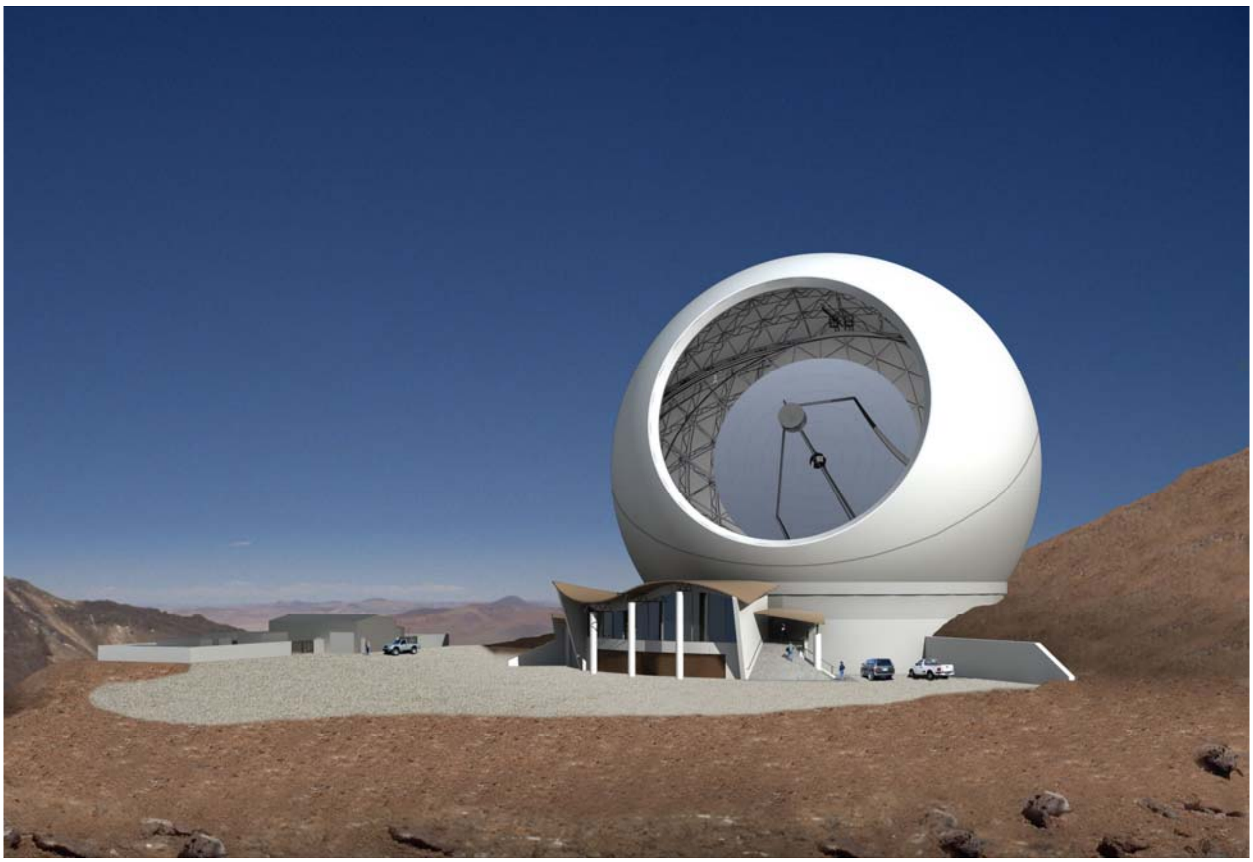
Cornell Caltech Atacama Telescope
(CCAT)

Feasibility/Concept Design Review

Presentations

January 2006



Cornell University
California Institute of Technology
Jet Propulsion Laboratory

CCAT Feasibility/Concept Study Review

Tuesday, January 17, 2006

8:00 AM	*Continental Breakfast & Chat*		0:30
8:30 AM	Welcoming Remarks	Thomas Tombrello	0:10
8:40 AM	The Vision of CCAT	Riccardo Giovanelli	0:10
8:50 AM	Overview of Study Results	Thomas Sebring	0:15
9:05 AM	CCAT Science & Requirements	Terry Herter/Jonas Zmuidzinas	0:35
9:40 AM	CCAT Requirements Summary	Simon Radford	0:10
9:50 AM	Optical Design & Analysis	German Cortes	0:30
10:20 AM	*Break*		0:10
10:30 AM	Facilities Concepts	José Teran, M3 Engineering	0:30
11:00 AM	Dome Concept	Nathan Loewen, AMEC	0:30
11:30 AM	Telescope Mount Concept	Dave Finley/Ed Reese, VRSI	0:30
12:00 PM	*Lunch*		0:45
12:45 PM	Primary Mirror Overview	Thomas Sebring	0:30
1:15 PM	Systems Engineering & Analysis	David Woody	0:30
1:45 PM	CFRP Panel Study	Bob Romeo, CMA Inc.	0:30
2:15 PM	Borosilicate Panel Study	David Strafford, ITT	0:30
2:45 PM	Telescope Calibration & Alignment	Gene Serabyn	0:30
3:15 PM	*Break*		0:15
3:30 PM	Laser Alignment System	Shanti Rao	0:30
4:00 PM	Hartmann Alignment Sensing	Thomas Sebring	0:10
4:10 PM	Wavefront Sensing Guider	Jamie Lloyd	0:10
4:20 PM	M2 & M3 Systems	Mike Cash, CSA Engineering	0:25
4:45 PM	CCAT Instrumentation	Gordon Stacey	0:30
5:15 PM	Electronics & Controls	Tom Sebring/Simon Radford	0:15
5:30 PM	*Adjourn*		
6:00 PM	*Reception*		1:30

Wednesday, January 18, 2006

8:00 AM	*Continental Breakfast & Chat*		0:15
8:15 AM	Site Selection and Testing	Simon Radford	0:20
8:35 AM	Operating in Chile	Riccardo Giovanelli	0:15
8:50 AM	Integration & Commissioning	Thomas Sebring	0:20
9:10 AM	Operations Planning	Simon Radford	0:20
9:30 AM	Project Management Plan	Thomas Sebring	0:20
9:50 AM	*Break*		0:10
	Executive Session: Review Committee, Administration, & CCAT Management		
10:00 AM	Preliminary Cost Estimate	Thomas Sebring	0:30
10:30 AM	Discussion		0:30
11:00 AM	Review Committee Caucus		1:00
12:00 PM	*Lunch (provided for Review Committee)*		1:00
1:00 PM	Committee Debrief		1:00
2:00 PM	*Adjourn*		

Meetings both days will be at: The Pasadena Sheraton

2006-01-03

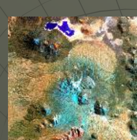
ATACAMA

CCAT : The Cornell-Caltech Atacama Telescope

A joint project of Cornell University,
the California Institute of Technology
and the Jet Propulsion Laboratory

Riccardo Giovanelli
Study Review
Pasadena, 17-18 Jan 2006

The CCAT:



- A 25m class FIR/submm telescope that will operate with high aperture efficiency down to λ = 200 μm, an atmospheric limit
- With large format bolometer array cameras (large Field of View > 15’) and high spectral resolution heterodyne receivers
- At a very high (elevation > 5000m), very dry (Precipitable Water Vapor column PWV<1 mm) site with wide sky coverage

CCAT Drivers

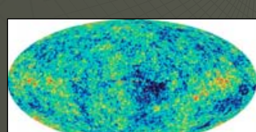
1. Scientific Excellence

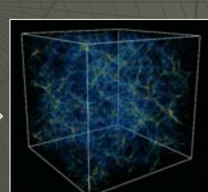
CCAT is a unique project geared towards the investigation of cosmic origins, from planets to galaxies, in the FIR/submm spectral region

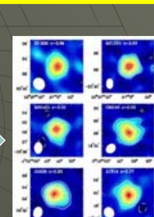
- Early Universe Cosmology
- Galaxy Formation & Evolution
- Disks, Star & Planet Forming Regions
- Cosmic Microwave Background, SZE
- Solar System Astrophysics

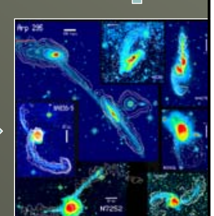
…to this?

How did we get from this

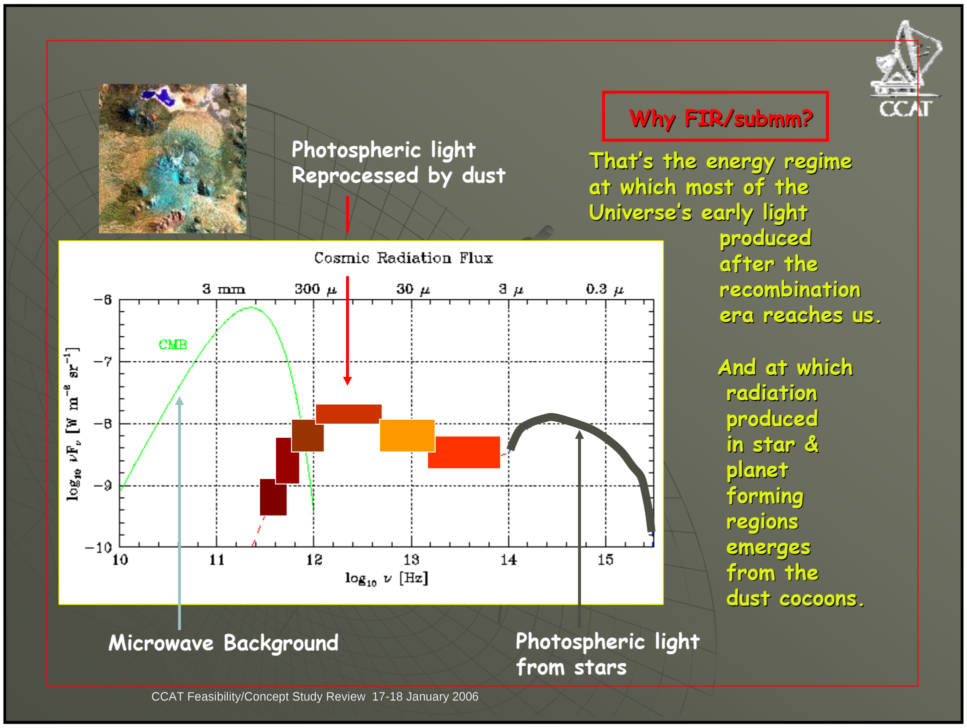


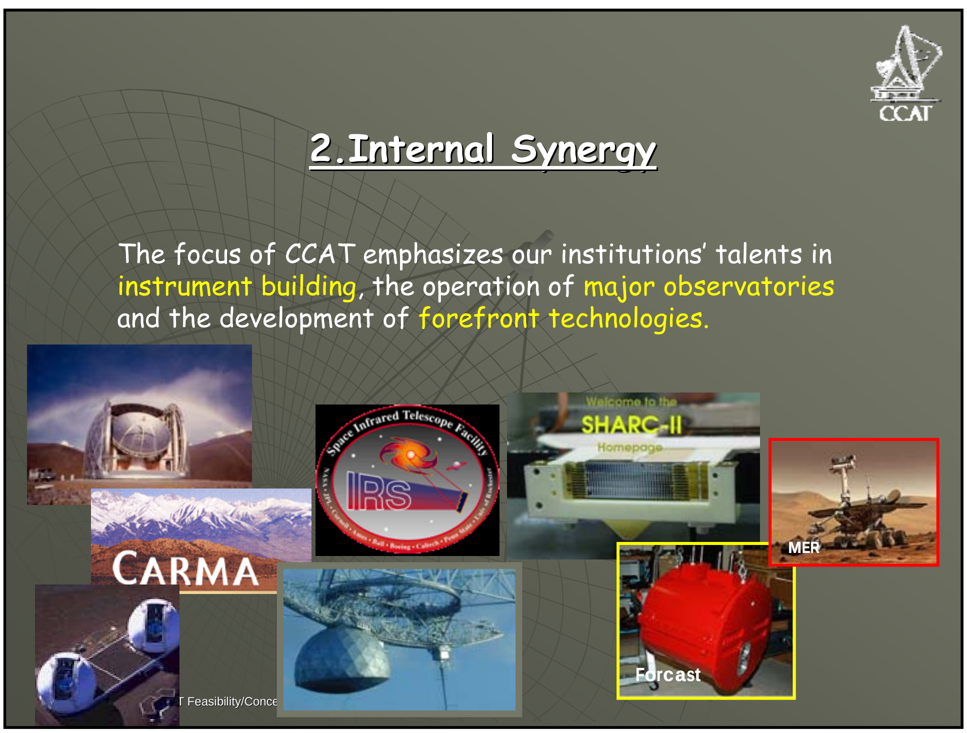






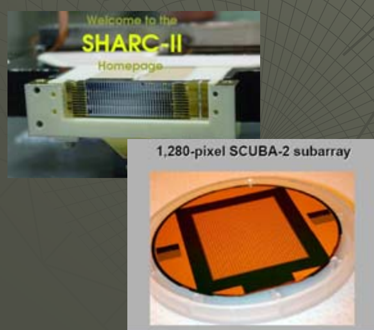
CCAT Feasibility/Concept Study


CCAT
Why FIR/submm?
That's the energy regime at which most of the Universe's early light produced after the recombination era reaches us.
And at which radiation produced in star & planet forming regions emerges from the dust cocoons.
Photospheric light Reprocessed by dust
Cosmic Radiation Flux
3 mm
300 μ
30 μ
3 μ
0.3 μ
CMB
$\log_{10} \nu F_\nu$ [W m^{-2} sr^{-1}]
$\log_{10} \nu$ [Hz]
Microwave Background
Photospheric light from stars
CCAT Feasibility/Concept Study Review 17-18 January 2006


CCAT
2.Internal Synergy
The focus of CCAT emphasizes our institutions' talents in instrument building, the operation of major observatories and the development of forefront technologies.
CARMA
Space Infrared Telescope Facility
IRS
Welcome to the
SHARC-II
Homepage
MER
Forcast

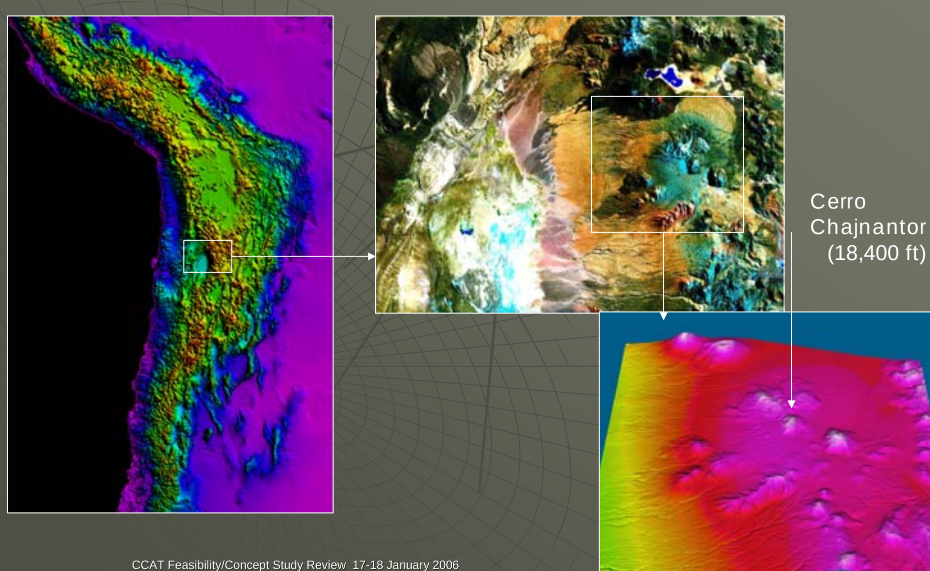
3.Ride the technology wave

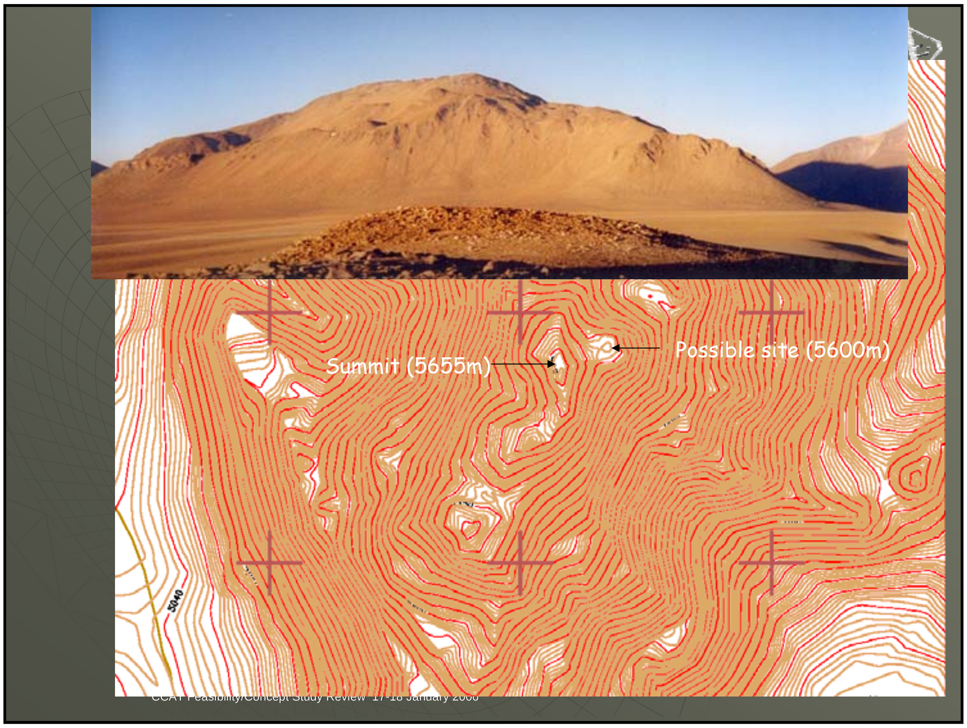
in one of the most rapidly developing technological fields in Astronomy: bolometer arrays

