Sub-Milliarcsecond Astrometry with Phase-Referenced VLBI

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Abstract. Astrometric VLBI observations of radio stars are being made to connect the Hipparcos optical reference frame and the extragalactic radio reference frame. The antennas are switched between a star and a strong, compact reference source a few degrees away every 2–3 minutes. After correlation, the strong reference source fringes are used to determine the exact delay and rate of the weak radio star fringes, allowing the visibilities to be measured and coherently integrated for the duration of the experiment. As a result accurate astrometry has been possible on radio stars with flux densities as low as 2 mJy. All five astrometric parameters (two positions, two proper motions, and one parallax) have been obtained for several stars, with formal errors and epoch-to-epoch residuals less than 1 milliarcsecond.

1. Introduction

Technical advances in Very Long Baseline Interferometry (VLBI) with the Mark-III data acquisition system (ROGERS *et al.*, 1983) have provided sufficient sensitivity to reliably detect radio-emitting stars over the last few years. There are about 400 stars that exhibit radio emission as compiled by WENDKER (1987). About half of these stars exhibit thermal free-free emission from very large ionized circumstellar envelops that are fully resolved by VLBI observations. The other stars exhibit non-thermal radio emission (gyrosynchrotron, synchrotron, coherent emission mechanisms) with typical source sizes of a few milliarcseconds (mas) or less. These non-thermal radio-emitting stars belong to a wide variety of physical classes, e.g. X-ray, RS CVn, Algol, dMe, FK Com, T Tauri. Most of these stars have radio flux densities of only a few milliJansky (mJy) or less, i.e., 100–1000 times weaker than compact extragalactic radio sources usually observed by VLBI. Nevertheless, 30 stars can be detected by phase-referenced VLBI observations and this number will grow with future improvements of the technique.

We have selected 11 radio-emitting stars with non-thermal emission (7 RS CVn, 2 X-ray and 2 Pre-Main-Sequence stars) for a high-accuracy VLBI astrometric monitoring program in support of the Hipparcos mission. The motivation of this program is to measure the radio positions and proper motions of radio stars which are optically bright enough to be observed by the Hipparcos satellite. This will allow us link the future Hipparcos optical reference frame to an extragalactic quasi-inertial reference system (LESTRADE *et al.*, 1992).

2. Phase-Referenced VLBI

The coherence time in standard VLBI is limited to less than ~15 minutes at centimeter wavelengths by the independent frequency standards at the different antennas. Consequently, the observed radio source must have a flux density high enough to be detected during a similar integration time. At the VLBI processor, the cross-correlation of the recorded signals leads to the measurement of the amplitude and phase of the complex visibility induced by the source brightness distribution convolved with the beam of the antenna pair for the duration of each integration period.

When a radio source is so weak that it cannot be detected within a few minutes, one has to resort to the phase-referencing VLBI technique. This allows multiple scans to be combined in a single coherent integration period, as we have demonstrated by our Hipparcos-related VLBI astrometric program. A reference for the VLBI phase must be established by observing an angularly nearby strong extragalactic source alternately with the weak program source using a switching time of 2–3 minutes (less than the coherence time). Such a phase-referencing technique allows increased sensitivity through use of much longer integration times (several hours) with minimum coherence loss. This strategy also allows high-accuracy differential astrometry because the prime observable used is the VLBI phase. The phase-referencing VLBI technique as applied in our radio star astrometry program is described in detail in LESTRADE *et al.* (1990).

3. VLBI Observations of the Radio Star σ^2CrB

σ^2CrB is an RS CVn close binary whose orbital motion has a period of 1.1 day and a semimajor axis of 0.3 mas (BARDEN, 1985). Phase-referenced VLBI observations of σ^2CrB were conducted at 12 epochs between May 1987 and August 1992. These epochs are listed in Table 1.

