Large Millimeter Telescope (LMT): an "Extremely Large Telescope" Platform for New Instruments and Large Surveys in the ALMA Era

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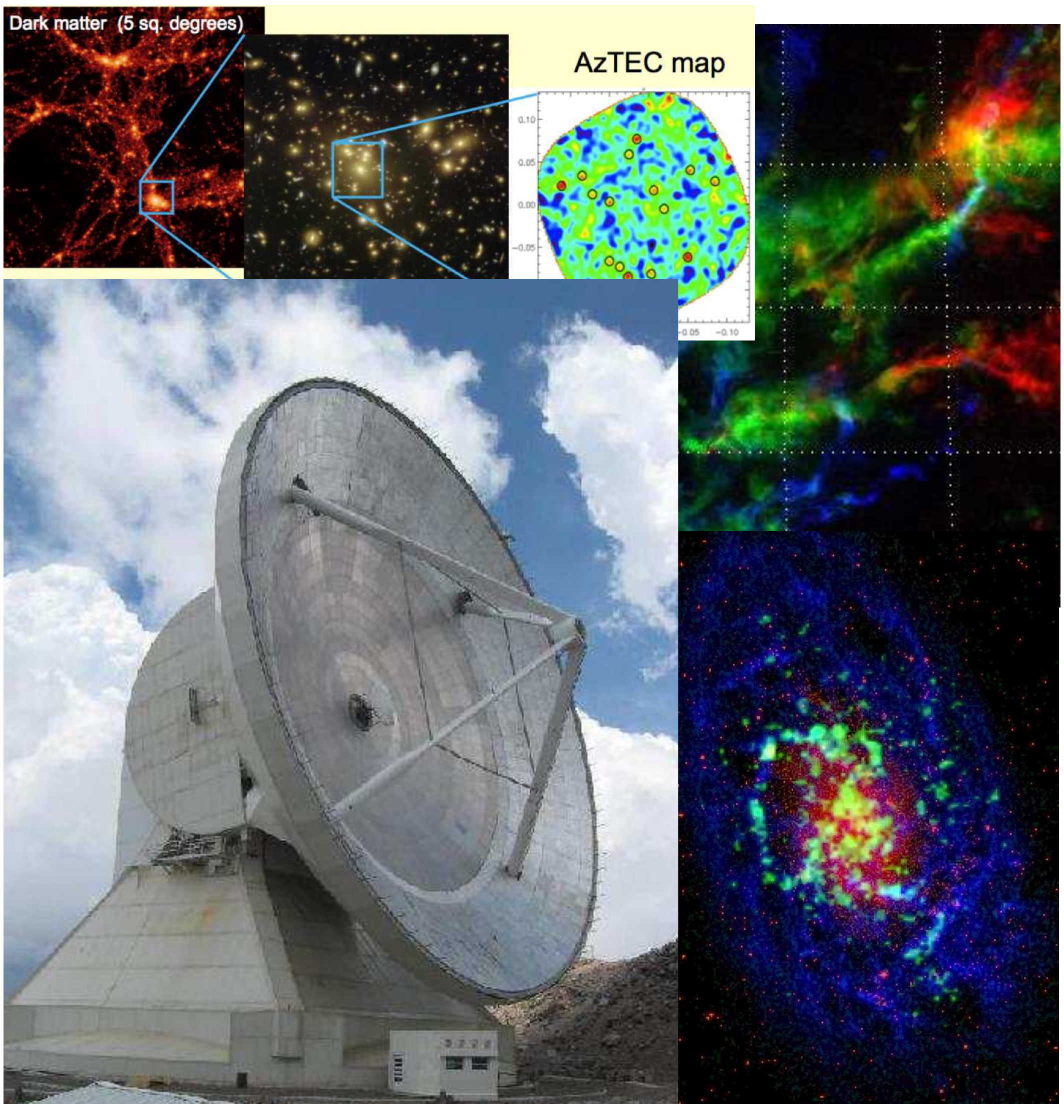

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1 Introduction

The scientific motivation for a 30 meter class optical/IR "Extremely Large Telescope" (ELT; also named GMT/GSMT/TMT) is easy to understand by its tremendous potential to produce new discoveries in all fields of astronomy and astrophysics, from the study of the Solar System to the first stars and the first galaxies. The improvement in sensitivity and angular resolution anticipated over the existing 10-meter class telescopes as well as the next generation instrumentation serve as the main driver behind the strong science case, as presented to the 2010 Decadal Review Panel by the respective consortia representing each project.

