On-line information for "Mapping the Milky Way" by Reid et al.

ABSTRACT

Recent advances in radio astrometry with the VLBA have resulted in near microarcsecond accurate trigonometric parallax and km s^{-1} accurate proper motion measurements for masers in star forming regions. We are now poised to directly measure the full 3-dimensional locations and motions of most high-mass star forming regions in the Milky Way and for the first time to map its spiral structure. Such measurements would also yield details of the kinematics of the Milky Way and determine its fundamental parameters (R_0 and Θ_0) with $\approx$ 1% accuracy. Coupled with other observations this would yield the distribution of mass among the various components (including dark matter) of the Milky Way. Here we propose a Key Project for the VLBA to measure the parallaxes and proper motions of $\approx$ 400 high-mass star forming regions over the next 5 years.

1. Technical Information

1.1. Parallax Observations

For our previous parallax measuremnts of 12 GHz methanol masers (program BR100; Papers I – V), we shared a single observing track between two target sources. For example, we alternated observing blocks of 20 minutes on NGC 7538 (and nearby background sources) and on Cep A (and its background sources). These maser targets were chosen because they have similar Right Ascensions and hence have parallax signatures that peak at about the same time of year. Each block consisted of rapid switching among the target maser (T) and one or more background quasars (Q). A typical block (B) that used the maser as the phase reference and 2 background quasars would consist of 40 sec scans in the following sequence:

- 20-min block (B): T, Q1, T, Q2, T, Q1, T, Q2, ...

We require target masers to have flux densities > 5 Jy for methanol masers and > 10 Jy for 22 GHz H_2O masers. We can use background quasars that have peak brightness > 5 mJy/beam, assuming 256 Mb/s recording rate. While we can conduct this project using 256 Mb/s recordings, we request the highest *sustainable* recording rate as this would allow us to use weaker backgroung quasars, which statistically will be closer to our targets, hence improving parallax accuracy which is typically limited by systematic errors.

The masers targets and the (weak) background quasars generally display simple structure, often dominated by nearly point-like features, and continuous (u,v)-coverage is not important for determining accurate positions. Thus, we can minimize observing time by sharing an observing track among 3 target maser sources (instead of the 2 targets done in the past). Including aomw calibration blocks (C), we would observe with target blocks (B) described above in the following sequence:

- 8-hr track: C1, B1, B2, B3...B1, B2, B3, C2, B1, B2, B3...B1, B2, B3, C3

The calibration (geodetic-like) blocks consist of 1-min scans on about a dozen ICRF quasars,whose positions are known to better than 1 mas. The sequence of quasars is chosen to maximize the source elevation differences among all antennas. For these blocks, we spread the IF bands to span the maximum bandwidth ($\approx$ 500 MHz) in order to optimize group-delay measurement. These group-delays are used to determine the slowly drifting, un-modeled, vertical atmospheric delays above each VLBA antenna. (Short term atmospheric fluctuations are removed by rapid switching within each target block.) We track changes in the vertical atmospheric delays by placing 3 or 4 geodetic-like blocks throughout each 8-hour track. (See Paper I for more details.)

The proposed time sequences of observing epochs for a methanol and H_2O observation are shown in Fig. 1. One year's observing is the natural period for parallax observations, and when observing maser spots that have limited lifetimes it is prudent to make measurements in the shortest timespan.

How many parallaxes can be measured in a one year period? Star forming regions are preferentially distributed toward the inner Galaxy, where lines of sight cross many spiral arms. Since parallax measurements are optiminally done when the Earth's orbit appears maximally extended as observed by the source, this leads to two periods in the year when large numbers of observations are required: March/April and September/October. To further complicate matters, for methanol masers our proposed observing sequence can have 2 tracks per source in one of those periods. So, for methanol masers, we plan to stagger the start of our yearly cycles (eg, start one source group in March/April, and thus having 2 observations in September/October, and starting another source group in September/October, and thus having 2 observations in March/April), we need on average 3 tracks for 2 source groups in either croweded period. In either 2-month period, the number of observing tracks is limited to about 60. Realistically, we can't expect to get more than about 40 tracks, and this limits the rate of parallax measurements. Observing 3 target masers sources per 8-hr track, we can do up to about 60 sources (20 groups) that require observations in the crowded months. Other methanol masers in the outer Galaxy, or water masers throughout the galaxy, do not need as many observations in the crowded periods and 20 or more such sources per year can be accomodated in order to fully map the Galaxy.

