2. Introduction

A major new astronomical facility is now under construction in Mexico. The Large Millimeter Telescope (LMT) will be the largest and most powerful telescope of its kind in the world. Operating at very short radio wavelengths, it will probe the early universe to study the processes which ultimately formed the galaxies, stars, and planets that we see today. In fact, the LMT will enable fundamental advances in all areas of astronomy and planetary science. In many ways equally important, the new telescope is by far the largest science project ever undertaken jointly by the United States and Mexico. Conceived as an equal partnership between these two neighbors, it is led by two institutions that are leaders in astronomy in their respective countries: The University of Massachusetts Amherst (UMass Amherst) in the United States and the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) in Mexico.

The LMT includes a single, extremely high precision antenna 50 meters in diameter which can point to any position on the sky, while the overall height of the telescope is roughly equivalent to that of a 20-story building. It is currently nearing completion at an altitude of 15,000 feet (4580 m) above sea level on an extinct volcano within the National Park Pico de Orizaba, about 100 km east of the city of Puebla and to the west of Veracruz and the Gulf of Mexico (Figure 2.1).

2.1 INAOE and Astronomy in Mexico

Astronomy in Mexico dates from ancient times. For the peoples that occupied the central area of Mexico south to Honduras from the first millennium before Christ to the sixteenth century—the Mesoamerican civilization—chronology was one of the basic motives for practicing astronomy. The desire to create an accurate calendar developed into an obsession, perhaps unparalleled in the history of human intellectual achievement. For example, for the Maya the word “kin” signified not only “time” but also “day” and “Sun.” Its meaning and glyphic form suggests, not surprisingly, that the art of time keeping was intimately connected with the practice of astronomy. According to some experts, the Mayas’ careful observation of the cyclic repetition of celestial events produced an elaborate

Figure 2.1 Map of Mexico, showing the site of the Large Millimeter Telescope (LMT); the Instituto Nacional de Astrofísica, Óptica y Electrónica is located near the city of Puebla.

calendar more accurate than the Gregorian calendar in world-wide use today. These pre-Hispanic cultures recorded dates on upright stone slabs (stelae), as well as in manuscript form, and many of the classical inscriptions are magnificent works of art. For all Mesoamericans, life on Earth was a reflection of the cosmic drama, and the astronomer-priest was in charge of bringing the heavenly order to his own society. Mesoamericans typically planned their cities following that celestial order, erecting magnificent buildings to perform their rites on special dates related to astronomical events. These Mesoamerican astronomers observed and predicted eclipses and planetary positions, full and new moons, and the time of equinoxes and solstices.

Figure 2.2 The Mayan glyph "kin," signifying "time," "day," and "Sun."[2]

The enigmatic civilization of ancient Mexico has intrigued many generations and continues to fascinate us to this day. Indeed, Mesoamerican archaeoastronomy is an active field of research; e.g., Galindo & Allen[1] present evidence suggesting that the Maya actually observed at least one of the 12th and 13th century transits of Venus, based on the frescoes at the Mayapan archeological site. The Dresden Codex, one of the very few surviving pre-Hispanic documents, stands as a strong testimony to the genius of the Maya priest–astronomer. It includes Venusian, lunar, and eclipse tables that, according to Aveni[2], are marvels of astronomical accuracy.

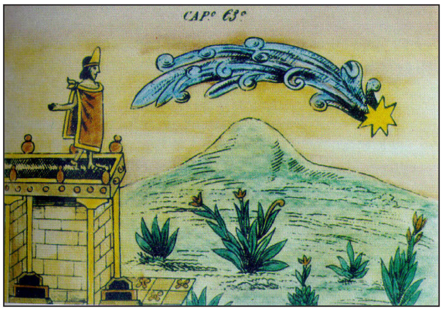
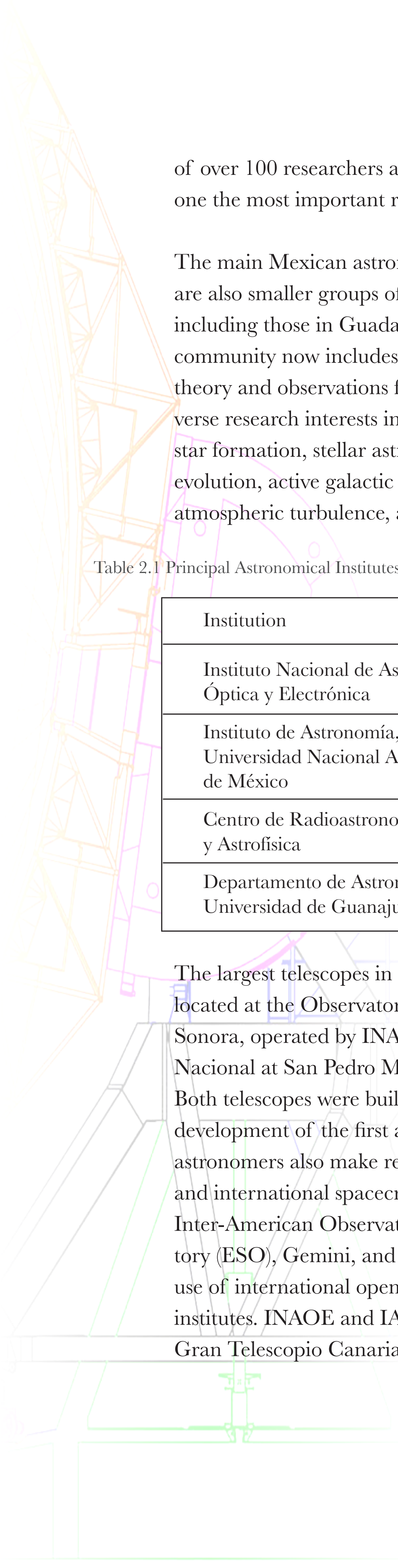


Figure 2.3 The emperor Moctezuma on the roof of his palace watches a comet[3].

