Post-print: Observations of Radio Stars Del Lib and HR 1099 Using Piggyback Phase-Referencing Mode in Geodetic Observations

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Abstract

Based on Gaia astrometric data, the Gaia Celestial Reference Frame (GCRF) exhibits certain systematic differences from the International Celestial Reference Frame (ICRF) established through Very Long Baseline Interferometry (VLBI), necessitating external independent evaluation of Gaia data to establish a connection between optical and radio reference frames. Internationally, the connection of reference frames generally employs celestial objects that emit radiation in both optical and radio bands, using quasars at the faint end (magnitude G$ 15)*andradiostarsatthebrightend*(*G* $13). Due to the long approval cycle and high difficulty of regular VLBI observation proposals, we attempt to shift part of radio star observations toward the more numerous geodetic observations, incorporating phase-referencing mode in geodetic observations to observe radio stars. To test the feasibility of this observation method, we incorporated phase-referencing observations in geodetic observations of IVS (The International VLBI Service for Geodesy and Astrometry) and LBA (Large Baseline Array), selecting Del Lib and HR 1099 as experimental target sources. The observations obtained VLBI images, flux densities, and single-epoch coordinates for these two radio stars, with coordinate precision higher than previous studies; simultaneously, combined with previous data, we performed parallax and proper motion fitting for these two radio stars, with results consistent with previous studies and Gaia, and partially higher precision. This validates the feasibility of incorporating phase-referencing observations of radio stars in geodetic mode, laying a certain foundation for subsequently enriching the VLBI astrometric sample of radio stars and connecting optical and radio reference frames.

Full Text

Observation of Radio Stars Del Lib and HR 1099 Using Piggy-Back Phase Referencing Mode in Geodetic Observations

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Abstract

The Gaia Celestial Reference Frame (GCRF), established from Gaia astrometric data, exhibits systematic differences from the International Celestial Reference Frame (ICRF) constructed through Very Long Baseline Interferometry (VLBI). An external independent evaluation of Gaia data is required to link the optical and radio reference frames. Celestial objects with radiation in both optical and radio bands are commonly used for this purpose: quasars at the faint end (magnitude $G \geq 15$) and radio stars at the bright end ($G < 13$). However, obtaining approval for regular VLBI observations involves long cycles and significant difficulty. To address this, we have shifted some radio star observations to the more frequent and numerous geodetic observations, implementing phase-referencing mode for radio star observations within geodetic campaigns. To test the feasibility of this approach, we employed piggy-back phase referencing in geodetic observations conducted by the International VLBI Service for Geodesy and Astrometry (IVS) and the Large Baseline Array (LBA), selecting Del Lib and HR 1099 as our experimental targets. Our observations successfully obtained VLBI images, flux densities, and single-epoch coordinates for both radio stars, with coordinate accuracies surpassing previous work. By combining our data with archival results, we performed parallax and proper motion fitting for these two radio stars. Our results are consistent with both previous VLBI studies and Gaia measurements, with improved precision in some cases. This work verifies the feasibility of observing radio stars using piggy-back phase referencing in geodetic mode, laying a foundation for enriching the VLBI astrometric sample of radio stars and linking optical and radio reference frames.

Keywords: Very Long Baseline Interferometry; radio star; astrometry; proper motion; parallax

1. Introduction

The latest Gaia optical satellite data release (Data Release 3) has revealed that Gaia parallaxes exhibit systematic errors that vary with sky position, magnitude, and color. Theoretically, extragalactic sources should have zero parallax, yet Gaia's quasar data yield an average parallax of approximately -29 as. Furthermore, the Gaia Celestial Reference Frame, based on astrometric data from the Gaia mission, shows small but significant differences from the International Celestial Reference Frame established through VLBI observations. These discrepancies necessitate external independent evaluation of Gaia data to establish robust connections between optical and radio reference frames.

