# The Millimeter Array

John E. Carlstrom
Department of Astronomy and Astrophysics
University of Chicago

**Abstract:** The U.S. National Radio Astronomy Observatory (NRAO) has proposed to build a large interferometric array, the Millimeter Array (MMA), for astronomical imaging at wavelengths ranging from 1 cm to 350 $\mu$m. The design of the Millimeter Array calls for 40 telescopes 8 m in diameter for a total collecting area of 2000 m$^2$. The array is to be located on a high dry site; a 5000 m plateau in Chile and a site at $\sim$ 3500 m on Mauna Kea, Hawaii are being tested. This paper provides a brief overview of the project including the astronomical motivation and resulting design specifications. The technological innovations required to meet these specifications will challenge researchers of all fields of engineering and device physics. Of particular interest for the participants of this symposium are the specifications for fast electronically tuned local oscillator sources spanning the entire frequency range and also for extremely low noise, image separation SIS mixers.

## 1 Introduction

The existing millimeter arrays (BIMA[1], IRAM[2], OVRO[3], NRO[4], and the CSO-JCMT submillimeter interferometer[5]) have demonstrated the feasibility of millimeter interferometry and its power to obtain critical data for a large range of astrophysics. Millimeter and submillimeter wave observations are used primarily for continuum and spectroscopic imaging of cold dust and gas (kinetic temperatures of 10 to 100 K). These observations are used to address a large range of astrophysical problems[6], ranging from the composition and shape of asteroids, atmospheric studies of the planets, the formation of solar-like stars and protoplanetary disks, the structure of the molecular clouds and cloud complexes, the structure of the Galaxy and external galaxies, the atmosphere of clusters of galaxies, and the intrinsic anisotropies in the cosmic microwave background which are the seeds of all structure in the universe today. It is likely that the youngest protostars and possibly the youngest galaxies (protogalaxies) will only be observable at these wavelengths due to the strong attenuation by dust at shorter wavelengths and the low emissivities at longer wavelengths.

Motivated by the success of the first millimeter arrays in the early 1980's, NRAO sponsored a workshop in 1985 to determine the scientific goals and set the design requirements of a large millimeter array. A second workshop was held in 1989 to update the scientific goals and design requirements for the preparation of a proposal that was submitted to the NSF in 1990. The National Academy of Sciences Decade Review of Astronomy[7] (the Bachall Report) strongly recommended the MMA in 1991. In 1994 the MMA became a project of the NSF and therefore available for funding. The proposal now awaits the approval of the National Science Board and then approval by Congress. The cost is estimated at 200M (1995$). The NSF has stipulated that at least 25% of the cost must be covered by another agency or a foreign partner.

## 2 MMA Site

The sensitivity and stability of a millimeter interferometer is limited by the atmosphere, with water vapor accounting for the largest contribution. As Figure 2 illustrates, suitable atmospheric frequency bands for observing ("windows") are located between the strong atmospheric oxygen lines near 60 GHz and 120 GHz and between the strong atmospheric water lines located throughout the millimeter and submillimeter spectrum. The opacity between the lines is still appreciable and increases with frequency due to the pressure broadened wings of the far infrared water lines. At frequencies above 1000 GHz, no usable windows exist from the ground until the mid–infrared regime is reached, except perhaps from an exceptionally dry site such as the south pole[8]. Water vapor is also refractive and therefore spatial and temporal variations of the water vapor lead to fluctuations