Modern astronomical research in Mexico started with the founding of the Observatorio Astrofísico de Tonantzintla in 1942 on the outskirts of the city of Puebla. At the time it hosted one of the largest Schmidt cameras in the world, leading to the discovery of Herbig-Haro objects, flare stars, and blue emission-line galaxies. In 1972 the Observatorio de Tonantzinla evolved into the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), the lead Mexican institution for the LMT. One of the research centers of the National Science and Technology Council (CONACyT), INAOE was founded with the mission of developing, advancing, and promulgating scientific knowledge, through the identification and solution of scientific problems and the training of specialists in the areas of astrophysics, optics, electronics, and computational sciences. With a staff

Figure 2.4 A view of the campus of the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) at Tonantzintla, Puebla.



of over 100 researchers and lecturers in these four disciplines, INAOE is one the most important research institutes in the country.

The main Mexican astronomical institutions are listed in Table 2.1. There are also smaller groups of astronomers working at other universities, including those in Guadalajara and Sonora. The national astronomical community now includes about 160 astronomers working on astrophysical theory and observations from radio wavelengths to gamma rays. The diverse research interests include planetary science, the interstellar medium, star formation, stellar astronomy, galactic dynamics, galaxy formation and evolution, active galactic nuclei, cosmology, astronomical instrumentation, atmospheric turbulence, and archaeoastronomy.

Table 2.1 Principal Astronomical Institutes in Mexico

Institution	Acronym	Location
Instituto Nacional de Astrofísica, Óptica y Electrónica	INAOE	Tonantzintla (Puebla)
Instituto de Astronomía, Universidad Nacional Autónoma de México	IA-UNAM	Mexico City and Ensenada
Centro de Radioastronomía y Astrofísica	CRyA-UNAM	Morelia
Departamento de Astronomía, Universidad de Guanajuato		Guanajuato City

The largest telescopes in Mexico are the two 2.1 m optical telescopes located at the Observatorio Astrofísico Guillermo Haro at Cananea, Sonora, operated by INAOE, and at the Observatorio Astronómico Nacional at San Pedro Mártir in Baja California, operated by IA-UNAM. Both telescopes were built mainly with national resources, leading to the development of the first astronomical instrumentation groups. Mexican astronomers also make regular use of larger-aperture optical/IR telescopes and international spacecraft facilities such as those at the Cerro Tololo Inter-American Observatory (CTIO), the European Southern Observatory (ESO), Gemini, and the Hubble Space Telescope (HST), through the use of international open time or international collaborations with partner institutes. INAOE and IA-UNAM are also partners in the 10.4 m optical Gran Telescopio Canarias (GTC) in Spain.

By the late 1980s it had become clear that the national observing facilities were insufficient for the needs of the growing astronomical community. It was also evident that creating a world-class facility could only be carried out in collaboration with international partners, given the technological complexity and resources required. It was concluded that the best opportunity was at millimeter wavelengths, in particular the important 1–3 mm band that is critical to studies of the early universe, star and planetary formation in the Milky Way, and astrobiology. The LMT proposal followed naturally, through a long-term collaboration between Mexican and U.S. astronomers.

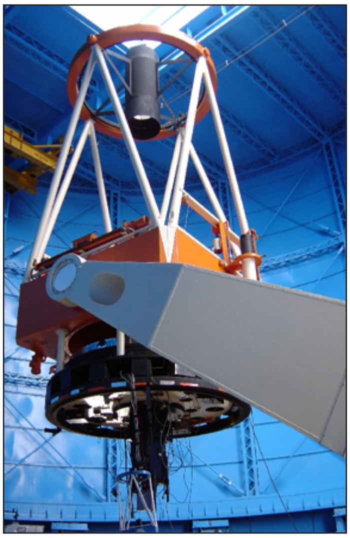


Figure 2.5 The 2.1 m telescope at the Observatorio Astrofísico Guillermo Haro at Cananea, operated by INAOE.

A familiarity with mm-wavelength astronomy is rapidly developing among INAOE staff and students, who regularly use for their research international mm-wavelength facilities such as those at the Caltech Sub-millimeter Observatory (CSO), the Arizona Radio Observatory (ARO), the Five College Radio Astronomy Observatory (FCRAO), the James Clerk Maxwell Telescope (JCMT) and the Institut de Radio Astronomie Millimétrique (IRAM); and who are members of the scientific teams of other mm facilities under development, such as the 2.5 m Balloon-borne Large Aperture Sub-millimeter Telescope (BLAST) or the 6 m Atacama Cosmology Telescope (ACT).

The LMT is the largest scientific project ever undertaken in Mexico in any field, with a budget ten times bigger than that of any comparable project. The national development of novel technologies was set as a requirement for approving the project, a test in itself of the capabilities of Mexico to construct large and sophisticated scientific instruments. In response to this challenge, the concrete foundations, the steel alidade, and the antenna structure have been manufactured in Mexico, according to the specifications of the antenna designer (MAN Technologie of Germany). Moreover, INAOE is currently building the secondary reflector and is committed to the development of microwave instrumentation. The LMT has thus already been successful in contributing to the national development of astronomy and technology in Mexico.