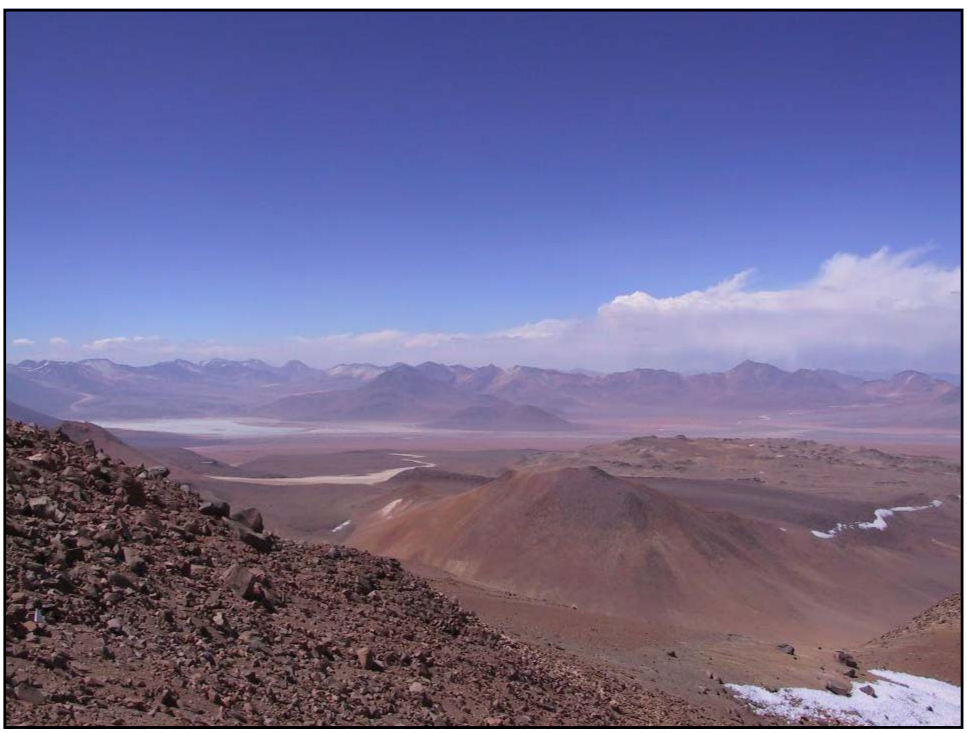


- Strawman First light instrument
  - Nyquist sampling a 5'x5' FOV at 350 μm: 170 × 170 pixel array
  - 30,000 pixels, or 6 times that of SCUBA-2
- Telescope designed with ~20'x20' FOV; future instruments will take advantage of the entire FOV

4. At the driest, high altitude site you can drive a truck to




Summit (5655m)
Possible site (5600m)
5040
CCAT Feasibility/Concept Study Review 17-18 January 2006



5. A facility of huge synergy with, and enabler to ALMA

CCAT will match ALMA in point source, continuum sensitivity at 500 μm and will be many orders of magnitude faster as a survey instrument. Although CCAT's beam will be a few arcsec, ALMA will have 100 times the spatial resolution.

➔ ideal complementarity

Scientists with favored access to CCAT will have exceptional leverage arm for ALMA follow-up science.

Foresee joint, large scale projects coordinated between the two facilities.

- Spring 2003 : Partnership initiated
- October 2003: Workshop in Pasadena
- Feb 2004: MOU signed by
  Caltech, JPL and Cornell
- Late 2004: Project Office established,
  PM, DPM hired,
  Study Phase pace accelerates
- July 2005: Study Phase Midterm Review
- Early 2006: Preliminary CDR
- 2006-2007: Detailed Conceptual Design
  finalize Site Selection
- 2007-2012: Engineering, Construction and
  First Light

CCAT Feasibility/Concept Study Review 17-18 January 2006

Overview of Study Results

T.A. Sebring

Initial Objectives of Cornell/Caltech MOU

- Technical Design of telescope, enclosure, etc.
- Evaluation of Atacama Sites
- Definition of Initial Instrument Suite
- Cost Estimates and Schedules
- Operations Plan
- Proposed Management Structure
- Assessment of Issues Regarding Chilean Ops
- Plan for Fund Raising

We have achieved substantial progress toward all these objectives.

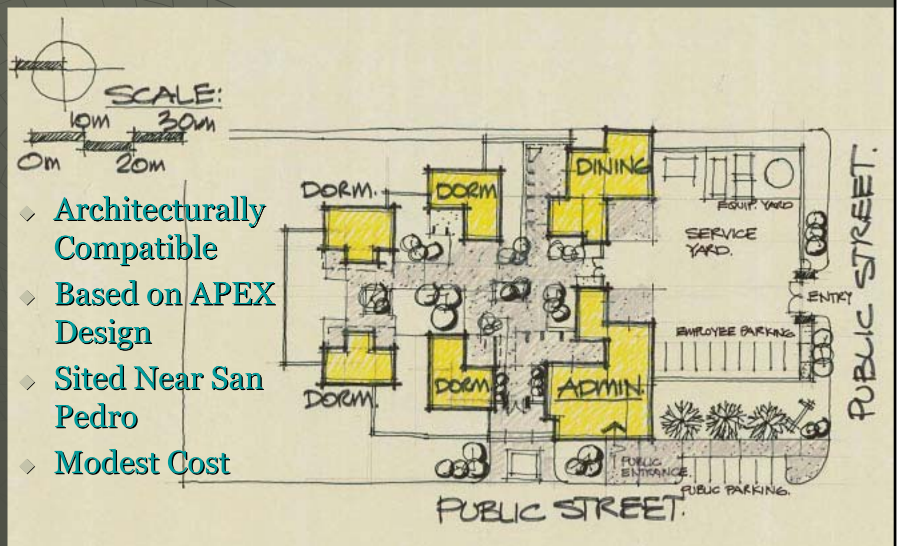
Study Process

- Development of Science Objectives
  - Science Committees — Proj. Scientists: T. Herter & J. Zmuidzinas
- Definition of 1st Suite of Instruments
  - Instrumentation Committee — Chair: G. Stacey
- Operational Approach and Requirements
  - Operations Committee — Chair: S. Radford
- Initial Requirements Definition
  - Derived from Science and Instrumentation Requirements
- Development of Telescope & Enclosure Design
  - Interactive Process with Cornell/Caltech/JPL
  - Use of Internal Resources and Industrial Contracts
- Cost and Schedule Derived Based on Design

Overview of Telescope Design: Facility

- Design by M3, Tucson
- Summit Facility
- Road and Site Design
- Oxygen Enriched Working Areas
- Minimum Scope to Support Long-Term Operations

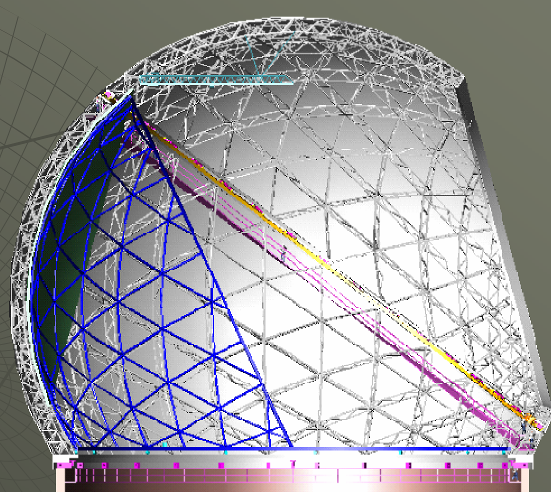
Support Facility Near San Pedro de Atacama



- Architecturally Compatible
- Based on APEX Design
- Sited Near San Pedro
- Modest Cost

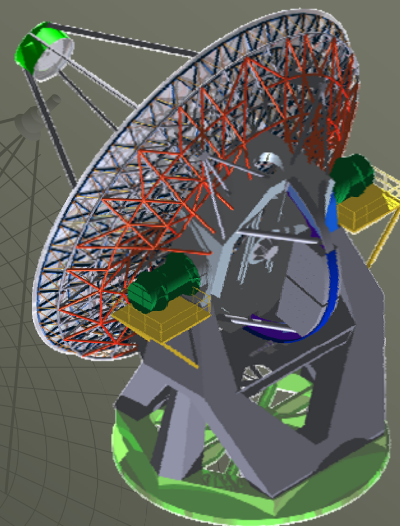
Telescope Dome Concept

- AMEC Dynamic Structures Design Study
- Calotte style chosen
- Developed Sufficiently for Feasibility Assessment



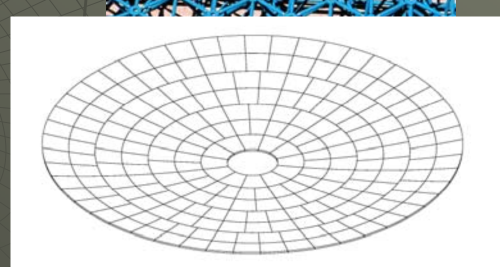
Telescope Mount Concept

- Vertex RSI (General Dynamics, Dallas
- Hydrostatic and Rolling Element Bearings
- Proven Drive Concepts
- First Order Servo Modeling



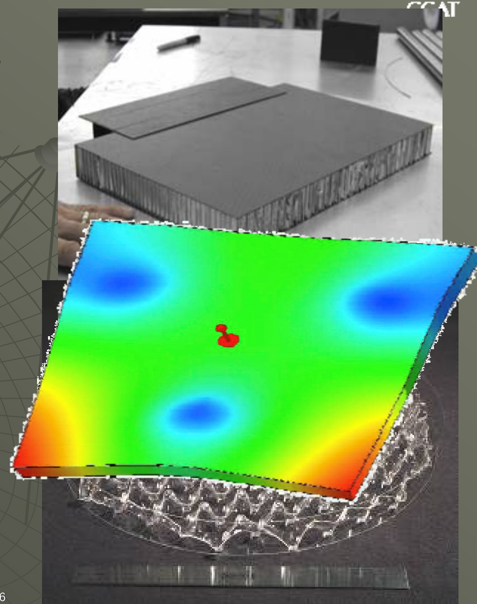
Primary Mirror

- Steel Truss: ~5x Lower Cost than CFRP
- Commercial Actuators Support Axial and Lateral Loads
- 7 Ring Panel Layout
- 7 Sets of Identical Panels
- Total ~ 210 Panels @ ~1.7m Major Dimension



Primary Mirror

- Two Panel Approaches
  - Replicated CFRP/Al Sandwich (CMA)
  - Precision Molded Lightweight Borosilicate (ITT)
- Panels Kinematically Supported on 3 Points (e.g. bipod flexures)
- ~5 μm rms Panel Figure <u>Total</u> Error



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Panel & Telescope Alignment

- Calibration Wavefront Sensor: G. Serabyn, JPL
  - Shearing Interferometer, Point Diffraction Interferometer or Hybrid of the Two
  - Uses Astronomy Imager Camera for Focal Plane
  - Analysis Verifies Acceptable Resolution
- Edge Sensors…Multiple Options
  - Fogale or Blue Line Engineering Commercial Options
  - TMT Developing System & JPL Looking at Lateral Effect Photodiodes
  - ~1000 Sensors Required
- Supplemental Sensors
  - JPL Distance Measuring Interferometry
  - Adaptive Optics Associates Hartmann Type Sensor
  - Wavefront Sensing Guider in IR…Depending on Panel Qualities
- JPL Integrated Model for Next Phase Investigation/Validation

This is Perhaps the Highest Priority Technical Issue

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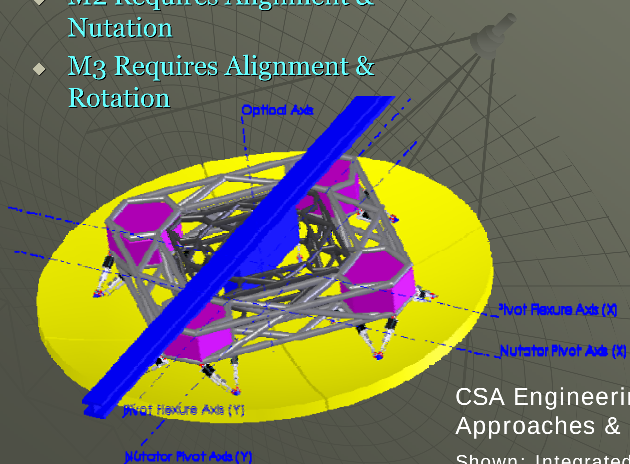
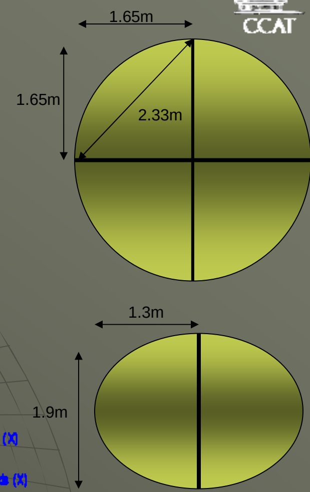
M2 & M3

- Segmented Design
  - Segments Same Technology & Process as PM's
- M2 Requires Alignment & Nutation
- M3 Requires Alignment & Rotation





CSA Engineering: 2 M2 Approaches & 1 M3

Shown: Integrated Positioning/Nutation

Other Study Results

- Definition and Concept Design of Two Instruments
  - Short Wavelength Camera: λ= 200, 350,450, 620 μ
    - Diffraction Limited
    - 20%-40% Throughput
    - Background Limited Performance
    - NIST SCUBA II Array Technology
  - Long Wavelength Camera: λ= 740 μ to 2 mm
    - λ=620 as a Future Upgrade
    - Antenna-Coupled Focal Plane Architecture

Other Study Results

- Preliminary Project Plan
  - Approaches to Organization & Governance
  - Schedules
  - Staffing
  - Procurement Approach
- Integration Plan
  - Subsystem Validation & Testing
  - Packaging and Shipping
  - On-Site Assembly
  - Control Integration, Tools, Commissioning

Other Study Results

- Site Characterization and Testing
  - Investigation of Chilean Site Access & Permitting
  - Preparation for Site Testing
  - Assessment of Logistics of Alternate Sites
- Operation Plan
  - Observing Modes
  - Logistics
  - Travel, Manpower, Facilities
  - Operations Cost Estimate

Other Study Results

- Schedules
  - MS Project Schedule Developed
  - Critical Path Analysis
- Cost Estimate
  - Based on Contractor Estimates
  - Standard Estimation Processes, Catalogue Prices
  - Validates $100m Target for Telescope & 2 Instruments

Summary: We Believe That We'll Show That:

- The Science is Compelling and Seminal
- The Telescope Requirements are Aggressive but Feasible
- The Concept Designs for Subsystems are Strong, Well Conceived, and Supported by Initial Analyses
- We Know the Major Risk Areas
- We Have a Good Organizational Approach
- Project Costs Can be Contained Within our Target of $100m

Let's Get On With It and See What You Think!

CCAT Science

CCAT

Terry Herter and
CCAT Science Steering Committee

CCAT Science Steering Committee Charter

- Establish top-level science requirements
  - Determine and document major science themes
- Flow down science requirements to facility requirements
  - Telescope, instrumentation, site selection criteria, operations, etc.
- Outputs
  - Science document
    - Write-ups on major science themes using uniform format (science goals, motivation/background, techniques, CCAT requirements, uniqueness and synergies)
  - Requirements document
    - Specifies requirements for aperture, image quality, pointing, tracking, scanning, chopping, etc.

