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MERLIN ASTROMETRY OF 11 RADIO STARS

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ABSTRACT

We report accurate positions in the International Celestial Reference Frame (ICRF) for 11 radio stars. Observations were made using the Multi-Element Radio Linked Interferometer Network at a radio frequency of 5 GHz. The positions are estimated to be accurate at the 5 mas level. Positions were obtained directly in the ICRF by phase referencing the radio stars to ICRF quasars whose positions are estimated to be accurate at the 0.25 mas level. We use our results together with results of previous observations to obtain proper-motion estimates for these stars. The average proper-motion uncertainties are 1.1 mas yr^{-1} in $\mu_{\alpha \cos \delta}$ and 1.2 mas yr^{-1} in μ_δ, comparable to the *Hipparcos* values.

Key words: astrometry — radio continuum: stars — techniques: interferometric

1. INTRODUCTION

The International Celestial Reference Frame (ICRF) is currently defined by the VLBI-determined radio positions of extragalactic objects (Ma et al. 1998; Gambis 1999, p. 87; Fey et al. 2004). The ICRF is the realization of the International Celestial Reference System (ICRS; Arias et al. 1995) at radio wavelengths and is the International Astronomical Union–adopted fundamental astronomical reference frame. The *Hipparcos* catalog (Perryman et al. 1997) is the realization of ICRS at optical wavelengths. The link between the *Hipparcos* catalog and the ICRF was accomplished through a variety of ground-based and space-based efforts (Kovalevsky et al. 1997), with the highest weight given to VLBI observations of 12 radio stars by Lestrade et al. (1999). The standard error of the alignment was estimated to be 0.6 mas at epoch 1991.25, with an estimated error in the system rotation of 0.25 mas yr^{-1} per axis (Kovalevsky et al. 1997).

At the epoch of our observations (2001.83), the error associated with the *Hipparcos*-ICRF frame link is estimated to be $\approx$2.6 mas. In addition to the uncertainties in the frame tie, there are also errors associated with the measured positions, proper motions, and parallaxes of individual sources. These errors are currently estimated to be in excess of 10 mas (epoch 2005) and combine to seriously limit the ability to align radio and optical images of particular sources. Frame rotation and proper-motion errors are particularly insidious, as their effects are cumulative over time.

The astrometric accuracy of future space-based missions at optical wavelengths will allow a more accurate connection between the stellar and extragalactic frames than was achievable with *Hipparcos*. Astrometric positions of Galactic and extragalactic sources obtained from these missions will likely surpass the accuracy of the current ICRF and may define a future-generation ICRF. However, there will continue to be a need for an accurate link between a radio reference frame and potential future optical realizations of the ICRF, as a precise link will enable astrophysical interpretations of high-resolution, multiwavelength imaging observations. Of the astrometric missions currently under development, only the European Space Agency's *Gaia* mission will accurately measure astrometric positions of a large number of extragalactic sources. Pointed missions such as NASA's SIM PlanetQuest mission will be limited to a small number of only the brightest extragalactic sources. As a result, it is still crucial to obtain the astrometric positions of a large number of Galactic sources visible in both the radio and the optical to provide a connection between the two frames.

An improved link between the radio and optical reference frames will have significant impact on many areas of astrophysics, e.g., the study of active binary stars. In particular, no consensus has yet developed concerning the physics of the formation and evolution of the radio emission associated with these active binary star systems. For most active binaries, the location of the radio emission with respect to the binary components is unknown; e.g., Is the radio-emitting region centered on one of the stars, is it located in the intrabinary region, or does it surround both stars? This uncertainty can be attributed, in part, to inadequacies in the radio-optical frame link.

