LAMA Memo 805
ALMA Calibration Source Counts at 250 GHz

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Abstract

Quasar source counts at millimeter and sub-millimeter wavelengths will be important for phase and delay calibration as well as focus and pointing observations. Some of these observations can be done at low frequencies, but some observations will need to be done at the target frequency. Having a good knowledge of the high frequency quasar source counts will help us with the ALMA calibration plan.

We compare source counts at 250 GHz derived from wide field imaging with mJy sensitivity with predictions based on models constrained by lower frequency observations of known flat spectrum radio source samples. While the statistics remain few, current data are consistent with flat spectrum AGN having an areal density $N(>10\text{mJy}) \sim 5 \pm 3.5\ \text{deg}^{-2}$ at 250 GHz. The observed counts exceed by a factor of 6 what is expected from source counts extrapolated upwards from 90 GHz. This level of source counts may be adequate for phase calibration via fast switching without requiring frequency boot-strapping. These sources show a high degree of variability, with the maximum measured flux being ∼3 times higher than the minimum measured flux. We also show that thermal sources show a cut-off in the counts at a few mJy, and that these thermal sources must be larger than $0.1''$, and hence are not useful calibrators on baselines longer than 1 km.

1 Introduction

ALMA will depend upon bright compact sources (ie, quasars) for calibrations such as fast switching. While the flat spectrum quasar source counts are in reasonably good shape at 90 GHz (Holdaway, Owen, and Rupen, 1993), very little has been done to nail down the source counts for higher frequencies. Holdaway and D'Addario (2004) have made estimates on source counts at higher frequencies, assuming that the measured spectral index distribution from 8 to 90 GHz steepens by 0.5 above 90 GHz, but this extrapolation has not benefitted from additional high frequency observations.

We do have options: if there are more sources at high frequencies than we assume, we will usually be able to perform fast switching phase calibration at the target frequency; if there are fewer sources than we assume, we will often need to perform the frequent phase calibration at 90 GHz, scaling the phase solutions up to the target frequency, and solving for the instrumental phase difference by performing an “instrumental sequence” on a more distant quasar which is bright at both the calibration and target frequencies, perhaps once every 5-10 minutes, the time scale over which the instrumental phase drifts will be small.

In this work, we present some actual data for source counts at 250 GHz which suggests at the very least that our high frequency source count estimates are not overly optimistic, and that the estimates may in fact underestimate the number of high frequency calibrators available to ALMA.

2 90 GHz Source Count Estimates and Extrapolation to Higher Frequencies

To spare the reader the trouble of looking up Holdaway, Owen, and Rupen (1994), we outline here the method by which we arrived at our flat spectrum quasar source count estimates at 90 GHz.

- First, we started with Condon’s well-determined source counts of flat spectrum quasars at 5 GHz. Flat spectrum is defined as having a spectral index $\alpha < 0.4$ for $S(\nu) \propto \nu^{-\alpha}$. These source counts were obtained with the NRAO 300ft telescope.

- While these quasars will be dominated by the flat spectrum core component, the fluxes are contaminated with some steep spectrum extended emission, mostly within the beam of the 300ft telescope. To estimate, statistically, the impact of the extended emission, we constructed a distribution of core fraction from the flat spectrum members of the 3CR2 catalog, and then modified Condon’s original counts to reflect the source counts of the flat spectrum quasar cores only.

- If these sources had a single spectral index, it would be trivial to estimate the source counts at higher frequencies. However, from 5 GHz to 90 GHz, these sources turn out to have quite a range of spectral index, from about -0.5 to over 1.0. We were quite careful to measure the spectral index distribution. We selected 367 flat spectrum sources from Patnaik et al’s sample of flat spectrum quasars observed with the VLA in A array at 8.4 GHz. Our sources were organized in four 8.4 GHz flux density bins of 100-200 mJy, 200-400 mJy, 400-800 mJy, and over 800 mJy. We then observed these sources at 90 GHz with the NRAO 12m telescope. We found no statistical difference in the distributions of spectral index from 8.4 to 90 GHz for these four bins, so we combined all the data, including non-detections, and solved for a distribution of spectral index between 8.4 and 90 GHz using the ASURV package (Feigelson, 1985

- Using our measured spectral index distribution, we further augmented the 5 GHz flat spectrum core source counts to estimate the counts of potential calibrators at 90 GHz.

