# The MDC Phase Calibration Working Group Report

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## 1 Summary

A major challenge for the MMA will be obtaining high quality images in the presence of less than perfect seeing conditions. Even at the best known sites some technique for correcting for the tropospheric phase fluctuations will be required, especially for the highest resolution configurations. Without atmospheric phase correction or improved mapping algorithms the projected fraction of time available for 0.1arcsec imaging is $\sim$4% on Mauna Kea, Hawaii, and $\sim$10% at Cerro Chajnantor, Chile. Significantly more time is usable for lower resolution imaging using shorter baselines. Special mapping techniques such as self-cal or correction for known decorrelation will increase the fraction of useable time at the highest resolution but this will not apply to all projects and the sensitivity loss from decorrelation will not be recovered.

Some method for improving the atmospheric seeing will be required for the MMA to achieve the full potential of the MMA.

Several methods are under development that should adequately correct for the atmospheric errors which are likely to be encountered by the MMA if it is located at a high mountain site. The most viable methods are those already being pursued by various members of this working group. These are fast phase calibration (FPC) and radiometer phase correction (RPC).

The idea of FPC is to observe an astronomical calibrator on time scales short enough that the atmosphere doesn't change significantly between calibrations and to use calibrators close enough to the target source that the path through the lower troposphere responsible for the phase fluctuations is essentially the same. This method will work very well if the array has sufficient sensitivity and can position switch fast enough to phase calibrate on sources within $\sim$1.5deg of the target source in a few seconds of lapsed time. At this point these requirements seem possible, but have not yet been proven.

RPC is based upon the facts that the dominant source of path length variations at millimeter wavelengths is caused by fluctuations in the water vapor along the line of sight and that this water vapor can be measured by its continuum or line emission. This method puts the burden on producing radiometer/receiver systems with sufficient stability and on developing robust algorithms for converting emission temperature to path delay. RPC

These two methods correct for somewhat complementary regions in the power spectrum of fluctuations with FPC correcting for fluctuations on time scales longer than the time period between calibrations while RPC works on time scales of $\sim$1sec up to a time scale set by the radiometer stability. Implementing both techniques should cover most observing conditions and operating modes, but a successful use of either technique would mean that the MMA will live up to its proposed imaging capability.

## 2 Nature of the problem

### 2.1 Millimeter seeing

Path length fluctuations through the troposphere dominate the seeing at millimeter wavelengths. Typical seeing at the existing millimeter arrays (OVRO, BIMA, Nobeyama and IRAM) is on the order of a few arcsec at 100GHz. The site surveys on Mauna Kea, Hawaii, and Cerro Chajnantor, Chile, indicate the seeing is better at these sites but not as good as the MMA goal of 0.1arcsec. The median seeing is $\sim$1arcsec on Mauna Kea and $\sim$.3arcsec on Chajnantor. Thus it is important to develop methods for correcting the atmospheric seeing for the MMA to operate efficiently in the higher resolution configurations.

The seeing on Mauna Kea and Cerro Chajnantor is measured by using interferometers monitoring an 11.2GHz satellite. The Mauna Kea survey includes the several years of data from the 100m baseline interferometer operated by SAO near the summit and half a year of data from last winter using the 300m interferometer at the VLBA site on the mountain. The data from these two Mauna Kea sites have similar statistics but are not well correlated, i.e. good seeing at one site does not indicate good seeing at the other site. This indicates

| conditions | net gain | atmosphere | antenna | electronics |
|---|---|---|---|---|
| best | 98% | 6deg=17um | 5deg=14um | 3deg=7um |
| median | 90% | 14deg=38um | 11deg=31um | 6deg=16um |
| 80th% | 50% | 36deg=100um | 28deg=79um | 14deg=40um |

Table 1: Phase stability specifications.

the complexity of the atmospheric phenomenon responsible for seeing and the importance of carrying out surveys very close to any proposed site for the MMA. The Cerro Chajnantor survey covers May and June 1995, corresponding to the Chilean winter.

The topic for this working group is the generic problem of phase calibration for the MMA. The details of site surveying and interpretation are beyond the scope of this report as are alternate imaging algorithms applicable during conditions of poor coherence or bad seeing.

