Techniques for Accurate Parallax Measurements for 6.7 GHz Methanol Masers

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Abstract

The BeSSeL Survey is mapping the spiral structure of the Milky Way by measuring trigonometric parallaxes of hundreds of maser sources associated with high-mass star formation. While parallax techniques for water masers at high frequency (22 GHz) have been well documented, recent observations of methanol masers at lower frequency (6.7 GHz) have revealed astrometric issues associated with signal propagation through the ionosphere that could significantly limit parallax accuracy. These problems displayed as a “parallax gradient” on the sky when measured against different background quasars. We present an analysis method in which we generate position data relative to an “artificial quasar” at the target maser position at each epoch. Fitting parallax to these data can significantly mitigate the problems and improve parallax accuracy.

Key words: astrometry – atmospheric effects – methods: data analysis – parallaxes – techniques: interferometric

1. Introduction

The Bar and Spiral Structure Legacy (BeSSeL) Survey uses the National Radio Astronomy Observatory’s Very Long Baseline Array (VLBA) to measure parallaxes of methanol and water masers associated with newly formed (or forming) high-mass stars throughout the Milky Way. In the first two years of the survey, observations were made using maser lines near 12 GHz (methanol) and 22 GHz (water). At frequencies above ≈10 GHz, the dominant source of astrometric error is usually uncompensated interferometric delays associated with water vapor in the troposphere. Astrometric techniques that can yield ~10 micro-arcsec parallaxes at these frequencies are described in Honma et al. (2008), Reid et al. (2009), and Reid & Honma (2014).

However, only about a dozen 12 GHz methanol masers were strong enough to serve as interferometer phase-reference sources and, hence, be optimum targets for parallax measurements. Therefore, the BeSSeL Survey sought to use the stronger and more numerous 6.7 GHz methanol masers. Because emission line features of methanol masers are longer-lived (typically decades) than water masers (often only several months), interferometer coherence times improve with observing wavelength, and atmospheric opacity is generally lower at longer cm-wavelengths, we anticipated that parallax accuracy would be comparable to or better than those obtained at 22 GHz. So, in 2015, new wide C-band receivers, funded by the Max Planck Institute for Radio Astronomy, were installed on the VLBA. Unfortunately, below ≈10 GHz, interferometric propagation delays associated with electrons in the ionosphere can severely increase astrometric errors, even after removing estimated ionospheric delays based on global total electron content models derived from Global Positioning System data (Walker & Chatterjee 1999).

The BeSSeL Survey strategy has been to use the target maser as the interferometric phase-reference source and rapidly switch between the maser and background quasars in order to remove short-term phase-delay fluctuations (mostly from water vapor) from the interferometric data. This essentially removes interferometer coherence-time limitations and allows one to use Earth rotation synthesis to improve interferometer (μ, ν)-coverage, imaging quality, and astrometric accuracy. We used several background quasars for each maser, to guard against occasional structural variability in a quasar limiting astrometric accuracy, as well as to provide several nearly independent parallax measurements.

Often the quasars surrounded the target maser on the sky. This was fortunate as it allowed us to detect systematic gradients in parallax estimates on the sky as sampled by the different quasars relative to the target maser source. Presumably these can be traced to uncompensated ionospheric delays that are present as “wedges,” which, over timescales of hours, distort relative-position measurements in a quasi-linear fashion over ≥5° on the sky. At any single epoch, it would be difficult to disentangle these effects from catalog position errors, which are generally ≥0.1 mas. However, for parallax measurements that involve multiple epochs spanning one year, this proved obvious, as will be shown below. As we do not see these effects at 22 GHz, which is a high enough frequency that residual dispersive ionospheric delays should be small (e.g., residual path-delays

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(≤1 cm), it is nearly certain that the astrometric problems seen at 6.7 GHz can be traced to the propagation of the maser signal through the ionosphere.

This paper describes the challenges faced when observing at 6.7 GHz and the techniques we used to minimize astrometric errors. In Section 2, we describe the astrometric problems evident in our data. In Section 3, we present a calibration technique that significantly improves parallax accuracy. Finally, in Section 4, we discuss the implications of the technique for the estimation of parallax uncertainty.

