ALMA Memo 373
Relative Pointing Sensitivity at 30 and 90 GHz for the ALMA Test Interferometer

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Abstract

We compare the relative sensitivity of conducting pointing measurements at 30 and 90 GHz with the ALMA Test Interferometer (TI) at the VLA site. If pointing is performed interferometrically, the 90 GHz system will actually be 2.3 times more sensitive than the 30 GHz system due to very similar system temperatures but a smaller beam at 90 GHz. If pointing is performed in single dish mode, the system will be subject to sky brightness fluctuations, which are worse at 90 GHz than at 30 GHz. Even so, the sky fluctuations will usually not dominate the system noise. There are no compelling reasons not to do the test interferometer pointing at 90 GHz.

1 Introduction

The ALMA Test Interferometer (TI) is planned to include receiver bands at 30, 90, and 230 GHz. The main uses of the 30 GHz band are:

- It may be more sensitive, resulting in stronger fringes, higher SNR to see various instrumental effects, and faster pointing measurements.
- The lower frequency results in a relaxed requirement for accuracy in many domains, including surface accuracy, baseline and delay knowledge, pointing, focus, etc.

It is arguable that the ALMA antennas are designed to operate at 1 THz, so first light at 90 GHz should be no problem. This reasoning is probably good, unless there is an unforeseen problem of disastrous proportions, in which case the 30 GHz system may actually be required to easily see what is happening.

2 Pointing Analysis

There are several factors which influence the sensitivity and reliability of pointing measurements:

1. **Beam size** favors higher frequency.

2. **System noise** should favor lower frequency, but for the ALMA sensitivity estimates, the noise is nearly flat between 30 and 90 GHz.

3. **Source counts** are assumed to fall off sharply with frequency, but our estimates indicate calibrator sources are nearly flat with frequency.

4. **Atmospheric Stability:** while phase errors and refractive pointing will affect the two bands equally, fluctuations in the atmospheric emission could sometimes limit the continuum sensitivity of single dish observations. Our calculations below indicate that the single dish sensitivity will not usually be limited by fluctuating sky emission.

We explore each affect in detail below.

Beam size varies inversely proportionally with frequency, so given pointing observations at 90 GHz and at 30 GHz with the same SNR, the 90 GHz observations will be able to determine pointing solutions with three times greater accuracy. In order to obtain a pointing solution of some predetermined absolute accuracy, the SNR on the 30 GHz observations must be 3 times higher than for the 90 GHz observations.

System noise: The general rule of thumb is that the system noise increases roughly linearly with frequency. However, arguing from Butler and Wootten (1999), where the receiver temperature is assumed to be $3h\nu/k + 4K$, we find the system noise is only a factor of 1.30 larger at 90 GHz than at 30 GHz. This is in large part due to the constant $4K$ in the receiver temperature expression, which may or may not be correct for the 30/90 GHz comparison.

Source counts: There should be about the same number of pointing sources at 30 GHz as at 90 GHz. Holdaway, Owen, and Rupen (1994) measured the 90 GHz fluxes of 367 flat spectrum compact sources selected based on their 8 GHz VLA A array flux. From the measured distribution of spectral index between the 8 GHz compact components and the 90 GHz single dish fluxes, and the distribution of core fractions for flat spectrum compact sources, we bootstrapped the 30 and 90 GHz flux count estimates from the well-determined 5 GHz flat spectrum source counts of Condon (1984). The estimated source counts at 30 and 90 GHz typically differed by only 10-20% over the range of .01 - 1 Jy. This counterintuitive result that there are as many pointing calibrators at 90 GHz as at 30 GHz is due to the 15% of the sources which displayed an inverted spectral index. The inverted spectral index has on occasion been called into question, but they can simply be explained as sources which are undergoing an outburst and are optically thin at the highest frequencies, but still optically thick at the lower frequencies. Even though typical flat spectrum sources have a falling spectral index of about -0.3, the small fraction of inverted sources is enough to push some of the more numerous faint 30 GHz sources up to brighter levels at 90 GHz.

Atmospheric Stability: First, there is no advantage at either frequency with regards to refractive pointing due to phase fluctuations as the water vapor is basically non-dispersive between 30 and 90 GHz. However, the inhomogenously distributed water vapor which causes the phase fluctuations will also cause variable sky emission which may dominate the system noise in total power continuum observations and thereby limit the sensitivity of such observations during moist unstable conditions. (For interferometric measurements, the variable sky emission is uncorrelated except for the very shortest baselines, and should not be a problem at all for the TI.)