### 2.2 Phase noise goals.

Inline with the desire to produce the best possible instrument an aggressive set of goals has been proposed. The *antenna based* goals for the phase noise at 300GHz on times scales from 1 to 100 sec are given below. Baseline based phases are sqrt(2) higher. The phase values in this table were adjusted upwards on October 3 to correct for a computational error.

The division between atmosphere, antenna and electronics is based upon the presumption that the atmosphere will be the most difficult to control and the electronics the easiest. The purpose of these goals is to push each aspect of the system to ensure the overall imaging capability of the MMA is not compromised at this early stage of development. Clearly there will be tradeoffs as the detailed design gets under way. Interestingly, one of the more stringent requirements arises from the need to use holography to measure the surface figure to the desired accuracy of better than 8microns, ie. wavelength/100.

## 3 Approaches to the solution

The working group has looked at many possible techniques for correcting the atmospheric phase errors. These are briefly discussed below in order of decreasing relevance to the MMA. The basic technique with its advantages and disadvantages is presented along with the current status and the impact it would have upon the MMA design.

### 3.1 Fast Phase Calibration (FPC)

FPC is a straight forward extension of the standard slow phase calibration but takes advantage of the much higher sensitivity of the MMA to utilize nearby ($\sim$1.5deg) calibrators and the proposed ability to position switch the antennas on a time scale of the order of one second.

This method has been well explored theoretically [MMA memo 84] and in preliminary VLA tests [MMA memo 126]. The basic idea is to observe an astronomical calibrator on time scales short enough that the atmosphere doesn't change significantly between calibrations and to use calibrators close enough to the target source that the path through the lower troposphere responsible for the phase fluctuations is essentially the same. The technique works because the dominant atmospheric fluctuations correspond to structure in the atmosphere on the scale size of the baseline and on time scales given by the wind crossing time.

Stated quantitatively, the residuals after phase calibration correspond to the phase structure function for spatial scales less than vt/2+d, where v is the wind velocity, t the time between calibrations, and d the distance between the beams to the calibrator and target at the height in the atmosphere responsible for the fluctuations. FPC begins to correct for atmospheric seeing when vt/2+d becomes less than the actual baseline length with smaller values of vt/2+d yielding better correction. For typical wind speeds (10m/sec), expected calibrator distributions, and a 10sec cycle time, the relevant spatial scale for the atmospheric phase structure function is 10[m/sec]*10[sec]/2+.025[rad]*2000[m] $\sim$ 100m. Note the 11.2GHz satellite phase monitors used for site surveys have baselines of 100m and 300m and thus directly sample the atmospheric structure function appropriate for evaluating the utility of the FPC technique.

FPC offers many advantages for the MMA. Applying the technique requires no calculations or assumptions about the source of the phase fluctuations, i.e. calibrating more often has to improve the map quality. No special receivers or configurations are required. An added benefit it that calibrating on a 10sec time scale greatly decreases the effect of temperature and other slow fluctuations on the phase stability of the antenna and electronics.

The disadvantages of FPC are the larger fraction of time spent calibrating and the added stress it puts on other aspects of the system. Achieving the fast antenna position switching ($\sim$1.5deg in $\sim$1sec) is not viable in existing radio telescopes and presents a major challenge to the telescope designer. Existing interferometers also have long setup and data dump times which preclude FPC. Although there is no inherent reason that a modern system cannot reconfigure the LO's, correlators, etc. in much less than a second, doing so will add some cost to the design and construction the computer systems and electronics.

FPC also requires that the MMA have the sensitivity, high gain/Tsys, and wide continuum bandwidth to be able to find and use weak calibrators close to the target sources. The most likely frequency for calibration will be in the 90GHz band or even lower. It is important that the LO system be built so that phase calibration at one frequency will also correct for drifts in the LO chains for the other bands as much as possible.

It is difficult to fully test this scheme on existing interferometers that have time overheads of many tens of seconds between changing sources. The fastest possible calibration cycles would typically only improve the imaging on baselines on the order of 500m or greater. The tests already done on the VLA [MMA memo 126] show the method works on baselines greater than 400m for an 80sec cycle time and a calibrator 2deg away. As suggested in the above memo, more observations using calibrators further away and in different weather conditions can be carried out to further explore the effectiveness of FPC. The BIMA array now has baselines as long as 1km, so it could be used verify some aspects of FPC.