Endorsed by the 2000 Decadal Review as one of the highest priority projects in astronomy and astrophysics, the Atacama Large Millimeter Array (ALMA) is an example of such an ELT operating in the millimeter (mm) and submillimeter (smm) wavelengths, with an anticipated completion date of 2012. The orders of magnitude improvement in sensitivity and/or angular resolution over its predecessor facilities and the resulting scientific discoveries are eagerly awaited by the entire astronomical community across the electromagnetic spectrum.

The construction of a second "ELT" operating in the millimeter band is already near its completion. The 50-meter diameter Large Millimeter Telescope (LMT), built by an international collaboration between the University of Massachusetts and the Instituto Nacional de Astrofísica, Óptica, y Electrónica (INAOE) in Mexico, represent a factor of 3 to 40 improvement in collecting area and up to 5 times higher angular resolution over the existing 10-15 meter class facilities and interferometers (see Table 1). Employing its suite of powerful first light instruments already in hand, the LMT is poised to achieve a broad range of new discoveries in the origin of life and the Universe through its break-through advances in sensitivity, mapping speed, and frequency coverage. In addition, its complementary advantage for conducting large surveys provides a critical opportunity to realize ALMA's full scientific potential. To be built and operated at only a small fraction of the cost of the ALMA, the LMT has more than 1/3 of the ALMA collecting area on a high altitude site (4600 m or 15000 ft elevation) and offers an exceptional raw sensitivity. Innovative new instruments multiplexing in angular- and the frequency-domain will offer *many orders of magnitudes improvements in mapping and discovery speed over the ALMA* and should open up a new discovery window into the time-domain science as well. Its $+19°$ latitude ensures an excellent overlap with the ALMA in the sky coverage (over 80%).

In this Technology Development white paper, we describe the LMT as a major platform for future innovative mm/smm instrument development programs in the US and elsewhere. Sensitive, large area imaging and spectroscopic surveys carried

Table 1: Present and future US millimeter/submillimeter facilities[a]

Telescope	Collecting Area (m^2)	Frequency Range	Status
GBT	7850	0.3 – 100 GHz	in operation
CARMA	730	85 – 300 GHz	in operation
ARO	79	85 – 500 GHz	in operation
CSO	79	200 – 800 GHz	in operation
SPT	79	200 – 800 GHz	in operation
SMA	38	200 – 800 GHz	in operation
LMT	1960	70 – 400 GHz	under construction
ALMA	5650	85 – 900 GHz	under construction
CCAT	490	200 – 900 GHz	in development

[a] based on the Radio, Millimeter and Submillimeter Planning Group report for the NSF 2005 Senior Review.

out using these instruments should provide the brightest and the most interesting targets for follow-up investigations in exquisite detail using the ALMA, maximizing the scientific return on the large investment already made in the ALMA project by the international astronomy community. Explorations of the new parameter space in the depth and breadth of the surveys as well as the exploration of the spectral and temporal domains should also lead to discoveries of new physical phenomena along with obtaining new insights on important familiar problems.

2 Current State of the Art and the ALMA

A detailed comparison of angular resolution and field-of-view among the representative subset of current (CSO and CARMA) and future (LMT and ALMA) millimeter and submillimeter facilities are shown in Figure 1. The ALMA stands out with its broad range of frequency and angular resolution coverage, as shown on the left panel. The present state-of-art interferometers like the CARMA and the SMA (not shown) cover a narrower frequency range and angular resolution and have only 5-35% of the collecting area. Existing single dish telescopes such as the CSO have a narrower frequency coverage and have even smaller collecting areas (~ 100 m^2; see Table 1 for a more extensive list).

The diffraction-limited field-of-view is a major shortcoming for most interferometers, and it is also one of the principal handicaps of the ALMA. As shown on the middle panel of Figure 1, the use of a multi-pixel array camera enables single dish telescopes like the LMT and CSO to fully utilize their focal plane and to image a much larger area instantaneously. Broadband bolometer arrays with 10^4 pixels are now readily available and are capable of increasing the continuum mapping speed by several orders of magnitude compared with interferometers. A comparison of sensitivity and mapping speed, shown in Figure 2, shows that indeed the ALMA has up to 3 times higher point source sensitivity over the LMT, but the LMT with its suite of first light instruments already has up to two orders of magnitude faster mapping/survey speed over the ALMA and over three orders of magnitude faster than CARMA. When compared with a single dish telescope of the same collecting area, an interferometer can achieve a higher angular resolution at the expense of surface brightness sensitivity, and this in turn means the LMT will have 2-6 times better brightness sensitivity than the ALMA despite its 3 times smaller collecting area.