More recently, Holdaway and D'Addario (2004) extrapolated these flat spectrum source count estimates to higher frequencies by assuming that the spectral index distribution steepens uniformly by +0.5, abruptly at 90 GHz. This spectral steepening results in the median spectral index going to 0.8, which is typical of the few quasars which have been well studied well above 90 GHz. The cumulative source count estimates for 90 GHz and extrapolated to 180, 250, 350, 490, 650, and 900 GHz, are shown in Figure 1. This estimate gave us a reasonably well-justified point to start calculations for fast switching at high frequencies, which will either require many nearby (1-3 degrees) calibrator sources which are bright at the target frequency to perform the calibration with, or at least require a few bright sources within 10-15 degrees to bootstrap the instrumental phase difference between 90 GHz and the target frequency if the calibration were to be performed at 90 GHz. However, no observations above 90 GHz have gone into these source count estimates.

3 MAMBO source counts

Bertoldi and Carilli have a long-standing program of wide field imaging using the Max-Planck Array of Millimeter Bolometers (MAMBO) at the IRAM 30m telescope (Bertoldi et al. 2004). The camera has an effective frequency of 255 GHz assuming the SED of a typical high redshift thermal source, or 245-250 GHz for a flat spectrum source, depending on the opacity, and a diffraction limited resolution of FWHM = $10.7''$. We have imaged three fields with a total area of about 2200 arcmin^2 to an rms sensitivity ranging from 0.7 to 2.5 mJy at 250 GHz. For comparison, the other large area (sub)mm survey project SHADES being done with the SCUBA device on the JCMT at 350 GHz has surveyed an area of 500 arcmin^2 to date (Dunlop et al. 2004). The main purpose of the MAMBO survey is to constrain the amount of cosmic star formation that occurs in dust-obscured starbursts, presumably corresponding to the formation of elliptical galaxies at $z > 2$. However, the area surveyed is large enough that we can begin to address the question of contamination of the sample by non-thermal sources, ie. flat spectrum, radio loud AGN. And most importantly for the purposes of this memo, the MAMBO data speaks to the question of the areal density of such non-thermal sources in the context of ALMA phase calibration.

We have imaged three different fields with MAMBO - the Abell 2125 field covering an area of about 1600 arcmin^2, the Lockman Hole covering an area of 400 arcmin^2, and the NTT deep field covering an area of 200 arcmin^2. The image of the Abell 2125 field is shown in Figure 2.

We detect four sources brighter than 10 mJy in the MAMBO survey, all in our largest field. These sources are listed in Table 1. Column 1 gives the source position. densities. Columns 2 – 5 give the flux densities at 1.4 to 95 GHz. Column 6 gives the mean 250

