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THE LARGE MILLIMETER TELESCOPE

D. H. Hughes,[1] F. P. Schloerb,[2] and LMT Project Team

RESUMEN

Este artículo, presentado a nombre del equipo del proyecto del Gran Telescopio Milimétrico (GTM), describe el estatus y los planes a mediano plazo para el telescopio y su instrumentación inicial. El GTM es una colaboración bi-nacional entre México y los EUA, dirigida por el Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) y la Universidad de Massachusetts en Amherst, para construir, comisionar y operar un radio telescopio de 50 m de diámetro en longitudes de onda milimétricas. Las labores de construcción están cercanas a ser concluídas en el sitio del GTM, a una altura de $\sim$ 4600 m en la cima de Sierra Negra, un volcán inactivo en el estado de Puebla en México. El movimiento del telescopio bajo control de computador tanto en azimuth como elevación ya se ha logrado. La primera luz en fuentes astronómicas en longitudes de onda centimétricas se obtuvo en Noviembre 2006. La instalación de segmentos superficiales de alta precisión para operación en longitudes de onda milimétricas está en curso. La zona central de 32 m de diámetro ya está completa y lista para recibir la primera luz en longitudes de onda milimétricas en 2008. La instalación del resto de la superficie reflectora continuará durante el año entrante y será concluída en 2009 para luego proceder a las pruebas finales de la antena. La antena completa del GTM, complementada por el primer grupo de instrumentos científicos, será un instrumento de frontera a nivel mundial para la investigación en astronomía en ondas milimétricas.

ABSTRACT

This paper, presented on behalf of the Large Millimeter Telescope (LMT) project team, describes the status and near-term plans for the telescope and its initial instrumentation. The LMT is a bi-national collaboration between México and the USA, led by the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) and the University of Massachusetts at Amherst, to construct, commission and operate a 50 m diameter millimeter-wave radio telescope. Construction activities are nearly complete at the LMT site, at an altitude of $\sim$ 4600 m on the summit of Sierra Negra, an extinct volcano in the Mexican state of Puebla. Full movement of the telescope, under computer control in both azimuth and elevation, has been achieved. First-light at centimeter wavelengths on astronomical sources was obtained in November 2006. Installation of precision surface segments for millimeter-wave operation is underway, with the inner 32 m diameter of the surface now complete and ready to be used to obtain first-light at millimeter wavelengths in 2008. Installation of the remainder of the reflector will continue during the next year and be completed in 2009 for final commissioning of the antenna. The full LMT antenna, outfitted with its initial complement of scientific instruments, will be a world-leading scientific research facility for millimeter-wave astronomy.

Key Words: early universe — Galaxy: general — radio continuuum: general — radio lines: general — surveys — telescopes

1. INTRODUCTION

1.1. *Concept*

The Large Millimeter Telescope (LMT) is a 50 m diameter millimeter-wave radio-telescope. The LMT is an "open-air" telescope with no radome or astrodome enclosure to obstruct its view. This configuration gives the optimum performance under the best observing conditions, particularly for measurements with sensitive, broadband continuum systems. The antenna designer, MAN Technologie (now MT Mechatronics), identified that enviromental effects, such as gravitational deformations, temperature gradients, and wind loads, posed significant problems in achieving the surface accuracy and pointing requirements of an "open air" LMT. Therefore, their design approach was to create an "active" telescope which can respond to these effects by correcting the shape of the primary reflector using a system of actuators to position the 180 individual segments that com-

[1]Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Luis Enrique Erro 1, Tonantzintla, Puebla, México (dhughes@inaoep.mx).

[2]Department of Astronomy, University of Massachusetts, Amherst, MA, USA (schloerb@astro.umass.edu).

prise the surface (Figure 1). The use of this system will allow gravitational deformations to be corrected, and we expect the telescope to work well under night-time and low wind conditions immediately.

