/05	3.7°
IM Peg	112997	5	91/12 - 94/07	0.7°

Table 1b : Formal uncertainties of the absolute positions, proper motions and trigonometric parallaxes of the 12 link stars determined by VLBI.

Star	Position Uncert. (ms.s)	Proper Motion Uncert. (mas/yr)	Trig. Parallax Uncert. (mas)
LSI61303	3.00	0.38	0.37
Algol	0.70	0.20	0.62
UX ARI	0.55	0.33	0.65
HR1099	0.30	0.30	0.35
HD283447	0.80	0.36	0.21
HD32918	0.75	0.70	0.20
HR5110	0.90	0.25	0.[illegible]0
σ^2 CrB	0.20	0.04	0.08
HD199178	0.80	0.42	0.30
Cyg X1	1.50	0.20	0.40
AR Lac	0.60	0.20	0.41
IM Peg	0.60	0.60	0.60

Table 2 : Formal uncertainties of the Hipparcos astrometric parameters for the link stars from the 37-month solutions for double stars by FAST (June 95)

Star	Position Uncert. FAST (mas)	Proper Motion Uncert. FAST (mas/yr)	Trig. Parallax Uncert. FAST (mas)
LSI61303	12.	16.	13.
Algol	1.38	1.70	1.38
UX ARI	0.87	1.37	1.01
HR1099	1.03	1.94	1.25
HD283447	2.99	3.36	2.41
HD32918	0.[illegible]3	0.74	0.94
HR5110	0.63	0.76	0.96
σ^2 CrB	0.94	1.23	1.07
HD199178	0.73	0.96	0.80
Cyg X1	0.92	1.37	1.19
AR Lac	0.59	0.98	0.78
IM Peg	0.93	1.10	1.26

3. HIPPARCOS ASTROMETRIC PARAMETERS OF THE LINK STARS

The Hipparcos astrometric parameters for the 12 link stars of this report were provided by FAST based on the 37-month solution for double stars as of June 1995. The FAST precisions are in Table 2.

4. GLOBAL ROTATION BETWEEN HIPPARCOS AND A VLBI REFERENCE FRAME

The rotation matrices of equations (1) and (2) are defined by A_1, A_2, A_3, 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 $\dot{A}_1, \dot{A}_2, \dot{A}_3$, 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 :

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

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

We have determined 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 $[\dot{R}]$ by a weighted least squares fit. The fitted parameters, the correlation matrix and the post-fit residuals are in Table 3. The goodness of fit normalized with the number of degrees of freedom is close to unity. This was achieved by increasing the quadraticly combined formal uncertainties of VLBI and FAST by 20% only. The relatively large value of A_3 in Table 3 is because there was no attempt by FAST to tie the 37 month solution to the FK5 as done previously for the 30 month FAST solution. This has no impact on the precision of the link. The formal uncertainties of A_1, A_2, A_3 and $\dot{A}_1, \dot{A}_2, \dot{A}_3$ are 0.5 milli-arcsec and 0.5 milli-arcsec per year (Table 3).

The robustness of the solution has been tested by splitting the 12 link stars into two independant subsets, one with the 6 stars : LSI61303, UXARI, HD283447, HD5110, CYGX1, ARLAC and one with the 6 stars Algol, HR1099, HD32918, σ^2CrB, HD199178, IMPeg. Rotation angles and rates have been solved for with these 2 subsets and compared. The differences are in Table 4 and are no more than the quadratically combined uncertainties of the 2 solutions.

Table 4 : Differences between the angles and rates of rotation determined after splitting the 12 FAST/VLBI link stars into 2 independent subsets of 6 stars each. The symbol σ is the quadratically combined uncertainties of the 2 solutions.

	Differences between solutions FAST1(6 stars) FAST 2(6 stars) (mas, mas/yr)
A_1	0.82 - 0.80
A_2	-10.22 $\sim 0.25\sigma$
A_3	1.71 $\sim 1.50\sigma$
$\dot{A}_1$	-10.59 - 0.600
$\dot{A}_2$	-10.17 $\sim 0.20\sigma$
$\dot{A}_3$	-10.14 $\sim 0.1\sigma$

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Weighted least-square-fit solution :

  Rotation angles at epoch 1991  4  2 13.1 :

  A1  =  -24.71 +/-  0.51 mas
  A2  =  -27.76 +/-  0.44 mas
  A3  =   56.33 +/-  0.56 mas

  Rotation rates :

  PA1 =  -0.34 +/-  0.49 mas/yr
  PA2 =  -1.03 +/-  0.40 mas/yr
  PA3 =   3.62 +/-  0.51 mas/yr
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Correlation matrix :

	A1	A2	A3	PA1	PA2	PA3
A1	1.00	-0.06	0.31	0.00	0.00	.00
A2	-0.06	1.00	-0.25	0.00	0.00	.00
A3	0.31	-0.25	1.00	0.00	0.00	.00
PA1	0.00	0.00	0.00	1.00	0.02	.11
PA2	0.00	0.00	0.00	0.02	1.00	.25
PA3	0.00	0.00	0.00	0.11	-0.25	[illegible]

Post-fit residuals (a priori measurement uncertainties)