2.2 Astronomy at the University of Massachusetts Amherst

UMass Amherst was a founding member of the Four College Astronomy Department, formed in 1960 to link undergraduate astronomy education at the university and Amherst, Mount Holyoke, and Smith colleges and subsequently expanded to a Five College Department with the founding

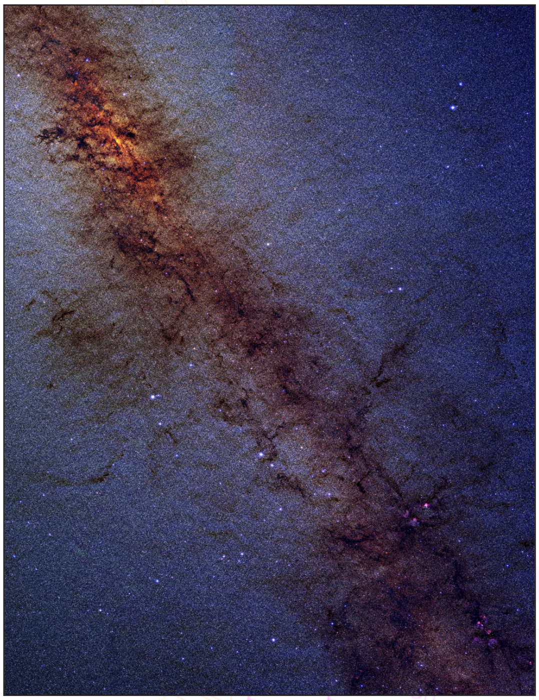


Figure 2.6 2MASS image of center of the Milky Way Galaxy (courtesy of 2MASS/UMass/IPAC-Caltech/NASA/NSF).

of Hampshire College in 1970. The graduate program, now based in the university's Astronomy Department, has offered M.S. and Ph.D. degrees since 1967. Over the years the 83 Ph.D. recipients have taken leading academic roles in the U.S. and abroad, and senior research positions in NASA, the National Radio Astronomy Observatory (NRAO), other government laboratories, and private industry, and one, Russell Hulse, a physics graduate student working in astronomy, won a Nobel prize for his research at UMass Amherst!

Theoretical astrophysics and ground- and space-based observations at wavelengths from the infrared to X-rays have been and continue to be significant components of the research program at UMass Amherst. For example, Astronomy faculty have led the Two Micron All Sky Survey (2MASS), played a major role in the Submillimeter-Wave Astronomy Satellite (SWAS), been significant users of the Hubble Space Telescope, the Spitzer Space Telescope and the Chandra orbiting X-ray telescope, and made fundamental contributions in theoretical cosmology and other areas of astrophysics.

Nonetheless, almost since the inception of the department, the principal observational program has been in radio astronomy. The Five College Radio Astronomy Observatory (FCRAO) was founded some 20 miles from campus in 1969, initially for the study of pulsars at meter-wavelengths using four linked, 100 ft-diameter Arecibo-type telescopes. The discovery of emission at mm-wavelengths from interstellar molecules, e.g., of carbon monoxide in 1970, prompted a change in direction which led to the dedication in 1976 of the 14 m-diameter dish, which was at the time the largest such telescope in North America. Since then the FCRAO 14 m telescope has played a major international role in astronomical research, producing among its significant contributions ground-breaking surveys of the distribution of molecular clouds in our Milky Way Galaxy and of the gas content of external galaxies, and pioneering studies of the chemistry of interstellar clouds, processes associated with star formation, and the chemistry and physics of comets.

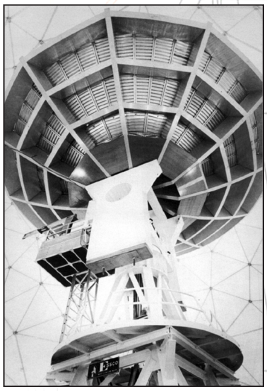


Figure 2.7 The 14 m-diameter mm-wavelength telescope at the FCRAO.

In addition to its role in graduate education and research, the FCRAO has consistently been in the forefront of new technology development, which is necessary in order for an observatory to remain internationally competitive. Such developments span the range from the special receiver that provided evidence for gravitational radiation and led to the Nobel Prize for Russell Hulse and Professor Joseph Taylor, to the first mm-wavelength cameras (focal plane arrays) now in use at FCRAO and destined for the LMT.

By 1988, however, it had become clear that the 14 m telescope, although still fulfilling a useful astronomical role, was no longer the leader in the field. Larger, more sensitive telescopes for use at short mm-wavelengths had been constructed in Europe, the U.S., and Japan. Given the experience of the FCRAO group, discussion began on the possibility of building a still larger-aperture radio telescope. However, it was clear that such a task was too large to be undertaken by a single university. Fortunately, UMass Amherst was already collaborating with astronomers in Mexico, who were also interested in constructing a major new facility for their country. This collaboration has led to the Large Millimeter Telescope.

2.3 Goals of the LMT Project

Both INAOE and FCRAO/UMass Amherst recognize a tripartite responsibility in their missions: pursuing pioneering research, training the next generation of scientists and engineers, and developing new technology for the benefit of society. All three of these areas are key to the LMT project.

