Submillimeter Array Technical Memorandum # 29

THE SMITHSONIAN ASTROPHYSICAL OBSERVATORY SUBMILLIMETERWAVE TELESCOPE ARRAY

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ABSTRACT

The Smithsonian Astrophysical Observatory is building a submillimeter-wavelength interferometer array. The project was initiated in 1983 and it is currently in a design study phase, with construction expected to start in 1991. The telescope will be located at a high mountain site and will operate in the major atmospheric windows from 200 to 900 GHz. The array will consist of 6 antennas, each of 6m in diameter. All antennas will be movable over a Y-shaped track, with maximum baselines of several hundred meters, giving sub-arcsecond resolution at all operating frequencies. The SMA will be able to operate simultaneously at 2 different frequencies, and will have a versatile digital spectrometer, permitting measurements of many different lines at once.

Keywords: submillimeter, interferometer, array, radio telescope

Table 1. Arav Characteristics

Number of antennas	6		
Diameter of antennas	6 m		
Antenna surface accuracy	15 μm rms		
Baseline Configuration	Y		
Maximum baseline	500 m		
Operating frequency	230 GHz	-	860 GHz
Maximum Resolution	0.4”	-	0.1”
Field of View	54”	-	15”
Number of simultaneous rx	2		
Bandwidth per receiver	2 GHz (700 km s^{-1} at 860 GHz)		
Correlator	XF Digital		
Channels per receiver	2048		

I. INTRODUCTION

The submillirneterwave interferometer array (SMA) project had its genesis in 1983 when a committee was set up at Smithsonian Astrophysical Observatory (SAO) to study the prospects for submillimeter interferometry. This committee produced a report (Moran et al. 1984), recommending that SAO proceed with plans to build a 6 element interferometer operating at submillimeter wavelengths. In 1986, the project was started when funding was secured to establish a receiver laboratory at SAO. In 1988, the two-year design study was initiated. Since then, the various aspects of the design have been studied, with the intention of commencing construction in 1991. If construction is funded as planned, first light will occur in 1996. The estimated cost of the project is $ 35 million, depending slightly on the choice of site.

At the time of writing, the design study is in its second year and a group of staff has been recruited to carry out the initial work. Not all fiial design choices have been made, but the basic design is similar to the concept described in the 1984 report. This report describes the current status of the array plans. Table 1 gives a brief overview of the characteristics of the planned array. It is planned that the array should be expandable, so many of the characteristics, such as i.f. bandwidth and number of simultaneous receivers may be increased later.

2. SCIENTIFIC GOALS

The scientific goals of the array include many aspects of star formation in our own and other galaxies, as well as topics in other fields of astronomy.

Operation of an imaging array at submillimeter wavelengths brings several advantages. First, the black-body spectrum peaks in the submillimeter region for objects with temperatures of a few tens of Kelvin. Second, at these wavelengths, thermal dust emission is almost always optically thin, rendering it an excellent tool for tracing column density in dense regions. However, the opacity of dust increases as ν^{1-2}, making submillimeter observations much more sensitive than those at longer wavelengths. Third, there are many important spectral lines from molecular and atomic species in the submillimeter region, including the important fine structure lines of atomic carbon, and high-J transitions of common light molecules.

The high angular resolution of an array is important for observations at submillimeter wavelengths. In general, the array will be most sensitive to emission from warm, dense material in molecular clouds. Such emission is usually found in relatively compact regions, either in the immediate vicinity of newly formed stars in our own galaxy, or in the bright star-forming regions of external galaxies. In such cases, high resolution (-1”) is crucial to understanding the structures and physical and chemical processes involved.

Some of the most important goals of the array include:

a) Molecular Clouds and Star Formation. The high resolution of the array will permit imaging of bound gravitational motions around young stars, perhaps permitting the detection of the elusive infalling material. The array will also be able to map the vitally important disks which are believed to control the final stages of accretion onto nascent stars, and which provide the raw material from which planets can be made. These disks are believed to have sizes on the order of 100 AU, which is less than 1", even in the nearest regions of star formation.

