October 31, 2003

The Case for a 25m class FIR/submm Telescope: Preliminary Report

Presented by the participants in a workshop held in Pasadena
on October 11, 2003, and edited by
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Scientists at Cornell and Caltech share the vision that the recent advances in large–format detector arrays for far–infrared (FIR) and submillimeter (submm) wavelengths have the potential to provide a unique opportunity for astronomical discovery in a spectral region which remains relatively unexplored. Because this spectral domain holds the keys to the understanding of cosmological problems such as galaxy formation and of the origin of stars and planets, we aim to jointly develop a telescope and suitable instrumentation that will allow us to realize these opportunities. In this preliminary report we outline the elements of an 18–month Study Phase for the development of a project that will lead to a 25m–class FIR/submm telescope built on a high altitude site in the Atacama region of the Andes where the exceptionally dry sky conditions necessary for submm observations are found. We estimate the cost of the study phase to be $2M, a cost to be shared by the two institutions. The deliverables of the study phase will be a baseline telescope concept, an instrumentation plan, demonstration through test observations that a site with the desirable atmospheric characteristics exists, a thorough project plan for the subsequent engineering design and construction of the instrumented telescope and ancillary support facilities, a post–construction operations plan, and budget estimates for construction and operation.

1. Introduction

On October 11, scientists from Caltech, JPL and Cornell met in Pasadena for a one–day workshop aimed at discussing the case for the construction of a 25m–class telescope that would operate primarily in the far–infrared and submillimeter spectral regime, at a high, dry site in the Atacama region of the Andes. This document reports on the proceedings of that meeting and proposes the fast–track implementation of a Study Phase for such a project. In doing so, it identifies the high priority areas that would be investigated in a Study Phase, estimates the resources that would be necessary to carry out that Study and proposes that an MOU between Caltech and Cornell establish a framework that would regulate the effort.

A preliminary set of Working Groups has been formed, that will provide the initial approach to the tasks of the Study Phase. They will evolve, as the effort becomes better organized under the coordination to be provided by a Project Office. At this time, the following groups have been set: **Science, Telescope/Enclosure, Instrumentation, Site, Coordination**. The next four sections of this report present the issues that emerged at the Pasadena workshop and summarize the tasks (as "bullets" at the end of each section) that would be tackled in the course of the Study Phase respectively for the Science, Telescope/Enclosure, Instrumentation and Site work areas. The Coordination WG will consider the project from an "integrated" viewpoint and produce cost estimates, evaluate the operation burden, investigate cross–group issues as well as those associated with construction and operation in a foreign country.

2. Science Justification

A 25m–class FIR/submm telescope at a high altitude, very dry site in Atacama would be a unique facility. Instrumented with the most advanced, large format detector arrays, and located high above nearly all of the atmospheric water vapor, such an Atacama Telescope (referred to as AT within this document) would be the most sensitive telescope of its kind in the world. The 25 m AT would be substantially larger than the existing (10–15 m) submm telescopes, would be located on a better site and would allow regular operation at shorter wavelengths. The angular resolution of the AT, 2" at 200 μm, would far exceed that of the space missions SIRTF (48" at 160 μm) and Herschel (14" at 200 μm). Equipped with large field–of–view (FOV) cameras that would exploit the fast-developing field of submm detector array technology, the AT would image quickly regions on the sky that are arcminutes or larger in size. It is the combination of high sensitivity, arcsecond angular resolution, and wide instantaneous field of view that would make the AT the appropriate scientific complement to ALMA. ALMA, currently the world's largest radio astronomy project ($\sim$ 1B$), is a mm/submm interferometer which will give images of sub–arcsecond resolution over a very much more restricted field of view (20" or less): the structure of cosmic sources of special interest found in large-scale AT surveys would be imaged with ALMA.

The scientific impact of the AT in 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 were discussed at the workshop. A schedule of the scientific talks is given in Appendix A.

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 submm/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 z. 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 submm/FIR observations – submm/FIR observations may in fact provide *most* of the picture. The characterization of the structure of the high z Universe is therefore linked to our ability to study large samples of galaxies in the submm 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 AT, would uncover vast numbers of more typical systems, through large, blind surveys in multiple submm bands. The improvement in angular resolution which accompanies the larger telescope size is also needed to overcome spatial confusion (see below).