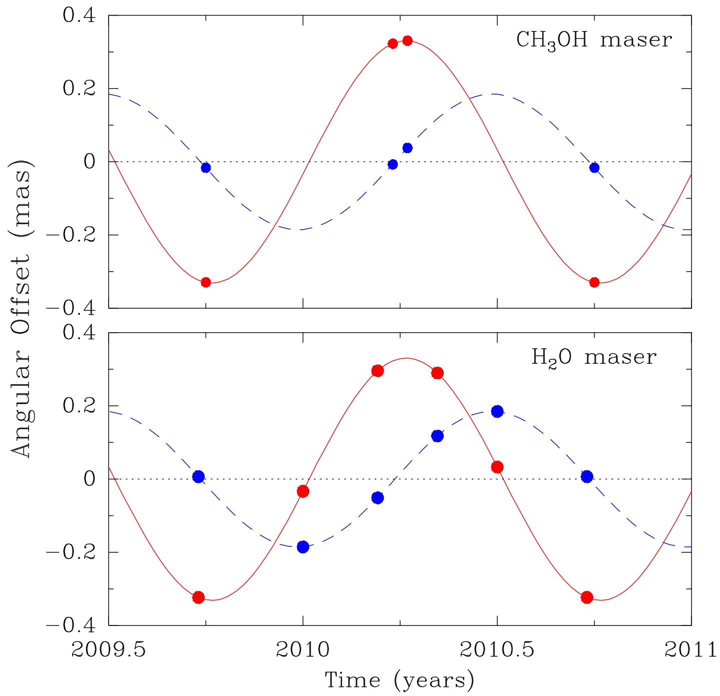

Fig. 1.— Example time sampling for near optimum parallax and proper motion measurements of a source at Galactic longitude 45° and a distance of 3 kpc. Solid red lines are for the Eastward parallax signature and dashed blue lines are for the Northward signature. *Top Panel:* Proposed methanol maser sampling. Because methanol masers have lifetimes typically >> 1 year, one can maximize the parallax accuracy for a minimum of observations by sampling at the peaks of the (often dominant) Right Ascension parallax signature. This sampling results in near-zero correlation coefficients among the parallax and proper motion parameters. *Bottom Panel:* Proposed H_2O maser sampling. Because individual H_2O maser spots have lifetimes that can be less than 1 year, one needs to observe more frequently (than for the methanol case) in order to separate the parallax and proper motion effects for maser spots that might live only about 6 months.

1.2. Calibrator Searches

If one looks for background sources (e.g. quasars) near any randomly chosen maser target using the VLBA calibrator search tool, one generally finds a compact enough source within $\approx 3^\circ$ degrees on the sky. Such a background source will usually **not** yield very accurate parallaxes, since transfering interferometer phase over that angular distance gives poor results. Since cancellation of systematic errors scales as the angular separation between target and background source, it is very worthwhile to find (even weak) background sources that are much closer to the target.

We have found previously unknown background sources in the following manner. We looked through the (L-band) NVSS source catalog for unresolved ($< 20''$) sources stronger than 10 mJy. Typically there are about 25 such candidates within about 1.5 degrees on the sky of any Galactic target position. Most of these are Galactic HII regions and not useful for our purposes. We observed these in snapshot mode with the VLA (hopefully in the B- or A-configurations) at X- and K-band in order 1) to put much tighter limits on compactness and 2) to verify a synchroton spectal index. This procedure removes the HII regions that appear unresolved in the NVSS. Typically, we find between 1 and 4 sources that are good candidates for being compact extragalactic sources. It takes about 2 hours of VLA time per target position to conduct these observations. In the past, if necessary, we have used the smaller VLA C-configuration for the calibrator searches and found sources that turn out to be good VLBI sources with about 70% success.

Unfortunately the VLA will be going into an extended period in the D-configuration, from 2009 October through 2010 May, followed by C-configuration until 2010 September. In order to do the calibrator searches before mid-to-late 2010, we propose an alternative method. We can use the GBT, in VLBI mode, with the VLBA to survey candidates. We would do this at X-band for maximum sensitivity in the shortest observing time with the least sensitivity to poor weather. Using 256 Mb/s sampling and on-source integration times of 60 seconds, we would achieve a 7-sigma detection threshold of 8 mJy on each GBT–VLBA baseline. Allowing for slew time and some fringe-finder scans, we could survey about 30 candidates per hour. Without the GBT as a super sensitive VLBI antenna, we would need to spend about 4 times the integration time to achieve our required sensitivity.

