OBSERVATIONS OF RADIO STARS IN GEODETIC VLBI EXPERIMENTS

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ABSTRACT. Proper motion and parallaxes of radio stars will enable us to align the latest International Celestial Reference Frame (ICRF3) based on VLBI observations with the optical astrometric catalogue obtained by the Gaia mission. The Gaia mission has observed approximately 500,000 extragalactic objects in optical with a competitive precision, and produced an independent astrometric catalogue of 2820 objects common to the ICRF2 (Gaia Collaboration et al. 2018) and contains astrometric solutions of parallaxes and proper motions for significant amount of stars. This provides a rare opportunity for independent verification of the VLBI astrometric catalogues. However, due to an average parallax zero-point of -29 μas of the Gaia catalogue (Lindegren et al. 2018), independent assessment of the Gaia parallaxes is required. Unfortunately, very few optically bright radio stars were observed with VLBI, therefore it is important to identify more Galactic stars that could be observed by both VLBI and optical mission for the parallax verification. Here we show the astrometric results for five radio stars (HR1099, UX Ari, HR132742, HR5907 and LSI+61 303) in several VLBI experiments between 2015 and 2019.

1. ASTROMETRIC OBSERVATIONS OF RADIO STARS IN THE PAST

Radio stars were observed since 1970s during some astrophysical projects (e.g. Lestrade et al. 1984). The brightest radio stars (optical magnitude brighter than 11 mag) could serve as transfer objects for the link between the optical and radio reference frames in the time of Hipparcos (Lestrade et al. 1986). Dedicated VLBI experiments in phase-reference mode were organised between 1983 and 1995 using VLBI facilities in USA and Europe (Lestrade et al. 1999). Van Leeuwen (2007) presented final results of the link of the Hipparcos and VLBI reference frames using 11 radio stars those final positional uncertainties were measured at the level from 0.12 to 5 mas. The solution also comprises the proper motions and trigonometric parallaxes of the objects. Ten stars were found to be in close binaries, and few of them are members of wide visual binaries. One star, UX Ari showed a statistically significant accelerated motion, probably, caused by a hidden companion.

Boboltz et al (2003, 2007) run new experiments using the Very Large Array and Pie Town VLBA antenna between 2000 and 2004 to determine astrometric positions of 59 radio stars in the International Celestial Reference Frame (ICRF). The new positions were estimated with position errors from 3 to 25 mas with a mean value about 10 mas. Combination of all available astrometric results over 1978-2004 resulted in estimation of the proper motion of all stars with formal uncertainties of about 1 mas/year.

2. NEW VLBI OBSERVATIONS

Since phase-reference VLBI observations demand at least one calibrator radio source, the estimated positions and proper motion of a radio star could be affected by either poor astrometric positions or intrinsic structure effect of the selected calibrators. Therefore, we tried to run a few VLBI experiments in the absolute astrometric mode, observing the radio stars at S and X bands simultaneously to calibrate the ionosphere effects. No calibrator radio sources are necessary in this mode. For the 'pilot project' four radio stars (HR1099, UX Ari, HR132742 and HR5907) were selected. They are all located near the equatorial zone, suitable for joint observations using Asian and Oceanian VLBI stations. In the observing sessions dedicated to absolute astrometry and geodesy, we inserted some scans of radio stars with a goal to detect them and obtain their positions estimation. Tianma65 or Parkes radio telescope was used as an anchor station in the observing network to improve the detection rate of the weak radio stars. The experiments are summarized in Table **??**.

Table 1: Summary of VLBI experiments with observations of radio stars.

