The Submillimeter Array

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***ABSTRACT* — The Submillimeter Array, a collaboration between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics of Taiwan, is a pioneering radio-interferometer made up of eight 6-meter diameter antennas designed for high angular resolution astronomical observations of the cool universe throughout the major atmospheric windows from about 200 to 900 GHz. Each antenna houses a single cryostat, with an integrated cryocooler that can cool eight heterodyne receivers to 4 K. Four receiver bands are available: 180–250 GHz, 266–355 GHz, 320–420 GHz, and 600–700 GHz, and simultaneous observations are possible in any pair of high and low frequency receiver bands.**

***Index Terms* — submillimeter wave antennas, submillimeter wave instrumentation, submillimeter wave astronomy.**

I. INTRODUCTION

It has long been recognized that the wavelength range 0.3 to 1.3 mm, observable with ground-based telescopes, offers unique opportunities in the study of cool (10 – 100 K) dust and gas clouds in the Milky Way and other galaxies. By the mid 1980's the California Institute of Technology 10 m diameter telescope (the Caltech Submillimeter Observatory), and the James Clerk Maxwell Telescope (JCMT), a 15 m diameter instrument of the United Kingdom, the Netherlands, and Canada, were under construction specifically for astronomical observations at submillimeter wavelengths. At their shortest wavelengths these instruments offered angular resolutions of approximately 6 – 10 arc-seconds.

During the same period, the pioneering millimeter wavelength interferometers at Hat Creek (University of California, Berkeley) and at Owens Valley (California Institute of Technology) offered spatial resolutions of somewhat less than 5". Two other interferometers, at the Plateau de Bure in the French Alps and at Nobeyama were being developed by the Institut de Radio Astronomie Millimétrique and by the National Astronomical Observatory of Japan, respectively. Both of these instruments were designed to offer significantly improved angular resolution, of order 1". Furthermore, having demonstrated high resolution imaging through interferometry at millimeter wavelengths, and with the anticipated success of the CSO and JCMT, a natural step forward was to propose to design and build a submillimeter wavelength interferometer.

In 1984, following a request by the Director, Dr. Irwin I. Shapiro, the Harvard-Smithsonian Center for Astrophysics set up a Submillimeter Telescope Committee to develop plans for a new facility for Submillimeter wavelength astronomy. They envisioned an array of six 6 m diameter antennas, situated at a dry high altitude site, configured to offer sub arc-second resolution in the wavelength range 0.3 to 1.3 mm. The committee also recognized that the investment in receiver technology would be both substantial and crucial to the ultimate performance of the array, and recommended that the development of a receiver laboratory be given the highest priority. The Smithsonian Institution provided start-up funding in 1989 to set up such a lab and, following a design study, Mauna Kea was selected as the site for the SMA in 1992. The Academia Sinica Institute of Astronomy and Astrophysics of Taiwan joined the SMA project four years later with an agreement to provide two more antennas and associated hardware to enable eight-element interferometry.

II. SMA CONFIGURATIONS

Having selected Mauna Kea as the SMA site it was immediately obvious that, unlike existing millimeter wavelength interferometers which made use of Y or T -shaped configurations and used rail or paved road for reconfiguration which offer clear advantages during construction and operation, the SMA antennas would have to be moved over more difficult terrain. In 1994 Keto [2] showed that interferometer layouts based on perturbed curves of constant width (in particular the Reuleaux triangle) offer the most complete sampling in the Fourier space of the image and hence the best image quality. In order to achieve optimal u-v plane coverage and good imaging capabilities, the SMA

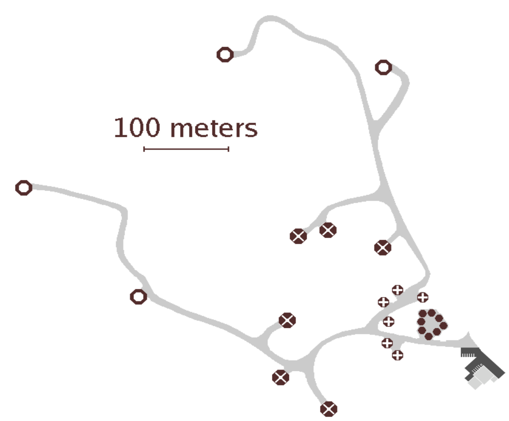

Fig. 1. The SMA antennas are usually configured in one of four approximately circular rings, with maximum baseline lengths of 25 to 508 m, offering angular resolutions of 5 to 0.25 arc-seconds at 350 GHz, the optimal frequency of the array for continuum sensitivity.

antennas are arranged following Keto's analysis. The antennas are moved into one of four different configurations using a rubber-tired, purpose-built transporter. At 350 GHz, the most compact configuration of the array provides an angular resolution of about 5 arc-seconds; which is roughly twice that of the JCMT and almost three times that of the CSO. In passing to the most extended configuration, the resolution of the SMA is improved by a factor of 20.

