Total Power observing with the ALMA Antennas

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1 Introduction

Particularly at the shorter wavelengths, the ALMA will need to do mosaic observing to cover large fields of view. Along with the mosaic pointing, there will need to be total power maps to fill in the interferometric short spacings and produce complete images. It is well known that this is best done with a single antenna that is two to three times the diameter of the interferometer antennas (Vogel,S.*etal*, ApJ, 1984, 283, 655). However, that will not be possible for ALMA; there are no 24m - 36m antennas available that will work well to 0.35mm wavelength. As long as a mosaic of pointings is employed in the interferometry, a single antenna map made with one of the interferometer antennas will suffice in principle (Ekers,R. and Rots,A, 1979, In Image Formation, etc., Dordrecht, Reidel). This is rarely done, largely because the interferometer antennas are not equipped to do it. Tests done at the VLA at cm wavelengths (Cornwell, T. 1988, A&A, 202, 316.) indicate that it should work, and at mm wavelengths in the CO(1-0) line, Marc Pound made a good map of the Eagle Nebula combining a Mosaic interferometer map made with the BIMA array and a single antenna map made with the Bell Labs 7m antenna (Pound, 1998, ApJ, 493L, 113). This capability must be in place for the ALMA antennas. How it is best done may be studied with the prototype antennas.

2 Candidate Schemes

There are five schemes that are usually considered for this purpose. The simplest is the on/off pointing method. Here one points at the source for a short integration, perhaps 10-30 seconds, and then at blank sky for the same time, and then takes the difference. The rest of the map results from a sequence of such measurements. For spectral line observations with narrow band widths, the receiver noise is usually large enough that it dominates both the atmospheric brightness fluctuations and the noise due to receiver gain fluctuations in this method, and it works. The second scheme is to use rapid frequency switching for spectral line observing, and this also works. Neither of these procedures will work for continuum measurements. That's obvious for the second method. For the first, the wider bandwidth means that the receiver noise is lower than that due to either the atmospheric brightness fluctuations or the effects of receiver gain fluctuations.

For continuum total power observations, there are three schemes that can be used. The most common method is to employ a nodding secondary mirror. A related alternative is the focal plane chopper. The third idea is On-The-Fly mapping (Emerson, Klein, and Haslam, 1979, A&A, 76, 92). In all three cases, differential ground spillover will be a problem and will probably set the fundamental limit to the accuracy and depth of the continuum single antenna maps.

The nodding secondary, giving a rapid comparison, avoids gain drifts. Its main weakness is that it is difficult to get a throw of more than a few arc minutes. While this will be adequate for some science programs, there are situations where one needs to chop to an "off" position that is 10-20 (or more) minutes away. This is especially the case at the shorter wavelengths where, in the Milky Way, the background dust emission is bright.

The focal plane chopper, on the other hand, can only throw large angles, typically 10 minutes or more. Other disadvantages for our application are that it is often difficult to have a good balance between the "on" and "off" and the mechanism would probably have to be mounted on each receiver separately, which could be an annoying complication for the ALMA antennas with their many receivers.

The On-The-Fly (OTF) method looks to be the most flexible and simplest, and we summarize its properties and requirements below. Whatever scheme is chosen, the maximum throw will limit the maximum spatial scales in the resulting maps.

3 OTF Mapping

The prospects for doing OTF mapping at the Chajnantor site have been discussed in detail by Holdaway, Owen, and Emerson (1995, MMA #137) (HOE). The basic idea is that a raster scan of the object under study will be made with a very rapid turn-around of the scan at the end of each row in a region that is off the source. During the scan across the source, the receiver power is read out at a rate which corresponds to at least the Nyquist sampling of the source structure. That is, at least as often as twice per beam width. Thus, there are many "on" observations across the source with an "off" observation at the end of each row. The "off" observations last about one second during the turn-around at the end of each row. The time on each "on" observation is much smaller.

HOE used the path length fluctuations as measured by the site testing interferometer at Chajnantor to infer the expected atmospheric brightness fluctuations. They were able to work out the magnitude of the fluctuations as functions of both the time and pointing angle with respect to the source. Under the assumptions that (1) the antenna could slew as rapidly as 1^o/second, (2) the antenna could accelerate and decelerate between normal tracking and full slew in one or two seconds, and (3) the correlator could dump the spectral data every .003s, they concluded that OTF mapping should work well at the Chajnantor site. Their Figure 2 shows that the expected receiver noise and atmospheric noise contributions will be about equal at 230 GHz 80% of the time for a scan that is a large as 1^o. For smaller scans the situation is even better.