The international standard for linking these reference frames employs celestial objects detectable in both optical and radio wavelengths. While quasars are utilized at the faint end (G magnitude ≥ 15), radio stars serve as the primary targets at the bright end ($G < 13$). Compared to quasars, radio stars offer superior astrometric precision and are not affected by large-scale jet structures that can complicate quasar observations, making them ideal for connecting bright optical and radio reference frames. However, the current sample of radio stars suitable for reference frame linking is limited to approximately 100 objects, with most astrometric parameters derived from observations conducted in the previous century and thus relatively low precision. To achieve better optical-radio reference frame alignment and avoid errors introduced by inconsistent observational epochs, it is crucial to expand the number of radio stars with precise VLBI astrometric parameters during Gaia's operational lifetime.

Regular VLBI observation proposals face lengthy approval cycles and significant challenges, making large-scale radio star observations time-consuming and difficult. Consequently, we have redirected some radio star observations to the more abundant geodetic observations, interleaving phase-referencing scans for radio stars during gaps in geodetic schedules. This piggy-back approach allows us to test the feasibility of phase-referencing observations for relatively faint radio stars within geodetic campaigns.

2. Observations

2.1 Observation Strategy

Our observational campaign consisted of two geodetic observation sessions that incorporated piggy-back phase-referencing mode for radio star observations. Table 1 summarizes the observation configurations, including project codes, dates, frequencies, data rates, durations, and participating stations.

Geodetic observations typically reduce data volume by recording only right circular polarization, so our images also contain only right polarization. We selected target radio stars that were visible at high elevation to all stations during the observation periods. This piggy-back phase-referencing approach involves inserting short scans on radio stars and their calibrators into the geodetic schedule.

2.2 Target Sources

Del Lib (δ Librae, HR 5586, HD 132742, HIP 73473) is an Algol-type eclipsing binary system and the 76th brightest star in the sky. The system comprises a hotter B9.5V main-sequence star and a cooler, less massive F1 IV subgiant that fills its Roche lobe, with material transferring from the subgiant to the primary star. The binary orbital period is approximately 2.33 days. Radio flare activity in Algol systems appears to follow a roughly 50-day cycle. Del Lib is also a long-period triple system.

HR 1099 (V711 Tauri, HD 22468, ADS 2644A) is an RS Canum Venaticorum (RS CVn) type close binary system discovered through spectroscopic and photometric observations in 1975 and 1976. The system consists of a K2 IV subgiant and a G5 IV-V main-sequence star with an orbital period of about 2.84 days. RS CVn systems are characterized by bright emission from high-temperature material in their transition regions and coronae. HR 1099 is also a triple system with a long-period orbit, where the third component (ADS 2644B, V = 4.91) has minimal physical influence on the inner binary.

2.3 Observation Details

Project AO010 (2016 July 27): This IVS geodetic observation involved stations across the Asia-Pacific region. The primary goal was astrometric observations of a set of geodetic sources, with piggy-back phase-referencing observations of Del Lib and its calibrator 1454-060 (separation 2.47°). The S/X band observation used a single-channel bandwidth of 16 MHz and a total data rate of 1024 Mbps. Phase-referencing scans were divided into two 2-minute segments separated by at least 30 minutes, totaling approximately 36 minutes of on-source time over a 10-hour span.

Project V515C (2018 July 19): This LBA geodetic observation included stations in China, Russia, and South Africa, providing much longer baselines than Australia-only observations. Although classified as geodetic, it included phase-referencing observations of HR 1099 using the strong source CTA 26 as calibrator (separation 2.46°). The 8.6 GHz observation used a 16 MHz bandwidth with 1024 Mbps data rate. HR 1099 had 180-second scans, while CTA 26 had 60-second scans, totaling 75 minutes of on-source time over approximately 10 hours.

3. Data Processing

Data correlation was performed at the Shanghai Astronomical Observatory correlator center for AO010 and at the ATNF correlator for V515C. The processing pipeline involved several key steps:

Initial Processing: We loaded correlated data into AIPS (Astronomical Image Processing System) and performed Earth Orientation Parameter (EOP) corrections, ionospheric corrections, and parallactic angle corrections. For amplitude calibration, we used antab files containing system temperature and gain information. When complete system temperature data were unavailable, we manually edited antab files using nominal SEFD (System Equivalent Flux Density) values for each antenna.