The large diameter of the LMT also leads to an angular resolution of $\sim 5''$ at 1mm, approaching the resolution of interferometers like CARMA and ALMA, while greatly exceeding that of the existing single dish telescopes like the CSO ($\sim 25''$ at 1mm). This means the LMT will be able to conduct large surveys rapidly at the angular resolution approaching that of the ALMA and identify the most interesting targets to follow-up, freeing the ALMA from conducting its own, very expensive surveys[1]. We note that the severe confusion noise associated with their large diffraction limited beams limits the usefulness of the existing 10-15 meter class millimeter and

[1]For example, the "Ultradeep ALMA continuum survey" outlined in the ALMA Design Reference Science Plan (http://www.eso.org/sci/facillities/alma/drsp/) would require 4120 hours to map less than 300 sq. arcmin to 4-20 μJy sensitivity at 850 μm.

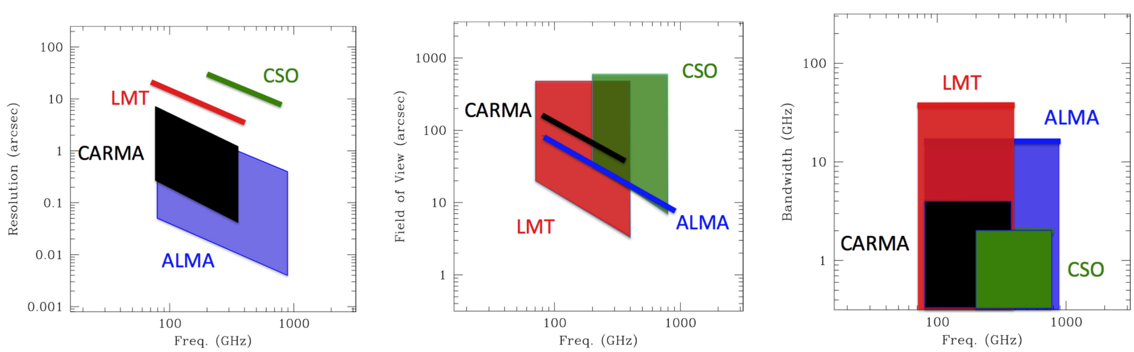

Figure 1: A comparison of angular resolution (left), field-of-view (FOV; middle), and spectral bandwidth (right) among current and future mm/smm facilities. The LMT closely matches the angular resolution of the compact configurations of interferometers like CARMA and ALMA while greatly exceeding their FOV.

	LMT	ALMA	CARMA	GBT
Collecting Area	1.0	2.9	0.4	4.0
Flux Sensitivity				
Line (3mm)	1.0	2.85	0.39	1.72
Continuum (1mm)	1.0	1.09	0.05	--
Brightness Sensitivity				
Line (3mm)	1.0	0.40	0.30	0.43
Continuum (1mm)	1.0	0.15	0.04	--
Mapping Speed				
Line (3mm)	1.0	0.17	0.13	0.0029
Continuum (1mm)	1.0	0.0055	5.2e-4	--

Figure 2: A comparison of flux density and surface brightness sensitivity and mapping speed. All figures of merit are normalized to that of the LMT (with its first light instruments) so that a value less than unity (blue) means the LMT has a superior performance. Assumptions made in these comparisons are found in the LMT Memo by M. Yun (http://www.lmtgtm.org/internal/Yun04Memo.pdf)

submillimeter telescopes for the study of galaxies in the early universe.

The advent of signal processing techniques and rapidly increasing computing capacity have also made the spectral bandwidth an important new performance parameter for an observational facility. In addition to the obvious benefit of better continuum sensitivity, a higher spectral bandwidth enables the full utilization of the spectral information such as a blind redshift search or multi-transition analysis of physical conditions of the emitting medium, particularly in the mm/smm bands that are extremely rich in molecular transitions. These scientific motivations have driven the total bandwidth requirement of the ALMA and its SIS receivers to 16 GHz. Adopting the MMIC technology, the LMT spectroscopic instruments have achieved a factor of several larger total bandwidth, particularly excelling in this area (see the right panel in Fig. 1).