At the time of the HOE memo, is was not clear whether their assumptions about the antenna and correlator would be met. We now have more information about the array components. The present NRAO design for the correlator will allow correlator read-out at the rate of once every .001 second, which is fast enough to permit OTF mapping of both continuum and line observations (J. Weber, private communication). The planning for the antenna prototype has included studies of the capability of the antenna to carry out the OTF observing. It appears that if feed forward is used in the drive servo design, it will be possible to turn the antenna around at the end of an OTF scan in about one second as assumed by HOE. The maximum smooth scan rate will be at least about 0.5^o/sec, comparable to the 1^o/sec rate assumed by HOE.

One further point that needs to be considered is the required receiver gain stability for the OTF scheme to work. The planned continuum bandwidth of 8 GHz calls for unusually good gain stability. The time between any of the "ons" and the off at the end of the scan is about one second. The gain must be stable over that time interval. The fractional total power noise for one of the "on" measurements is: $\Delta T/T = 2/SQRT(Bt_s)$. B is the bandwidth, and t_s is the time on each source. The 2 is the usual factor due to switching. Here the long "off" time reduces the noise in the subtraction, but it is also about twice as long as the total "on" source observing time. The fractional total power fluctuation due to gain variations is: $\Delta T/T = \Delta G/G$. If we take the scan time to be always one second, then t_s depends on the scan length and the beam width. For scan lengths between $5'$ and $60'$ and beam widths between $25''$ (220 GHz) and $6''$ (800 GHz) the time on source varies between .08 sec and .002 sec. For B=8 GHz, and equating the receiver noise fluctuation to that due to the gain fluctuation, we find a necessary gain stability in the range of 0.8×10^{-4} to 5×10^{-4}. Thus, a receiver gain stability of about 1×10^{-4} over a time scale of about 1 second is required for the receiver. This level of stability can certainly be achieved, but it requires careful attention to the construction of the receiver.

The above argument leading to a gain stability requirement of 1×10^{-4} depends on the relative time on each " on " during the scan being small compared with the total scan time of about 1 second. Thus, the OTF method works best for large scans (M. Wright, private communication). Even for short scans, it will still work reasonably well, requiring a little more gain stability. It will be important to keep the total scan time to be about the same time as the turnaround time, in order that the overall observing be efficient.

Another question concerns the number of antennas that must be used to achieve the necessary sensitivity in the single antenna measurements to equal the corresponding array sensitivity. The answer here depends on the amount of redundancy in the short interferometer spacings. If there is no redundancy in the short interferometer spacings, then, for approximately equal sensitivity in the OTF measurements, the same amount of time must be spent on the single dish map as on any of the array baselines. That means about the same amount of time in the single dish mode as in the array mode. The only difference is in the factor of 2 in the OTF (switched) mode. This implies that a measurement with 4 antennas for the same duration as the array observation would suffice. However, with the likely large redundancy in the short interferometer spacings, much more time in the single dish mode will be required. Exactly how much time will depend on the details of the compact interferometer array. Probably most of the antennas will be required to operate in the single antenna mode simultaneously to produce the uv plane sensitivity comparable to the of the array. The requirement that all the antennas have the good gain stability makes the most sense. It is not a difficult requirement, and it will benefit the interferometer operation as well.

4 Summary

The major limitation in the accuracy of the single dish mode will be due to differential spillover in the "on'' - "off'' comparison. It is difficult to know in advance whether the nodding secondary or the OTF scanning scheme will be more plagued by this. The antenna background is likely to be of the order of 10K. Whether the modulation of this by the moving secondary or scanning across the ground is worse can only be determined by experiment. Thus, it will be important that the prototype antennas be equipped for both kind of observing and tests be carried out. Both good gain stability and chopping secondaries must be installed. It may be possible to test these options on existing systems. It may also be possible to test further the "homogeneouos array$''$ operation (array with single dish one of the array antennas) using one of the existing antenna systems.

Another activity that would be important in the near term would be to test the calculations of HOE with atmospheric data taken at higher frequencies. The atmospheric conditions on Mauna Kea are probably close enough to those at Chajnantor that JCMT observations would be useful for this.

Among all the possible methods to obtain the total power data for the array, the OTF scheme is the simplest and least expensive, and it appears that it should work. The main requirement is a fractional receiver gain stability of about 1×10^{-4} in a one second time interval for all the antennas. There should be no difficulty in achieving this.