Code	Date	Dur. (hr)	Data rate (Mbps)	Stations[a]
AOV003	17-May-2015	24	256	HbHoIsKeKmT6TsWwYg
AUA011	12-Jul-2016	24	1024	HoKbPaT6Ur
AOV010	27-Jul-2016	24	1024	HoIsK1KeKgKmPaShT6TsUrWwYg
V515C	19-Jul-2018	24	1024	BdHhHoKmShSvZc
AUA020	01-May-2017	24	1024	BdHhHoKvShSvZc
AOV019	23-Jan-2018	24	1024	HoIsKbKeKmShT6UrWwYg
AOV033	20-Mar-2019	24	1024	HoIsKeKmT6UrWwYg
AOV034	03-Apr-2019	24	1024	HoIsKbKeKmKvT6UrWwYg

[a] Bd: Badary; Hb: Hobart12; Hh: HartRAO; Ho: Hobart26; Is: Ishioka; K1: Kashim11; Kb: Kashim34; Ke: Kath12m; Kg: Koganei; Km: Kunming; Kv: Sejong; Pa: Parkes; Sh: Seshan25; Sv: Svetloe; T6: Tianma65; Ts: Tsukub32; Ur: Urumqi; Ww: Wark12m; Yg: Yarra12m; Zc: Zelenchk.

For the first experiment AOV003 in 2015, we used standard S/X dual band geodetic mode with a data rate of 256 Mbps. The radio stars were scheduled in the same way as geodetic sources. We set a priori flux densities of those stars to a fix value of 40 mJy, and required that all baselines in one scan met the minimum SNR requirement. Thus, only four stations (Tianma65, Parkes, Kunming and Tsukuba32) were scheduled to observe the stars. The results show only HR1099 was detected on a few baselines, which indicate the other two stars were much weaker than their a priori flux densities.

We conducted two experiments in July 2016. In order to reach higher baseline sensitivity, both sessions were performed at a data rate of 1 Gbps. The session AUA011 was almost scheduled in the same way as AOV003, but the radio stars were expected to be as weak as 20 mJy. Unfortunately, we still only detected HR1099. The session AOV010 was a great success. We inserted manually scans of radio stars into geodetic blocks. For each radio star scan, all visible stations were used to form as many baselines as possible. HR1099 and UX Ari were observed in a few scans of 480 s length. For HD132742, we tested a piggy-back phase referencing mode. A radio source 1454-060, with a separation angle of 2.47°, was selected as a calibrator source. We observed both HD132742 and 1454-060 in a set of scans of 120 s length. Those scans were divided into three blocks with each block spanning approximately 40 minutes. The gap between two blocks is at least one hour in order to produce better UV coverage. The total on-source time of HD132742 is 36 minutes.

One experiment (V515C) was organized in 2018 as a part of the Long Baseline Array radio astrometric program V515 supported by the ATNF, CSIRO. As Tianma65 was unavailable, we conducted a similar piggy-back phase referencing observations of HR1099, using a strong radio source CTA26 as the calibrator. The angular distance between the target and CTA26 is 2.46°. The scan length is 180 s for HR1099 and 60 s for CTA26 respectively. The observational network is very large with participation of the Russian stations operated by Institute of Applied Astronomy and 26-m HartRAO antenna in South Africa. The total on-source time of HR1099 is 75 minutes, but there were fewer participating stations and only middle size antennas available compared to AOV010.

The fourth radio star HR5907 was observed in the absolute astrometric mode in four experiments in 2017-2019. This is one of the most rapidly rotating magnetic B-type stars with a rotation period 0.508276 day (Grunhut et al. 2012). Its radio emission detected in a range of GHz frequencies with flux density from 46 to 104 mJy (Murphy et al. 2010) is supposed to be generated by a strong magnetic field induced by the rapid rotation. Independently, Healey et al (2007) detected a strong emission at 8.4 GHz at the VLA array. Therefore, in spite of a greater distance from the Solar system (annual parallax of 7.64 ± 0.37 mas) with respect to other three stars, it has a stronger signal and was detected in all four experiments.

3. RESULTS

We processed each experiment in the same way as used in regular geodetic observing sessions. After data correlation and fringe fitting, group delay observables for radio stars and geodetic sources were extracted. Then data analysis was performed to derive the positions of radio stars. We also estimated flux densities of radio stars based on fringe SNRs at X and S band respectively. Table **??** shows the statistics on solutions of absolute astrometric data.