To improve the antenna performance under more challenging conditions, MAN proposed the *Flexible Body Compensator* (FBC), wherein the shape of the surface is *inferred* from other measurements on the structure. MAN demonstrated that a large number of temperature sensors could be used to measure thermal gradients within the structure and derive the surface shape. Similarly, they showed that antenna pointing offsets due to wind loads could be predicted from measurements of the relative inclination of the two elevation bearings in the structure. Other measurements are also possible, including introduction of a laser metrology system to measure the location of the secondary mirror with respect to the nominal optical axis. The full FBC system should allow the telescope to be operated within specifications during all day-night conditions for winds speeds less than 10 m/s.

1.2. *Site*

The LMT site was selected in 1997 following radiometric testing at a number of potential mountain sites in México. The location of the LMT at a latitude of +19 degrees was a significant factor in its selection, providing very good coverage of the southern sky, with the Galactic center culminating at an elevation of about 45 degrees. The high altitude of the LMT site (4600 m) was found to be necessary in order to achieve the best millimeter-wavelength atmospheric opacities which, as measured by a 225 GHz tipping radiometer, are low for most of the year. The summer months, however, are relatively humid and cloudy so that the best high frequency observing conditions occur during the winter. The site opacity statistics for data obtained during 1999–2007 demonstrate that, from October through May, the third quartile opacity at 1.3 mm is < 0.3, while the first quartile opacity falls below 0.1. Thus, the site has submillimeter qualities during a significant portion of the year. Even during the summer months, the site is good for observations in the 3 mm window.

Meteorological data from the site show that the site conditions are favorable to a large antenna. There is only a small seasonal variation of the daily median temperature ($\leq 1^\circ$ C) and the diurnal temperature cycle is small ($< 5^\circ$ C). The median wind speed, as measured at two locations on the site, is < 5 m/s, demonstrating that observations up to the design limit (10 m/s) are possible 90% of the time.

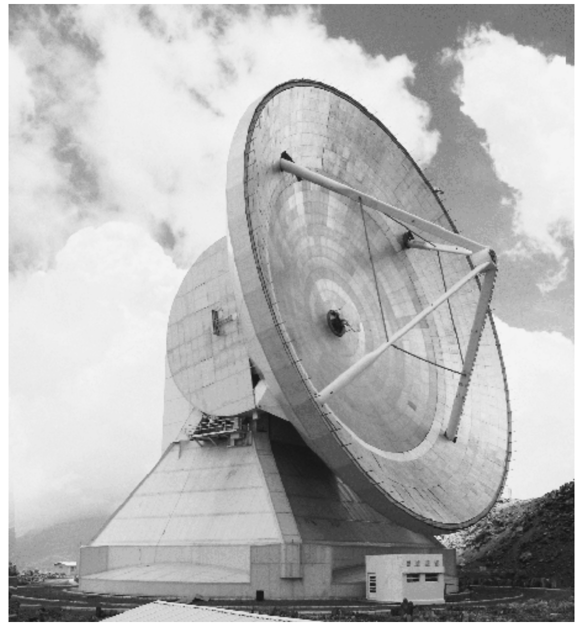

Fig. 1. The 50 m diameter Large Millimeter Telescope, at an altitude of 4600 m on the summit of Sierra Negra, showing the inner 32 m of installed Media Lario surface segments (*i.e.* interior to the tetrapod legs). The outer two rings of segments are temporary structures to provide the necessary balance and protection of the antenna backup-structure from the adverse weather conditions.

2. CURRENT TELESCOPE STATUS

2.1. *Antenna Structure*

The basic antenna, consisting of the alidade and reflector backup structure, has been complete since early 2006. The major remaining components to be finished and installed on the antenna structure are the primary surface, the secondary and tertiary mirrors (see below), and also the final installation of the elevation gear which has been postponed until the reflector surface is fully completed. The latter is currently installed in a temporary fashion to allow immediate testing and achievement of the first-light milestone.

2.2. *Reflector Surface*

The 50 m diameter reflector surface of the LMT consists of 180 segments arranged in five annular rings. Each segment is comprised of 8 precision subpanels (fabricated by Media Lario in Italy) which are mounted in the segment structure and aligned in the INAOE aspherics laboratory before transportation to the LMT site and installation on the antenna.

