THE MILLIMETER ARRAY

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ABSTRACT

A brief review of the purpose and design of the Millimeter Array is given. Particular attention is paid to the effects of the atmosphere, and to millimeter wavelength components which are the antennas, the low-noise input stages and the local oscillator system.

INTRODUCTION

The millimeter array (MMA) is a radio astronomy instrument planned for construction in the decade of the 1990's. It will consist of 40 antennas working in the range 30 to 350 GHz for imaging cosmic sources with an angular resolution as fine as 0.06 arcseconds. The antennas are to be movable between sets of foundations so as to provide four two-dimensional configurations in which the overall size of the array can be varied from 70 m to 3 km. The angular resolution can thereby be selected to match a wide range of astronomical requirements. The receiving system of the array and the mode of operation will be very similar to those of the centimeter-wavelength VLA located on the Plains of San Augustine, NM (Napier *et al.* 1983; Napier 1992). Cosmic signals are converted to intermediate frequency and transmitted to a control building over optical fiber cables. Local oscillator signals at the antennas are locked to a phase reference to preserve the coherence of the received signals at the IF. At the control building cross correlations are formed between all 780 possible pairings of antennas. The resulting data, referred to as complex visibility, are related to the two-dimensional brightness distribution (image) at the source by a Fourier transform (see, *e.g.*, Thompson *et al.* 1986). Microwave components in the array are the antennas, the low noise input stages, and the local oscillator system.

The MMA provides very similar angular resolution to the VLA, and like the VLA it is intended for the study of a wide range of objects from planets to distant galaxies. However, the one to two orders of magnitude shorter wavelengths of the MMA offer astronomers access to a very different series of scientific phenomena from those provided by the VLA. The millimeter wavelength radiation is largely excited by thermal processes, in contrast to the non-thermal radiation which dominates the lower frequencies observed by the VLA. Further, the spectrum at millimeter wavelengths is richer in molecular lines than it is in the centimeter wavelength range. The relative strengths of such lines provide information on the physical parameters as well as the chemical composition of cosmic material.

An important difference in the operation of millimeter and centimeter wavelength instruments results from the earth's atmosphere. In the millimeter region there are bands with high atmospheric attenuation due to water vapor and oxygen, with "windows" of relatively low attenuation in between, as shown in Fig. 1. The observing bands with which the MMA is concerned are as follows: 30-50 GHz, 68-115 GHz, 130-183 GHz, 195-314 GHz and 330-366 GHz. Even within the windows the

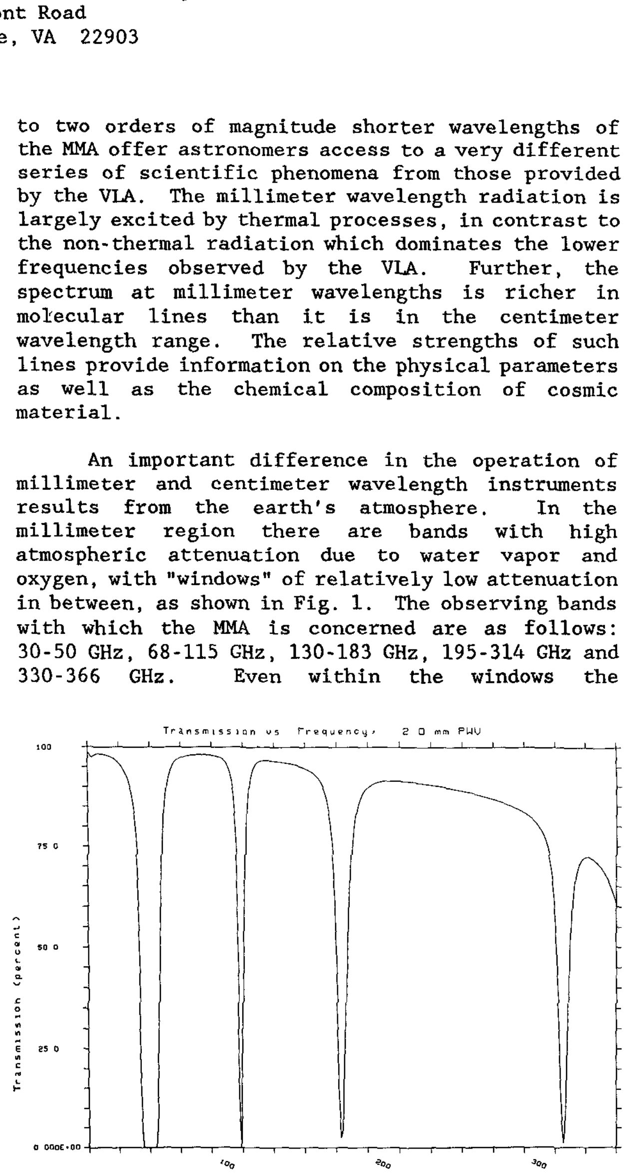

Fig. 1. Transmission of the atmosphere as a function of frequency modeled from radiosonde observations and the atmospheric propagation model of Liebe (1989). The data correspond to an elevation of 10,500 ft. with 2 mm of precipitable water. Curve from NRAO (1990), computed by F. R. Schwab.

