The Large Atacama Submillimeter Telescope

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ABSTRACT

Cornell and Caltech are undertaking a two year conceptual design study for a 25-m class sub-mm telescope. The nominal location for this facility will be the high Atacama Desert of Northern Chile. The baseline design is a segmented mirror telescope optimized for operation at wavelengths longer than 200 microns to take advantage of a low precipitable water vapor at the site. We discuss science drivers and their implications for telescope design and technical requirements, and planned technical study areas.

Keywords: telescope, sub-millimeter, Atacama, Chile

1. INTRODUCTION

Scientific and technical progress on systems operating in the sub-mm regime has been tremendous over the past decade. The success of CSO (Caltech Submillimeter Observatory) and JCMT (James Clerk Maxwell Observatory) has been clearly demonstrated (see results posted at their respective web sites for more information: www.submm.caltech.edu/cso and www.jach.hawaii.edu/JACpublic/JCMT). This success is will continue with the construction of the LMT (Large Millimeter Telescope, www.lmtgtm.org), a 50-m antenna located on Sierra Negra (4600 m) about 250 km east of Mexico City, and ALMA (Atacama Large Millimeter Array, www.alma.nrao.edu), an interferometer array of not less than 64, 12-m antennas located in the Chajnantor region (5000 m) of the Atacama desert. ALMA will operate from 350 μm to 10 mm. While the LMT is designed for operation from 1 to 4 mm it may eventually extend to shorter wavelengths.

The need for larger telescopes is twofold. First is the greater intrinsic sensitivity associated with a larger aperture. In the sub-mm regime we expect diffraction limited performance so that sensitivity will scale as the squared of the aperture and hence the speed of a given observation will increase as the fourth power of the aperture. The second reason is confusion. For instance, SCUBA observations from JCMT at 850 microns have reached the confusion limit. ALMA overcomes both of these factors by having a large number of telescopes and a large baseline. However, ALMA will have a limited instantaneous field-of-view. Single aperture telescopes can easily obtain large fields-of-view through the use of array technologies in the focal plane.

Cornell University and the California Institute of Technology have signed an agreement to perform a two year concept study for a 25-m class sub-mm telescope (hereafter call the AT25). We believe such a telescope will provide exciting science and complement ALMA. Pending a (likely) successful outcome of the concept study, the goal is to complete the AT25 by 2012. Since the AT25 is a relatively late player in this field, it is critical that it cover sufficient new phase space to pursue compelling new science. In order to ensure this, design requirements have been imposed on the aperture, water vapor burden, surface accuracy, and field-of-view. These include:

1. Aperture: 25 meter class. This is significantly larger than APEX, SMT, CSO or JCMT and ensures that it is not confusion limited in exposures of 24 hours or less in the shorter wavelength bands.

2. Water Vapor Burden: < 1 mm. This is needed to reach the short wavelength sub-mm windows

3. Surface Accuracy: ~ 12 microns rms. A high surface accuracy is needed to obtain good efficiency in the 200 micron window (1.5 THz)

4. Field of View: > 5 arcminutes. Faint source surveys will be a primary niche for this facility; therefore a large that could be populated with 10,000 element arrays is required.

In addition to refining the science, the concept study will look at a number of trade areas including the shortest wavelength of operation (200 vs. 350 microns), aperture, closed vs. open figure control, and dome design.

Currently the nominal location is in the high Atacama Desert of Northern Chile near the ALMA site. The telescope will be located on one of the peaks in the region thereby reducing the water vapor overburden compared to ALMA. Figure 1 shows a plot of the point-source, continuum sensitivity of various sub-mm telescopes that are either operating or under construction operation compared to our expectations for a 25-m telescope. Here we assume 1000 microns of water vapor ALMA and “optimized” values for AT25 (see Note at end). Spitzer, Herschel, APEX, JCMT, and LMT are taken to be confusion limited. The confusion limit for AT25 is also shown. The AT25 does surprisingly well when compared to ALMA at the shorter wavelengths. This is due to better atmospheric transmission, better surface accuracy for the telescope, and larger bandwidth. In addition, assuming 10000 pixel arrays with Nyquist sampling, the AT25 will have an instantaneous field-of-view that is about 600 times larger than ALMA. Of course, ALMA’s forte will be its high sensitivity and high spatial resolution.