With the initial 84 segments installed for the inner three rings (32 m diameter), the next step will be the global alignment of the segments by surface actuators to a common parabola during the summer of 2008 using the holography system described in § 4. In order to achieve the full scientific capabilities the specification for the r.m.s. error of the full 50 m diameter surface is $\sim 70\mu$m.

2.3. *Optics*

The secondary mirror system consists of a 2.5 m carbon-fiber mirror and a hexapod "positioner". The mirror is an in-house development of INAOE. A second attempt to fabricate the mirror to a specific r.m.s. accuracy of $\sim 12\mu$m is currently underway, and is due to be completed by early fall of 2008. The secondary positioner is a hexapod system that is already built and is under final calibration at CIATEQ, A.C., Centro de Tecnología Avanzada, a National Institute in México. The positioner is expected to be delivered to the project for acceptance testing and integration with the telescope control system in the summer of 2008.

The LMT is a bent Cassegrain optical design. The M3 (Tertiary) mirror directs the beam from the antenna along the elevation axis to the Cassegrain focal point located inside the elevation bearings of the telescope. This mirror must track the elevation of the antenna in order to follow a source, so the positioner is a critical part of the system. The M3 system is also being fabricated at CIATEQ. The mirror is complete (see Figure 2) and the technical team is working on the motor controller for the elevation tracking at this time. It is expected that the M3 system will be delivered to the project in the summer of 2008 for acceptance testing and integration with the telescope control system.

2.4. *Control Systems*

The LMT Control System has been under development for many years at the Five College Radio Astronomy Observatory (FCRAO) at UMass. The Monitor and Control Systems Software is broken down into three major elements: (1) the software framework, within which the LMT applications are written; (2) the Telescope Control System (TCS) which runs the telescope and all subsystems; and (3) the Data Collection System (DCS), which coordinates the functions of the telescope and instruments to take and record scientific data. We have been able to implement and test the system on the FCRAO 14 m telescope, on the (now decommissioned) Infrared Optical Telescope Array in Arizona, and on the recently completed Korean VLBI Network Antennas. The system has been directly tested on the LMT during initial pointing and tracking tests with the antenna drive system in 2006. Based on our experiences, we have a stable and versatile system ready for more routine LMT operations later this year.

Fig. 2. (left) Photograph of M2 (secondary mirror) positioner and first mirror fabricated by the project; (right) Photograph of M3 (tertiary mirror) and its positioner system.

The Antenna Drive System encompasses all the hardware (e.g. drive motors and sensors, including safety interlocks and limits) that is necessary for moving the antenna on its two axes. This system was acquired from MAN Technologie by the University of Massachusetts and delivered to the LMT site in 2004. The hardware for this system is installed and the system has been used to drive the antenna and track radio sources at 3 cm wavelength during an initial demonstration of the antenna in 2006. Further testing, and final checkout of safety interlocks and limits, was carried out in May 2008 in order to begin characterization of the tracking behavior of the antenna. Recent successful tests of simulated on-the-fly maps for holography show that the LMT is ready for installation of the holography receiver system for setting the surface.

The Active Surface Control System includes the hardware necessary for the 720 actuators needed to move the 180 surface segments in order to maintain alignment of the reflector. The actuator program, managed by INAOE, has successfully demonstrated the operation of a prototype actuator and is now moving towards full production of the 720 actuator units.