Access to multiple submm bands will also allow the AT 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 submm 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 158 μm), 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 submillimeter bands to understand and remove point-source contamination. The CMB and SZ science topics accessible to a fully instrumented AT 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 ($M < 3M_\odot$) 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 AT, 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 AT will be uniquely fertile in the discovery of protostars. Images of the polarization of the submm/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 AT will enjoy substantial advantages over those possible with current facilities. Thanks to the smaller beam of the AT, 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 submm 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/submm 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 submillimeter telescopes, cometary studies are now limited to very bright (e.g. Hale-Bopp) or nearby (e.g. Hyakutake) comets. The AT 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 submm space observatory Herschel. The AT 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 a 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/submm wavelengths, by detecting their thermal emission. Because of the faintness of KBO FIR emission and because of confusion with background sources, the FIR/submm technique is currently applicable to only the few very largest KBOs (diameters > 800 km) with existing telescopes. The AT 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 AT. 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.

Angular Resolution and Spatial Confusion

The diffraction–limited angular resolution of current single–aperture mm/submm/FIR telescopes is no better than $\gtrsim 10''$, which becomes a problem in crowded fields and deep exposures, making it difficult to separate adjacent objects. This problem of "beam confusion" plays an important role in deep survey work, as it does in the detection of faint Solar System objects, such as KBOs and irregular satellites of giant planets. The AT, with its $\sim$ 2–4$''$ resolution in the submm/FIR bands, would have the ability to integrate many hours before reaching the confusion limit, and would therefore be the instrument of choice to determine the properties of such objects in a statistically significant fashion.

Complementarity with Other Major Facilities/Projects

With a significantly larger collecting area, located at a superior site and with access to multiple submm atmospheric windows, the AT will easily outclass existing 10m–class submm facilities such as APEX, CSO and the JCMT. Operating at shorter wavelengths and, again, at a superior site, it will be far less vulnerable to source confusion and better suited to deep surveys than the 50 m millimeter–wave telescope LMT, which is now under construction. The AT will have particularly important synergies with two future facilities.

The large FOV, excellent sensitivity, and good angular resolution of the AT combine to yield excellent survey potential, which will complement the high spatial and spectral resolution and small FOV of ALMA; the latter will provide ideal follow–up capabilities for objects discovered with AT surveys. Especially as the two telescopes will have very similar sensitivities, observational data acquired with the AT will provide strong leverage to AT users for access to ALMA, and enable the definition of coordinated science programs of more ambitious scope than those made possible by access to either telescope alone.

In the longer term, the Astronomy & Astrophysics Decadal Report has recommended that NASA pursue the development of an ambitious submm/FIR $\sim$ 10 m cold space telescope, known as "SAFIR", with a launch perhaps in the 2020 time frame. The AT would be a key scientific and technological precursor/complement for SAFIR, demonstrating the detector array technology needed for SAFIR, and providing crucial data on the population of dusty galaxies at high redshifts. As a consequence, the construction and operation of the AT could facilitate a substantial Cornell/Caltech participation in the SAFIR mission.

Study Phase Issues

Several issues were raised at the workshop that will need further evaluation in a Study Phase:

- Carefully evaluate the "discovery space" for the AT in each area of research, *vis–a–vis* other facilities, particularly ALMA, other ground facilities such as the LMT, APEX and SPT, and the airborne/space facilities SIRTF, SOFIA and Herschel.
- Analyze in more detail the scientific opportunities offered by the unique capabilities of the AT in each area of research, paying special attention to the rapid, sensitive, wide–field surveys that will be made possible.
- The shortest submm wavelength band available from the ground is at 200 μm, and is very rarely

accessible except in exceptional conditions at sites such as Atacama and the South Pole. Since the desire for high aperture efficiency at 200/260 μm will be a main technology driver (the next telluric band is centered near 350 μm), it is important to effectively evaluate the scientific importance of access to this band, *vis–a–vis* the related statistics of atmospheric transparency.

- What is the "incremental science" delivered by 12 μm total surface error over, say, 20 μm?, or rather:
- If we cannot achieve high aperture efficiency/mapping speed at 200 μm relative to the other bands, how will this affect the overall science goals?
- What is the actual level of polarization fidelity required by the measurements of polarization of the dust emission?
- Is moderate–resolution spectroscopy of the fine–structure lines the best route for determining redshifts and dynamics of primordial galaxies?
- What is the role of high–resolution (heterodyne) spectroscopy ?

