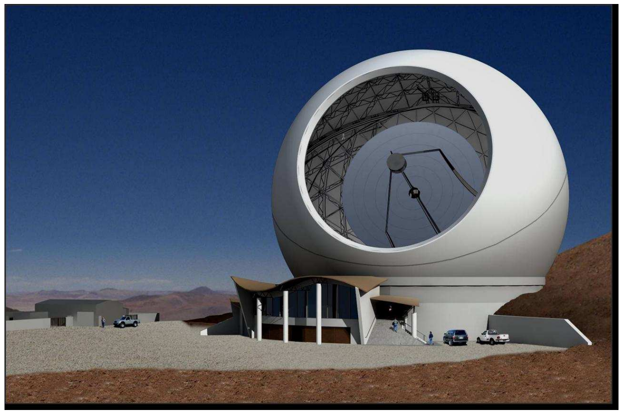

CCAT

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Summary

Star formation drives the evolution of baryonic matter in the universe. The energy density of the Far Infrared (FIR) and submillimeter (submm) extragalactic radiation is roughly equal to that of the integrated optical and UV starlight. Comprehensive pictures of the processes of galaxy, star and planetary formation thus require high sensitivity and high angular resolution observations in that spectral region. CCAT will be a primary player in furthering our understanding of the processes of formation of cosmic structures on all scales and the characterization of star formation through cosmic time.

• CCAT will be a 25 m telescope for observations at submm wavelengths, with actively controlled optics and sensitivity that will match that of the full ALMA array at those wavelengths.

• At 18500 ft elevation, 2000 ft above ALMA, the CCAT site is the best on Earth in terms of the combined requirements of atmospheric transparency, sky coverage and ease of access.

• The high sensitivity and mapping speed of CCAT will complement ALMA's exquisite angular resolution, yielding extraordinary synergies.

• Operation of the facility will emphasize remote observing, flexible scheduling, instrument alternation and observing modes, dynamically matched to changing weather conditions.

• As a second generation submm facility optimized for surveys, CCAT will have a FoV large enough to accomodate megapixel detector arrays, a feasible development within the next decade thanks to rapid progress in detector and multiplexing technology in this most challenging spectral regime.

• With NSF support, CCAT will be the large aperture submm facility available to the U.S. community, in the tradition of CARMA and CSO.

• A large fraction of CCAT observing will be devoted to large scale surveys of high z galaxies, the Milky Way, nearby galaxies including the Magellanic Clouds, molecular clouds and Solar System targets. Continuum surveys will be complemented by programs with multi–object spectrometers.

• Surveys will be conducted with community participation; public release of mature data products and robust access tools will take place in a timely manner to maximize science productivity.

• CCAT will guarantee that a strong U.S. academic tradition continues to flourish in the increasingly important area of submm science training and instrumentation.

1 Key Science Goals

In this Section we briefly discuss some of the science paths CCAT will tread. A broader and more detailed scenario can be found at *submm.org*[1].

1.1 Measuring the Star Formation History of Galaxies Across Cosmic Time

A comprehensive picture of galaxy formation and evolution must account for the bolometric luminosities of galaxies across cosmic time. COBE revealed a cosmic far-infrared (FIR) extragalactic background radiation with flux approximately equal to the integrated extragalactic optical and ultraviolet starlight in the Universe. This FIR background is likely dominated by optically thin thermal emission from dust grains heated to 10–100 K by optical and ultraviolet light from embedded hot, young stars in galaxies. Indeed, the most luminous star forming galaxies emit the bulk of their light in the FIR/submm and most of the light from high z galaxies reaches us in that spectral domain.

Galaxies grow through mergers and accretion of intergalactic gas. The funnelling of gas into nuclear regions stimulates bursts of star formation and presumably the growth of supermassive black holes at their centers. Submm observations from 200 μm to 2 mm provide views of the epoch of galaxy formation, when stellar masses were being built up. Submm spectral probes are keenly sensitive to physical conditions of the gas, thereby elucidating the context for star formation and providing a crucial observational link between the buildup of the stellar masses and central supermassive black holes.

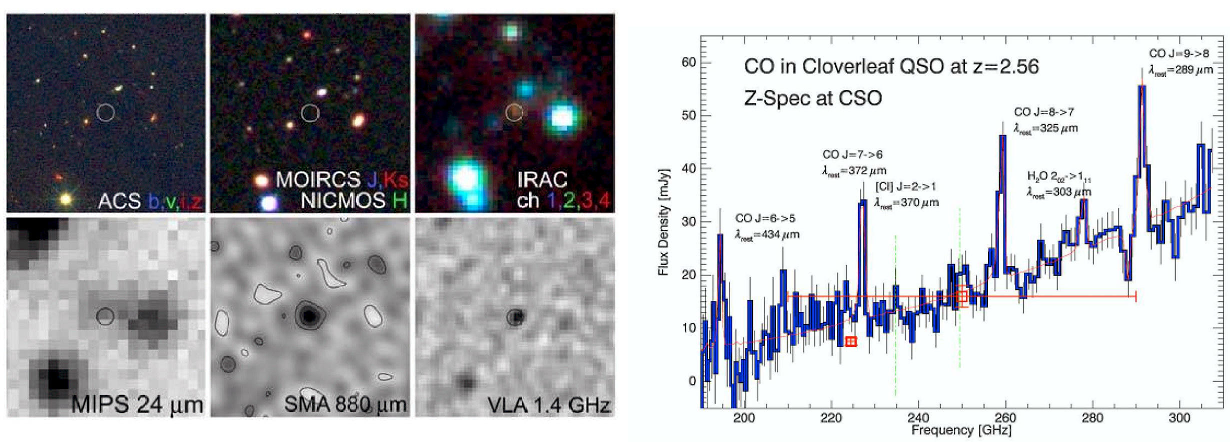

Figure 1: *Left*: The submm galaxy GOODS 850-5 (within the circle at center) in the optical (*Hubble*), IR (*Hubble*, Subaru, *Spitzer*), submm (SMA) and radio (VLA). GOODS 850-5 has a FIR luminosity of 2×10^{13} $L_{\odot}$, yet it is invisible at optical and near-IR wavelengths. Redshift estimates based on the FIR/radio ratio and the stellar light observed by *Spitzer* suggest a $z = 4 - 6$. *Right*: Z–Spec spectrum at CSO of the Cloverleaf quasar. A fit to the continuum and spectral lines is in red. The red boxes denote continuum measurements from MAMBO and Plateau de Bure.

[1]See Science White Papers by Bally *et al.* , Blain *et al.* , Carpenter *et al.* , Golwala *et al.* , Lis *et al.* , Stacey *et al.* for further details and bibliographical references to science results.

The last decade has brought major advances in our knowledge of galaxies at high z. Among them is the understanding that the star formation rate per unit co-moving volume at $1 < z < 3$ was 30 times the present rate. However, key questions about the galaxy formation process remain, such as: When did the earliest galaxies form? Can we identify high-redshift examples of the types of progenitors that grew to modern-day galaxies? What is the bolometric luminosity function of galaxies as a function of redshift? How are supermassive black hole and stellar mass growths related? Submm observations with CCAT will help address each of these questions.

