MMA Project Book, Chapter 2

MMA SCIENCE REQUIREMENTS

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1998-08-08: First version
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2.1 Summary

The scientific capabilities required in the MMA were refined in community science workshops sponsored by the NRAO throughout the decade of the 1980s and confirmed by the September 1995 MMA Science Workshop held in Tucson, AZ. Five reports were written following the Tucson Workshop that summarize the science goals in the following categories:

1. Cosmology and Extragalactic
2. Star Formation and Stellar Evolution
3. Galactic Molecular Clouds and Astrochemistry
4. Solar System
5. Sun and Stellar

These reports are available on the MMA WWW pages. While these different scientific areas emphasize different capabilities, they all require precision imaging over the millimeter and sub-millimeter wavelength bands and over resolutions from arcseconds to less than a tenth of an arcsecond. The science requirements and the technical requirements that each implies are summarized in Table 2.1.

Table 2.1 MMA Science Requirements

Science Requirement	Technical Requirements Needed to Achieve
High Fidelity Imaging	Reconfigurable Array Robust Instantaneous uv Coverage, N>30 Precision Pointing, 6% of the HPBW Antenna Surface Accuracy RMS lambda/40 Primary Beam Deviations < 7% Total Power and Interferometric Capability Precision (1%) Amplitude Calibration Precision Phase Calibration Fast Switching
Precision Imaging at 0."1 Resolution	Interferometric Baselines of 3 km Instrumental Phase <10 deg w/Compensation Correction System for Atmospheric Phase

Routine Sub-milliJansky Continuum Sensitivity	Array Site with Excellent Transparency Array Site with Low Water Vapor Emission Quantum-limited SIS Receivers Antennas with Low Warm Spillover -Low Aperture Blockage -Cassegrain Optics (Minimum Reflections) Antennas of High Aperture Efficiency Wide Correlated IF Bandwidth Dual Polarization Receiving System Large Collecting Area, ND^2
Routine Milli-Kelvin Spectral Sensitivity	Array Site with Excellent Transparency Array Site with Low Water Vapor Emission Quantum Limited SIS Receivers Antennas with Low Warm Spillover -Low Aperture Blockage -Cassegrain Optics (Minimum Reflections) Antennas of High Aperture Efficiency Dual Polarization Receiving System Large Collecting Area, ND^2 Large Collecting Length, ND
Wideband Frequency Coverage	Receivers that Cover Atmosphere Windows Tunable Local Oscillator Large Dewar for Many Receivers
Widefield Imaging, Mosaicking	Highly Compact Array Configuration Complete Instantaneous uv Coverage, N>30 Precision Pointing, 6% of the HPBW Antenna Surface Accuracy RMS lambda/40 Total Power and Interferometric Capability Precision Amplitude Calibration Precision Phase Calibration Rapid Correlator Dump Times, millisecs Ability to Handle Large Data Volumes/Rates
Sub-Millimeter Receiving System	Array Site with Excellent Transparency Array Site with Low Water Vapor Emission Quantum Limited SIS Receivers Antennas with Low Warm Spillover -Low Aperture Blockage -Cassegrain Optics (Minimum Reflections) Antennas of High Aperture Efficiency Instrumental Phase Stability <10 degrees Correction for Atmospheric Phase Variation

Full Polarization Capability	Measure all Stokes Parameters Cross correlate to Determine Stokes V Ability to Calibrate Linear Gains
System Flexibility	Ability to Phase Array for VLBI Sum Port for External Processing Sub-arraying Capability Ability to Observe the Sun

2.2 General Requirements

1. Frequency Coverage

The instrument needs to cover all the available frequency windows between about 30 and 900 GHz. These requirements are summarized in the M MA Frequency Bands whitepaper . This requires an outstanding site as discussed in the Site Selection Document.

2. Spectral Line and Continuum

The MMA must operate as both a sensitive spectral line and continuum array. This implies using the widest continuum practical from the point of view of the IF and the correlator which appears now to be 8 GHz and a flexible correlator as described in the MMA Correlator Whitepaper .

3. Sensitivity

The array must maximize both point source and surface brightness sensitivity. For antennas with the same overall properties, this requires maximizing the different quantities, nD2 (for point source sensitivity), nD (for surface brightness sensitivity in a sparsely filled array) and n(1/2) (for a tightly packed array or total power mode). See MMA Memo #177.

4. High Resolution

Given the expected brightness and size of sources considered in the science documents, this implies baselines of at least 3 km and 10 km as a design goal. This requirement demands the MMA be adequately phase stable both internally and in the presence of atmospheric phase fluctuations. This will be discussed further in section 2.3.