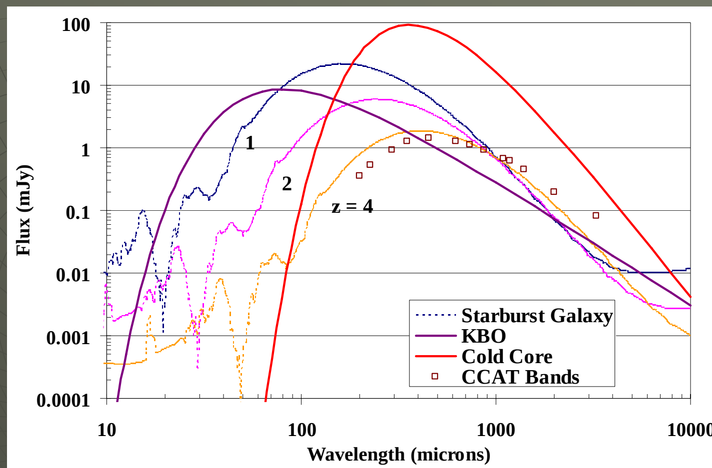
CCAT SSC Membership

- Co-Chairs
  - Terry Herter (Cornell) and Jonas Zmuidzinas (CIT)
- Leads on Science Themes
  - Distant Galaxies – Andrew Blain (CIT)
  - Sunyaev-Zeldovich Effect – Sunil Gowala (CIT)
  - Local galaxies – Gordon Stacey (Cornell)
    - + Shardha Jogee (UT)
  - Galactic Center – Darren Dowell (JPL/CIT)
  - Cold Cloud Cores Survey – Paul Goldsmith (JPL)
    - + Neal Evans (UT)
  - Interstellar Medium – Jonas Zmuidzinas (CIT)
  - Circumstellar Disks – Darren Dowell (JPL/CIT)
  - Kuiper Belt Objects – Jean-Luc Margot (Cornell)
- Ex-officio members
  - Riccardo Giovanelli (Cornell), Simon Radford (CIT)

CCAT Science Strengths

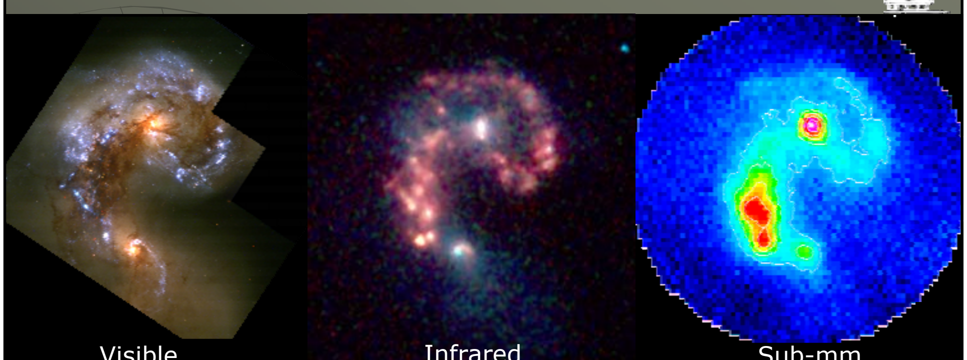
- CCAT will be substantially larger and more sensitive than existing submillimeter telescopes
- It will be the first large submillimeter telescope designed specifically for <u>wide-field imaging</u>
- It will complement ALMA
  - CCAT will be able to map the sky at a rate hundreds of times faster than ALMA
- CCAT will find galaxies by the tens of thousands
- It will map galaxy clusters, Milky Way star-forming regions, and debris disks

Many Sources Peak in the Far-IR/Submillimeter



Flux density vs. wavelength for several example sources that peak in the far-infrared/submillimeter – a 10^{12} $L_{\odot}$ starburst galaxy at redshifts of 1, 2, and 4, a T = 8K, 0.03 $M_{\odot}$ cold cloud core located in a nearby (140 pc) star forming region, and a 300 km diameter Kuiper Belt Object located at 40 AU. The CCAT bands are indicated by the open squares (which are the 5-sigma, 30-beams/source confusion limit for CCAT).

Interacting Galaxies



Images of the Antennae (NGC 4038/4039) in the visible (left), infrared (center), and submillimeter (right) showing how the submillimeter reveals regions hidden at shorter wavelengths. For this galaxy and many like it, the submillimeter represents the bulk of the energy output of the galaxy, and reveals the real luminosity production regions which are otherwise hidden. CCAT will have 2.5 times better resolution in the submillimeter giving a spatial resolution like that of the infrared image (center). Credits: visible (HST), infrared (Spitzer), and submillimeter (Dowell et al.)

Debris Disks

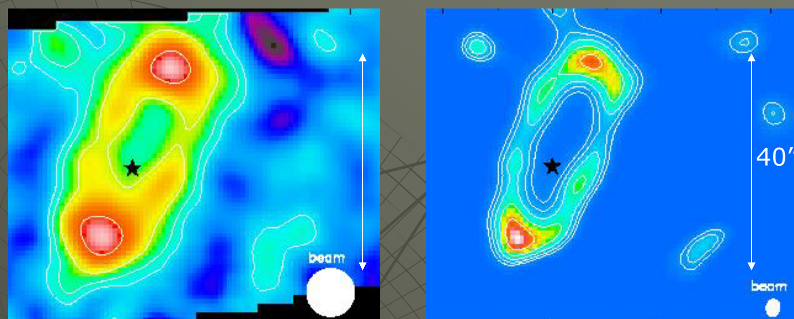
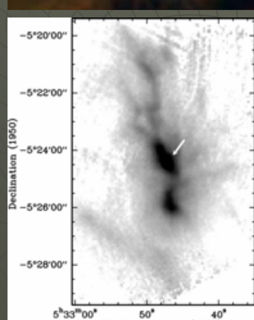
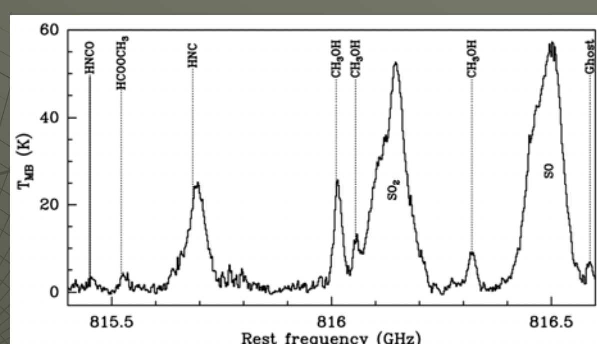


Image of Fomalhaut debris disk acquired with the CSO/SHARC II (Marsh et al. 2005, ApJ, 620, L47). Left: The observed image which has 10″ resolution and shows a complete ring of debris around the star. Right: A resolution enhanced image with 3″ resolution. CCAT will have this resolution intrinsically, with the capability to achieve ~1″ resolution through image enhancement techniques. From the CSO image, we can already infer the presence of a planet due to the asymmetry of the ring. CCAT imaging should show substructure which will pinpoint the location of the planet. The vertical bars in each image are 40″ in length.

Sub-mm is rich in spectral lines



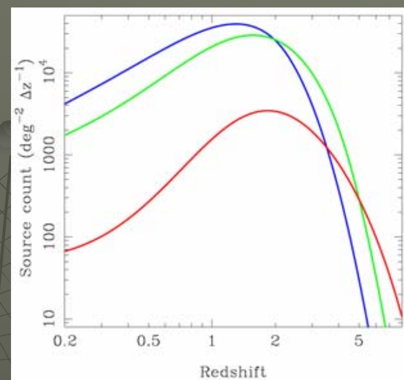


Spectrum Orion KL region in the 350 μm window showing a few of the molecular species accessible in the sub-mm (Comito et al. 2005). This is a very small portion (~1%) of the available window. The spectral resolution is ~ 0.75 km/sec.

Orion Molecular Cloud – Top: Optical image. Bottom: 350 μm map. The arrow points to the location where the spectrum was taken.

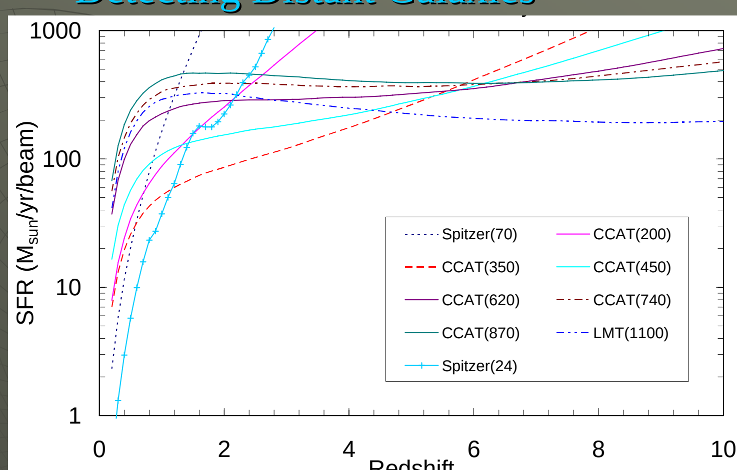
CCAT Science – I

- How did the first galaxies form?
  - CCAT will detect hundreds of thousands of primeval galaxies from the era of galaxy formation and assembly (z = 2 – 4 or about 10-12 billion years ago) providing for the first time a complete picture of this process.
  - CCAT will probe the earliest bursts of dusty star formation as far back as z ~ 10 (less than 500 million years after the Big Bang or when the Universe was ~ 4% of its current age).



Estimated redshift distribution of galaxies that will be detected by CCAT at 1 mJy for 200 (blue), 350 (green), and 850 (red) μm.

Detecting Distant Galaxies



Sensitivity to star formation rate vs. redshift for an Arp 220-like galaxy. All flux limits are set by the confusion limit except for CCAT(200) which is 5σ in 10^4 sec. The conversion used is 2 M_{sun}/yr = 10^{10} L_{sun} & L_{Arp220} = 1.3×10^{12} L_{sun}.

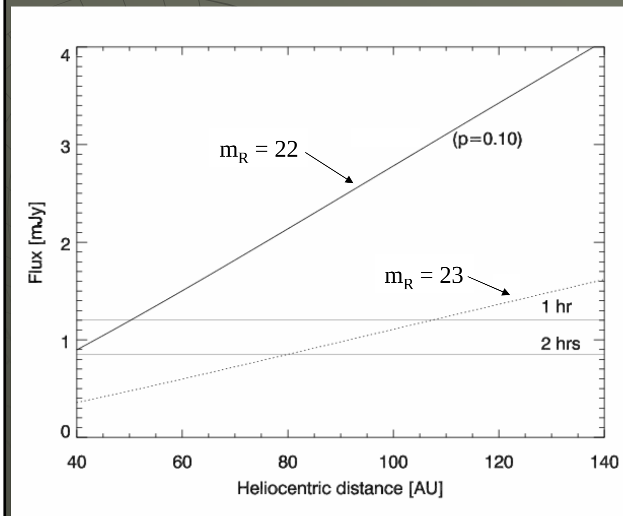
CCAT Science – II

- What is the nature of the dark matter and dark energy?
  - CCAT will image hundreds of clusters of galaxies selected from current and planned southern-hemisphere cluster searches (via the Sunyaev-Zeldovich Effect).
  - CCAT imaging will be important in understanding how clusters form and evolve, and in interpretation and calibration of the survey data to constrain crucial cosmological parameters (Ω_M, Ω_Λ, dark energy equation of state) independently of other techniques (Type Ia supernova and (direct) CMB measurements).
- How do stars form?
  - CCAT will survey molecular clouds in our Galaxy to detect the (cold) cores that collapse to form stars, providing for the first time a complete survey of the star formation process down to very low masses.
  - In nearby molecular clouds, CCAT will be able to detect cold cores down to masses well below that of the lowest mass stars (0.08 $M_\odot$).

CCAT Science – III

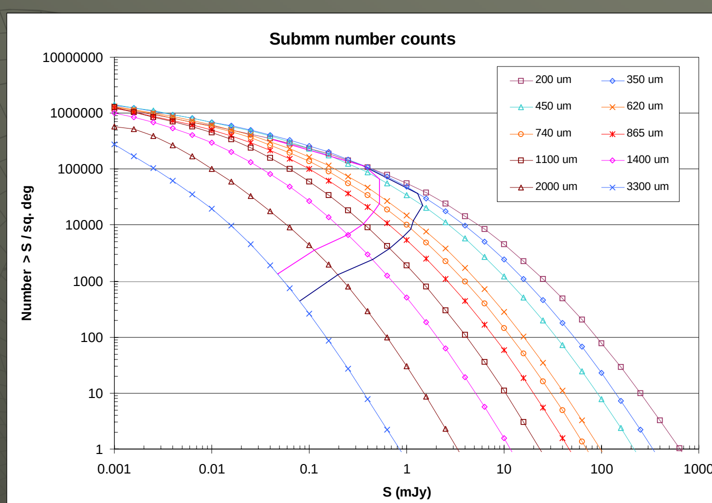
- How do conditions in circumstellar disks determine the nature of planetary systems and the possibilities for life?
  - In concert with ALMA, CCAT will study disk evolution from early (Class I) to late (debris disks) stages.
  - CCAT will image the dust resulting from the collisional grinding of planetesimals in planetary systems around other stars allowing determination of the (dynamical) effects of planets on the dust distribution, and hence the properties of the orbits of the planets.
- How did the Solar System form?
  - The trans-Neptunian region (Kuiper Belt) is a remnant disk that contains a record of fundamental processes that operated in the early solar system (accretion, migration, and clearing phases).
  - CCAT will determine sizes and albedos for hundreds of Kuiper belt objects, thereby providing information to anchor models of the planetary accretion process that occurred in the early solar system.

KBO sub-mm advantage



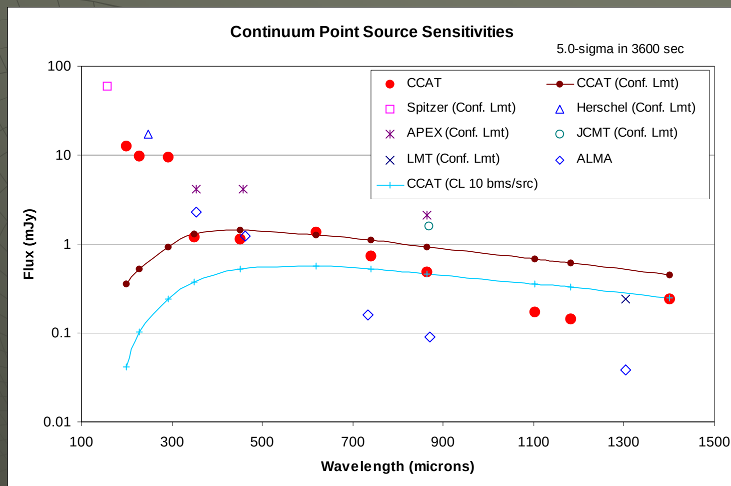
Predicted 350 um flux for KBOs with 10% albedo (m_R=22, solid and m_R=23, dotted) or 4% albedo (m_R=23, solid and m_R=24, dotted). Horizontal lines show 5-sigma detection in 1 and 2 hours, respectively for CCAT.

Sub-mm Number Counts & Confusion Limits



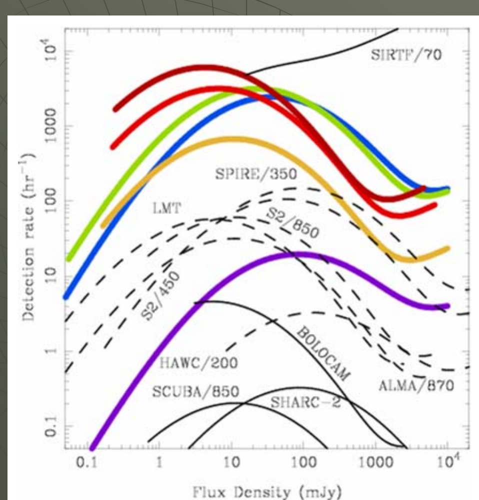
Sub-mm galaxy counts vs. flux density (number of sources with flux greater than S vs. S) for different wavelengths (after Blain et al.). Crossing lines show 30 (lower) and 10 (upper) beams/source confusion limits for D = 25 m.

CCAT Sensitivity



5σ, 1-hour CCAT and ALMA sensitivities. CCAT sensitivities computed for precipitable water vapor appropriate to that band. Confusion limits shown are 30 beams/source except for 10 beams/src case shown for CCAT.