The study of atomic carbon is likely to be important for understanding chemical processes in molecular clouds, as well as for analyzing the physical conditions in the atomic boundary regions between molecular and ionized gas.

b) Structure of Normal Galaxies. The continuum emission, which will be imaged with excellent sensitivity and angular resolution, will provide a measure of the position and luminosity of the youngest stars which are invisible at most other wavelengths, due to their surrounding molecular clouds. The complementary information provided by the CO emission which traces the location of the clouds themselves, and the CI, which should be produced when the clouds are dissociated by ultraviolet radiation from massive new stars, will significantly improve our knowledge of the spiral structure of galaxies and the relation between spiral arms and star formation.

c) Quasars and Active Galactic Nuclei. Many quasars and active galaxies have strong far-infrared emission which may be due to dust or to synchrotron emission in their compact nuclei. There is also strong evidence for links between galaxy mergers, the starburst phenomenon, and active galactic nuclei. The SMA will have a unique ability to image galaxies in the submillimeter continuum, permitting direct tests of the emission mechanism and tracing of the connections between starbursts and active nuclei.

The predicted sensitivity of the SMA, both with current and possible future receivers is shown in Table 2. It can be seen that even with current receivers, rather high resolution will be possible for spectral line sources with brightness temperatures of a few tens of Kelvin. The continuum sensitivity will permit very high quality measurements of many sources, and also the measurement of polarization in stronger objects, giving unique information on the magnetic field structure.

3. STRUCTURE AND SITING OF THE ARRAY

The array will consist of at least 6 antennas of 6 m diameter. The choice of diameter is set by the smallest size consistent with the large and expensive receiver package required at submillimeter wavelengths and by the sensitivity required on each baseline for phase calibration. With 6 antennas, 15 baselines are available simultaneously, permitting reasonable maps to be made in a single transit of a source. This is an important consideration when the atmospheric transmission can fluctuate rapidly. The range of baselines available with a single configuration of 6 antennas is roughly a factor of 10. To cover baselines ranging from 6m to 500 m, all of the antennas must be movable.

Table 2: Predicted Sensitivity of the SMA

ν (GHz)	T_r (K)	T_s [1] (K)	$5\sigma T_B$ [2] (K)	$5\sigma_S$ [3] (mJy)
345	400 [4]	740	6	13
345	165 [5]	370	3	7
860	6000 [4]	79000	57	1400
860	620 [5]	1100	8	200

[1] Effective system temperature at 60” elevation, assuming a zenith transmission of 0.82 at 345 GHz and 0.25 at 860 GHz, 5% spillover loss, digital processing loss factor of 1.2, and antenna coupling efficiencies of 1.0 at 345 GHz and 0.5 at 860 GHz.
[2] Minimum detectable Rayleigh-Jeans brightness temperature (5 x rms noise level) for angular resolution = 1", velocity resolution = 1 km s^{-1}, integration time = 10^5 s.
[3] Minimum detectable flux density (5 x rms noise level) for bandwidth = 1 GHz and integration time = 10^5 s.
[4] Single-sideband receiver temperature with currently available technology.
[5] Receiver temperature = $10h\nu/k$, ten times the quantum limit at 345 GHz, and 15 $h\nu/k$ at 860 GHz.

The basic shape of the array will be a Y, which provides a good range of baselines. For the smallest configurations, however, the *uv* plane sampling of a Y may not be complete enough and some additional stations may be added near the center of the array.

The choice of site for the array is dominated by the need to minimize atmospheric water vapor, which is highly opaque at submillimeter wavelengths, with optical depth at the shortest wavelengths greater than 1 for a column of 1 mm of precipitable water vapor. Two high mountain sites are therefore being considered, Mauna Kea in Hawaii, and Mount Graham in Arizona. A considerable amount of water vapor data exist for Mount Graham, collected by the University of Arizona. Although there have been several studies of Mauna Kea in the past, SAO has joined with NRAO to install a 225 GHz water vapor radiometer there for a longer test. This radiometer has been operating since the summer of 1989 and will continue into 1991.