### 3.2 Radiometric Phase Correction (RPC)

RPC uses continuous monitoring of the atmospheric emission along, or nearly along, the line of sight to determine the changes in the atmospheric path delay. This method is based upon the well founded assumptions that the dominant source of tropospheric phase fluctuations at millimeter wavelengths is caused by fluctuation in the amount of water vapor along the line of sight and that these fluctuations reveal themselves as time varying atmospheric emission. The basic concept has been proven by the JPL 22GHz water vapor radiometers used in VLBI, and especially for geodesy experiments where the precision is on the order of a few millimeters. This precision is not sufficient, however, for millimeter interferometers and systems currently under development are being designed to work in linked arrays with nearly a factor of 100 times better precision. The radiometers will monitor the 22GHz or 183GHz emission lines or the continuum emission from water vapor. RPC will provide an essentially continuous measure of the path delay so atmospheric phase fluctuations that occur on time scales shorter than the astronomical calibration can be corrected.

RPC presents several design challenges. The radiometer must have high sensitivity and excellent stability on time scales from 1 to 1000sec. Achieving wavelength/20 (.05mm at 1mm) will require measuring the emission to a precision .1% to .01% on the time scale of the calibration cycle. The ratio of emission temperature to path delay, C[K/mm_delay], will depend in general upon the details of the atmospheric model and the altitude of the fluctuating water vapor component. A successful system will probably incorporate some sort of learning algorithm based upon several metrology parameters and the observed calibrator phase. Some offline iterations of the ratio of emission temperature to path delay will be required to recover the best images. There is an open question of how to link optimally the source to calibrator given the relatively large change in emission temperature associated with the change in airmass between the two.

Fortunately for the MMA several groups are pursuing different forms of water vapor radiometers for existing millimeter arrays. OVRO is developing a 22GHz water line spectrometer. The JCMT and CSO submillimeter interferometer group is working on a 183GHz water line monitor. BIMA is stabilizing the receivers and IF electronics so that the system noise power can be used as a measure of the sky emission at the astronomical observing frequency. IRAM has used the system temperature at 230GHz to correct the phase at 86GHz. These systems are all at an early stage of development but astronomical images processed using these techniques should start to show up in the next year or two.

Each system has its advantages and disadvantages. The line emission monitors offer the ability to reject extraneous continuum emission from antenna spillover, liquid water, and ice. These later atmospheric components can contribute a large emission temperature but very little path delay. The 22GHz line is unsaturated even in wet low elevation climates and the ratio of emission temperature to delay, C, depends only weakly upon the height of water vapor fluctuations. The 183GHz line is saturated at most existing interferometers, but should be usable at high mountain sites and can have a sensitivity ten times larger than the 22GHz line. The line monitors will probably require separate dedicated instruments and optics offset from the astronomical beam. The continuum monitors offer the advantage that the astronomical receivers can be used if they are designed with the necessary stability, but the measurements can be corrupted by extraneous sources of continuum emission.

The proposed MMA receiver configuration with all the receivers above 60GHz mounted in the focal plane and looking at the sky at the same time, albeit in slightly different directions, offers a lot of possibilities. If each receiver has its own LO, then they can all be used as radiometers simultaneously. In particular the receiver covering the 183GHz line could have a special IF spectrometer dedicated to monitoring the water line. It would be advantageous to divide the receiver bands so that the division is at 183GHz. Then when astronomy is performed near 183GHz there will another receiver available for water vapor monitoring.

The biggest effect on the MMA system is the frequent data dumps required if it is necessary to take out erroneous corrections made in real time or apply the corrections offline.

RPC's are still at an early stage in their development for millimeter interferometers, but there is a real need for them on the existing arrays and for millimeter VLBI where the existing systems do not allow fast position switching and the sensitivity is not high enough to find sufficiently close calibrators for the FPC to work. It is hoped great progress will be made in this field on the time scale of one to two years.

### 3.3 Sub-array of MMA antennas

In this approach, half of the MMA antennas would be dedicated to observing a nearby calibrator. The calibrator phase would then be applied to nearby antennas observing the target source. This is an instantaneous version of the FPC technique, but comes at the sacrifice of half of the collecting area and 3/4 of the baselines. The loss in baselines is not as serious in compact configurations where the phase screen may be measured using less than half of the array and you can time multiplex to recover all of the baselines. Normal phase correction would also have to be done to remove instrumental phase errors. For this method to work well, it would be necessary to use configurations where antennas are placed in pairs, thus greatly reducing the UV coverage. Although the method should work well, it seems to be a very wasteful solution to the atmospheric seeing problem.