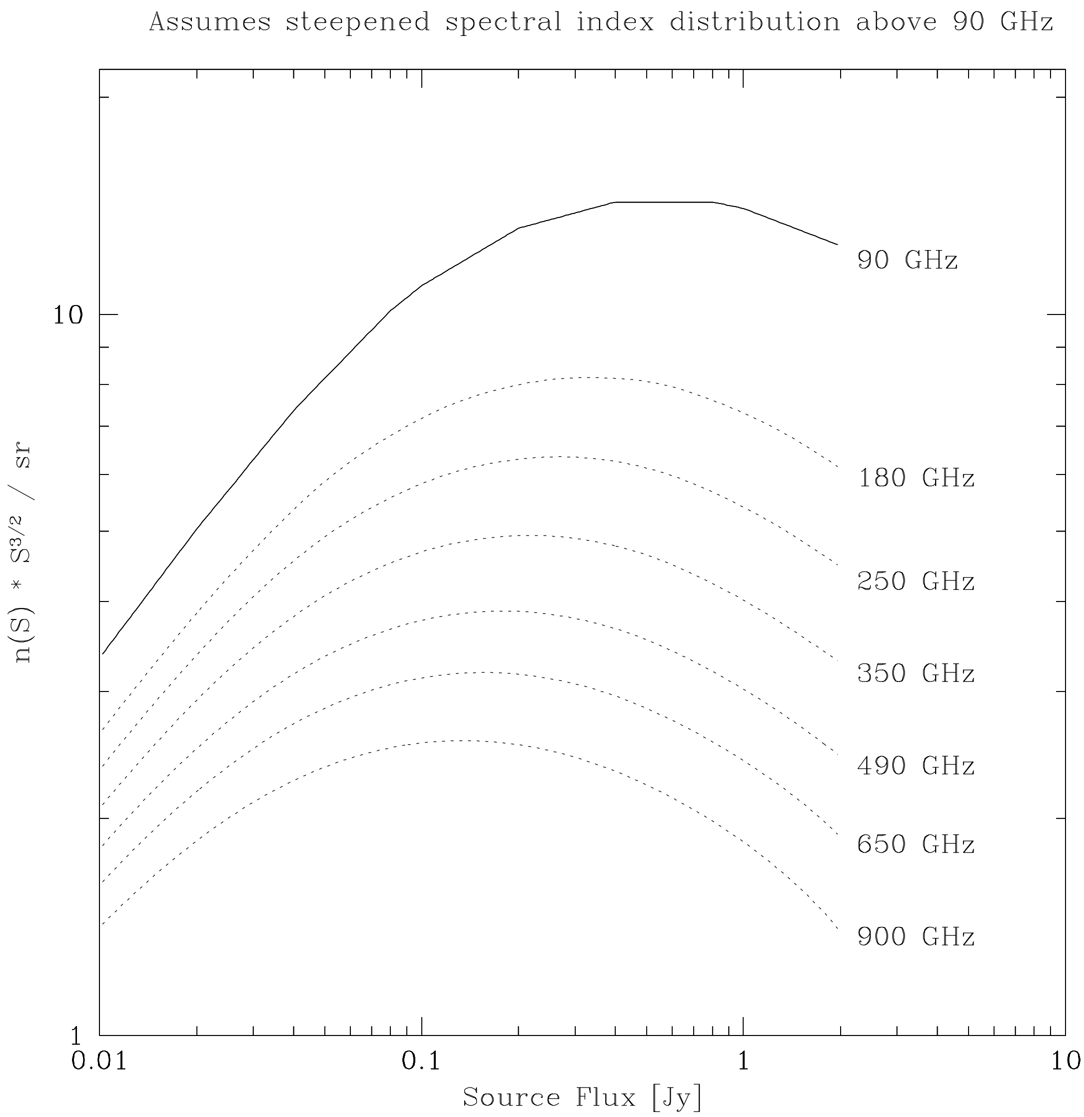

Figure 1: Quasar source count estimates for 90 GHz from Holdaway, Owen, and Rupen (1994), and extrapolations to higher frequencies, assuming a spectral steepening of +0.5 above 90 GHz.

GHz flux, and column 7 gives the range of observed flux densities at 250 GHz (we are monitoring the four bright sources at 250 GHz using MAMBO). Column 8 gives the source redshift and column 9 indicates if the source has been detected in Xrays. Column 10 gives the source type.

For three of the four brightest sources the optical and Xray data, and the radio spectra and variability, indicate that the observed emission at 250 GHz is non-thermal synchrotron radiation, corresponding to a flat spectrum, radio-loud AGN. The fourth source has properties more in-line with those of fainter (sub)mm sources, ie. optically faint, and a rapidly rising spectrum from cm to mm wavelengths, suggesting that the 250 GHz emission is thermal in origin. This forth source was only found in our most recent expansion of the MAMBO fields, and has had less monitoring at 250 GHz.

Gravitational lensing can occur near the center of a cluster of galaxies, which in turn can amplify a more distant source to make it appear to be brighter than it actually is. However, the three non-thermal sources are about 10 arcminutes or more away from the center of the cluster, far enough to make gravitational lensing highly unlikely.