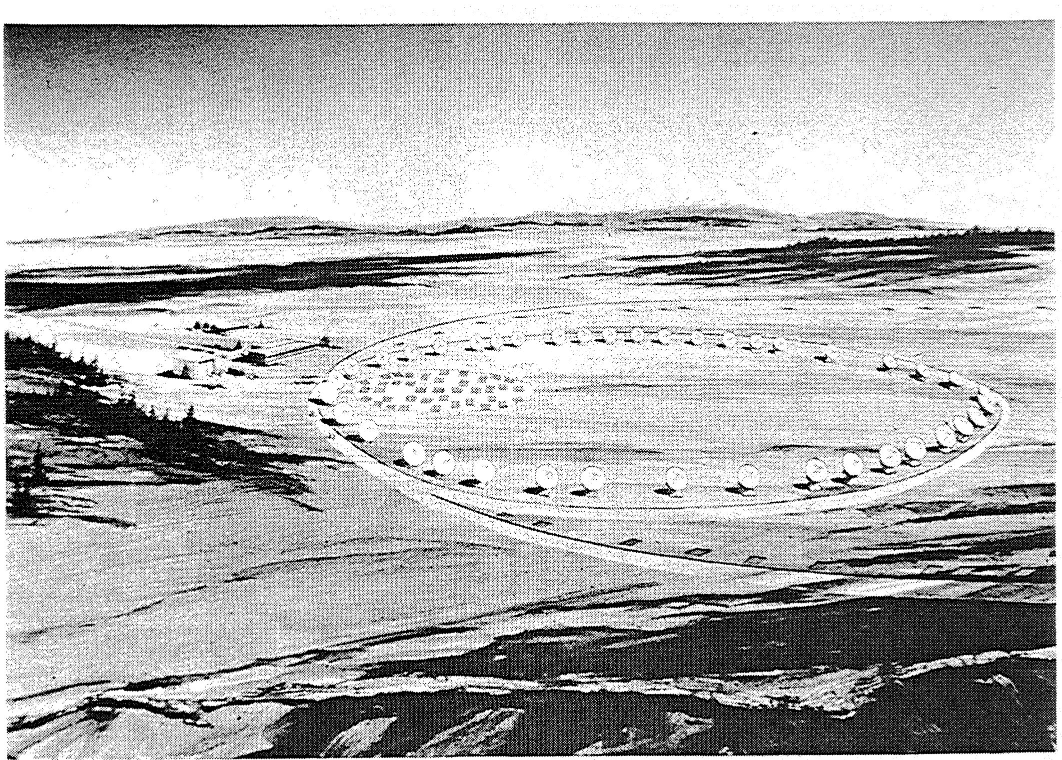


Figure 1. Sketch of the proposed Millimeter Array

in the atmospheric path lengths above each of the interferometer elements causing decorrelation of the signal. Obviously the quality of the atmosphere above the MMA site is exceedingly important. Since the scale height of water is only a few kilometers, a high dry site greatly reduces the atmospheric opacity. However, it appears that the stability of the atmosphere is not a function of the total precipitable water vapor and realtime corrections must be made to the phase response of the interferometer[9].

At this time NRAO is considering two sites for the MMA, one on a 5000 m plateau in Chile and one near the VLBA site on Mauna Kea, Hawaii at $\sim$ 3500 m. The Chilean site is located near the Chilean border with Bolivia and Argentina. It is not developed, but there is good road access and it is roughly an hour drive from the small resort town of San Pedro de Atacama. Site testing has been ongoing on Mauna Kea for several years and on the Chilean site for roughly a year. Opacities are generally lower above the Chilean site and were truly exceptional during the Chilean 1995 winter. As shown in Figure 3, the opacity measured with a NRAO 225 GHz tipping radiometer showed that the zenith tau was less than 0.029 for 25% of the time, 0.040 for 50% and 0.069 for 75%. This corresponds to precipitable water vapor much less than 1 mm for a large fraction of the time making the site suitable for observing in the submillimeter windows. Mauna Kea is a proven submillimeter site but suffers from moist periods when the local inversion layer rises above the proposed MMA site, often resulting in a strong diurnal effect in the opacity[9].

The atmospheric stability above either site is not sufficient for reliable long baseline observing without compensation for the varying atmosphere path lengths. Several methods are now being considered and tested for what is essentially "adaptive optics" for millimeter interferometry. One method is to interleave observations of known point sources, such as masers or quasars, to calibrate the instrumental phase (differential path length) on time scales of seconds. As discussed below this

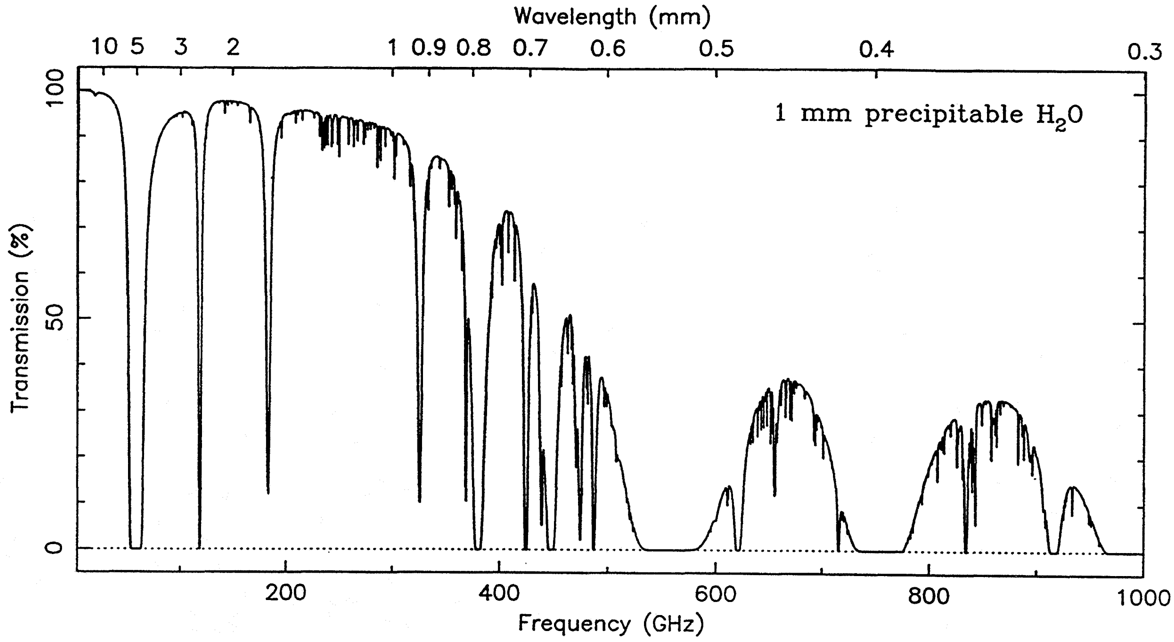



Figure 2. Model of the atmospheric transmission[10] at a 4000 m altitude and for 1 mm precipitable $H_2O$.

places stringent requirements on the telescopes and the LO systems. A second method is to use the many MMA receivers to measure the water vapor emisson accurately, possibly tuning some of the receivers to the wings of atmospheric water lines, and then using the measured emission to calculate the excess path length. This method places severe requirements on the receiver gain stability and its frequency coverage.