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attenuation gives rise to atmospheric noise that can increase the system noise temperature, for example, by about 30 K at 250 GHz for observations near the zenith under good conditions. It is therefore important to choose a site at a high elevation with a minimum of water vapor in the atmosphere to minimize the atmospheric contribution. The conditions that have been specified in the search for a site are: elevation greater than 9,000 ft., precipitable water vapor no greater than 2 mm for large fractions of the time, and latitude south of 36°N (to allow good coverage of the southern celestial hemisphere). An array configuration in which the antennas are located at non-uniform intervals around the circumference of a circle has good imaging characteristics, so it is desirable that the site be large enough to accommodate a circle of 3 km radius. Three possible sites within New Mexico or Arizona have been identified.

The excess path length, *i.e.*, the amount by which the effective path length through the atmosphere exceeds the corresponding path length in free space, has components resulting from water vapor as well as dry atmospheric gases. For 2 mm of precipitable water, a small amount, the excess path in the zenith is approximately equal to 1.3 cm. At 9,000 ft. elevation, the component resulting from dry gases is approximately 1.5 m in the zenith direction. The wet component is variable with time, but the larger dry component is more stable. The overall effect is that the path length may fluctuate by more than a wavelength for any frequency within the MMA range. It is therefore generally not possible to calibrate the phase of the measured visibility. However, for groups of three or more antennas, the phase is constrained by closure relationships. For two antennas, denoted by subscripts 1 and 2, the measured visibility phase is given by

$$\phi_{12} = \Phi_{12} + \theta_{i1} - \theta_{i2} + \theta_{a1} - \theta_{a2}$$

where Φ_{12} is the true visibility phase for the spacing of antennas 1 and 2, ϕ_{12} is the corresponding measured visibility, the θ_i terms represent the instrumental phase of the receiving system for each antenna, and the θ_a terms represent the atmospheric phase for the wave path to each antenna. Then for three antennas the true and measured visibility phases are related by the closure expression

$$\Phi_{12} + \Phi_{23} + \Phi_{31} = \phi_{12} + \phi_{23} + \phi_{31}$$

which is free from the unknown atmospheric terms. Since the individual visibility phases are not known, it is not possible to obtain the radio image by a single Fourier transformation, and a commonly used approach is to start with a simple model of the source and bring the corresponding visibility phases into conformity with the observed closure relationships by an iterative process. This technique works best in arrays with fairly large numbers of antennas, like the 27-antenna VLA, on which it is routinely used.

Requirements for precision operation of the antennas place tight tolerances on the surface accuracy, pointing accuracy, and mechanical uniformity of the antennas. Surface irregularities result from a combination of:

(a) gravitational deformations of the backup structure,
(b) thermal deformations,
(c) surface panel irregularities,
(d) panel setting errors,
(e) surface errors in the Cassegrain subreflector and any later reflectors in the beam path.

In the antenna specification for the MMA, the root-sum-squared combination of the above errors must not exceed 1/40 of a wavelength at 300 GHz, *i.e.*, 25 μm. The resulting loss in aperture efficiency is 10% at 300 GHz and 17% at 400 GHz. The general design of the antennas will be aimed at simplicity and good mechanical reliability to keep the initial cost and subsequent maintenance within bounds. These considerations lead to a mechanically stiff design with surface panels that are not adjusted during operation. Computer control of the surface through the use of electrically adjustable panel mounts, or the more complex requirements for homologous deformation (in which the design is such that gravitational effects cause the dish to deform into another parabolic shape) are not appropriate for the MMA. For a stiff structure, the surface accuracy places an upper limit on the size of the antennas. With steel construction the deformations under gravity limit the accuracy to 25 μm for a diameter of approximately 8 meters. From considerations of sensitivity, the total geometrical collecting area required is 2000 m^2, *i.e.*, the equivalent of a single 50-meter antenna, so the number of 8-meter antennas required is 40. The cost of a large part of an antenna varies in proportion to the cube of the diameter, so a given total area is most economically achieved by using a large number of small antennas. Also, increasing the number of antennas increases the number of baselines on which the visibility data are sampled, which is beneficial in the derivation of detailed images. On the other hand, the cost of a large part of the receiving electronics is proportional to the number of antennas. Detailed cost analysis, and model calculations of source-imaging performance, confirm that 40 antennas of 8-m diameter is close to an optimum choice.