Mapping speed comparing other facilities



- CCAT is an ultrafast mapper
- Assumptions
  - 10000 pixel detector, Nyquist sampled at all bands 0.2, 0.35, 0.45, 0.67, 0.85,1.1mm (in order from violet-red)
  - Observationally verified counts (good to factor 2)
  - Confusion and all sky limits
- 1.2/0.85/0.35mm imaging speeds are compatible
  - To reach confusion at 0.35mm go several times deeper at 0.85mm
- Detection rates are
  - ~150×SCUBA-2; ~300×ALMA
  - About 100-6000 per hour
  - Lifetime detection of order $10^{7\text{-}8}$ galaxies: ~1% of ALL galaxies!
  - \`1/3 sky survey': ~1000 deg^{-2} for 3 deg^{2}hr^{-1} gives 5000 hr

Selected (Key) Facility Drivers

- Aperture
  - Sensitivity improves as $\propto D^2$ (hence time to a given S/N $\propto D^{-4}$)
  - Confusion limit $\propto D^{-\alpha}$ ($\alpha \propto 2$ and 1.2 at 350 and 850 μm respectively)
- Field-of-view (5' x 5' initially, up to 20' across eventually)
  - The major role of CCAT will be its unchallenged speed for moderate-resolution wide-field surveys
  - CCAT strongly complements ALMA (which will do follow-up)
- Chopping/Scanning
  - Bolometer arrays require modulating the signal through chopping and/or scanning the telescope
  - For chopping, this must be done at the secondary (~ 1' at ~ 1Hz)
  - Scanning requires moderately large accelerations for reasonable efficiency (~ 0.2 deg/sec^2) [R];
- Pointing & Guiding
  - For spectrographs require placing to a fraction of slit width
  - And guiding to maintain spectrophotometric accuracy
  - => 0.61" [R] and 0.35" [G] arcsec pointing/guiding (1D rms)
- Precipitable Water Vapor
  - Provide significant observing time at 350/450 μm

Time Available to Observe

Band λ [μm]	Band ν [GHz]	Time to CL [hr]	Ref. PWV [mm]	Sairecabur (5500 m) Time Available [hr yr^{-1}]	Sairecabur (5500 m) Time Available [%]	Sairecabur (5500 m) CL fields [yr^{-1}]	ALMA (5050 m) Time Available [hr yr^{-1}]	ALMA (5050 m) Time Available [%]	ALMA (5050 m) CL fields [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
Time (PWV < 1.1 mm)				6312	72		5084	58	

Number of hours/year (round the clock) available for observing at a given λ (PWV) for Sairecabur (5500 m) vs. the ALMA region (5050 m). "CL fields" is the number of fields that can be observed to the confusion limit over a year. The "Total Time" is the sum of available hours and represents all time (day or night) with PWV < 1.1 mm. Because observations at some wavelengths require similar conditions, i.e., 350 μm and 450 μm, they share a common range. Note that at CSO, 350 μm observations are done when PWV < 0.9 mm.

Time to Complete Programs

Band λ (µm)	ν (GHz)	PWV (mm)	Time Available Sairecabur (5500 m) (hr yr^{-1})	ALMA (5050 m) (hr yr^{-1})	Science Program Time (hr)	Time to Complete Sairecabur (5500 m) (yrs)	ALMA (5050 m) (yrs)
200	1500	0.26	281	84	204	0.7	2.4
350	857	0.47	1936	1084	4881	2.5	4.5
620	484	0.64	716	723	5832	8.1	8.1
740	405	0.75	639	690	256	0.4	0.4
865	347	0.86	1223	1205	1128	0.9	0.9
1400	214	1.00	1517	1299	350	0.2	0.3

"Science program time" is the total time to perform the baseline science for camera observations only – this does not include spectroscopic follow-up. This is the on-sky integration time needed according to best estimates of the sensitivity and does not include observing overhead or other inefficiencies.

Next Phase

- Refinements
  - What have we left out?
  - Parametric trade analysis, e.g. when surface roughness changes, how do program time change.
- Detailed survey planning
  - Teaming – bring together necessary expertise
  - Selection of fields and/or objects
  - Institute critical precursor surveys (e.g. Spitzer) or other observations
- Data reduction requirements
  - Establish requirements:
    - Quicklook tools, pipelines, etc.
    - Calibration
- Data analysis
  - Identifying steps to produce science from calibrated data
- Archiving
  - Scope out problem in more detail – storage, access requirements, processing/reduction level, etc.

Requirements Summary

Simon Radford

Radiometry

	Requirement	Goal	remark
Wavelength	350 – 1400	200 – 2500	µm
Aperture	25 m		
Field of view	10'	20'	
Half WFE	< 12.5 µm	< 9.5 µm	rms
Site condns.	< 1.0 mm	< 0.7 mm	median pwv
Polarization	0.2%	0.05%	after cal.
Emissivity	<10% @ >300 µm <20% @ 200 µm	< 5% @ >800 µm	

Pointing and Scanning

	Requirement	Goal	remark
Pntg, blind	2"	0.5"	rms
Pntg, offset	0.3"	0.2"	within 1°
Pntg, repeat.	0.3"	0.2"	rms, 1 hour
Scanning rate	$0.2° s^{-1}$	$1° s^{-1}$	slow/fast
Scan. accel.	$0.4° s^{-2}$	$2° s^{-2}$	short/long λ
Pointing knowledge	0.2"	1"	rms
M2 nutation	±2.5' @ 1 Hz		azimuth only

Instrument

- Symmetric Nasmyth foci, 3 instr. each
  - Bent Cassegrain for smaller instruments
- Short and long wavelength cameras
  - SWCam: 350–650 µm 5' × 5'
  - LWCam: 750–2000 µm 15' × 15'
- f/8, 20' unvignetted diameter
- No facility instruments or field rotators

Environmental

	Operations	Survival	remark
Wind	10	65	m s^{-1}
Temperature	–20 to +15	–30 to +25	°C
Rel. Humid.	0% – 95%		
Snow load		100	kg m^{-2}
Ice build up		25	mm
Precipitation		25	mm hr^{-1}
Seismic		Zone 4	UBC
Daytime operations			If no sun on dish

CCAT
Optical Design

Germán Cortés-Medellín
National Astronomy and Ionosphere Center
Cornell University

Outline

- Telescope Optical Parameters and Design
- FOV Performance Analysis
- Sub-reflector Sensitivity Analysis
- Active Surface Segmentation Analysis
- Conclusions

CCAT Optical Design Parameters

Design: Ritchey-Chrétien/Nasmyth Focus

Input Design Parameters	Symbol	Value	Units
Aperture Diameter	D	**25**	[m]
Primary Focal Ratio	f_1/D	**0.6**	
System Focal Ratio	$f/\#$	**f/8**	
Back Focal Distance	B	**11**	[m]
Field of View	FOV	**20**	[arcmin]
Minimum Operating Wavelength	λ_{min}	**200**	[µm]

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Ritchey-Chrétien Design Parameters

Design: Ritchey-Chrétien/Nasmyth Focus

Derived Design Parameters	Symbol	Value	Units
M1 Diameter	D_1	**25**	[m]
Eccentricity	ε_1	**1.000774**	
Vertex Radius of Curvature	$\mathbf{R}_{C1}$	**30.000**	[m]
Focal Distance	f_1	**15.000**	[m]
Edge Angle from Prime Focus	θ_1	**45.24**	[deg]
M2 Diameter (with provisions for FOV)	D_2	**3.20**	[m]
Eccentricity	ε_2	**1.169098**	
Vertex Radius of Curvature	$\mathbf{R}_{C2}$	**3.922**	[m]
Edge Angle from Secondary Focus	θ_2	**3.58**	[deg]

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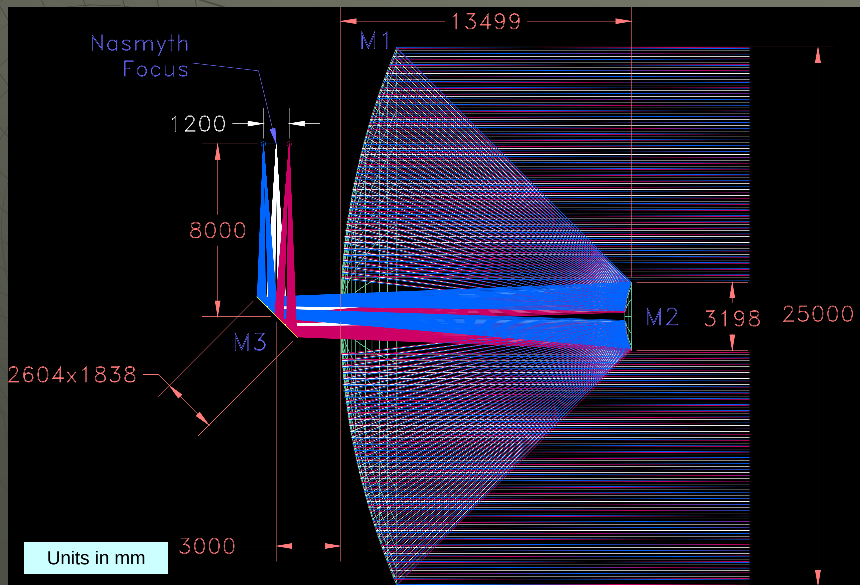
CCAT 25m Optical Layout



FOV Characteristics

- FOV Size and radius of Curvature
- Performance on-axis and at edge of FOV
- Calculated Co-Pol and Cross-Pol performance
- Performance Variation across FOV
  - Strehl
  - HPBW
  - Sidelobe level
  - Antenna Gain loss (with –11 dB Edge Taper)
  - Antenna aperture efficiency (with –11 dB Edge Taper)
- Available Number of Beams in the FOV

CCAT Filed of View Parameters

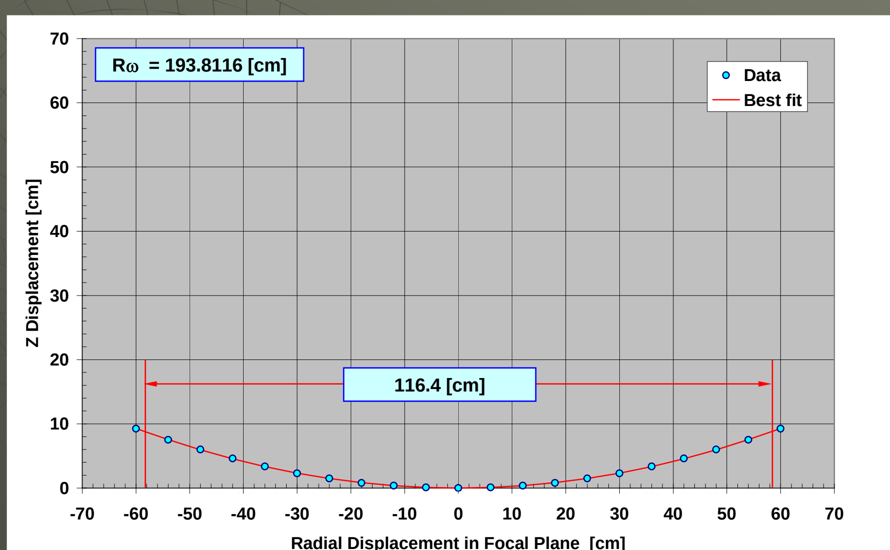
CCAT

Field of View Parameters	Symbol	Value	Units
Specified Field of View	FOV	20.0	[arcmin]
Image Scale at Nasmyth Focus	IMS	1.031	[arcsec/mm]
Optimum Radius of Curvature	R_ω	1.938	[m]
Size of 20 arcmin FOV		1.164	[m]
Diffraction Spot-size at 200 μm		1.920	[mm]

Calculated Angular Aberrations	Symbol	Value	Units
Specified Field of View	FOV	20.0	[arcmin]
Angular Tangential Coma	*ATC*	0.00	[arcmin]
Angular Astigmatism	*AAS*	2.83	[arcmin]
Angular Distortion	*ADI*	0.48	[arcmin]

FOV: Optimum Focal Surface Geometry

CCAT



On Axis Performance

Wavelength: 200 [µm]
Frequency: 1499 [GHz]

	Uniform Illumination	Edge Taper -11 dB	
HPFW Beam Width:	**1.861**	**1.983**	[arcsec]
Aperture Strehl:	**100.00**	**100.00**	[%]
Polarization Efficiency:	100.00	100.00	[%]
Beam Efficiency:	76.21	85.97	[%]
Aperture Plane Efficiency:	98.73	87.58	[%]
Spillover Efficiency	-------	88.37	[%]
Antenna Gain:	-------	110.76	[dB]
Overall Antenna Efficiency:	-------	**77.40**	[%]
Side Lobe Level (SLL):	**-16.70**	**-22.27**	[dB]
Cross-Polarization Level:	-326.30	-326.73	[dB]

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Performance at Edge of 20' FOV

Wavelength: 200 [µm]
Frequency: 1499 [GHz]

	Uniform Illumination	Edge Taper -11 dB	
HPFW Beam Width:	1.892	2.008	[arcsec]
Aperture Strehl:	**96.75**	**98.39**	[%]
Polarization Efficiency:	99.99	99.99	[%]
Beam Efficiency:	74.41	84.65	[%]
Aperture Plane Efficiency:	95.59	85.41	[%]
Spillover Efficiency	-------	88.37	[%]
Antenna Gain:	-------	110.66	[dB]
Overall Antenna Efficiency:	-------	**75.48**	[%]
Side Lobe Level (SLL):	**-15.71**	**-20.89**	[dB]
Cross-Polarization Level:	-51.21	-52.63	[dB]

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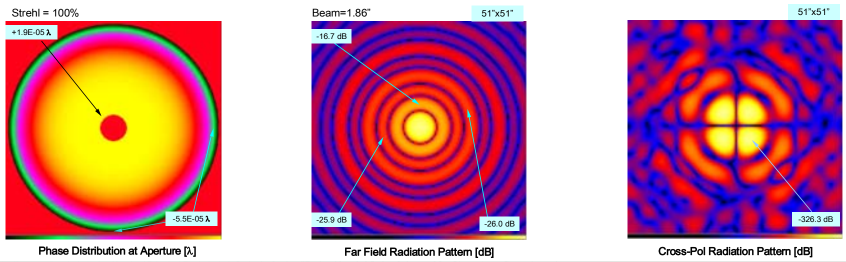
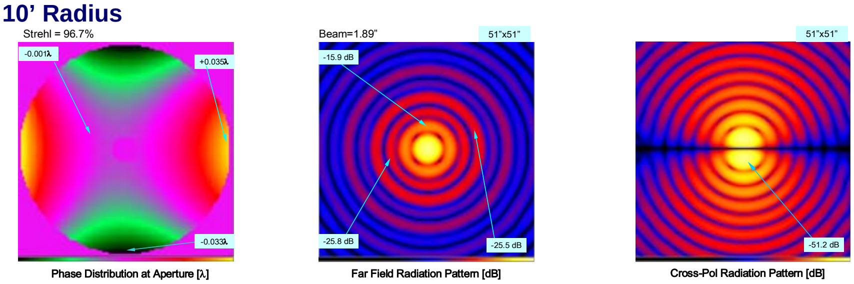
FOV Performance at 200 μm

