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THE SUBMILLIMETER ARRAY: CURRENT STATUS AND FUTURE PLAN

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ABSTRACT

The Submillimeter Array (SMA), a collaborative project of the Smithsonian Astrophysical Observatory (SAO) and the Academia Sinica Institute of Astronomy & Astrophysics (ASIAA), has begun operation on Mauna Kea in Hawaii. A total of eight 6-m radio telescopes comprise the array with currently working receiver bands at 230, 345, and 690 GHz. The array will have 8 receiver bands covering the frequency range of 180-900 GHz. The backend is flexible analog-digital correlator with a full bandwidth of 2GHz, which is very powerful to cover several line emissions simultaneously. The current status and future plans of the SMA are described with emphasis on Taiwanese efforts.

Key words : instrumentation — interferometers — submillimeter — telescopes

I. INTRODUCTION

The submillimeter window (λ =0.3-1.0 mm) is the final frontier for ground-based astronomy. While submillimeter continuum emission traces cold dust, high excitation lines at submmilimeter wavelengths trace warm and dense gas. In the 1980's, single-dish telescopes specifically designed for submillimeter wavelengths started observations, (e.g., the James Clerk Maxwell Telescope (JCMT) of 15 m and the 10 m telescope of the Caltech Submillimeter Observatory (CSO)), or were under construction. The angular resolutions of these single-dish telescopes were $\sim 6''$-$15''$ at their highest frequencies. It was our strong desire to achieve high angular resolutions at submillimeter wavelengths, and an interferometer is the only possible instrument to do it.

The Submillimeter Array (SMA) Project was conceived at the Smithsonian Astrophysical Observatory (SAO) in 1983, and a formal proposal of the SMA project was submitted to the Smithsonian Institution in 1984 (Moran et al. 1984). In 1987, the initial funding of the project to set up a receiver laboratory was received, and the construction funding of the array started in 1992. Several sites for the array, including the South Pole and the Atacama desert in Chile, were considered, and Mauna Kea in Hawaii was ultimately selected as the site, in part because of the existence of good infrastructure.

While the initial concept for the SMA was six 6 m antennas, in 1996, the Academia Sinica Institute of Astronomy & Astrophysics (ASIAA) joined the SMA project by agreeing to add two more antennas and all the associated electronics, including a doubling of the correlator and additional receiver systems. The Academia Sinica founded the expansion of the SMA as the first astronomical project at the ASIAA. The additional two antennas increase the number of instantaneous baselines from 15 to 28, nearly doubling the mapping speed of the array.

It is the first time for the ASIAA to construct submillimeter telescopes and receivers. A key for the institute to construct two antennas in Taiwan was to find expertise at industries. The Aeronautical Research Laboratory (ARL) was selected as a general contractor for the antenna construction because of their considerable experience in high-precision assembly of jet airplanes. The mounts that support the antennas were constructed at the China Shipping Building Corporation (CSBC) because of its experience in manufacturing and handling large metal parts for ships. Carbon fiber reinforced plastic tubes for the backup structures supporting the reflecting surface of each antenna were manufactured by NYTEX (currently GIGAN TEX), one of Taiwanese leading composites manufacture. In fact, tubes made in Taiwan are so good yet economical that they were also used in all the antennas constructed by the SAO.

In order to develop and deliver receiver systems for two additional antennas, the ASIAA has established a laboratory for submillimeter receivers. In addition, the ASIAA has started collaborations with National Tsinghua University in Taiwan, Nobeyama Radio Observatory in Japan, and the Purple Mountain Observatory in China to produce SIS junctions for the SMA receiver system.

By the end of 2003, all eight antennas of the array had been deployed on the top of Mauna Kea, and the SMA was formally dedicated on 2003 November 22. More details of the SMA are found in Ho, Moran, & Lo (2004). Figure 1 shows the completed SMA in the compact antenna configuration. Table 1 provides the basic characteristics of the SMA.