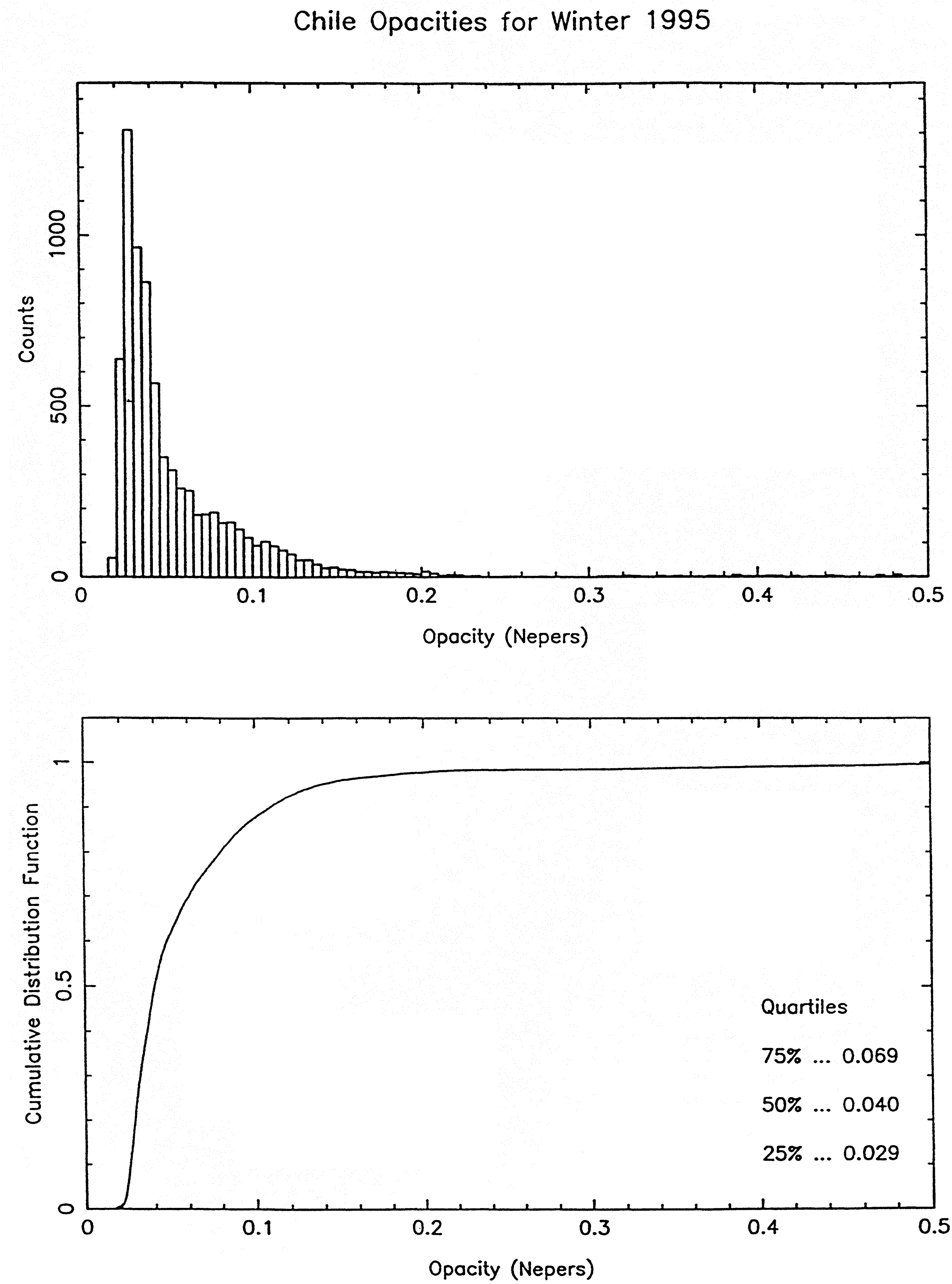
## 3. Design of the MMA

### 3.1 Mutual Development Consortium

Recently the Mutual Development Consortium has been established to coordinate efforts within the BIMA, OVRO and NRAO groups to overcome some of the technical challenges to improving, expanding, and combining the existing U.S. university arrays and to refine the design of the NRAO Millimeter Array. Five technical working groups were established and each produced a report in 1995 Fall. The reports are available from NRAO and also posted on the WWW. The groups and their chairs are listed in Table 1. The Systems working group is concerned with the correlator, as well as IF and LO generation and distribution. No report currently exists for the Software working group.