For the VLA site, the ATM atmospheric model (Pardo, 2001) indicates that

$$\begin{aligned} \tau_{30GHz} &= 0.001409 * PWV + 0.01453 \\ \tau_{90GHz} &= 0.007024 * PWV + 0.01975. \end{aligned} \tag{1}$$

The difference in opacity makes a negligible contribution to the system noise, but the factor of five difference in the wet term will result in a substantial difference in the variable sky emission at these two frequencies.

To quantify the difference in sky emission between 30 and 90 GHz, we use the analysis of Holdaway (1995) which scales the phase fluctuations as measured with a site testing interferometer to estimate the sky brightness fluctuations:

$$dT \simeq T_{sky} w(\nu)/6.3 * \sqrt{\tilde{D}_l(vt+d)}, \tag{2}$$

where T_{sky} is the physical sky temperature, $w(\nu)$ is the coefficient of the PWV in the opacity equation (Equations 1), 6.3 is the conversion from millimeters of water vapor to millimeters of path delay, D_l is the path length structure function as determined by the site testing interferometer, and $\tilde{D}_l(vt+d)$ is the effective structure function for beam switching. $\tilde{D}_l(vt+d)$ is an empirical construction in which the complexities of switching strategies, different wind directions, and interpolation are all thrown into a pile of simulations and a new effective structure function is derived from the old one (Holdaway, Lugten, and Freund, 1998). For an initial root structure function with unit variation at 1m, $D_l = \rho^{\alpha}$, it was determined through simulations that the effective structure function in the regime of $(\rho) < DishDiameter$ (ie, the near field column criteria), for normal beam switched observations (dubbed BS0) was $\sqrt{\tilde{D}_l(\rho)} = 0.25\rho^{\alpha+0.52}$. If interpolation is performed between two OFF measurements in correcting for the ON measurement (dubbed BS1) , the residual fluctuations are cut in half and the effective root structure function becomes $\sqrt{\tilde{D}_l(\rho)} = 0.11\rho^{\alpha+0.65}$. In the cases worked here, the interpolated beam switching, or BS1, results in about half the residual error, and it should probably be implemented on some telescopes.

For the argument of the effective structure function, we calculate $vt+d$ by assuming a $2\lambda/Diameter$ beam throw in a turbulent layer 1 km above the VLA site, a 15 m/s wind velocity aloft, and 0.1 s cycle time. For 30 GHz, $vt+d$ is 3 m, and for 90 GHz, $vt+d$ is 2 m, justifying the assertion of being in the near field column regime.

Accounting for the reduction in structure function due to the two beam switching techniques mentioned, we can convert the measured VLA phase stability data for *median conditions* (Butler and Desai, 1999) into estimates of residual sky brightness fluctuations. The sky brightness fluctuations are converted into Jy by multiplying by a factor of 25 so they can be compared directly with the system noise. These results are presented in Table 1, which shows median fluctuations for each month, day and night. The system noise in a 0.05 s integration, as might be appropriate for 10 Hz beam switching, is 0.070 Jy at 30 GHz and 0.091 Jy at 90 GHz. Even though the fluctuations at 90 GHz are 5 times more severe than the fluctuations at 30 GHz, the median fluctuation residual sky noise is always less than the thermal noise associated with a single 10 Hz cycle, even during summer days. As long as the system noise is larger than the equivalent sky brightness fluctuations over the same time, and as long as we are removing long time scale trends caused by large scale water vapor gradients by some form of double beam switching, the sky fluctuations will average down pretty well and will not limit the observations.

The double beam switching technique presents some problems. We would like to double beam switch (ie, OFF_LEFT - ON_TARGET - OFF_RIGHT - ON_TARGET) to optimally remove the atmosphere. On and off axis beams are distorted in different ways by the optics, and will have slightly different gains. Hence, beam switching is usually done symmetrically (ie, the ON and OFF are equally off-axis in opposite directions). Then it is not really feasible to implement double beam switching in an optimal manner. At the 12m telescope, double beam switching was implemented by performing the symmetric LEFT - RIGHT beam switching with the target source in the RIGHT beam for about 5 s, then repointing the telescope and beam switching such that the target source was in the LEFT beam for about 5 s. With this style of beam switching, any systematic trends with time scales greater than about 10 s would be removed from the data, and the more random short term fluctuation residuals would average down. However, there will be some small fraction of systematic sky fluctuations on intermediate time scales which are not removed. Unfortunately, the analysis of Holdaway, Lugten, and Freund does not address this slow (ie, accomplished by repointing the telescope) double beam switching technique. So, at this point in the logic, we make a caveat and a recommendation: simply requiring the atmospheric sky noise to be less than the system noise on the time scale of a switching cycle may not insure that the system noise dominates, and any implementation of beam switching should try to perform double beam switching (ie, getting OFF positions on both sides of the ON position) as quickly as possible to minimize the systematic effects of large scale atmospheric structure.

