Calibration of Submillimeter Observations with SiO Masers: Does the MMA Need Dual Band Capability?

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Abstract

We investigate how well calibrating 690 GHz observations with SiO masers at 86 GHz will work, and take a look at how many SiO masers are bright enough to act as phase calibrators at 690 GHz. Although some SiO masers are fantastically bright, they have a bandwidth of only about 10 km/s. Masers brighter than 20 Jy will work $\sim$ 80% of the time for simultaneous 86 GHz and 690 GHz observations, or $\sim$ 40% of the time for time shared multiband observations. Masers fainter than 4 Jy will seldom be very useful for either technique because the time required to detect them with sufficient SNR is greater than the atmospheric stability time scale. We estimate there are about 100 SiO masers with peak fluxes greater than 4 Jy. With an 86 GHz beam width of $75''$, simultaneous dual band calibration will be relevant to about 0.04 square degrees. And finally, since SiO masers are usually associated with evolved stars, most types of MMA observations would not be aided by calibrating on an SiO maser in the beam.

Because of the very limited usefulness of simultaneous dual band calibration, and because the Chilean atmosphere plus fast switching or radiometric phase correction will permit observing at 690 GHz for a substantial fraction of the time, we argue against incorporating simultaneous dual band observations with the MMA.

1 Introduction

Several working groups at the October 1995 MMA Science Workshop expressed a desire to be able to observe with two or more bands simultaneously. The technical working group countered that dual band capability on the MMA would complicate the optics, and that dual band capability should be avoided unless absolutely required by the science. The meeting came to an understanding that dual band observing was scientifically justified when the source structure changes on time scales of seconds, as in the case of solar observing, and perhaps when the atmosphere changes on time scales of seconds, as in the case of submillimeter observing where simultaneous low frequency observations may be used for phase calibration.

The solar group was the only group who could justify the need for simultaneous dual band observing on the basis of the astronomical source structure changing over seconds, but they have since stated that subarrays chosen to provide comparable resolution is a more appropriate solution to their problem.

For the submillimeter calibration issue, we compare here the effectiveness of true simultaneous dual band observation on an 86 GHz SiO maser for calibration and a target source at 690 GHz, and time sharing between 86 GHz and 690 GHz.

2 Sensitivity on SiO Masers at 86 GHz

If an SiO maser could be observed at 86 GHz simultaneously with a target source at 690 GHz, we could transfer the atmospheric phase from the lower frequency to the higher. This is attractive because the SiO maser is much brighter than the target source at 690 GHz, and the system sensitivities are much better at the lower frequency.

Lets say our maser has an average flux of 10 Jy over a bandwidth of 3 MHz (10 km/s), or a peak flux of about 20 Jy. With $T_{sys} = 40K$, the noise per visibility for a single visibility (both polarizations included) will be 1.14 Jy in one second. (A T_{sys} of 40 K at 86 GHz is much more optimistic than we assumed in the recent exploration of fast switching in MMA Memo 139.) The error in the gain solution will be about

$$\sigma_G = \frac{\sigma_v}{S\sqrt{N-3}},$$

or about 0.02 for our 10 Jy maser, leading to $1.^\circ 14$ rms phase errors. When scaled to 690 GHz, these will become $9.^\circ 1$ rms phase errors per antenna, or 13° per baseline. However, this is only part of the contribution of the phase error. We must also determine how much the atmospheric phase changes over our 1 s of integration.

3 Residual Phase Errors

The residual phase error after simultaneous dual frequency calibration will be approximately

$$\sqrt{D_\phi(vt_c/2)},$$

where D_ϕ is the phase structure function, v is the atmospheric velocity, and t_c is the time it takes to detect the antenna based phase on the SiO maser calibrator with the required SNR. In terms of the temporal structure function $\bar{D}_\phi(t)$, which we measure with the site test interferometer,

$$\sqrt{\bar{D}_\phi(t_c/2)}.$$

Use of the temporal structure function for this application is desirable as it bypasses the need to know the atmospheric velocity.