The total data integration times were between 5 and 8 hours at each epoch. The Mark-III VLBI data acquisition system was used to record a bandwidth of 28 MHz (ROGERS *et al.*, 1983); the corresponding detection threshold is about 2 mJy (10σ). Cross-correlation of the recorded signals was carried out on the Mark-III VLBI processor at the Haystack Observatory.

The 5 astrometric parameters of σ^2CrB (2 coordinates, 2 proper motion components, and parallax) were estimated by a least squares fit to the 24 coordinates measured at the 12 epochs. The uncertainties of the measured VLBI coordinates were set to 0.2 mas to make the reduced-χ^2 close to unity for the number of degrees of freedom in the fit (19). The weighted rms of the post-fit coordinate residuals is 0.2 mas. With such an adjustment, the formal uncertainties for the 5 fitted parameters are 0.08 mas for the relative position between σ^2CrB and the reference source 1611 + 343, 0.04 mas/year for the proper motion, and 0.08 mas for the trigonometric

Table 1. VLBI observations of σ^2CrB at 12 epochs.

Obser. date	Orbital phase (cycle)	Frequency (GHz)	Flux density (mJy)
87/05/26	0.56	5.0	10
88/11/16	0.93	5.0	28
89/04/13	0.25	5.0	7
90/04/21	0.53	8.4	6
90/11/16	0.37	5.0	3.8
91/04/12	0.86	8.4	19.5
91/09/14	0.53	5.0	4.3
92/01/15	0.88	8.4	4.6
92/04/05	0.96	8.4	18
92/04/22	0.76	8.4	6
92/06/08	0.89	5.0	13
92/08/03	0.06	8.4	8.3

Table 2. Differences between two astrometric solutions.

Parameter	Differences	$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$
$\Delta\alpha$	+0.18 mas	1.0 σ
$\Delta\delta$	−0.32 mas	1.5 σ
$\Delta\mu_\alpha$	+0.02 mas/yr	0.2 σ
$\Delta\mu_\delta$	−0.14 mas/yr	1.5 σ
$\Delta\pi$	−0.01 mas	0.1 σ

parallax. The correlation matrix indicates that the 5 parameters are well separated.

The number of degree of freedom (19) is high enough to make the statistical significance of the formal uncertainties reliable. Various tests have been made for the robustness of the solution. One test has been to make two separate astrometric solutions, one with the first 6 epochs and one with the last 6 epochs of observations. Table 2 indicates the parameter differences between the two solutions.

Also, the 5 astrometric parameters of σ^2CrB determined by VLBI match, within uncertainties, the best (but less precise) optical determinations.

4. Implications for Planets Orbiting σ^2CrB

The lack of a sinusoidal signature in the post-fit coordinates residuals sets a limit on the presence of planets around σ^2CrB. The rms of these post-fit residuals (0.2 mas) can be taken as an upper limit on any systematic departure from linear motion for the star. Interestingly, the present accuracy of our VLBI measurement corresponds exactly to the detection threshold for a Jupiter-like planet around σ^2CrB when

12 years of data have been collected.

This interpretation is optimistic since BLACK and SCARGLE (1982) note that the fitted linear proper motion absorbs part of the planetary perturbation. These authors show that with observations sampling a single orbital period, the amplitude of the planetary perturbation is underestimated by as much as 47%. However, if the classical model (position, proper motion and trigonometric parallax) is complemented by a sinusoidal function and the *a priori* values for the amplitude, period and phase chosen to cover a large volume of the parameter space, no absorption of the planetary perturbation would occur and the 3 additional parameters can be fitted.

The location and stability of the radio centroid within the spectrocopic binary is a crucial question. There is no detailed model of the radio emitting region that can be used to derive this stability. It must be determined observationally and the rms of our post-fit coordinate residuals (0.2 mas or 1 $R_\odot$ at σ^2CrB) can also be interpreted as a measure of this stability. If the radio emission is coincident with one of the stars as expected, then the astrometric error induced by its motion around the other star could be reduced dramatically by solving for the binary motion. We have confirmed that the radio emission is indeed associated with a single star in the Algol system (LESTRADE *et al.*, 1993).