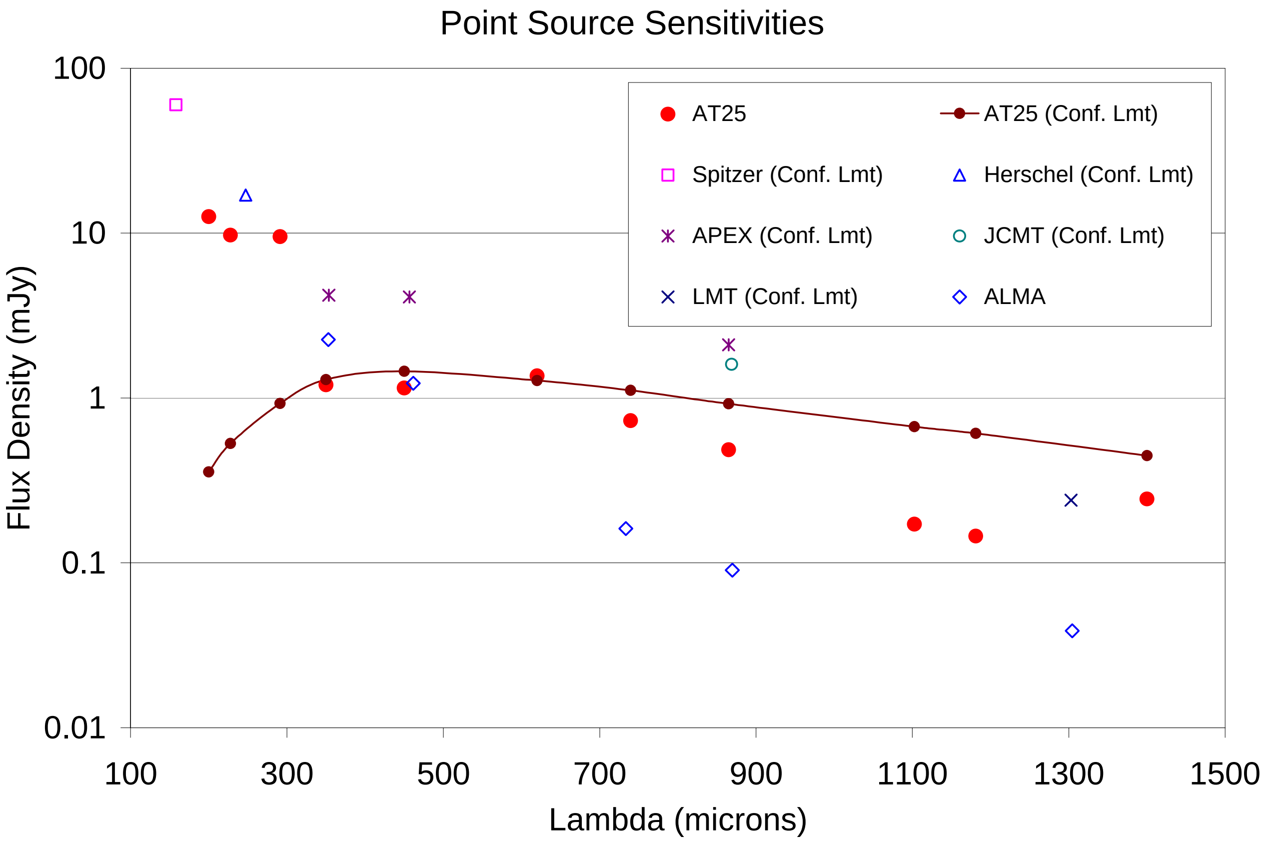

Figure 1: 5-sigma, 3600 second point-source, continuum sensitivity of various current and planned sub-mm telescopes. For Spitzer, Herschel, APEX, JCMT, and LMT confusion limit are given. The AT25 confusion is also shown.

In the following sections we outline some of the science justification and some technical aspects of the AT25. Many of these topics will be active areas in the concept study. We have formed eight study groups to explore these issues further during the study phase. There are four science and four technical groups which are listed in Table 1 along with the chairs of each of the groups.

