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Distance to Possible Calibration Sources as a Function of Frequency for ALMA

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Abstract

The assumption that so-called "fast switching" calibration will always be done by observing a calibrator at 90 GHz is examined. It is found that it may be better to observe the calibrator at the same frequency as the target, since suitable calibration sources may be just as close at higher frequencies as they are at 90 GHz (all roughly 1° for continuum bandwidths). In the end it will depend on the characteristics of the sources (size, mostly). Observing the calibrator at 90 GHz will require an additional calibration to be performed on fairly short timescales (of order minutes) to calibrate the relative complex gain between the target and calibrator frequency, since the electronics will change between scans. This extra calibration is not required if calibrator and target are observed at the same frequency. In addition, observing the calibrator at the same frequency as the target removes the requirement of having very accurate atmospheric modelling in order to transfer the phase and amplitude from calibrator frequency to target frequency (especially problematic in regions of dispersion near strong telluric lines). Because of the uncertainty in the sizes of the sources, it is not recommended to change the current paradigm of calibrating at 90 GHz, but the option of calibrating at the target frequency should be kept in mind, and exercised if it turns out that the sources considered herein are appropriate to use as calibrators (small enough).

1 Introduction

Atmospheric fluctuations cause perturbations in visibility phase which, if not corrected, seriously limit both the sensitivity and imaging quality of an interferometric array. The method of correcting for these perturbations on currently operating arrays involves periodic observations of a nearby calibrator, under the assumption that the phase on a given baseline can be corrected by interpolation between such observations. This period is often minutes to 10's of minutes, depending on baseline length and frequency (an exception is the VLA, where the period can be as short as 40 s). For ALMA, the period under which this assumption holds can be quite short, of order 10's of seconds at least in many cases. There are two proposed methods to deal with this: water vapor radiometry (WVR - Hills & Richer 2000); or so-called "fast switching" (Holdaway 2001). In fast switching, the general assumption has been that the calibrator is observed at 90 GHz, regardless of which frequency is used to observe the astronomical target source (Holdaway 2001; Holdaway & Pardo 2001; Holdaway 1998; Holdaway 1997; Woody et al. 1995; Holdaway et al. 1995). This type of calibration scheme causes two problems: the complex gain difference between frequencies caused by the electronics must be calibrated regularly, perhaps every few minutes (and, in fact, it has not shown that this can even be done properly); and the calibration must utilize a very accurate atmospheric model in order to transfer the complex gain between frequencies (Holdaway & Pardo 2001).

2 Required Flux Density

In order to be a reasonable calibrator, a source must have sufficient flux density, as shown in Table 1. The numbers in that table are calculated assuming that the calibrator is observed for 3 seconds in continuum mode, and that the signal to noise must be 50 over the entire array (to achieve 2% amplitude stability). Opacities are scaled so that the higher frequencies are only observed under better conditions. Strictly speaking, there should also be a factor for decorrelation, but if observing conditions really do match frequency, then this factor should be small, 10% at most (Holdaway 2001), and can hence be ignored to first order in these scaling arguments.

Table 1: Required Calibrator Flux Density for SNR=50 in 3 seconds.

Frequency (GHz)	S (mJy)
90	10
230	15
345	35
410	60
675	180
850	250

3 Distance to Sources

Assume that the number count of sources larger than flux density S at frequency ν scales like:

$$N_\nu \propto S_\nu^{-1.5}\, \nu^{3.5} \quad , \tag{1}$$

where the scaling with flux density comes from Kitayama et al. (1998) and the scaling with frequency comes from Franceschini et al. (1998) and agrees with that in Toffolatti et al. (1998). Now, the distance to a source scales like:

$$D_\nu \propto \frac{1}{\sqrt{N_\nu}} \quad , \tag{2}$$

so that, given a known distance for some given frequency ν_o and flux density S_{ν_o}:

$$D_\nu = D_{\nu_o} \left(\frac{S_\nu}{S_{\nu_o}}\right)^{3/4} \left(\frac{\nu}{\nu_o}\right)^{-7/4} \quad . \tag{3}$$