The alternative to simultaneous dual frequency calibration is to time share between the 86 GHz and 690 GHz bands. For this analysis, we have two extra parameters, the time

SiO Maser Flux, Jy	Approximate number of masers	Dual Band success rate	Time Sharing success rate
20	35-100	83%	43%
10	50-200	53%	25%
4	75-500	9%	3%

Table 1: What fraction of the time will calibration on an SiO maser of some flux result in residual phase errors of 30° or less at 690 GHz? These numbers are calculated using the May-August 1995 Chile phase stability database. The cumulative source count estimates are derived from the arguments in the next section.

required to switch between frequencies t_s, and the fraction of time spent on the target source f. The residual phase errors are now

$$\sqrt{\bar{D}_\phi((t_c + 2t_s)/(2(1-f)))},$$

or for $f = 0.5$ and $t_s = 1$ s,

$$\sqrt{\bar{D}_\phi(t_c + 2\ s)}.$$

With the target source fraction of 0.5, the noise in our time sharing observations will increase by $\sqrt{2}$. For our 20 Jy SiO maser, we plot the distributions of residual phase errors for dual band calibration and for time sharing calibration for the May-August Chile atmospheric phase stability conditions in Figure 1. Table 1 indicates the fraction of time the atmosphere will be good enough to use 20, 10, and 4 Jy SiO maser calibrators.

We can draw a few important conclusions on phase calibration of a 690 GHz target source with an SiO maser at 86 GHz:

- SiO maser calibration works very well for masers which are 20 Jy or brighter.
- SiO maser calibration does not work very often for masers weaker than 4 Jy.
- For a given maser strength, the atmosphere permits dual band calibrated observations about twice as often as time sharing calibrated observations.

4 SiO Maser Source Counts

How many SiO masers are there? Considering the data from Jewell *et al.* (1991), which includes information on all previously known masers as well as masers they identified, in the v=1, J=1-0 line at 43 GHz, The survey of Izumiura *et al.* (1993) of SiO masers in the Galactic bulge does not find any masers as bright at 4 Jy peak flux. We also assume that the 43 GHz peak fluxes and velocity widths are comparable to those of the 86 GHz line which would be observed by the MMA. These data, if complete down to 25 Jy, imply a cumulative distribution function like

$$N(>S) = 233 S^{-0.60},$$

or about 100 SiO masers with peak flux brighter than 4 Jy. (Jewell *et al.* only cover about 75% of the sky, so there will be somewhat more SiO masers which can be viewed from the MMA, which can see about 90% of the sky if located in Chile or Mauna Kea.) Jewell *et al.* will be incomplete below some flux level, but there is no strong indication of incompleteness at the 25 Jy level in the log(N), log(S) plot shown in Figure 2.

The -0.60 power law is a bit odd for the source counts. If known SiO masers were dominated by local sources of similar intrinsic luminosities, we would expect an isotropic distribution and a 3-D integrated source count law like $S^{-3/2}$. If known SiO masers were dominated by sources along our spiral arm alone with similar luminosities, we expect a 1-D integrated source count law like $S^{-1/2}$. If known SiO masers were scattered uniformly through the Galactic plane, we would expect a 2-D integrated source count law like S^{-1}. The distribution of known SiO masers with brighter than $S\Delta v/2$ greater than 20 Jy km/s (our 4 Jy, 10 km/s minimum useful calibrator) is shown in galactic coordinates in Figure 3, and in celestial coordinates in Figure 4. The distribution of masers does not cry out for any of these possibilities. The 1-D source count law, which comes closest to the power law which we derive from the data, can be ruled as SiO masers come at all galactic longitudes. Accounting for the part of galactic coordinates which was not seen by the SiO surveys (ie, south of declination -30), about 75% of the masers brighter than 4 Jy are distributed quasi-uniformly, while the band within 20° of the plane contains an additional 25% of the masers. Masers brighter than 50 Jy are not clumped towards the plane, indicating that at this level the source counts really are dominated by local objects. That the masers are more clumped towards the plane at lower levels indicates that we have run out of local sources, or that we have integrated beyond the scale height of SiO masers, and the more distant plane sources have kicked in. The odd power law exponent of -0.60 is probably due to a combination of effects such as the local sources showing up only as very bright masers, the adding together of local and plane sources, and possibly different populations of SiO masers with different intrinsic luminosities. This all casts a bit of doubt on the true number of masers there may be which are brighter than 4 Jy, but we expect that our estimated number is in error by well under an order of magnitude.