3. TIMELINE AND MILESTONES

Figure 3 presents a summary schedule for the continued development of the LMT during 2008–2012. The most recent major project milestone has been the completion of the installation of the inner 50% of the reflector surface (Figure 1). The antenna drive system is in place and has already been successfully tested. Thus, the final steps to millimeter-

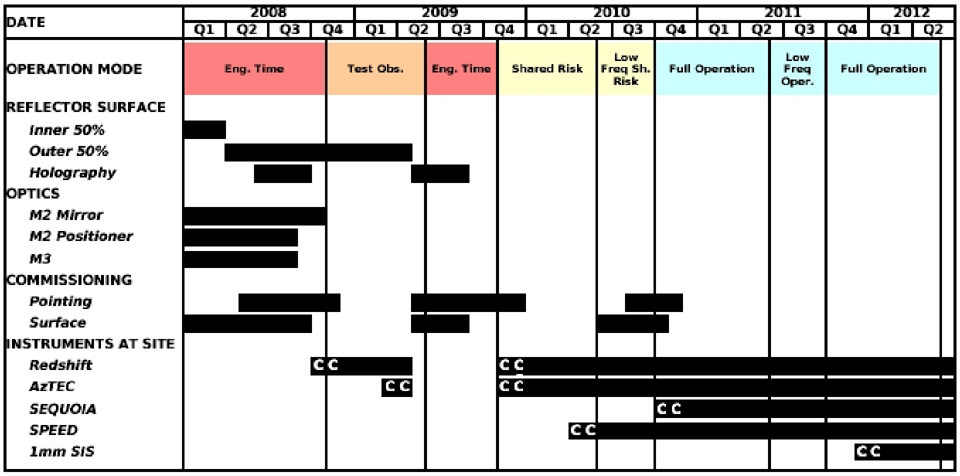

Fig. 3. Summary Schedule of LMT long-range plan (2008–2012). cc = commissioning time.

wave first light will be to: (1) align this inner 32 m diameter region using the technique of microwave holography; (2) complete and install the secondary mirror system; (3) complete and install the tertiary mirror system; (4) complete and install a system of actuators for control of the active primary surface; and (5) install UMass' Redshift Search Receiver as the initial millimeter-wave instrument for antenna testing and demonstrations.

This ambitious set of tasks is scheduled to be completed within this calendar year, enabling a technical demonstration of the capabilities and potential of the antenna. As this initial step is achieved, the remaining area of the antenna will be installed over the next year in order to achieve the complete 50 m diameter surface. The initial commissioning and demonstration effort, with the inner 32 m of the reflector, will shorten the total time needed to bring the telescope into full operation. A plan is in place to allow continued installation of the reflector surface in the remainder of the antenna while t he telescope is simultaneously used for on-going test observations. Initially, the commissioning will be conducted with the Redshift Search Receiver, an ultra-wideband receiver-spectrometer designed to observe the entire 74–110.5 GHz band. Late in the 2008–2009 observing season, however, we will install AzTEC, a 144-pixel focal plane array for continuum imaging for 1.1, 1.4, and 2.1 mm wavelength, on the LMT for some initial observations at higher frequencies with the inner 32 m diameter region of the surface.

Once the installation of the full 50 m surface is completed in 2009 we will align the full surface using holography, carry out a suite of pointing and tracking tests, and reinstall the telescope with two of its initial science instruments (Redshift Search Receiver and AzTEC) so that initial shared risk scientific operations can begin. The installation of the remaining instruments (SEQUOIA: a 32-element heterodyne focal plane array for 3 mm wavelength; SPEED: a four-element multifrequency continuum instrument allowing simultaneous observations at 2.1, 1.3, 1.1, and 0.85 mm in each pixel, and a dual polarization SIS Receiver covering 210–275 GHz) will be completed over the next two years.

4. INSTRUMENTATION STATUS

The instrumentation effort for LMT has been led by the Five College Radio Astronomy Observatory (FCRAO) at the University of Massachusetts at Amherst. A variety of instruments have been constructed for commissioning the antenna as well as first-light science.

4.1. *Commissioning Instruments*

4.1.1. *Optical Pointing Telescope*

The optical pointing telescope is a simple CCD camera system that will be used to measure the pointing of the antenna mount and test its tracking performance. The system was completed and tested initially on LMT in 2006, and is now being used during final tracking tests in preparation for the holography work in the summer of 2008.