Table 1.

| Technical Working Group | Chair | |
|---|---|---|
| Antennas | P. J. Napier | (NRAO) |
| Receivers | W. J. Welch | (BIMA) |
| Phase Calibration | D. P. Woody | (OVRO) |
| Systems | A. R. Thompson | (NRAO) |
| Software | S. L. Scott | (OVRO) |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Counts
0
500
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0.1
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Opacity (Nepers)
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0
0.5
1
Quartiles
75% ... 0.069
50% ... 0.040
25% ... 0.029
0
0.1
0.2
0.3
0.4
0.5
Opacity (Nepers)

Figure 3.

In the Fall of 1995 NRAO also enlisted a large number of astronomers to update again the scientific goals of the MMA. This was done to ensure that input was given to the MDC technical working groups so that design decisions would be made in the best interest of the astronomical goals. The science working groups and their chairs are listed in Table 2.

Table 2.

| Science Working Group | Chair | |
|---|---|---|
| Cosmology and Extragalactic | J. E. Carlstrom | (U. Chicago) |
| Star Formation and Stellar Evolution | J. Bieging | (U. Arizona) |
| Giant Molecular Clouds and Astrochemistry | E. F. van Dishoeck | (Leiden Univ.) |
| Solar System | F. P. Schloerb | (U. Massachusetts) |
| Sun and Stars | T. Bastian | (NRAO) |

The reports of the science working groups are available from NRAO and also are posted on the WWW. A look through them will impress the reader with the power of millimeter and submillimeter astronomical observations and with the challenges the MMA presents to the designers of the associated instrumentation.

### 3.2 Science driven technical specifications for the MMA

In this section the requirements set by the science working groups are reviewed.

#### 3.2.1 Telescopes

The collecting area should be optimized for maximum sensitivity, but not at the expense of compromising the imaging capabilities of the array. The current plan is for 8 m diameter elements. A larger diameter has been suggested by several groups, but the antenna working group finds it difficult to meet the other design criteria with a large element. The minimum design goal for the total collection area of the array is 2000 $m^2$.

A major design goal of the MMA is high quality, essentially instantaneous imaging. For observations of molecular clouds and galaxies, low brightness emission will often extend beyond the field of view of the array making mosaicing necessary[11]. This requires good instantaneous u,v coverage. These constraints on the imaging capabilities are quite different from those at longer wavelengths where bright non-thermal emission is imaged against an essentially blank background. The large number of telescopes specified, 40, is set to help ensure adequate imaging capabilities.

#### 3.2.2 Array configurations

For imaging extended sources, especially the cosmic microwave background, a compact configuration of the 40 telescopes in roughly a 70 m diameter diameter region is required (note the compact stations in Figure 1). Each science working group also offered examples of observations which would benefit from baselines up to 10 km – the solar group requested 30 km. This puts extreme constraints on the site, favoring the Chilean site over the Mauna Kea.

#### 3.2.3 Frequency coverage

The science working groups requested continuous frequency coverage from 26 to 380 GHz, with the exception of a small gap near 60 GHz where strong oxygen lines render the atmosphere opaque. There are several other strongly absorbing atmospheric oxygen and water vapor lines. However, these same transitions are of interest for astronomical observations; water vapor lines are often found to be strongly masing and are easily observed through rather high atmospheric opacities. Furthermore, by performing accurate radiometry near the strong atmospheric water lines, variations in the water content above each telescope can be monitored and, in principle, used to correct for the variable atmospheric refraction.

Once the science groups realized that the sites being considered would support submillimeter (submm) observations and that the telescope specifications for mosaicing at 350 GHz[11] are sufficient for submm observations, they all pushed for eventual operation in all of the submm windows. It was strongly recommended that the first complement of receivers include a 610 to 730 GHz band.

3.2.4 Instantaneous IF bandwidth

A minimum of 8 GHz IF bandwidth per sideband with a goal of 16 GHz was requested for the SIS receivers. Large IF bandwidths recently were reported for a tunerless SIS mixer[12]. The high bandwidth allows high continuum sensitivity, observations of many molecular species simultaneously, and increases the capability of searches for line emission from distant galaxies.

3.2.5 Polarimetry capabilities

For increased sensitivity, dual channel receivers observing orthogonal polarizations will be used. Accurate polarimetry requires much higher specifications for the polarization purity as well as twice the number of cross-correlations. Such capabilities are desired for measuring the linear polarization of continuum emission from dust and also Zeeman splitting of molecular lines. It is proposed that accurate polarimetry be possible for at least select frequencies within each receiver band and possibly at all frequencies. It is accepted that the number of spectral channels for polarimetric observations likely will be reduced when obtaining all four Stokes parameters.

