Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Trigonometric parallax, proper motion, and structure of three southern hemisphere methanol masers

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Abstract. We present the trigonometric parallax, proper motion, and structure of three methanol masers from the Southern Hemisphere Parallax Interferometric Radio Astrometry Legacy Project (SπRALS). All three masers have better than 5% parallax accuracy, which we attribute to the new inverse MultiView calibration technique.

Keywords. astrometry - proper motions, parallaxes; masers - methanol; techniques - Very Long Baseline Interferometry

1. Introduction

The spiral structure of the 4th quadrant of the Milky Way; $180° < l < 359°$ and visible almost exclusively to the southern hemisphere; has long remained shrouded in uncertainty. Until very recently, accurate trigonometric parallax measurements to masers in high mass star forming regions have been unattainable. The best maser species candidates for trigonometric parallax measurements are 22 GHz water and 6.7 GHz methanol; the former species is structurally variable and should be observed within a 1 yr span before maser spots may disappear. Overall, at least 8 observational epochs are ideal for parallax measurements of both species. In the past, scheduling for strict time constraints posed a challenge for the Australian Long Baseline Array (LBA), the sole Very Long Baseline Interferometric (VLBI) array in the southern hemisphere. The species at 6.7 GHz is much more stable and theoretically can be observed over many years. However at this frequency, uncorrected dispersive delays caused by the ionosphere can significantly and adversely affect astrometric observations. (e.g., Krishnan *et al.* 2015; Reid *et al.* 2017).

In order to address the issue of scheduling, the University of Tasmania outfitted two of their 12 m geodetic antennas (Hobart 12 m and Katherine 12 m; Lovell *et al.* 2013) with 6.7 GHz receivers capable to make an array of four antennas with Ceduna 30 m

Table 1. Methanol maser names (1), correlated positions (2-3), measured parallaxes (4), proper motions in the north-south (5) and east-west (6) directions, and reference (7). Units are given on the second row where applicable.

Name	R.A (h m s)	Decl. ($^\circ$ $'$ $''$)	π (mas)	μ_x (mas yr^{-1})	μ_y (mas yr^{-1})	ref.
G309.92+00.47	13 50 41.78	−61 35 10.2	0.291 ± 0.011	-5.560 ± 0.025	-1.561 ± 0.070	-
G323.74−00.26	15 31 45.45	−56 30 50.1	0.364 ± 0.009	-3.239 ± 0.025	-3.976 ± 0.039	1
G328.80+00.63	15 55 48.45	−52 43 06.6	0.381 ± 0.016	-3.492 ± 0.044	-3.276 ± 0.116	2

Notes: 1 - Hyland *et al.* (2022); 2 - Kumar (2023)

(McCulloch *et al.* 2005) in South Australia and Warkworth 30 m (Woodburn *et al.* 2015) in Auckland, New Zealand (operated at the time by the Auckland University of Technology). This array has the flexibility to dedicate hundreds of hours per year exclusively to the astrometric observations of 6.7 GHz methanol masers (Hyland *et al.* 2018; Hyland *et al.* 2021).

The final piece of the puzzle was the development of inverse MultiView (Hyland *et al.* 2021, 2022). This calibration technique facilitates the accurate removal of tropospheric and ionospheric residual delays and allows astrometric positioning down to the uncertainty caused by the thermal noise. In addition, it allows the use of quasar calibrators much further away than traditionally accepted (i.e., 7° at 8.4 GHz).

And so the Southern Hemisphere Parallax Interferometric Radio Astrometry Legacy Survey (SπRALS; Hyland *et al.* 2021) was started, with the aim to measure the spiral structure of the 4th quadrant of the Milky Way using trigonometric parallaxes of 6.7 GHz methanol masers. Here we present our first three novel maser parallaxes, their proper motions, and structure.

2. Results

Table 1 contains the measured trigonometric parallaxes and proper motions for the southern hemisphere methanol masers G309.92+00.47, G323.74−00.26, and G328.80+00.63. The parallax and proper motion fits to the astrometric data for each maser are shown in Figure 1. Two of the masers have parallax accuracy ~ 10 μas, the current gold standard for relative astrometry. Even for parallax measurements of 22 GHz water masers on the Very Long Baseline Array (VLBA), parallax accuracy at this level is uncommon.

