RESULTS OF VLBI OBSERVATIONS OF RADIO STARS AND THEIR POTENTIAL FOR LINKING THE HIPPARCOS AND EXTRAGALACTIC REFERENCE FRAMES.

Jean-Francois Lestrade[1], Robert A. Preston, Arthur E. Niell[2], Robert L. Mutel[3], and Robert B. Phillips[4]

(1) Bureau des Longitudes, Paris, France, on leave at the Jet Propulsion Laboratory, Pasadena, California, (2) Jet Propulsion Laboratory, Pasadena, California, (3) Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, (4) Haystack Observatory, Westford, Massachusetts.

ABSTRACT

VLBI observations of bright radio stars have been initiated in an attempt to measure the positions and proper motions of their radio components in order to tie the future HIPPARCOS stellar frame to a VLBI extragalactic reference frame. Through VLBI observations of a sample of 20 known radio stars we have identified 11 stars that should be appropriate for both astrometric VLBI and HIPPARCOS observations. Our measurements indicate that the angular extent of their radio emitting regions is small, i.e. $<$ 3 milliarcseconds for 7 of them. Most of these radio stars belong to the RS Canum Venaticorum class of binary systems.

1. INTRODUCTION

The HIPPARCOS project conducted by the European Space Agency will place optical astrometry into the Space Age. The HIPPARCOS satellite will measure the positions and proper motions of 10^5 stars brighter than 13th magnitude, providing a stellar reference frame with an expected intrinsic precision of about 2 milliarcseconds (per year for the proper motions) for the objects brighter than 11th magnitude (Kovalevsky 1980). The full potential of this precision will be attained only through the link of the HIPPARCOS system to a nearly-inertial system such as that provided by an extragalactic reference frame. Precise absolute positions and proper motions should, in principle, enhance studies of stellar and Solar System dynamics. In addition, this tie will result in a unified optical/radio high precision celestial reference frame.

We are attempting to achieve this link with the JPL VLBI celestial reference frame, which is composed of radio cores of distant quasars and galaxies. It currently contains ~ 130 sources spread

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uniformly over the sky from −45° to +84° declination. The estimated uncertainities in source positions fall primarily in the range 0.003″ to 0.010″ and have a mean value of ~ 0.007″ (Fanselow et al. 1983, Niell et al.; this conference).

None of the optical counterparts of the extragalactic radio sources of the JPL VLBI catalog can be detected by the telescope aboard the HIPPARCOS satellite due to its magnitude limit, and thus a direct link is impossible. However, some stars brighter than 11th magnitude, which can be observed by HIPPARCOS, exhibit radio emission, and, therefore, might serve as transfer objects for the link via VLBI measurements of their positions and proper motions with respect to angularly nearby extragalactic VLBI sources. Conceptually, only two such radio stars are necessary to link the two frames. In practice, however, according to the modeling and simulation of Froeschle and Kovalevsky (1982), 5 to 15 radio stars are desirable to be confident of the result.

2. SELECTION OF A SAMPLE OF RADIO STARS FOR HIPPARCOS AND VLBI OBSERVATIONS.

Stars which exhibit radio continuum emission can be categorized as either quasi-steady thermal emitters or highly variable non-thermal emitters. Generally, the bremsstrahlung in an optically thick ionized circumstellar shell enclosing a hot star is responsible for the thermal radio emission. Gyrosynchrotron (Ramaty 1969) and coherent radiation processes (Melrose and Dulk 1982) have been proposed to account for the non-thermal radio emission.

The well-known stellar system Algol was the first star detected with a connected-element radio interferometer (Ryle and Elsmore 1973) and then with the VLBI technique (Clark, Kellermann and Shaffer 1975 ; Clark et al. 1976). Since then, a few other radio stars have been detected with VLBI : SS 433 (Schilizzi et al., 1979, Walker et al. 1981, Niell, Lockhart and Preston 1981), CIR X-1 (Preston et al. 1983). However, of these stars, only Algol is optically bright enough for HIPPARCOS.

By analyzing the compilation of radio stars of H.J. Wendker (1982), we selected 22 stars as good candidates for HIPPARCOS and VLBI observations (Lestrade, Preston and Slade 1982). The criteria used were: a) optical magnitude brighter than 11 ; b) reported radio flux densities higher than 10 millijansky ; and c) probable compact radio component (<0.01″). It is conspicuous that 16 stars of this selection belong to a single stellar class, the RS Canum Venaticorum close binary systems. These selected stars exhibit non-thermal radio outbursts that are variable in intensity on time scales of a few hours, or less. Their radio flux densities vary from less than 1 mJy to 1 Jansky, although a typical outburst is below 100 mJy.

We have omitted the UV Ceti flare stars in our selection because their radio emission, although strong at meter wavelengths, is weak (<10 mJy) at centimeter wavelengths. However, we think they are still good candidates for the frame tie, considering the planned hardware improvements in sensitivity of several VLBI facilities. We have deliberately omitted the thermal stellar radio emitters since they have source sizes too extended (typically 0.1'' to 1'') for position determination at the milliarcsecond level of accuracy.