In this paper we present 5 GHz observations of 11 radio stars made using the Multi-Element Radio Linked Interferometer Network (MERLIN) in 2001 October. The observations described here represent a continuation of a long-term program (since 1978) to obtain accurate astrometric radio positions and proper motions for $\approx$50 radio stars that can be used to connect the current radio-based ICRF to future space astrometry reference frames. Previous astrometric radio star observations derived from Very Large Array (VLA) data collected from 1978 through 1995 have been presented by Johnston et al. (1985, 2003). The average position uncertainty from these observations was estimated to be $\approx$30 mas per coordinate. There has also been a successful VLA pilot program (Boboltz et al. 2003) using the VLA in its most extended A configuration (this configuration provides the longest baselines possible with the VLA alone) linked by fiber optic transmission line to the Very Long Baseline Array (VLBA) antenna located in Pie Town (PT), New Mexico. Using improved techniques, including fast phase switching, and observing at a frequency of 8 GHz, these VLA + PT observations yielded position uncertainties of $\approx$10 mas. The observations of

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TABLE 1

Observed Radio Stars and Corresponding ICRF Calibrators

Star Name	*Hipparcos* Number	ICRF				Separation (deg)
		Calibrator	Category[a]	α(J2000.0)[b]	δ(J2000.0)[b]	
LSI 61 303	12469	0302+625	C	03 06 42.659558	62 43 02.02417	3.5
Algol	14576	0309+411	D	03 13 01.962129	41 20 01.18353	1.0
UX Ari	16042	0333+321	O	03 36 30.107599	32 18 29.34239	4.2
HR 1099	16846	0336−019	C	03 39 30.937787	−01 46 35.80399	2.5
B Per	20070	0420+417	C	04 23 56.009795	41 50 02.71277	8.5
KQ Pup	36773	0727−115	O	07 30 19.112472	−11 41 12.60048	3.0
54 Cam	39348	0749+540	D	07 53 01.384573	53 52 59.63716	3.6
RS CVn	64293	1308+326	D	13 10 28.663845	32 20 43.78295	3.6
HR 5110	66257	1315+346	C	13 17 36.494189	34 25 15.93266	4.4
δ Lib	73473	1511−100	C	15 13 44.893444	−10 12 00.26435	3.6
σ^2 CrB	79607	1611+343	C	16 13 41.064249	34 12 47.90909	0.4
β Lyr	92420	1901+319	O	19 02 55.938870	31 59 41.70209	3.0
HD 199178	103144	2037+511	D	20 38 37.034755	51 19 12.66269	7.5
AR Lac	109303	2200+420	O	22 02 43.291377	42 16 39.97994	3.6
IM Peg	112997	2250+190	N	22 53 07.369176	19 42 34.62843	2.9

[a] ICRF source category (Ma et al. 1998; Gambis 1999; Fey et al. 2004): (D) defining; (C) candidate; (O) other; (N) new in ICRF extension 1.

[b] ICRF Extension 1 source positions (Gambis 1999). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

Boboltz et al. (2003) were carried out in 2000 December on a subset of the Johnston et al. (2003) list. When combined with the previous observations, Boboltz et al. (2003) calculated proper-motion uncertainties rivaling those from *Hipparcos*. These authors also used their data to check the alignment between the *Hipparcos* and ICRF frames. It was found that at epoch 2000 December there was no significant misalignment between the *Hipparcos* frame and the ICRF at the level of the formal errors of ≈3 mas.

We combine our MERLIN positions with the VLA positions obtained by Johnston et al. (1985, 2003) and Boboltz et al. (2003) to obtain updated estimates of the proper motions for 9 of the 11 detected radio stars and compare the resulting proper motions with the corresponding *Hipparcos* values and those of Boboltz et al. (2003).

2. OBSERVATIONS AND ANALYSIS

Observations were made on 2001 October 27–30 using the six antennas of the MERLIN array. The configuration and operation of the array is described in Thomasson (1986). Observations were made at a radio frequency of 5 GHz using a total bandwidth of 16 MHz. At an observing frequency of 5 GHz, MERLIN has a nominal resolution (synthesized beam) of ≈50 mas.