To determine the amount of energy that has been released by galaxies, it is essential to measure their rest-frame FIR radiation, which peaks at 50 - 200 μm and is redshifted into the submm bands for $z > 1$. Dust emission comprises 50% of the total integrated luminosity of galaxies. That fraction is even larger for the most luminous galaxies and galaxies at high z. The amount of FIR/submm emission — and thus of star formation — from dusty galaxies is impossible to infer from the spectral properties of the escaping optical/UV light alone (see Fig. 1). Submm observations have a strong advantage in searches for high redshift galaxies. Because the slope of the product of the Planck function and the emissivity function of dust grains is so steep on the Rayleigh-Jeans side of the spectrum ($S_\nu \propto \nu^{3.6}$), the observed brightness of a galaxy is independent of z from $1 < z < 10$, in that spectral regime. This has been referred to as a "negative-K-correction". Thus submm surveys provide a natural means for identifying high-redshift ($z > 5$) galaxy candidates within large-scale surveys: those with weak 200 - 700 μm emission and bright 800 μm to mm–wave emission.

Existing observations of high z FIR/submm galaxies are currently limited to the most luminous examples (i.e., $> 10^{13}$ $L_\odot$). They are known in small numbers. Redshifts and stellar masses for these galaxies can sometimes be determined from optical and near-IR observations, but total luminosities, gas and dynamical masses must be derived from FIR/submm observations of gas and dust. Without this information, FIR/submm-dominated high-redshift galaxies appear to be little different from optically-selected galaxies at the same redshifts, despite their much greater luminosity.

SCUBA-2 on the JCMT and the *Herschel Space Observatory* will have an important impact in this field in the next few years. However, both telescopes will be confusion limited at few to several mJy, while the confusion limit of CCAT will be $\sim$0.3 mJy or better, allowing it to reach substantially further down the luminosity function. SCUBA-2 will observe only at 450 and 850 μm– a much more restricted wavelength range than CCAT (future JCMT observations at $\lambda < 450$ μm are impaired by the telescope's surface roughness). Furthermore, *Herschel* is a cryogenic mission which will be completed approximately when ALMA comes on line, precluding any opportunities for coordinated observations or surveys. On CCAT, a 10 square-degree survey – covering a cosmologically relevant volume – could be covered to a depth of 0.2 mJy rms at 350 μm in 2,000 hours, yielding of order 10^5 mostly faint, distant galaxies. Moreover, CCAT will carry out a spectroscopic survey of submm galaxies, using multi–object versions of broadband direct-detection grating spectrometers such as Z–Spec and ZEUS, now in use at the CSO (see a spectrum of the Cloverleaf quasar obtained with Z-Spec in Fig. 1). *Conceptual development indicates that spectrometers capable of observing 10–100 objects simultaneously while spanning multiple atmospheric windows will be feasible.* Continuum surveys at CCAT will be paralleled by spectroscopic ones capable of determining redshifts via the [CII] or CO lines.

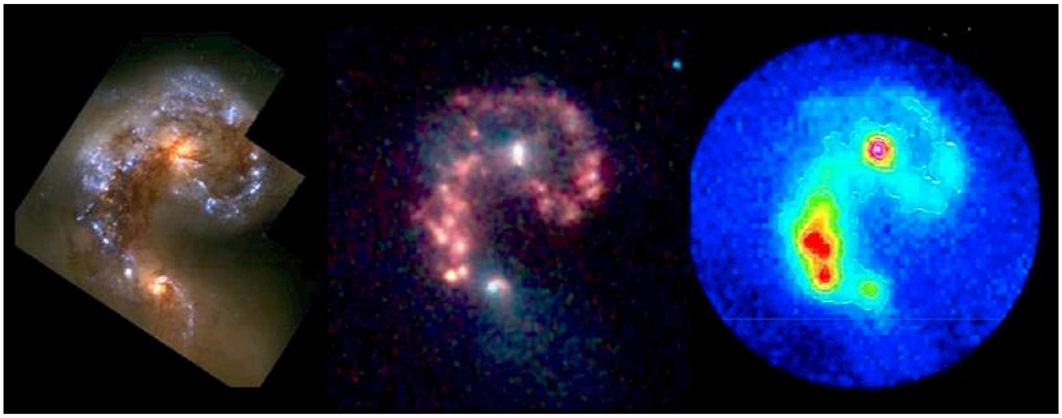

Figure 2: NGC 4038/4039 at optical, IR and submm wavelengths. In the *Hubble* image on the left, light from hot, young stars is visible, as well as dark dust lanes. In the central panel from *Spitzer*, more sites of star formation become visible. In the right panel, the 350 μm CSO image shows that the bulk of the luminosity derives from star formation invisible at shorter wavelengths. At 350 μm, CCAT will have the same resolution as the *Spitzer* image.

1.2 Star Formation and the ISM in Nearby Galaxies

To understand the strong evolution of star formation over cosmic time, nearby, spatially resolved galaxies must be studied to relate the astrophysical probes to high z systems: Resolved submm images (see Fig. 2) will reveal the interplay between the star formation process and the natal interstellar medium (ISM), helping to understand the line emission from distant galaxies. Of particular interest are the most active regions in nearby normal and starburst galaxies because it is these regions that will provide the best templates for distant, LIRG and ULIRG-class galaxies responsible for the bulk of the cosmic FIR background.

Multi-wavelength studies in concert with submm observations will address fundamental questions about star formation in galaxies, such as: What are the relationships between the age (chemical abundances) of the ISM, the degree of star formation activity, galactic morphology, and the environment? What triggers galaxy-wide starbursts? Do starbursts burn themselves out by consuming all the available fuel or by disrupting the natal enviroment through stellar winds?

Multiband images can trace the process of gas compression in spiral density waves, the formation of stars in molecular cloud cores, and the disruption of the parent clouds by newly formed stars. Moreover, the FIR/submm spectral regime provides a wide variety of extinction-free spectral–line probes of both ambient radiation fields and the physical properties of interstellar gas (e.g., density, temperature, dynamics, radiation intensity and hardness). Most of those lines lie within a few hundred K of the ground state and have modest critical densities; the emitted radiation is nearly always optically thin. Therefore, these lines are important (often dominant) coolants for the phases of the ISM relevant to star formation processes.

The most important FIR and submm lines include fine-structure lines from abundant species (C, CII, NII, NIII, OI, OIII), plus the mid-J (J = 4–3 to 13–12) rotational transitions of CO. These lines are very bright in star forming galaxies, often summing to more than 1% of the total galaxy luminosity. The ([NII], [NIII], and [OIII]) lines cool ionized gas regions and the [CII] 158 μm line is the dominant coolant of the neutral gas and photodissociation regions on the surfaces of far-UV exposed molecular clouds. It is often the brightest single emission line from star–forming galaxies. In the Milky Way, the line is 6×10^7 solar luminosities, or about 0.3% of the FIR luminosity. While unobservable from the ground in nearby galaxies, it has been detected with the Cornell instrument ZEUS at the CSO in half dozen high z galaxies and two quasars, one at $z = 6.42$, indicating that it will be an important probe of star-formation activity at high z. The CO molecule is typically the dominant coolant for molecular gas; the run of line intensity with J constrains the gas temperature, density and mass, as well as a means to discriminate among excitation mechanisms such as UV starlight, X–rays, cosmic rays and shocks.