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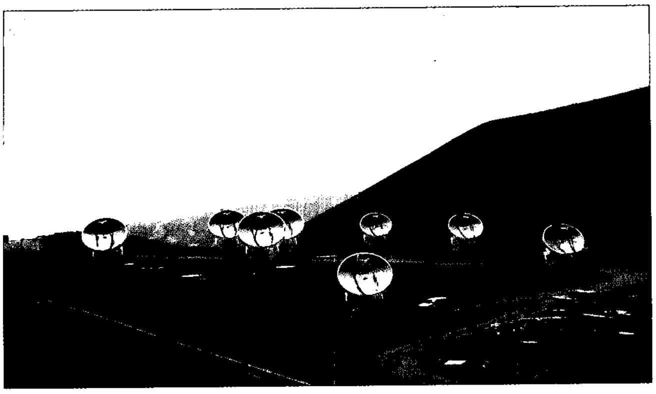

Fig. 1.— The completed SMA. The transporter used to move antennas is also shown in the right side of the foreground.

II. CURRENT STATUS OF THE ARRAY

(a) Antennas

Eight 6 m telescopes are basically working together for regular scientific observations. The main reflector, which consists of 72 machined cast aluminum panels, have been adjusted using the holography technique. The averaged surface accuracy is currently $\sim$ 20 μm rms, with the most accurate one having 12 μm rms. The optimization of the surface accuracy of each antenna is still continuing. The reflector surfaces have been also monitored to check long-term stability: the surface accuracy seems to be stable at $\sim$ 11 μm rms on the time scale of several months.

The positions of the sub-reflectors also have to be optimized at different elevations to keep a better beam pattern and focus. Each sub-reflector can be moved in three axes. Optimized positions of each sub-reflector were measured as a function of elevation by observing a bright planet with multiple sub-reflector positions. The measured "focus" curves are used to move the sub-reflectors during observations and to optimize the positions of sub-reflectors at each elevation.

The antenna pointing is another important aspect. The pointing model for each antenna is derived from full-sky optical pointing measurement and radio pointing measurements on bright planets in the single-dish mode. Optical measurements are carried out using the optical guidescopes mounted behind holes on the main reflectors. From full-sky optical pointing measurements of more than 100 optical stars, pointing models of 19 parameters are determined. Single-dish radio pointing measurements are used to derive the offset between the radio and optical axes and the radio specific term, i.e., the sag term. Radio pointing measurements are usually performed at 230 GHz, while we measure feed horn offsets between the 230 GHz band receiver and other frequency band receivers (i.e., currently 345 GHz and 690 GHz) to make radio pointing models for other frequency bands. Two radio beams are typically aligned within 5″. The pointing error of the SMA antennas is ~2-3″ rms on average. During the observations, interferometric radio pointing measurements on bright quasars are often performed to verify and further improve the antenna pointing.

TABLE 1.
BASIC CHARACTERISTICS OF THE SMA

Components	Spesifications
Antennas	Eight 6 m, f/0.4 paraboloids, bent-Nasmyth optics
Antenna mount	Alt-azimuth
Antenna backup structure	Carbon fiber struts, steel nodes, rear cladding
Primary reflector	Four rows of 72 machined cast aluminum panels
Surface accuracy	12 μm rms
Secondary reflector	Machined aluminum, 10 Hz chopping
Array configuration	Four nested rings, 24 pads, up to eight pads per ring
Available baselines	9-500 m
Operating frequencies	180-900 GHz
Maximum angular resolution	$0''.5 - 0''.1$
Primary beam field of view	$70'' - 14''$
Receiver bands	230, 345, 460, 690, and 850 GHz
Number of receivers	Eight per antenna, two simultaneous bands
Correlator	Hybrid analog-digital, 2×28 baselines
Number of spectral channels	172,000
Maximum bandwidth	2 GHz
Maximum spectral resolution	0.06 MHz
Maximum data rate	>10 GB day^{-1} with 1 s integrations

