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THE SMITHSONIAN SUBMILLIMETER ARRAY

P. T. P. HO
Harvard-Smithsonian Center for Astrophysics

SUMMARY

The Smithsonian Astrophysical Observatory is currently designing and constructing the Submillimeter Array (SMA). This instrument will consist of six 6-m telescopes, which can be moved and reconfigured in four concentric ring-like arrangements with maximum baselines of 500 m. Pending negotiations, the SMA will be sited on Mauna Kea at the 4000 m plateau, adjacent to the existing CSO and JCMT submillimeter telescopes. The goal of the SMA is to provide imaging at sub-arcsecond resolution for the wavelength range of 1.3 mm to 0.35 mm. This instrument will therefore improve the angular resolution achieved with present submillimeter telescopes by more than an order of magnitude. As the cool (10–100 K) dust and gas in the Milky Way and other external systems will radiate principally in the submillimeter wavelengths, we expect the SMA to provide unprecedented resolution and to make fundamental contributions to many different problems including the studies of our solar system, star formation and circumstellar disks, galaxies and molecular cloud structures, quasars and active galactic nuclei, and perhaps even galaxy formation in the early universe.

THE DESIGN OF THE SMA As is illustrated in Figure 1, the SMA is designed to operate in an unique area of the wavelength-resolution plane. Its purpose is to extend the capabilities of the current generation of millimeter wavelength interferometers into the submillimeter band. The SMA project began with the 1984 conceptual proposal to the Smithsonian Institute by Moran, Elvis, Fazio, Ho, Myers, Reid and Willner. After receiving favorable reviews, the project received initial funding in 1987 to construct a submillimeter receiver laboratory. A two-year design study was funded in 1989, and the start of construction was funded in 1991. The design of the SMA is driven by a number of considerations: *Sensitivity.* The minimum sensitivity requirement is set by demanding that the collecting area should equal at least the largest existing single element submillimeter wavelength telescope. This gives the SMA the intrinisic sensitivity to study any phenomenon which has been detected or studied so far in the submillimeter wavelengths. This imposes a lower limit to the equivalent physical collecting area of about 200 m^2. *Speed.* Because the SMA will operate in adverse atmospheric conditions where the best transmission and best phase stabilities will be achieved only 15% of the time, this array must sample enough (u,v) spacings in an 8-hour track to make a reasonable map without requiring reconfiguration. This means at least 6 telescopes which is distributed

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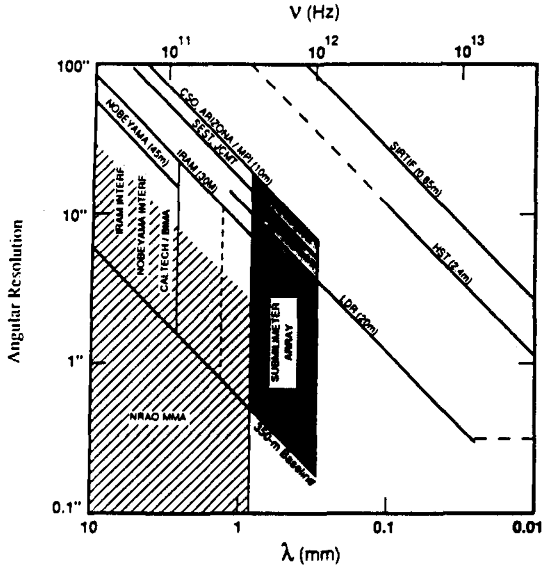

Fig. 1. The wavelength-resolution plane as populated by existing and planned instruments. The single-dish telescopes such as Swedish-ESO Submillimter Telescope, Caltech Submillimeter Observatory, James Clerk Maxwell Telescope, IRAM 30-m, and Nobeyama 45-m are all operational in the domain above their plotted lines. The Arizona/MPI Submillimeter Telescope is under construction. The Caltech, Berkeley-Illinois-Maryland Array, IRAM, and Nobeyama arrays are all in the process of expansion by adding further elements. The planned Japanese Large Millimeter Array and the Southern Hemisphere Millimeter Array would occupy the same domain as the proposed NRAO Millimeter array. Shortward of 350 μm, only spaceborne platforms are being planned, of which only the Hubble Space Telescope has been launched so far.