The choice of material for the major structural parts is between steel and carbon fiber reinforced plastic (CFRP). CFRP has advantages of lightness and lower thermal expansion than steel, but it is more expensive and requires more expensive techniques at joints. It is likely that the final design will incorporate some CFRP members, mainly in the reflector backup structure. Surface panels may be machined aluminum or CFRP constrained to shape by an aluminum honeycomb backing. The desired pointing accuracy of the antenna is 1/20 of the half-power beamwidth at 350 GHz, *i.e.*, 1 arcsec. This high precision is required because in the observation of wide sources it is necessary to be able to measure the radio brightness accurately at the edges of the beam where the response changes most rapidly with pointing angle. Achieving such accuracy, which is close to the current state-of-the-art, is one of the more challenging aspects of the antenna design.

The antennas must be movable so that the configuration of the array can be varied to suit the desired angular resolution and brightness sensitivity. The simplest solution is to maintain a smooth road surface connecting all foundations and to use a special transporter vehicle, running on rubber tires, that is capable of lifting and carrying an antenna. The weight of an antenna is small enough to handle without the use of rail, which would be an added expense. Shrouding of the backup structure of the main reflector may be necessary to prevent ice buildup in severe weather. This question can best be addressed when the final choice of site has been made.

The main reflector will be a paraboloid and the secondary reflector a hyperboloid, and no shaping to increase the gain will be applied. Shaping generally reduces the angular field of view, and this is undesirable because the use of array feeds is a likely development in the future. Incoming signals reflected from the subreflector are focused through a hole in the main reflector, and then guided by a series of plane mirrors down to the receiver room in the base of the antenna pedestal, as shown in Fig. 2. There they are directed to one

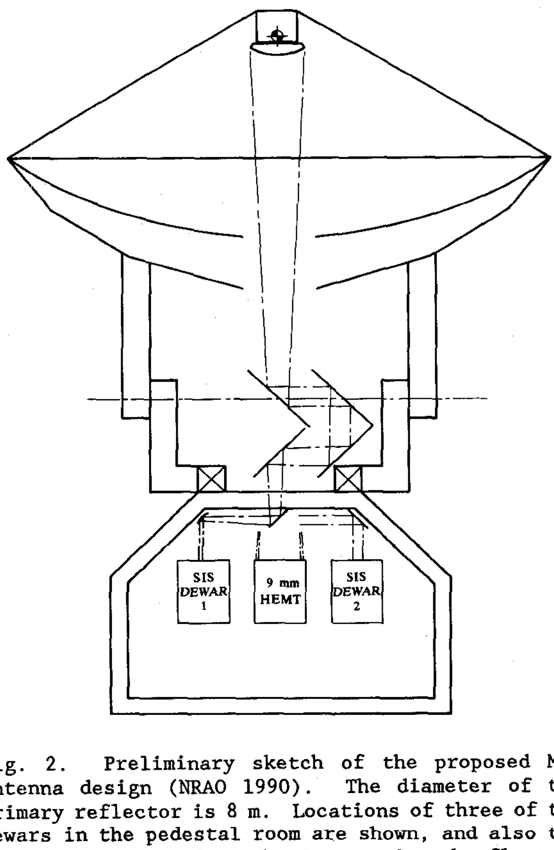

Fig. 2. Preliminary sketch of the proposed MMA antenna design (NRAO 1990). The diameter of the primary reflector is 8 m. Locations of three of the dewars in the pedestal room are shown, and also the paths of the rays from the Cassegrain subreflector. The mirror at the center of the room is rotated to direct the radiation into the desired receiver.

of several feed horns attached to low-noise receivers. Provision will be made for a minimum of five receivers to cover the 30-366 GHz range, and, in some cases, it will be possible to receive in two different bands simultaneously by means of frequency selective optics.

At the lowest frequency band, 30-50 GHz, the input stages will consist of HFET amplifiers cooled to 20 K. With current technology, a noise temperature of less than 30 K and a gain of greater than 30 dB can be obtained with a five-stage amplifier (Pospieszalski 1992). Signals from the feed horn will be split into opposite circularly polarized components by a septum polarizer and fed to separate amplifiers. In the higher frequency bands, SIS mixers followed by HFET amplifiers will be used, the mixers being cooled to 4 K. In this case, the input will be separated into two linearly polarized components by a Martin-Puplett interferometer, and these are directed to separate cooled feed horns within a dewar. Mixer designs for the MMA are under development at NRAO (Kerr and Pan 1990). A particularly promising approach uses a series of individually tuned junctions in a coplanar transmission line circuit on a suspended substrate. This design has been demonstrated in a unit that covers the full range 75-110 GHz without tuning adjustment and has a noise temperature in the 40-80 K range (Kerr and Pan 1990). Figure 3 shows the arrangement of the junctions and coplanar line. Figure 4 shows the best measured receiver temperatures achieved in the NRAO Central Development Laboratory.