2.3.1 Science

The very interdisciplinary nature of astronomy ensures that new discoveries will impact many areas of science, including physics, chemistry, geology and planetary science, and biology. But why are observations at mm-wavelengths important? The reasons are related to the facts that much of the material in the universe is very cold, that star-forming galaxies contain a significant amount of particulate matter (the astronomers' "dust" or "grains"), and that the universe is expanding! Thus, much of the interstellar gas and dust that is not heated by nearby stars is at temperatures of 10-20 K, too cold to radiate at wavelengths shorter than the mm/sub-mm range, and so only observable in emission at these longer wavelengths. Moreover, the dust in the Milky Way and other spiral galaxies is concentrated in the very clouds where new stars form, and it obscures the most interesting interior regions of these

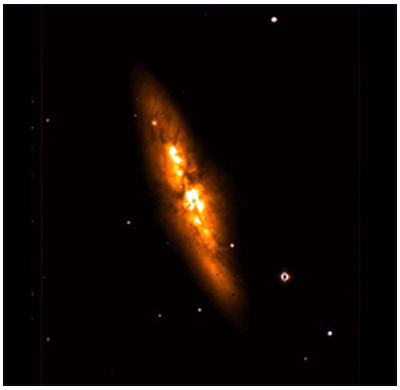


Figure 2.8 The galaxy M82 as imaged in R-band at the Observatorio Astrofísico Guillermo Haro in Sonora, operated by INAOE[4].

clouds at optical, ultraviolet, and even infrared wavelengths. However, it is transparent at mm wavelengths, since the dust grain dimensions are smaller than this. The dust concentrated in the plane of a typical spiral galaxy is clearly evident in Figure 2.8. Finally, much of the ultraviolet and visible radiation emitted by young stars is absorbed by dust and re-radiated in the infrared. In fact, galaxies that are forming massive stars or that contain active galactic nuclei (AGN), presumably powered by super-massive black holes, emit the bulk of their energy in the mid- and far-infrared. But the expansion of the universe shifts this emission for very distant galaxies into the millimeter and submillimeter range. Consequently, one of the major research areas for the LMT will be the study of the early universe and the origin of the structures that became galaxies, stars, and planets.

The importance of the LMT for several areas of astronomy is discussed in some detail in Chapters 3 to 6. Of course, as is usually the case when major advances in instrumental capability occur, the most significant findings may well be completely unexpected!

2.3.2 Human Resources

Training the next generation of astronomers and engineers/technicians has always been a basic responsibility of both INAOE and UMass Amherst. Both institutions grant M.S. and Ph.D. degrees in astronomy and in related areas of science and engineering. At UMass Amherst more than half of all the astronomy Ph.D. students have done the major part of their research in radio astronomy, and there is no question that the LMT will enable this trend to continue. Given the very large investment of the U.S. in millimeter astronomy, including nearly a billion dollars in the Atacama Large Millimeter Array (ALMA) and NRAO facilities such as the Greenbank Telescope, it is crucial that students continue to be trained to carry out research with these instruments and to make the resulting scientific advances. Over the years, approximately half of all the observing time on UMass Amherst's FCRAO has gone to investigators from other universities, including many students pursuing doctoral degrees. This openness to students and scientists from outside the collaboration will continue with the LMT.

Likewise, a major reason for Mexico's investment in the LMT is the opportunity it provides to develop the country's scientific and technical infrastructure. Since the initiation of the LMT project, the number of students being trained in related areas at INAOE has increased significantly. Not only astronomers, but also engineers and technicians trained in the very latest developments in electronics, optics, control systems, cryogenics, and other

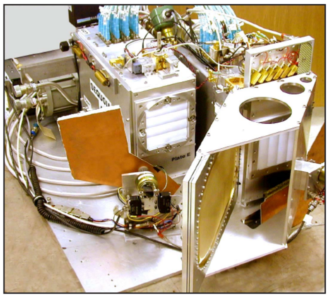


Figure 2.9 The SEQUOIA focal plane array (mm-wavelength camera) that will be one of the first instruments on the LMT. It is currently in use at the FCRAO.

areas critical for modern millimeter astronomy, are being educated. To an even greater extent than at UMass Amherst, a significant number of these graduates are entering private industry and contributing to the modernization of Mexico's technological base.

2.3.3 Development of New Technology

In order to study emission from galaxies billions of light years away, or interstellar molecules in the Milky Way at a fractional abundance less than a part per billion, or tiny icy bodies on the outskirts of the solar system, radio telescopes must not only, like the LMT, have large collecting areas but they must also be equipped with exquisitely sensitive electronics. Such receivers and spectrometers cannot be bought off the shelf; they must be developed and built by the participating institutes.

Even when so equipped, the LMT would be of little use if it could not maintain the precise shape of its primary mirror (the dish) against the distorting effects of gravity and thermal gradients, and if it could not point to extreme accuracy—to take full advantage of the telescope's resolution on the sky, it must be pointed to better than 1 arcsecond, equivalent to "hitting" a one-peso coin at a distance of 2 km (or, if you prefer, a dime at one mile). No other telescope can point to this accuracy. To maintain the shape of its giant dish and to achieve the precision pointing required, the LMT will be a "smart" telescope; its sensors and control system will continuously make the necessary adjustments in its shape and orientation. As one astronomer states, silicon becomes more important than steel for the LMT.

