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VLBI Multiview Astrometry of Radio Stars

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The expected emission mechanisms for radio loud M dwarfs include plasma emission, gyrosynchrotron emission during short lived (<2 hrs) flares, and Electron Cyclotron Maser Instability (ECMI) which can occur in planetary aurorae, and interaction between a star and a planetary companion.
VLBI offers a way to study the nature and location of the radio emission from nearby M dwarfs. We are implementing our own version of the MultiView technique to correct for ionospheric disturbances, which should lead to an astrometric accuracy for the VLBI observations comparable to that of the *Gaia* mission. This allows us to compare the location of the optical and radio emission.
In this contribution we discuss our ongoing observations of radio loud M dwarfs, in particular of Ross 867 and WX UMa.

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1. MultiView

In radio interferometry, it is common to use a bright, compact phase reference source near the target of interest to correct for ionospheric and tropospheric refraction, applying the measured corrections to the target source as well. How well this correction works for the target depends on the angular separation between the phase calibrator and the target, and the strength of the phase fluctuations induced by turbulence in the ionosphere and troposphere at the observing frequency. With the phase reference source not exactly at the same position on the sky as the target, and possibly not observed at the same time, some residual error will remain. MultiView[1] is a technique in radio interferometry which uses multiple phase reference sources around a target to map the phase errors in its vicinity, and interpolate the phase corrections to the position of the target source.

Most VLBI cm-wave antennas do not offer multiple beams, and the spatial density of calibrator sources makes it unlikely to find a good phase calibrator in-beam, let alone multiple ones. Utilizing MultiView then requires visiting the phase calibrators and target in sequence, trading sensitivity for a better phase calibration and improved astrometrical accuracy.

In our implementation of the MultiView technique we use three phase calibrators, preferably in a triangle surrounding the target source, and use 2D linear (barycentric) interpolation to estimate the phase correction over time for the target source. Calibration of the phases is done for each of the phase calibrators using AIPS[3], and then the phase solution for the target position is calculated in a routine which we have implemented using ParselTongue[4].

2. Using *Gaia* positions in VLBI

The *Gaia* mission has published the position, proper motion and parallax of billions of stars to unprecedented accuracy. This opens up the possibility of comparing the location of the emission in radio against the optical position. However, the achievable accuracy of this comparison can be impacted by a number of factors. The major contribution to the uncertainty in the propagated *Gaia* positions is the uncertainty in the proper motion values, multiplied by the number of years between the *Gaia* DR3 epoch and the VLBI observation. This results in $1\,\sigma$ uncertainties in position of e.g. 0.2 mas for Ross 867 and 868 (see below).

The *EVN* synthesized beam at L-band can be as small as $\theta_B = 1.2 \cdot 18\,\text{cm}/11,812\,\text{km} = 3.7\,\text{mas}$. The resolution is then $\sigma_{\text{pos}} \approx \theta_B / SNR$, which becomes comparable with the *Gaia* DR3 positional uncertainty when the SNR of the detection is above 20. In regular VLBI observations, the actual positional accuracy at L-band is $\approx$ 2 mas due to ionospheric effects, but MultiView can improve on this by at least an order of magnitude. To obtain suitable phase reference sources, we made use of the VLBI Calibrator search engine[6], selecting candidates close to our target of interest and with sufficient compact flux at S-band. VLBI astrometric positions are relative to the position of the phase reference sources, which in our observations have uncertainties between 0.13 mas and 0.22 mas. This is further compounded by the slight differences between geodetic (group delay based) and astronomical (phase based) positions due to core shift effects[10] and structure, as the calibrator locations are for S-band, whereas the observation is in L-band.

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3. Ross 867 and 868

Ross 867 (M4.5V, V639 Her, Gliese 669B) and Ross 868 (M3.5V, V647 Her, Gliese 669A) are M dwarfs in a loose (1793 ± 0.1 au) binary system[5]. Ross 867 was already known as a radio loud star, and detected in archival GMRT and (J)VLA data. In contrast, no detections of Ross 868 were found in the same archival data, and we found only a single detection in the literature[7]. These two stars, which have a similar age, mass and environment, make an interesting case study to compare the differences in radio emission between similar M dwarfs.

In an initial feasibility study (EVN project code EB070) using simple phase referencing, Ross 867 was detected as a 0.15mJy ($10\,\sigma$) source with RHCP polarization (positive Stokes-V). This recording was also used to test the VLBI detectability of a number of in-beam phase reference sources (see Figure 1), which we had identified in archival VLA data.