For the known distance, use a value of 0.6° for 35 mJy at 345 GHz, as indicated in Figure 4 of Toffolatti et al. (1998). This is similar to, but slightly lower than the number in Kitayama et al. (1998), who show 0.8° (see their Figure 1c). Plugging this into equation 3, the distances shown in Table 2 result. Note that at 90 GHz, equation 1 above is not accurate, since it does not account for flat spectrum quasars. We use the direct estimate of Toffolatti et al. (1998) in Table 2 instead of the one derived from equation 1 (see the 100 GHz panel in Figure 4 of Toffolatti et al.). This value is at least roughly consistent with the calculation in Foster (1994), which gives a median distance of 0.7° for a 25 mJy calibrator at 90 GHz, based on the 90 GHz source counts in Holdaway et al. (1994).

Table 2: Source Distance as a Function of Frequency.

Frequency (GHz)	D_ν (deg)
90	0.6
230	0.6
345	0.6
410	0.7
675	0.6
850	0.5

This may be a surprising result to some - the idea that sources are few and far between at the high frequencies seems to have become accepted wisdom. These results show that this is not the case at all, rather the distance to a source which has enough flux density to be a reasonable calibrator is roughly the same at all frequencies, $\lesssim 1^{\circ}$.

This result holds in general for line observations - the relative values in Table 2 will remain the same, they will just increase. Similarly, they hold if higher SNR is required (e.g., for a 1% calibration, a calibrator with twice the flux density would be required).

4 Source Sizes

In order for a source to be a reasonable calibrator, it is not sufficient to merely have enough total flux density. If the source is too large, or has unmodellable structure, then it may not be suitable as a calibrator (and in fact might not even have enough flux density for antennas which have few short baselines). Ideally, we would like the calibration sources to be unresolved at all frequencies and in all configurations of ALMA (i.e., the sources should have a size of $\lesssim 5$ masec). So what are the sizes of the sources whose distances are given in Table 2? The source count models generally account for two types of sources: quasars; and early-type galaxies (Toffolatti et al. 1998). The quasars are generally flat spectrum and small spatially, while the early-type galaxies have a strong spectral dependence and are of unknown size. Figure 4 of Toffolatti et al. (1998) shows the relative contribution of the two source populations as a function of frequency. At lower frequencies ($\lesssim 150$ GHz), sources of the flux densities of concern here are dominated by the quasars. Around 220 GHz, the contribution from the two populations is roughly similar. At higher frequencies, the early-type galaxies dominate. The question to be addressed then is what is the size of the early-type galaxies (or, more appropriately, what is the size of the emission region from these galaxies)? If the emission comes from dust distributed throughout the galaxy, then the sizes should be roughly 1 asec or so (see, e.g., the galaxy size distribution in Shen et al. 2003, and note that the mm and sub-mm emission size from dust in galaxies is usually of order the optical size divided by 2 or 3 - Franceschini et al. 1998). In this case, the sources are likely too large to be used as reasonable calibrators for ALMA, at least in many situations. If, however, the emission comes from either a central AGN or from massive starburst regions in these galaxies, then the emission might be on much smaller scales, in fact as small as the quasars. There is some evidence that this kind of emission from early galaxies is not so uncommon (Muxlow et al. 1999; Cox et al. 2002; Smail et al. 2003). In this case, it would be quite reasonable to use these sources as calibrators.

5 Conclusions

It was shown that the distance to sources with enough flux density to possibly be used as calibrators is roughly the same for all ALMA frequencies, $\lesssim 1^{\circ}$. However, it may turn out that the majority of these sources, at least at frequencies $\gtrsim 230$ GHz, are unsuitable as calibrators because of their (relatively) large size. If this is not the case, and the sources *are* suitable as calibrators, then it may be more attractive to observe the calibrator at the same frequency as the target when doing fast switching with ALMA, since the overall calibration scheme would then be simpler (because no inter-band calibration must be done, and no very accurate atmospheric model is needed). Even in the case that the sources are suitable calibrators, a more complete simulation is needed to test under which conditions it might be better to fast switch at the target frequency rather than at 90 GHz. Because of the uncertainty in the sizes of the sources, it is not recommended to change the current paradigm of calibrating at 90 GHz, but the option of calibrating at the target frequency should be kept in mind, and exercised if it turns out that the sources considered herein are appropriate to use as calibrators (small enough).

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