Astrophysical Masers:
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Structure of the Milky Way: View from the Southern Hemisphere

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Abstract. The exclusive association of Class II methanol masers with high mass star formation regions and in turn spiral arms, makes them ideal tracers of spiral structure. The bright and compact nature of masers also makes them good sources for Very Long Baseline Interferometry, with their fluxes visible on some of the longest terrestrial baselines. The success of the BeSSeL (Bar and Spiral Structure Legacy) project has demonstrated the use of masers in large scale high–precision trigonometric parallax surveys. This survey was then able to precisely map the spiral arms visible from the Northern Hemisphere and recalculate the fundamental Milky Way parameters R_0 and θ_0. The majority of the Milky Way is visible from the Southern Hemisphere and at the present time the Australian LBA (Long Baseline Array) is the only Southern Hemisphere array capable of taking high–precision trigonometric parallax data. We present the progress–to–date of the Southern Hemisphere experiment. We will also unveil a new broadband Southern Hemisphere array, capable of much faster parallax turnaround and atmospheric calibration.

Keywords. galaxies: structure, astrometry, masers, telescopes, techniques: interferometric

1. Introduction

Despite living inside the Milky Way Galaxy, until very recently we had very little information about the exact shape, size and number of spiral arms. This is due to our unique position inside the disk with little to no perspective on the distance to stars and objects in the sky above us. Distance remains the elusive quantity it has always been in all aspects of astrophysics with the only tried and true method to calculate distances being trigonometric parallax.

In 2004, the BeSSeL (Bar and Spiral Structure Legacy) project began with the aim to calculate the distance to masers associated with High Mass Star Formation, therefore tracing the spiral structure of the Milky Way. In 2008, Japan's VERA (VLBI Exploration of Radio Astrometry) project also joined in that endeavour, and together they have catalogued well over 100 parallaxes to water and Class II methanol masers in the Northern Hemisphere.

This collection of data allowed recalcualtion of the fundamental parameters of the Milky Way: $R_0 = 8.34 \pm 0.16\,\mathrm{kpc}$ and $\Theta_0 = 240 \pm 8\,\mathrm{km\,s^{-1}}$ and implied the Milky Way was ~50% more massive than previously thought (Reid *et al.* 2009, 2009b, 2014). Reid *et al.* (2016) use a baysian approach to assign sources with non–parallax distances to spiral arms, leveraged by the high–accuracy parallax distances. However due to the lack of parallaxes in the Southern Hemisphere, the structure of the 3rd and 4th quadrants of the Milky Way remain uncertain.

2. Progress to date: V255

The Australian Long Baseline Array (LBA) is the only array in the Southern Hemisphere with the capabilities to perform high–precision VLBI. Due to this, the V255 LBA large project began March 2008 with the aim to observe and calculate parallaxes to as many 6.7 GHz class II methanol masers as possible. In the time since then, has collected complete data (four or more epochs) for 27 masers and partial data for a further 4 (Table 1). Largely successful, so far the V255 project has produced 3 parallaxes towards the sources G339.884-1.259, G305.200+0.019 and G305.202+0.208 (Krishnan *et al.* 2015, 2017).

Despite the ongoing V255 project, time allocation and technical short–fallings limit the potential and rate of parallax measurements. The LBA is only available for a few weeks per year, with the V255 project allocated ∼3 days per year. The time required to gather enough data for 100 parallaxes is on the order of another 15 years. In addition, the times that are allocated are often non–optimal for sources, which can lead to a factor of 2 loss in parallax sensitivity.

Table 1. Sources observed to–date by the V255 project, epoch of observation and experiment code of epoch.

