Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Southern Hemisphere Maser Astrometry

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Abstract. Many astrophysical phenomena can only be studied in detail for objects in our galaxy, the Milly Way, but we know much more about the structure of thousands of nearby galaxies than we do about our own Galaxy. Accurate distance measurements in the Milky Way underpin our ability to understand a wide range of astrophysical phenomena and this requires observations from both the northern and southern hemisphere. Our ability to measure accurate parallaxes to southern masers has been hampered a range of factors, in particular the absence of a dedicated, homogeneous VLBI array in the south. We have recently made significant advances in astrometric calibration techniques which allow us to achieve trigonometric parallax accuracies of around 10 micro-arcseconds (μas) for 6.7 GHz methanol masers with a hetrogeneous array of 4 antennas. We outline the details of this new "multiview" technique and present the first trigonometric parallax measurements that utilise this approach.

Keywords. interstellar masers, astrometry, calibration, distance

1. Introduction

The BeSSeL and VERA surveys have provided accurate distances to more than 200 star formation regions in the part of the Milky Way accessible to northern hemisphere instruments (Reid *et al.* 2019). However, this excludes the majority of the fourth quadrant of the Milky Way and obtaining trigonometric parallax measurements to this region of the Galaxy has been a long-standing issue.

We know more about the structure of thousands of nearby galaxies, as our location within the plane of the Milky Way hinders our ability to determine the number and location of the spiral arms due to obscuration at most wavelengths. Trigonometric parallax is the only direct (model independent) method which can be used to measure distances to objects outside the solar systems, hence it represents the "gold standards" for determining distances. While the *GAIA* mission will measure accurate distances and proper motions for millions of stars within the Milky Way (see the talk by Rygl et al. in these proceedings), extinction at optical wavelengths prevents it from observing objects close to the Galactic Plane which are more than a few kiloparsecs from the Sun. The result is that *GAIA* will not significantly improve our knowledge of the number or location of the Milky Way's spiral arms and instead we have to utilise parallax measurements at radio wavelengths which are not hindered by obscuration. Interstellar masers are closely associated with young high-mass star formation regions (which by definition trace the spiral arms) and so are ideal targets for such measurements.

The BeSSeL and VERA surveys have primarily targeted 22 GHz H_2O and 12.2 GHz methanol masers and in the best cases are able to achieve a formal uncertainty in the parallax measurements of around 10 micro-arcseconds (hereafter, μas). This enables distances to be determined with an accuracy of better than 10% to the Galactic Center.

2. Challenges for Southern Hemisphere Trigonometric Parallax Measurements

The fundamental accuracy which can be obtained in relative astrometry measurements from very long baseline interferometry observations depends on the accuracy to which a wide range of factors have been measured or calibrated. Critical factors include the location of the antennas, the position and any structure of the reference sources, the stability of the frequency standards (clocks), electronic delays and the ionospheric and tropospheric delay contributions at each antenna (and how they change over the course of the observation). It is this final factor which prevents accurate astrometric measurements being made for sources at low-elevation (Honma *et al.* 2008), hindering measurements of fourth quadrant masers with the VLBA, VERA and other northern arrays. Good atmospheric calibration has been more difficult to achieve for southern hemisphere arrays for a number of reasons.

(1) Ionospheric calibration is traditionally obtained through the use of total electron content (TEC) maps extracted from measurements made by a network of Global Navigation Satellite System (GNSS) stations. There is a much lower density of such stations in the southern hemisphere and the result is that the TEC data for the south is often of lower accuracy (e.g. Deller *et al.* 2009).
(2) Tropospheric calibration is best achieved through observations of sources at low-elevations, sampling a range of azimuths and spanning a wide range of frequencies, often called the “geo-block” technique as it was developed for geodetic very long baseline interferometry (e.g. Reid *et al.* 2009). Hetrogeneous very long baseline interferometry arrays are generally less able to make good “geo-block” measurements due to differences in the receiver frequency coverage and antenna parameters such as the slew speeds and elevation limits between the different elements.

Furthermore, the wavelength dependence for ionospheric and tropospheric delays have the opposite signs, which further complicates the impact on astrometry when the residual uncertainty in the calibration of both terms is of comparable magnitude. The best astrometry at radio wavelengths has been achieved using homogeneous arrays (such as the VLBA and VERA) operating at frequencies above 10 GHz where the ionosphere impacts less. Furthermore, the timing of the peaks in the amplitude of the parallax signature depends on the ecliptic longitude of the target source and so can be most accurately measured if the observations are timed within a few weeks of the optimal times during the year.