On Axis

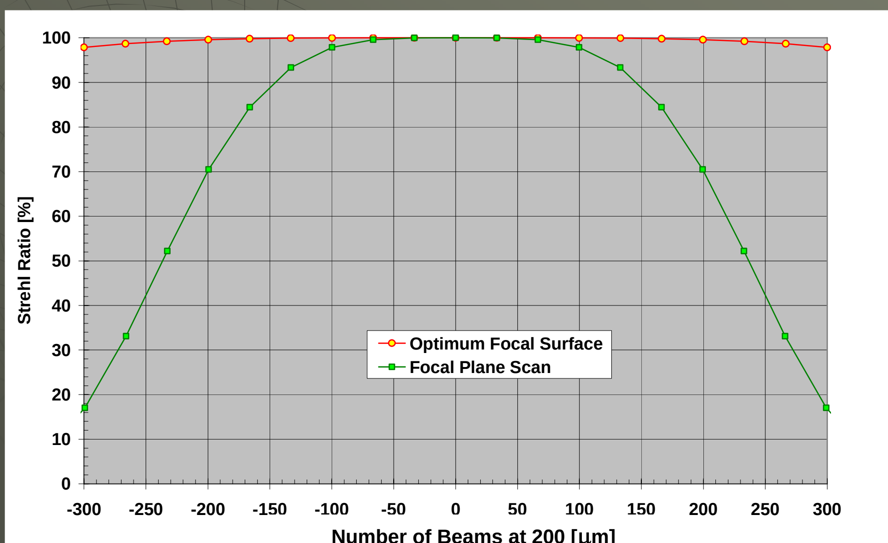


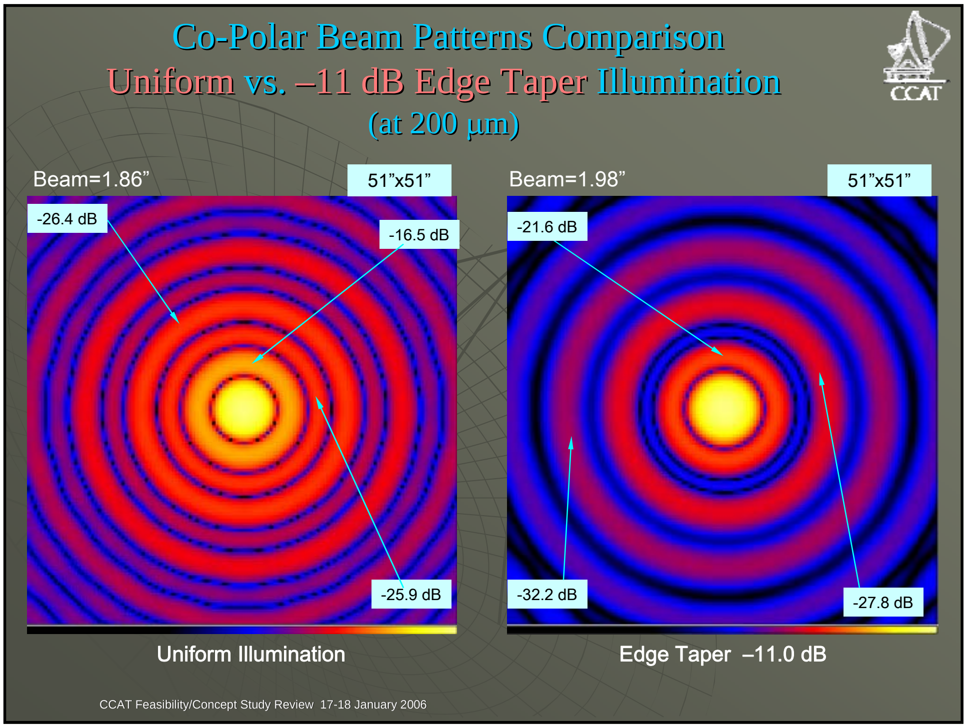
At 10' Radius



Strehl Ratio vs. Number of Beams

λ= 200 μm, Uniform Illumination




Co-Polar Beam Patterns Comparison
Uniform vs. –11 dB Edge Taper Illumination
(at 200 μm)
CCAT
Beam=1.86”
51”x51”
-26.4 dB
-16.5 dB
-25.9 dB
Uniform Illumination
Beam=1.98”
51”x51”
-21.6 dB
-32.2 dB
-27.8 dB
Edge Taper –11.0 dB
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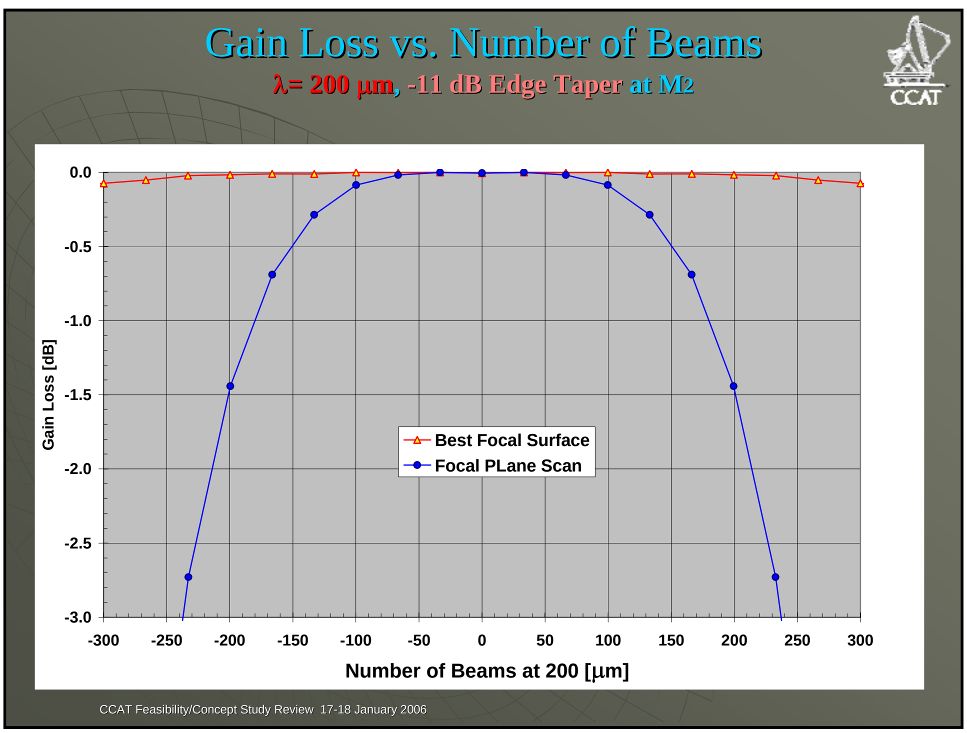
Gain Loss vs. Number of Beams
λ= 200 μm, -11 dB Edge Taper at M2
CCAT
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Gain Loss [dB]
Best Focal Surface
Focal PLane Scan
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
300
Number of Beams at 200 [μm]
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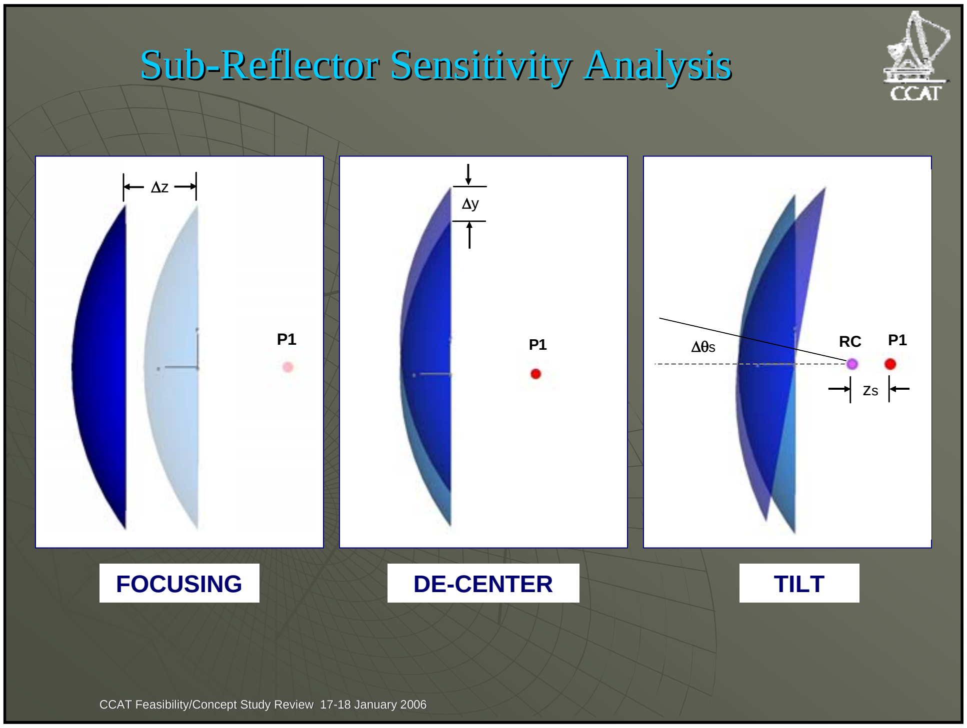
M_2 Sensitivity Analysis

Sub-Reflector Sensitivity Analysis

- Sub-reflector Sensitivity
  - focusing
  - De-Centering
  - Tilt/Tip
- Beam Deviation due to Sub-Reflector motion
- Set limits for sub-reflector positioning based on
  - Image quality
  - Pointing requirements.
- Analyzed the image characteristics for sub-reflector chopping



Sub-Reflector Sensitivity Analysis
CCAT
Δz
P1
Δy
P1
Δθs
RC
P1
zs
FOCUSING
DE-CENTER
TILT
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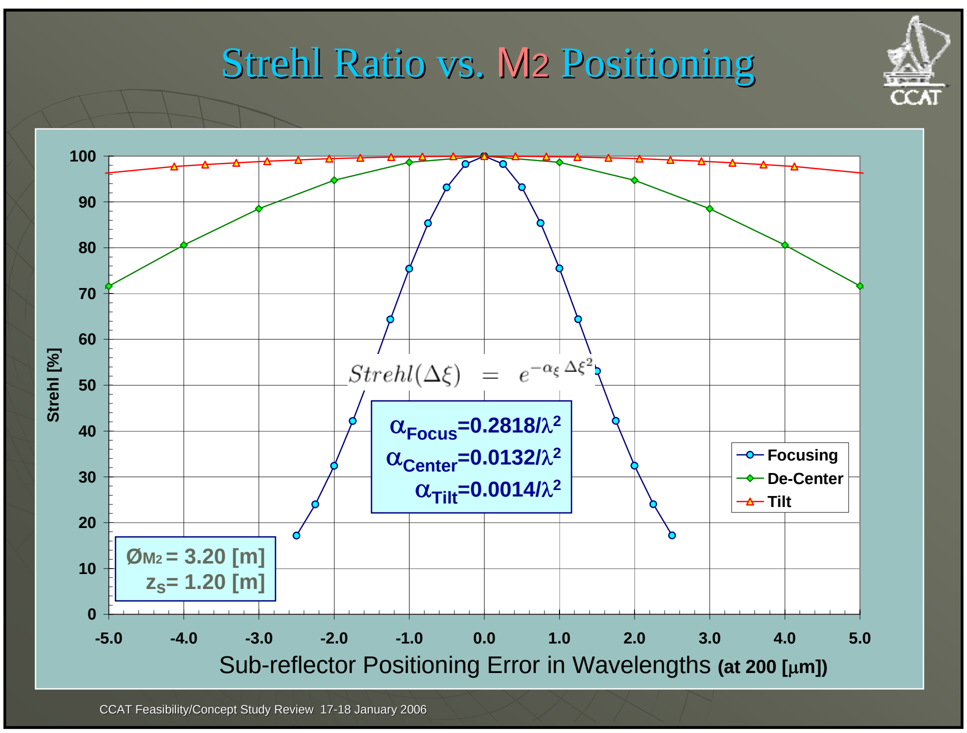

Strehl Ratio vs. M2 Positioning
CCAT
Strehl [%]
$Strehl(\Delta\xi) = e^{-\alpha_\xi \Delta\xi^2}$
α_{Focus}=0.2818/λ^2
α_{Center}=0.0132/λ^2
α_{Tilt}=0.0014/λ^2
Focusing
De-Center
Tilt
ØM2 = 3.20 [m]
z_S= 1.20 [m]
Sub-reflector Positioning Error in Wavelengths (at 200 [μm])
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Beam Deviation and M2 Chopping

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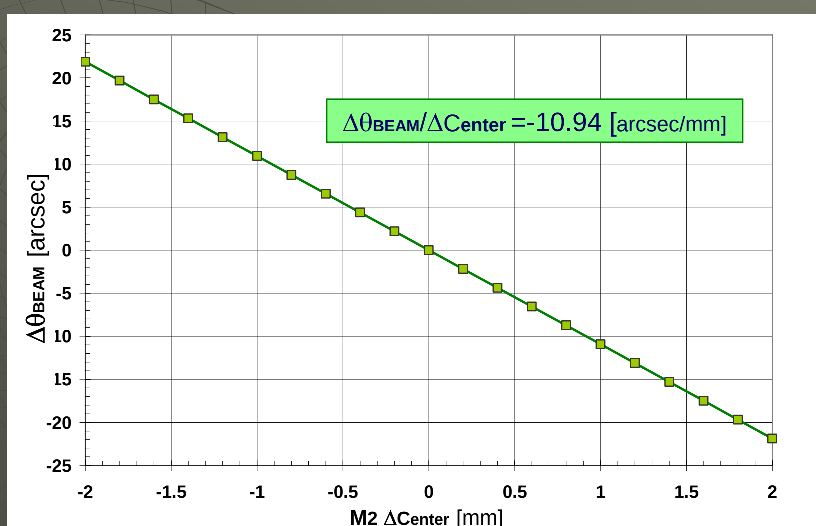
Beam Deviation vs. M2 De-Centering



at 200 [μm]

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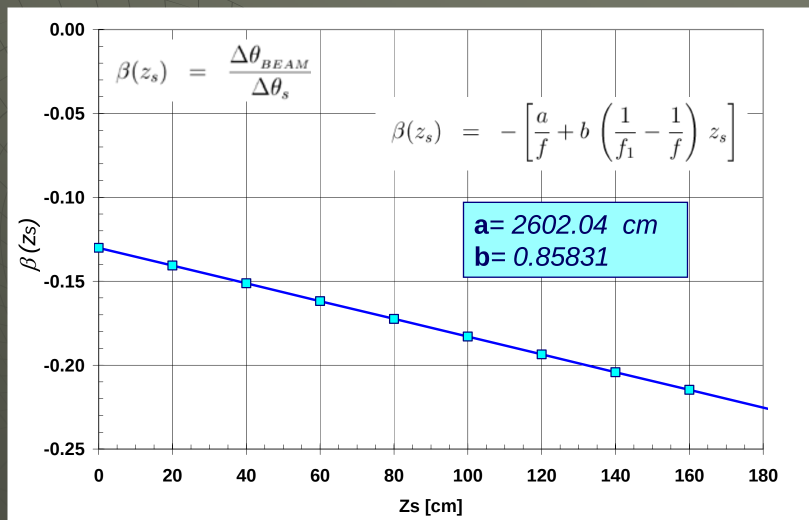
Beam Deviation vs. M2 Tilt



at 200 [μm]

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M2 Positioning Requirements at 200 μm

	Focus $\|\Delta z\|$ [μm]	De-center $\|\Delta x^2+\Delta y^2\|^{1/2}$ [μm]	Tilt eqv $\|\Delta\theta\| \times Ø_{M2}$ [μm]	Tilt $\|\Delta\theta\|$ [arcsec]
Image Quality: Strehl > 95%	< 80.0	< 380.0	<1,085.	< 70.0
Pointing: $\Delta\theta_{BEAM}$ < HPBW /10	--------	**< 18.1**	**<u>< 16.0</u>**	**< 1.03**

$Ø_{M2}$ = 3.20 [m]
z_S = 1.20 [m]

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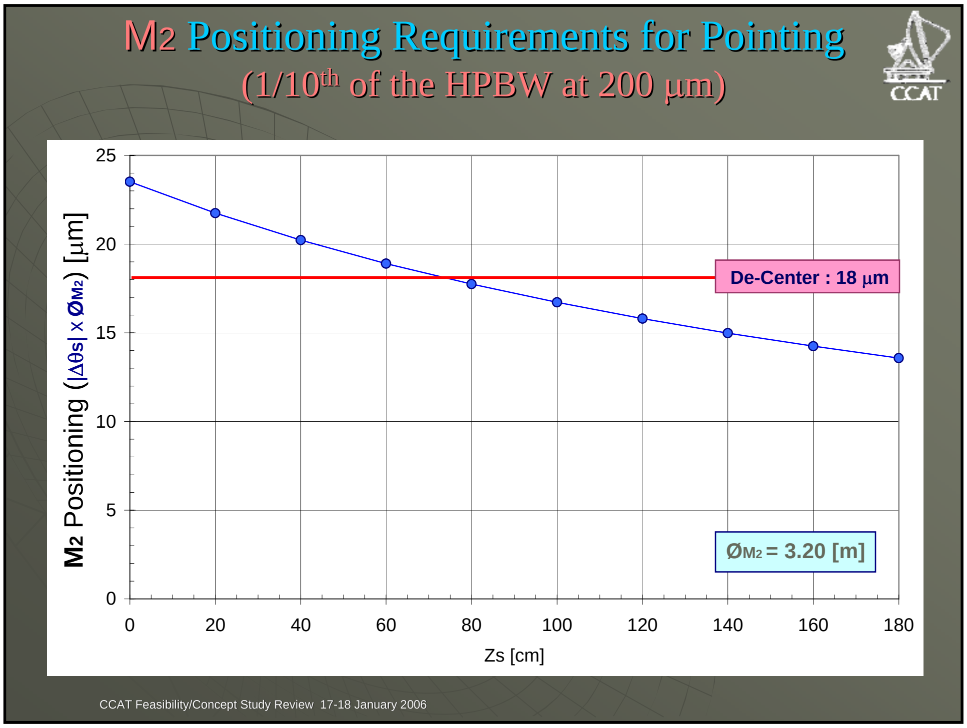
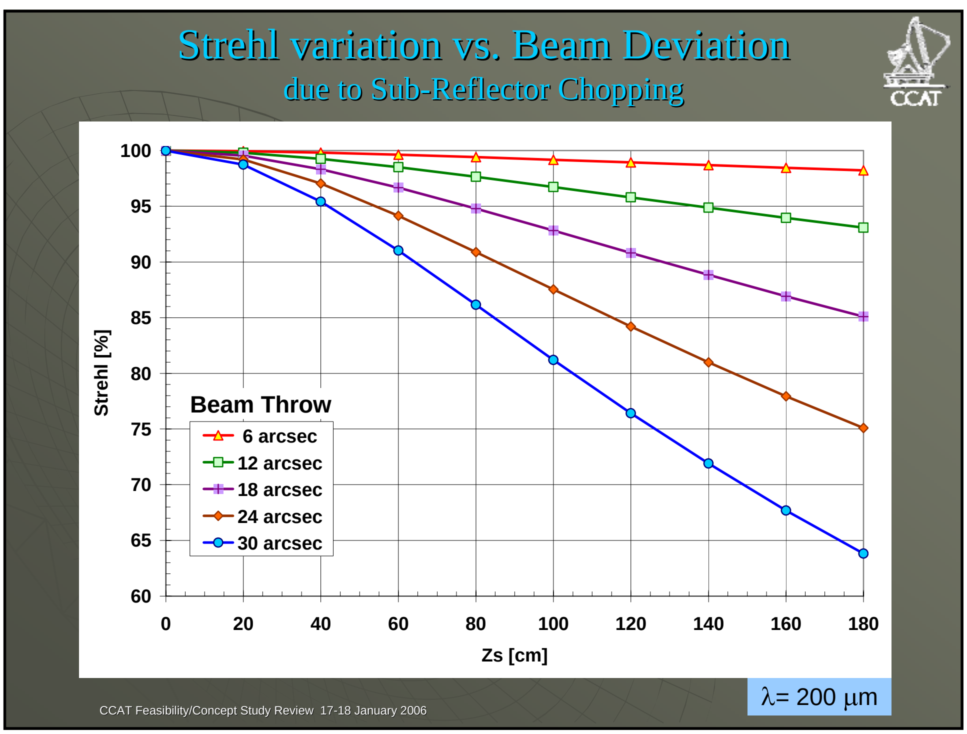