Source	Epochs	Experiments
G9.62+0.20	2008 Mar, Aug ; 2009 Feb, Sep, Dec; 2010 Oct	V255a,b,e,f,h,m
G8.68–0.73	2008 Mar, Aug ; 2009 Feb, Sep, Dec; 2010 Oct	V255a,b,e,f,h,m
NGC6334F	2008 Nov ; 2009 Feb, Sep ; 2010 Mar, Jul	V255c,d,g,i,j,z
NGC6334I(N)	2008 Nov ; 2009 Feb, Sep ; 2010 Mar, Jul	V255c,d,g,i,j,z
G329.066–0.308	2010 Jul, Oct ; 2011 Mar, Jul, Nov	V255k,l,n,o,p
G329.029–0.205	2010 Jul, Oct ; 2011 Mar, Jul, Nov	V255k,l,n,o,p
G329.031–0.198	2010 Jul, Oct ; 2011 Mar, Jul, Nov	V255k,l,n,o,p
MonR2	2011 Mar, Jul, Nov ; 2012 Mar	V255n,o,p,q
G188.95+0.89	2011 Mar, Jul, Nov ; 2012 Mar	V255n,o,p,q
G339.884–1.259	2012 Mar ; 2013 Mar, Jun, Aug, Nov ; 2014 Mar, Nov	V255q,r,s,t,u,v,w
G339.681–1.208	2012 Mar ; 2013 Aug, Nov ; 2014 Mar, Nov	V255q,t,u,v,w
G339.682–1.207	2012 Mar ; 2013 Aug, Nov ; 2014 Mar, Nov	V255q,t,u,v,w
G305.200+0.019	2013 Mar, Jun, Aug, Nov ; 2015 Mar	V255r,s,t,u,x
G305.202+0.208	2013 Mar, Jun, Aug, Nov ; 2015 Mar	V255r,s,t,u,x
G305.208+0.206	2013 Mar, Jun, Aug, Nov ; 2015 Mar	V255r,s,t,u,x
G263.250+0.514	2013 Mar, Jun, Aug, Nov ; 2015 Mar, Jul; 2017 Aug	V255r,s,t,u,x,y,ad
G287.371+0.644	2014 Mar, Nov ; 2015 Mar, Jul, Sep; 2017 Aug	V255v,w,x,y,z,ad
G291.274–0.709	2014 Mar, Nov ; 2015 Mar, Jul, Sep	V255v,w,x,y,z
G316.640–0.087	2014 Mar, Nov ; 2015 Jul, Sep	V255v,w,y,z
G316.811–0.057	2014 Mar, Nov ; 2015 Jul, Sep	V255v,w,y,z
G345.003–0.224	2015 Jul, Sep ; 2016 Mar, Jun	V255y,z,aa,ab,ac
G345.003–0.223	2015 Jul, Sep ; 2016 Mar, Jun	V255y,z,aa,ab,ac
G345.010+1.797	2015 Jul, Sep ; 2016 Mar, Jun	V255y,z,aa,ab,ac
G345.010+1.792	2015 Jul, Sep ; 2016 Mar, Jun	V255y,z,aa,ab,ac
G294.990–1.719	2016 Mar, Jun ; 2017 Mar, Aug	V255aa,ab,ac,ad
G298.262+0.739	2016 Mar, Jun ; 2017 Mar, Aug	V255aa,ab,ac,ad
G326.475+0.703	2016 Jun ; 2017 Mar, Aug	V255ab,ac,ad
G328.808+0.633	2016 Jun ; 2017 Mar, Aug	V255ab,ac,ad
G328.809+0.633	2016 Jun ; 2017 Mar, Aug	V255ab,ac,ad
G339.617–0.117	2017 Aug	V255ad
G340.050–0.250	2017 Aug	V255ad

The heterogeneous nature of the LBA leads to a very small mutual–frequency window around the observation frequency. As a spanned bandwidth is used to calculate delays due