The $\sim$40 SiO masers brighter than 20 Jy will permit phase stable observations at 690 GHz of several interesting galactic regions in and out of the plane, even under marginal phase stability during the Chilean winter. On the other hand with a $75''$ primary beam at 86 GHz, all of the usable SiO masers will make less than one tenth of a square degree of of sky accessible to 690 GHz observations, and mostly in the regions about evolved stars where SiO masers tend to live. Clearly, a more general technique, such as radiometric correction or fast switching, will be required to phase calibrate the typical source at 690 GHz. Preliminary investigations of fast switching phase calibration at 690 GHz indicates that it should work about 25% of the time during the Chilean winter at 690 GHz. Since methods which do not require dual band capability will work a reasonable fraction of the time, it seems that simultaneous dual band observations are not justified.

Acknowledgements

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References

Izumiura, H., *et al.*, 1994, ApJ, 437, 419.
Jewell, P.R., *et al.*, 1991, A&A, 242, 211.

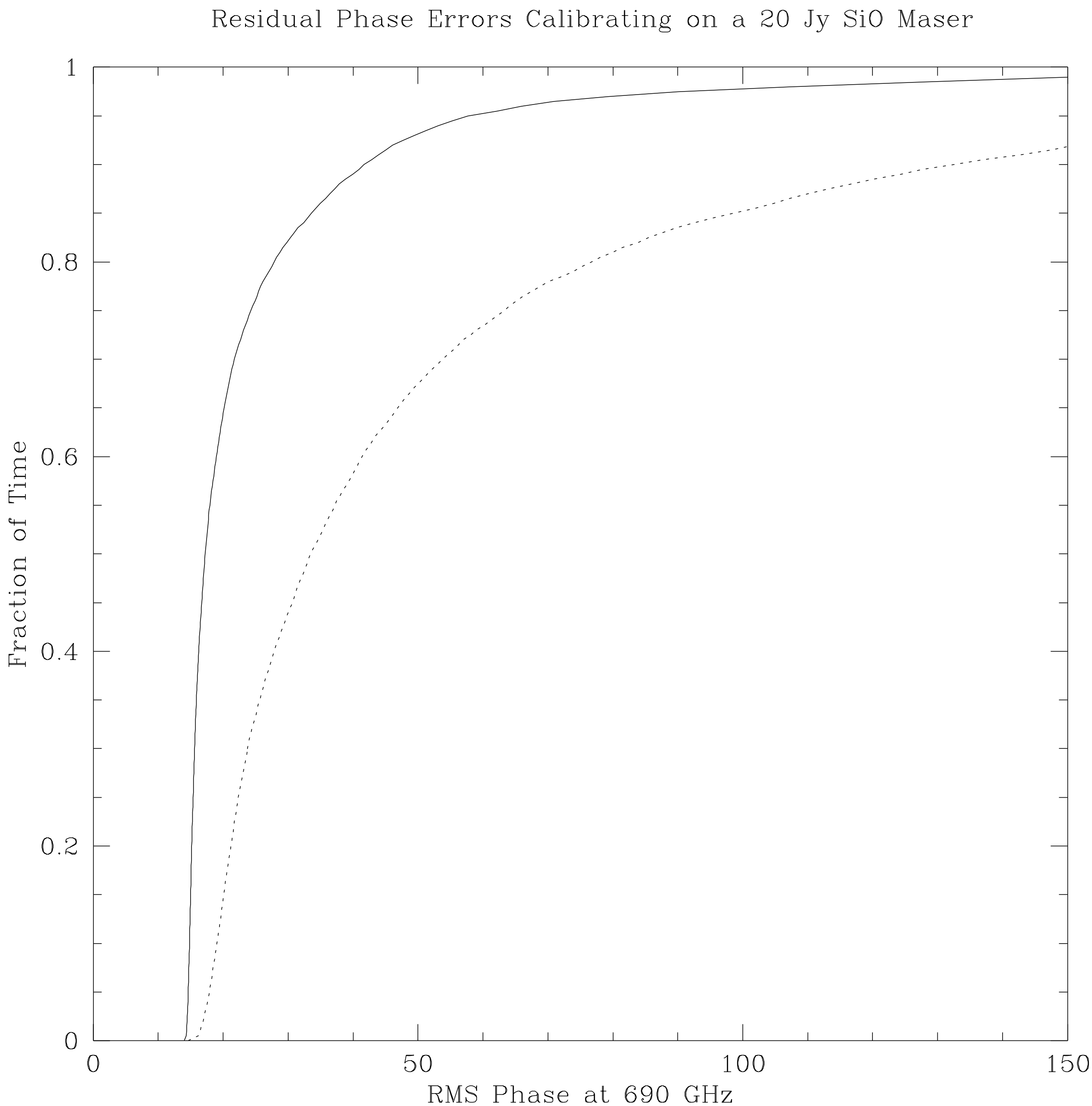

Figure 1: Residual phase errors per baseline on a target source at 690 GHz for simultaneous dual band calibration on a 20 Jy peak flux SiO maser (solid line) and for time sharing observations spending half the time on the target source (dashed line). The sharp cutoff at 13° is due to the effect of system noise on tha gain solution in 1 s of integration on the SiO maser. Our rule of thumb is that 30° residual phase errors will result in very good images.

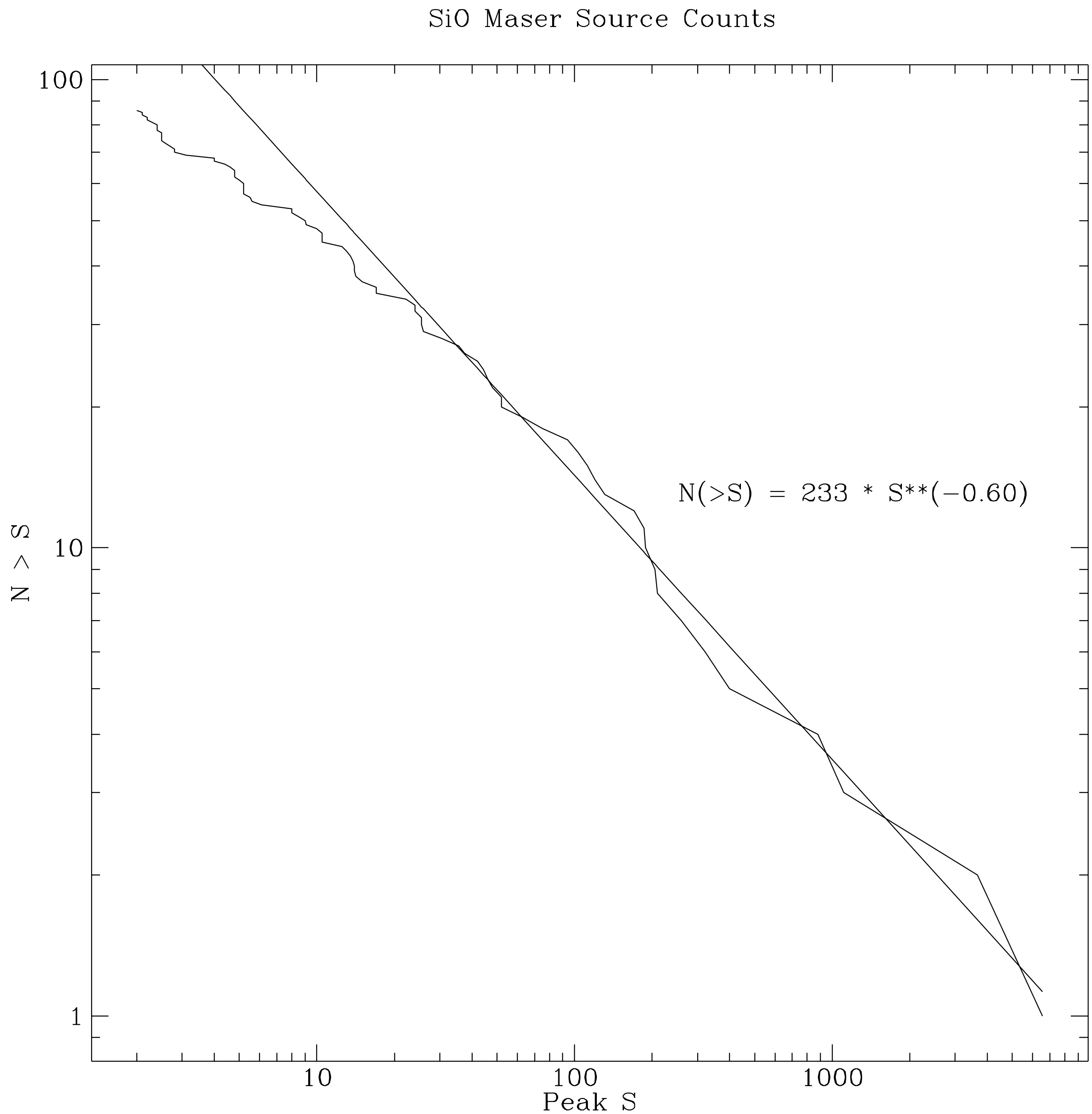

Figure 2: $log(N > S_{peak}), log(S_{peak})$ plot for known SiO masers brighter than 2 Jy peak flux. The straight line is a fit to the data for masers with peak flux brighter than 25 Jy. There does not appear to be any significant problem with completeness in Jewell *et al.s*'s sample at the 25 Jy level.