3 Current/Future Instruments and Large Surveys

Aside from obtaining a large collecting area inexpensively, a large single dish telescope also provides an ideal platform for innovative instrument development. Unlike the case for the ALMA where an upgrade requires a set of $\geq$50 identical new instruments at $\geq$ \$30M per band, a new receiver system for the LMT requires a single unit of custom-made and highly optimized instrument, guaranteeing high performance

Instrument	*Status*	*Description*
SEQUOIA	**COMPLETE; deployed on UMass 14m antenna.**	**32 pixel heterodyne focal plane array for 85-115 GHz**
AzTEC	**COMPLETE; deployed on JCMT and ASTE telescopes.**	**144 pixel bolometer focal plane array; Si-Ni spider-web bolometers; Operating bands 1.1, 1.4, and 2.1mm**
Redshift Search Receiver	**COMMISSIONED at UMass 14m telescope.**	**Dual pixel, dual polarization ultra-wideband receiver for 75-111 GHz**
SPEED	**UNDER DEVELOPMENT**	**4 pixel x 4 frequency array; Frequency Selective Bolometers at wavelengths 0.85, 1.1, 1.4, and 2.1 mm.**
1mm Heterodyne Receiver	**UNDER DEVELOPMENT**	**Single pixel, dual polarization, SIS, heterodyne receiver for 210-275 GHz; 8 GHz bandwidth in each sideband.**

Figure 3: A summary of the first generation LMT instruments.

and efficiency at a reasonable total cost. Innovative, cheaper instruments built as a research project (often by students) is the hallmark of the university instrument program in the US, generally for a large single dish telescope. Technology development and student training in the instrumentation program have been the key component of the UMass/FCRAO group, and this tradition will continue into the LMT era. The next generation LMT instruments may cost as much as $5M or more, requiring collaborative efforts involving external research groups.

A brief description of the first generation LMT instruments is given in Figure 3. They are designed to take full advantage of all “performance multipliers” (large focal plane, angular resolution, spectral bandwidth) and to achieve the sensitivity and mapping speed previously only imagined. They are also intended to serve as prototypes for larger next generation instruments that will follow once the telescope is fully operational. The two array imagers SEQUOIA and AzTEC have already been completed and produced high-impact science results. The Redshift Search Receiver (RSR) has also been commissioned and produced some exciting early science results. The development of the two remaining instruments SPEED and 1mm receiver is still ongoing. When installed on the LMT, these first light instruments will become the most powerful instruments of their type in the world immediately. The superb raw sensitivity of the LMT will demand even more powerful and innovative instruments to fulfill its scientific and discovery potential.

In advocating the importance of wide-field surveys in the next decade, Strauss

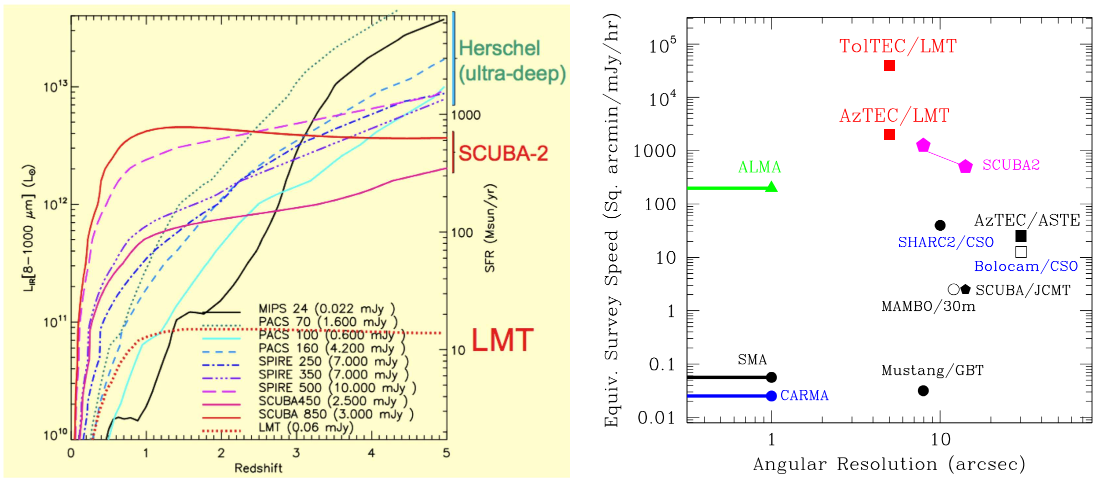

Figure 4: **(LEFT)** Comparison of confusion-limited sensitivity for IR luminosity (star formation rate; SFR) among Herschel, SCUBA-2, and the AzTEC on LMT. The AzTEC on LMT is the only instrument sensitive enough with sufficient angular resolution to probe galaxies with SFR∼10-30 $M_\odot/yr$. **(RIGHT)** A comparison of survey speed for bolometer cameras on LMT with other survey instruments.