3.2.6 Spectral resolution – digital correlator

The science working groups requested the possibility of correlating up to 8 subbands within the 8 GHz IF bandpass for a total of at least 1024 complex frequency channels. The spectral capabilities should allow resolutions spanning 1 kHz to a resolution coarse enough ($\sim$ 16 MHz) to cover the entire bandpass with the available channels. The Solar System group requested a resolution as high as 10 Hz for planetary radar experiments. Due to the enormous number of correlations that must be performed, it is clear that a single correlator must be flexible enough to cover all of the observers' needs; adding an additional correlator would require an enormous amount of extra cabling. The data output of the correlator will be large; a single dump will produce of order, 780 baselines $\times$ 1024 complex numbers $\sim$ 1.6 Mbytes of data.

3.2.7 Mosaicing capabilities

Large fields, $0.5 \times 0.5$ deg$^2$ will be mosaiced, of order $10^4$ pointings of the array. This will require On–The–Fly (OTF) mapping techniques, in which the correlations are performed as the array scans the source. The correlator will need to be read at a rate of roughly 1 Hz. Most likely only a reduced number of spectral channels will used in this mode to reduce the $\sim$1 Mbyte s$^{-1}$ data rate. Proper mosaicing also requires total power capabilities, which may require a nutating subreflector on each telescope. It is hoped that the stability of the receivers will be high enough and the telescope position switching fast enough so that nutating secondaries can be omitted.

3.2.8 Fast frequency switching

The original MMA design called for the simultaneous observations with two or possibly four receivers. The mirrors and wire grids necessary to implement such a scheme would add noise, so the receiver group has sought an alternative design (see below). The simultaneous observing specification has now been replaced with a fast frequency switching specification. It is requested that the array be tuned to any frequency within 1 s. This can be used for phase calibration on masers, to interleave observations of transitions that do not fall within the instantaneous IF bandwidth (such as several CO rotational transitions), and to determine spectral indices. The Solar science working group requested frequency switching on 0.1 s time scales for multi–frequency observations of solar flares.

4 Recommendations of the Technical Working Groups

Here we only summarize the reports of the Receiver and Antenna Technical Working Groups. The reports of all the groups can obtained from NRAO and are also readily found on the WWW.

4.1 Receivers

4.1.1 Optics, polarimetry, and calibration

The receiver working group concentrated on taking full advantage of the low atmospheric opacities above the candidate sites. They strove to minimize beam transport losses. The optical design is similar to the one implemented on the BIMA telescopes. The cooled feed horn and lens assemblies point directly at the secondary reflector; the primary and secondary reflectors are the only warm optical elements in the design. All receivers stare at the secondary and thus the sky at all times. The only possible exception is that a pick off mirror may be used when the 26 - 55 GHz bands are selected.

The lack of additional warm mirrors is to avoid the $\sim$ 1.5 K each mirror is expected to add to the DSB noise temperature. The above design will also be more reliable as there are no moving parts. Switching between bands only requires an offset in the telescope pointing.

It is expected that a single feed followed by an orthomode transformer (OMT) will be used for each receiver band. Work is under way to construct a satisfactory broadband waveguide OMT for use at millimeter wavelengths.

In addition to the possible mirror for the 26 - 55 GHz band, it is expected that an assembly for improving the polarization purity would be moved into the beam path when needed. For accurate polarimetry of weakly linearly polarized emission it is best to observe in right and left circularly polarized emission. However, a broadband OMT will likely produce orthogonal linear polarization requiring an accurate $\lambda/4$ plate to produce the desired circular polarization states.

The receiver group also called for the absolute calibration accuracy of 5% or better. This will entail bringing two blackbody calibration sources into the beam path.

#### 4.1.2 Image separation receivers

An interferometer correlates signals from the two receiver sidebands essentially separately, but with the noise (and signal) of both input sidebands present. Therefore, even for continuum observations it is advantageous to reject the image sideband, i.e., it is the SSB system temperature that is relevant. Therefore, it is planned to use image separation receivers for the MMA[13]. Even for a system with 5 K spillover (achieved at BIMA and the MMA specification), an atmospheric opacity of 0.03 (achieved 25% of the time at the Chilean site in 1995 Summer), and a receiver DSB noise temperature of 22 K DSB ( $2h\nu/k$, the design specification of the MMA), the resulting SSB system temperatures are 61 K, and 73 K, respectively, for the image separation receiver and for a standard receiver with equal sideband gains. The advantage of image separation strongly increases with increased atmospheric opacity. Since the image rejection is motivated primarily to lower the noise, even 10 dB rejection is adequate. Simulations and first tests with a prototype system show that much higher rejection can be achieved over a large RF bandwidth using a fixed tuned design[13]. Note that the MMA receiver for each band has four output ports: two polarizations and two sidebands.

#### 4.1.3 SIS versus InP HEMT receivers

As shown in Figure 4 (from M. Pospieszalski (NRAO)), the sensitivity of receivers employing InP HEMT amplifiers for the first stage rivals that of SIS receivers at frequencies below 100 GHz. The amplifiers also offer very broad instantaneous bandwidth (10 – 30 GHz) and require only modest cooling. The current plan it to use HEMT receivers for the 26 – 55 GHz band, and also probably for the 60 – 90 GHz band. SIS receivers are expected to be used at all higher frequencies.