in an optimum configuration. *Calibration.* Since calibration at submillimeter wavelengths will be difficult at best, individual elements of the array should be large enough to have the sensitivity to calibrate individual baselines. Driving against this requirement is the recognition that the primary beam at 350 μm will be small for a large aperture which will exacerbate short-spacing problems for extended sources. A good compromise is 6 m for the aperture. This immediately yields a total collecting area of 170 m^2. *Angular Resolution.* To improve on existing angular resolution by at least an order of magnitude, we aim for an ultimate resolution of 0.1 arcsecond (10 AU at 100 pc, 1.5 pc at 3 Mpc). This implies a maximum baseline of 500 m. Atmospheric effects will of course limit the achievable angular resolution. At 0.1″ level, self-calibation techniques or other measures will be necessary.

<u>THE SPECIFICATIONS OF THE SMA</u> The 6-m telescopes will be constructed in-house by the SAO. Initial assembly and testing will be done at Haystack Observatory before shipment to the site. These telescopes will have a surface accuracy of 15μm, pointing accuracy of 3″, bent-Nasmyth optics, steel pedestal, carbon fiber backup structure, machined aluminum panels, a chopping secondary, a relatively large receiver cabin between the elevation bearings, and a linear actuator for the elevation drive. The telecopes will be moved with a rubber-tired vehicle on serviceable roads. This antenna transporter is being designed in-house to be able to lift 30 tons with three chain/lift hooks which are driven with hydraulics. It will be able to travel over unimproved roads with less than 15% grade. Multiple receivers will be accomodated in a single dewar with closed-cycle cryogenics. The receivers will use SIS technology and solid-state LO sources. Initially, a 230-GHz receiver will always be online simultaneously with a higher frequency receiver. This allows calibration at the higher frequency to be scaled from the observations at 230 GHz. Fiber optics will be used for the IF transmission. The correlator has been chosen to be of the XF design with modular units which can be swapped for optimizing bandwidth versus resolution and which can also be positioned to process several lines at once. Although the final architecture depends on the choice of correlator chip, we intend to process 4 IF chunks per antenna with 1 GHz maximum bandwidth per IF.

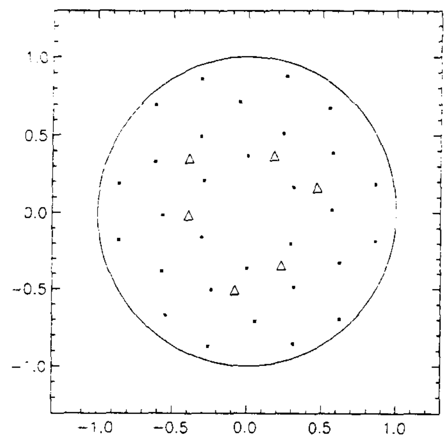

Fig. 2. Proposed configuration for a six-element array. The triangles plotted are the position of the antennas in relative coordinates. The dots plotted represent the coverage in the (u,v) plane again in relative coordinates.

<u>CONFIGURATION OF THE ARRAY</u> The configuration of the array was optimized for the most uniform coverage in the (u,v) plane. Numerous configurations have been proposed previously, including the VLA Y-design (Chow 1972) and the MMA circle-design (Cornwell 1988). The SMA design used a neural net algorithm designed by Eric Keto. In this algorithm, the nodes of the net represent the points in the (u,v) plane sampled by the proposed array.

The object of the algorithm is to stretch the net to achieve the desired topology of a uniformly covered circle in the (u,v) plane. For six antennas, the optimum configuration turns out to be approximately two sets of triangles rotated. This is shown in Figure 2. The triangular configuration can be understood intuitively as the optimum way to separate three antennas with the least redundancy in projected baselines. In order to sample a large range of baselines, there will be four concentric configurations scaled from the basic six-antenna pattern shown in Figure 2. The underlying philosophy is that each configuration will be optimized on its own.

THE OPERATIONS OF THE SMA While first light with the SMA is still some 4 years away, the actual operation of the array has been considered in terms of the impact on the design of the instrument. It is envisioned that operations will be fully automated with data links to a sea-level basecamp and also back to Cambridge, MA. Changing receiver bands and retuning of the electronics will be computer driven. The control of the telescope as well as diagnostics can be performed from a remote terminal off site. This ensures that regardless of the actual personnel on site, off-site engineers and staff can check, verify, and alter the performance of various parts of the array in real time. The actual operations of the array will be via a programmed script, which will knit together various experiments. However because of the variability of the weather and the need to take advantage of all possible periods of outstanding weather, the day-to-day scheduling of the array may be quite dynamic. Data calibration and analysis will be possible in real time using computers at the site and at Cambridge. Guest observers will be able to log in from their home institutions to monitor the progress of their experiments as well as to do some diagnostic analysis.