Table 1: Concept Study Groups

Group	Topic	Group Chair
S1	Solar System	Don Campbell
S2	Star Formation	Paul Goldsmith
S3	Galaxies	Andrew Blain
S4	Cosmology	Sunil Golwala
T1	Telescope	Jonas Zmuidzinas
T2	Instrumentation	Gordon Stacey
T3	Site	Riccardo Giovanelli
T4	Management	Tom Phillips/ William Langer

2. SCIENCE OVERVIEW

Below we discuss some of the areas we believe the AT25 will have a scientific impact. These include the fields of galaxy formation, evolution of cosmic structure, cosmic microwave background (CMB) astrophysics, interstellar and nearby galaxy structure, stellar and planet formation, circumstellar disks, polarization work and Solar System studies. The science return will be traded-off against telescope and instrumentation requirements, and ultimately cost.

High Redshift Galaxies:

Among the potentially most important results of Cosmology in the last decade is the realization that the star formation rate at redshifts $z > 1$ was much higher than at present, and that much of the light produced by stars at high redshift reaches us in the FIR, after having been reprocessed by the dust in these galaxies. Indeed, most of the sub-mm/FIR radiation background discovered by the COBE satellite, which amazingly is equal in energy to the optical/IR background, appears to have been produced by dusty galaxies at high redshift. The understanding of the process of galaxy formation and the star formation history of the universe must therefore contend with these facts; a complete picture cannot be obtained without sub-mm/FIR observations -- sub-mm/FIR observations may in fact provide *most* of the picture. The characterization of the structure of the high redshift Universe is therefore linked to our ability to study large samples of galaxies in the sub-mm spectral regime. At this stage, existing ground-based facilities are giving us just a glimpse at the most luminous objects. A significantly larger, more sensitive telescope, such as the AT25, would uncover vast numbers of more typical systems, through large, blind surveys in multiple sub-mm bands. The improvement in angular resolution which accompanies the larger telescope size is also needed to overcome spatial confusion.

Access to multiple sub-mm bands will also allow the AT25 to not only an estimate of a galaxy's spectral energy distribution, but also a rough measurement of its redshift by photometric means. The estimated accuracy of photometric sub-mm redshifts is ~ 20%, sufficient to effectively map the history of the star formation of the Universe, as well as the evolution of its clustering properties by monitoring the scaling properties of the 2-point angular correlation function $\omega(\theta)$ at different redshift intervals.

Access to spectral lines, such as high rotational quantum number transitions of carbon monoxide (CO) and, especially, the fine structure transition of ionized carbon [CII] (rest wavelength of 158μm), will play a very important role in yielding accurate redshifts, dynamical information of merging systems and insights in the physics of the star-forming gas.

CMB and the Sunyaev–Zel'dovich Effect

A 25m telescope at a good site capable of operating at millimeter wavelengths would provide the best combination of angular resolution and mapping speed for survey work, among telescopes currently operating, under construction, or being proposed. By probing higher angular scales and lower signal levels over large areas of sky, such a telescope would open a new set of possibilities in Cosmic Microwave (CMB) and Sunyaev-Zeldovich effect (SZE) science. Such measurements are powerful tools for the determination of cosmological parameters, the understanding of cluster astrophysics, and the study of large-scale structure. At the lowest signal levels, CMB/SZE science goals are greatly aided by use of sub-mm bands to understand and remove point-source contamination. The CMB and SZ science topics accessible to a fully instrumented AT25 are (i) blind surveys for galaxy clusters using the thermal SZE and CMB secondary temperature anisotropy due to the thermal SZE; (ii) detection and measurement of the kinetic SZE in galaxy clusters, which will permit measurement of the cosmic peculiar velocity field at redshifts much higher than currently accessible by optical and radio surveys; (iii) temperature anisotropy due to various kinetic SZEs arising from inhomogeneities in the perturbations of the velocity field from the Hubble flow (Ostriker-Vishniac effect) and in the baryon ionization fraction.