(b) Receivers

Each antenna is equipped with a single cryostat, with an integrated cryocooler capable of cooling up to eight receivers to 4 K. Three receivers, covering 180-250 GHz, 260-355 GHz, and 600-700 GHz are currently installed into each cryostat, and the former two receivers have been used for regular scientific observations. Each receiver uses a single SIS junction as a mixing component for heterodyne observations. The mixers are of tuner-less waveguide design. Local oscillator (LO) power to each receiver is provided by a mechanically tunable Gunn oscillator followed by frequency multiplier or multiplier combination. The LO is injected into the optical path via a simple mesh grid for lower frequencies, while it is injected via a Martin-Puplett diplexer for the 690 GHz band. All the receiver systems, except for a part of 690 GHz receivers, are motorized, which allows us to tune and optimize the receivers remotely. The typical double-sideband receiver temperatures of the operational system at Mauna Kea are currently 100 K, 150 K, and 500 K for 230, 345, and 690 GHz band, respectively. Dual band operation, with one lower frequency receiver (either 230 GHz or

345 GHz band) and one higher frequency (currently 690 GHz band only), is under testing. This dual band operation system will be also used for the dual polarization operation at a frequency range of 330-350 GHz. More details on the SMA receivers can be found in Blundell (2004).

(c) Correlator

The SMA correlator has a flexible hybrid analog-digital design. Each side-band data covering 2 GHz bandwidth centered at 5 GHz is divided into six continuous blocks of 328 MHz each after the first conversion. Each block of 328 MHz, recentered at 1GHz, further split into four basebands of 104 MHz with 82 MHz spacing, providing a maximum of 1344 multilag cross-correlation. The digital part of the correlator consists of 90 boards, each with 32 custom-designed correlator chips (Whitney 2004). This means that a minimum of 2 correlator chips can be devoted to each baseband correlation. Since each correlator chip has 128 lags (i.e., 64 complex lags), a minimum of 128 channels for each baseband with 2 chips are obtained with the full bandwidth coverage of 2 GHz, providing a spectral resolution of 0.8125 MHz. The full bandwidth coverage with this medium spectral resolution is very powerful to observe many spectral lines from active star formation regions, such as hot cores, for example (Beuther et al. 2004). A higher spectral resolution is possible by using fewer numbers of basebands. For example, it is possible for us to allocate up to 16 correlator chips to one baseband in each block, if we use only one receiver. Note that each correlator board with 32 correlator chips takes care of 2 baselines, 2 receivers, and one block. This high spectral resolution mode provides 1024 channels for each baseband, achieving 0.1016 MHz spectral resolution. The highest resolution we have tested is 0.2031 MHz.

(d) 690 GHz Observations

The SMA is expected to conduct observations at submillimeter wavelengths. 345 GHz (λ = 870 μm) is the lower edge of the submillimter window, while the 690 GHz (λ = 440 μm) would be one of the main bands in the submillimeter window. At the 690 GHz band, ^{12}CO ($J = 6-5$), CS ($J = 14-13$), H_2O maser, and so on, as well as stronger dust continuum can be observed. We have been trying to obtain reliable data at the 690 GHz band using the SMA (Young et al 2004). As easily imaged, interferometric observations at such a higher frequency is challenging. There are a couple of difficulties in making observations at such a high frequency. The obvious one is the weather. In order for us to obtain usable and reliable data, opacity at 230 GHz should be at most ~0.05, corresponding to ~ 1.2 as opacity at 690 GHz. Statistically, the chance to meet this condition at Mauna Kea is ~10 %, according to the opacity data taken at CSO. However, the time that can be used for observations may be less than 10 % of the whole time because good weather has to last at least a couple of hours for us to obtain usable data, including calibration. So, the occasion for us to make observations at 690 GHZ is very limited, and the array, in particular receivers, has to be always ready to make observations at 690 GHz.

Another serious issue is calibration. In particular, phase calibration (phase referencing) during observations is very difficult because there are not many phase calibrators at 690 GHz. Although some of targets could be calibrated using self-calibration, such a case seems to be very rare. In order for us to make reliable phase calibration with phase referencing, the flux density of a calibrator should be at least ~5 Jy, or preferably more than 10 Jy. Unfortunately, there is no quasars having such a large flux density at 690 GHz. It might be possible for us to use an ultra compact HII (UCHII) region, for example, as a phase calibrator, but we have not found any appropriate UCHII regions that are compact and strong enough for phase calibration. The H_2O maser line at 658 GHz, often observed toward evolved stars, is sometimes strong enough for phase calibration. Ganimede, Callisto, and Titan are also strong enough to be a phase calibrator. Only sources nearby these possible calibrators can be observed at 690 GHz.