A second site characteristic, which has not been measured extensively thus far on either site, is the quality of the radio seeing. It is known that the phase stability of the atmosphere at radio wavelengths is dominated by fluctuations in water vapor content, and these fluctuations are believed to have a turbulent character, with larger amplitudes at larger baselines. Existing data on this characteristic are limited to sites with existing interferometers, which are generally flat plains, rather than mountain peaks.

To characterize the radio seeing, both for the purpose of site comparison and for design of the optimum array, SAO has constructed a radio-seeing monitor. The device is a small interferometer, with a baseline of 100 m. which measures a beacon tone from a geostationary satellite, at a frequency of 11.7 GHz. Although the frequency is much lower than that of the SMA, the atmosphere is nearly non-dispersive in the radio regime, and the measurements can easily be extrapolated. The seeing monitor has been completed and is expected to reach the required sensitivity of 30 µm in 1 second of integration. It will be installed at Mauna Kea in the late summer of 1990. An identical system is being built for Mount Graham.

The decision about the choice of site will be made in early 1991. It will be based on the available opacity and phase data from these two sites, along with other information about the weather, costs, and environment.

Whichever site is chosen, the operation of an interferometer at a remote mountain location will pose a number of difficulties beyond those usually faced by radio interferometers. For example, it will not be possible to make the array level at the longest baselines, which will necessitate more complex compensation for atmospheric path errors, and moving of the antennas will be complicated by the gradients involved.

There will be a control and workshop building at the mountain-top site of the array, but it is envisaged that remote control will be the normal mode of operation, with the operation of the array controlled from a low-elevation site and ultimately from Cambridge. To make best use of the weather conditions, the scheduling of the interferometer will be adjusted during observations, according to the prevailing amount of water vapor.

4. HARDWARE

4.1 Antennas

The antennas represent the largest single cost of the project. Developments for IRAM and the SMT antennas have shown that sufficiently accurate (15 μm surface) antennas can be made from c.f.r.p., but the use of metal has not yet been ruled out for our rather small antennas. The primary beamwidth is small and pointing is a challenge at the highest frequencies. Studies of a number of approaches, including radome-enclosed antennas, are being carried out in conjunction with several different companies, to explore the advantages and limitations of different technologies in electromagnetic performance and in physical robustness. The initial results have shown that there is little difficulty in dealing with gravitational forces by homology, but that thermal gradients and wind loads will be critical factors. These studies will be completed by the first quarter of 1991, when a formal request for quotations will be issued for the final design and the construction of the first antennas.

The antennas will be transportable, probably by a wheeled or tracked vehicle rather than rail, in view of the steep gradients on the mountain sites.

4.2 Receivers

The largest technical challenge is presented by the receivers. In the upper octave (>500 GHz), suitable receivers have not yet been built, but up to 500 GHz, current technology or extrapolations from it can provide adequate receivers. At these lower frequencies, SIS receivers in conjunction with multiplied Gunn local oscillators give the best performance. At higher frequencies, the receivers in current use for astronomy employ Schottky diode mixers and laser local oscillators, which would not be very suitable for an interferometric array. Superconducting mixers are therefore intended for all frequencies of the array. It is expected that future development of local oscillator and superconducting mixer technology will extend the range of these receivers to cover the needs of the SMA at all frequencies.

A receiver laboratory was the first part of the SAO submillimeter effort. It was established in 1987 and is working on the development of superconducting receivers and local oscillators. A waveguide receiver has been constructed for 230 GHz and experiments are being carried out with quasi-optic receivers and with various concepts for high-frequency receivers. Work is also proceeding on the fabrication of Niobium junctions using the facilities of the Harvard physics department.

The receivers in the array will be cooled by refrigerators to 4 K. Several receivers will be mounted on each antenna at any one time, with facilities for quick changes among them to make best use of good weather. Two receivers will be operable simultaneously, usually at different frequencies to facilitate phase calibration and to maximize the speed of the array. Dual receiver polarizations will be available at at least one frequency initially to permit polarimetry. It is planned that this frequency will be 345 GHz, where the array should have its best sensitivity to optically thin dust emission.