Figure 3 shows the source counts at 250 GHz based on the MAMBO surveys. Note that these are cumulative counts, and hence the bins are not independent. Below 8 mJy or so the counts can be fit with a differential model involving a power-law of index -2 and an exponential cutoff at about 3 mJy. However, including the 3 bright sources in the fields at flux densities above 10 mJy leads to a possible flattening in the counts to higher flux densities. This second 'population' can be fit with a differential power-law of index -2.0, with no cutoff. Interestingly, this flattening occurs at the point where the source population changes from being dominated by thermal emission from galaxies to non-thermal emission from AGN. The open square on Figure 3 shows the counts if we remove the three clearly non-thermal sources from the distribution, and supports the exponential cut-off in the thermal source population.

Admittedly the statistics are few, with the counts above 10 mJy based on only 4 sources, but these MAMBO surveys are by far the widest field mm surveys to date with mJy sensitivity, and hence provide our best look into the source counts at flux density levels relevant to ALMA. Considering only the non-thermal sources, the prediction is an areal density of:

$$\mathrm{N}(>10\mathrm{mJy}) \sim 5 \pm 3.5\ \mathrm{deg}^{-2}\ \mathrm{at}\ 250\mathrm{GHz} \qquad (1)$$

For the thermal source population, even if there were no cut-off in the population, these sources are not likely to be good phase calibrators for ALMA in configurations with baselines longer than a few kilometers. From brightness temperature considerations, it is easy to show that such sources must be larger than:

$$\theta > 1.2(1+z)^{1/2}\mathrm{S}^{1/2}\mathrm{T_B}^{-1/2}\lambda\ \ \mathrm{arcsec} \qquad (2)$$

where θ is the source FWHM, λ is the observing wavelength in cm, S is the observed flux density at λ, and $\mathrm{T_B}$ is the intrinsic brightness temperature. Even in optically thick

Table 1: Four Brightest Sources in MAMBO Fields. Errors in 250 GHz fluxes are 2 mJy. Upper limits are 3 σ.

Source	$S_{1.4}$ mJy	$S_{4.9}$ mJy	S_8 mJy	S_{95} mJy	S_{250} mJy	S_{250} range	z	Xray	Optical
154000.01+660551.6	26	5		26	14	12-19	0.2914	+	AGN
154137.21+663031.8	0.108	<0.09	<0.05		9.5 ±1				Galaxy
154141.01+662237.9	53	58	24	37	12	11-28	1.3820	+	AGN
154321.31+662154.5	26	28		89	42	30-90	1.0?		AGN

cases such as ULIRGs, the far IR thermal emission from warm dust in galaxies always has brightness temperatures < 100 K. Using this as an upper limit to the intrinsic brightness temperature, and assuming the median redshift for submm galaxies of $z = 2.3$, a 10 mJy source at an observing wavelength of 1.2 mm has a lower limit in size of $\theta > 0.08''$. For comparison, the resolution on a 10 km baseline at 250 GHz is $0.025''$.

The variability and flat (ie. self-absorbed) spectra of the non-thermal sources imply very high brightness temperatures, implying they are very compact, making them very good candidates for ALMA calibrators. However, unlike thermal sources which will be rising in flux with frequency, these non-thermal sources will be flat or slowly falling in flux as the observing frequency increases.

4 Comparing the MAMBO Counts with our Quasar Source Count Estimates

It was somewhat surprising to find three non-thermal sources brighter than 10 mJy in the 2200 square arcminute region sampled by Bertoldi et al. (2004), but just how surprising is it? At the bottom of Figure 3, which shows the cumulative counts in the MAMBO fields, we show our extrapolated estimates for quasar source counts at 250 GHz. The top of the pair of curves assumes no spectral steepening above 90 GHz (ie, that the spectral index measured between 8 and 90 GHz is valid up to 250 GHz), while the lower of the pair of curves includes a spectral steepening of +0.5 above 90 GHz as discussed earlier in the text. The observed counts of non-thermal sources from the MAMBO fields are a factor of 6 higher than our source count estimates.

It is important to note the very different redshifts for the three sources in question (see Table 1). This implies that we are not looking at a single cluster of sources which would skew the statistics.