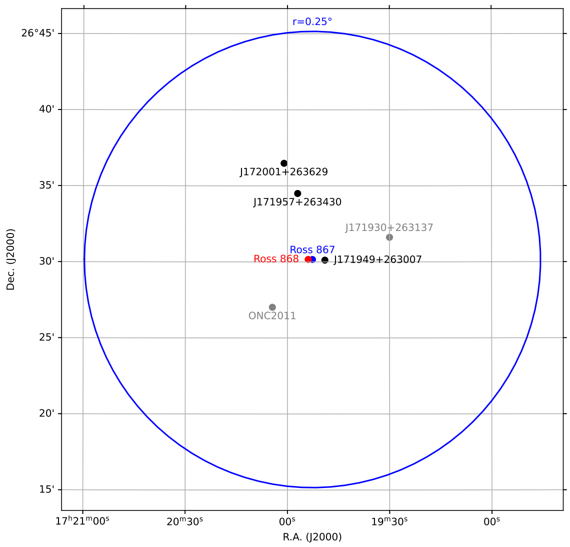

Figure 1: The field around Ross 867/868: Targets in blue and red, in-beam phase reference sources in black, and VLBI non-detections in grey. The blue circle represents the primary beam of a 25 m dish at L-band.

We then embarked on a campaign of astrometric VLBI observations of these radio stars, to shed more light on the possible emission mechanism in this case. Three phase calibrators were selected, as depicted in Figure 2a, with the primary phase calibrator J1716+2616 only 0.67° away from the target.

For these observations we used polarization calibration to measure the circular polarization, and MultiView to achieve the highest possible astrometric accuracy. Using the high sensitivity of the *EVN* we also searched for any traces of emission from the companion Ross 868. A ten hour observation with the full *EVN* at L-band, assuming 50% on-source time, achieves a sensitivity of $10\,\mu$Jy/beam.

By mid 2022, we have observed 7 epochs on Ross 867/868, although two of them are still being processed. Ross 867 has been detected in 4 out of 5 epochs, always strongly polarized with a polarization fraction on the order of 60%, and a positive sign for the Stokes-V component. We have not detected Ross 868 in any epoch.

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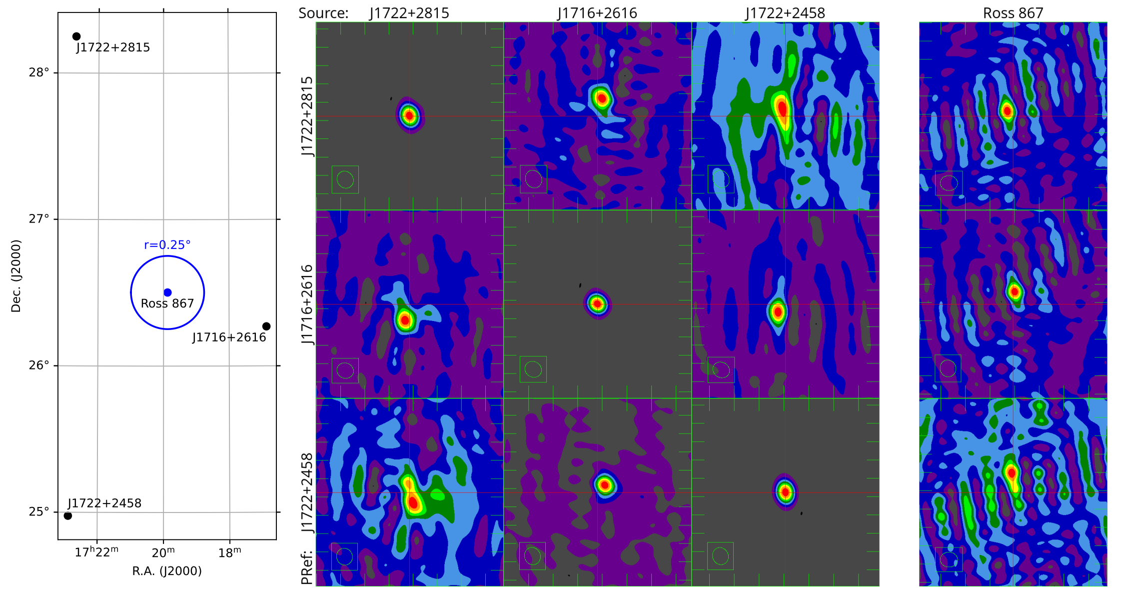
To test the effectiveness of the phase referencing solution, the data of our first MultiView epoch was calibrated in AIPS by fringing and self-calibrating on each of the three phase reference sources individually. The three phase reference sources were then imaged, using the calibration results of each of the three phase reference sources. As shown in Figure 2b, the outcome of this matches expectations: the images calibrated using the solutions for the phase reference source itself are compact and have a high signal to noise ratio. The red crosses here mark the center of the image, and the position of each of the phase reference sources when calibrated using its own phase solutions. The image quality clearly deteriorates as the separation between a phase calibrator and the imaged source increases. Positional offsets between pairs of calibrators are mirrored, indicating that these are robust offsets. These offsets can be due to ionospheric turbulence, but also due to systematic offsets in their a-priori positions. We plan to disentangle the two effects by averaging their positions over the six MultiView epochs that we will eventually have available. Figure 2c is analogous, and shows the results of applying each of the three calibration solutions for the phase reference sources to Ross 867.