There is a different approach for the piggy-back phase referencing observations. We need to convert the correlator output into FITS-IDI data format and then generate images of radio stars with the AIPS. Figure **??** shows the X-band images of HD132742 and HR1099. The HD132742 image made from AOV010 data and the HR1099 image made from V515C data. Each image was performed with natural weighting. We plotted contours that start at three times the noise level of images. It is interesting that HR1099 shows a binary structure. Therefore additional phase reference observations of this radio star are important.

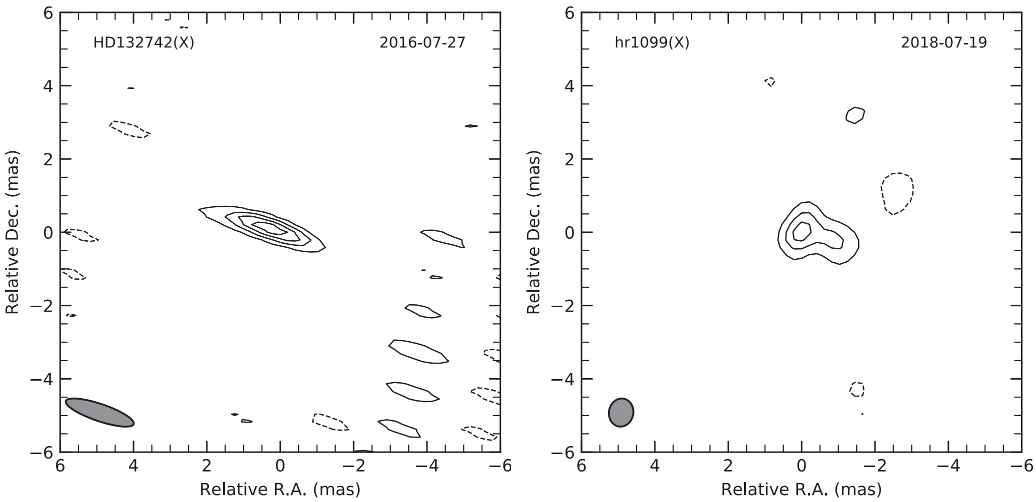

Figure 1: The images of HD132742 (left panel) and HR1099 (right panel) made from X band (8.39 and 8.60 GHz) data using natural weighting. The peak has been shifted to the image center. The SNR (the ratio of the flux density of peak to the rms) are 15.24 and 11.80 respectively. The synthesized beam is represented by the black ellipse in the bottom left corner of each panel.

Based on the imaging results, we could determine the relative position between a target star and a calibrator source. Since the position estimates from a single session are not so accurate, we used the positions of calibrator sources in the ICRF3 as reference. Finally we obtained the position of target stars as shown in the last two rows of Table **??**.

Table 2: Astrometric positions of all radio stars between 2015 and 2019

Code	Star	α(J2000.0) (h m sec)	δ(J2000.0) (° ' ")	σ_α (ms)	σ_δ (mas)	#Obs	F_X (Jy)	F_S (Jy)
AOV003	HR1099	03 36 47.2573	+00 35 13.470	0.8	4	6	0.02	0.03
AUA011	HR1099	03 36 47.2562	+00 35 13.308	0.34	2	10	0.01	0.02
AOV010	HR1099	03 36 47.2569	+00 35 13.269	0.03	0.3	56	0.02	0.03
AOV010	UX Ari	03 26 35.4353	+28 42 52.596	0.1	1	6	0.01	0.01
AUA020	HR5907	15 53 55.84739	-23 58 41.5622	0.02	0.4	4	0.05	0.05
AOV019	HR5907	15 53 55.84654	-23 58 41.5783	0.06	0.3	16	0.09	0.07
AOV033	HR5907	15 53 55.84558	-23 58 41.6062	0.04	0.6	12	0.10	0.05
AOV034	HR5907	15 53 55.84533	-23 58 41.6081	0.04	0.4	16	0.05	0.03
UF001I	LSI+61 303	02 40 31.66387	+61 13 45.5905	0.37	4.3	/	/	/
AOV010	HD132742	15 00 58.27745	-08 31 08.3003	0.013	0.12	/	0.003	/
V515C	HR1099	03 36 47.25259	+00 35 12.9481	0.006	0.08	/	0.004	/

Note. Besides the solutions of absolute astrometric data, the phase referencing results are listed in last two rows.