Of course, three non-thermal sources qualifies as "small number statistics". How likely is it that the MAMBO field just got lucky? To address this issue, we have performed Monte Carlo simulations, generating fake sky fields which are populated by non-thermal sources of different flux, but consistent with the extrapolated 250 GHz source counts

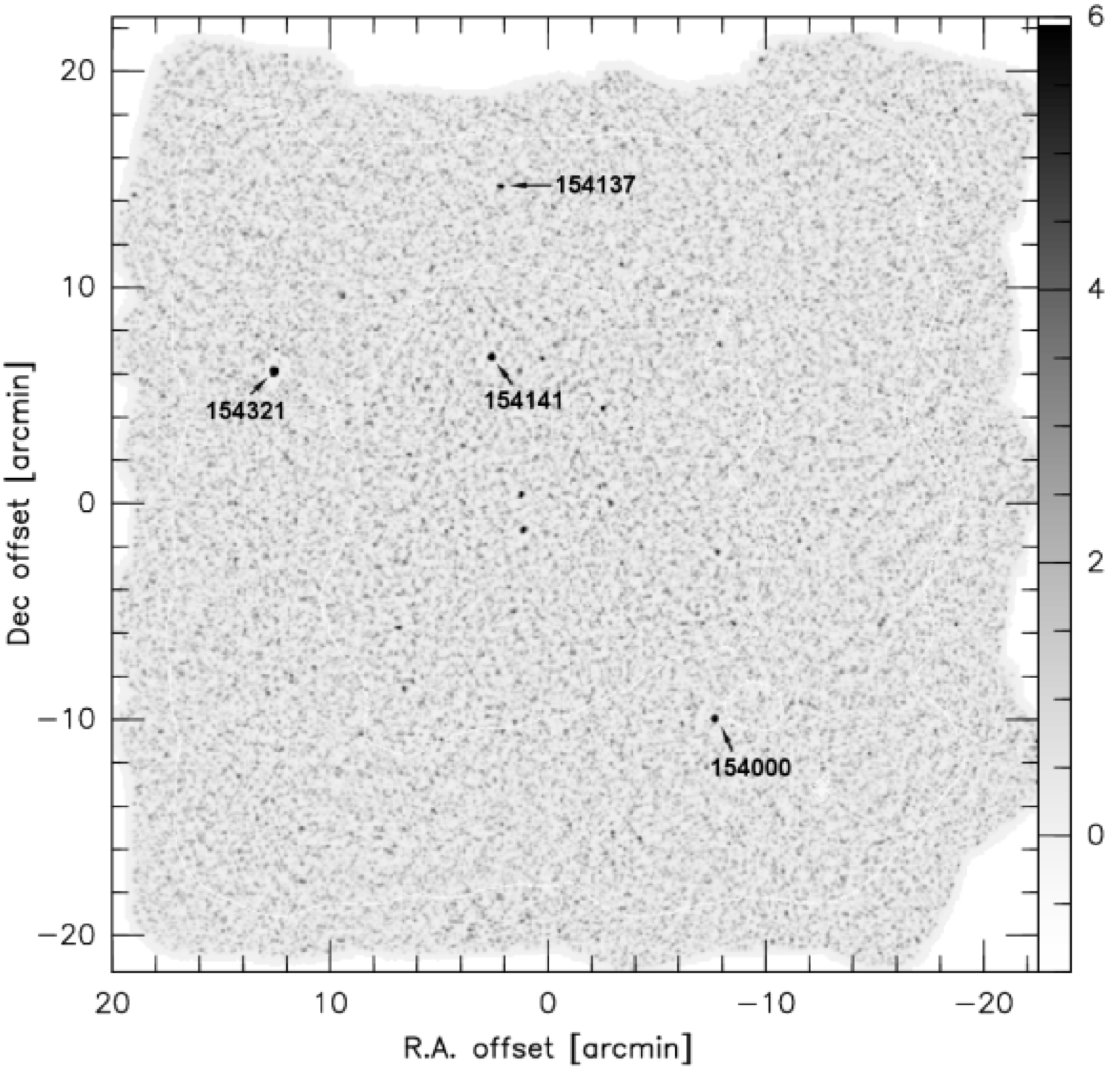

Figure 2: The image of signal-to-noise ratio derived from the MAMBO data for the A2125 field at 250 GHz. The rms sensitivity varies from about 0.5 mJy at the field center to 3.0 mJy at the field edges. The diffraction limited beam FWHM = 10.7″ (from Bertoldi et al. 2004). The (0,0) point of the relative coordinates corresponds to 15 41 16.0 +66 15 55.0, and the four bright sources are annotated.