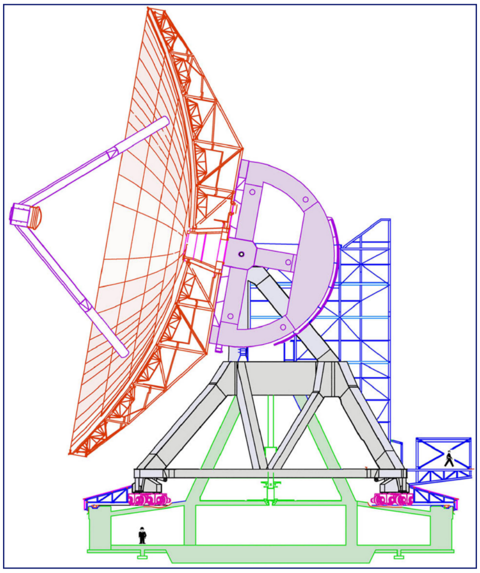


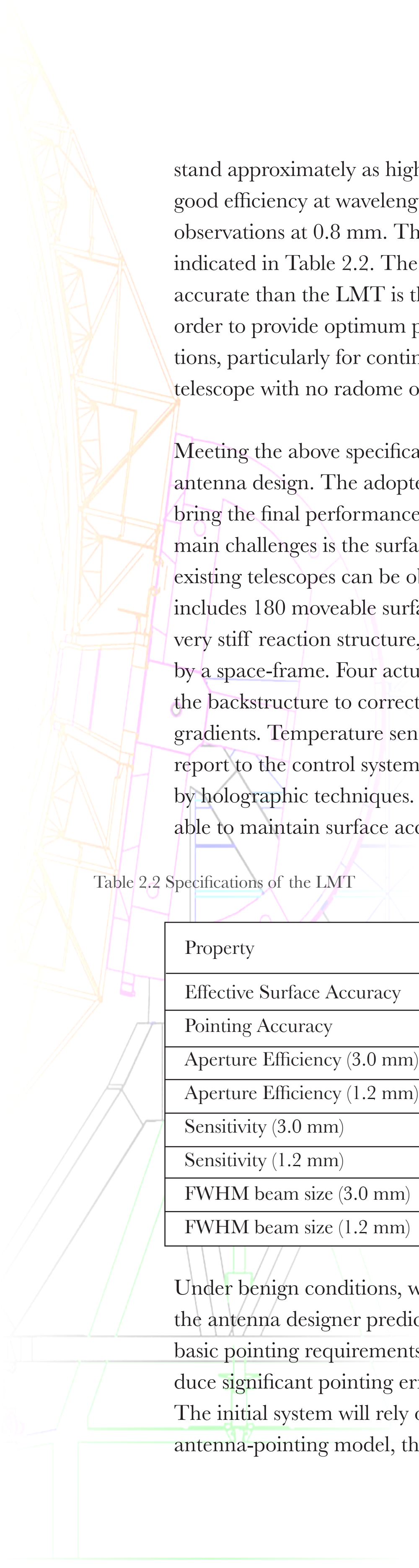
Figure 2.10 Schematic diagram of the LMT.

The engineering research and development required to build and equip the LMT will inevitably produce important new technology, benefiting the economies of both Mexico and the U.S. The programs in radio astronomy and in control systems at UMass Amherst have both led to the foundation of new high technology companies.

2.4 The Large Millimeter Telescope

2.4.1 Antenna

The LMT is a filled-aperture (single dish) mm-wavelength telescope whose reflecting surface will have a diameter of 50 m, so that the telescope will



stand approximately as high as a 20-story building. It will operate with good efficiency at wavelengths as short as 1 mm, and it will be capable of observations at 0.8 mm. The specifications for the LMT are ambitious, as indicated in Table 2.2. The largest existing telescope with a surface more accurate than the LMT is the much smaller 15 m JCMT in Hawaii. In order to provide optimum performance under the best observing conditions, particularly for continuum observations, the LMT will be an open-air telescope with no radome or astrodome enclosure.

Meeting the above specifications requires a significant step forward in antenna design. The adopted strategy employs various active systems to bring the final performance within the requirements. The easier of the two main challenges is the surface accuracy. Much of the improvement over existing telescopes can be obtained with an open loop active surface that includes 180 moveable surface segments. Each segment is supported by a very stiff reaction structure, which is attached to the reflector backstructure by a space-frame. Four actuators can adjust each space-frame in relation to the backstructure to correct for deformations due to gravity and thermal gradients. Temperature sensors on all relevant parts of the structure will report to the control system, and the surface will be periodically measured by holographic techniques. Simulations indicate that the LMT should be able to maintain surface accuracy in the presence of winds up to 10 m/s.

Table 2.2 Specifications of the LMT

Property	Specification	Goal
Effective Surface Accuracy	75 µm rms	70 µm rms
Pointing Accuracy	1.0 arcsec	0.6 arcsec
Aperture Efficiency (3.0 mm)	0.65	0.70
Aperture Efficiency (1.2 mm)	0.40	0.45
Sensitivity (3.0 mm)	2.2 Jy/K	2.0 Jy/K
Sensitivity (1.2 mm)	3.5 Jy/K	3.1 Jy/K
FWHM beam size (3.0 mm)	15 arcsec	
FWHM beam size (1.2 mm)	6 arcsec	

Under benign conditions, with low wind and stable nighttime temperatures, the antenna designer predicts that the structure is capable of satisfying the basic pointing requirements. However, wind and thermal loads introduce significant pointing errors that must be sensed and compensated for. The initial system will rely on standard techniques, such as the use of an antenna-pointing model, thermal stabilization of the structure, and careful attention to the design of the antenna motion controllers. These basic principles will be supplemented by measurements to characterize the behavior of the structure, including inclinometers mounted near the telescope elevation axis and temperature sensors on the structure, which may be used with finite element models to determine structural deformations and predict pointing behavior. Ultimately, metrology systems to actually measure structural deformations, such as the shape of the primary mirror and the location of the subreflector with respect to the best fit parabola, will be used to bring the pointing properties of the antenna to the final performance goal.