Many of our targets lie in fields imaged by the CORNISH VLA survey (C-band, B-configuration, with coverage between $10^\circ < \ell < 65^\circ$ and $|b| < 1.1^\circ$), and for these targets we anticipate that we can greatly reduce the number of candidates (compared to the L-band, D-configuration NVSS). Thus, we will need to survey either about 10 or 25 background candidates per target depending on whether we can use CORNISH or must rely on the NVSS survey for candidates. This translates to background source searches for about 1 to 3 maser target regions per hour. For our proposed ≈ 80 target parallaxes per year, we would need ≈ 40 hours of GBT–VLBA time for the calibrator survey in the first year. In the subsequent years, we probably would not need as much survey time, since many of our targets will be separated by $< 1^\circ$ on the sky and we should often be able to use some previously discovered calibrators.

However, this calibrator survey would be extremely valuable, not only for our parallax project, but also for many VLBA, EVLA and even ALMA projects, since the density of known calibrators in the Galactic plane is low. Therefore, instead of conducting the search toward individual maser targets in yearly blocks, we could do a single complete Galactic plane survey in the first year. It would take approximately 160 hours of GBT–VLBA time to survey all compact sources stronger than ~ 10 mJy in the range $0 < \ell < 240^\circ$ and $|b| < 1.0^\circ$ based on the CORNISH and NVSS "point" sources. From our experience this would produce about about 500 calibrators or about 1 calibrator per square degree. (For EVLA use one would then need to conduct snapshot observations at several bands, to determine arcsecond-scale structure, but we do not propose to do this as part of our project.)

The VLBI calibrator survey just described is actually preferable to a VLA survey as detection guarantees compact structure at the milli-arcsecond (mas) scale. Also, even a single group-delay and fringe-rate measurement on up to 10 GBT–VLBA baselines would yield a position to better than $\approx$ 20 mas, which is adaquate to start VLBA observing. (Ultimately, we always include an ICRF calibrator, whose position in known to $\sim$ 1 mas, in the parallax observation schedule in order to refine all absolute source positions to a few mas. It is crucial that the phase reference source, usually a maser spot, be known to that accuracy to avoid phase-referenced imaging degradation.)

1.3. Maser Selection and Position Determinations

Published catalogs of masers will be used to select the parallax targets. Our first choice of maser targets are methanol masers. There are approximately 50 known 12 GHz methanol masers with peak flux density stronger than 5 Jy (and hence strong enough to be the phase reference source). We have measured or are currently measuring parallaxes for about 20, so there are about 30 more to do. Ultimately, when the VLBA has new 4–8 GHz receivers that can reach the 6.7 GHz frequency of the strongest methanol maser transition, we will switch to observing this transition. There are currently 374 of these masers with peak flux density greater than 5 Jy in the catalog of Pestalozzi, Minier & Booth (2005), of which about 220 are visible from the VLBA.

Until the new 4-8 GHz receivers are available (at least 2 years from now), we will observe 22 GHz water masers for parallaxes of high-mass star forming regions. Water masers are strong and numerous, with over 200 known (with $\delta > -30°$) that have peak flux densities greater than 10 Jy (Palagi et al. 1993), which is the minimum required for phase-reference detection in this band. The reason that H_2O masers are second choices for parallax observations is that individual maser spots generally have lifetimes less than the 1 year that is optimum for parallax measurement. However, some spots do live longer than 1 year and similar parallax accuracies as for methanol masers have been obtained, but these have been done using denser sampling in time in order to separate parallax from proper motion parameters for spots that live less than 1 year.

Most masers (both methanol and water) were discovered with single-dish surveys and have not had interferometric positions measured. Their position uncertanties are often $> 10''$, which is inadequate for our VLBA observations (owing to fringe-rate smearing on longer baselines). Thus, we need to determine maser positions with sub-arcsecond accuracy before starting VLBA observations. We propose to do quasi-snapshot VLA observations of all targeted H_2O and methanol masers. This will take comparatively little observing time ($\approx$ 16 hours total) and can be accomplished even in the D-configuration, as we only require $\approx 0.5''$ positional accuracy. Also, it will provide us with a current spectrum of the masers in order to verify that they are strong enough to seve as phase reference sources. Since the EVLA does not yet have receivers covering 12 GHz, for the small number of remaining 12 GHz methanol masers with single-dish positions, we would measure and use the positions of closely associated 6.7 GHz masers.