#### 4.1.4 SIS Receivers

All of the SIS receivers are to be tunerless (no mechanical tuning elements) for ease of use and high reliability. The noise specification has been set at $2h\nu/k$ at the center of the bands and less than $4h\nu/k$ at the band edges which typically are located at frequencies of high atmospheric opacity. To put these specifications in perspective, Figure 5 shows a plot of the SIS receiver noise temperatures compiled in 1995 September[14]. To reduce the required LO power requirements and also to reject excessive noise from the LO port, balanced SIS mixers are advantageous[13].

#### 4.1.5 Freguency bands

The 26 to 380 GHz band will be covered by two HEMT receivers to cover 26 - 40 GHz and 40 – 55 GHz. The 60(65) – 90 GHz band may covered by either a SIS or HEMT based receiver. The 90 – 380 GHz band will be covered with 4 to 6 SIS receivers. The quantity of state–of–the–art SIS receivers to be built is staggering: 7 bands $\times$ 2 polarizations $\times$ 40 telescopes = 560 SIS mixers. Clearly, they must be easy to manufacture and reliable.

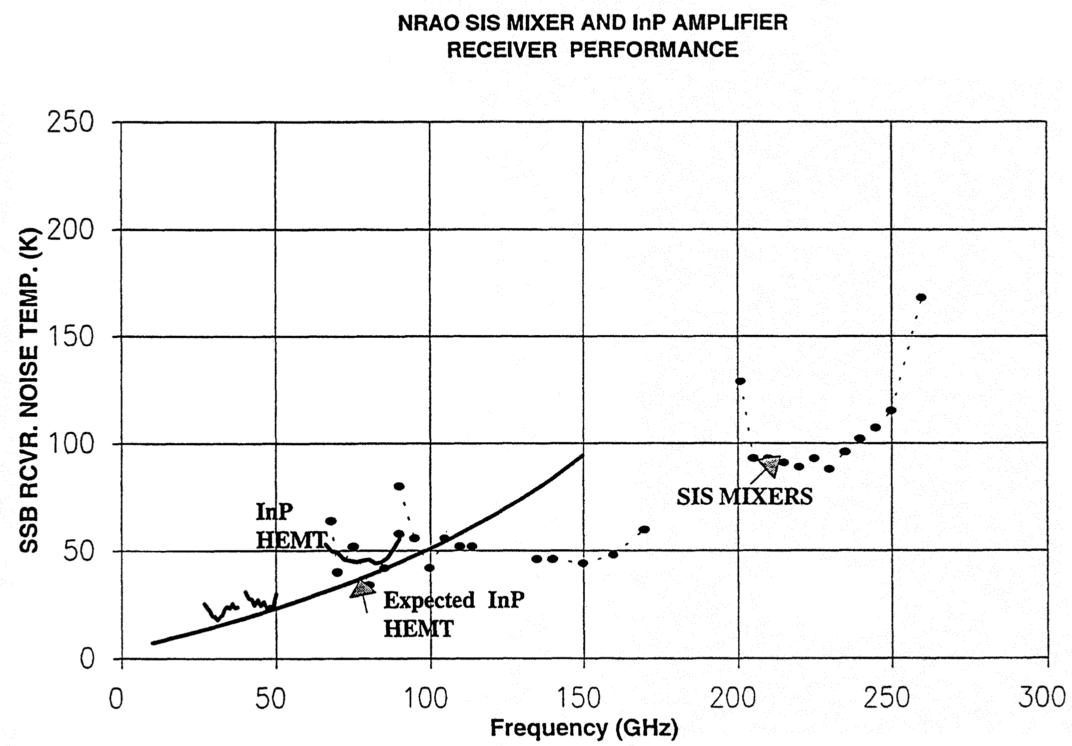


Figure 4.

4.1.6 Local Oscillators

The fast frequency switching requirement ($\leq$ 1 s) places severe constraints on the local oscillator system and it is best met by a completely electronically tuned system. Eventually this system should be capable of producing power from 26 to 1000 GHz in 25% wide bands and with complete phase modulation capabilites. The noise generated by the necessary power amplifiers and multipliers, especially those pumped at high input signal levels, needs to be determined. The use of balanced SIS mixers in the receivers would reduce the power requirements as well as the noise performance specifications of the LO system.

4.2 Telescopes

The telescopes are the most important investment of the MMA, accounting for $\sim$ 30% of the total cost. They will not be replaced during the lifetime of the array and therefore must be designed carefully. Also, with 40 elements being built, the total collecting area of the array is unlikely to be increased significantly after it is built and therefore the diameter of the telescopes should be chosen carefully.

At the present time it appears that 8 m diameter telescopes offers the best compromise between raw sensitivity (i.e., total collecting area), imaging quality (i.e., number of elements) and cost. The antenna working group found that it was just possible to meet the design specifications with an 8 m telescope.