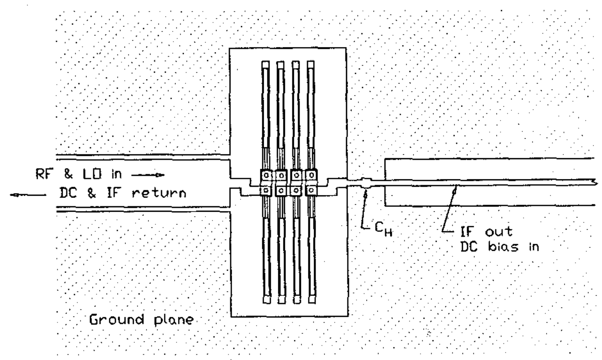

Fig. 3. Array of eight individually tuned SIS junctions used in a tunerless mixer covering 75-110 GHz. The junctions are fabricated in a coplanar transmission line, located on a quartz substrate 0.010" thick by 0.028" wide. The input at the left is coupled to WR-10 waveguide. The capacitor C_H tunes out the inductance of the hole in the ground plane in which the junctions are located. From Kerr and Pan (1990).

Martin-Puplett interferometers can also be used for local oscillator injection and to provide a degree of image rejection when required (see, *e.g.*, Payne 1989). The first IF band will be centered in the 1-4 GHz range with a bandwidth of 1 GHz. Experience in the field with the VLA and

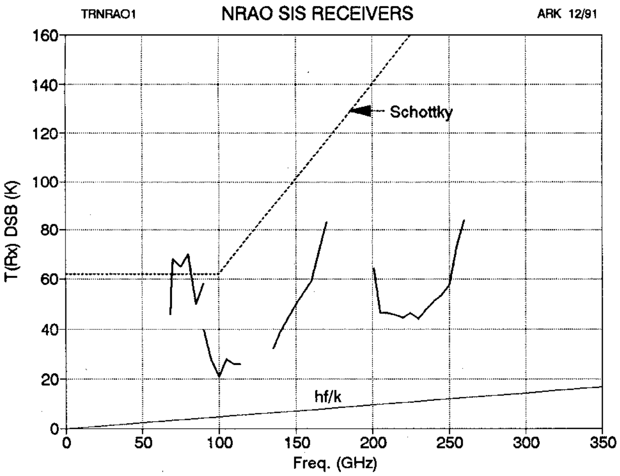

Fig. 4. Double-sideband noise temperatures for SIS-junction receivers developed at NRAO (Kerr and Pan 1990). Also shown, for reference, are the present performance for cooled Schottky mixers and the photon noise temperature hf/k.

VLBA (Kellermann and Thompson 1985) has demonstrated that for 20 K cryogenic systems the reliability is sufficient to allow satisfactory performance with the number of units required. With 4 K systems, experience at NRAO is based on many years of operation of single antennas, but has not involved the numbers of units required for the MMA. The location of the cryogenics and input stages at ground level in the antenna pedestal will greatly facilitate maintenance.

As currently conceived, the first local oscillator will be produced by a combination of Gunn or transistor oscillators and frequency multipliers. Some of the more promising millimeter wavelength devices now being developed, such as Resonant-Tunneling-Diode or Tunnel-Transit-Time oscillators, may also be used depending on the available performance when construction takes place. Providing for tunability of the oscillators over the wide range of observing frequencies will be one of the challenging aspects of the design. The oscillators will be phase locked to harmonics of a reference frequency of 1 or 2 GHz, and a lower frequency in the range of 200 to 500 MHz will also be used to provide a smaller tuning increment. These frequencies will be distributed to the antennas on a system of optical fiber cables which will run underground between the control building, where the frequency standards are located, and the antennas. Temperature coefficients of 1 part in 10^7 per °C are currently achievable in optical fibers, and the longest run to an antenna will be 4.7 km (a half circle of 3 km radius), for which the effect of temperature would be 0.5 mm per °C. The temperature of the buried portion of the fibers should be constant to less than 1°C for time intervals of hours, so phase variations due to the LO reference frequencies will be much smaller than those due to the atmosphere. The effects of temperature variations in the unburied portions of the cables, and flexing of the fibers as the antennas track, can be monitored by means of a round-trip phase measurement in which a part of the reference signal is reflected from the antenna back to the control building where its phase is compared with that of the outgoing signal. This measurement may not be needed for some observations, but will be important for diagnosis of problems and checking the performance of the array.

A proposal for construction of the Millimeter Array is under consideration by the National Science Foundation. When construction is started, it is likely to extend over a period of five to ten years, as has been the case for the VLA and VLBA. The Millimeter Array can clearly be built with existing microwave technology, and further developments which may occur before completion are likely to enhance the anticipated performance and reliability.

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