Figure 2.11 The LMT site: Tliltepetl (Volcán Sierra Negra, 4585 m) in the foreground and Citlaltepetl (Pico de Orizaba), Mexico's highest peak (5747 m), in the background[5].

2.4.2 Site

The LMT is sited at an altitude of 4585 m (about 15,000 feet) atop Tliltepetl (Volcán Sierra Negra), an extinct volcano in the state of Puebla that is adjacent to Citlaltepetl (Pico de Orizaba), the highest mountain in Mexico. The site is convenient to INAOE, with the total travel time from the Institute being about two hours. This location was selected following radiometric tests at a number of potential mountaintop sites in Mexico. The 19-degree latitude was a significant factor in the site selection, and the LMT will have excellent coverage of important southern sky sources such as the Galactic center, which will culminate at an elevation of about 45 degrees. The atmospheric opacity, as measured by a 225 GHz tipping radiometer, is low, with a median value corresponding to about 2 mm of precipitable water vapor during approximately nine months of the year (Figure 2.12).

The meteorological conditions at the site are quite mild for such a high altitude. Snowfall is generally light throughout the year, the diurnal temperature cycle is typically only 2 degrees C, and the average temperature varies seasonally by only about 5 degrees C. For antenna performance, the most critical factor is the wind speed, since the wind distorts the surface of the dish and affects the antenna pointing. The first, second, and third quartiles of the wind speed distribution are 2.2 m/s, 4.0 m/s, 5.8 m/s, respectively. The telescope has been designed with the goal of meeting its specifications in a wind of 10 m/s, which will be the case approximately 90% of the time (Figure 2.13).

Nonetheless, operation at such an altitude will not be a trivial matter. Oxygen enrichment of key rooms at the telescope site will be employed, and a remote observing capability will be developed that will enable visitors to operate the telescope from a more favorable altitude.

2.4.3 Instrumentation

Instrumentation for the LMT is of two basic types: spectroscopic and continuum. In spectroscopy the detected radiation is analyzed to measure the signal strength as a function of frequency (or wavelength), utilizing heterodyne techniques to obtain extremely high frequency resolution. Continuum systems, in contrast, measure the entire amount of energy received within a broad frequency range.

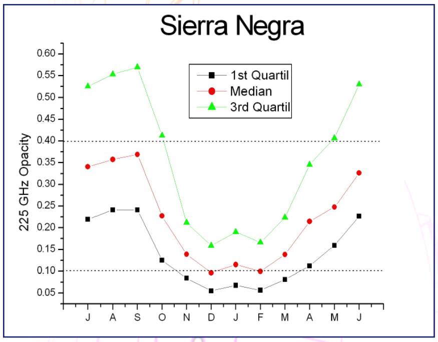


Figure 2.12 Opacity measured at 225 GHz for Tliltepetl (Sierra Negra), the LMT site. Horizontal scale gives month from July (J) to June (J). Opacity given for median, first quartile, and third quartile[6].

With nearly 2000 m^2 of collecting area and excellent surface accuracy, the LMT's sensitivity will exceed that of existing mm-wavelength telescopes by a wide margin. This basic sensitivity is enhanced for continuum observations by the single dish's ability to make use of very wide bandwidth incoherent detectors (bolometers). The LMT will consequently take a valuable place in the world's complement of mm-wave facilities, as shown in Table 2.3.

A binational LMT Science Team from UMass Amherst and INAOE has selected an initial set of instrumentation that emphasizes the special capabilities of the large single dish, as well as the practicalities of beginning to commission and operate the telescope. Of course, to keep the LMT in the forefront in future years, new instrumentation will continually be developed at UMass Amherst and INAOE.

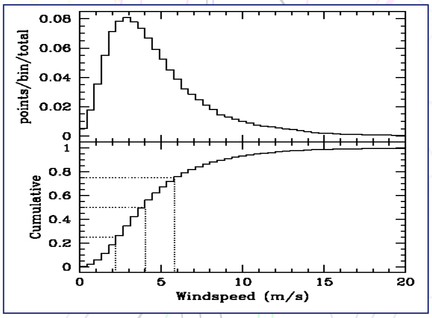


Figure 2.13 Wind speed for Tliltepetl, the LMT site: differential and cumulative probability distributions (upper and lower panel, respectively). Data from October 2000 to August 2003[7].

Already completed and operating on the FCRAO 14 m telescope is a 32-pixel, dual polarization heterodyne focal plane array for spectroscopy in the 85-115.6 GHz frequency band, christened SEQUOIA (SEcond QUabbin Optical Imaging Array; Section 8.3.1), with an associated digital autocorrelation spectrometer. SEQUOIA will be transferred to the LMT when it begins operation. It represents a real breakthrough in mm-wave radio astronomy receivers, utilizing the lowest noise amplifiers ever built in this frequency range (InP MMICs designed at UMass Amherst, with

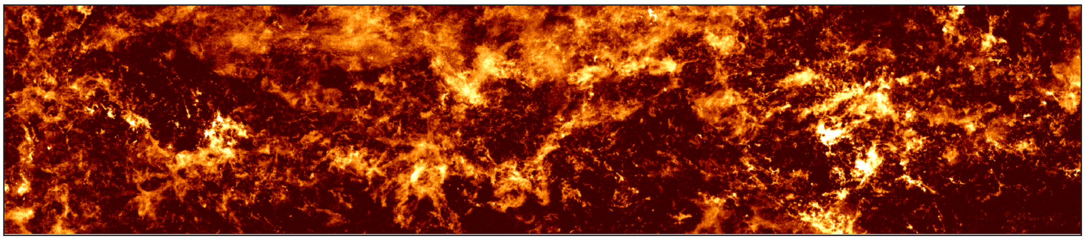


Figure 2.14 A 330 square-degree portion of the outer Milky Way mapped with an old version of SEQUOIA, showing the emission of carbon monoxide (CO), the standard tracer of molecular gas in galaxies[8].

narrow band noise as low as 30K at 103 GHz). It has already produced, for example, by far the largest scale images of the gas distribution in the Milky Way ever obtained (e.g., Figure 2.14). It will also play a major role in studies of the physics and chemistry of interstellar material in the Milky Way and other galaxies.