A total of 15 radio stars were observed. Observations were made in a phase-referencing mode using high astrometric quality ICRF reference sources to obtain high-accuracy radio star positions. The positions of ICRF quasars are estimated to be accurate at the ≈0.25 mas level. Each star was observed approximately three times over the course of the experiment. Each "observation" consisted of approximately eight scans (alternating between 6 minutes on the source and 2 minutes on the ICRF reference calibrator) for a total on-source time of ≈48 minutes per observation. The radio stars observed and their associated ICRF phase reference calibrator sources are listed in Table 1.

Due to unknown reasons, only 11 of the 15 observed stars were detected. In addition, not all stars were detected in all observations. These nondetections could be due to poor phase coherence in the troposphere for short periods of time, leading to unsuccessful phase transfer between the calibrator and the program source. Alternatively, radio stars are known to be variable over a time span of days, ranging in flux density anywhere from quiescent levels of a few millijanskys to many tens of millijanskys during flares, so the nondetections could be due simply to a lack of sensitivity. Since the duration of the observations reported here spanned several days, we suggest that the latter is likely the case, at least for those stars detected in only one or two of the scheduled observations. The four stars that were not detected in any observation were most probably too weak to be detected using the given observing parameters.

The data were calibrated and then imaged using the Astronomical Image Processing System (AIPS) software. Each observation was processed separately (i.e., the data from each observation were not combined for imaging), and an image was made from each observation. Gaussian models were fitted to the emission in the final images using the AIPS task *jmfit* to obtain a least-squares estimate of the position and associated formal uncertainty for each star for each observation.

3. RESULTS

3.1. *Positions in the ICRF*

The final estimated positions of the detected radio stars together with their associated uncertainties are listed in Table 2. As a direct result of our use of the phase-referencing technique to reference the radio stars to ICRF quasars, the positions listed in this table are given directly in the ICRF. The average (median) position uncertainties for all 11 detected stars is 4.6 mas (4.1 mas) in right ascension, $\alpha \cos \delta$, and 5.7 mas (5.2 mas) in declination, δ.

Not all stars were detected in all observations (presumably for the reasons discussed in § 2). This is noted in the last column of Table 2 as the number of successful observations (independent position estimates) that went into the listed positions and their associated uncertainties. The positions and uncertainties listed in Table 2 were estimated in one of two ways, depending on whether the source was detected in multiple observations or in only a single observation.

If a given star was detected in more than one observation, the weighted mean position was calculated using the *jmfit* least-squares position estimates for the individual observations,

TABLE 2
RADIO STAR POSITIONS FOR JULIAN EPOCH 2001.8276 (MJD 52,212.02)

Star Name	*Hipparcos* Number	α(J2000.0)[a]	δ(J2000.0)[a]	N_{obs}[b]
LSI 61 303	12469	02 40 31.6638 ± 0.00091 (±0.0066)	61 13 45.594 ± 0.0068	3/3
Algol	14576	03 08 10.1343 ± 0.00024 (±0.0027)	40 57 20.335 ± 0.0031	3/3
UX Ari	16042	03 26 35.3877 ± 0.00028 (±0.0037)	28 42 54.086 ± 0.0047	1/3
HR 1099	16846	03 36 47.2869 ± 0.00025 (±0.0038)	00 35 15.617 ± 0.0050	1/3
B Per	20070	04 18 14.6276 ± 0.00043 (±0.0041)	50 17 43.713 ± 0.0052	1/3
KQ Pup	36773	...	...	0/2
54 Cam	39348	08 02 35.7768 ± 0.00039 (±0.0032)	57 16 24.945 ± 0.0096	3/3
RS CVn	64293	...	...	0/3
HR 5110	66257	13 34 47.8224 ± 0.00059 (±0.0071)	37 10 56.653 ± 0.0055	3/3
δ Lib	73473	15 00 58.3425 ± 0.00028 (±0.0041)	−08 31 08.225 ± 0.0067	1/2
σ^2 CrB	79607	16 14 40.8120 ± 0.00021 (±0.0026)	33 51 30.821 ± 0.0042	3/3
β Lyr	92420	...	...	0/3
HD 199178	103144	20 53 53.6549 ± 0.00063 (±0.0067)	44 23 11.087 ± 0.0051	2/3
AR Lac	109303	22 08 40.8073 ± 0.00054 (±0.0057)	45 44 32.189 ± 0.0066	3/3
IM Peg	112997	...	...	0/2