Star and Planet Formation and the ISM

The majority of pre-main-sequence stars of low mass ($M < 3\ M_{\rm sun}$) are thought to have circumstellar disks of gas and dust. These are the precursors of planetary systems. Planets form in these disks, and the process is tightly related to the formation and evolution of dust. Circumstellar disks probably only last a few million years before dissipation. An understanding of the structure and evolution of disks is necessary to explain their ubiquity, as well as the processes and timescales associated with the formation of planets. With the AT25, the determination of dust and gas masses of disks around young stars will be possible to mass limits well below that of our primitive solar nebula, thereby establishing (a) how stars form planetary systems similar to our Solar System, and (b) the evolutionary time scales for the gas/dust to constrain the formation time for planets. Wide-area, galactic plane multiband surveys with the AT25 will be uniquely fertile in the discovery of protostars. Images of the polarization of the sub-mm/FIR dust emission can yield important clues on the topology of magnetic fields and their influence on the process of star formation; this polarization is already known to exist at the level of a few percent.

Studies of the interstellar medium (ISM) chemistry with the AT25 will enjoy substantial advantages over those possible with current facilities. Thanks to the smaller beam of the AT25, higher definition of spectral lines widths will be possible; broad band line surveys of large sky areas will be enabled, aimed for example at young stellar objects; absorption line spectroscopy of nearby Active Galactic Nuclei will make possible effective discrimination of emissions processes. Access to multiple sub-mm bands will make possible the determination of density and temperature profiles of cold cloud cores, the future sites of star formation.

Solar System Studies

The understanding of the formation of our planetary system and the origin of life on earth is a major astrophysical quest. Some of the fundamental clues to unveiling its mysteries lie with the objects that have undergone less evolution since the formation of the Solar System, such as comets and Kuiper Belt objects (KBOs), which remain for most of their lifetime outside the orbit of Pluto. Since the sizes of those objects are small, internal heating is negligible and they are thought to have largely retained and preserved pristine material from the early solar nebula.

Recent FIR/sub-mm studies of comets Hyakutake and Hale-Bopp illustrate the unique insights on cometary chemistry made possible by studies in that spectral regime the number of molecules in cometary material have tripled in recent years, including organic species such as ethylene glycol ($HOCH_2CH_2OH$). Given the sensitivity and angular resolution of existing sub-mm telescopes, cometary studies are now limited to very bright (e.g. Hale-Bopp) or nearby (e.g. Hyakutake) comets. The AT25 would allow extending these studies to a large number of comets and establishing the Solar System/ISM connection through detailed chemical studies. The deuterium abundance in water, the main cometary volatile, provides perhaps the best quantitative chemical constraint for the origin of comets and the evolution of the Solar System, as well as a key test for theories of the origin of terrestrial water. The determination of D/H in a number of comets is a major goal of the HIFI spectroscopic instrument on the ESA/NASA sub-mm space observatory Herschel. The AT25 would be substantially more sensitive than HIFI, thus offering statistically more robust prospects in this field.

Over the last decade, several hundred KBOs have been discovered. These objects are small and very distant. The largest among them are Pluto and its moon Charon, respectively 2400 km and 1200 km in diameter; the third largest among KBOs is Varuna, with an estimated diameter of about 900 km. The measurement of the size of KBOs is an important goal, not only because we wish to know the population properties but also because knowledge of the size allows estimates of the albedo and permits us to draw inferences on the physical conditions of their surfaces. With angular diameters of – at best – a few tens of milliarcseconds, they will appear unresolved in imaging surveys. A direct measurement of KBO sizes is possible at FIR/sub-mm wavelengths, by detecting their thermal emission. Because of the faintness of KBO FIR emission and because of confusion with background sources, the FIR/sub-mm technique is currently applicable to only the few very largest KBOs (diameters > 800 km) with existing telescopes. The AT25 would change that, making it possible to detect objects of sizes near 100 km. While the size distribution of KBOs down to D=100 km is not well known, it is likely that the number of such objects range in the hundreds of thousands. Thus a statistical investigation of both the size distribution and surface properties of KBOs would be possible with the AT25. A similar approach would allow the detection of irregular satellites of the giant planets in the Solar System, down to sizes of a few km.