Nearby galaxies will make excellent targets for CCAT. With Fabry-Perot, Fourier transform, or waveguide–fed multiobject spectrometers, CCAT will be able to deliver spectroscopic images of galaxies in the [NII] 205 μm, [CI] 370 and 609 μm, mid–J CO (e.g. 4–3, 6–5, 7–6) and ^{13}CO(6–5 and 8–7) rotational lines at angular resolutions as fine as 2". In the nuclei of some galaxies (e.g. ULIRGs), it would detect CO emission up to J = 13-12 (200 μm) arising from nuclear clouds highly excited by starbursts, or even CO emission from AGN-excited molecular tori, thus providing a link between stellar mass buildup and supermassive black hole growth.

1.3 From Clusters of Galaxies to the Solar System

The Formation of Clusters of Galaxies. Clusters of galaxies are the largest gravitationally bound structures in the Universe and thus still forming at the present time. Most of their baryons are in the hot intracluster medium (ICM). The Compton–scattered CMB photons travelling through the ICM provide a tool to study cluster structure via the Sunyaev–Zeldovich effect. Understanding the thermodynamic state of the ICM as clusters form and evolve is required in order to elucidate the evolution and variety of interactions of cluster galaxies. The South Pole Telescope and the Atacama Cosmology Telescope are carrying out extensive surveys and will detect a large number of clusters. With its broad spectral coverage, large FoV and high sensitivity, CCAT will provide high angular resolution cluster images over fields comparable to cluster virial radii, separate the emission of dusty submm galaxies from the cluster thermal SZ, and possibly detect the kinetic SZ effect to yield cluster peculiar velocities.

The Origin of the Stellar IMF. In the Milky Way, the stellar Initial Mass Function (IMF) is remarkably consistent across a variety of environments. The origin of this uniformity is unknown. Among the physical processes that may lead to a seemingly invariant IMF are gravitational or turbulent fragmentation, feedback from stellar winds and outflows, competitive accretion, ejection of protostellar cores and stellar mergers. An intriguing possibility is that the mass function of dense clumps in molecular clouds, identified by their thermal dust emission, has a similar shape to the stellar IMF, suggesting that the clump mass function translates into the stellar IMF. CCAT observations will establish if the clump mass function follows the stellar IMF to the substellar (brown dwarf) regime, and if the clump mass function is similar over a wide range of environments in the Galaxy. If the clump mass function is invariant, it will provide compelling evidence that the stellar IMF is imprinted in the fragmentation structure of molecular clouds. To make a definitive determination, observations specifically require (see Carpenter *et al.* science white paper):

- Sensitivity to clumps capable of forming a 0.01 $M_\odot$ brown dwarf, an order of magnitude more sensitive than current surveys.
- Angular resolution $< 5''$ to resolve 0.05 pc clumps to 1 kpc and to relieve the source confusion of imminent surveys with *Herschel* and SCUBA-2 on the JCMT.
- Observations of both the dust continuum and molecular lines: dust emission probes dense regions where molecules may deplete onto grains; high spectral resolution observations of molecular lines yield the kinematic state (collapse, expansion, stability) of the clumps.
- Surveys over tens of square degrees to image molecular clouds, and of many fields in order to sample different environmental conditions.
- Multi-wavelength observations to measure dust temperatures and emissivity; because dust temperatures can range from $\sim$10 K to $>$ 100 K, observations at $\lambda \leq 350\ \mu$m are needed.

Sensitivity, resolution, mapping speed and λ–coverage of CCAT will uniquely enable Galactic surveys that can link the stellar IMF to the physics and topology of the ISM.

Exploration of the Molecular Universe. Molecules are a critical diagnostic of the chemical evolution of material as it cycles from diffuse clouds to the creation of planetary systems and finally to dying stars that enrich the ISM. Wideband spectroscopy in the submm bands will yield a rich dataset to extract the properties of the gas along each step of this cycle. The resulting large line survey data sets will contain a complete chemical inventory, the chemical history and evolutionary state, the line to continuum ratios, the excitation and cooling conditions and a nearly complete dynamical picture of all objects surveyed. They will provide a foundation and an overall context for more detailed investigations of specific sources and processes with more limited spectral coverage. The fundamental questions to be addressed by these studies are: What is the life cycle of molecules in the Universe, from the diffuse interstellar medium to planetary systems? What are the chemical pathways leading from simple atoms and diatomic molecules to complex organic species? What is the distribution and types of organics that seed the habitable zone around stars? Since the inception of molecular astronomy, it was accepted that CO and its isotopologues are the best tracers of temperature and total column of molecular gas, while high-dipole moment molecules (e.g. H_2CO and CS) best traced the dense star-forming core. Today we know that prior to star formation the dense gas is cold and these species are frozen onto grains. Star formation is thus viewed in the light of our growing understanding of the complex cloud core chemistry. While ALMA will study the heart of star formation, the area where collapse likely begins, a complete picture will ultimately require looking beyond the central condensation to explore the initial collapse dynamics from cloud to envelope and central core. This requires sensitivity to large scales that are accessible to CCAT, underscoring again its complementarity with ALMA.

The Sizes of Trans–Neptunian Objects. In recent years, several hundred Solar System objects beyond Neptune have been discovered (TNOs). They are believed to have formed very early on in the outer reaches of the protoplanetary disk around the Sun and to have undergone very little evolution since then. The primitive nature of the material in this region holds important clues towards our understanding of the formation and evolution of the Solar System. The measurement of TNO sizes is important not only because we wish to know the population properties but also because a knowledge of the sizes yields albedos and inferences on their surface properties. CCAT will make possible a statistical investigation of both the size distribution and surface properties of those objects.

2 Technical Overview

2.1 General Characteristics

The CCAT science case, observatory requirements, and conceptual design were developed as part of a $2M study jointly funded by Cornell and Caltech/JPL, which resulted in a Feasibility/Concept Design Study Report[2]. The overall specifications for the CCAT observatory are listed in Table 1, reproduced from Section 5.1 of the CCAT Feasibility Study report. These specifications were derived by considering a broad spectrum of science programs ranging from studies of TNOs in the outer Solar System to surveys for high z submm galaxies. Commonly recurring themes include the need for high sensitivity approaching that of ALMA, excellent angular resolution to enable target identification as well as to overcome spatial confusion, and a wide wavelength coverage in order to constrain the spectra and luminosities of dusty objects. These considerations led to the choice of a 25 m telescope with a 20' field of view, a half-wavefront error (HWFE) around 10 μm rms for high aperture efficiency at 350 μm, and a location on a high (5600 m) mountain site in Atacama above the ALMA plateau for routine access to the 350 μm atmospheric window.

Figure 3: *Left:* Cerro Chajnantor as seen from the ALMA plateau. *Right:* A view of the CCAT proposed site.