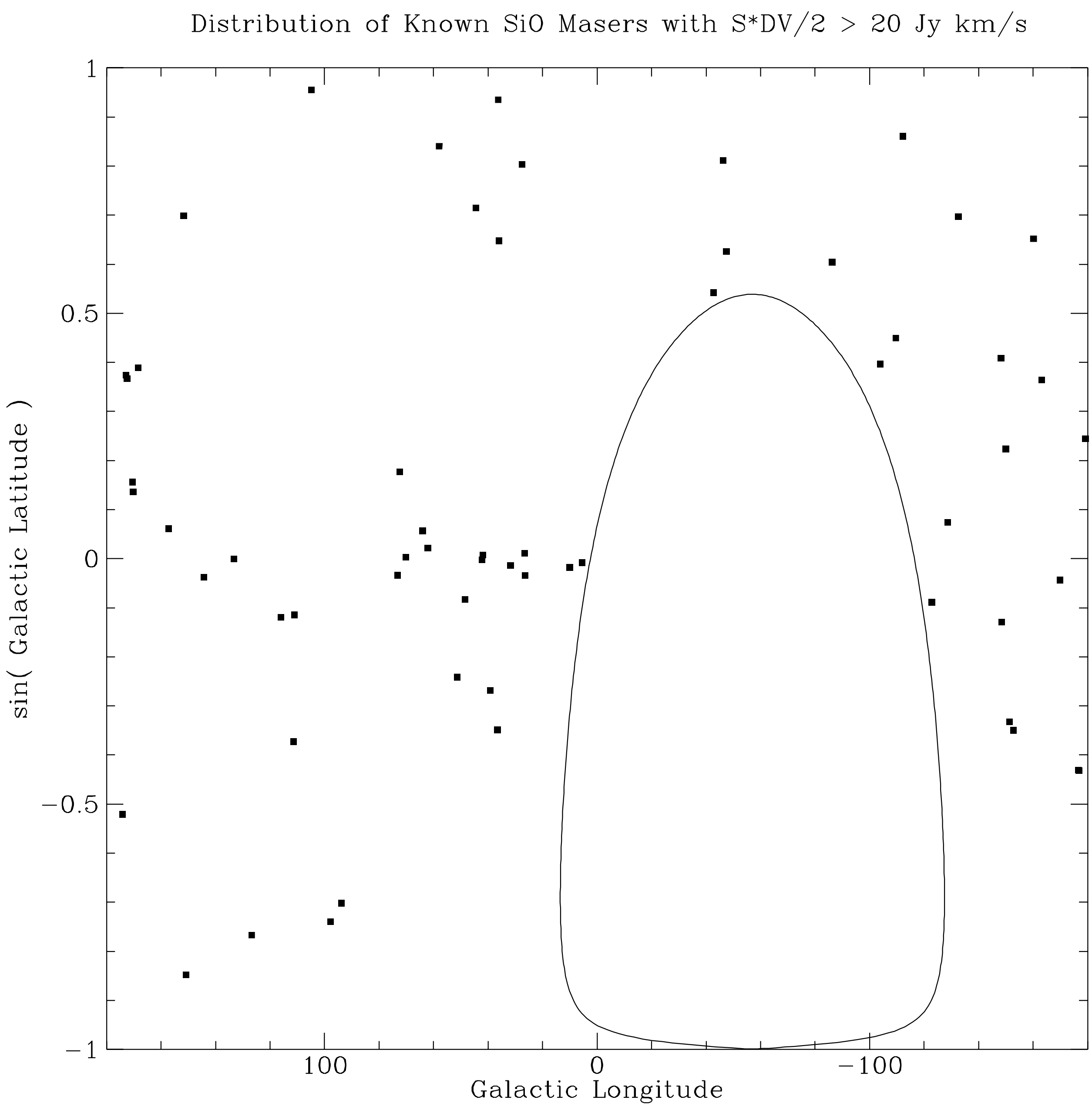

Figure 3: Distribution of known SiO masers brighter than 4 Jy peak flux in Galactic coordinates, sin of latitude preserves sky area. The solid line indicates the region in galactic coordinates which is below declination -30, and was not accessible to the Effelsberg telescope.