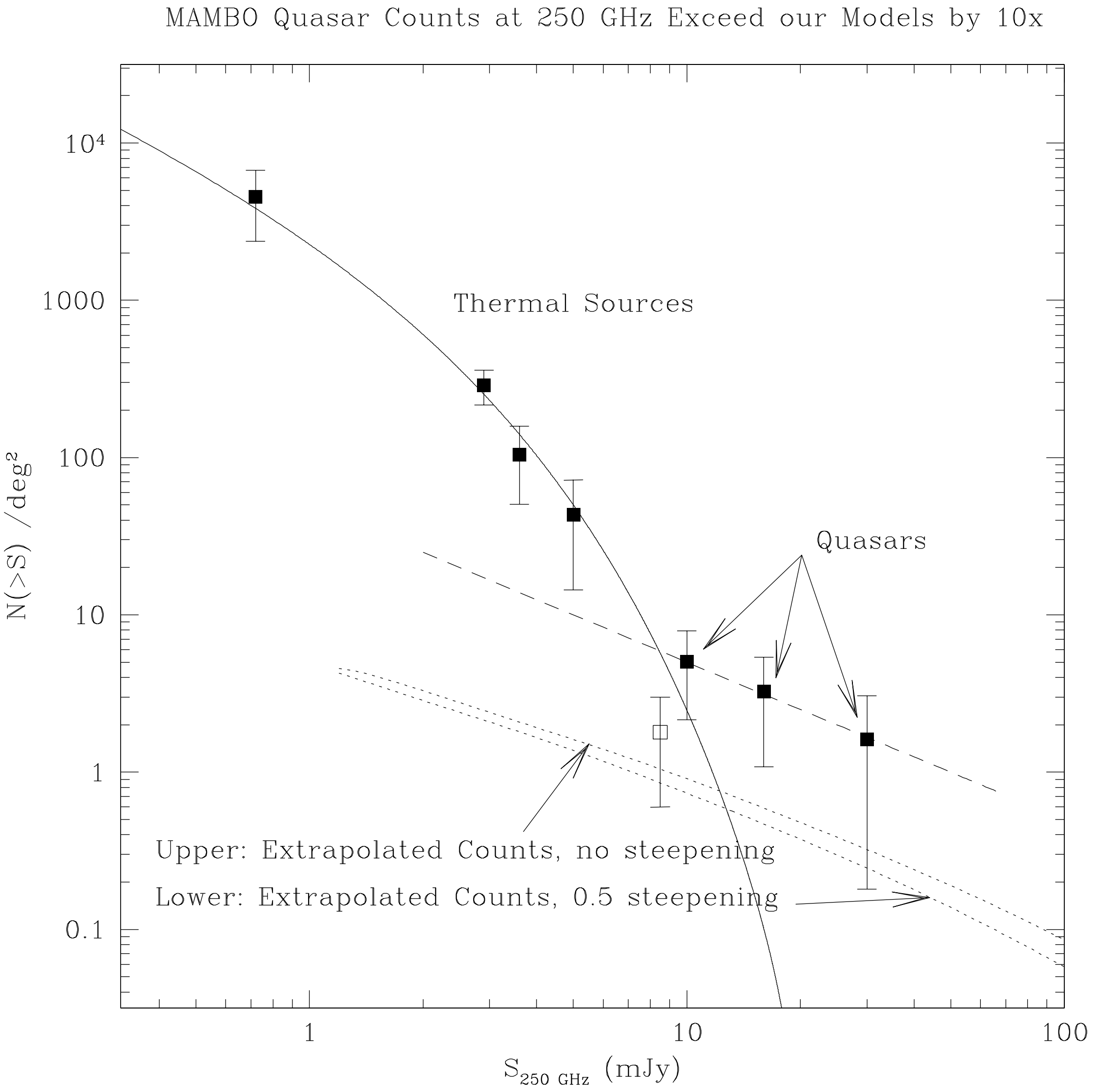

Figure 3: The cumulative source counts based on wide field MAMBO imaging at 250 GHz (from Bertoldi et al. 2004), with our extrapolated quasar source counts for 250 GHz at the bottom. The open square represents the source counts if the non-thermal sources were removed, indicating the need for the exponential cutoff in the thermal source counts.