et al. write in their 2010 DR Position Paper[2] that facilities designed for wide-angle surveys have been important engines for new discoveries and many of the most important questions in astrophysics are best tackled with well coordinated massive surveys. As the most powerful survey facility to provide the complementary mm/smm data for future massive multi-wavelength surveys as well as the main complementary facility for ALMA, we intend to develop the LMT as a powerful platform for innovative new mm/smm instrument programs, both within our institutes and those located elsewhere.

Continuum Instrument Program and Time Domain Science

The AzTEC camera has already been demonstrated as the best current generation instrument of this type by conducting a wide range of successful scientific programs as a visiting instrument at the 15-m JCMT on Mauna Kea (2005-2006) and at the 10-m ASTE telescope in northern Chile (2007-2009), more than quadrupling the area and number of sources detected compared with the surveys done by other instruments (SCUBA, MAMBO, BOLOCAM) combined. When installed on the LMT, mapping speed of AzTEC will exceed that of the ALMA and SCUBA-2 on JCMT (see Fig. 4).

[2] http://www8.nationalacademies.org/astro2010/DetailFileDisplay.aspx?id=432

More important is that the higher angular resolution ($5''$ at 1100 μm) achieved on the LMT is required to get past the confusion noise limiting the present surveys on 10-15 meter class telescopes and to resolve the majority of the mm/smm extragalactic background. For example, AzTEC can uniquely study *a large sample* of the faintest sources identified by deep Herschel surveys (see left panel of Fig. 4).

There are several important reasons as why an even more powerful continuum instrument is needed. As stated by Strauss et al. in their white paper, wide-area surveys will continue to expand their role in shaping our understanding of the Universe, and yet no mm/smm instrument can resolve most of the extragalactic IR background or detect an L^* galaxy during the galaxy formation epoch at $z > 2 - 3$. In the millimeter band, the well-known negative k-correction enables the detection of dust emission from sources at $z = 10$ as easily as at $z = 1$, and the millimeter bolometer cameras like AzTEC on LMT have the potential to *discover* the first massive galaxies during their formation. The TolTECH instrument, a concept monolithic camera with 10^4 pixels, will achieve a mapping speed of 10 deg^2/mJy/hr on LMT, and such a combination of sensitivity and mapping speed is needed to survey large enough areas to the required depths and find these rarest objects. Such a high mapping speed is also required to patrol a significant fraction of the sky each day and to bring the time-domain science within reach. Beyond the highly variable, beamed flat-spectrum radio sources, very little is known about the time-domain behavior of the mm/smm sky. Recent discoveries of mm/smm flares associated with high-z gamma ray bursts and accretion events associated with the nearest super-massive black holes (SgrA*/M81*) as well as some of the young stellar objects offer a glimpse at exciting new discoveries to be made in the time-domain.

The SPEED instrument currently under-development is a prototype of a much larger multi-band "color" camera that will be extremely powerful for probing the coldest and the highest redshift sources through a color-selection technique. Such an instrument would also offer a powerful new tool that can exploit other frequency-dependent phenomena such as a high resolution study of the Sunyaev-Zel'dovich effect and related cluster physics. Again, this is an entirely new type of instrument with a great potential for new discoveries when mounted on the LMT.

Spectroscopic Instrument Program

The 16 dual polarization heterodyne array camera SEQUOIA has been the main facility instrument for the FCRAO 14-m telescope, producing several high impact studies such as the Galactic Ring Survey (Jackson et al. 2006, ApJS, 163, 145), the COMPLETE Survey of Star-Forming Regions (Ridge et al. 2006, AJ, 131, 2921),