We plotted the time series of the HR1099 positions (Figure **??**) based on the previous optical and radio observations (Boboltz et al. 2003). Our analysis of the time series with assumption on the linear motion yields the proper motion of $\mu_\alpha \cos\delta = -2.09 \pm 0.02$ ms/y in right ascension and $\mu_\delta = -160.9 \pm 0.3$ mas/y in declination. These estimates are consistent with the Boboltz et al (2003) numbers ($\mu_\alpha \cos\delta = -2.12 \pm 0.02$ ms/y and $\mu_\delta = -161.7 \pm 0.25$ mas/y).

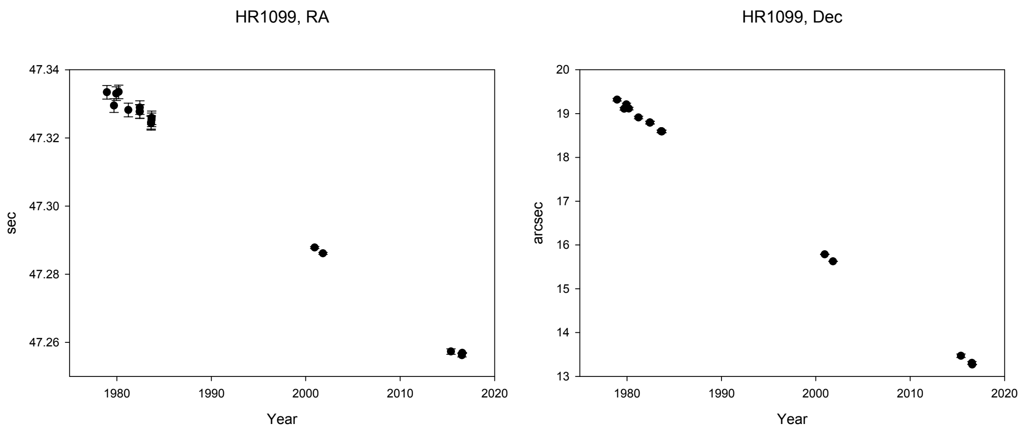

Figure 2: Time series of HR1099 astrometric positions

The radio star UX Ari is a very special object for astrometric research. This is an active binary star (type RS CVn) with period 6.44 days. Additionally, in contrast to most other radio stars, UX Ari exposes a significant non-linear proper motion. Lestarde et al. (1999) reported that the found acceleration term (-0.54 $\pm$ 0.07 mas/y^2 in right ascension and -0.29 $\pm$ 0.07 mas/y^2 in declination) may be induced by the gravitational attraction of a hidden counterpart with a long period. Boboltz et al. confirmed this effect with new estimates (-0.60 $\pm$ 0.03 mas/y^2 in right ascension and -0.31 $\pm$ 0.07 mas/y^2 in declination). Duemmler and Aarum (2001) measured systematic variations of the center of mass velocity with spectroscopic data and proposed a third star with periods of 10.7 and 21.5 years for circular and elliptical orbits. Peterson et al (2011) concluded a presence of the third component with orbital period about 111 years.

In spite of the fact that only one epoch positions were measured in our experiments (Figure **??**), it favours a shorter orbital motion of the third component than was suggested by Peterson et al (2011). As the discussion on the systematic factors is beyond of the scope of this paper, we conservatively estimate the orbital period of the third component to be between 20 and 30 years, i.e. closer to the Duemmler and Aarum (2001) elliptical motion hypothesis. More observations are required to solve the UX Ari system problem.