4.1.2. *Holography Receiver*

A 12 GHz holography receiver system is mounted at the prime focus of the antenna with one feed illuminating the surface and a second feed pointing at a geosynchronous satellite source. The holography system goal for measurements of the surface is

50μm rms at a resolution of 40 cm and 25μm rms at a resolution of 80 cm. This accuracy is sufficient to determine relative positions of the segments on the antenna to an rms of approximately 25μm. This receiver has been installed at prime focus for initial testing in July 2008.

4.2. *Initial Science Instruments*

4.2.1. *Redshift Search Receiver*

The FCRAO Redshift Search Receiver (RSR) has been developed as a first generation instrument for the LMT (Erickson et al. 2007). Its frontend uses a very novel construction for a mm-wave receiver and the spectrometer is a set of wide-band analog autocorrelators. There are four receivers covering 74–110.5 GHz instantaneously in a dual-beam, dual-polarized system. The input includes a novel electrical beam switch (at 1 kHz) which overcomes the 1/f noise originating within the front-end amplifiers as well as atmospheric noise to ensure excellent baseline stability. The front end uses MMIC amplifiers and two very wideband mixers to convert each receiver band to two 18.5 GHz wide IF channels. Overall receiver noise is 70–80 K across the band for all pixels. After further conversion the IF signal passes into a spectrometer based on analog autocorrelation. Sets of tapped delay lines sample and multiply the signal with progressive delays to generate a spectrum with 6.5 GHz bandwidth and 31 MHz resolution. Six spectrometers with overlaps cover the 36.5 GHz band.

The Redshift Search Receiver was successfully deployed on the FCRAO 14 m telescope in the Spring 2007 and 2008 seasons for commissioning and early science observations. These efforts successfully demonstrated the innovative design and fabrication of the RSR instrument and related software to facilitate its use as the first light instrument for the LMT in 2008. Given that the spectral baselines are generally flat to within the noise, which integrates down radiometrically for times as long as 20 hr, we expect to detect molecular (CO) lines from large samples of dust-enshrouded optically-obscured galaxies in the early universe.

4.2.2. *AzTEC*

The Astronomical Thermal Emission Camera (AzTEC) is a large-format bolometer array camera constructed at UMass in collaboration with the BOLOCAM instrument team at CalTech, JPL, the University of Colorado and the University of Cardiff. AzTEC uses the same focal plane array of detectors and cryogenic electronics as used in the BOLOCAM instrument (Wilson et al. 2008). While AzTEC is, in concept, a copy of the original BOLOCAM instrument now operating on the 10 m CSO, many significant modifications have been implemented to improve performance and simplify its operation. These include the use of a 3-stage, closed-cycle ^{3}He refrigerator to cool the array and a robust and efficient cryostat to extend the cryogen hold time. The warm readout electronics for AzTEC have also been redesigned to minimize the analog signal path, simplify the electrical connections between the front-end and back-end electronics, and eliminate signal ground connections between all computers and the radiometer. The system architecture utilizes fiber optic connections carrying the AES/EBU protocol for commanding, clock distribution, and signal transmission. All clocks in the system are derived from (and phase locked to) a single master crystal that resides in the back-end electronics.

AzTEC has been deployed at both the 15 m James Clerk Maxwell Telescope (JCMT) in Hawaii and the Japanese 10 m Atacama Submillimeter Telescope Experiment (ASTE) telescope in Chile, and it has achieved notable success. In its 1.1 mm wavelength configuration, the instrument achieves background-limited detector noise and atmosphere-limited mapping speeds. The existing AzTEC deep survey data demonstrate that the instrument integrates down as $1/\sqrt{\mathrm{time}}$ to noise levels of 0.5 mJy rms on a 10 m diameter telescope (Scott et al. 2008). We have not attempted to go deeper than this sensitivity limit owing to the high level of source confusion at these depths at 30$''$ resolution. The instrument is robust; it has operated continuously for 3 months at the JCMT and then for 5 months at the ASTE telescope, where operations were interrupted only once by a vacuum leak that was readily repaired. The software pipeline (for point-source detections) has been developed and extensively tested. Our three years of use has demonstrated a mature and scientifically productive imaging array now used by over 120 astronomers from 12 countries. The instrument will be run for one more season in Chile and then be available for deployment on LMT late in the winter of 2008–2009 for initial use with the inner three rings of the reflector surface.