### 3.4 Atmospheric monitoring array

The idea of this technique is to use a dedicated array to measure the atmospheric phase screen over the whole array and apply the appropriate phase corrections to the MMA antennas. The phase screen could be measured using astronomical point sources or monitoring satellite transmitters (GPS or communication satellites). This technique assumes that the atmospheric fluctuations are accurately characterized as a fixed phase screen blowing over the array or that you have enough small telescopes to measure the path delay near the line of sight of each MMA antenna. This method will yield a large amount of information about the nature of the fluctuations in the atmosphere, but it has yet to be demonstrated that the a simple fixed phase screen is a valid characterization of the atmosphere, especially at the long baselines proposed for the MMA. The method also requires a large number of specialized small antennas and its own correlator. Scientists at Nobeyama are pursuing this technique and at this point the MMA can aford to wait and see what they learn.

### 3.5 Techniques at other wavelengths

There are several other methods for measuring water vapor using techniques developed at other wavelengths. One of the more interesting methods is LIDAR (LIght Detection And Ranging) which applies standard RADAR techniques to infrared laser ranging systems. The most sensitive LIDAR systems use two frequencies, one at a water line and another nearby to correct for aerosol scattering. At present LIDAR systems are very expensive and the precision may not be sufficient for use in the MMA. This is a developing technology and should improve in sensitivity and decrease in cost in the future.

A nice feature of LIDAR is that it gives water vapor as a function of altitude, and thus may be very useful in determining the atmospheric profile. Along the same lines there are radiometers operating on the oxygen lines which measure temperature versus altitude and radar systems which measure wind velocity profiles. This information could be very useful in improving the path delay retrieval algorithms for use with radiometer measurements. It might be appropriate to have one advanced metrology system at the MMA that uses these techniques to accurately characterize the atmosphere.

A variation on the microwave or millimeter wave radiometry is to monitor the infrared water lines. These lines are currently used by the GOES satellite to measure water vapor in the atmosphere. It would be worthwhile to determine if the desired .05mm delay precision can be achieve using this technique.

## 4 Finding Calibrators

It is important that suitable calibrators be identified for use by the MMA. FPC requires a large number of strong calibrators distributed throughout the sky. It is also advantageous to have nearby calibrators even for standard slow phase calibration. Preliminary survey work carried out at Kitt Peak indicates the MMA will have a 100mJy calibrator within 2deg 70% of the time [MMA memo 124]. This would be sufficient for FPC if the results hold up over most of the sky. Work still needs to done in determining how to find and select calibrators since most are variable sources.

Rather than simply maintaining an extensive catalogue, it may be more time efficient to simply spend time at the beginning of each observation looking for nearby calibrators. This would start with lists of potential calibrators (known flat spectrum sources, known MM calibrators from pervious observations, and known cm sources). By using a site testing interferometer in real time to get the wind velocity aloft and the phase structure function, we will know at the time of the observations what the optimal calibrator is and the highest frequency that can be observed with some residual phase error. If none of the cataloged calibrators are suitable, then a blind search for a (presumably) fainter, closer calibrator could be performed on the single square degree surrounding the target source via single dish mapping at 30GHz followed by interferometric mapping at 90 GHz (the calibrator frequency). This process could take anywhere from a few minutes to a half hour.

## 5 Conclusion

There are two viable techniques, fast phase calibration (FPC) and radiometric phase correction (RPC), which will improve the seeing for the MMA. If either technique lives up to its expectations, then the MMA will be able to do most of the proposed science without the need for the other technique. The MMA will be in trouble only if neither technique is possible or practical.

The two techniques, FPC and RPC, are complementary in that they work on different time scales. FPC works best at removing the slow fluctuations occurring on long baselines while RPC works best at correcting short time scale fluctuations, but there is a large overlap from 5 to 500 seconds where both systems could work. It will be difficult to slew the telescopes fast enough to use FPC on the shortest time scales and it will be difficult to achieve the gain accuracy and stability required for RPC to accurately correct the large fluctuations on the longest time scales. It seems prudent at this time to pursue both techniques during this early stage of the design process.