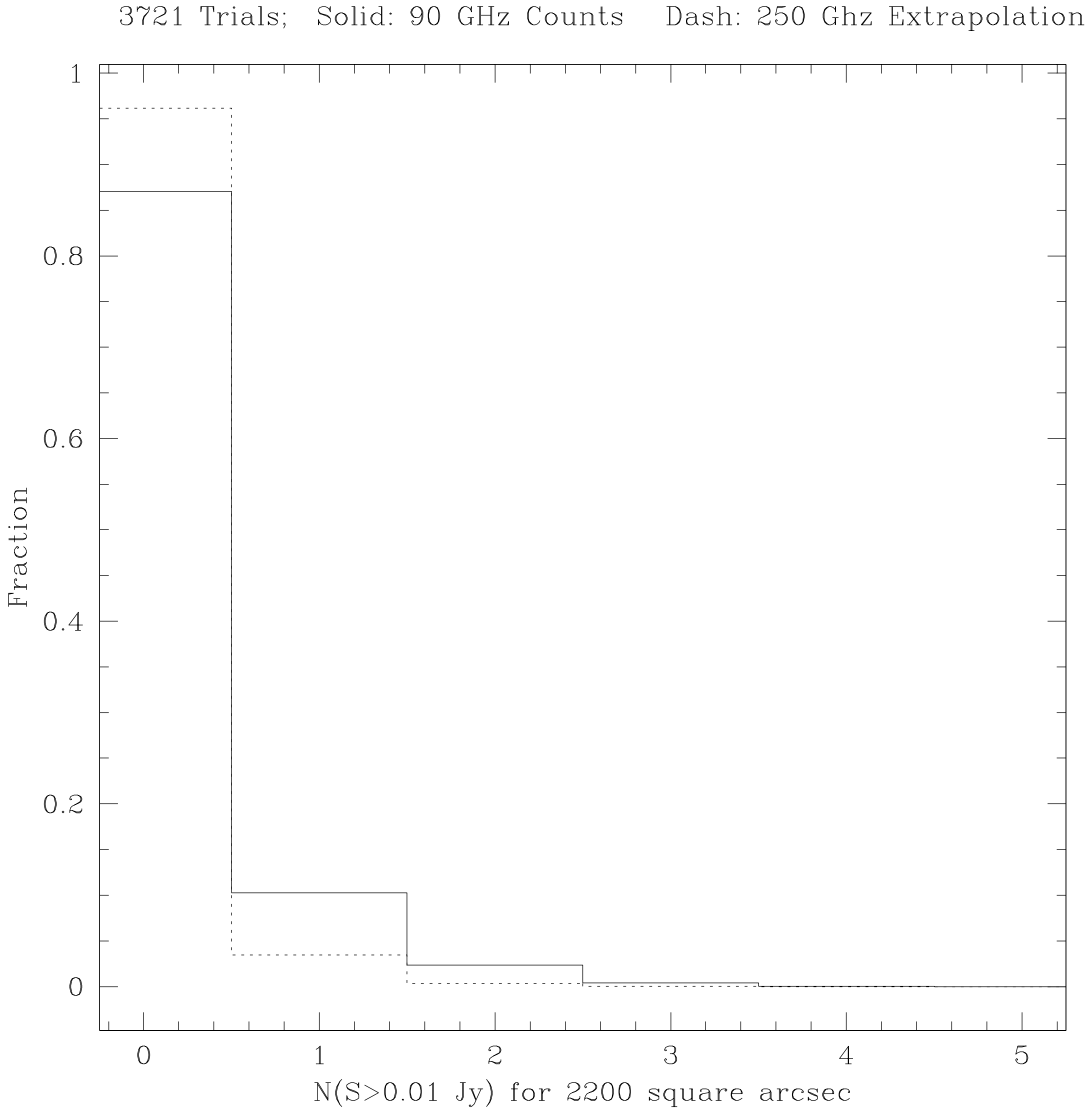

Figure 4: Histogram of the number of non-thermal sources brighter than 10 mJy we expect to find in a 2200 square arcsecond field, based on our source count estimates for 90 GHz and our source count extrapolations for 250 GHz. In all, 3721 Monte Carlo fields were generated, and only 0.4% of the fields had as many as 3 sources brighter than 10 mJy at 250 GHz.

model. We generated 3721 fields sprinkled with millimeter source counts which were consistent with our source count estimates, isolated a 2200 square arcminute region, and counted the number of sources brighter than 10 mJy at both 90 GHz and 250 GHz. The histogram of the number of sources brighter than 10 mJy is shown in Figure 4. Of the simulated fields, only 0.4% had three or more sources brighter than 10 mJy at 250 GHz. Even at 90 GHz, where the sources tend to be much brighter and the source counts are much more justified by observations, only 2.7% of the fields had three of more sources brighter than 10 mJy. From these simulations, we can say that either the estimated source counts for 250 GHz severely underestimate the true number of bright non-thermal sources in the sky, or the MAMBO fields were extremely lucky in finding such sources.

What could possibly be wrong with our source count estimates?

- The original 5 GHz source counts sample sources down to the mJy level, but the sources used to measure the distribution of spectral index between 8 and 90 GHz were 100 mJy or brighter at 8 GHz. The 90 GHz 3-sigma detection limit was about 75 mJy. As no statistical difference was seen in the spectral index distribution among 100, 200, 400, and 800 mJy sources, we assumed it was safe to use the same spectral index distribution for weaker sources as well. While it doesn't seem likely, it is possible that weaker sources (less than 10 mJy) have a very different spectral index distribution and many such sources are flat or inverted and show up in the 250 GHz MAMBO fields.