CURRENT ACTIVITIES: ANTENNA DESIGN At the moment, the main efforts are being focused on the construction of the telescopes. Figure 3 shows the present design for the antenna. For financial reasons, the SAO will be the prime contractor for the telescope construction. After detailed designs are made, outside subcontractors will build the parts and components. SAO engineers will then do the actual assembly at a site being prepared at the Haystack Observatory in Westford, MA. Currently, work is proceeding on the chopping secondary within SAO Central Engineering, while design work is being completed on the transporter for the telescopes, the steel mount, the carbon fiber backup structure, and the reflector panels to be made out of machined aluminum. One of the main concern is the thermal performance in an open-air environment. The backup structure will therefore be covered, with forced air circulation to stabilize the temperature of the reflector. Similarly, the pedestal and the receiver cabin will also be insulated from the ambient environment in order to stabilize their temperatures. The backup structure will be made with carbon fiber reinforced plastic (CFRP) struts because of superior thermal performance and superior strength to weight ratio. The CFRP struts will be connected via steel nodes and a central steel hub. CFRP would have been the choice for panel material as well except for survival considerations in an open-air environment. Under severe weather conditions, where ice, sand, or vulcanic cinder material could be blown against the panels, CFRP would be subjected

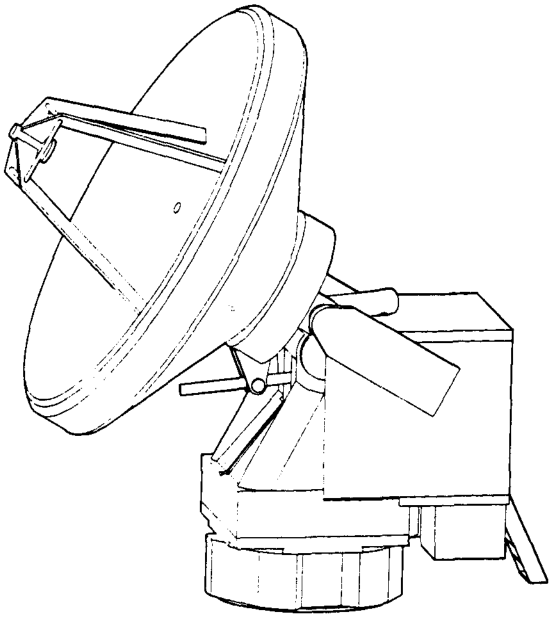

Fig. 3. A drawing of the SMA telescope as it is envisioned. Various parts of the telescope such as the steelwork for the mount, the carbon-fiber backup structures, the panels, will be constructed as separate contracts. SAO will do the final assembly at a facility being built at Haystack Observatory in Massachusetts.

to microscopic or larger punctures leading to subsequent delamination. The conservative choice of machined aluminum is made for the panels, with the panel sizes small in order to minimize temperature gradients across individual panels. A second major concern is the phase stability of the antenna structure. The resulting stiffness requirement on the telescope mount is achieved by having a relatively heavy structure.

<u>CURRENT ACTIVITIES: RECEIVERS</u> Also underway is the construction of the receivers. A working 230 GHz SIS receiver was built and installed at the SEST telescope this past winter. Work is underway on receivers at the 460 GHz and 350 GHz bands. A suite of eight receivers will be installed ultimately within a single cryogenic dewar at each telescope. Figure 4 shows a possible arrangement. Two receivers can be used at any one time via a wire grid polarizer and a rotating mirror. Even more receivers can be used simultaneously by adding a dichroic system. The individual receivers will be complete systems which can be pulled out and plugged in with ease in the event of failures. It is anticipated that at the lower frequencies, waveguide mixers will be used. At higher frequencies, an open structure mixer may well be required, although the design is still too early to finalize. The mixers will use SIS junctions. The current junction material that is being developed is Nb/Al-Oxide/Nb, although