[2] *http://www.submm.org/doc/2006-01-ccat-feasibility.pdf.* See also Section 4

Table 1: CCAT Specifications

Specification	Requirement	Goal	Remarks
Aperture	25 m		sensitivity, confusion
Wavelength range	$350 - 1400\,\mu$m	$200 - 3500\ \mu$m	dust SED
Field of view	10'	20'	large-format arrays
Angular resolution	3".5–14"	2"–35"	$\theta = 1" \times \lambda/(100\,\mu\text{m})$
Half Wavefront Error	$< 12.5\ \mu$m	$< 9.5\ \mu$m	rms (HWFE)
Site conditions	< 1 mm	< 0.7 mm	median pwv
Polarization	0.2%	0.05%	after calibration
Emissivity	$< 10\%$, $\lambda > 300\ \mu$m	$< 5\%$, $\lambda > 800\,\mu$m	sky loading is low
	$< 20\%$, $\lambda = 200\ \mu$m		
Elevation range	$5 - 90°$		from horizon
Azimuth range	$\pm 270°$		from north
Pointing, blind	2"	0".5	rms
offset	0".3	0".2	within 1°
repeatability	0".3	0".2	rms, one hour
Scan rate	$0°.2\ s^{-1}$	$1°\ s^{-1}$	slow and fast modes
acceleration	$0°.4\ s^{-2}$	$2°\ s^{-2}$	efficient scan patterns
pointing knowledge	0".2	0".1	rms
Secondary nutation	±2'.5		@ 1Hz, azimuth only

2.2 Proposed Site and Infrastructure

Consistently superb observing conditions are crucial for achieving CCAT's scientific objectives. For observations at submm wavelengths, a site with very little atmospheric water vapor is paramount. The proposed site for CCAT is at an altitude of 5612 m, on a plateau about 50 m below and 200 m east-north-east of the summit of Cerro Chajnantor (Fig. 3), within the Science Preserve established by the Chilean Government, and 600 m above the ALMA site. Several alternative locations within the Science Preserve were considered. A radiosonde campaign[3] showed that very significant gains in atmospheric transparency at far IR wavelengths could be achieved, with respect to the ALMA plateau at 5000 m, at sites a few hundred m above it. This was corroborated by simultaneous measurements on Cerro Chajnantor and at the 5000 m ALMA plateau with two $350\,\mu$m tipping radiometers previously cross-compared at the plateau[4]. Cerro Chajnantor is indeed an excellent submm site, significantly superior to the ALMA plateau, with a $350\,\mu$m opacity ratio of around 0.6–0.7 between the two locations. This opacity advantage can be quantified in terms of observing time: relative to the plateau, the CCAT site offers nearly twice as much high-quality observing time in the crucial $350/450\,\mu$m atmospheric windows (see Table 3).

CCAT plans have been made assuming existing infrastructure as of 2006 (roads, communications, access control, emergency management, etc.). With the construction of ALMA and efforts by the partnership of the various projects underway in the Science Preserve, local conditions are constantly improving. As described in Section 4, CCAT has established a partnership with Associated Universities Inc. with a view towards employing that institution's resources in Chile to support CCAT Operations.

[3]Giovanelli *et al.* 2001, PASP 193,1102

[4]Radford, S.J.E. 2008, SPIE Conference Series vol. 7012

2.3 Sensitivity

Multiple factors – the 25 m aperture, the improved atmospheric transparency of the higher site, the use of broadband continuum detectors instead of narrow band heterodyne receivers, the high aperture efficiency resulting from $\sim 10\,\mu$m rms optics and the possibility of achieving sensitivities limited by photon statistics and not by (heterodyne) receiver noise – combine to give CCAT a continuum point-source flux sensitivity in the 350 μm and 450 μm atmospheric windows that is comparable to ALMA on a per-pixel basis. Therefore, with the use of large array cameras, the mapping speed for CCAT will be many orders of magnitude faster than ALMA, enabling large–scale surveys and providing extraordinary complementarity with ALMA.

The predicted sensitivity for CCAT is shown in Table 2; the corresponding details may be found in the Feasibility Report. For deep imaging, the raw sensitivity (NEFD) must be supplemented by estimates of the source confusion limit. Because CCAT's sensitivity and angular resolution will allow us to probe much more deeply into the submm galaxy population than current instruments, the confusion limit is not yet well known and must be predicted using models [5] that extrapolate existing (shallower) measurements. At $\lambda = 350\,$um, and using a very conservative value of 30 beams per source, CCAT will yield a confusion-limited areal density of ∼40,000 sources per square degree, which is quite comparable to deep 24 μm counts with Spitzer[6]. Fig. 4 shows that CCAT and ALMA should have comparable continuum sensitivities at 350 and 450 μm, with ALMA gaining advantage at long wavelengths and CCAT gaining at shorter ones. However, the use of large focal plane arrays makes CCAT's mapping speed orders of magnitude faster than ALMA even at long wavelengths. Relative to existing 10-15 m telescopes, CCAT will be well over an order of magnitude faster to reach a given flux level, and will have a deeper confusion limit. For spectroscopy, line flux sensitivities (1–σ, 1 s) are given in the Feasibility Report and lie in the range $2.2 \times 10^{-18}\,\mathrm{W\,m^{-2}\,s^{1/2}}$ at $\lambda = 350\,\mu$m to $1.6 \times 10^{-19}\,\mathrm{W\,m^{-2}\,s^{1/2}}$ at $\lambda = 1.2\,$mm.

2.4 Construction

Construction of the CCAT observatory includes the following items:

1. **Road Improvements & Utilities**: The access road will be improved to provide access for the required construction materials and subassemblies and to provide safe transit consistent with regular operations. CCAT plans to be energy self sufficient, with electrical power to be provided by two 750 kVA diesel generators at the base of the summit access road.

2. **Base & Telescope Facility**: A base facility will be built at lower elevation, possibly near San Pedro. It will consist of a dedicated group of buildings within a *recinto*, including dormitories, offices, a kitchen/dining room, lab space and a warehouse. The Telescope Facility on the summit is described in more detail in the Feasibility Report: a metal building with concrete foundations and ring wall for dome support.

[5] Blain, A.W. *et al.* 2002, Phys. Reports Lett. 369(2), 111
[6] Papovich *et al.* 2004, ApJSS 154, 70

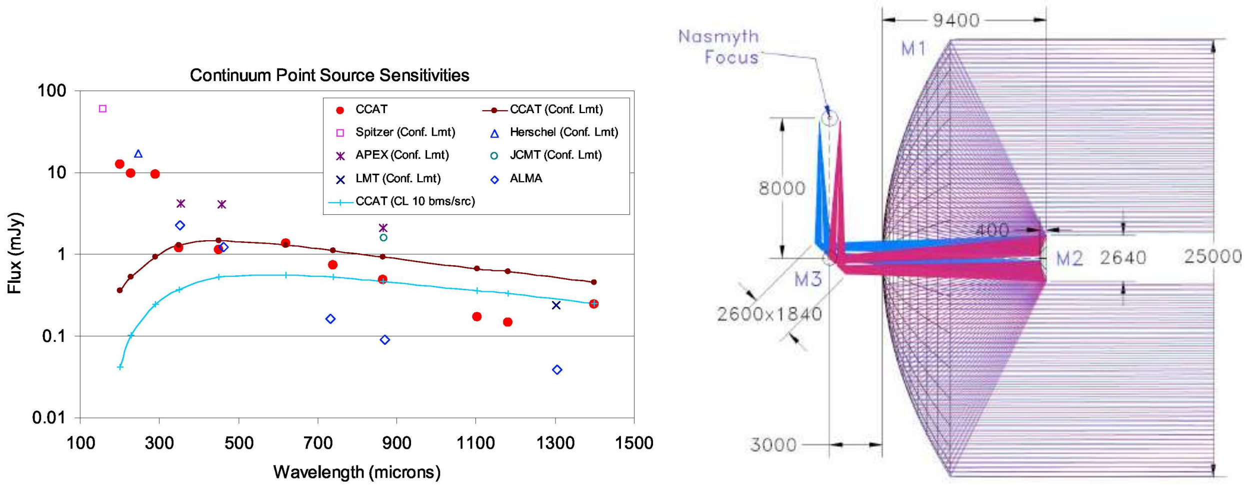

Figure 4: *Left:* CCAT continuum point-source sensitivity per pixel compared to other facilities, calculated for a 5σ detection in one hour integration. *Right:* Optical layout and ray–tracing of the CCAT design, including overall dimensions for optical components in mm.