M2 Positioning Requirements for Pointing
(1/10th of the HPBW at 200 µm)
CCAT
M2 Positioning (|Δθs| x ØM2) [µm]
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
Zs [cm]
De-Center : 18 µm
ØM2 = 3.20 [m]
CCAT Feasibility/Concept Study Review 17-18 January 2006


Strehl variation vs. Beam Deviation
due to Sub-Reflector Chopping
CCAT
Strehl [%]
100
95
90
85
80
75
70
65
60
0
20
40
60
80
100
120
140
160
180
Zs [cm]
Beam Throw
6 arcsec
12 arcsec
18 arcsec
24 arcsec
30 arcsec
λ= 200 µm
CCAT Feasibility/Concept Study Review 17-18 January 2006

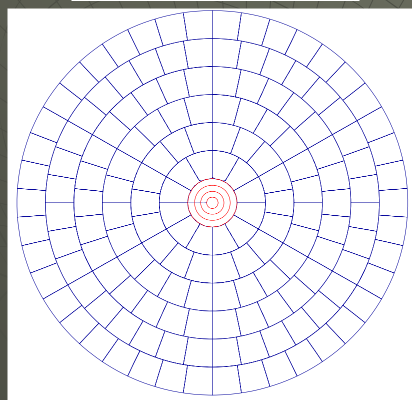
Active Surface Segmentation

Active Surface Segmentation

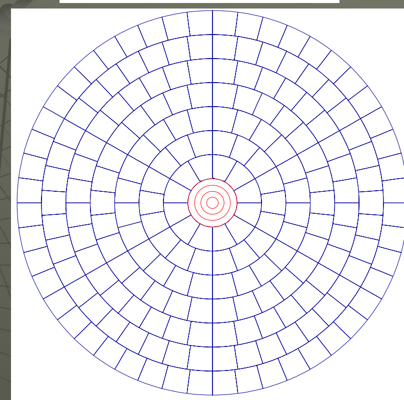
- We analyzed an active surface composed of 162 pie-shaped segments distributed with 6-fold symmetry in 6 rings
- Grating lobes symmetry, power level and location in the far field.
- Segment Positioning Error Analysis
- For Segment Piston errors, tilt/tip errors, radial and azimuth segment positioning errors, segment twists.
- Characterization of Segment positioning errors in terms of Ruze's coefficients relating segment position standard deviation errors with optical performance.
- Thermal expansion effects.

CCAT M_1 Active Surface Layout

A. 162 Segments
6 Rings



B. 210 Segments
7 Rings



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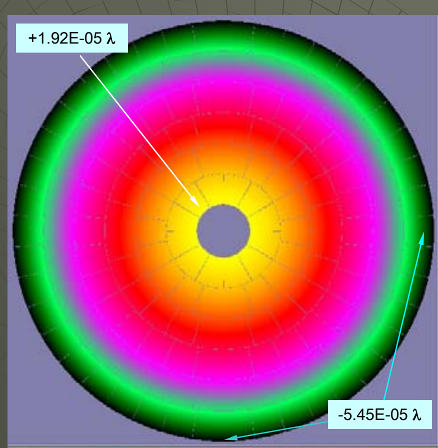
Segmentation Effects

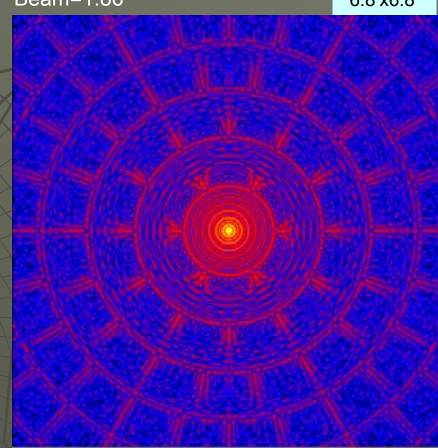
(λ=200 μm, Uniform Illumination)



Phase Distribution at Aperture [λ]

Beam=1.86”

6.8’x6.8’



Far Field Radiation Pattern [dB]

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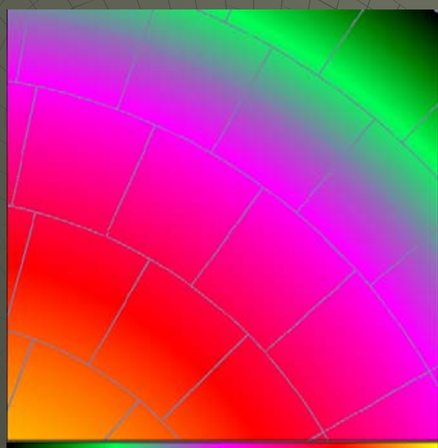
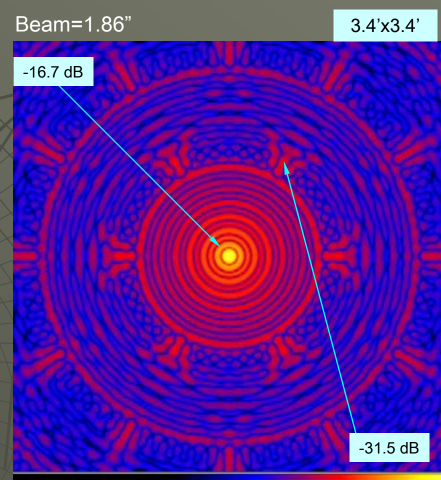
Segmentation Effects

(λ=200 μm, Uniform Illumination)

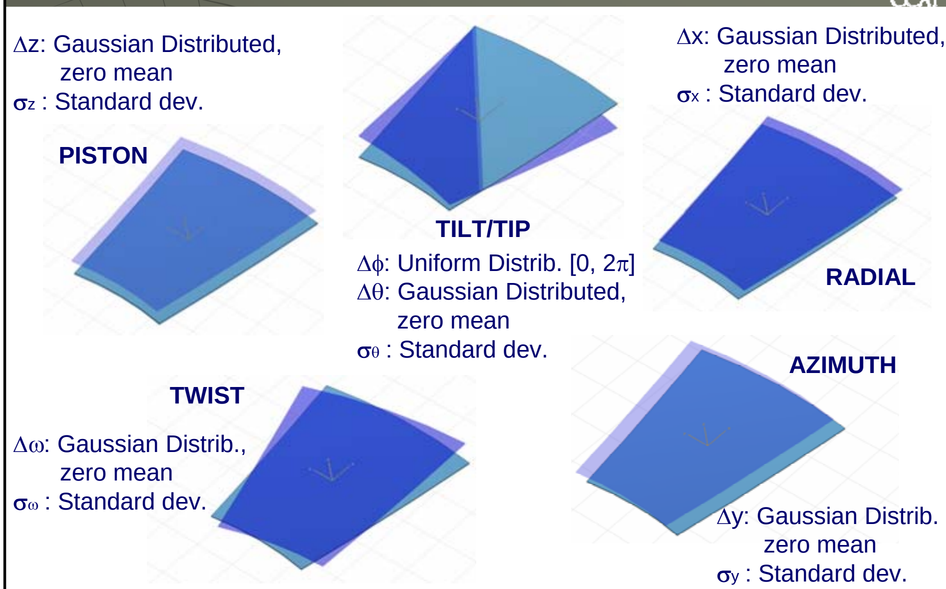


Phase Distribution at Aperture [λ]



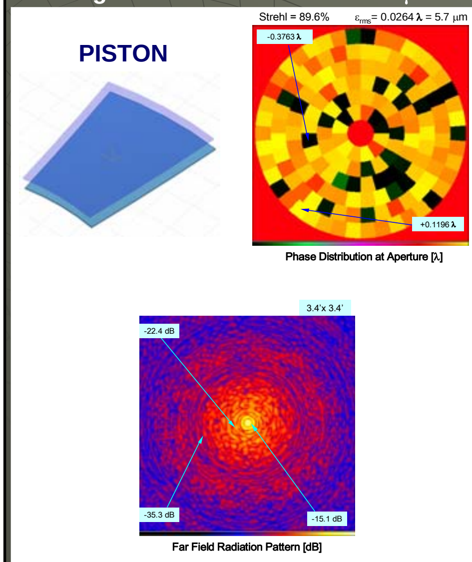
Far Field Radiation Pattern [dB]

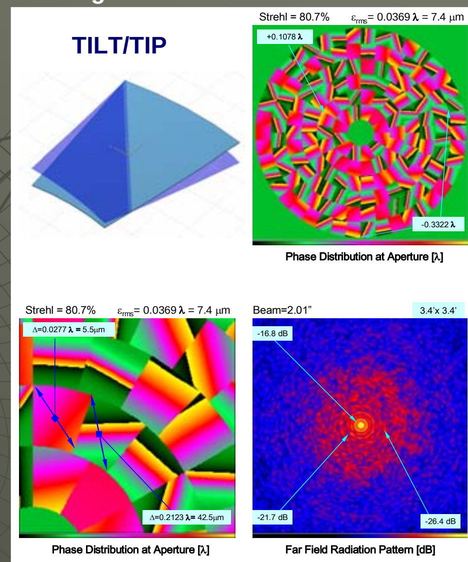
Segment Positioning Errors



Segment Positioning Errors Samples I

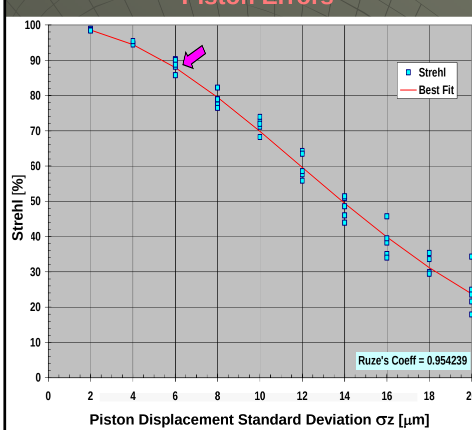
Segment Piston Errors: σz= 6 μm | **Segment Tilt Errors: $\sigma\theta$= 3 arcsec**



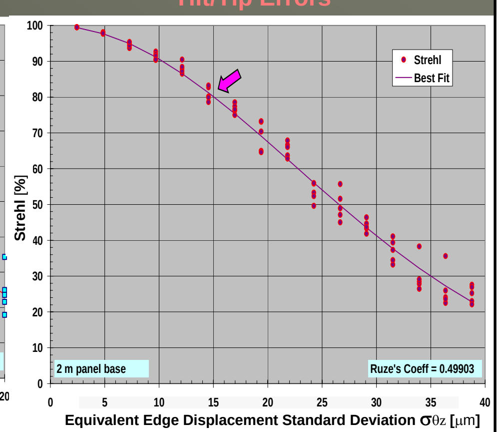


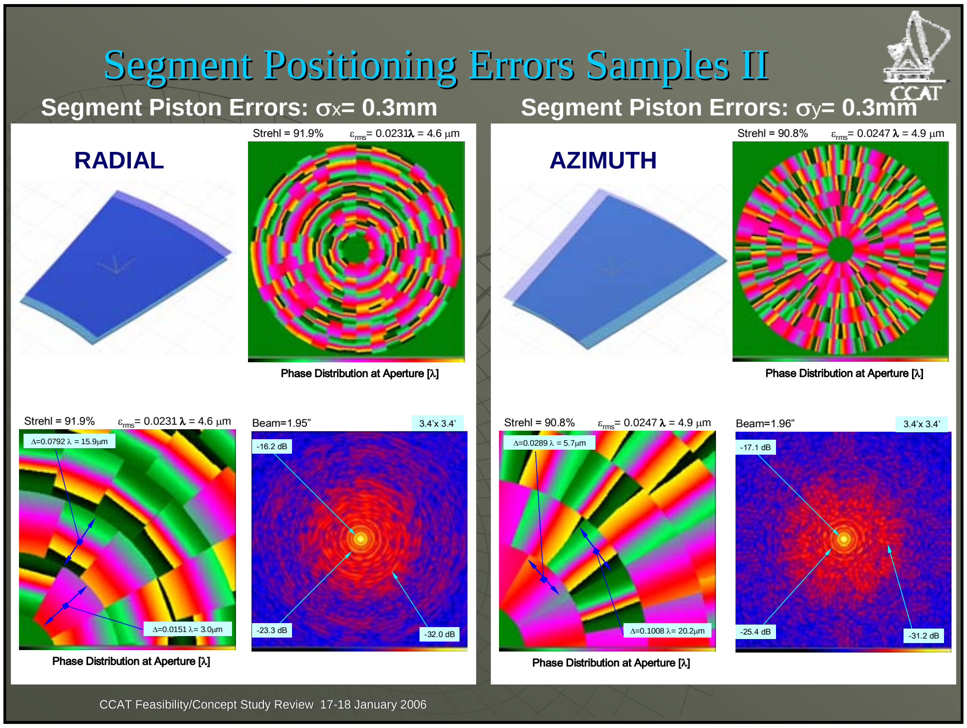
Strehl vs. Segment Positioning Errors

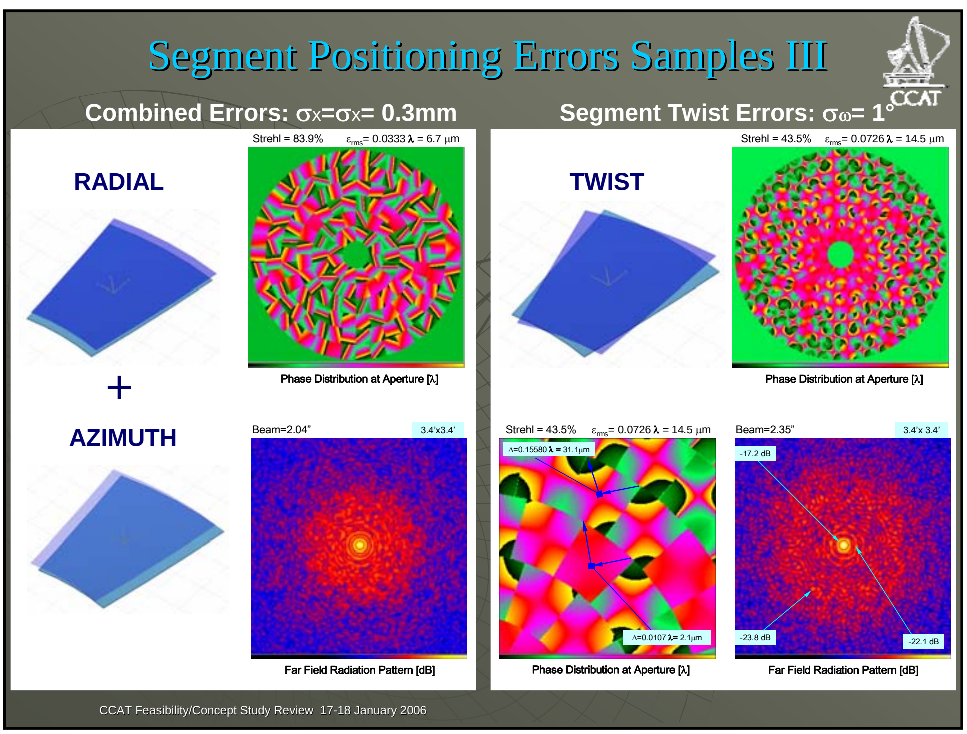
Piston Errors



Tilt/Tip Errors




Segment Positioning Errors Samples II
CCAT
Segment Piston Errors: σx= 0.3mm
Segment Piston Errors: σy= 0.3mm
RADIAL
Strehl = 91.9%
Phase Distribution at Aperture [λ]
Beam=1.95"
3.4'x 3.4'
-16.2 dB
-23.3 dB
-32.0 dB
AZIMUTH
Strehl = 90.8%
Phase Distribution at Aperture [λ]
Beam=1.96"
3.4'x 3.4'
-17.1 dB
-25.4 dB
-31.2 dB
CCAT Feasibility/Concept Study Review 17-18 January 2006