[a] Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Errors in parentheses for the right ascension are given in arcseconds.
[b] The number of successful observations over the number of attempted observations. Each "observation" represents eight scans (alternating between 6 minutes on the source and 2 minutes on the ICRF reference calibrator) for a total on-source time of ≈48 minutes.

weighted by the *jmfit* formal position uncertainties. This is the position listed in Table 2 for sources detected in more than one observation. Next, the weighted rms (wrms) position scatter was calculated for each of these stars. Finally, as an estimate of the position uncertainty for each star, the root-sum-square (rss) of the wrms position scatter and the largest value of the *jmfit* least-squares formal uncertainty for all scans of a source was calculated. This last step is meant to conservatively account for possible systematic errors introduced into the positions by such factors as the variable troposphere, etc. The resulting rss values are the position uncertainties listed in Table 2 for sources detected in more than one observation.

If the source was detected in only a single observation, the reported position in Table 2 is the *jmfit* least-squares value. The associated uncertainty was estimated by taking the rss of the *jmfit* formal position uncertainty and the average value of the wrms position scatter calculated above for sources with multiple observations. The average wrms position scatter for the seven stars detected in more than one observation is 3.7 mas in $\alpha \cos \delta$ and 4.7 mas in δ. Again, this last step is meant to conservatively account for possible systematic errors in the measured positions.

As a measure of the accuracy of our results, we compare our estimated positions with those of *Hipparcos*. Differences between our MERLIN positions and the *Hipparcos* positions updated to the epoch of our observations for the 11 detected radio stars are shown in Figures 1 and 2. The average differences are 3.4 mas in $\alpha \cos \delta$ and 9.8 mas in δ. If we exclude the star UX

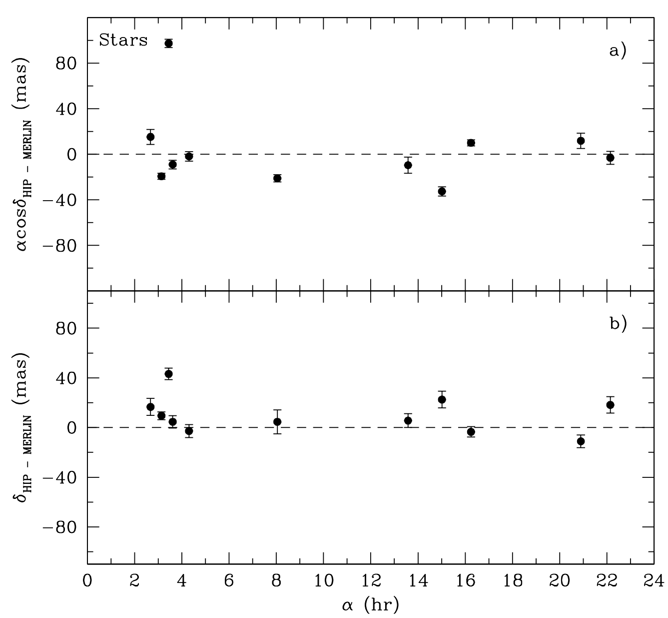

FIG. 1.—Differences between our MERLIN positions and the *Hipparcos* positions updated to the epoch of our observations for the 11 detected radio stars. Differences are (*a*) $\Delta\alpha \cos \delta$ and (*b*) $\Delta\delta$ plotted as functions of right ascension α. Error bars are from our MERLIN measurements only. The discrepant data points at $\alpha \sim 3^h$ are for UX Ari.