The structures of all three masers are shown in Figure 2. All three masers have a multitude of emission regions, and show a diverse range of overall structures. G323.74−00.26 appears to trace a shock, G309.92+00.47 has a linear structure with a clear velocity gradient, and G328.80+0.63 has a 'paired' structure.

The data for G323.74−00.26 is published in Hyland *et al.* (2022) and for G328.80+00.63 is presented in Kumar (2023). The analysis of G309.92+00.47 is still in the preliminary stage and the final results will be fully presented in an upcoming publication.

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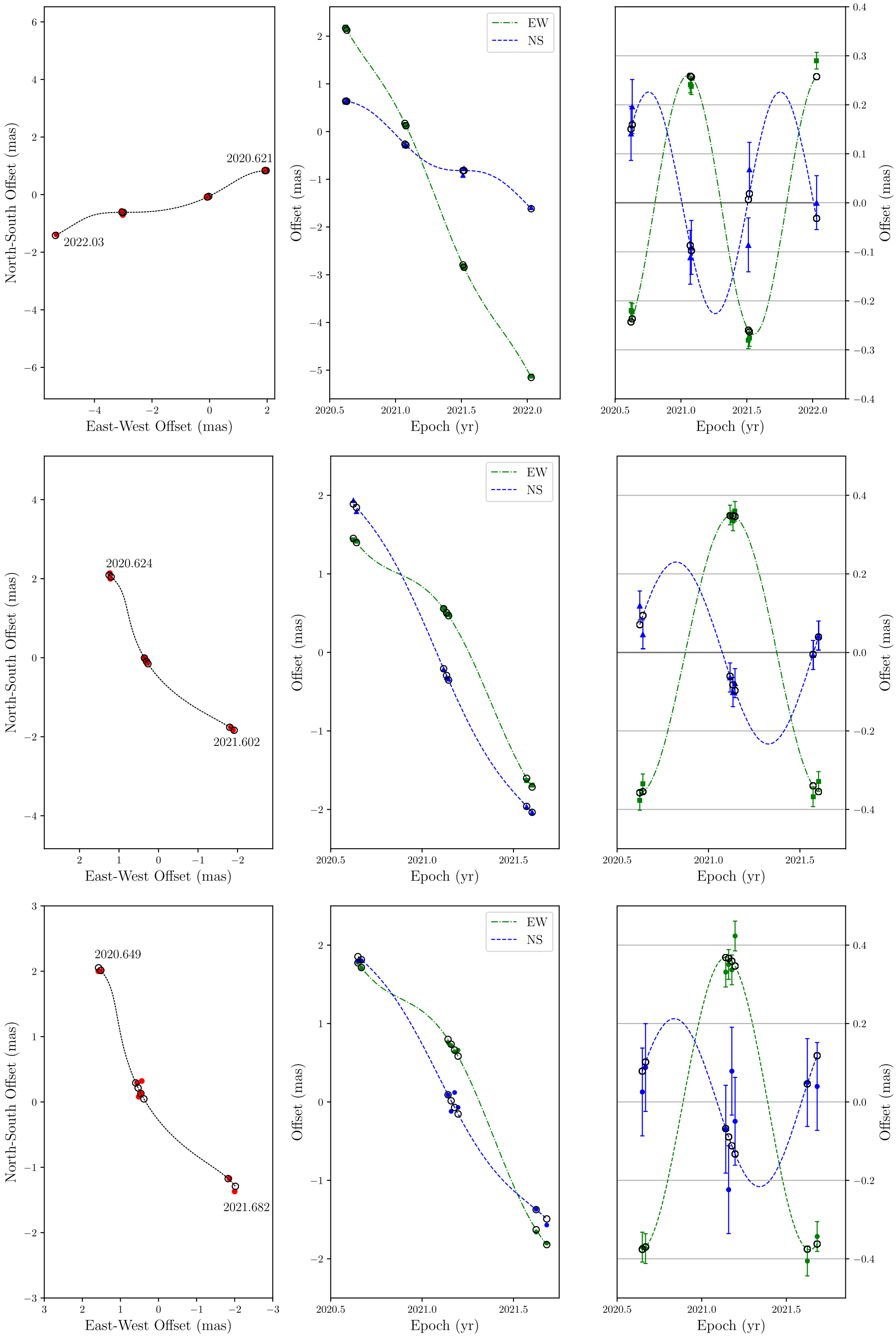

Figure 1. Trigonometric parallax and proper motion fits to astrometric data for all three masers. Top to bottom: Fits for G309.92+00.47, G323.74−00.26, and G328.80+00.63. Left to right: Total sky motions relative to reference positions, sky positions decomposed into EW (green dot-dashed) and NW (blue dashed) positions over time, and proper motion-subtracted position over time showing the parallax motion.