3. VLBI OBSERVATIONS

Several experiments were conducted using the high sensitivity Mark III recording system (Rogers et al., 1983) at 1.65, 2.3, 5 and 8.4 GHz. Arrays with wide ranges of baseline lengths were used because, in spite of the fact that the high time variability of the flux densities of the non-thermal stellar systems suggested compact structure, their source sizes were never directly measured and even reported to be possibly large with respect to their orbital dimensions (<3 milliarcseconds), according to various unpublished VLBI materials on RS CVn systems. In addition, the eclipsing RS CVn system AR Lac was observed by two groups of radio observers during optical eclipses. In its quiescent state of emission (<10 mJy), AR Lac showed no drop of its radio flux density and this was interpreted as evidence of a radio emitting region substantially larger than the component stars (Brown, Broderick, and Neff, 1979 ; Doiron and Mutel 1983). However, during a moderate outburst, Brown et al. report an eclipse of the radio emission of AR Lac.

The stations involved during our observations were the NASA Deep Space Stations at Goldstone and Madrid, the antennae of the U.S. VLBI Network, including the phased VLA, and the Effelsberg 100-m radiotelescope. The observing strategy for each experiment was a sequence of ''snapshots'' on approximately 15 radio stars from our list.

The purpose of these experiments was to ascertain if some of our candidate stars meet the basic requirements to be astrometrically used in VLBI. In that respect, their radio source sizes needed to be at the milliarcsecond level, or smaller, and their radio activity be sufficient that, although variable, they would be fairly dependable.

4. PRELIMINARY VLBI RESULTS : RADIO SOURCE SIZES AND ACTIVITY.

The data acquired during these experiments were correlated at Haystack Observatory using the NASA-NSF Mark III VLBI processor (Rogers et al., 1983). The calibration of the cross-correlation amplitudes to obtain flux densities was done by applying the measured system temperatures in the standard manner (Cohen 1975). Baseline aperture efficiencies were derived from VLBI observations and from quasi-simultaneous total flux density measurements, made with the 64-m antenna at Goldstone or with the VLA, of unresolved (or almost) strong extragalactic sources.

In Table 1 we show the degree of radio activity of the stellar systems detected during our experiments. Their relatively weak total flux densities were measured either by using an interferometer with a 20 km baseline at the Goldstone complex or with the VLA. During these experiments a total of 20 stars were observed and 11 were detected.

VLBI observations provide direct measurements of angular radio extent. In Table 2 we present the source sizes, or upper limits, as the full width half maximum (FWHM) of circular Gaussian sources fitted to the measured visibilities. However, the actual structure of the source on a scale of one milliarcsecond is almost certainly more complex, as suggested by the non-zero closure phases found in HR1099 and UX Arietis on large baseline triangles during two experiments. The angular size (FWHM) is generally smaller than the size of the overall stellar system (Radii + orbital diameter ~ 1 to 3 milliarcseconds), but on 83 July 27, UX Arietis has shown however clear evidence of a halo significantly larger containing 75% of the total flux density. Data analysis and discussion of the possible mechanism of the radio emission in HR5110, UX Arietis and HR1099 can be found in Lestrade et al. (1984) and Mutel et al. (1984). The large upper limits (<10 milliarcseconds) given in Table 2 come from stars unresolved on the sensitive but short baseline between Owens Valley and Goldstone in California (200 km); the actual radio source sizes are likely to be much smaller. The compactness of the radio emission from the stellar systems listed in Table 2 makes them good candidates for future VLBI astrometric measurements.

Star name	m_V	12/19/82 λ = 3.6cm	02/13/83 λ = 18cm	03/20/83 λ = 3.6cm	05/11/83 λ = 13cm	05/11/83 λ = 3.6cm	07/27/83 λ = 6cm
LSI 61°303	10.8	80		18	15	N	15
Algol	3	N		54	80	110	41
UX Arietis	7.3	90	95	14	20	N	127
HR1099	5.9	24	210	400	N	N	12
HR5110	5	32		15	13	N	165
Cyg X1	8.6						15
AR Lacertae	7	N		N	N	N	14
SZ Piscium	8.3				N	N	23
λ Andromedae	4			N	8	N	19
II Pegasis	8	100		9	N	N	N

The following stars were observed but not detected, the number of observations is in parentheses: UV Psc (2), CC Cas (1), β Lyr (1), R Aql (2), HD195040 (1), RT Lac (5), HR 8575 (2), HD216489 (3), HR9024 (1)

Table 1 : Total flux densities (milliJansky) of the stars detected during five Mark III VLBI experiments. The letter N indicates observation but non-detection.