5. Large Source Imaging

On the other end of the size scale, this implies imaging objects both close to and bigger than the primary beam. This requirement has several implications. First, 3)+ 4) + 5) require that the array be reconfigurable into configurations optimized for the resolution and sensitivity required by each experiment. Second, the array must be able to make large mosaicked images (multiple pointings) to image regions on the order or larger than the primary beam. Third, the array must have a sensitive, stable total power system so that spatial frequencies smaller than are available in interferometer mode can be measured. Since the primary beams at the highest frequencies for antennas on the order of 10m are < 10 arcsec, modes 2 and 3 should be very common, perhaps the vast majority of all observations with the array.

6. High Fidelity Imaging

Especially in the modes discussed in 5), a significant fraction of the experiments and some the most important require high fidelity imaging. That is the signal-to-noise is high enough and source complex enough that errors in pointing and calibration can degrade the scientific usefulness of the experiment (Cornwell memo/Rupen memo).

Such problems require 1) excellent pointing, 2) high quality amplitude and 3) phase calibration which will be discussed in section III.

7. Polarization

Both linear and circular polarization of lines and continuum emission is a significant part of the MMA science program. At centimeter and longer wavelengths interferometers produce linear polarization by correlating the opposite circular polarizations from different antennas, that is R with L and L with R. However, it appears technically difficult to do this at millimeter wavelengths across the broad bands we want with the MMA. Thus it seems best to observe in the more natural linear polarization with the MMA. This means we crosscorrelate to calculate the V stokes parameter; we get I, Q and U from linear combinations of the two linear correlations. This requires both linears be present all the time and that either their relative gains remain very stable and/or we have the necessary internal calibration signals to measure their changes. (see Cotton, 1998).

8. Solar Observations

Requirements for observing the sun are discussed in the Sun and Stars science document and by Bastian et al, 1998.

9. VLBI

The highest resolution with the MMA will be obtained from VLBI observations using the MMA as a single element. The requirements for this are discussed by Claussen and Ulvestad, 1998.

10. Pulsar/High Speed

Pulsar observations will require a gating mode with the correlator as well as a sum port like the VLA which can be attached to specialized external recording equipment. This latter capability would also be available for any high speed phenomena which may be discovered in the future.

2.3 Implications

The requirements summarized above imply the need for the array capabilities summarized here.

1. Phase Stability

As the observing frequency increases into the submillimeter the electrical path length through the atmosphere and through the electronics must be increasingly stable in order to enable the MMA to produce high fidelity images.

- Internal Phase Stability. The electronics systems must be stable enough that they do not degrade the imaging relative to those path length fluctuations caused by atmospheric effects. At 900 GHz the instrumental phase must be less than 10 degrees. A system to monitor and compensate for electrical path length changes in the instrument is necessary.
- Atmospheric Phase Stability. Atmospheric path length changes must be measured and corrected to preserve the capability for high fidelity imaging. Techniques to be developed to accomplish this include fast switching of the array antennas and radiometric techniques for measuring and correcting atmospheric phase distortion.
  - *Fast Switching.* In this mode the antennas are rapidly cycled between a nearby calibrator source and the program source before the atmosphere can change significantly. The method has proven to be effective (MMA Memo 139); it requires the antennas to have the capability to move between source and calibrator that are separated by less than 2 degrees on the sky on a cycle time of less than 10 seconds.
  - *Radiometric Phase Correction.* Since water vapor in the atmosphere is responsible for both temporal changes in the sky opacity and changes in the electrical path length (the phase), measurements of the changing sky brightness can be used to infer changes in the atmospheric phase distortion. The techniques require stable radiometry and are best employed using either the 22 GHz atmospheric water line or the 183 GHz water line. The expected efficacy of the techniques, and the precision required by the MMA, are discussed in Carilli et al. 1998.

2. Amplitude Stability

The capability to measure and maintain amplitude stability of the MMA at the level of one percent is needed to combine imaging information from one array configuration to another reliably and permit accurate comparison of line strengths to determine such physical parameters as the excitation temperature of interstellar clouds or material in galactic nuclei. This will require use of an external calibration system such as discussed in MMA Memo #225.

3. Integration Times

The fastest integration time needed by the MMA will be driven as much by the need to perform total power continuum observations and fast on-the-fly mosaicking as it will be by the need to measure time variability in astronomical sources. This issue is evaluated quantitatively in M MA Memo #192.

4. Contingency Scheduling

This is an operational issue. The MMA will need to be scheduled to allow the most demanding submillimeter observations, and mosaicking observations in the most compact configuration, to be done in conditions of favorable transparency and low prevailing wind. To accomplish this the array will need to be scheduled in near real time.

5. Data Flow

This is another operational issue. The astronomer will benefit by the ability to see his or her data in near real time. Most observations requiring longer than a few hours will be scheduled such that they are made over several source transits so little or no data is taken at extreme hour angles where the low elevation will compromise the system noise. This provides the opportunity for the astronomer to refine his or her observational techniques as the observations are in progress. The design requirement is for real-time imaging and for the capability for those images to be transmitted from the Chile site to the astronomer in the U.S. or elsewhere in a timely way. This requirement and its implications are explored in M MA Memo #164.