III. SMA Antennas

With the requirement that the SMA be at least as sensitive as existing submillimeter telescopes, and given that at least six antennas are required to provide reasonable imaging quality for an interferometer without multiple reconfigurations, the SMA was initially conceived as an array of six 6 m diameter antennas with a total collecting area almost identical to that of the JCMT. The addition of a further 2 antennas from ASIAA improved both the imaging quality and sensitivity of the array. The requirement to have a relatively large receiver enclosure, fixed in elevation to maintain a physically stable environment for the cryogenically cooled receivers, resulted in an antenna design based on a bent Nasmyth configuration.

The design of the antenna pedestal was driven primarily by the stiffness required to maintain pointing and phase accuracy for the expected wind loads. Detailed thermal analysis determined that an all steel structure could maintain the required performance as long as it is properly isolated from the external environment. To this end, the bulk of the structure is housed inside the temperature-controlled receiver cabin. The base, below the azimuth bearing, is thermally insulated from its surroundings.

Fig. 2. Photograph of the SMA antenna pedestal. The structure above the elevation bearings connects to the reflector assembly.

Although aluminum-coated carbon fiber reflector panels are light weight and offer inherently good temperature stability, the SMA antenna reflector assembly was designed to incorporate machined aluminum panels which are better able to survive the severe weather conditions of the Mauna Kea environment. Thermal considerations excluded the use of panels larger than 1 m in extent, so a 4-ring structure was chosen with 12 panels in each of the inner two rings and 24 in each of the outer two. The panels are supported above the steel nodes of a back-up structure made up of a truss-work of 648 carbon fiber tubes. Apart from the inner ring of panels which each has 3 support points, a redundant four point panel support scheme was chosen. In this way, individual panels could be deformed in-situ to correct for certain large scale manufacturing defects. To meet focus and pointing stability requirements, a carbon fiber quadrupod was selected to support a chopping secondary mirror assembly.

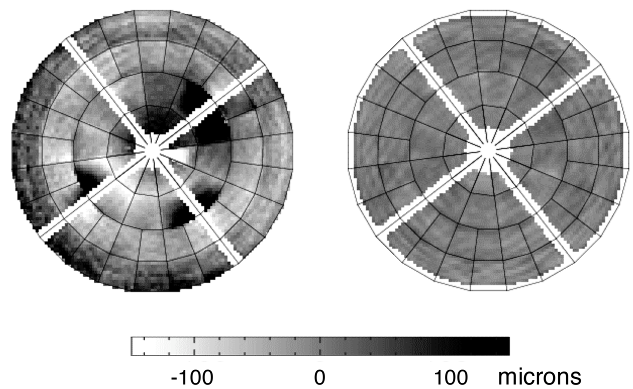

Fig. 3. The SMA antenna reflectors are typically set to 60 µm rms (left) using a mechanical swing arm. A near-field holographic technique, using a phase-locked beacon at 232.4 GHz, is then used to progressively improve the surface. Three iterations are generally required to reach the design specification of 12 µm rms (right).

A ball-screw arrangement was selected for the antenna elevation drive. For the azimuth drive, a more standard drive system was chosen. It consists of two motors driven in opposition against a spur gear cut directly onto the azimuth bearing of the antenna. In both cases high torque, 1,100 Nm, brushless servo motors were incorporated, in part to fulfill the desire for fast antenna position switching. In order to provide the required controlled antenna motion and to easily accommodate the variability of the elevation gear ratio a digital servo control drive system was implemented. The overall quality of the servo control system is best assessed through the tracking and slewing performance of the antennas during observations. Under calm conditions sidereal-rate tracking errors are typically 0.3" rms on both axes, and in high winds tracking errors remain below the specification of 1.3" rms on all antennas.