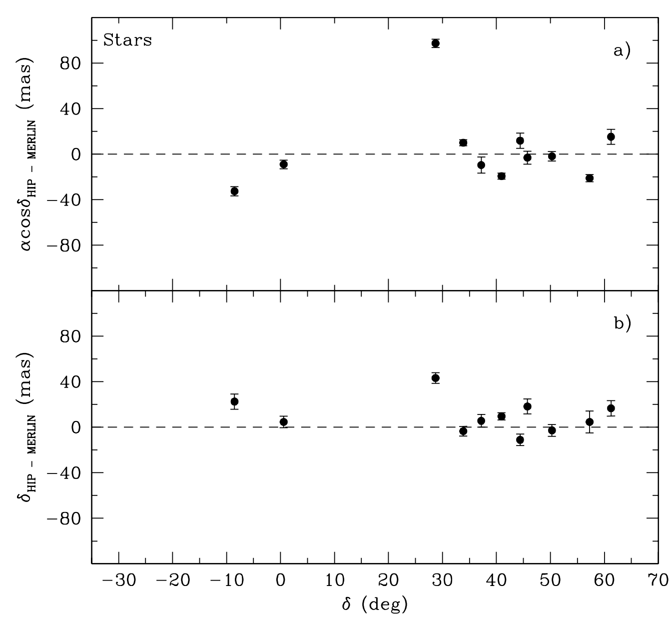

FIG. 2.—Differences between our MERLIN positions and the *Hipparcos* positions updated to the epoch of our observations for the 11 detected radio stars. Differences are (*a*) $\Delta\alpha \cos \delta$ and (*b*) $\Delta\delta$ plotted as functions of declination δ. Error bars are from our MERLIN measurements only. The discrepant data points at $\delta \sim 30^\circ$ are for UX Ari.

TABLE 3
Radio Star Proper Motions

Star Name	*Hipparcos* Number	N_{pos}[a]	$\mu_{\alpha \cos \delta}$ (mas yr^{-1})	μ_{δ} (mas yr^{-1})
LSI 61 303[b]	12469	2	...	...
Algol[c]	14576	7	3.30 ± 0.74	−2.87 ± 0.76
UX Ari	16042	15	37.81 ± 0.51	−105.55 ± 0.51
		15	27.77 ± 0.51[d]	−110.24 ± 0.51[d]
HR 1099	16846	14	−31.79 ± 0.46	−161.63 ± 0.48
B Per	20070	6	45.85 ± 1.37	−58.72 ± 1.41
54 Cam	39348	3	−36.06 ± 1.55	−57.06 ± 1.61
HR 5110	66257	6	85.17 ± 1.12	−9.52 ± 1.12
δ Lib	73473	5	−64.90 ± 1.68	−5.38 ± 1.76
σ^2 CrB	79607	3	−267.18 ± 1.44	−86.84 ± 1.54
HD 199178[b]	103144	2	...	...
AR Lac	109303	6	−51.13 ± 1.42	47.36 ± 1.42

[a] Number of positions used in the weighted least-squares fit to estimate proper motions.
[b] No statistically significant proper motion could be obtained for these radio stars.
[c] Positions for Algol were referenced to the center of mass of the triple-star system before fitting.
[d] UX Ari proper motions with acceleration terms included; evaluated at (Julian) central epochs of 1999.4212 in $\alpha \cos \delta$ and 1999.4117 in δ.

Ari, which is a known ternary system with ≈0.″3 between the most widely separated components (Boboltz et al. 2003), the average differences are −5.97 mas in $\alpha \cos \delta$ and 6.4 mas in δ.