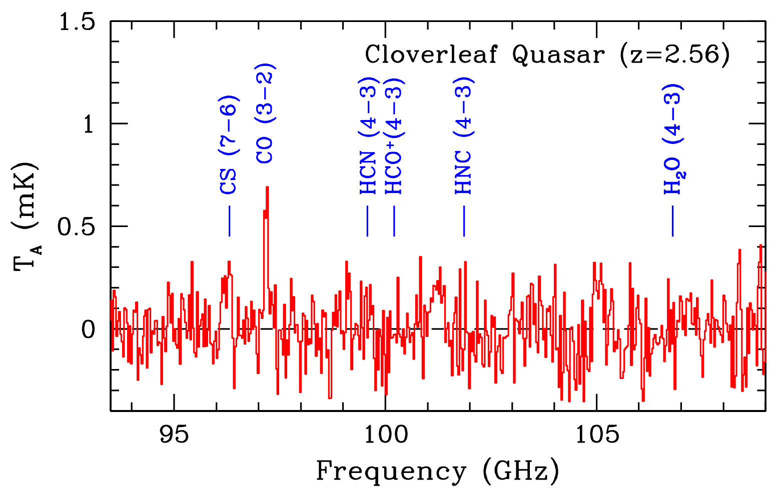

Figure 5: A 16 GHz wide Redshift Search Receiver spectrum of the $z = 2.56$ Cloverleaf Quasar obtaining using the FCRAO 14-m telescope. The redshifted CO (3–2) is clearly visible near 97.1 GHz. This line can be detected with the same S/N in just 1/40th of time (6 minutes) on the LMT.

and the Taurus Molecular Cloud Survey (Narayanan et al. 2008, ApJS, 177, 341). Such a multi-beam spectroscopic array camera on the LMT will have the sensitivity to enable detailed investigations of molecular ISM physics and gas dynamics in the entire Milky Way and in nearby galaxies.

The large sample of high-z dusty starbursts and AGNs identified by the LMT continuum instruments may be too faint to be studied by the traditional optical techniques – many of the securely identified AzTEC sources using the SMA are undetected in deep optical images (see Younger et al. 2007, ApJ, 671, 1531). The Redshift Search Receiver (RSR) is designed to measure the redshifts of such heavily obscured and gas-rich galaxies in the early universe. The RSR will offer not only the redshift information on the gas-rich galaxies identified by AzTEC, Spitzer, and Herschel, but it will also offer information on the physical and chemical properties of their molecular ISM. An extremely stimulating idea for a powerful future instrument is to combine these two instruments to create a multi-beam spectroscopic imager that can map the distribution of $\sim 10^{5-6}$ gas-rich galaxies over a wide-range of redshifts, tracing the formation and evolution of large scale structure and the mass build-up history of individual galaxies (see Astro2010 Science White Papers by Yun et al. and Putman et al.). Given the urgent need for large, deep spectroscopic surveys and the paucity of large aperture spectroscopic survey telescopes planned for the next decade (see Astro2010 Science White Papers by J. Gunn et al. and D. Eisenstein et al.), the scientific impact of such an instrument will be enormous.

VLBI

The large collecting area (second only to ALMA) and its fortuitous location connecting the ALMA and the existing mm/smm VLBI elements in the US makes the LMT a highly attractive addition to the future mm-VLBI experiments – see Astro2010 science white papers by Doeleman et al., Greenhill et al., and Braatz et al. When equipped with the requisite VLBI instrumentation, the LMT will play a key role in testing general relativity and strong field gravity and will enable precision measurements of the geometry of the Universe through accurate determination of geometrical distances and the Hubble constant.

4 Summary, Timeline, and Recommendations

A large collecting area on a high altitude site (4600 meter) translates to an enormous raw sensitivity, and the 50-m LMT is truly an "ELT" rivaling and complementing another mm/smm ELT, the ALMA. When combined with the state-of-the-art new instruments, the LMT will become a powerful new mm/smm survey facility complementing other future wide-area surveys and shape our understanding of a broad range of astronomical problems during the next decade. Given the cost and effort involved in building the next generation instruments, our group will seek extensive collaboration with other groups in the US and elsewhere. The great raw sensitivity of the LMT demands the more powerful new instruments, including innovative guest/PI instruments, to fulfill its scientific potential.

We anticipate all construction and commissioning activities to complete in 2011-2012. Science operation using the first generation instruments should begin 2011. Discussions and concept studies of the second generation instruments have already begun, and the development and construction should start in 2011. A more detailed discussion of the LMT timeline is found in the report submitted to the Astro2010 Programs Subcommittee.

We recommend the Astro2010 Review Committee to recognize the LMT as a powerful platform for new instrument development and to endorse the use of these powerful instruments for conducting large surveys as a key component of the coordinated wide-area survey campaigns and for maximizing the scientific potential of the ALMA.