One possible strategy, which could overcome this difficulty in the phase calibration, is the dual-band calibration method: we make observations at a lower frequency (e.g., 230 GHz) as well as at 690 GHz simultaneously, and use the data at the lower frequency to calibrate the data at 690 GHz. We have just started testing for this method, and hope that results will be obtained at the 690 GHz band using this method.

III. EARLY SCIENCE AND SCIENCE OPERATION

During the array commissioning phase, we have carried out early science observations with more than 5 antennas since May 2002. The purpose of this partial operation for the early science was not only to produce first scientific results using the SMA, but also to verify the array performance for future full operation. Seven areas were identified for the early science; the solar system, low-mass star-forming regions/circumstellar disks, high-mass protostars, evolved stars, Galactic center, nearby galaxies, and distant galaxies. We formulate a team for each area, and each team selected a limited number of objects for each area. We have observed the same objects repeatedly until we were sure that the obtained results were reasonable. The early science observations were continued until the dedication, and 17 papers showing results of the early science were published as a special issue of the Astrophysical Journal Letter (November 20th issue) in 2004. Four papers in the special issue were led by people in Taiwanese institutions: A high velocity outflow in V Hya(Hirano et al. 2004), detection of organic molecules at the protostar IRAS 16293−2422 (Kuan et al. 2004), the nearby galaxy M51 (Matsushita et al. 2004), and a search for compact continuum sources toward UCHII regions (Su et al. 2004).

After the dedication, we have started full-science operation based on proposals. Proposals have been called approximately every 3 months (note that approximately every 6 months after September 2004), and the Time Allocation Committee (TAC) ranks proposals. Actual observation scheduling is decided dynamically according to weather condition and other factors. About 50 % of the useful time would be used for observations at 345 GHz. Two nights in each week are still used for various array tests to improve the array performance, and to test and implement new observational technique and hardware/software. Observations are carried out only in night time. This is mainly because the phase stability is not good enough in day time. In addition, the pointing should be different between day time and night time, whereas we have not derived reliable pointing models for day time observations. Furthermore, there are still considerable technical works, including testing new hardware/software, which have to be done in day time. Nevertheless, it would be worth while considering day time observations, in particular observations at 230 GHz over the weekend, when there is no day time technical works at the site. Observations in night time are divided into two shifts, and second-shift observations (nominally after 2 am in Hawaiian Standard Time) in weekdays are remotely performed either from the SAO or the ASIAA in Taiwan.

The time allocation fractions for the SMA partner institutions (including Institute for Astronomy at University of Hawaii; IfA) are nominally 72 %, 13 %, and 15 % for the SAO, the ASIAA, and the IfA, respectively, and about 10 percent of the SAO time is now open to external principal investigators. The ASIAA time is also now open to the astronomical community in Taiwan. Astronomers in the East Asian regions are strongly encouraged to collaborate with staff at the ASIAA to initiate projects using the SMA. The ASIAA has its own TAC to rank proposals submitted to the ASIAA. SMA observations at the ASIAA have been led by three science groups, i.e., star formation, extra galactic, and evolved stars. Since the machine time for the ASIAA is limited, each of the SMA science teams at the ASIAA intensively discusses scientific projects using the SMA to polish up each project.

IV. PLANS FOR NEAR FUTURE

The biggest plan for near future is linking the SMA with the JCMT 15 m telescope and the CSO 10 m telescope. We expect the sensitivity for compact sources to be improved by a factor of three with the enhanced SMA including these two telescopes. The current SMA correlator can handle the full bandwidth of 2 GHz on all 45 baselines produced by the enhanced SMA with one receiver. The initial test of the link will be started by the middle of 2005. In addition, we just started testing on dual band operation. We will perform dual band calibration using this capability. Finally, a new receiver band covering 330-430 GHz will be available in addition to the current three receiver bands. This new receiver band will allow us not only to make observations at new frequencies, but also to carry out efficient dust polarization measurements, or to increase the sensitivity of the continuum emission by a factor of a square root of 2.

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