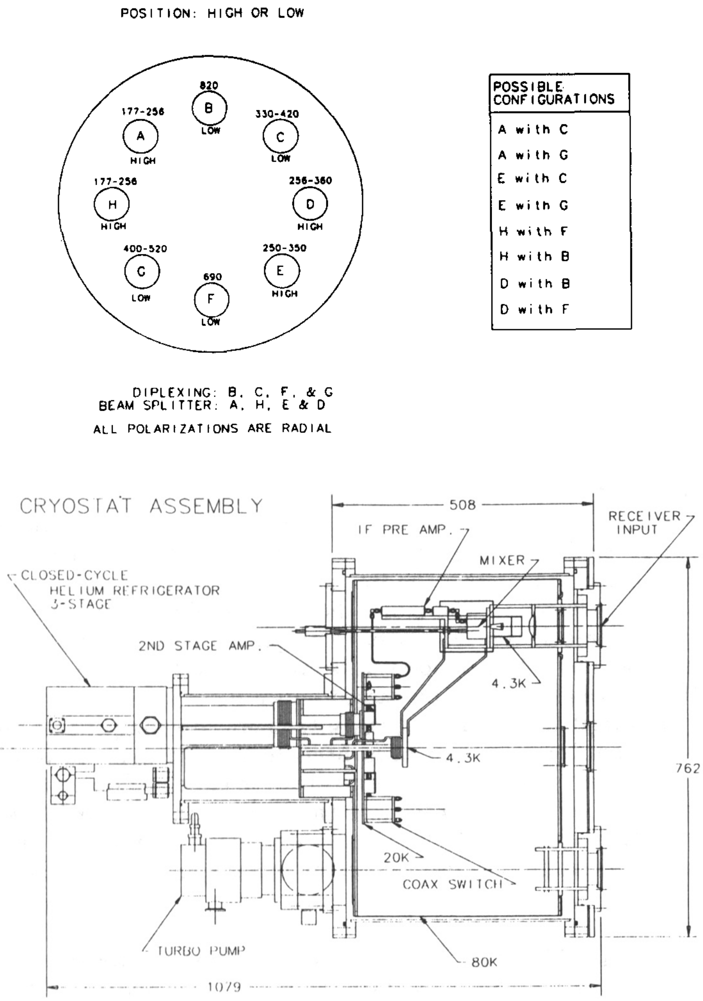

Fig. 4. A schematic of the possible arrangements of receivers inside a single dewar. With the bent-Nasmyth optics, the dewar will be stationary while the telescope is pointed. A wire grid polarizer and a rotating mirror will be used to select two receivers simultaneously.

the SEST receiver at 230 GHz made use of a PbInAu junction provided by Ron Miller at Bell Labs. There is an in-house effort to develop junction devices within the Havard Division of Applied Sciences. An effort is also underway to enter into collaborative efforts with outside junction groups. The mixer blocks themselves as well as other components such as lenses and mandrils are now being made within our own machine shops by a dedicated machinist. This has greatly improved the turn-around time and the control over design. In the area of local oscillators, the intention is to use diode multipliers with Gunn oscillators at 60–115 GHz. Commercial sources appear to be available and the required

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power levels for the SIS junctions seem to be achievable. Alternative LO sources may be considered if they become feasible downstream.

CURRENT ACTIVITIES: CORRELATOR The SAO is collaborating with the Haystack Observatory to develop the SMA correlator system. As has been shown by d'Addario (1989), for an array which has a small number of antennas and which is intended to process large bandwidths, the XF style correlator is to be preferred. The data are first cross correlated and then Fourier transformed. To increase flexibility, the current design also calls for the input signals to be first divided into smaller chunks before they are correlated. This hybrid design allows the individual chunks to be placed independently across the band with different spectral resolution in each chunk. This is particularly useful for simultaneously studying a large number of spectral lines. Of course, the final design of the correlator depends on the choice of the correlator chip. SAO is currently collaborating with Haystack and NASA in designing a new chip.

CURRENT ACTIVITIES: ELECTRONICS The principle tasks here are to synthesize the LO reference signals, distribute them to the various receivers, process the IF signals and return them to the correlators. The LO reference signals will be used to control the frequency and phase of the Gunn diode LO sources at each telescope. The Gunn diode LO's which operate at around 100 GHz, will be phase locked and then multiplied up to sky frequencies. It is anticipated that the LO reference will be at 4 to 8 GHz, while the IF will be at 1 to 2 GHz. These signals will be passed between the telescopes and the control building via optical fibers. Good quality temperature-compensated-delay fibers are available commercially and have been tested. It may be possible to use buried fiber cables without active time-delay compensations. Current efforts are in stabilizing the temperatures of the laser diode transmitters as well as the photodiode receivers. Efforts are also underway to design both the control software and the control electronics for the telescope.