Errors in the absolute pointing of each antenna are removed with the help of an optical guide-scope and a multi-parameter mount model in the usual way and residual pointing errors of 2" rms are typical. In addition to an optical pointing model, models of the radio pointing of each SMA antenna are made on a regular basis and radio to optical offsets are incorporated into each antenna pointing model. The antennas slew at a rate of $4°s^{-1}$ in azimuth and $2°s^{-1}$ elevation, and a duty cycle of better than 50% is typically achieved for on-source times as short as 10 s. However, with a source acquisition time of 3 s in azimuth and 2 s in elevation, the observing efficiency degrades significantly for shorter timescales.

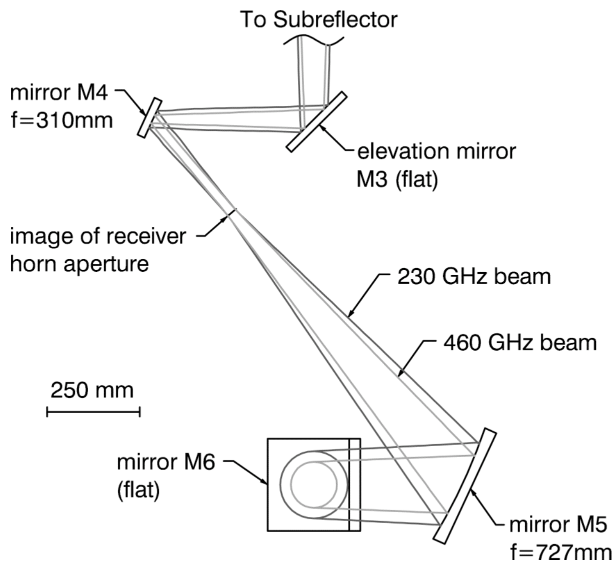

Fig. 4. The SMA antenna beam waveguide assembly used to couple radiation from the antenna to the receivers produces a compact image of the feed between the two ellipsoidal mirrors and provides a convenient location for receiver gain calibration and for the quarter wave plates required to enable polarimetry observations.

Besides providing efficient coupling to the receivers, the antenna also provides a phase stable environment for the entire signal path within the antenna receiver cabin including the beam waveguide, receiver optics, reference frequency distribution, and intermediate frequency transmission. For example, a 1°C temperature change in a 2 m long optical train, supported by a structure made predominantly from steel, results in a phase change of 1 radian at the highest operating frequency of the SMA. Each antenna incorporates an air handler; basically a blower and two dampers that mix inside and outside air in the proper proportions to obtain the desired temperature stability. This system maintains the cabin air temperature to ±0.5°C for indefinite periods under a variety of atmospheric conditions. A slight overpressure is maintained inside the cabin to keep dusty air out.

IV. SMA RECEIVERS

A. Coupling to the Antenna

Referring to Fig. 4, a flat tertiary mirror is used to couple radiation from the subreflector to a pair of ellipsoidal mirrors in the horizontal plane of a bent Nasmyth configuration. An additional flat mirror is used to direct the signal beam downwards and into the receiver package. Coupled with a lens in front of each mixer, the ellipsoidal mirrors M5 and M4 are used to produce a frequency independent image of the feed horn aperture at the subreflector. Furthermore a compact image of the feed produced between these mirrors provides a good location for receiver gain calibration and for the insertion of switchable quarter wave plates required for polarimetry.

B. The SMA Receiver Package

A single cryostat capable of cooling eight receivers to 4 K is used to house the superconductor-insulator-superconductor mixers which currently enable observations across the four frequency bands shown in Table 1 below.

TABLE 1
SUMMARY OF RECEIVERS AVAILABLE AT THE SMA

Designation	Frequency range	Polarization
200	180 – 250 GHz	↗
300	266 – 355 GHz	↗
400	320 – 420 GHz	↖
650	600 – 700 GHz	↖

The lowest frequency of operation was set by the need to be able to operate reliably and make useful astronomical observations in periods of average weather conditions, and for calibration and testing of the instrument. The highest frequency was set by the need to have reasonable atmospheric transmission during periods of good weather. In order to provide accurate phase calibration during the highest frequency observations, dual frequency operation, in which a low frequency receiver is paired with a high frequency receiver, is possible through polarization diplexing. In addition, a full dual polarization capability is included in order to permit efficient polarization measurements of the dust continuum in the frequency range of maximum sensitivity of the array: 330 – 350 GHz.