Table 2: CCAT Continuum Sensitivity

λ (μm)	ν (GHz)	PWV (mm)	NEFD[a] (mJy $s^{1/2}$)	CL flux[b] (mJy)	CL time[c] (min)	CL density[d] 10^3 deg^{-2}	CL mapping[e] deg^2 yr^{-1}
200	1500	0.3	151	0.36		116	
350	857	0.4	14.4	1.29	52	38	26
450	667	0.5	13.8	1.45	38	23	60
620	484	0.5	16.3	1.27	68	12	23
865	347	1.0	5.83	0.92	17	6.2	319
1180	254	1.0	1.74	0.61	3.4	3.3	2300
1400	214	1.5	2.93	0.45	18	2.4	436
2000	150	1.5	2.30	0.20	58	1.2	80
3300	90.9	1.5	2.82	0.08	513	0.43	9

[a] The NEFD is the $1\,\sigma$ flux sensitivity achieved for an integration time of one second, calculated using the appropriate precipitable water vapor (PWV), as listed.

[b] The source flux density level reached at the confusion limit (model prediction).

[c] The time required to reach the confusion-limited flux, calculated for $5\,\sigma$ detection.

[d] The source density at the confusion limit (CL), in units of 1000 sources, taken to correspond to 30 beams per source. For reference, deep 24 μm imaging with Spitzer (Papovich *et al.* 2004, ApJS 154, 70) yields $N(S_{24\,\mu\mathrm{m}} > 30\,\mu\mathrm{Jy}) \approx 60{,}000$ deg^{-2}.

[e] The confusion–limited mapping speed, taking into account PWV statistics (see Table 3), for a PWV-scheduled observing program utilizing instruments with 50,000 detectors.

Table 3: Available Observing Time

Band		Time	Ref.	CCAT (5612 m)			ALMA (5050 m)		
λ	ν	to CL[a]	PWV[b]	Time Available[c]		CL fields[d]	Time Available[c]		CL fields[d]
(μm)	(GHz)	(hr)	(mm)	(hr yr^{-1})	(%)	(yr^{-1})	(hr yr^{-1})	(%)	(yr^{-1})
200	1500	1248	0.26	281	3		84	1	
350	857	0.86	0.47	1936	22	2244	1084	12	1257
620	484	1.14	0.64	716	8	629	723	8	634
740	405	0.43	0.75	639	7	1488	690	8	1607
865	347	0.28	0.86	1223	14	4413	1205	14	4348
1400	214	0.30	1.00	1517	17	5093	1299	15	4361
Total time for PWV < 1.1 mm:				6312	72		5084	58	

[a] Time to reach the confusion limit (CL) – see Table 2.

[b] The reference precipitable water vapor (PWV) is the adopted maximum value for observations in a given wavelength band. Several bands have equivalent thresholds (e.g. 350/450 μm) and for simplicity only one band is listed.

[c] Time available at Ref. PWV or better, not already used at lower λ.

[d] Number of confusion-limited fields per year.

(a) **Dome**: A steel frame with either steel, aluminum or fiberglass cladding, the Calotte–type, 40 m diameter dome will weigh ~500 tons (see cover page). It will use two rotational stages for azimuth and elevation motions. Using a geodesic structure, it will be easily transported and assembled at the challenging site.

(b) **Telescope Mount**: A steel, altitude/elevation mount will use both hydrostatic and rolling element bearings, multiple drives, optical encoders, with both Nasmyth and bent Cassegrain instrument locations. It will weigh ~650 tons and is designed in modules for ease of transportation to the site and simple on-site assembly.

(c) **Primary Mirror** (PM): A segmented structure will mount via linear actuators to the PM truss. The baseline design is a bolted steel space frame; carbon-fiber options are also being reviewed. The truss will be assembled on site without welding or adjustment and will attach to the telescope mount. Gravitational and thermal distortions of the PM assembly will be corrected via the segment actuators. Control of segment positions will be closed–loop using data from distributed sensor systems.

(d) **Mirror Segments, M2/M3**: Two alternative approaches to mirror segmentation are under consideration: (a) large ($\sim$ 1.7 m) composite, monolithic panels and (b) smaller panels mounted on rafts. M2/M3 are ~2.7 m in diameter (1.9m$\times$2.7 m for M3). M2 assembly will include a hexapod for alignment and a nutator. M3 will be mounted to a turntable to allow the image to be directed to either Nasmyth or Bent Cassegrains instrument locations (see Fig. 4).

While Cerro Chajnantor is certainly a challenging site for construction, this is offset somewhat by the ALMA experience and the demonstrated capabilities of Chilean construction companies to construct complex facilities at similar locations. The major subsystems are being designed with site assembly in mind. Field welding and alignment will be minimized and pre-shipment trial assembly will be emphasized. All workers on site will be required to use supplementary oxygen for both safety and efficiency.

3 Technology Drivers

The optical design of CCAT foresees a compact Ritchey–Chrétien with f/0.4 hyperboloid PM, which allows for a relatively compact 40 m dome. The system f–ratio is f/8, with excellent Strehl ratios to the edge of a 20' FoV. The optical layout is shown in Fig. 4. Three areas of special importance as technology drivers for the project are discussed below.

3.1 Precision Active Surface

Figure 5 graphically illustrates the technical challenge of constructing a telescope according to CCAT's specifications. Of the total $\sim 10\,\mu$m rms half-wavefront error (HWFE), around 7 μm rms is allocated to the 25 m primary surface. This specification places CCAT well beyond the standard gravitational limits and approaches the thermal limits for the best materials such as Carbon fiber reinforced plastics (CFRP). An active surface is necessary, in which the reflector surface is segmented and the reflector segments are attached via actuators to the truss (back-up structure). The actuators are periodically adjusted to allow the deformations of the truss to be compensated, allowing the surface precision to be maintained. This approach is followed in other recently constructed large telescopes such as the 100 m GBT. However, for those telescopes the active surface is generally operated "open–loop", typically using table look–up to correct for gravitational distortions. The GBT is currently experimenting with the use of out–of–focus holography using a bolometer camera in order to correct for large scale thermal distortions every few hours[7]. Given the demanding requirements for CCAT, a more rigorous closed–loop operating mode has been adopted, in which the actuator commands incorporate information from a distributed network of sensors, loosely modeled after the edge-sensor approach used by the Keck telescopes, but supplemented by angle sensors such as a Shack-Hartmann camera. In predicting the performance of the telescope, it is necessary to consider the thermal deformation properties of individual reflector segments and their size limitations in addition to the properties and performance of the sensor system. Thus, the choice of segment technology is a key issue. Both options being considered — CFRP monolithic panels, and compound panels (see Fig. 5) — at present appear to lead to viable solutions for CCAT's active surface.[8] [9] [10]

3.2 Imaging and Spectroscopic Instruments

The scientific power of CCAT derives from recent advances in submm detector array technology. As shown in Figure 6, array sizes have been growing exponentially. At present, the

[7]Hunter, T. *et al.* 2009, *www.astro.caltech.edu/USNC-URSI-J/Boulder%202009%20presentations/Wednesday%20PM/Hunter_URSI_09.pdf*