5. Future VLBI Astrometric Observations

As a by-product of our Hipparcos program, we have demonstrated that phase-referenced VLBI observations of the radio star σ^2CrB can achieve an astrometric precision of 0.2 mas (post-fit position residuals). Similar results have been obtained for the other stars of our Hipparcos program but with an astrometric precision 3 to 5 times larger. The best result is for σ^2CrB because the angular separation between this star and the reference source used is the smallest (0.5°).

The theoretical astrometric precision (SNR-limited) for phase-referenced interferometry is

$$\sigma_{\alpha,\delta} = \frac{1}{2\pi}\frac{1}{SNR}\frac{\lambda}{B} \tag{1}$$

(THOMPSON *et al.*, 1986). For our observations, $\sigma_{\alpha,\delta}$ is <26 *microarcseconds* with $B = 3000$ km, $\lambda = 3.6$ cm, and SNR > 15.

The astrometric precision achieved for σ^2CrB is several times the SNR-limited precision calculated above. There are at least four systematic error sources that prevent current observations from reaching this ultimate precision: 1) the extrapolation of the reference source VLBI phase in beam-switched observations to the time of the star observation, 2) the differential contribution of the atmosphere and ionosphere along the lines of sight to the reference source and target star, 3) the radio morphology of the reference source and, possibly, of the star, and 4) the orbital motion of the subgiant star (in binary systems). During the next 1–2 years, we intend to study the best approach to reducing these systematic errors. Our current efforts include faster antenna switching, improved ionosphere and troposphere models, finding closer reference sources, mapping reference source structure, and the inclusion of orbital motions in our astrometric fits.

6. Summary

Over the next two years, we plan to use one star, σ^2CrB, as a test-bed to reduce the present systematic errors in our astrometric measurements and, possibly, reach the SNR-limited precision of 20–30 microarcseconds on US-continental baselines. The sensitive Deep Space Network 70-m antenna at Goldstone along with the continental US VLBA antennas will provide a relatively continuous range of baselines from 1000 to 4000 km which correspond exactly to the angular resolution required for the RS CVn radio stars we observe. In addition, future improvements in sensitivity due to the construction of the Green Bank Telescope and the development of wider bandwidth data recording systems (e.g. Mark-IV) will allow a much larger sample of radio stars (and other weak radio sources) to be observed routinely with VLBI.

REFERENCES

BARDEN, S. C. (1985): *Ap. J.*, **295**, 162.

BLACK, D. C. and SCARGLE, J. D. (1982): *Ap. J.*, **263**, 854.

LESTRADE, J.-F., ROGERS, A. E. E., WHITNEY, A. R., NIELL, A. E., PHILLIPS, R. B. and PRESTON, R. A. (1990): *Ap. J.*, **99**, 1663.

LESTRADE, J.-F., PHILLIPS, R. B., PRESTON, R. A. and GABUZDA, D. C. (1992): *Astr. Ap.*, **258**, 112.

LESTRADE, J.-F., PHILLIPS, R. B., HODGES, M. W. and PRESTON, R. A. (1993): *Ap. J.*, **410**, 808.

ROGERS, A. E. E., CAPPALLO, R. J., HINTEREGGER, H. F., LEVINE, J. I., NESMAN, E. F., WEBBER, J. C., WHITNEY, A. R., CLARK, T. A., MA, C., RYAN, J., COREY, B. E., COUNSELMAN, C. C., HERRING, T. A., SHAPIRO, I. I., KNIGHT, C. A., SHAFFER, D. B., VANDENBERG, N. R., LACASSE, R., MAUZY, R., RAYHRER, B., SCHUPLER, B. R. and PIGG, J. C. (1983): *Science*, **219**, 51.

THOMPSON, A. R., MORAN, J. M. and SWENSON, G. W. (1986): *Interferometry and Synthesis in Radio Astronomy*, John Wiley, New York.

WENDKER, H. J. (1987): *Astr. Ap. Suppl.*, **69**, 87.