3.2. *Proper Motions*

We have combined our MERLIN positions at epoch 2001.83 with the VLA positions obtained by Johnston et al. (1985, 2003) and the VLA + PT positions of Boboltz et al. (2003) to compute updated estimates of the proper motions for 9 of the 11 detected radio stars. Two of the observed stars (LSI 61 303 and HD 199178) have insufficient data at the present time to calculate a statistically significant proper motion. Additional observations are needed for these stars. Weighted linear least-squares fits were performed using the combined data set. Position errors of the previous VLA observations were estimated to be 30 mas in $\alpha \cos \delta$ and δ by Johnston et al. (2003), and we have adopted these values. Position errors for the VLA + PT observations were taken from Table 2 of Boboltz et al. (2003), and the position errors of the MERLIN observations are from Table 2 of this paper. Because the sampling interval of the combined data set is not sufficient to determine parallax independently, *Hipparcos* values were used to adjust the positions (i.e., remove the effect of parallax) before fitting. In addition, the positions for Algol, a known ternary system, were referenced to the center of mass of the triple-star system before fitting for proper motion. The resulting proper motions are listed in Table 3.

As a measure of the accuracy of our proper-motion results, we compare our estimated values with those of *Hipparcos* and of Boboltz et al. (2003). The average proper-motion uncertainties from Table 3 are 1.1 mas yr^{-1} in $\mu_{\alpha \cos \delta}$ and 1.2 mas yr^{-1} in μ_{δ}. When compared to the *Hipparcos* values of 0.85 and 0.84 mas yr^{-1}, respectively, we see that we have almost reached the same level of accuracy as *Hipparcos* for these nine radio stars. Indeed, for several of the stars listed in Table 3, our proper-motion errors are better (smaller) than those obtained by *Hipparcos*. Shown in Figure 3 are the differences between the proper motions listed in Table 3 and the corresponding *Hipparcos* values. Error bars are the rss of the errors given in Table 3 and those from the *Hipparcos* mission.

The average proper-motion values from the VLA + PT observations of Boboltz et al. (2003) are 1.5 mas yr^{-1} in $\mu_{\alpha \cos \delta}$ and 1.4 mas yr^{-1} in μ_{δ}. Shown in Figure 4 is a comparison between the proper motions listed in Table 3 and the corresponding VLA + PT values from Boboltz et al. (2003). Error bars are the rss of the errors given in Table 3 and those from Table 4 of Boboltz et al. (2003). Examination of this figure shows that our computed proper motions are almost in complete agreement with those of Boboltz et al. (2003). This is not an unexpected result, since the two analyses share a common data set, with the addition of our MERLIN observations as the primary difference. However, the excellent agreement in the computed proper motions indicates

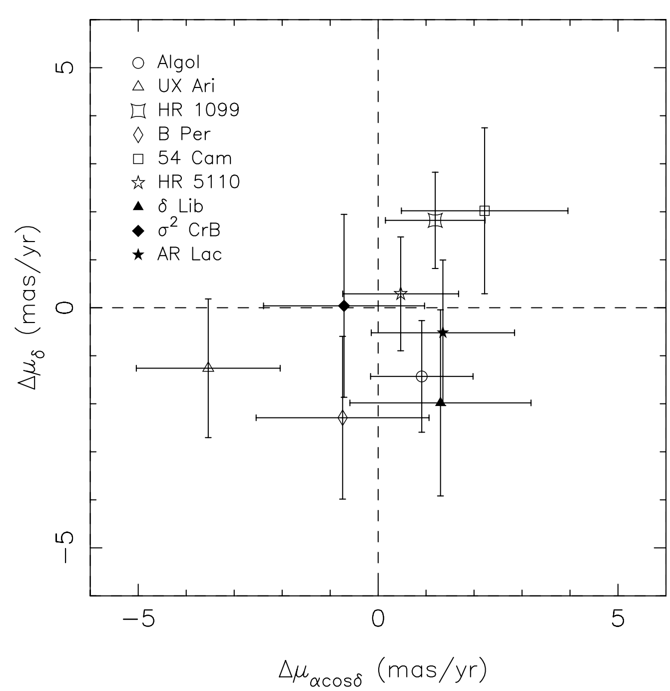

Fig. 3.—Differences between the proper motions listed in Table 3 and the *Hipparcos* proper motions. Error bars are the rss of the errors given in Table 3 and those from the *Hipparcos* mission.