CMB/SZE science requires a specific set of preliminary studies:

- Make a realistic estimate of expected per-pixel sensitivities, including the expected opacity distribution, in order to accurately model the sky noise.
- Use of analytic and numerical methods to predict expected thermal SZ and kinetic SZ signals. This should include expected cluster counts and abundance functions, expected peculiar velocities, and expected anisotropy power spectra. A realistic assessment of the effect of current theoretical uncertainties, both in predicting the dark matter power spectrum and in predicting the gas physics that yields the SZ effects, should be included.
- Study of the effect of thermal SZ survey type (deep, narrow vs. wide, shallow) on resulting science output.
- Study of the effect of beam size on science output.
- Get a realistic evaluation of the ability to separate kinetic and thermal effects using simulations, with appropriate overall calibration and spectral bandpass uncertainties included.
- Assess realistically the confusion levels, including those by dusty radio point sources and by lower-mass clusters.

3. Telescope/Enclosure Engineering

Succesful completion of the AT will require a careful evaluation of the trade–offs 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 was 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 AT. 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.

It is recommended that the Study Phase start from 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 trade–offs as they will dictate costs.

Pointing and tracking with the required precision will present a major challenge, given that at 200 μm wavelength the 25m telescope beam will be less that 3" FWHM. 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 the water vapor gradients across the telescope aperture 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 $\sim$ 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.

In summary, some of the main isues that will be adressed by the Study are:

- In order to achieve the desired surface accuracy: can small adjustments to the segment positions be made open–loop or will a full active approach be needed, with sensors and closed–loop adjustments ?
- What type of actuators and sensors ?
- Investigate the use of CFRP in place of steel in the main structure supportingn the surface panels. CFRP can have very low coefficient of thermal expansion (CTE) and obviate most of the temperature–related problems.

- Investigate the use of different panel materials. If inexpensive panels can be made from a very low CTE material, it then may be possible to apply the edge sensor and actuator technology developed in optical telescopes such as Keck.
- What is the incremental technical challenge posed by a 12 μm surface error requirement as opposed to 20 μm?
- Radome or astro–dome? Produce a preliminary design for the telescope enclosure.
- What FOV is achievable ? How many interchangeable instruments can be simultaneously mounted? Is a Naismyth focus needed?
- How will the desired pointing and tracking accuracy be achieved?
- What is the trade–off between cost and polarization fidelity? Is 0.1% fidelity achievable ?
- Given the rugged environmental conditions likely to be met at the site, it should be planned that for a substantial fraction of the time the telescope will operate in remote mode. The Study Phase will need to investigate how this will impact the design and operation of the facility.
- Daytime vs. night time performance: will, e.g., wind or thermal gradients limit daytime observations to the longer wavelengths only?

4. Instrumentation

A key ingredient to success of the proposed facility is the availability of large format submm/FIR cameras, that will deliver FOVs of tens of square arcminutes, with on the order of 10^4 pixels. The current state of the art in array format is the 12×32 pixel NASA/GSFC array in the SHARC II camera at the Caltech Submillimeter Observatory (CSO). By the summer of 2004, a demonstration of 32×32 pixel superconducting bolometer arrays with multiplexed readouts (TES/SQUID) is expected, as part of the “SCUBA II” project, which will be a large camera for the 15 m JCMT telescope. It seems reasonable to expect to have 64×64 arrays within a few years, and 128×128 pixel arrays on hand by the turn of the decade. A vigorous superconducting detector development program exists at JPL/Caltech, with the goal of producing large–format arrays.

An excellent strawman submm/FIR camera would observe simultaneously in two, or perhaps three spectral bands. The bands could be split by a dichroic in the optical path, and the total optical efficiency (including the detector quantum efficiency) can be kept near 40 percent. Each band would have a 128×128 pixel array, and the band centers would be chosen to best take advantage of the changing weather. In one configuration, observations could be made at 850 and 740 μm, while in a second configuration, the 450 and 350 μm bands could be observed simultaneously. Band-pass filters could be rotated in front of the array to select the band of choice. Since the backgrounds are about 10 times higher at 200 μm, and the beam size is quite a bit smaller at 200 μm as well, it may be desirable to have a dedicated array (the third band, or a separate camera) for use at 200 μm. At this stage, a 350/450 μm bolometer array camera may be the most favored choice as a first–light instrument.

Grating spectrometers are natural candidates for wide–bandwidth, low resolution spectroscopic applications. A versatile redshift machine would have enough pixels to cover an entire submm window in a single pointing, and could readily change from one telluric window to the next. For a resolving power of the grating of 1000, about 100 resolution elements (200 pixels) will cover a telluric window, since each window is $\simeq$10% wide. A grating spectrometer with $R \sim 1000$, and a 4×256 pixel (spatial × spectral) array would make an extremely powerful system. Cornell is currently developing a smaller version of this spectrometer (8×64 pixel array). A long–term goal would be to develop a multi–object spectrometer, as is done at optical wavelengths, to further exploit the capabilities of the AT.