4.3 Correlator

The correlator will use conventional digital technology. There will be no separate analog continuum cot-relator, because an analog correlator would require the construction of analog delay lines and would itself be a significant development task for the required bandwidth. However, a bandwidth of 4 GHz (2 GHz per receiver) will be available from the digital correlator at all times, even when observing in high-resolution line mode. The XF technique has been chosen over the FX, because it is more economical for the number of antennas and bandwidths involved in the SMA and because it offers greater flexibility in the placement of channels across the observing band.

A study of the correlator design has been carried out by Haystack Observatory (Levine and Rogers 1989). The study concluded that was that the NFRA chip was currently the most economical device, but that the final decision should wait for 2 years to make best use of new developments. The correlator which was devised in the Haystack study breaks the 4 GHz band up into 32 MHz segments, each of which is digitized and then demultiplexed by a factor of 2 for processing by the NFRA chips. Enough chips are provided for 15 baselines and 4096 complex channels. This is sufficient for a 2 GHz full-polarization (4-quadrant) continuum correlator. In non-polarization mode, 2048 channels cover the 4 GHz band at low resolution (2 MHz) and a further 2048 channels are available for distribution across parts of the band to increase the spectral resolution. At all times, therefore, the full band will be covered at 2 MHz resolution, permitting accurate continuum measurements even when there are strong lines in the band.

4.4 L.O. and I.F. transmission

The distribution of stable local oscillator signals is again harder than in existing interferometers, because of the high frequency of operation, but there are no fundamental obstacles. The use of optical fibers for this task will be explored, since they will probably be used in any case for the I.F. Transmission of wideband I.F. signals (> 1 GHz) is difficult in cable because the losses are large and significant equalization is required across the band. Fiber-optic links are available which will transmit bands of more than 10 GHz; these will give flexibility in choice of I.F. center frequency and will allow room for future expansion of the I.F. bandwidth.

4.5 Computing

The real-time computing for the array will be handled in the conventional manner by a network of micro computers. It is planned that data calibration and preliminary imaging will be performed nearly in *real* time for monitoring the progress of the observations. The off line demand for calibration, imaging and analysis will be handled by a mini-supercomputer. The exact specification and purchase of this will, of course, be left until the latest possible moment. to take full advantage of the rapidly developing technology.

5. CALIBRATION AND DATA REDUCTION

Amplitude calibration of the array will be carried out by conventional 'chopper-cal' methods. Phase calibration presents more of a problem, particularly at the highest frequencies, where the system sensitivity will be fairly low. Most of the quasars and AGN's conventionally used for radio calibration have spectra which decrease in strength at higher frequencies, compounding the problem. For short baselines it may be possible to use thermal sources such as evolved stars as calibrators, but at the longest baselines, such objects do not have sufficient brightness temperature.

It is planned, therefore, that during high-frequency operation, simultaneous observations will be made at lower frequencies (< 345 GHz) for the purpose of phase calibration. The electronics will be designed so that the phase of the high frequency receiver will track that of the low frequency one closely. Then it will be possible to use the low frequency phase calibration to correct the drifts at the high frequency, since most sources of phase drift are simply delays and therefore have phase proportional to frequency. Even the atmosphere is nearly non-dispersive in the partially transparent windows.

Self-calibration will be possible for the strongest sources, but it may be more dificult than at centimeter wavelengths because the timescales for phase variations are much shorter on the shorter baselines employed at submillimeter wavelengths, and because there are fewer sources with bright compact components to facilitate calibration. Self-calibration is, of course, possible on extended sources, but it is generally less effective.

The restricted field of view may be a significant limitation for some sources, particularly at the highest frequencies. Extensive use of mosaicing will probably be necessary. It is intended that the individual antennas will be equipped for operation in single-dish mode to collect the information on large scale structures which is needed to supplement the interferometric data.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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