3. SITE DESCRIPTION

The site of choice is one of the high peaks (5200-5700m) in the Chajnantor plateau of northern Chile near the ALMA site. Figure 2 shows the location in South America and a topographic image of the Chajnantor Plateau. Site survey work has shown that the precipitable water vapor content is low (typically less than 800 μm and < 200 μm ~25% of the time for the high peaks)[1, 2]. Figures 3 shows results from radiosonde measurements from survey campaigns in the latter half of 1998. Other more recent campaigns produced similar results.

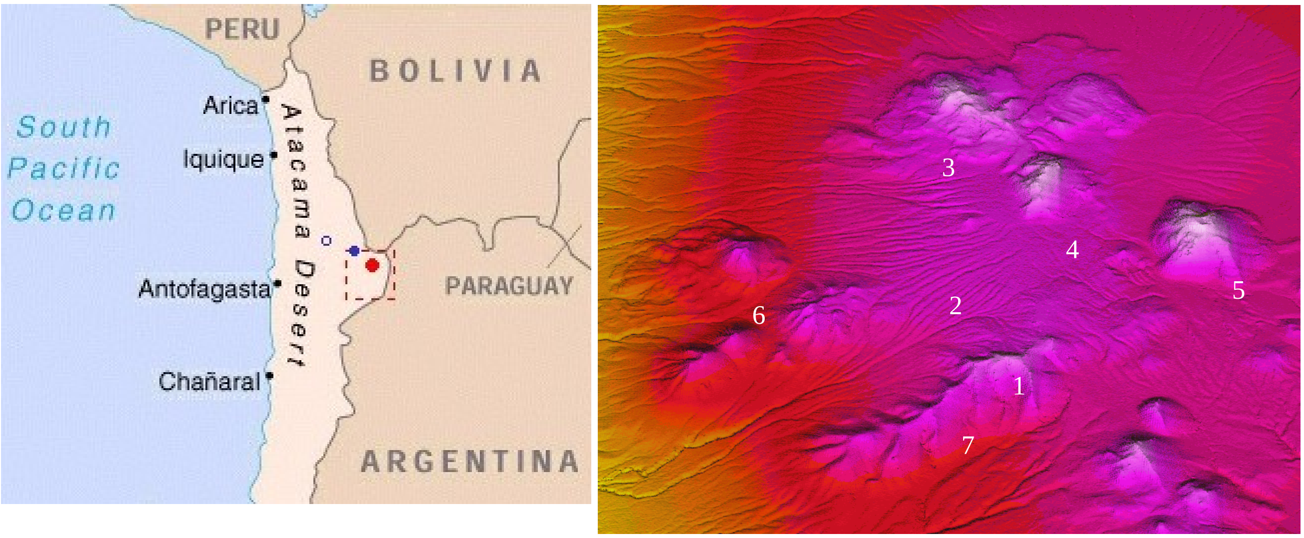

Figure 2: (Left) Location of ALMA site in northern Chile. (Right) Topgraphic image of Chajnantor region show various locations and peaks: 1: ALMA site (5030m), 2: Cerro Chico (5175m), 3: Cerro Toco (5650m), 4: Cerro Chajnantor (5700m), 5: Cerro Chascon (5750m), 6: Cerro Negro (5050m), 7: Cerro Honar

Site survey work is continuing as part of the study phase. Cerro Negro is of particular interest since it lies in the foreground of the plateau towards the prevailing wind direction.