Star name	dist. (pc)	Overall size of binary system	12/19/82 λ = 3.6cm (*)	02/13/83 λ = 18cm (**)	03/20/83 λ = 3.6cm	05/11/83 λ= 13cm	05/11/83 λ= 3.6cm	07/27/83 λ= 6cm
LSI 61 303	2300				<10			
Algol	25	2.7			2.1 ±0.3	2.0 ±0.2	0.5 ±0.2	0.8 ±0.25
UX Arietis	50	1.7		<2.1	<10			1.4 ±0.25 (+ extended component)
HR1099	35	2.3		<2.1	0.8 ±0.12			<5.
HR5110	52	1.3	<1.4		<10			0.90 ±0.30
σ Cor. Bor.	23				<10			0.8 ±0.25
Cyg X1	2500							0.8 ±0.25
AR Lacertae	47	1.3						<3.
SZ Piscium	100	0.7						0.6 ±.25
λAndromedae	23	2.						<4.
II Pegasis	29	3.			<10			

References : (*) Lestrade et al. 1984, (**) Mutel et al. 1984.

Table 2 : Angular sizes (milliarcsecond) of the radio sources detected in 5 RS CVn systems, in Algol and in Cyg X1. The angular sizes are derived as the full width half maximun (FWHM) of a circular Gaussian source fitted to the measured visibilities. The uncertainities are formal errors.

5. PLANS TO LINK THE HIPPARCOS AND RADIO EXTRAGALACTIC FRAMES :

5.1. Radio stars identification

In the northern sky 70 close binary systems are known to be RS CVn from their optical and spectroscopic properties (Hall 1981). It is unclear, to our knowledge, if high sensitivity radio surveys have probed all of them. In the southern sky 40 close binary systems exhibiting Ca II H and K emissions, which is one of the spectroscopic properties of the RS CVn systems, have been identified (Weiler and Stencel 1979). Very few attempts have been made to detect radio emission from the stars in this hemisphere.

For our astrometric goal of tying the stellar and extragalactic frame, coverage of the celestial sphere as uniform as possible is desirable. We are conducting a high sensitivity survey with the VLA between 90° and -45° of declination; 7 new RS CVn systems have been detected at low flux density level (<10 mJy). Two Australian radio astronomy groups are planning experiments related to this search with the Deep Space Network facilities and Parkes.

5.2. Astrometry with radio stars

Sensitive VLBI observations of radio stars over a few years should yield their proper motions in addition to their positions at epoch. Comparison of the positions and proper motions measured by VLBI to those to be measured by HIPPARCOS should give the global rotations and rotation rates of the stellar sphere with respect to the stable extragalactic VLBI reference frame according to the formulation :

$$\vec{\mu}_{VLBI} = [R]\,\vec{\mu}_{HIP}$$

$$\dot{\vec{\mu}}_{VLBI} = [R]\,\dot{\vec{\mu}}_{HIP} + [\dot{R}]\,\vec{\mu}_{HIP}$$

where $\vec{\mu}_{VLBI}$, $\vec{\mu}_{HIP}$, $\dot{\vec{\mu}}_{VLBI}$, $\dot{\vec{\mu}}_{HIP}$, are directions and the proper motions of a star measured respectively by VLBI in the extragalactic reference frame and by HIPPARCOS in its own coordinate system. $[R]$ and $[\dot{R}]$ are the matrices containing the 3 rotation angles and their rates transforming the stellar coordinates into the extragalactic ones.

These astrometric VLBI observations will be performed using the technique of differential VLBI. Alternate observations of a radio star and an angularly nearby extragalactic source will yield differenced observables which should provide an accurate differential position between the two sources owing to the cancellation of the systematic effects. Two separate approaches to the differential measurements will be investigated :

a) Diurnal phase signature : observations at two antennae over more than six hours will provide a diurnal signature in the differenced VLBI phase between the two sources from which the angular separation can be determined. Since each source is not continuously observed, the phase history for each one must be unambiguously connected (no 2π slips) through observing gaps (Shapiro et al. 1979).

b) Absolute phase : If the integral number of cycles in the differenced VLBI phase between the two sources can be determined for a short or intermediate baseline length (20 to 200 km), then phase connection is not required. At a minimum, only two observations of the source pair would be required to determine the angular separation. Determination of the integer number of cycles requires accurate a priori knowledge of the source separation, which might be accomplished by using differential unambiguous delays and fringe rates measured on a longer baseline (>1500 km) or by the VLA. The ability to resolve the ambiguities will depend on baseline length and source separation.

The ultimate precision in determining radio positions and proper motions of stars will depend on the mechanism(s) which generate(s) their radio emission. It is still unknown where and how stable the radio emitting region is with respect to the optical counterpart; future continuous monitoring of their positions will address these questions.

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Discussion:

TOWNES: What red giants have you detected and how many others can you do?
NIELL: I don't quite know the stellar contents of these and I don't know which are red giants (radio stars).
WALTER: Considering the large time requirements, how many radio stars will your installation be able to deal with on a regular basis thus ensuring the determination of accurate proper motions?
NIELL: It will be difficult to observe more than a few sources as often as twice a year.
DEBARBAT: Do you have any detailed astrometric positions for Algol?
NIELL: We have a preliminary reduction for the position at one epoch only.