A second receiver system is also under development at UMass Amherst for use in the 3 mm band. This ultra-wideband receiver/spectrometer will switch rapidly between two positions on the sky with dual polarization feeds which simultaneously cover the range from 75-111 GHz with a spectral resolution of 30 MHz (Section 8.3.2). Called the Redshift Search Receiver, its principal purpose is to measure the redshift of spectral lines from galaxies in the early universe, thus determining their distance and properties. The associated spectrometer will be an analog autocorrelator with a large dynamic range.

Figure 2.15 AzTEC cryostat and readout electronics in the UMass Amherst Cryogenic Device Laboratory[9].

After the LMT surface accuracy and pointing have consistently reached the goals described above, it is expected that the 1.3 mm-wavelength atmospheric window will be its primary frequency band. A dual-polarization, sideband separation SIS (superconductor-insulator-superconductor) mixer receiver for the 210-275 GHz frequency band is currently being built at UMass Amherst for testing the antenna and for initial scientific observations (Section 8.3.3). Planning has begun for a state-of-the-art focal plane array (mm-wavelength camera) for spectroscopy at 1 mm, using receivers of this type.

One of the strengths of a large single dish telescope is the ability to use wide band incoherent detectors to obtain very high continuum (as opposed to spectral line) sensitivity. Such detectors are known as bolometers and are the optimum way to observe the continuous emission from dust particles or from high-energy charged particles. The LMT project is collaborating with an international group to construct a sensitive bolometer array for the LMT, called AzTEC (Astronomical Thermal Emission Camera). It will be a second realization of the Bolocam I instrument, which is being used successfully at the CSO. It provides 144 pixels and is designed to operate in the 2.1 and 1.1 mm bands. It will be a principal tool in the search for newly forming galaxies in the young universe, for astrochemical studies of dust in galaxies, for identifying protostellar cores in molecular clouds, and for the study of asteroids and comets in the solar system.

Whereas AzTEC is optimized for mapping in one frequency band at a time, a second continuum instrument known as the SPEctral Energy Distribution (SPEED) camera is being designed for simultaneous multiband photometry. SPEED uses a recently developed bolometer technology known as Frequency Selective Bolometers (FSBs) to simultaneously measure power in four frequency bands ranging from 2.1 mm to 0.85 mm wavelength. Measurements of the spectral energy distribution with SPEED will, for example, locate and study distant galaxy clusters by the distortions that they imprint on the Cosmic Microwave Background, and determine the temperature of dust emission in cometary atmospheres or interstellar molecular clouds in the Milky Way and other galaxies.

2.4.4 Very Long Baseline Interferometry with the LMT

Very Long Baseline Interferometry (VLBI) delivers sub-milli-arcsecond angular resolutions, and provides a singularly powerful method of studying energetic astrophysical phenomena on the smallest size scales. VLBI accomplishes this by correlating cosmic radio signals recorded at widely separated radio antennas, and using these data to synthesize a telescope whose effective aperture diameter is the antenna separation. Because of its extreme angular resolution, the VLBI technique has made unique contributions to astrophysics, including:

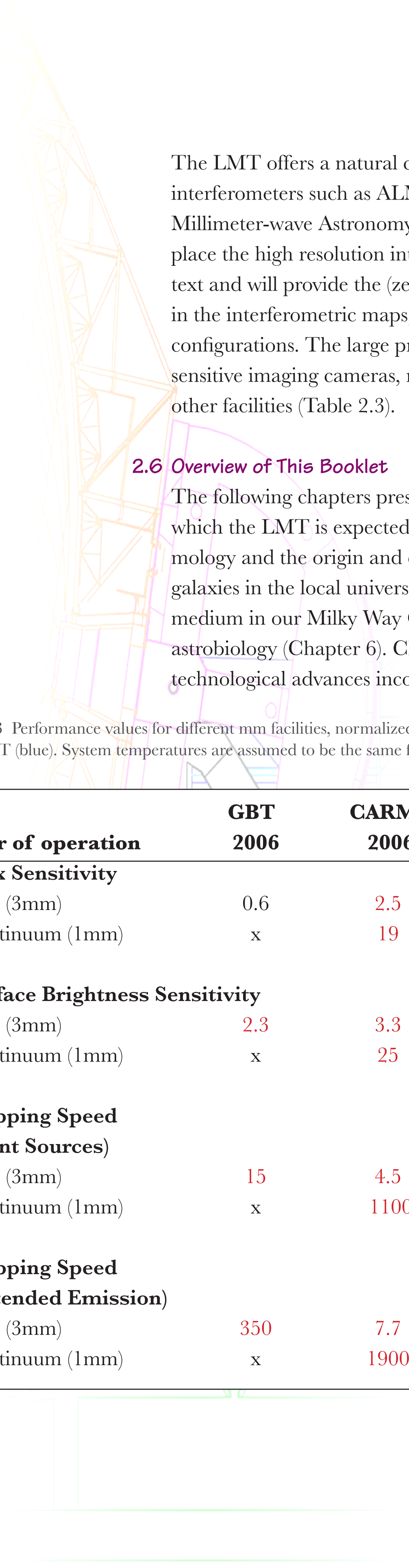
- Discovery of superluminal motions and relativistic jets in active galactic nuclei (AGN);
- The best evidence for the existence of Massive Black Holes in the nuclei of galaxies;
- The first ‘movies’ of Supernovae and Gamma-ray Burst explosions;
- Detailed study of star formation in merging galaxies through direct observation of Radio Supernovae;
- Directly linking accretion disks feeding AGN to the origins of relativistic jets;
- High-resolution ‘movies’ of maser emission in the circumstellar environments of evolved stars and protostars.