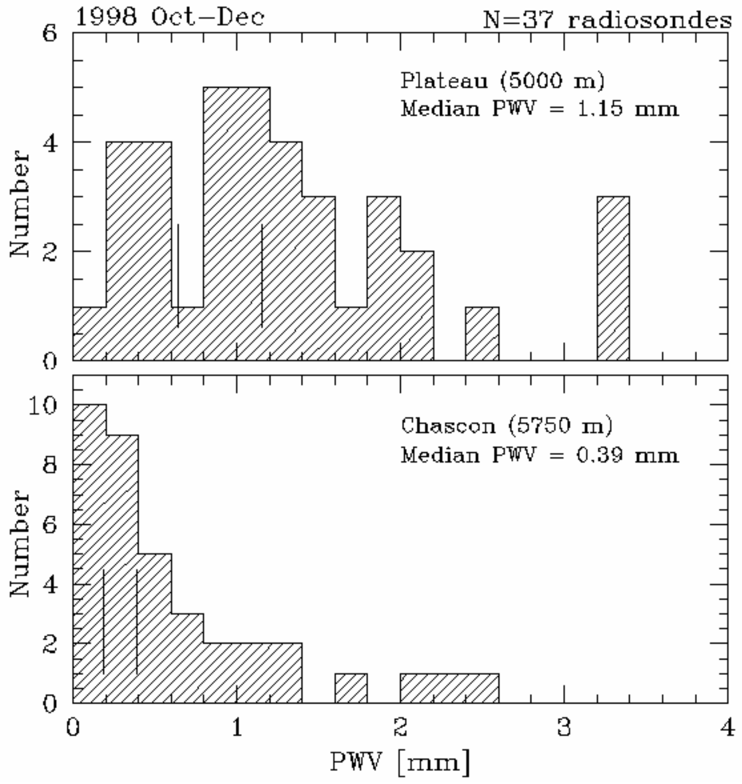

Figure 3: Distribution of precipitable water vapor based on 37 radiosonde measurements made between October and December 1998. The water vapor content drops dramatically between the Plateau and the high peaks. The median water vapor is 1.15 mm and 0.39 mm for the Plateau and Chascon respectively. Figure adapted from Giovanelli et al. 2001[1, 2].

4. INSTRUMENTATION

The study phase will investigate the instrumentation needed to implement the baseline science. Of importance is not only enabling the science but understanding the impact on the telescope design and which instruments will be required at first light. Some of the current instrument concepts include

1. Bolometer Array Cameras – more than 10,000 pixels
    a. 350 and 450 μm at first light
    b. 620 and 850 μm,
    c. 200 μm
2. Direct Detection Spectrometers with coverage over various atmospheric windows
    a. R = 1000
    b. R = 100
3. Coherent spectrometers for high spectral resolution science: e.g. Galactic star formation studies

5. TELESCOPE AND ENCLOSURE

Successful completion of the AT25 will require a careful evaluation of the tradeoffs between performance parameters and cost. The key technical parameters affecting the cost are the diameter and the shortest wavelength for high efficiency operation. The starting point for the technical aspects of a study phase will be a 25m diameter telescope that would operate efficiently at wavelengths as short as 200 μm.

The parameter space for some of the other design decisions has been discussed, based on previous engineering experiences. While an unblocked aperture would have several optical performance-related advantages, it appears clear that the added complexity and cost involved with such a design would not be a cost-effective solution for a size as large as that being considered for the AT25. Considerations of cost-effectiveness for handling the pointing and surface distortions caused by wind also favor shielding of the telescope by an enclosure. It will also be necessary to carefully investigate the desirability of active control of the telescope's surface, which raises the issue of how to develop an effective reference system and a stable measuring system.

The study phase will start with the investigation of a relatively conservative baseline design, based upon a steel structure with aluminum panels and short stroke actuators, Cassegrain geometry and small cross section secondary support legs. The actuators would operate open-loop and correct for gravity distortions and measured thermal gradients in the structure. The structure would be optimized so that most of the gravity distortions can be corrected by small shifts in the position of the secondary. Such a homology concept has been succesfully implemented on several modern millimeter telescopes.

The issues raised by the engineering challenge are among the most serious and delicate to be tackled by a study phase. One of the main tasks will be to develop the “baseline design” described above with sufficient engineering detail to deliver accurate cost/performance estimates. The telescope design task will be divided into two main parts; (1) dome and telescope mount, including the panel support structure and (2) panels, actuators and active control. The performance and cost of the dome and mount are predictable and estimates should be doable with a fairly low degree of uncertainty and will be contracted with commercial design firms. The final performance of the telescope will depend critically on the panels, actuators, and the method used to control them. Cost estimates of these items will be more uncertain, within the purview of the study phase, and they will largely depend on work to be done using in-house engineering know-how.