- We have made no measurements of spectral index above 90 GHz. It is possible that our population shows a change in spectral index above 90 GHz. However, the two curves at the bottom of Figure 3 indicate the source counts we expect if the spectral index distribution above 90 GHz is the same as that below 90 GHz (top curve) and if the spectral index distribution steepens by 0.5 above 90 GHz (bottom curve). These two curves are actually quite close together on this graph. A huge shift towards inverted spectral index is required to make the estimated source counts rise up to the measured counts from the MAMBO field, and this seems highly unlikely.

- If the MAMBO counts of non-thermal sources are not just a statistical fluke, then the large descrepancy with the predictions based on brighter sources implies a new AGN source population below about 50 mJy at 250 GHz.

- A combination of factors? Perhaps the counts from the MAMBO field are a bit high by chance, and our estimated counts are a bit low by one of the reasons mentioned above.

The descrepancy between the counts of non-thermal sources in the MAMBO fields and our estimates for quasar source counts obviously deserves more attention.

It should be noted that the Monte Carlo simulations of Holdaway and D'Addario (2004) determine the optimal calibrator, its position, and flux, for each simulated field.

Hence, at each frequency, we have a distribution of calibrator fluxes. From that work, we can infer that only the brightest of these three sources (154321.31+662154.5, at 30-90 mJy) would be a useful phase calibrator. However, the existence of these three sources above 10 mJy infers the existence of other sources which would be useful as phase calibrators.

5 Future Work

While the results presented here are encouraging, we will need to perform more extensive observations to get more significant results for the number of bright quasars at high frequencies. We plan to use the ALMA prototype interferometer (API) at the ALMA Test Facility (ATF), located at the Very Large Array (VLA) site to determine the distribution of spectral index (DSI) between 90 and 250 GHz so we can more accurately predict the numbers, distances to, and fluxes of, potential high frequency calibrators (HFC). A more complete knowledge of the flat spectrum quasar source counts at high frequencies will help us better define the calibration plan for ALMA. Also, more single dish observations of wide fields at 250 GHz and 350 GHz will give us a different angle on what is going on in the sky at high frequencies.

References

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