4.2.3. *SEQUOIA*

SEQUOIA is a 32-element heterodyne focal plane array receiver for the 85–115 GHz frequency band. The system makes use of MMIC preamplifiers and covers 15 GHz of instantaneous bandwidth. The instrument was used at the FCRAO 14 m antenna between 1998–2006. Despite its age, SEQUOIA is still the largest, most sensitive 3 mm focal plane array available today. The instrument will upgraded in 2009, following its time since 2006 in "storage", by replacing the noisiest pixels, and expanding its spectrometer bandwidth. It is our intent to field SEQUOIA on the LMT in the fall of 2010.

4.2.4. *SPEED*

The SPEctral Energy Distribution camera (SPEED) is a prototype instrument to demonstrate the technology of the frequency selective bolometer (FSB). The camera is configured as a 2×2 array with each pixel housing a 2.1, 1.3, 1.1, and 0.85 mm detector. By sampling these wavebands simultaneously, SPEED measures the millimeter spectral energy distribution of a source in a single pointing with the same angular resolution, eliminating the need for repeated observations of the same target. The efficiency with which SPEED obtains multi-frequency observations makes the camera ideal as a complement to a mapping instrument like AzTEC. SPEED is being developed by a collaboration including UMass, the University of Chicago, Case Western Reserve University, NASA/GSFC, and Argonne National Labs. Our current plan calls for SPEED to go to the LMT in 2010 for initial testing and for use in the scientific program in the fall of 2010.

4.2.5. *1mm SIS Receiver*

A novel dual-polarization sideband-separation SIS (superconductor-insulator-superconductor) heterodyne receiver is being built by FCRAO to cover the 1.2 mm atmospheric window. It is designed to operate in the 210–275 GHz band and should provide an SSB receiver temperature less than 100K with a scheme to separate the upper and lower sidebands. Each of the two polarizations provide 8 GHz of effective bandwidth per sideband (16 GHz total) without the use of cumbersome mechanical tuners. The 1 mm SIS receiver may be used with either the correlator backends or with the wideband redshift receiver analog backend spectrometer. The latter mode with the LMT and the 1 mm receiver will be especially powerful for observations of galaxies at redshifts below ∼3. The current instrument plan calls for the 1mm receiver to be completed after the installation of SEQUOIA on the LMT; it will be ready for scientific use in the fall of 2011.

4.2.6. *Spectrometers*

FCRAO has been developing a new wide-band digital correlator to process the I.F. streams from SEQUOIA, the 1 mm receiver, and future heterodyne focal plane arrays on the LMT. This new system provides sufficient bandwidth ($\Delta\nu$=800 MHz) for all extragalactic programs and high spectral resolution modes to carry out spectral line surveys. Analog signals from the frontend I.F. output are sampled at 1600 MHz and split into 16×100-MHz data streams that are fed to a Digital Correlator Card. Each Digital Correlator Card is identical, with sixteen Canaris correlator chips, each with 1024 lags that run at 100 MHz clock speed. The Digital Correlator Card can operate within the conventional autocorrelation mode for spectroscopy or a cross-correlation mode from opposite polarization I.F.s to measure circular polarization.

The Wide Band Spectrometer is the core of a more capable system which will enable multiple IF bands to be simultaneously observed with SEQUOIA and future heterodyne arrays. A digital router will be built to send sampled signals from three IF bands, including the basic wideband IF and two existing 50 MHz IF bands from SEQUOIA to the correlator. This configuration enables multi-line observations with spectral resolution as high as 3 kHz. In addition, to allow use of the spectrometer with other receiver frontends, an IF switching system will be constructed to connect the 1mm receiver (and future arrays) and the Redshift Receiver frontend to the spectrometer.

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