2. Observed Astrometric Problems

The equipment setup and calibration procedures for previous BeSSeL Survey observations at 12 and 22 GHz are documented in Reid et al. (2009). Importantly, for this paper, we use global models of the ionosphere’s total electron content to remove an estimate of the dispersive delay along a ray-path toward any source. The application of these models reduces residual dispersive delays by a factor of between two and five (Walker & Chatterjee 1999). While this is generally adequate to reduce dispersive path-delays to ~1 cm for 22 GHz observations, because dispersive delays scale as $\nu^{-2}$, where $\nu$ is the observing frequency, at 6.7 GHz residual path-delays can be ~10 cm. This is roughly an order of magnitude larger than our target accuracy of ≤1 cm, which is necessary to achieve a parallax accuracy of ≈0.01 mas (Reid & Honma 2014). If this is not dealt with, it could limit parallax accuracy to ~0.1 mas and, thus, limit a distance measurement to ≤1 kpc with 10% accuracy.

The left panels of Figure 1 show a range of examples for parallaxes of 6.7 GHz masers as measured against different quasars as a function of the locations of the quasars relative to the Galactic maser. Of course, being at very great distances, all quasars used as background sources should yield the same parallax for the target maser within measurement uncertainty. However, separate parallax measurements for a maser based on different quasars that projected close together on the sky can explain the variation in our 6.7 GHz parallax results of ≈0.01 to ≈0.05 mas deg$^{-1}$ for a maser source relative to background quasars.

As discussed earlier, there is strong circumstantial evidence that uncompensated ionospheric delays are at the root of the relative-position wedges. However, the details of how this happens are not clear. The VLBA antennas span about 90º in longitude, or six hours of solar hour-angle, which should result in significant differences in ionospheric conditions above many of the antennas. Thus, one might expect that the effects of ionospheric delays would be only partially correlated among the different sites and would somewhat “average out” in an image made with the entire array over a 6-hr observation. However, it is likely that the total electron content models used to remove most of the ionospheric delays may systematically over or under estimate the electrons, leading to significant correlations in the residual (uncompensated) delays and enhancing relative-position shifts. While this should be investigated in the future, it is beyond the scope of this paper, which is primarily concerned with a mitigation strategy to improve parallax accuracy regardless of the cause of the problem.

3. Analysis Methods

In order to deal with the problem of position gradients across our sources, we take advantage of their distribution on the sky. Rioja et al. (2017) recently demonstrated a technique called “MultiView” that uses a two-dimensional interpolation of interferometer phase from a distribution of sources to calibrate phase toward a central target source. They have shown impressive astrometric results at a frequency of 1.6 GHz, where ionospheric effects are more severe than for our observations at 6.7 GHz. Unfortunately, the BeSSeL Survey observations were not conducted in a manner that allows direct use of MultiView calibration. The background quasars were selected to be close to the target, which generally required weak sources that could only be detected in images that combined data from multiple baselines and spanning hours of observation. However, we can use a variant of MultiView with positions measured from images to improve our astrometric accuracy.

Conceptually, one could take the relative-position measurements (maser minus quasar) at each epoch and estimate what the measurement relative to an “artificial quasar” near or at the position of the maser would be, and then fit the artificial quasar positional data to estimate the parallax and proper motion of the...
The simplest approach would be to average the positions of all quasars (relative to the maser) to generate the artificial quasar data at each epoch. However, this would not take into account the distribution of the quasars with respect to the maser.

Given the quasi-linear behavior on the sky of the parallax results, a better method is to allow for a gradient in relative position as a function of separation from the maser. We investigated two such methods.

Method-1 fits a plane through the two-dimensional relative-position measurements. Specifically, given the measured position of the \( j \)th quasar relative to the maser at epoch \( i \), \((x_j^i, y_j^i)\), and the separation on the sky of that quasar relative to the maser, \((\Theta_x^i, \Theta_y^i)\), we fitted the components of the measured positions with the model

\[
x_j^i = S_x^i \Theta_x^i + S_y^i \Theta_y^i + C^x, \tag{1}
\]

and

\[
y_j^i = S_x^i \Theta_x^i + S_y^i \Theta_y^i + C^y. \tag{2}
\]

To avoid potential confusion, we use the term “separations” to refer to the degree-scale separations of individual quasars from a maser target, and the term “positions” to refer to the measured mas-scale position differences of the quasars from the maser after removing the degree-scale separations.
In Equations (1) and (2), the $S$ (slope) parameters allow for a tilt of the plane and the $C$ (constant) parameters give the estimated position of the artificial quasar at the maser position. The superscript for the $S$ parameters indicates the component of data being modeled, whereas the subscript indicates the direction of separations for which the slope parameter applies. Fitting this model requires at least three quasars, as for each direction on the sky, there are three parameters. A drawback of this method is that the parameters can become degenerate as the quasars approach a linear distribution on the sky.