Segment Positioning Errors Samples III
CCAT
Combined Errors: σx=σx= 0.3mm
Segment Twist Errors: σω= 1°
RADIAL
+
AZIMUTH
Strehl = 83.9%
Phase Distribution at Aperture [λ]
Beam=2.04"
3.4'x3.4'
Far Field Radiation Pattern [dB]
TWIST
Strehl = 43.5%
Phase Distribution at Aperture [λ]
Beam=2.35"
3.4'x 3.4'
-17.2 dB
-23.8 dB
-22.1 dB
Far Field Radiation Pattern [dB]
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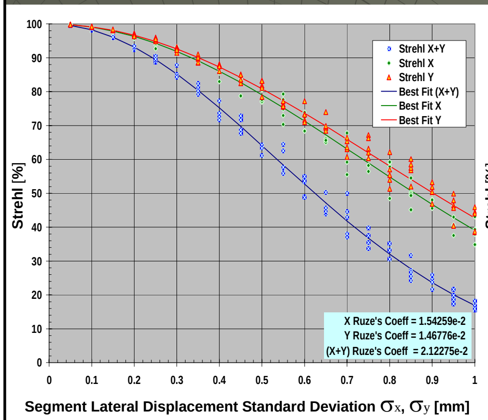
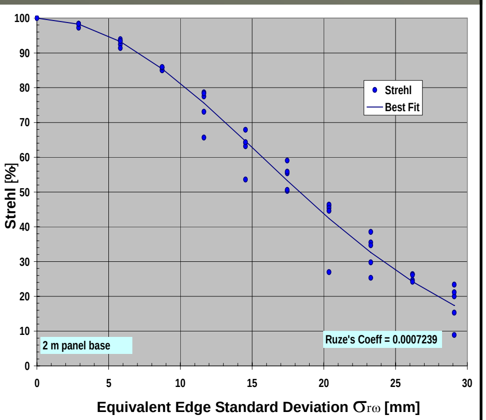
Strehl vs. Segment Positioning Errors

Combined Radial + Azimuth Errors



Segment Twist Errors



Best Fitted Ruze's Coefficients

Ruze's Coefficient

$$\eta_{RUZE_i} = e^{-\left(\frac{4\pi\,\kappa_i\,\sigma_i}{\lambda}\right)^2}$$

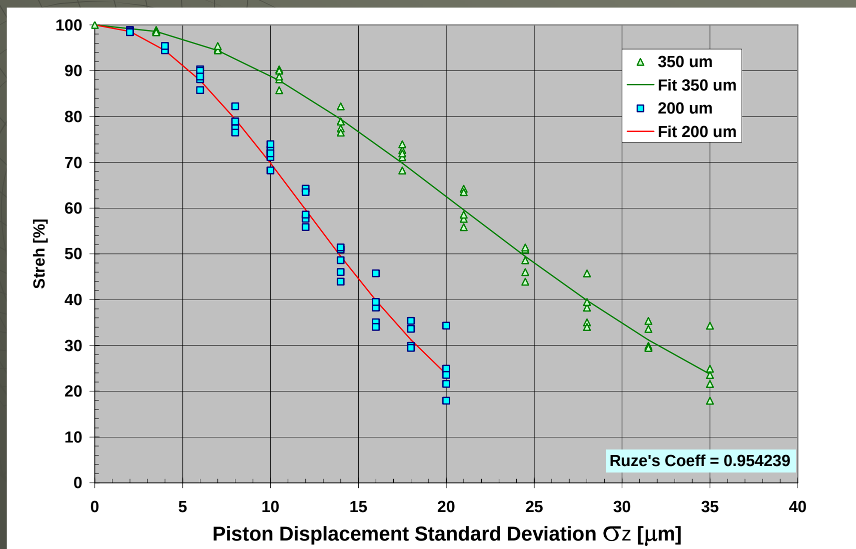
	Symbol	Best Fitted Value
Segment Piston Displacement	κ_Z	0.95424
Segment Tilt/Tip (Equiv. Edge Displacement*)	κ_{TILT}	0.49903
Segment Radial Displacement	κ_X	0.01543
Segment Azimuth Displacement	κ_Y	0.01468
Segment Twist (Equiv. Edge Displacement*)	κ_{TWIST}	0.00073

$$\epsilon_{rms} = \sqrt{(\kappa_z\,\sigma_z)^2 + (\kappa_{tilt}\,\sigma_{tilt})^2 + (\kappa_x\,\sigma_x)^2 + (\kappa_y\,\sigma_y)^2 + (\kappa_\omega\,\sigma_\omega)^2}$$

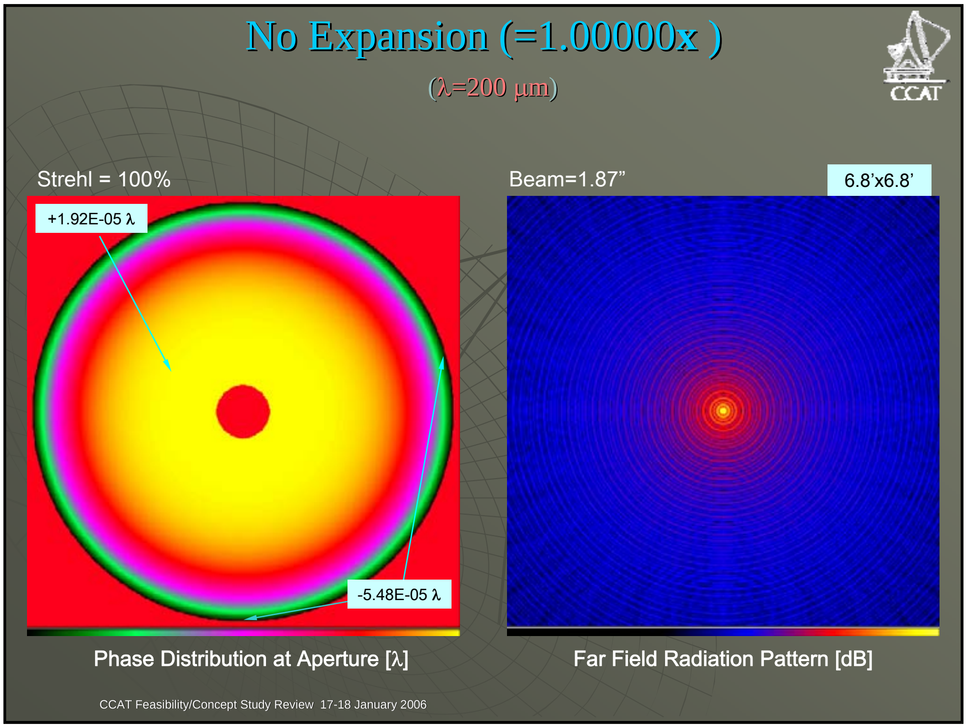
*** Panel Base Size = 2.0 [m]**

Strehl vs. Piston Displacement

λ= 200 μm and 350 μm



Thermal Expansion Effects


No Expansion (=1.00000x)
(λ=200 μm)
CCAT
Strehl = 100%
+1.92E-05 λ
-5.48E-05 λ
Beam=1.87”
6.8’x6.8’
Phase Distribution at Aperture [λ]
Far Field Radiation Pattern [dB]
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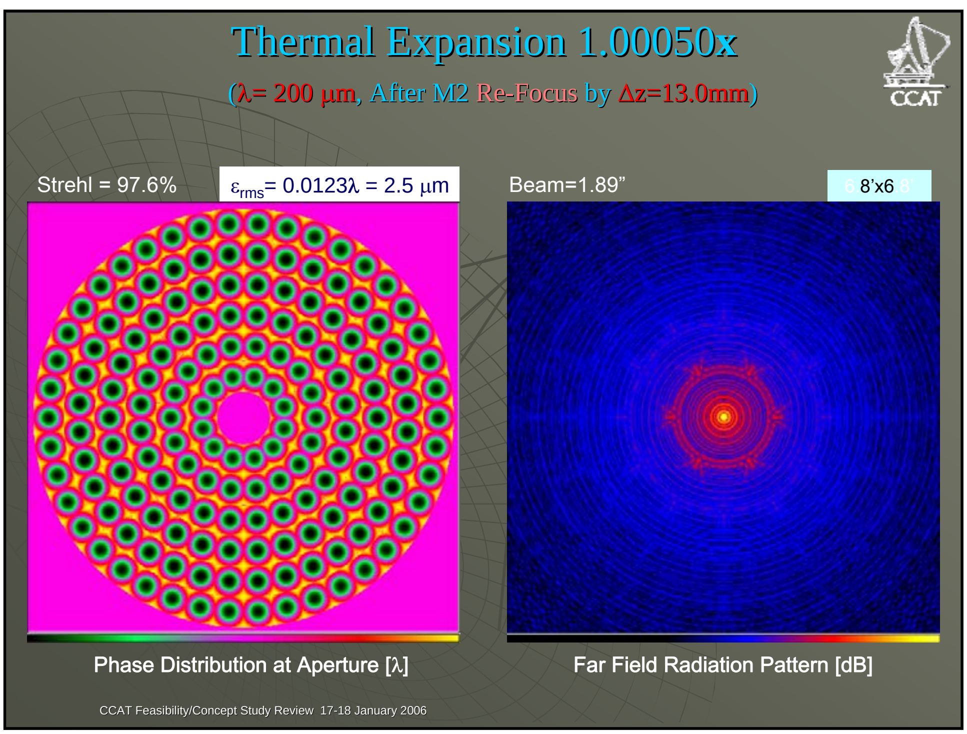
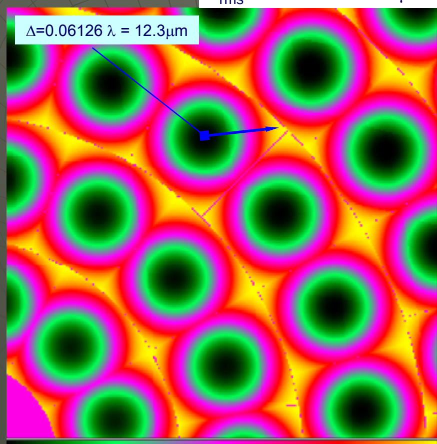

Thermal Expansion 1.00050x
(λ= 200 μm, After M2 Re-Focus by Δz=13.0mm)
CCAT
Strehl = 97.6%
ε_rms= 0.0123λ = 2.5 μm
Beam=1.89”
8’x6
Phase Distribution at Aperture [λ]
Far Field Radiation Pattern [dB]
CCAT Feasibility/Concept Study Review 17-18 January 2006

Thermal Expansion 1.00050x

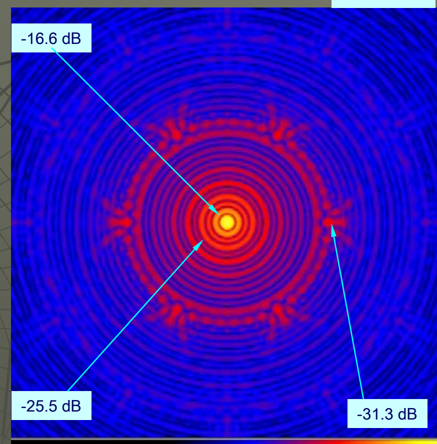
(λ= 200 μm, After M2 Re-Focus by Δz=13.0mm)

Strehl = 97.6% ε_{rms}= 0.0123λ = 2.5 μm



Phase Distribution at Aperture [λ]

Beam=1.89” 3.4’x 3.4’



Far Field Radiation Pattern [dB]

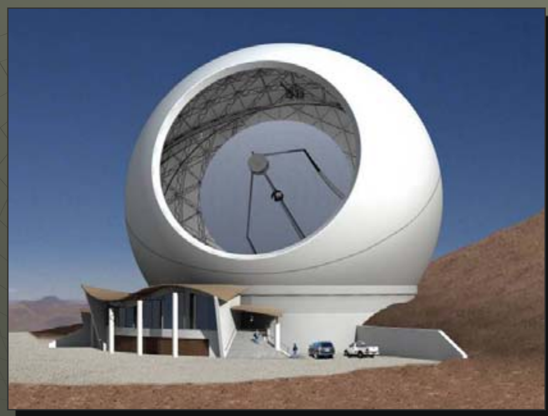
Conclusions

- We have designed a 25m f/8 Symmetric Reflector Sub-Millimeter telescope in a double Nasmyth Ritchey-Chrétien configuration with a FOV of 20’.
- The optimal focal surface has a diameter of 1.16 m, and a radius of curvature of 1.94 m. The calculated Strehl ratio variations over this FOV are better than 97%.
- The 20 arcmin FOV is capable to accommodate up to 1200x1200 (Nyquist Sampled) Pixels at 200 μm.
- The calculated maximum Cross-polar level at the edge of FOV are –51 dB and –52 dB for uniform and Gaussian illumination, respectively.
- The Far Field Side-Lobe Level (SSL) over the FOV is > –16 dB with an uniform Illumination, and better than –20 dB with a –11.0 dB Gaussian illumination taper.
- We have obtained the sub-reflector sensitivities for focusing, de-centering and tilt/tip motion.
- A pointing requirement of θ_{HPFW}/10 at 200μm, imposes a maximum de-centering of the sub-reflector of < 18μm, and maximum edge-to-edge displacements of the sub-reflector, resulting from tilt/tip, between 14μm and 24μm, depending on the location of the center of rotation.
- Maximum chopping amplitude is limited to 10 beam widths for 90% or better Strehl ratio at 200μm, and maximum defocusing of < 80μm.

Conclusions Cont…

- We have analyzed the segmentation effect of an active surface CCAT. The gaps between segments produce a series of grating lobes levels about –31 dB down, and are distributed with a six-fold symmetry in the far field pattern.
- We have calculated the effects, in terms of Strehl ratio, of random segment positioning errors of the active surface, including piston, tilt/tip, lateral displacement and twist segment errors.
- We have found a set of coefficients relating the standard deviation of a particular segment positioning error with its resultant structural rms surface error. We have concluded that the piston errors have the largest effect on the antenna performance, followed by tip/tilt errors being half as important.
- Although, segment piston, and tilt/tip errors are directly controllable by the active surface actuators, we found that un-controllable lateral segment displacements may be compensated by tip/tilt corrections.
- Segment twist errors are not controllable, neither can be compensated by a piston-tilt actuator system alone. Nevertheless, telescope performance is very insensitive to twist errors.
- We have calculated the effects of a uniform thermal expansion of the back-structure by a factor of 1.0005x. This produces a quadratic phase error distribution across of each of the segments, and a overall defocusing of the telescope. After refocusing the achievable Strehl ratio is better than 97%.

End



CCAT

CCAT Facilities Concept

Feasibility/Concept Study Review

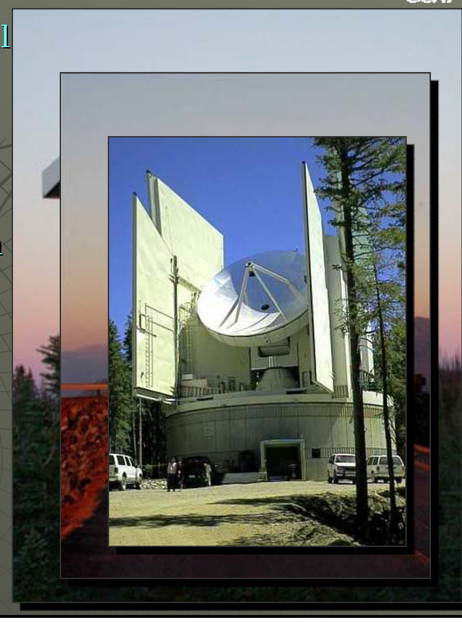
M3 Engineering & Technology Corporation

Presentation Summary

- M3 Engineering & Technology Corp.
- Scope of Work
- Site Access Road
- Mountain and Support Facility Requirements and Concept Design
- Support Facility Requirements and Concept Design
- Critical Risk Assessment

M3 Engineering & Technology Corp.