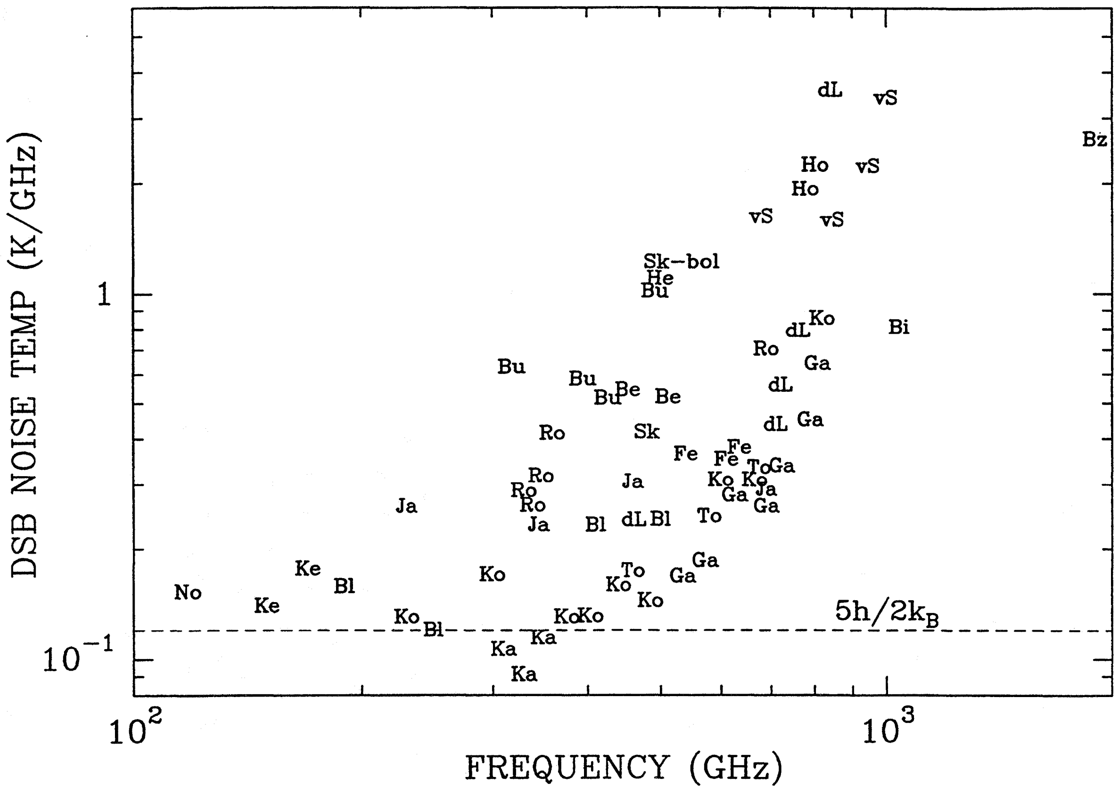


Figure 5. Compiled SSB noise temperatures for SIS receivers[14].

The surface accuracy specification of the telescopes is set by the need to make high dynamic range mosaiced images[11] at 870 μm (350 GHz). The resulting specification is 25 μm rms. Note this allows standard non–mosaicing imaging with high aperture efficiency to much higher frequencies.

The pointing accuracy of the telescopes is also determined by the mosaicing capabilities at 350 GHz. The specified accuracies are better than 1″ for 50% of the time and better than 3″ for 75% of the time. The different percentages include the statistics of the wind conditions. During the 1995 Winter the wind speed at the Chilean site exceeded 7 m/s more than 50% of the time.

The Antenna group also set a specification on the dynamic performance of the telescopes to allow fast phase calibration on point sources (usually Quasars). With the projected sensitivity of the MMA, there should always be a suitable phase calibration source within 1.5° of any direction on the sky. The goal of the Antenna group is a design that will acquire a 1.5° position change with less than a 3″ error within 1 s. So far this has not been possible. However, by using a smoothly varying acceleration function and friction drives on a stiff structure (resonant frequency of 10 to 12 Hz), they believe they can acquire the position change in 2 s.

The Antenna group has been considering two designs: a conventional on axis Cassegrain telescope similar to the design of the BIMA telescopes, and a novel slant axis design. Sketches of the two designs are shown in Figure 6. The slant axis design offers a lower moment of inertial and the lack of a counterweight makes it lighter. It was thought that it would be easier to meet the dynamical performance specification with the slant axis design. However, the large monopod to hold the secondary reflector lowers the resonance frequency of the structure.

Both designs utilize carbon fiber reinforced plastic (CFRP) tubes for the backing structure and feed legs. The primary reflectors will be made with CNC machined, stress relieved cast aluminum panels. Telescopes of either design are believed to cost about $ 1.5 M each.

The focal plane properties of the conventional Cassegrain telescope are much better than the asymmetric slant axis design. The current receiver design discussed above requires a large focal plane and therefore provides support for the conventional design. The slant axis design can be corrected by inserting two flat mirrors, but this leads to additional losses and noise. In fact, the Antenna group finds that the small gain advantage of the mostly clear aperture of the slant axis design is lost when two additional mirrors are added.

At this point the Antenna group feels that with either design could work, but favors the conventional design. They stress that no matter which design is selected, a prototype should be built soon and fully tested.