Star	CosDECxRA (mas)	DEC (mas)	CosDecxPMRA (mas/yr)	PMDE (mas/yr)
LSI61303	-2.68(15.0)	1.54(12.5)	4.40(16.9)	0.53(16.2)
ALGOL	4.76(1.8)	-0.97(1.4)	1.20(1.6)	-0.40(1.7)
UXARI	-2.89(2.4)	-1.93(1.6)	-1.01(3.0)	0.65(2.7)
HR1099	0.02(1.4)	0.10(1.2)	0.51(1.7)	2.12(1.6)
HD283447	6.66(4.2)	-6.54(4.1)	-1.36(3.9)	2.19(2.9)
HD32918	-1.71(1.8)	2.25(1.5)	0.37(1.0)	-2.02(1.6)
HR5110	-1.10(1.4)	-1.25(1.1)	0.38(0.7)	0.10(0.6)
SIGCRB	2.83(1.7)	-1.89([illegible])	-1.31(2.1)	4.11(2.2)
CYGX 1	0.60(1.8)	4.66([illegible])	-0.42(1.9)	0.97(2.2)
HD199178	0.35(0.9)	[illegible](0.9)	-0.84(1.2)	-0.11(1.1)
ARLAC	-0.68(0.8)	[illegible](0.9)	-0.18(0.8)	-0.21(0.8)
IMPEG	-1.24(1.1)	-1.10(0.8)	0.06(1.2)	0.39(1.1)

```
Post-Fit residual coordinates: Wmean =  2.10 mas      Wrms =  2.07 mas
Post-Fit residual p.m.       : Wmean =  0.18 mas/yr   Wrms =  1.10 mas/yr
Non-nor. goodness of fit =  44.65 Number of degrees of freedom =  44
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Table 3 : Preliminary parameters for the VLBI-FAST 37 month solution link: 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 12 link stars. Post-fit residuals in $\alpha, \delta, \mu_\alpha, \mu_\delta$ are given.

5. THE VLBI EXTRAGALACTIC REFERENCE FRAME USED IN THE ANALYSIS

The angles of rotation A_1, A_2, A_3 in Table 3 are directly related to the IERS celestial reference frame through the VLBI coordinates of the reference quasars of Table 5. The IERS celestial reference frame is a compilation of VLBI catalogues produced by several independant VLBI groups every year and combined in such a way that the directions of axis are maintained fixed over the years since 1988 (Arias, Feissel and Lestrade 1991). 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 Table 3. The IERS coordinates of the quasars in Table 5 will be revised by IERS before the release of the Hipparcos catalogue but only submilliarcsecond changes are expected. The rotation angles and rates of 'J'able 3 are specific to the 37 month solutions provided by FAST in June 1995 and will be superseded by the final 37 month solution for the release of the catalogue.

'J'able 5: IERS VLBI coordinates (J2000) and uncertainties ($\pm\sigma_\alpha$ and $\pm\sigma_\delta$) of the reference quasars used in the analysis. Most of these coordinates are from the IERS Annual Report for 1991 (published in 1992 by the Observatory of Paris).

Link Stars	Reference Quasars	Right Asc. (, σ_α) h m s (mas) J2000	Declination ($\pm\sigma_\delta$) ° ' " (mas) .1?000
1,s161303	0241-{ 622	0244 57.69680s (3.00)	I 622806.51429 (1(10)
Algol	0309-1411	0313 01.962) 1 (o 30)	| 41 20 01.1833 (0.38)
UXARI	0326-I 278	0329 57.669412 (0.42)	I 2'756 15.49912 (().32)
HR1099	0336- 019	0339 30.9377'/4 (0.18)	01 4635.80336 (0.18),
111)283447	0405-1305	04 08 20.377573 (0.75)	I 303230.10080" (0.11)
111)32918	0530- 727	0529 30.(11 ?3(11,1 (30)	72 45 28.50700 (0.26)
HR5110	1315-| 346	13 1736.4 {)1211 ((18)	3425 15.9:i26(i (0.24)
HR5110	1338-| 381	13 40 22.951785 ((90)	37 54 43.83 228 (0.67)
σ^2 CrB	1611-1343	1613 41,061 ?5(; (018)	34 124'7.90889 (0.19)
Cyg xl	1955-| 335	1957 40.54994 (120)	I 33 3827.9458 (1 .20)
111)199178	2100-1468	21 02 17.056062 ((' 18)	| 47 0216.25393 ((1.1?)
BL Lac	2200-} '120	2202 43.291377 ((' 1 1)	4216 39.9'/995 (,0.17)
IM Peg	2251-{ 158	2253 57.747944 (018)	16 08 53.56114 (0.17)

6. CONCLUSION

The formal precisions of the preliminary link of the Hipparcos 37 month FAST solution to a VLBI extragalactic reference frame are 0.5 milliarcsecond in global rotation and 0.5 milliarcsecond per year in residual rate of rotation. Although, these precisions should not significantly changed in the final link, the actual angles A_1, A_2, A_3, $\dot{A}_1$, $\dot{A}_2$, $\dot{A}_3$ will be modified to reflect the final Hipparcos 37 month solution that will become the Hipparcos catalog and the slight changes of coordinates of the reference quasars take.rl in the VLBI celestial reference frame that is being completed by IERS for the Hipparcos link.

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