For high resolution spectroscopy, heterodyne receivers using superconducting mixers are needed. Caltech and JPL have a strong capability in this area, and are developing instruments for Herschel and SOFIA as well as the CSO. For the AT, interesting capabilities would be possible, such as very high spectral resolution

($\sim 0.1\,\mathrm{km/s}$) across 24 GHz instantaneous bandwidths, operation in the 200 μm band, as well as imaging array receivers.

Towards verifying what instrumentation will be needed on the AT in order to achieve the main science goals, the following issues will be carefully evaluated in a Study Phase:

- The workshop presentations have emphasized multi–wavelength, large–area continuum surveys. How many different wavelength observations are required to meet these goals, and how large of areas on the sky need to be surveyed?
- How critical are 200 μm maps to the science goals?
- Do we need separate arrays for each submm band, or will we have a single camera for all bands?
- Should we aim to have simultaneous observations in two (or more?) bands like SCUBA?
- If multi–wavelength continuum maps are needed to optimize the science, is it feasible to develop large-format submm cameras to achieve roughly equal mapping speed at each of the required wavelengths? This may be a challenge for 200 μm, since there will be limited time available for such observations, and we will need a large camera in order to map comparable areas relative to 350 μm and 850 μm.
- What moderate–resolution spectroscopic instrumentation is desirable ? Which of the submm bands should be covered ?
- Heterodyne receivers:
    - Which submm bands?
    - Receiver arrays? If yes, how many elements?
    - What type of backend spectrometers?

5. Site

The atmospheric characteristics of the Atacama region have been studied extensively over the last several years, as a result of test studies (including those of Cornell) carried out for ALMA and other projects, and the operation of facilities such as CBI (Readhead/Caltech). According to the CBI experience, atmospheric conditions at the Chajnantor Plateau allow observations about 85% of the time. Tipping radiometer and radiosonde data indicate that the median precipitable water vapor (PWV) at the Plateau is approximately 1.2 mm, which is significantly better than Mauna Kea and only slightly higher than at the South Pole. The median zenith optical depth at 350 μm at Chajnantor is $\tau_{350} = 1.68$, while the values for the South Pole and Mauna Kea are respectively 1.52 and 2.15. The optical depths for the best quartile are respectively 1.21 (Chaj), 1.23 (SP) and 1.46 (MK). A group from the Harvard/Smithsonian Center for Astrophysics (CfA) has carrried out two years of Fourier transform spectrometer (FTS) measurements of the submm atmospheric transmission at Cerro Sairecabur, a site of elevation 5500 m (about 500 m higher than from the Chajnantor Plateau). These measurements yield atmospheric opacity and PWV values about 2/3 of those measured at Chajnantor. We thus already know that significantly better conditions than at the Chajnantor Plateau (ALMA site) exist in the Atacama region. However, the Sairecabur site is geographically quite removed from the ALMA site (40 km NNW), and therefore would not enjoy the full benefit of ALMA–related logistical synergies.

Moreover, the Sairecabur site is very close to the Bolivian border (less than 1 km), which may pose an altogether different set of logistical problems (the 2–year operation at the site of the CfA group suggests that the latter may be a relatively tractable problem, however). While we are confident that a site of the expected quality for the 25 m telescope is available, we wish to investigate the suitability of sites close to ALMA, for the reasons discussed above.

Radiosonde measurements launched from Chajnantor show that the PWV is generally trapped below T–inversion layers above the Plateau. There is promising evidence — from radiosonde launches and time delays in phase stability measured by different sets of test interferometers — that peaks a few hundred meters above the surrounding plateau often emerge above the T–inversion layer, thus enjoying significantly increased atmospheric transparency. Cerro Negro, a 5100 m peak 10 km to the West of the ALMA site, is seen as an attractive possibility as a site for the AT. Although its elevation is not significantly higher than that of the ALMA site, it rises some 600 m above its surrounding plateau. While PWV measurements above its summit are not yet available, computational fluid dynamics simulations suggest that its median PWV may be significantly lower than that at the ALMA site, perhaps comparable with Sairecabur. Because of its western location with respect to the main Cordillera, Cerro Negro's weather conditions are significantly better than those at the ALMA Plateau and Sairecabur, as indicated by the CBI experience. In addition, the summit's topography is well suited for the installation of an Observatory, as is that of Sairecabur.