Since the positions of all sources will be known to better than 1″ (allowing for maser spots within any source to be spread on the sky by roughly that amount), we can integrate for 1 second in the correlator and thus will require only a single correlator pass to process the raw data.

2. "Frequently Asked Questions"

- Will a large proper motion increase the uncertainty of the parallax measurement?

  No. For a well designed parallax observation, e.g. as shown in Fig. 1, the correlation coefficients among the parallax and proper motion parameters can be made close to zero. This means that the parallax measurement is essentially independent of the proper motion. Only if the sampling is not optimal, as can happen for H_2O maser spots that do not live for 1 year, will there be a substantial correlation among the parameters. Even then, the magnitude of the proper motion is not important, only the *uncertainty* in the proper motion can affect the parallax.

- Will structural changes in the background QSO (jet) limit the parallax measurement?

  In principle, changes in the structure of the background sources (as well as in maser spots) will affect the parallax measurement. Were we to use strong jet-dominated quasars, such as 3C 273, as position references, structural variations would probably be problematic. However, the weak background sources we find in our surveys generally display little if any jet-like structure at the (high) frequencies we observe. Also, while unresolved structural changes could add "noise" to position measurements, it is highly unlikely that it could mimic the sinusoidal parallax signatures, both in period and phase.

- Since typical H_2O maser spots don't live 1 year, how can you measure a parallax to these masers?

  While 1 year is the optimum period for measuring parallax (as one can obtain near-zero correlation among parallax and proper motion parameters), one can still measure a parallax with about a half-year of data. For example, using only a subset of the data containing four adjacent samples for the H_2O maser example in the lower panel Fig. 1, one obtains correlation coefficients of 0.2 to 0.9 between the parallax and the eastward proper motion parameter. The lower correlation coefficient comes from using only the central 4 samples and the higher correlation comes from using only the first (or last) 4 samples, which have less curvature to separate the parallax effect from the proper motion. Of course if one has several (or many) maser spots, as is common for H_2O maser sources, one can do a combined solution using only a single parallax parameter and improve the results.

- Does one really need 40 minutes for the geodetic-like blocks used to measure the vertical atmospheric delays for each antenna?

The vertical atmosperhic delay calibrations done with these blocks rely on separating the delay effects from different antannas via source zenith-angle differences. We have conducted tests using blocks of different lengths and found that, for the locations of the VLBA antennas, the zenith delay uncertainties decrease as the square-root of time for blocks longer than about 30 minutes,. However, for blocks shorter than 30 minutes, it is difficult to obtain a wide range of *different* zenith angle among antennas, and the parameter uncertainties are greater than based on the square-root of time. Realistically, allowing for some loss of source data, owing to common observing problems at the antennas, we find that 40 minutes is nearly optimal, resulting in robust zenith path delay uncertainties of ~ 1 cm (~ 0.03 nsec).

- Can one measure parallaxes with similar accuracies for high and low Declination sources?

  No. Even after using geodetic-like blocks to improve the zenith path-delay errors (which are often the dominant source of parallax uncertainty) from the correlator model (~ 5 cm) to about ~ 1 cm, parallaxes for low Declination sources are worse than for high Declinations. Our experience indicates that we can achieve parallax uncertainies of ± 6 μas for sources at high Declination (e.g. S 252), whereas for sources near the Galactic center we have uncertainties of ± 20 μas (e.g. G23.0-0.4). Since low Declination source parallaxes are limited more by systematic error than thermal noise, we plan to add a an extra geodetic-block to the observing tracks in order to more carefully track and remove zenith path-delay errors. Even better would be to finish the deployment of GPS receivers (6 antennas already have them) at the remaining 4 VLBA antennas, as this would allow *continuous* monitoring of zenith path delays. Either or both of these enhanced calibrations should improve the parallax accuracy compared to our previous results. Of course for a modest number of very distant sources at low Declinations, we can improve parallax accuracy by $\sqrt{2}$ by observing for a second year's cycle.

REFERENCES

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