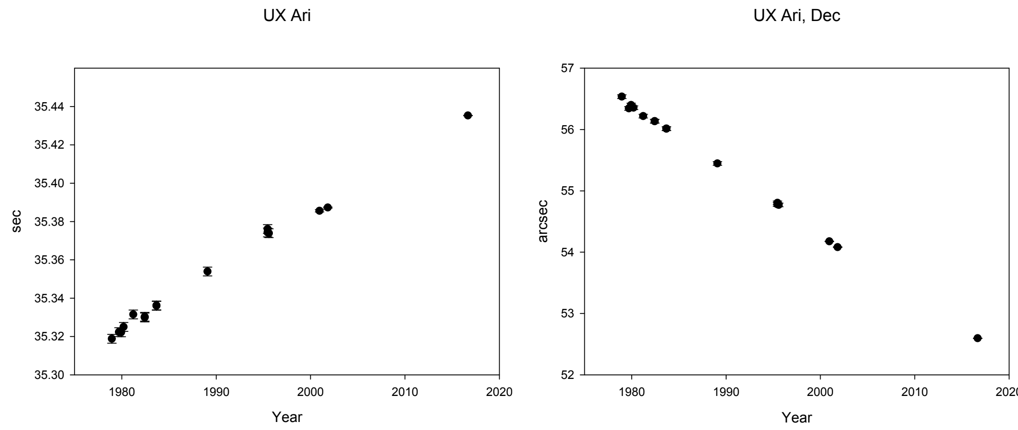

Figure 3: Time series of UX Ari astrometric positions

Also we found a set of legacy geodetic experiments including a radio star LSI+61 303 in 1990s organised by Marshall Eubanks (private communication). However, the daily positions of the radio star are not precise due to a weak flux density of the source. This radio star was also detected at a recent VLBA experiment (UF001I) on 27 May 2017 and the positions are presented in Table **??**. Unfortunately, this set of data is not able to produce accurate proper motion (Figure **??**).

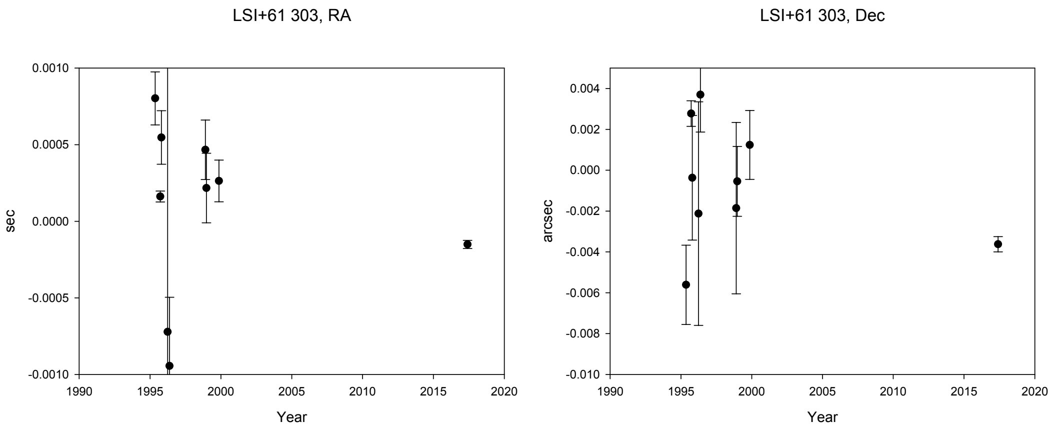

Figure 4: Time series of LSI+61 303 astrometric positions

4. CONCLUSION

We are aiming to detect some radio emitting stars in the absolute astrometric mode using S/X VLBI observations. Four radio stars (HR1099, UX Ari, HR5907 and LSI+61 303) have been detected in a few experiments. The minimum flux density of detection could reach as weak as 10 mJy. The success of detections benefits to the improved baseline sensitivity in term of participation of large radio telescopes and increased data rate. However, it can be challenging to obtain good quality data of weak stars at both S and X bands due to limited frequency coverage and more serious radio frequency interferences at S band. Moreover, two radio stars (HD132742 and HR1099) with flux densities below 10 mJy were detected in phase-reference mode.

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