Concerns of the Study Phase:

- An extremely important priority for the Study Phase is that of measuring the PWV and general conditions at a site such as Cerro Negro, a goal best achieved by establishing a robotic tipping radiometer on the summit, next to an already operational weather station. Were Negro to be found unsatisfactory, Cerro Honar or Cerro Chascón could be tested, while the feasibility of Sairecabur should be more thoroughly explored.
- How many days/nights will be available for 200 μm, 350 μm, and 850 μm observations?
- What will be the impact of high altitude on operations?
- What will be the impact of high altitude on construction costs?

6. Rough Order of Magnitude Overall Cost Estimate

Rough order of magnitude estimates of the cost of a 25m and of a 30m submm telescope were discussed, using engineering scaling laws as they apply separately to each component of the telescope. The reference was provided by the costs obtained from two different antenna contractors, that presented estimates for the ALMA 12 m antennas. The results of this exercise indicated overall costs of approximately $50M and $70M, respectively for a 25 m and for a 30 m telescope; cost estimates also included site preparation and telescope enclosure. They assumed that the primary segment quality of the ALMA antennas, of rms about 5 μm, would yield a total surface error of 12–15 μm in the controlled environment of a dome. These estimates are of course very rough and preliminary, and possibly optimistic. A very important reason for caution is the uncertainty on the possibility of maintaining as low a surface error figure as 12–15 μm with a substantially more massive structure than that of a 12 m telescope, even if protected from the wind. Estimates of the cost of the telescope enclosure were also recognized as being very uncertain. In addition, the cost of a first–light instrument, possibly a large format camera, is highly uncertain at this time, due to fast–moving technology. It is however likely to be an important fraction of the overall project.

• A major task of a Study Phase will be that of firming up estimates in these important drivers of the overall cost.

7. Study Phase Framework, Management, Personnel and Cost

At the workshop, the desire was expressed from both the Caltech and Cornell sides for a fast–track development of the project, and completion in coincidence with the planned completion of ALMA by 2012 was seen as an ideal goal. Thus, a possible, aggressive project development schedule could be as follows:

- A *Study Phase*, to start after a Caltech–Cornell MOU is signed, say by January 2004. This phase ends in June 2005, with the delivery of a report (shall we call it the *Red Book*?) and a Conceptual Design Review.

- An *Engineering Design Phase* of 2.5 year duration, leading to an Engineering Design Review in January 2008.
- A *Construction Phase*, leading to commissioning by January 2012.

The Study Phase will establish overall feasibility of the project, obtain a more focused outlook of the science possibilities, evaluate broad–brush alternative technical options, achieve a realistic estimate of cost and site characteristics and propose a detailed timeline of activities that will lead to first light. The management of the Study Phase would be regulated via an MOU between competent representatives of Caltech and Cornell, which would outline the tasks and clearly define the responsibilities and goals of the Study effort. The total cost of an 18 month Study Phase is estimated at approximately $2.0M, as detailed in Appendix B.

We estimate that the study phase tasks will require 91 work-months of effort over 18 calendar months, this is approximately 5 FTEs. Because the range of skills needed for these tasks is large — it includes contract management, antenna engineering, detector technology, site testing, Chilean politics and more — more than 5 people need to be involved, in their majority being part-time over the 18 month Study Phase. Progress in the Study Phase will thus largely rely on existing staff at Cornell and Caltech who can be assigned to the various tasks for the time required to complete them. As a crude estimate, this means both Cornell and Caltech will supply to the project Study Phase tasks the equivalent of 5 people working half-time over the 18 months.

APPENDICES

A. Atacama Telescope Workshop Agenda and Participants

Time	Topic	Speaker
0800	Introduction to the Project	Ricardo Giovanelli
0820	CMB Science	Sunil Golwala
0850	Distant galaxies	Andrew Blain
0910	Nearby Galaxies	Gordon Stacey
0930	The Insterstellar Medium	Tom Phillips
0950	Polarization Science	Darren Dowell
1010	Break	
1030	Star & Planet Formation	John Carpenter
1050	Solar System Studies	Darek Lis
1110	Synergies with ALMA etc.	Bob Brown
1130	Break and Discussion	
1230	Site Selection Issues	Riccardo Giovanelli
1250	The CBI Experience	Tony Readhead
1310	Engineering/cost Scaling Laws	Bob Brown
1330	Engineering Challenges	Dave Woody
1350	Break and Discussion	
1500	Imaging Instrumentation–1	Sunil Golwala
1520	Imaging Instrumentation–2	Darren Dowell
1540	Spectroscopy Instr.–1	Matt Bradford
1600	Spectroscopy Instr.–2	Gordon Stacey
1620	Polarization Instr.	Darren Dowell
1640	Heterodyne Receivers and	Jonas Zmuidzinas
	Breakthrough technologies	Jonas Zmuidzinas
1710	Break and Discussion	