CURRENT ACTIVITIES: SCIENCE As is amply demonstrated by this conference, this past decade has seen the completion and full-time operation of four millimeter-wave interferometers (BIMA, OVRO, NMA, and IRAM), and a number of submillimeter observatories. The exciting results which have come out of these instruments serve as the scientific drivers for the SMA. The various results reported at this conference on protostars, outflows and jets, circumstellar envelopes, galactic nuclei, high-redshift objects, and many other systems, look to be promising targets for the SMA. Calculations show that nearly every hot molecular cloud core, giant molecular cloud, and molecular outflow can be mapped in the Galaxy with the SMA. Extragalactic nuclei can be mapped out to distances of 40 Mpc, while protostellar disks can be imaged within 100 pc. Figure 5 shows the kind of studies which can be done for a cloud core at 1″ resolution. Although predicting the interesting science on the SMA so far ahead is adventuresome at best, one might just suggest some possibilities. At 350 GHz, the most interesting study may be dust continuum emission. Calculations show that this band may be the most sensitive one for continuum given current

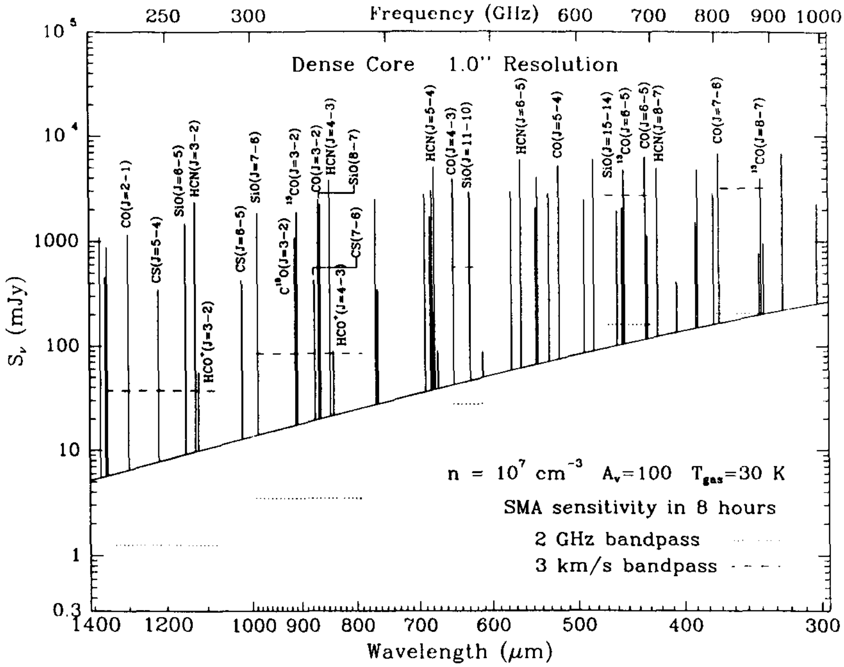

Fig. 5. Calculated line and continuum intensity for a dense cloud core. Both the continuum and line sensitivity of the SMA are plotted for the various wavelength bands. At 1″ resolution, there is enough sensitivity to image a variety of lines.

projections on receiver performances. At the 460 GHz band, the most important study may be the CI line at 490 GHz. At 690 GHz, perhaps the J=6–5 line of CO may be most interesting since it is substantially above the ground state and the Einstein coefficient is also high enough that this line may probe much hotter and denser regions as compared to the J=1–0 line. At the 870 GHz band, the most interesting lines could be the higher transition of CI, and the CII line at 158 μm redshifted into the submillimeter band. This CII line, a dominant coolant, radiates on the order of 0.5% of the luminosity of the entire galaxy. It may therefore be a very interesting probe of protogalaxies at z=1–2. Many more interesting phenomena may be found with the SMA which cannot be imagined at the moment. In the meantime, single-dish submillimeter observations and millimeter wave interferometry will continue to drive our preparations for the SMA.

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