The only southern hemisphere very long baseline interferometry array which has previously made trigonometric parallax observations has been the Long Baseline Array (LBA), with antennas operated by CSIRO Space and Astronomy, the University of Tasmania (e.g. Deller *et al.* 2009; Krishnan *et al.* 2015). These observations have been at frequencies less than 10 GHz, which means that they are more heavily impacted by inaccurate ionospheric calibration and the timing of the observations has not been optimal because the LBA is an ad-hoc array. The result is that the accuracy of the limited number of trigonometric parallax observations which have been made of both pulsars and masers with the LBA have had an astrometric accuracy typically of 100 μas or worse, a factor of 10 poorer than the best obtained from northern instruments. With this level of precision it is only possible to obtain sufficiently accurate distances to sources within a few kiloparsecs of the Sun (i.e. comparable to *GAIA*).

3. Multiview

The challenge for obtaining accurate relative astrometry for hetrogeneous very long baseline interferometry arrays (particularly in the southern hemisphere), has been to find an alternative atmospheric calibration approach. A range of approaches have been developed and trialed and a comprehensive review of developments can be found in Rioja and Dodson (2020). One of these techniques "multiview" involves making observations of multiple calibrators distributed around the target sources and from these data determining the time-variable two-dimensional phase-slope produced by the residual delay error. The efficacy of this approach for measuring and correcting for residual delays has been demonstrated by Hyland *et al.* (2022) who showed that it was possible to obtain a single-epoch relative astrometric accuracy of 20 μas with a four-antenna array at 8.4 GHz. Multiview is able to produce good astrometric accuracy in the presence of any residual delay errors which vary on timescales which are slower than the time it takes to determine the 2D phase-slope. This will depend on a range of factors and we have insufficient experience in implementing Multiview to be able to give clear guidance as to which of those are most critical in setting the timescale (Hyland *et al.* 2022). At frequencies between 5 and 10 GHz going around the multiple calibrators within 20-30 minutes generally allows unambiguous tracking of the changes in the phase slope. It is important to realise that for Multiview, having some of your calibrators with larger separations from the target source is advantageous, this is in contrast to standard phase referencing, or inverse phase referencing, where the closer your calibrator to the target the better. A larger separation between calibrator and target allows better measurement of the phase slope, but perhaps the most important factor for good Multiview calibration is to have an even azimuthal distribution of calibrators around the source.

The first trigonometric parallax observations towards a 6.7 GHz methanol maser obtained using inverse multiview have been obtained by Hyland *et al.* (2023). This paper reports measurements towards two sources, one (G232.62+0.99), is in the southern hemisphere but sufficiently close to the equator that it has a distance measured by the BeSSeL survey. The trigonometric parallax measured for the 6.7 GHz methanol maser in this source of 610 ± 11 μas is consistent with the measurement based on the 12.2 GHz methanol maser observations from the VLBA (596 ± 35 μas Reid *et al.* 2009). The efficacy of the Multiview calibration approach is clearly demonstrated by this result, as is has been possible to obtain a formal uncertainty in the parallax measurement with a 4-antenna hetrogeneous array that is a factor of three better than that obtained at a higher frequency with a 10-antenna homogeneous array. The other parallax measurement is for G323.74−0.26 at a declination of -56°, which is completely inaccessible to northern instruments. Hyland *et al.* (2023) measure a parallax of 364 ± 9 μas for this source, corresponding to a distance of 2.75 ± 0.07 kpc for this southern star formation region.

4. Conclusions

Application of the Multiview calibration technique is able to achieve astrometric accuracies in trigonometric parallax observations of around 10 μas with a four-antenna, hetrogeneous antenna array at a frequency of 6.7 GHz. This is comparable with the best relative astrometry which has been achieved at radio wavelengths and opens the potential for better astrometry with a range of hetrogeneous very long baseline interferometry arrays. Application of Multiview with the VLBA may enable significant improvements in its best astrometric accuracy. Additional observations covering a wider range of frequencies, times and calibrator distributions are required to better understand the critical factors which determine the accuracy of Multiview.

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