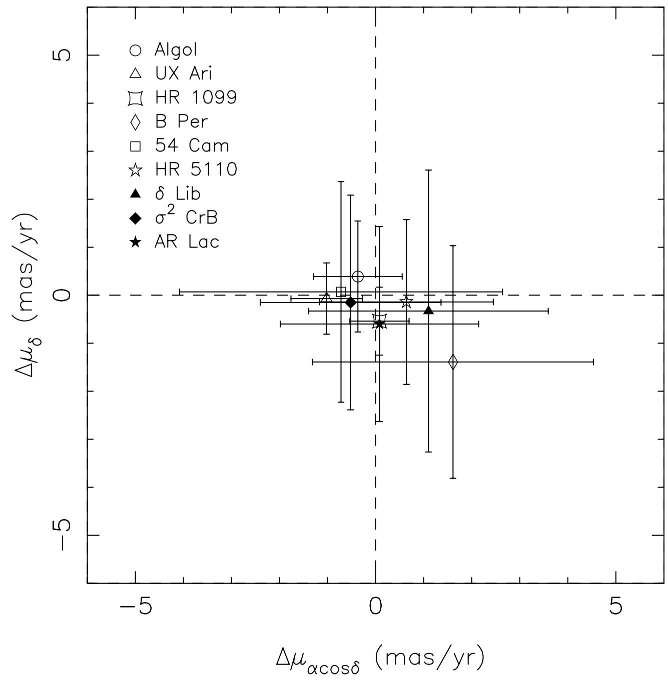

FIG. 4.—Differences between the proper motions listed in Table 3 and those of Boboltz et al. (2003). Error bars are the rss of the errors given in Table 3 and those from Table 4 of Boboltz et al. (2003).

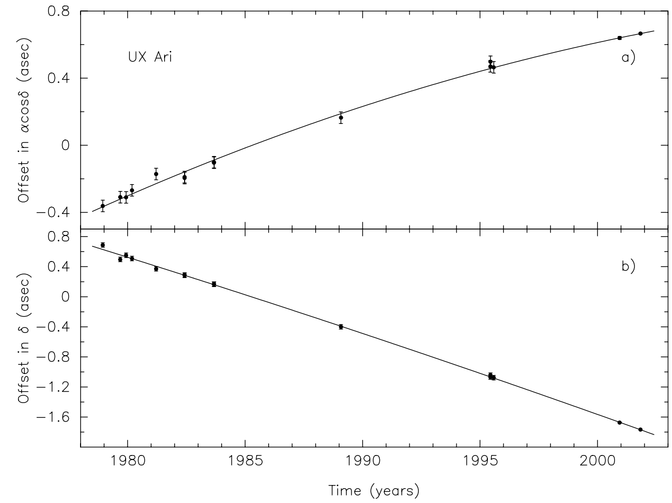

FIG. 5.—Position time series of UX Ari from the combined data of Johnston et al. (2003), Boboltz et al. (2003), and Table 2 of this paper, showing proper motion in (*a*) $\alpha\cos\delta$ and (*b*) δ. The solid curves represent weighted least-squares fits of a second-order polynomial (linear term plus acceleration) to the data. The central epoch of the data is 1999.4212 in $\alpha\cos\delta$ and 1999.4117 in δ.

that, as was shown for the VLA + PT by Boboltz et al. (2003), MERLIN is a viable instrument for astrometric observations of this nature. This conclusion is supported by the results of Garrington et al. (1998), who demonstrated the potential of MERLIN for differential astrometry by evaluating the accuracy of the ICRF-*Hipparcos* link using a set of radio stars independent from those of Lestrade et al. (1999).