While the residual sky noise inferred from the median rms phase is less than the thermal noise per cycle, there will undoubtedly be more extreme conditions, especially during summer days, where the residual sky noise will dominate.

Water droplets. The sky brightness fluctuation calculations of the preceding section result in the counterintuitive conclusion that 90 GHz continuum observations are seldom limited by sky fluctuations. However, these are "clear sky" brightness fluctuations. The fluctuations that usually spoil continuum observations are due to water droplets.

The drastically enhanced emission from water droplets, as compared to water vapor, and the inherently clumpy nature of clouds, result in impossibly difficult sky fluctuations and system temperature fluctuations. Water droplets are a worse problem at 90 GHz than at 30 GHz, and it is likely that during some conditions around the onset of droplet formation, observations at 30 GHz may be possible while observations at 90 GHz would not. The frequency dependence of emission from water droplets is partially understood, but we have no site characterization or statistics on the nature of the water droplets above the VLA site. Given the lack of information on water droplets, we assume that the affects of water droplets on 30 GHz and 90 GHz observations will be similarly destructive, and we do not consider water droplets to give an advantage to 30 GHz over 90 GHz.

3 Conclusions

- For generic interferometric measurements, the 90 GHz system will be a factor of 1.3 less sensitive than the 30 GHz system. This is a marginal argument in favor of 30 GHz.
- For pointing measurements, where the beam width must be factored in, the 90 GHz system is a factor of $(90/30)/1.3 = 2.3$ times more sensitive for interferometric measurements.

- The wet term in the opacity is five times larger at 90 GHz than at 30 GHz, so sky brightness fluctuations will be more problematic at 90 GHz than at 30 GHz. We have quantified this effect, and find that at 90 GHz, even during summer days, the sky noise will usually not dominate the system noise.

4 Acknowledgement

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month	day/ night	median phase [deg]	α	residual sky noise [Jy] 30 GHz BS0	BS1	90 GHz BS0	BS1
1	d	3.8	0.66	0.0086	0.0043	0.0269	0.0130
1	n	2.5	0.63	0.0067	0.0034	0.0210	0.0101
2	d	3.7	0.65	0.0088	0.0045	0.0277	0.0134
2	n	2.1	0.61	0.0063	0.0032	0.0198	0.0095
3	d	5.2	0.66	0.0117	0.0060	0.0368	0.0177
3	n	2.7	0.62	0.0077	0.0039	0.0240	0.0116
4	d	6.7	0.66	0.0151	0.0077	0.0474	0.0228
4	n	3.1	0.63	0.0083	0.0042	0.0261	0.0125
5	d	6.3	0.67	0.0134	0.0068	0.0421	0.0203
5	n	3.0	0.63	0.0080	0.0041	0.0252	0.0121
6	d	7.6	0.68	0.0153	0.0078	0.0480	0.0231
6	n	3.4	0.64	0.0086	0.0044	0.0270	0.0130
7	d	10.0	0.70	0.0180	0.0091	0.0564	0.0271
7	n	5.5	0.67	0.0117	0.0059	0.0368	0.0177
8	d	11.9	0.70	0.0214	0.0108	0.0671	0.0323
8	n	6.2	0.68	0.0125	0.0063	0.0392	0.0189
9	d	13.6	0.70	0.0244	0.0124	0.0767	0.0369
9	n	6.1	0.68	0.0123	0.0062	0.0385	0.0186
10	d	8.1	0.66	0.0183	0.0093	0.0574	0.0276
10	n	4.3	0.65	0.0103	0.0052	0.0322	0.0155
11	d	5.5	0.67	0.0117	0.0059	0.0368	0.0177
11	n	3.8	0.64	0.0096	0.0049	0.0302	0.0145
12	d	3.4	0.63	0.0091	0.0046	0.0286	0.0138
12	n	2.2	0.62	0.0062	0.0032	0.0196	0.0094

Table 1: The left side of this table shows the phase fluctuations at the VLA site split into monthly and diurnal components (Butler and Desai, 1999). The reported phase is the median of 10 minute rms phases on the site testing interferometer's 300 m baseline, over the reporting period, and the α is the exponent of the root structure function. The right side of the table indicates the inferred residual sky noise after beam switching, converted into Jy, for the beam switched 1 and beam switched 2 techniques (see text).