Fringe Fitting: For AO010, we performed global fringe fitting on a bright source with strong fringes at all stations, then applied the solutions to the target. Due to severe phase jumps at Kunming station (KM), we split this into two steps: fringe fitting for all other stations first, then separately for KM, before combining the solutions.

Imaging: For V515C, after EOP, ionospheric, and parallactic angle corrections, we performed global fringe fitting on CTA 26. Since CTA 26 showed extended jet structure rather than a point source, we used DIFMAP to create a source model through two iterations, reducing the impact of complex structure before applying solutions to HR 1099.

Amplitude Calibration: We performed approximate flux calibration using nominal SEFD values. After imaging, we used the gscale parameter in DIFMAP to compare measured and catalog fluxes of calibrators, adjusting the amplitude calibration to achieve gscale values between 0.9-1.1, indicating reliable amplitude calibration within 10-20% accuracy.

4. Results and Analysis

4.1 Imaging Results

Del Lib: The 36-minute total observation yielded an image with a synthesized beam of 2.38×0.51 mas, showing poor east-west coverage but good north-south coverage. The image exhibits clear sidelobe effects due to limited uv-coverage. Previous observations indicate Del Lib's quiescent flux at 8.3-8.4 GHz is 1-10 mJy, rising to 34 mJy during flares. Our approximate amplitude calibration measured a flux of about 20 mJy, suggesting we may have observed during a flaring state.

HR 1099: The 75-minute total observation produced an image with a 0.83×0.71 mas beam. The image reveals a clear two-component structure with a larger western component and smaller eastern component, resembling a core-halo morphology. Previous studies show HR 1099's flux varies dramatically from 5-25 mJy at 4.86 GHz in quiescence to over 100 mJy during outbursts, with significant changes occurring within hours. Our approximate calibration measured about 5.4 mJy at 8.6 GHz, consistent with previous observations. The brightness temperature, estimated using the standard formula, is approximately 2×10^9 K for Del Lib and 5×10^8 K for HR 1099, indicating non-thermal emission.

4.2 Astrometric Results

Table 3 presents the single-epoch coordinates, fluxes, beam sizes, and position uncertainties for both radio stars. The position errors are formal errors from JMFIT, with overall astrometric precision (σ{position}) *calculated using the empirical formula* σ{position}   0.5 ×   / SNR, where   is the beam's full width at half maximum and SNR is the signal-to-noise ratio.

Our astrometric precision is approximately one order of magnitude better than previous VLA+PT (Very Large Array + Pie Town) observations, likely due to our longer baselines providing higher resolution. Table 4 compares our parallax and proper motion fits with previous VLBI results and Gaia DR3. For Del Lib, our proper motion in the x-direction agrees with Gaia DR3 within error, while the y-direction shows slight differences possibly due to lower precision in earlier data. Our parallax and proper motion fitting precision exceeds that of previous studies. For HR 1099, our results agree with both previous VLBI work and Gaia DR3, though with errors about twice as large as Gaia's due to our limited number of epochs.

5. Conclusion and Outlook

Using piggy-back phase-referencing in geodetic mode, we successfully obtained VLBI images, flux densities, and single-epoch coordinates for Del Lib and HR 1099 with relatively short observing times. Combining these with archival data, we derived proper motions and parallaxes that agree with previous results while improving precision in some cases. This work demonstrates the feasibility of observing radio stars using piggy-back phase-referencing in geodetic observations.

Future applications of this method could: 1. Serve as pilot tests for formal radio star astrometry observations to verify target flux levels 2. Enrich the radio star astrometric sample by interleaving such observations in numerous geodetic campaigns 3. Make efficient use of observation time while contributing to optical-radio reference frame linking

However, since geodetic observations typically record only right circular polarization, formal radio star astrometry observations would be required for studies of polarization properties.

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Note: Figure translations are in progress. See original paper for figures.