## 5 Summary

The MMA will be a fantastic instrument for Astrophysics and undoubtedly will lead to new discoveries. Building the MMA presents technical challenges in many fields of research. Specifically to the participants of this Symposium are challenges in local oscillator technologies and in low noise SIS receiver development.

These challenges are being faced now at the existing millimeter arrays and by the Smithonsian Submillimeter array, the SMA[15], which is being built near the summit of Mauna Kea. The U.S. university groups and NRAO are working together through the MDC to develop, design and test new techniques and instrumentation.

## 6 Acknowledgements

I am grateful to the acting MMA project director, R. L. Brown of NRAO who unfortunately was unable to attend the Symposium. He still provided many of the vu–graphs. I am grateful also to A. R. Kerr and M. Pospieszalski for their help in the preparation of this talk. The NRAO WWW site at http://www.nrao.edu was extremely helpful and I recommend it to anyone interested in the MMA or other NRAO projects.

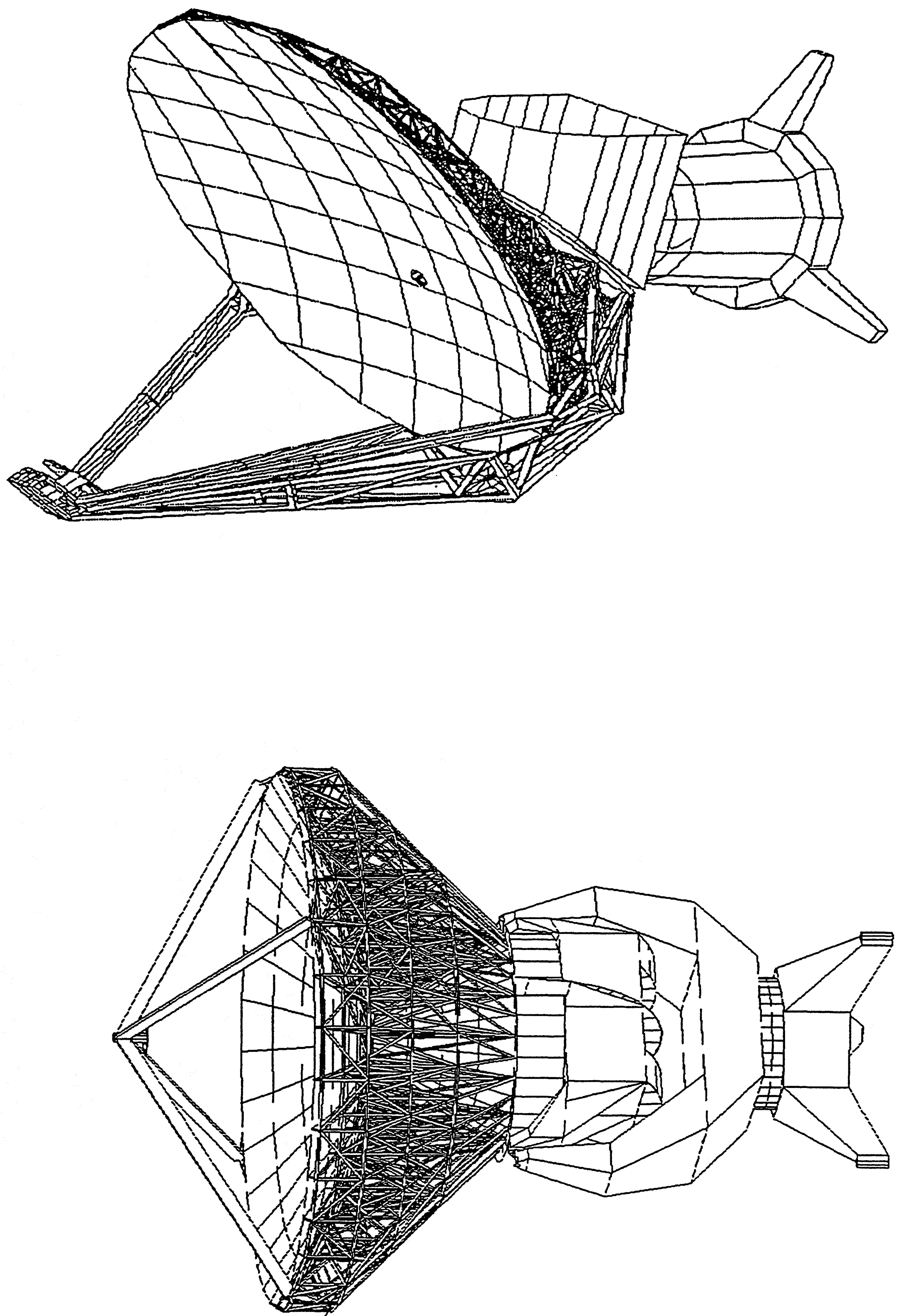

Figure 6.

Two candidate antenna designs for the MMA: (a) the conventional design. (b) the offset/slant-axis design.

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The Science and Technical Working Group reports listed in Tables 1 and 2 are available from NRAO and are also posted on the WWW.

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