[8]MacDonald, D. *et al.* 2008, SPIE Conference Series vol. 7012

[9]Woody, D. *et al.* 2008, SPIE Conference Series vol. 7012

[10]Von Hoerner, S. 1967, *Astron. J.* 72, 35

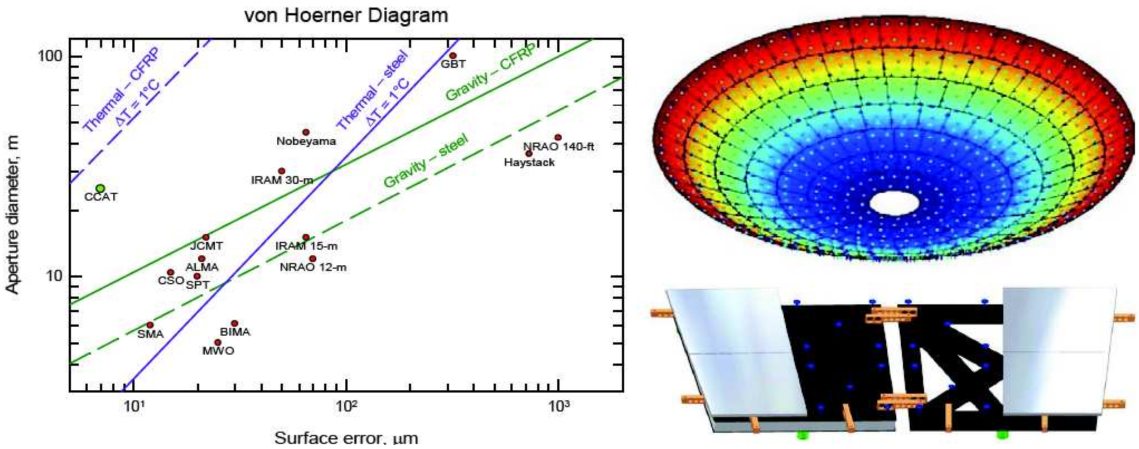

Figure 5: *Left*: Aperture vs. surface rms error, after von Hoerner. The "gravity" and "thermal" lines illustrate limits for passive structures due to the physical properties of materials (steel and CFRP). *Right, top:* Baseline "keystone" segmentation with $\sim 2\,$m panels, 210 panels total. *Right, bottom:* A "compound panel" utilizing smaller reflector tiles attached to a CFRP subframe to synthesize a larger segment. This approach allows segment sizes of order 3-4 m to be considered.

state of the art is represented by the kilopixel-scale arrays of superconducting transition-edge sensor (TES) bolometers now in use at SPT and ACT. The SCUBA 2 instrument, in commissioning at the JCMT, also has roughly 1 kilopixels functioning at present, but ultimately will have 10^4 pixels once the science-grade arrays are installed. For CCAT, the goal is to have cameras with up to ~ 50 kilopixels available at "first light".[11] Two cameras are envisioned: one at short wavelengths, $200 - 620\,\mu$m, and one at long wavelengths, covering $740 - 2000\,\mu$m. With 50,000 Nyquist-sampled pixels, CCAT's field of view could be filled at $\lambda = 1\,$mm. However, since the number of pixels required scales as λ^{-2}, filling the field of view at 350 μm would require of order 400 kilopixels. Clearly, building instruments at this scale presents a broad spectrum of technical challenges: the related cryogenics, optics, baffling, shielding, electronics, and mechanical issues must all be dealt with. These are long-term challenges: it is important to remember that CCAT can produce outstanding science even with existing kilopixel-scale arrays.

Similar challenges exist for spectroscopic instrumentation[12]. A CCAT goal is to construct broadband direct-detection grating spectrometers, capable of determining z via the [CII] or CO lines. Existing examples include the ZEUS and Z-spec instruments now in use at the CSO. However, CCAT will go beyond these single-beam instruments and host multi-object spectrometers capable of observing 10–100 objects simultaneously while spanning multiple atmospheric windows. Again, this presents numerous technical challenges. It is now also possible to construct large heterodyne array instruments for high-resolution spectral mapping. The 64-pixel 350 GHz system in construction at U. of Arizona provides one example; ultimately, heterodyne systems with 256–1024 pixels should be possible.

[11]Stacey, G. *et al.* 2006, SPIE Conference Series vol. 6275

[12]*http://www.submm.org/mtg/2008/2008-05-boulder/2008-05-boulder.html*

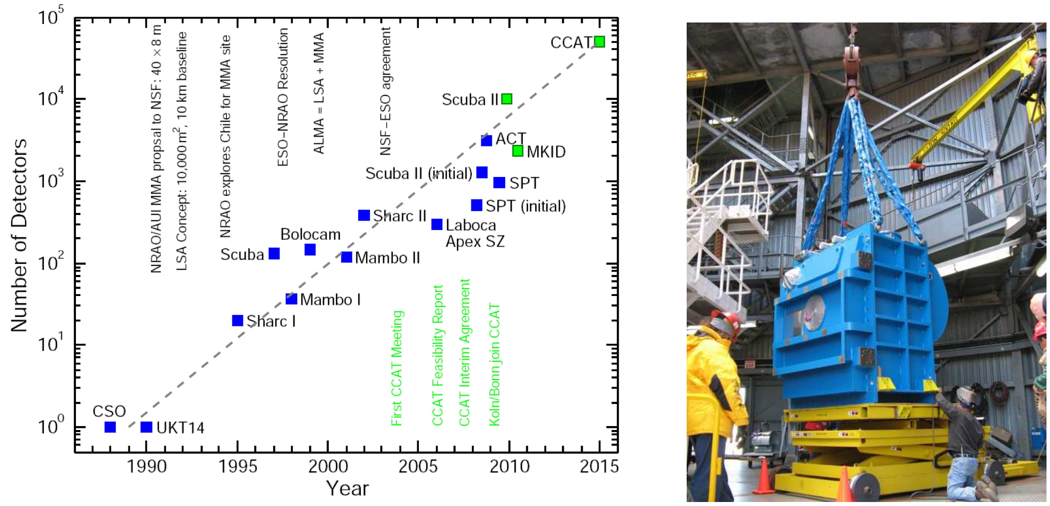

Figure 6: *Left:* The growth of mm/submm detector array size as a function of time has followed an exponential trend over the past two decades, with a growth rate exceeding a factor of 2 every two years. Blue points represent existing (or obsolete) instruments; the green points are projections. *Right:* The SCUBA–2 instrument arriving at the JCMT in 2008.

3.3 Large-Format submm Detector Arrays

As shown in Fig. 6, the number of detector pixels in mm/submm instruments has been growing exponentially. Early single-pixel bolometer instruments, and JCMT's SCUBA 1, used hand-assembled bolometers in which a germanium or silicon thermistor chip was attached to an absorbing substrate and was suspended from a metal frame using very thin leads. Readout was performed using individual low-noise JFET pre-amplifiers operated at ∼100 K, with leads for each pixel running from the cold stage to the JFETs. A major step forward was the introduction of lithographic fabrication[13], which greatly reduces the labor needed to fabricate arrays. This technology was adopted for instruments such as CSO's SHARC 1 (20 pixels) and Bolocam (144 pixels). However, the readout scheme was the same, with individual JFET preamps and large numbers of leads.