Method-2 assumes that the $x$-components of the measured position differences depend only on the $x$-separations of the quasars from the maser on the sky (and the same for the y-components):

$$x_i = S_i x \theta_i + C_x,$$

and

$$y_i = S_i y \theta_i + C_y.$$  

This method has only two parameters per coordinate and, hence, only requires two quasars at minimum to work. If more quasars are available, one will get more robust artificial quasar data. This method also allows for linear distributions of quasar on the sky, which in principle could yield excellent artificial quasar data. Using this method, we generated artificial quasar data at each epoch and used these to fit for parallax and proper motion of the masers. The parallax values generated in this fashion are indicated in the left panels of Figure 1. Based on a visual inspection of the three cases presented, these give reasonable values.

Table 1 lists the parallax results for the three examples shown in Figure 1 both for a standard fitting approach, where all background quasars are assumed to yield the same parallax for the target maser, and for the fitting approach of Method-2 described above. In both cases, the parallax uncertainties are estimated from the magnitude of the post-fit residuals. For these three examples, Method-1 and Method-2 returned parallax values within a few micro-arcseconds of each other and nearly identical formal uncertainties. However, in some other cases, Method-1 gave larger formal uncertainties. Because of this, and because Method-1 requires solving for more parameters, we adopted the simpler Method-2 over Method-1 for our application.

As is evident in Figure 1, G030.78+0.20 displays an unusually large parallax gradient on the sky, and the parallax uncertainty from Method-2 artificial quasar data is 50% of that in the standard method. The source G111.25−0.76 displays a moderate parallax gradient on the sky, and the artificial quasar uncertainty is 70% of that in the standard estimate. In the final example, G013.71−0.08, little or no parallax gradient is detected, and the standard and artificial quasar methods produce similar results. Because, in the presence of significant parallax gradients, the artificial quasar (Method-2) almost always gave smaller post-fit residuals than did a simple combined fit using all quasars, which does not take into account possible position gradients on the sky, we adopted it as the method of choice for the BeSSeL Survey 6.7 GHz data.

4. Other Considerations

When we planned BeSSeL Survey observations for VLBA programs BR149 and BR198, we scheduled the minimum number of epochs for parallax and proper motion observations, which would yield uncorrelated parameter estimates and the
lowest parallax uncertainty. This could be accomplished with four epochs scheduled to sample the peaks of the parallax signature in R.A. For example, for sources at low Galactic longitude, we would schedule one observation in March, two in September, and one in the following March. We optimized based on the R.A. component of the parallax signature, because (1) that component has a larger amplitude than the decl. component for most Galactic sources, and (2) VLBA measurements are generally more accurate for that component than for the decl. component (Reid et al. 2009).

By observing three or four quasars for each maser target, we planned to have sufficient degrees of freedom to estimate true astrometric accuracy from the magnitudes of the residuals to the parallax fits. For example, with four background quasars for a maser target and four epochs of observations, there are 16 relative-position measurements in the critical R.A. direction. All background quasars should yield the same parallax and motion for the maser, each additional quasar only adds one extra parameter, a correction to its position offset, while adding four extra data points. Thus, for this example, there would be 16 data points and 6 parameters to solve for, yielding 10 degrees of freedom.

However, in order to mitigate the effects of position gradients across our source groupings, we used up most of our degrees of freedom to generate the artificial quasar data. Fits to this data for four epochs have only one degree of freedom when the R.A. data dominates. This in no way biases the parallax estimates, but it leads to uncertain estimates for the uncertainty in the parallax. Figure 2 shows the results of 10⁷ simulated parallax fits with only one degree of freedom (i.e., using four optimally sampled data points and three parameters). The true parallax value was set at 1.00 mas and the R.A. (1σ) position uncertainty was set to 0.10 mas. These values should lead to a true parallax uncertainty of 0.05 mas, as we actually measure twice the parallax amplitude. The left panel of the figure shows that we retrieve the correct values, and there is no bias in the parallax estimate. The right panel shows the distribution of formal parallax uncertainties estimated from the scatter in the post-fit residuals. The probability density is asymmetric, with mean and median values of ≈0.0444 mas (about 10% below the correct value of 0.05) and a tail to larger values. Being conservative, we have inflated our parallax uncertainties accordingly to remove this slight bias. Following this correction, the symmetric 68% confidence range for the parallax uncertainties for this example spans from 0.029 to 0.073 mas about the correct value of 0.05 mas. Thus, the uncertainty in the uncertainty can be expected to be significant (±44%). In conclusion, even though the parallax estimate is unbiased, one should exercise caution when using the estimate of its uncertainty from our 6.7 GHz parallax measurements.

Facility: VLBA.

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