(a) Phase References **(b)** Phase reference sources calibrated against each other **(c)** Applied to target

Figure 2: Applying MultiView to the phase reference sources, and to the target. The blue circle in (a) represents the HPBW of a 25 m dish at L-band. Declination tickmarks in (b) and (c) are 5 mas apart.

We then use the MultiView technique to interpolate the phase solutions to the position of Ross 867. The red crosses in Figure 3 now mark the expected position of the source as calculated from the position, proper motion and parallax published in *Gaia* DR3. Note that we have not yet determined which portion of the phase correction terms corresponds to actual ionospheric turbulence, and therefore Figure 3 is only intended to show that our implementation of MultiView produces somewhat plausible results: the position is closer to the expected one and the S/N has improved slightly, although the overall flux has decreased. Once we have calibrated the data from all the observing epochs, we will be able to fix the relative positions of the phase calibrator sources, and then re-apply the MultiView calibration. We can then verify its performance using the other in-beam sources in the target field.

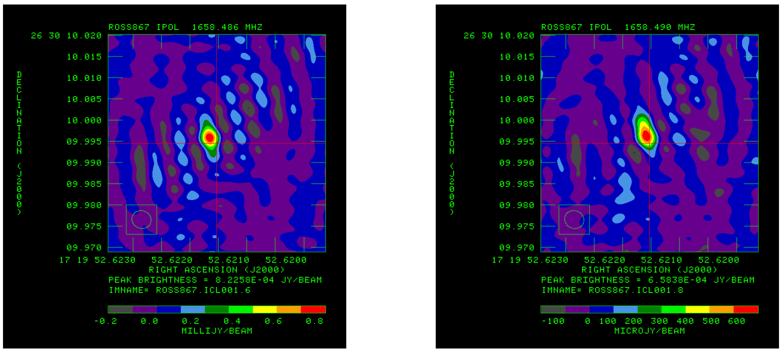


Figure 3: Ross 867 calibrated using the nearest phase calibrator (left), or MultiView (right).

4. WX UMa

The *LOFAR* radio telescope has surveyed a large part of the Northern sky in full polarization (LoTSS)[8]. Cross matching detections in Stokes-V against stars detected in *Gaia* has resulted in identifying 17 radio loud stars, all nearby M dwarfs[9]. We have observed three promising candidates that are expected to be still detectable at L-band. WX UMa has been detected in our VLBI follow-up with a strong, circularly polarized signal: 2.14 mJy in Stokes-I, and -1.45 mJy in Stokes-V. Intriguingly, the emission is detected at an offset of 6.5 mas from the position we estimate by propagating the *Gaia* proper motion and parallax for this source. This offset would amount to 0.032 au, 6.8 solar radii, or 57 stellar radii, which is well outside the corona of the star[11]. We have proposed a series of astrometric observations with a similar setup as used for Ross 867. By mid 2022 all three epochs have been observed, and one epoch has been fully processed. The radio emission of WX UMa is highly variable, and unfortunately the first epoch has resulted in a non-detection.

5. Future Work

Work is progressing on calibrating the data from all of our VLBI observations of Ross 867/868 and WX UMa. We plan to release our ParselTongue implementation of MultiView once we have completed our work on these radio stars.

Furthermore, we have observed other sources identified as radio stars in the LoTTS survey, and are performing follow-up observations on these as well.

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