The presentations themselves can be downloaded from *http://www.astro.cornell.edu/atacama/workshop.html*.

The Workshop participants were : A. Blain (Caltech), M. Bradford (Caltech), R. Brown (Cornell), J. Carpenter (Caltech), P. Day (JPL), C.D. Dowell (Caltech), R. Giovanelli (Cornell), S. Golwala (Caltech), T. Herter (Cornell), L. Hillenbrand (Caltech), H.G. LeDuc (JPL), D. Lis (Caltech), T. Pearson (Caltech), T. Phillips (Caltech), A. Readhead (Caltech), A. Sargent (Caltech), G. Stacey (Cornell), T. Tombrello (Caltech), D. Woody (Caltech), J. Zmuidzinas (Caltech).

B. Atacama Telescope Project: Study Phase Schedule of Cost

Notes for the Study Phase schedule of costs (table in the next page):

1. Personnel costs assume (a) benefits but no indirect charge to be levied by Caltech or Cornell; (b) a \$10K/month–person is budgeted as a simple average without distinction between professional roles. Personnel are assumed to be mostly in–house employees, working part–time on the Atacama telescope project. Every personnel entry is not necessarily a different person, i.e. a single person could perform several tasks.

2. The task manager is a (usually) in–house person working part–time on the Atacama project Study Phase for the total indicated in each line, over the 18 months duration of the Study Phase.

3. Two telescope "vendors" will be approached, provided with a set of passive telescope specs. and asked to develop an engineering concept, as discussed in Section 3.

4. Contract work follows our review for existing designs; one of the designs (or a derivative of one of the designs) is chosen and presented to one or more potential vendors, with the request for a budgetary estimate.

5. Assumes shared expenses with Optical Site Survey.

6. This could be a full–time person, possibly to be recruited soon, or a position to be shared by two or more individuals.

7. This is a half–time administrative person to assist in managing the Project Office.

8. All Study Phase travel is combined in this line, estimated using a rate of \$15K/month.

Study Phase Schedule of Cost

Atacama Study Phase Project Task	Personnel Work Mos.	Personnel Cost (k$)	Contracts (k$)	Subtotal (k$)	Notes
1. Telescope & Enclosure					
1.1 Task Management					
Task Manager	6	60		60	1,2
Set Baseline Specifications	1	10		10	1
1.2 Telescope					
Contract Concept Design Vendor #1	2	20	200	220	1,3
Contract Concept Design Vendor #2	2	20	200	220	1,3
1.3 Enclosure					
Review CELT,LBT,HET,ESO,NRAO	1	10		10	1
Set Baseline Specifications	1	10		10	1
Contract Cost Estim. w/Vendor	2	20	100	120	1,4
1.3 Active Control Options					
In–house effort	6	60		60	1
2. Instrumentation					
2.1 Task Management					
Task Manager	6	60		60	1,2
Set Baseline Specs for 1st light	2	20		20	1
2.2 Incoherent Instruments					
Set Baseline Plan for Procurement & Fabrication of Front Ends	6	60		60	1
2.2 Coherent Instruments					
Set Baseline Plan for Procurement & Fabrication of Front Ends	4	40		40	1
Set Baseline Plan for Procurement & Fabrication of Back Ends	2	20		20	1
3. Site					
3.1 Task Management					
Task Manager	6	60		60	1,2
Set Site testing Plan	2	20		20	1
3.1 Site Testing Studies					
Procure Testing Instruments	2	20	30	50	1
Solar Electrical System	2	20	40	60	1
Deploy Solar Electrical System, Tipper & other instruments	4	40	60	100	1
Site Road Improvement	1	10	60	70	1,5
Site Test Studies Support	6	60		60	1
4. Project Management & Costing					
Manager	18	180		180	1,6
Other Personnel	9	90		90	1,7
Project Travel, Supplies, etc.			250	250	8
5. Contingency				150	
TOTAL	91	910	940	2000	