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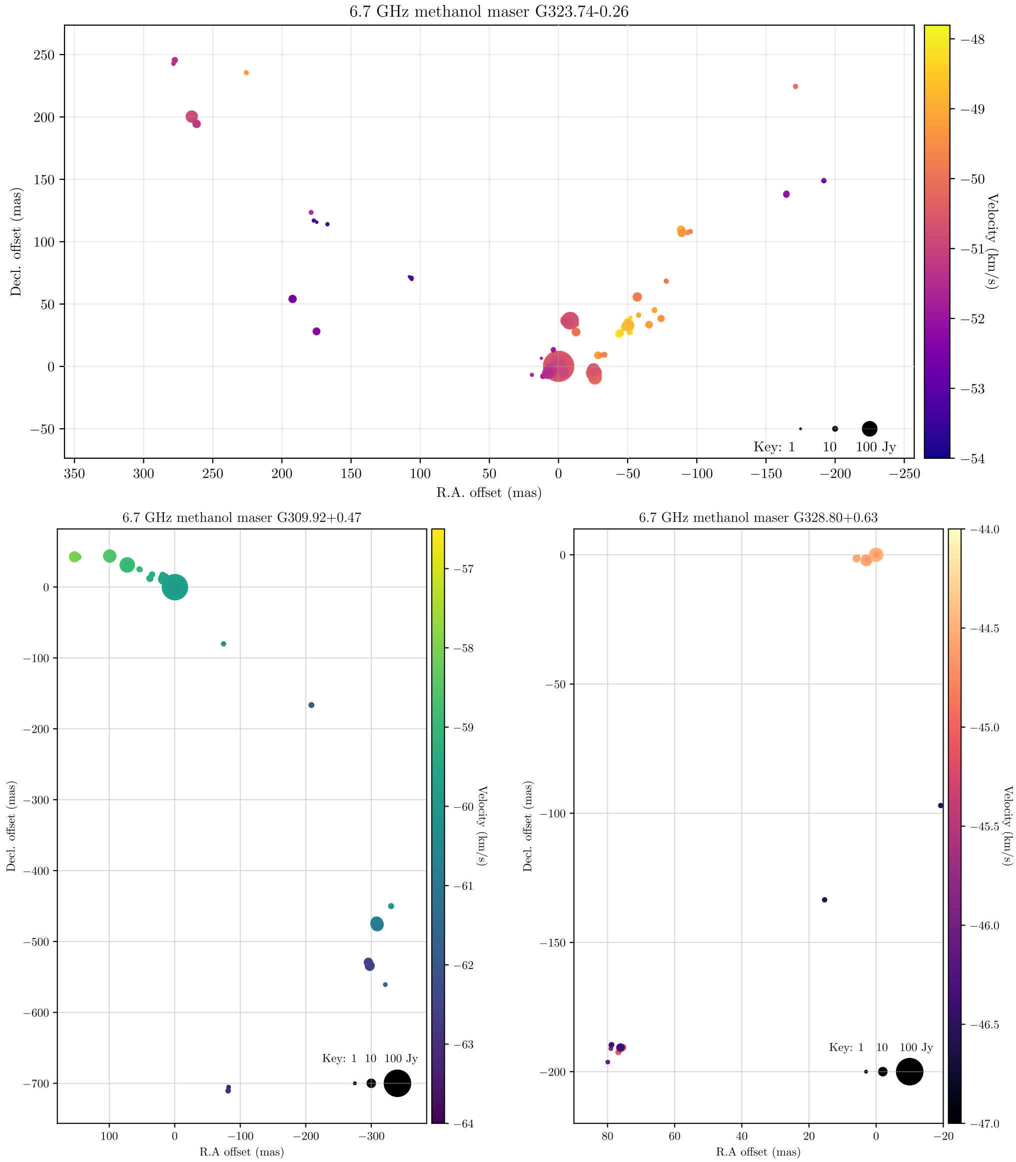

Figure 2. Spot maps displaying the structures of the three masers, giving each spot position relative to a reference feature. The size of the spot indicates the flux density (Jy), with a key given at the bottom right of each map. A color bar on each map indicates the LSR velocity of the spot.

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