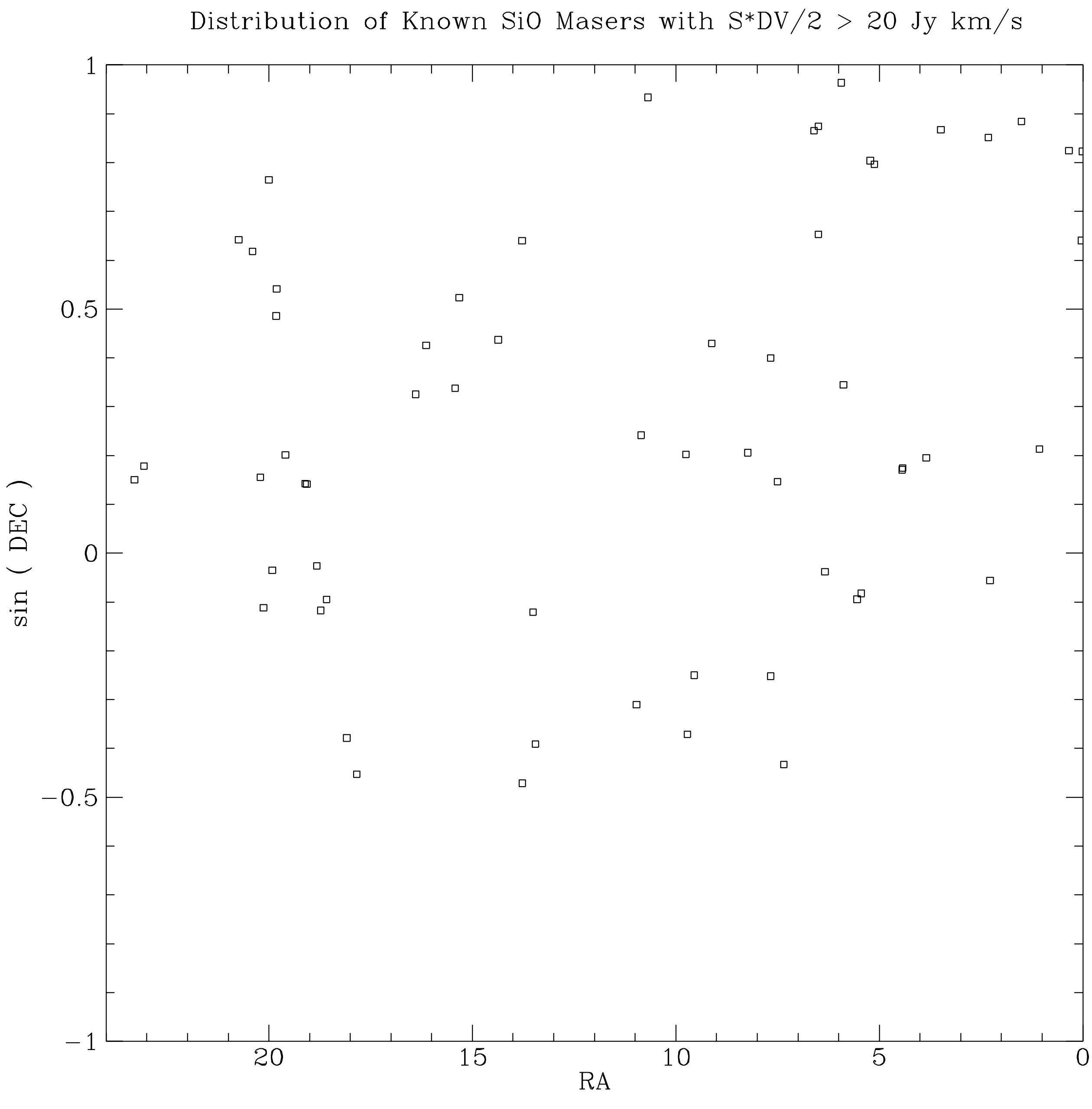

Figure 4: Distribution of known SiO masers brighter than 4 Jy peak flux in celestial coordinates.