VLBI is now poised to undergo a transformative increase in capability in the next few years that will greatly expand prospects for exploration of a wide variety of astrophysical phenomena at even higher angular resolutions. This advance is due to two major developments on the horizon. The first is the commissioning and planning of new mm and sub-mm wavelength telescopes that will significantly increase the collecting area of VLBI arrays in the 86 GHz to 230 GHz frequency ranges. Chief among these new facilities is the LMT. At 86 GHz, an array comprising the Very Long Baseline Array (VLBA) and the LMT would be over twice as sensitive as the VLBA alone. At 230 GHz, the difference is even more striking, with the addition of the LMT increasing current sensitivities of 1 mm wavelength VLBI arrays by more than a factor of 3. The second key development is the rapid increase in capability of next-generation VLBI recording systems, which will increase their bandwidth by a factor of 16 in the period prior to LMT first light. Taken together, these advances translate to an order of magnitude increase in sensitivity for high frequency VLBI with maximum angular resolutions between 70 and 35 micro-arcseconds—a resolution equivalent to hitting a dime on the opposite of the Earth! Such unprecedented capability will permit groundbreaking observations in several areas (Sections 4.6 and 5.3). Although a VLBI correlator is not included in the initially planned instrumental complement of the LMT, one can be borrowed until such time as purchase is possible.

2.5 Relation to Other Telescope Projects

The 50 m LMT is a unique facility, equipped with an exciting array of state-of-the-art instruments that are complemented by the high angular resolution and sensitivity provided by the large collecting area. These properties provide the capability to carry out critical new scientific investigations.

For example, the resolution of the LMT, 4.2 to 14.8 arcsec between 850 μm and 3 mm, is higher by a factor 3 to 5 than that provided at the same wavelengths by current single-dish telescopes such as the CSO 10 m, the JCMT 15 m, and the IRAM 30 m, and is hence sufficient to resolve the extragalactic background into discrete sources. In contrast, the deepest imaging surveys conducted by the existing sub-mm/mm telescopes are confusion-limited at a sensitivity level that can resolve only 20-50% of the individual sources that contribute to the integrated emission of the extragalactic background. Furthermore since less than 0.01% of the sky has been mapped and resolved at mm-wavelengths, the LMT will survey large regions of the sky to characterize the typical properties of the extragalactic millimeter population (Chapter 3).



The LMT offers a natural complement to the next generation of (sub-)mm interferometers such as ALMA and the Combined Array for Research in Millimeter-wave Astronomy (CARMA). The LMT's extended imaging will place the high resolution interferometer maps into an environmental context and will provide the (zero-spacing) emission that will be resolved-out in the interferometric maps, even when they operate in their most compact configurations. The large primary-aperture of the LMT, coupled with its sensitive imaging cameras, result in a mapping-speed 100 times faster than other facilities (Table 2.3).

2.6 Overview of This Booklet

The following chapters present in more detail the scientific areas within which the LMT is expected to make major contributions, including cosmology and the origin and evolution of galaxies (Chapter 3), the nature of galaxies in the local universe (Chapter 4), star formation and the interstellar medium in our Milky Way Galaxy (Chapter 5), and planetary science and astrobiology (Chapter 6). Chapter 7 then describes some of the principal technological advances incorporated in the LMT, while the instrumental

Table 2.3 Performance values for different mm facilities, normalized to the LMT. For values in red, performance is better with LMT (blue). System temperatures are assumed to be the same for all facilities at the indicated wavelengths[10]

Year of operation	GBT 2006	CARMA 2006	LMT 2008	ALMA 2008	ALMA 2012
Flux Sensitivity					
Line (3mm)	0.6	2.5	1.0	1.1	0.3
Continuum (1mm)	x	19	1.0	2.9	0.7
Surface Brightness Sensitivity					
Line (3mm)	2.3	3.3	1.0	3.3	2.5
Continuum (1mm)	x	25	1.0	8.8	6.6
Mapping Speed (Point Sources)					
Line (3mm)	15	4.5	1.0	1.1	0.1
Continuum (1mm)	x	1100	1.0	34	2.2
Mapping Speed (Extended Emission)					
Line (3mm)	350	7.7	1.0	10	5.8
Continuum (1mm)	x	1900	1.0	320	180

complement for use on the telescope is presented in Chapter 8. The role of the LMT project in the development of human resources in both the U.S. and in Mexico is the topic of Chapter 9, and outreach to the public is discussed in Chapter 10. The LMT will be operated through the Large Millimeter Telescope Observatory, the organization of which is given in Chapter 11, along with present plans for operating the telescope. Finally, opportunities for LMT observing by the astronomical communities in Mexico, the U.S., and worldwide are given in Chapter 12, including procedures for bringing guest instruments. A glossary concludes this publication.

2.7 References

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