C. SMA Receiver Inserts

Each of the SMA receiver bands makes use of a receiver insert similar to that shown in Fig. 5. Signal and local oscillator power (LO), provided by a Gunn oscillator – frequency multiplier combinations, are combined optically ahead of the insert using either a simple wire mesh coupler or a Martin-Puplett diplexer. A single-ended, fixed-tuned waveguide SIS mixer forms the core of each receiver insert. In all cases, the SIS junction, with the appropriate tuning circuit, is deposited onto a crystalline quartz substrate which is simply sandwiched between the scalar feed and a copper back-piece containing a waveguide section, machined to the appropriate depth [3]-[4]. The intermediate frequency (IF) output from the mixer at 4 – 6 GHz passes to a low-noise cryogenic amplifier and is then multiplexed via a solid-state switch mounted on the 20 K plate of the cryostat.

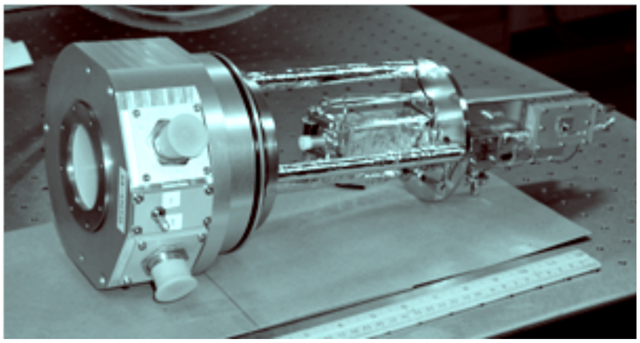

Fig. 5. Photograph of a 650 GHz receiver insert showing, from left to right, the vacuum window, electrical connectors, radial o-ring seal, interface to the 70 K radiation shield, mixer feed with Teflon dust cover. Further to the right: IF isolator and 4 – 6 GHz preamplifier.

V. Reference Frequencies and Signal transmission

The LO reference system for the SMA starts with a 10 MHz reference oscillator from which all frequencies are derived. Two master reference generators (MRG), one for each active receiver band, generate a tone with a phase noise of less than -140 dBc in the band from 6 to 8.5 GHz. A separate 109 MHz tone for each receiver is derived from a direct digital synthesizer and contains the phase and frequency offsets necessary to stop all of the fringes. The transmission of these signals between the control room and the antennas is done using three buried single mode optical fibers that have a very low temperature coefficient, which is almost zero close to the mean annual temperature at Mauna Kea. The MRG and 4-6 GHz IF signals from the receivers are transmitted over the fibers using commercially available transmitters and receivers with 10 GHz or more analog link bandwidth and operating at 1310 nm. The low frequency reference tones are transmitted at 1550 nm using lower bandwidth devices.

The two MRG tones are combined and connected to a single optical transmitter. The resulting optical signal is divided 10 ways and sent over one fiber to each antenna. This minimizes the number of separate elements in each antenna's path for this critical signal. The other two fibers are each associated with one receiver and transmit the IF signal in one direction and the low frequency reference tones in the other using wavelength division multiplexing. Each LO system has a YIG oscillator phase locked to one of the MRG tones to separate it and clean up any high frequency phase noise. The millimeter-wave Gunn oscillators which drive the frequency multipliers to generate the LO for each receiver are locked to a harmonic of the MRG tone offset by the 109 MHz tone.

VI. The SMA Correlator

The SMA correlator processes two IF sidebands, 1.968 GHz wide, separated by 10 GHz. The upper sideband (USB) and the lower sideband (LSB) are each divided into 6 "blocks", 328 MHz wide, and then further divided into 4 slightly overlapping "chunks", 104 MHz wide, each with a usable bandwidth of 82 MHz. For single (dual) receiver operation, the default correlator mode provides 1024 (512) channels per block across all 6 blocks per sideband. Although the same correlator configuration applies to both USB and LSB, the SMA correlator is very flexible. For example, in the default mode, the 1024 channels may be allocated equally among the 4 chunks in each block, or in any combination so long as the number of channels per chunk is a power of 2 between 64 and 1024. However, if all of the available channels are allocated to a single chunk in a block, then the other 3 chunks will have zero channels and are discarded.

Higher spectral resolution modes are also available that provide up to 4096 channels for a given chunk. Other correlator modes are being developed, for example to handle full polarization products from dual 350 GHz observations.

VII. Summary

The SMA has been in operation for the past three years and makes pioneering astronomical observations using state-of-the-art SIS mixer receivers across much of the submillimeter spectrum. While limited observations have been made at the highest angular resolution, enhancements to the array will soon enable similar observations to be made more frequently.

References

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