The introduction of the superconducting transition edge sensor[14] (TES) as a replacement for semiconductor thermistors and the invention of multiplexed superconducting readouts [15] reduced the lead counts and enabled kilopixel–scale arrays. The SCUBA 2 array is the most ambitious attempted so far and provides an interesting case study. The TES detector array is produced using fairly conventional lithographic and micromachining processes, and is then hybridized (indium bump-bonded) to the readout multiplexer (see Fig. 7). Multiplexer fabrication is the most difficult and expensive aspect of the array production.

The superconducting (SQUID-based) TES multiplexing schemes now in use have various limitations in terms of cold power dissipation, multiplex factor, expense and complexity, etc. The simplest solution is to avoid superconducting active electronics altogether, and to

[13] Downey, P.M. *et al.* 1984, *Applied Optics* 23(6), 910
[14] Irwin, K.D. 1995, *Applied Phys. Lett.* 66(15), 1998
[15] Chervenak, J.A. *et al.* 1999, *Applied Phys. Lett.* 74(26), 4043

use passive frequency–multiplexed superconducting microresonators as detectors.[16] In this "MKID" scheme, the complex readout electronics resides at room temperature (see Fig. 7). Meanwhile, fabrication of the MKID arrays is quite straightforward and the multiplexing is built-in, so bump bonding is unnecessary. A 2304-detector MKID camera is currently under construction for the CSO. Scaling up either TES or MKID technology to the 50-100 kilopixel range represents a significant but not insurmountable technical challenge.

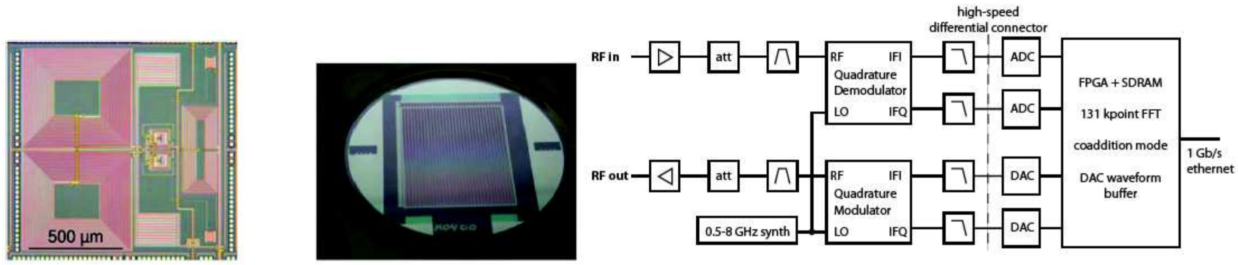

Figure 7: *Left*: The 32 × 40 SCUBA-2 readout multiplexer is a complex, wafer–scale, custom superconducting integrated circuit. The readout circuitry for each pixel occupies an area around 1 mm^2. Device fabrication involves Nb/Al-oxide/Nb tunnel junctions, 10 lithography levels, and 60 reticles (mask patterns). Credit: Gene Hilton, NIST. *Right*: A block diagram of the radio-frequency multiplexing electronics being developed for the CSO MKID camera, using mass-produced digital and wireless silicon integrated circuits. The circuitry shown fits on a modest-sized board, dissipates ~ 30 W at room temperature, and is capable of reading out > 1000 detectors at ∼$10 per detector.

4 Activity Organization, Partnerships, and Current Status

The CCAT partnership was initiated in 2004 through an MOU signed by Cornell University and the California Institute of Technology (also representing the Jet Propulsion Laboratory), following which a Project Office was established and a Project Manager and a Deputy Project Manager were hired. The consortium was later joined by the University of Colorado, a consortium of Canadian universities (University of British Columbia and Waterloo University) and the United Kingdom through its Astronomy Technology Center at Edinburgh. An Interim Consortium Agreement was drafted and signed by those partners and a first meeting of the project's interim board was held at Waterloo in 2007. More recently (Feb. 2009), the CCAT partnership was joined by a consortium of German Universities (Cologne and Bonn) and by Associated Universities, Inc. of Washington, D.C. (March 2009). The participation of AUI is intended to help development and operation of the CCAT Project in several ways. It will provide a legal presence in Chile; advice, expertise and logistic support developed in the construction and operation of ALMA; hiring of local personnel and accreditation of international staff in Chile; Observatory operation in Chile. Moreover, AUI is interested in playing a proactive role in coordinating US community access to CCAT and its future data products.

[16]Day, P.K. *et al.* 2006, *Nuclear Instruments & Methods inn Physics Research Section A*

Following site survey activities by Cornell at earlier times, a \$2M Feasibility/Concept Design Study was carried out between 2004 and 2006. Its primary goal was to define a facility whose scientific capability would represent a substantial advance over the present generation of 10–15 m class submm telescopes and which, unlike most existing mm/submm telescopes, would be designed from the start to have a very wide field of view in order to exploit the rapid ongoing development of submm detector array technology. It was recognized that in order to make best use of the nation's substantial investment in ALMA, the US astronomical community would need access to an instrument located in the southern hemisphere, capable of making rapid wide-field surveys with a flux sensitivity sensitivity comparable to ALMA. A report of that activity (*http://www.submm.org/doc/2006-01-ccat-feasibility.pdf*) was reviewed by a committee chaired by Robert Wilson of Harvard U. and including Mark Devlin of the U. of Pennsylvania, Fred Lo of NRAO, Matt Mountain of STScI, Peter Napier of NRAO, Jerry Nelson of U.C. Santa Cruz and Adrian Russell of ALMA/North America. The Rewiew Committee was flattering to the Project in its praise. It concluded as follows: *"CCAT is an important and timely project that will make fundamental contributions to our understanding of the processes of galaxy, star and planetary formation, both on its own and through its connection with ALMA. It should not wait."*

Following consolidation of the partnership, the Project is currently gearing up to initiate an Engineering Design Phase. The main technical tasks of this phase include the detailed analysis of the higher risk areas of the Project, especially the design and manufacture of the PM, the active control of the optics and the reliability of the calotte design of the dome. The financial resources to complete the Project are not yet fully in hand, hence efforts at fundraising remain an important part of the Project's activities. The manpower resources of the Project are limited. Thus a significant fraction of the current technical activities takes place through work packages at the partner institutions, coordinated by the Project Office to maximize institutional synergies.

5 Activity Schedule

CCAT will take six years to complete from the date when sufficient funding is in hand. Planning has continued to improve as the design has matured and additional site information has become available. The following schedule outlines activities by Project Year.

Year 1: Project staffing, finalization of requirements, systems engineering flow-down of requirements to subsystems and performance validation analysis. Architectural and civil engineering design of facilities. Award of contracts and initiation of work for site improvement and award of contract for general construction of observatory facility and support facility. Award of contract for dome development. PM segment fabrication experiments. Initiate procurement for Mount and Primary Mirror truss. Begin M2/M3 and PM segment edge sensor procurement documentation. Instrument definition and technology downselects.