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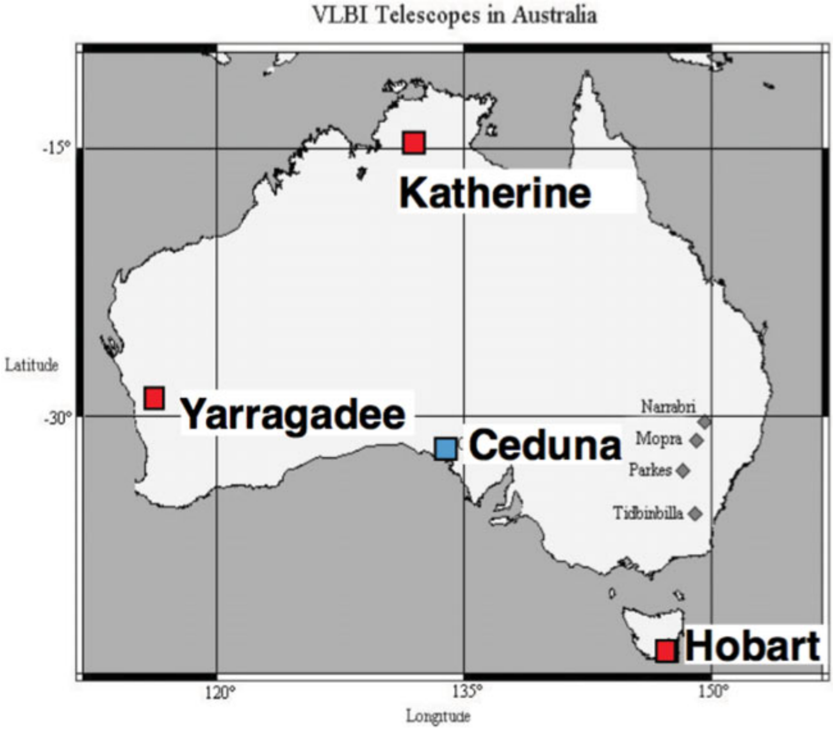

Figure 1. Positions of the radio telescopes in Australia. Empathised are the sites for the Hobart 12m, Katherine 12m, Yarragadee 12m and Ceduna 30m. Together these four telescopes form the ASCI Array.

to the troposphere in the current data–reduction pipeline, the small bandwidth available leads to large uncertainties.

The final and most severe issue is the lack of reliable ionospheric correction. The LBA uses Total Electron Content (TEC) maps derived from GPS observations in the same manner as the BeSSeL uses on the VLBA. However, due to the relative lack of GPS stations in the Southern Hemisphere, Krishnan *et al.* (2015) found that the static ionospheric delays due to the uncertainty in the maps contributed the most to final position uncertainty. The VLBA utilises additional linear–combination of delays to further reduce the ionospheric delays, however this requires a larger spanned bandwidth than the LBA possesses.

3. Future work: ASCI

The University of Tasmania (UTas) own and operate five radio telescopes. Ceduna 30m and Hobart 26m participate in VLBI as part of the LBA, whilst the remaining three 12m telescopes are dedicated to geodetic VLBI. Katherine, Yarragadee and Hobart 12m form the AuScope array (Lovell *et al.* 2013), equipped with S/X geodetic receivers operating $\sim$200 days per year.

A collaboration involving UTas, Max Planck Institut für Radioastronomie, CSIRO Astronomy and Space Science, Geoscience Australia, Auckland University of Technology and Harvard–Smithsonian Centre for Astrophysics secured funds for the design and construction of three wideband receivers for the AuScope array. The receivers are part of

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the VLBI Global Observing System (VGOS; Sun *et al.* 2014) upgrade for the geodetic antennas.

This upgrade presents an opportunity to use the three 12m geodetic antennas for parallax observations – they are free ∼100 days per year and operation and correlation is undergone at UTas. Designed and built by *Callisto*, the receivers cover the frequency range $2.3 - 14$ GHz which includes the 6.7 GHz methanol line of interest. Also, this large frequency range is comparable with that used by BeSSeL on the VLBA ($3 - 7$ GHz) to correct for the troposphere and ionosphere. The cryogenics only cool the LNAs down to 40 K, which is optimised for geodetic VLBI. Due to this, Ceduna 30m will be added to the array to boost sensitivity and provide intermediate baselines (Figure 1). Together these four telescopes will form the AuScope–Ceduna Interferometer, or ASCI.

Rioja *et al.* (1997) show that there exists a plane of ionospheric delay present above each telescope. The authors write that to correct for this, a phase referencing technique called *MultiView* (previously called *cluster–cluster*) can be implemented. This involves cycling through multiple calibrators around the target within a duty cycle, thus solving for a phase plane solution that can be interpolated to the target position. This has been shown to significantly reduce systematic error due to ionospheric effects at low frequencies, where the effect is much greater (Rioja *et al.* 2017). Tests to utilise this method with the ASCI array are currently under–way with the current receivers, and will continue once the broadband receivers are installed.

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