Examination of Figure 4 shows that our proper motions are consistent with those of Boboltz et al. (2003) at the 1 σ level, with the exception of UX Ari in $\alpha\cos\delta$, which is marginally different at only the 1.4 σ level. As discussed in § 3.1, UX Ari is a known ternary system with $\approx 0\farcs3$ between the most widely separated components. The closer pair has been resolved using speckle techniques nine times since 1985, most with separations greater than about 50 mas (B. Mason 2005, private communication). The most recent measure of Balega et al. (2004) was at only 42 mas. There is most certainly motion in this system, but it has yet to be characterized. Which star of the pair is detected in the radio is also uncertain and may be the reason for the discrepant position shown in Figures 1 and 2.

Both Lestrade et al. (1999) and Boboltz et al. (2003) report statistically significant nonlinear proper motion (acceleration) in both coordinates of UX Ari. Boboltz et al. (2003) report values of $\dot{\mu}_{\alpha\cos\delta} = -0.60 \pm 0.03$ mas yr^{-2} and $\dot{\mu}_\delta = -0.31 \pm 0.02$ mas yr^{-2}. These values are in complete agreement with those of Lestrade et al. (1999). To further investigate nonlinear motions, weighted least-squares fits with the addition of an acceleration term were performed for all sources (i.e., the data were fitted with a second-order polynomial). A central epoch,

$$\mathcal{E}_c = \frac{\sum_i \mathcal{E}_i \sigma_i^{-2}}{\sum_i \sigma_i^{-2}},$$

was computed in both right ascension and declination for each star before fitting. Only the star UX Ari unambiguously shows a statistically significant nonlinear proper motion. Figure 5 shows the position time series in $\alpha\cos\delta$ and δ for UX Ari. The calculated acceleration terms are $\dot{\mu}_{\alpha\cos\delta} = -0.65 \pm 0.03$ mas yr^{-2} and $\dot{\mu}_\delta = -0.30 \pm 0.03$ mas yr^{-2} at central epochs of 1999.4212 and 1999.4117, respectively. These fits are shown as solid lines in Figure 5. Our results are in complete agreement with those of Boboltz et al. (2003).

Two additional stars (HR 1099 and AR Lac) show indications of nonlinear proper motion but, while statistically significant (based on the formal errors of the fit), do not have sufficient data sampling for an unambiguous measurement. The star HR 1099 is a close active binary of the RS CVn type with an orbit diameter of ~1.5 mas. The close binary is part of visual binary ADS 2644A, with an angular separation of $6\farcs2$ and an orbital period of 2102 yr (Lestrade et al. 1999). Nonlinear motion of this system is therefore possible, but additional data are required for confirmation. The star AR Lac is an eclipsing close binary, also of the RS CVn type, with an orbital diameter of ~1.0 mas. Unambiguous detection of nonlinear motion in this system would be interesting, as there is no known widely separated third component in this system.

4. SUMMARY

We have observed 15 radio stars using MERLIN and report astrometric positions given directly in the frame of the ICRF for 11 stars. Uncertainties are estimated to be on the order of 5 mas or better. Average differences between our MERLIN positions and the *Hipparcos* positions updated to the epoch of our observations are 3.4 mas in $\alpha\cos\delta$ and 9.8 mas in δ. If we exclude the star UX Ari, which is a known ternary system with a separation of $\approx 0\farcs3$ between the most widely separated components (Boboltz et al. 2003), the average differences are −5.97 mas in $\alpha\cos\delta$ and 6.4 mas in δ. We have combined our MERLIN positions at epoch 2001.83 with the VLA positions obtained by Johnston et al. (1985, 2003) and the VLA + PT positions of Boboltz et al. (2003) to compute updated estimates of the proper motions for nine of the detected radio stars. The average proper-motion uncertainties are 1.1 mas yr^{-1} in $\mu_{\alpha\cos\delta}$ and

1.2 mas yr^{-1} in μ_δ. These values are comparable to the *Hipparcos* values for these stars. For several of the observed stars, our proper-motion errors are better than those obtained by *Hipparcos*. The star UX Ari unambiguously shows a statistically significant nonlinear proper motion. Two additional stars (HR 1099 and AR Lac) show indications of nonlinear proper motion but do not have sufficient data sampling for an unambiguous measurement.

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