Year 2: Improvement of road to site completed. General construction of facilities begins. Dome detailed design completed and fabrication initiated. Mount & PM truss design complete and fabrication begins. PM actuator system procurement documentation, contract awarded. PM panel tooling development and initiation of production. PM edge sensor procurement completed, design begun. PM truss manufacture complete and trial erection

begun. M2/M3 detailed design complete and fabrication initiated. Design of Telescope Control System (TCS) underway. Instrument design.
Year 3: Construction of support facility completed, occupied by CCAT staff as needed. Mount fabrication complete, trial erection begun. PM truss completed, packing and shipping commence. M2/M3 assembly and test begins. Begin software development of TCS. Dome delivered to site. Mount final acceptance testing complete, packing and shipping commence. PM truss on site, ready for assembly. PM Panel shipping begins. M2/M3 fabrication complete, packing and shipping commence. Instrument construction.
Year 4: Observatory facility complete, stocked, and occupied. Key Project team members move to Chile to support Integration activities. Dome and mount installed and tested. Installation of PM Truss begins. M2, M3 and PM actuator system on site, available for installation. PM panels arriving and stored. TCS interface with subsystems accomplished as they are installed. Instrument construction.
Year 5: PM panel actuators, edge sensors, and panels installed and debug of panel control begun. Calibration WFS completed and shipped. TCS interface to mount, dome, and facility completed. M2 & M3 installed. Supplementary PM panel alignment system installed and debugged. Experiments in PM alignment and control, overall optical alignment and general debugging conducted. PM panel fabrication completed, last panel shipped. Panel installation continues. First Light occurs with temporary camera. Instrument optimization.
Year 6: PM panel installation complete, PM panel control and overall Observatory function attained. TCS functional. First Light followed by Commissioning. Project Team reduced as success is attained. Key members transitioning to operations. Instrument deployment and commissioning. Full science operations begin.
Funding Profile: The anticipated funding profile of the Project foresees: \$2.5M, \$8.5M, \$18M, \$34.5M, \$37M and \$10M respectively for years 1 to 6.
Milestones: Assuming availability of funding to initiate Year 1 activities by early 2010, the major milestones of the Project are: completion of the Low Elevation Support Facility by 4/2011 and of the Observatory Facility by 2/2013; installation of Dome and Telescope Mount by 11/2013 and of PM Truss by 1/2014; completion of PM by 1/2015 and First Science by 9/2015.

Work has been planned to accommodate the ability of the Project Team to perform the work necessary to initiate procurements and for an appropriate annual rate of funding. Sufficient slack exists in schedules for development of subsystems to accommodate likely schedule deviations without impact to the overall schedule. Completion is most likely gated by the fabrication of the final mirror segments and the time/rate of accomplishment of commissioning. Key factors in the rapid development are: multiple parallel contracts for development of major subsystems by qualified vendors; interface definitions negotiated and compliance verified prior to shipping; trial erection of dome and mount to validate performance at vendor facilities; modular construction of major subsystems for ease of assembly on site; validation of telescope control system interface with subsystems prior to shipping.

The lifetime of the Observatory is estimated to be no less than 20 years.

6 Cost Estimate

The current estimates of cost for the telescope and associated facilities are based on the analysis carried out in the course of the Feasibility Study of 2004–2006. Contractors were funded to develop concepts for major subsystems of the Observatory and to provide detailed cost estimates. Taking into consideration the most recent experiences in construction in the high Atacama region, of current market prices of key materials such as steel and of currency fluctuations, updates of cost estimates have been kept current. Areas not estimated by contractors were estimated by the CCAT Project team, using cost data from prior telescope projects, catalogue prices, and information solicited from vendors. Contractor estimates have been adjusted to reflect the evolving design of CCAT. A contingency of 25% is adopted during the development of the design. This will be reduced appropriately as the design matures and areas of risk reduced. Table 4 provides a current breakdown of cost estimates, expressed in units of 2009 US$1M.

Table 4: CCAT Cost Summary (unit=10^6 US$)

WBS Area		Cost		
	Contracts & Purchases			
1.1	Observatory Facility	7.62		
1.2	Lower Elevation Support Facility	2.81		
2.0	Telescope Dome	10.22		
3.0	Primary Mirror	13.95		
4.0	Secondary and Tertiary Mirrors	2.68		
5.0	Mount	14.20		
6.0	Optical Assemblies	2.02		
7.0	Misc. Electronics	0.25		
8.0	Telescope Control System	0.44		
9.0	System Engineering Contracts	1.00		
10.0	Integration & Commissioning	1.02		
11.0	First Light Instrumentation	20.00		
12.0	Management non–labor Costs	0.28		
	Total for Contracts & Purchases		76.48	
	Labor Costs			
1.0	Raw Labor	7.16		
2.0	Fringes & Benefits 32%	2.29		
3.0	Overhead 10%	0.94		
	Total Labor Costs		10.39	
	Additional Costs			
	Travel 20% of Raw Labor		1.43	
	Contingency 25% of Budget		22.07	
	Total Project Cost			110.37

CCAT operations will involve two coordinated but distinct activities: routine operation of the telescope itself and scientific exploitation of the observations, in particular surveys. In the planning for CCAT, these activities have been considered separately.

Telescope operations. The CCAT Feasibility Concept Design Study included an operations model for the telescope, developed by considering the examples of the CSO, APEX and other telescopes operating on the Chajnantor Plateau. The model includes routine operations and maintenance of the telescope itself, of the scientific instruments, and of associated facilities and support systems; transportation; power generation and other utilities; support facility accommodations; materials and services; relations with the Chilean authorities; and land use fees. In late 2005, annual costs for these activities were estimated at $5.25 M. Although there has been considerable economic turmoil since 2005, a rough estimate of the cost in late 2008 is $6M per year. Roughly 3/4 of this total is expenses in Chile, notably resident staff. Although the cost estimate includes staff astronomers to oversee observations and telescope performance, major science activities were considered separate.

CCAT surveys. With a large instantaneous field of view and rapid mapping speed, CCAT is optimized for wide field submm imaging. A prime science objective is conducting large–scale surveys, to which the consortium anticipates devoting about half of the available observing time. It will take considerable effort to design and plan these surveys, to schedule and carry out the observations, to calibrate and process the data, and to produce and release catalogs and other data products to the community in a timely manner and through robust access tools. In late 2008, the US CCAT partners met to consider survey strategies and seek advice from representatives of several previous and ongoing surveys. These points were agreed: CCAT surveys would be led by members of the consortium but would be open to community participation; surveys will be designed to produce mature catalogs and other data products; survey data will be released to the community immediately upon completion of calibration, quality control, and preliminary processing; mature data products will follow soon thereafter. To support the survey activities, the estimated annual cost is about $6M overall. This estimate does not include telescope operations, discussed previously.

Cost Responsibility. Responsibility for the ongoing costs of CCAT operations and surveys would rest with the consortium members in proportion to their capital investments. Presently, US universities represent about half of the consortium interest. Hence the overall US responsibility for telescope operations and survey activities would be about $6M (2008) per year. The US CCAT partners anticipate requesting funds for operations and surveys from the NSF. Caltech would close the CSO, presently supported by the NSF, in preference for CCAT. In return for NSF funding, CCAT would be in position to release survey catalogs and data products to the community. These surveys will be rich resources for identification of exceptional individual objects for detailed follow up study with ALMA and other facilities. In addition to and distinct from support for operations and surveys, the US CCAT partners anticipate requesting about $1.5M per year in aggregate for support of science activities, i. e., scientific exploitation of the survey results, follow up observations, etc.

Capital contribution. Although the US CCAT partners anticipate raising the majority of the CCAT construction funds privately, there is an opportunity for NSF contribution to CCAT construction. Such a contribution would allow community input to the design of the telescope and instruments and would provide community access to the non survey fraction of the observing time on the telescope.