We anticipate that a preliminary design of the dome and telescope mount, including the panel support structure, will be produced through engineering consulting firms. The goal of this effort will be to produce the "best possible" homologous structure for supporting the panels with good thermal characteristics. A major design option that must be investigated by the contractors is the use of steel or carbon fiber reinforced plastic (CFRP) in the panel support structure. The material chosen will have a large effect on the requirements for the actuators and control strategy which will be investigated by the in-house project staff. This will require good interactions between the in-house and the external design teams. Commercial firms will perform the finite element analysis (FEA) of the performance of the structure under gravity, thermal and light wind loads. Detailed design and construction costs will also be produced.

In parallel with the commercial design efforts, the project staff will work on methods for achieving the very demanding surface accuracy requirements. This will entail investigations of panel construction techniques and materials as well as actuators and sensors. An important result of this effort will be the evaluation of a Keck-like concept for a closed-loop system (with thermally stable panels and edge sensors), versus an open-loop system (with temperature sensors to control the actuators, using a detailed FEA model). Most of the performance uncertainty will be associated with this aspect of the design and the project staff would be best placed for evaluating the performance tradeoffs as they will dictate costs.

Pointing and tracking with the required precision will present a major challenge, given that at 200 μm the beam diameter for a 25m telescope is ~ 2". An optical guide telescope will allow correction for wind, thermal and dry air refraction during night time, but there will be a limited number of optical guide stars suitable for day time observations. It is anticipated that there will be refraction errors from the turbulent water vapor in the atmosphere that are not tracked by an optical guide star. The magnitude of this effect will be evaluated during the study phase and the practicality of using a four quadrant water vapor radiometer to measure water vapor gradients across the telescope will be investigated. This technique has been proposed for other telescopes but has yet to be implemented or seriously analyzed. Achieving the best possible "blind" pointing will be important for day time observations and will improve the performance when using guide stars. The initial goal will be to reach 0.2" blind pointing over a time scale of ~ 1 hour. This will require special attention to the encoders and pointing reference structures. This effort will build on the development of the ALMA telescopes which incorporate advanced techniques for meeting their 0.6" pointing specification. It is anticipated that enclosing the telescope within a dome will greatly facilitate achieving the factor of three improvement we require relative to ALMA.

7. OPERATIONS

A major goal is to achieve long-term operation of the facility through remote access to the telescope and instruments. Of course, this is best done if it is part of the design process from the start. Some of the requirements for remote operations include

- Robust, reliable equipment/infrastructure
- Proper monitoring and sensing capability
- On-line science instruments with mechanical coolers rather than open cycle cryogens
- Sufficient remote communication bandwidth to allow monitoring of all functions including science observations

A goal would be to have complete robotic operation; however it is likely that personnel will be present on-site during astronomical operations even if the telescope is being controlled from offsite.

Queue scheduling a significant fraction of the observations is likely. This will provide the flexibility to tailor scientific programs to weather and atmospheric conditions (such as low water vapor or exceptionally good seeing) and will have the additional benefit of ensuring projects are not subject to being “weathered out.”

8. CONCLUSIONS

We are confident that the telescope concept and design we have chosen should allow us to construct a facility within a reasonable budget and timescale, and that the site allows for the exploitation of a unique scientific niche. The baseline design is a 25-m mirror telescope optimized for operation for wavelengths greater than 200 μm. The high peaks of the Chajnantor region have periods of very low water vapor allow excellent sensitivity at sub-mm wavelengths. A joint two year concept design study will also us to refine the science and engineering in sufficient detail to allow us to proceed with the next phase of the project.

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1. Giovanelli, R. et al. 2001, PASP, 113, 789.
2. Giovanelli, R. et al. 2001, PASP, 113, 803.

Note: Figure 1 is updated according to the latest (April 2005) sensitivity estimates for the AT25. The AT25 sensitivity limits are computed with appropriate water vapor content for each wavelength band. Precipitable water vapor values of 0.3, 0.4, 0.5, 0.5, 0.7, and 1.0 mm are assumed for 200-290, 350, 450, 620, 740, 860-1400 μm observations respectively. This was not done for ALMA since we do not have insight into ALMA operations. Confusion limits for all telescopes are computed according to source count models by Blain et al. (1999, MNRAS, 302, 632), updated by Blain et al. (2002; Physics Reports, 369, 111; astro-ph/0202228). The confusion limit is taken to be 30 beams/source.