- Full Discipline Architectural and Engineering Firm
- Offices in Arizona, Mexico
- Specialize in Telescope Enclosures and Support Facilities
- Over 17 Years Experience in Telescope Observatory Design and Construction
- Projects in Arizona, California, Hawaii, New Mexico, Texas and Chile
- Design Experience of All Observatory Sizes and Dome Configurations



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M3 Current Telescope Enclosure Projects

- ALMA AOS Site Infrastructure and Technical Support Facility, Chajnantor, Chile
- Discovery Channel Telescope Observatory, Happy Jack, Arizona
- SST Enclosure, White Sands Missile Range, New Mexico
- Mew Mexico Tech Interferometer Array, Magdalena Ridge, N.M.
- GMT Enclosure Concept Design and Cost Study
- TMT Facilities Concept Design and Cost Study
- LSST Concept Design and Cost Study

M3 Engineering & Technology Corp.
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Scope of Work

- Concept Design Study and Budget Estimate
  - Site Access Road
  - Mountain Facility: Cerro Chajnantor
    - Telescope Foundation
    - Telescope Base Enclosure and Control Facility (Excluding Dome)
    - Site Infrastructure and Improvements
  - Support Facility, San Pedro de Atacama
    - Administration and Dormitory Facilities
    - Site Infrastructure and Improvements

Site & Access Road

- Three Potential Sites in the Atacama Region
  - Sairecabur (Existing Road Used by Smithsonian Telescope)
  - Cerro Chascon
  - Cerro Chajnantor (For the purpose of the conceptual design, CCAT selected Cerro Chajnantor as the preferred site.
- Road Design Criteria:
  - 4 meter Wide, Single Lane, Dirt Access Road with Guardrails and Safety Pullouts
  - Minimum Width Required to Transport Large Instruments and Telescope Parts
  - Minimize Switchbacks
  - Maximum 10% Grade
  - Cut and Fill Slopes at 2:1
  - Culverts for Proper Drainage, Minimize Erosion
  - Locate the access road on the mountain side exposed to the sun thereby minimizing snow and ice build-up

M3 Engineering & Technology Corp.
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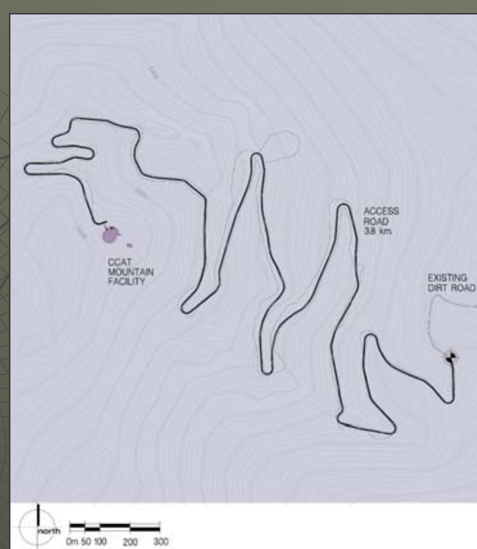
Site Access Road: Cerro Chascon

- Located Within the CONICYT Science Preserve
- Site Elevation: 5675m
- Total Length: 13 Kilometers
- 3.0 Kilometers of Road at 10% Grade.
- 5 Switchbacks
- Most of the Road Located on the Southeast Side of the Mountain

Site Access Road: Cerro Chajnantor

- Within the CONICYT Expanded Science Reserve
- Site Elevation: 5600m
- Total Length: 6.26 Kilometers
- 15 Switchbacks
- Most of the Road on the East and North Side of the Mountain.
- Plateau Just Northeast of the Peak is the Preferred Mountain Facility Location



Mountain Facility Requirements

- Telescope Foundation
- Dome Foundation
- Control Building
  - Local Control Room and Open Office Space
  - Conference Room, Kitchenette, Toilet/Shower
  - Computer and Backend Room
  - Instrument Preparation Lab and Workshop
  - Mechanical / Electrical Support Space
- Utility Building and Lay Down Yard
  - Electric Power Generators and Transformers
  - Chillers and Pumps
  - Domestic and Fire Water Holding Tank and Pumps

Mountain Facility: Site Plan

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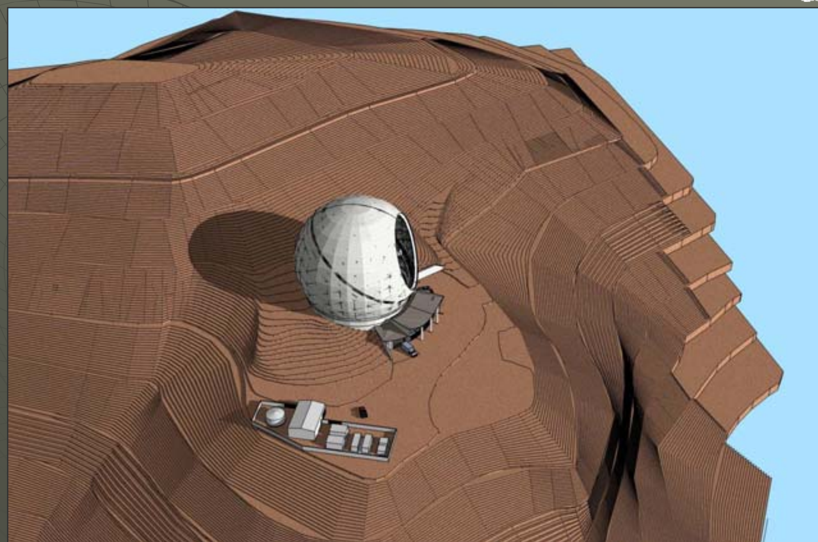
Mountain Facility: Aerial View



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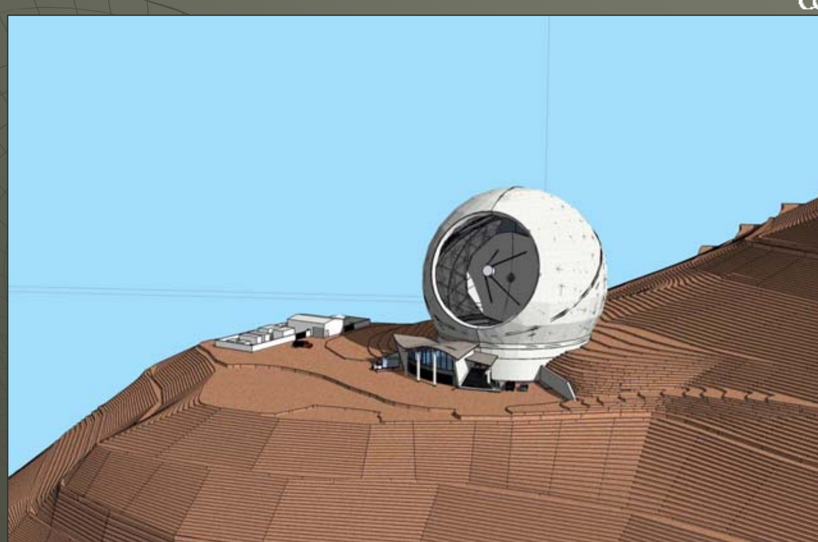
Mountain Facility: Aerial View



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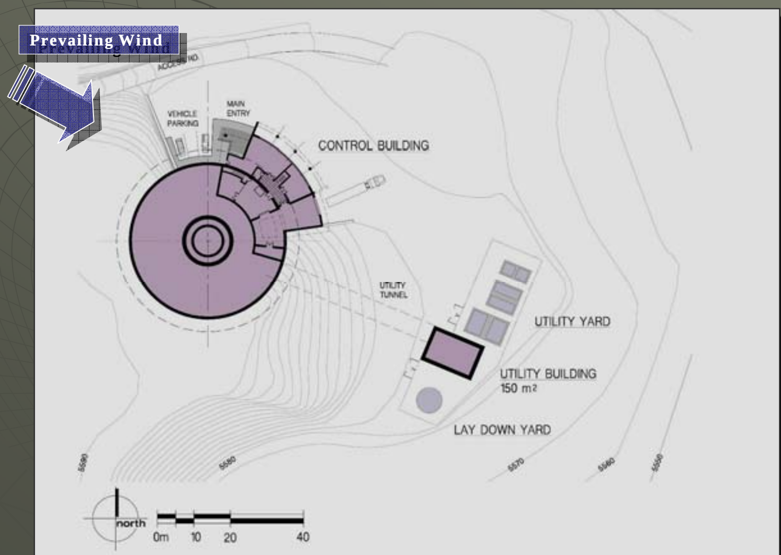
Mountain Facility: Site Plan



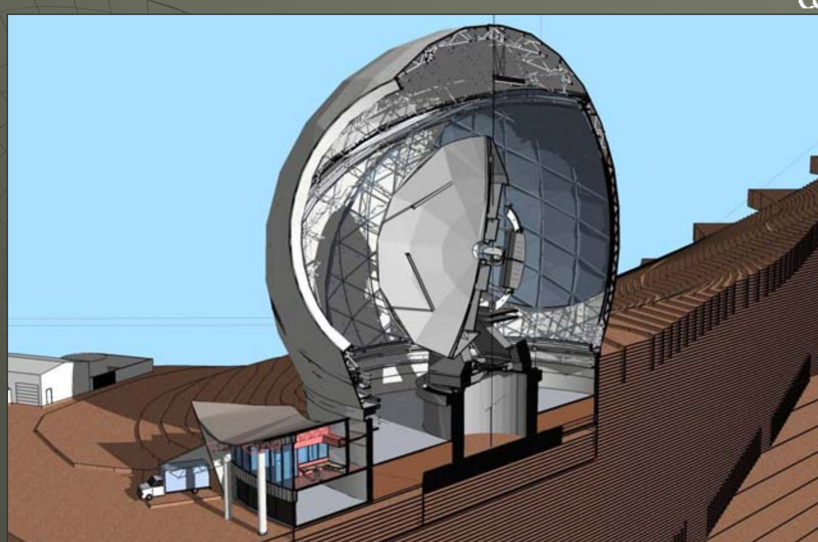
Mountain Facility: Grade Level Plan

- Receiving
- Computer Backend
- Instrument Lab
- Mechanical, HVAC, Hydrostatic Oil
- Electrical
- Circulation to Second Level

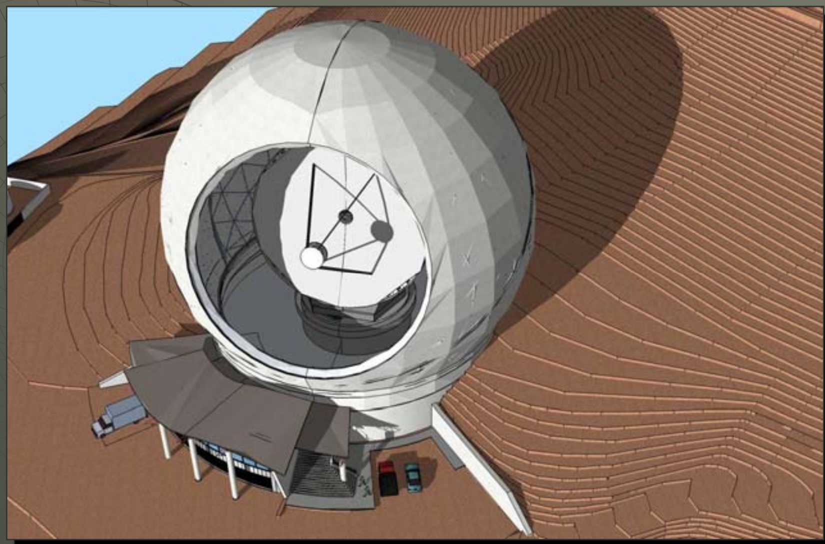
Mountain Facility: Observing Level Plan

- Main Entrance
- Control Room / Open Office
- Conference Room
- Kitchenette, Toilet & Shower
- Telescope Chamber
- Capture Mountain Views

Mountain Facility: Building Section



Mountain Facility: Exterior



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Mountain Facility: Exterior

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Mountain Facility: Exterior

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Support Facility Requirements

- Site Improvements and Infrastructure
  - Electric Power Generators and Transformer
  - Domestic Water and Sewage System
  - Parking
- Support Facility
  - Remote Control Room
  - Offices
  - Instrument Labs
  - Workshops
  - Warehouse
  - Dormitories
  - Cafeteria and Kitchen
  - Mechanical and Electrical Support Space

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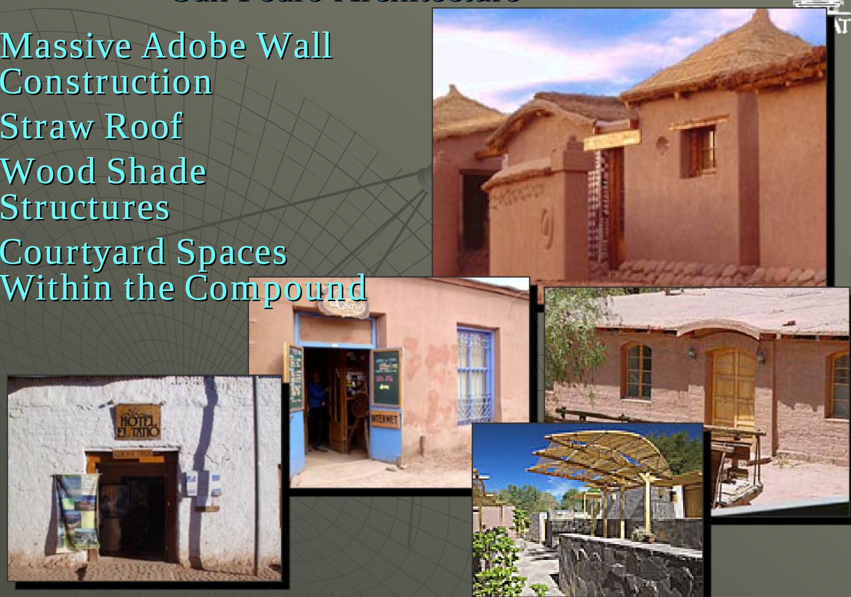
San Pedro Architecture

- Massive Adobe Wall Construction
- Straw Roof
- Wood Shade Structures
- Courtyard Spaces Within the Compound



Support Facility: Site Plan

Critical Risk Assessment

- Minimizing Risks:
  - Keep it Simple.
  - Follow Traditional Construction Methods and Systems.
  - Use Materials that are Used Commonly by Local Contractors.
- Support Facility:
  - The Use of Materials such as Concrete Block, Adobe, Wood and Steel are Traditional Materials. This Facility does not have Significant Risks in the Design or Construction.
- Mountain Facility:
  - The Construction Materials are Poured-in-Place and Pre-cast Concrete, Steel, Metal Panels, etc. These Materials are very Easy to Fabricate and Erect at a Typical, Low Altitude Site but can be Very Challenging at a Remote, High Altitude Site such as Cerro Chajnantor (5500m) with a Low Oxygen Level.

Critical Risk Assessment

- **Mountain Facility Challenges:**
  - **Contractor's Availability:**
    - Santiago Construction Industry is Booming. Many Contractors Prefer to Work in the City and not at High Altitude, Remote Sites.
    - Copper Prices are Above $2.00US/lb. Contractor's are Overwhelmed with Mining Work Especially in the Northern Region of Chile.
  - **Remote Site Complication:**
    - Provide Contractor's Camp, Room and Board for their Workers at a Lower Altitude Site.
    - Transport Workers to the Construction Site Every Day.
    - Availability of Materials and Labor Needs to be Well Coordinated and Scheduled in Advance.
    - Why Work at a Difficult Site when there is Plenty of Work at Lower Elevation Sites?
  - **Weather and Construction Seasons:**
    - Severe Weather and Limited Construction Seasons.
    - Productivity Diminishes Significantly with Unfavorable Weather Conditions.
    - Mobilize Onsite Several Times and the Project Needs to be Phased.

Critical Risk Assessment

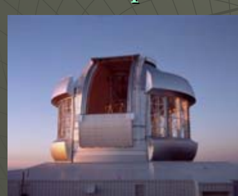
- **Mountain Facility Challenges:**
  - **Lack of Oxygen:**
    - Use of Portable Oxygen Tanks and Masks.
    - Difficult to Build within Typical Construction Tolerances Requiring Modifications or Rebuilding.
  - **Equipment Operation and Warranty:**
    - Typical Mechanical and Electrical Equipment is Rated for Sites Under 3000m
    - Built to Withstand Normal Environmental Conditions.
    - Equipment Performance Guarantee is Usually not Available for Equipment at 5500m Altitude or Higher.
    - Off the Shelf Equipment Needs to be Modified to Withstand the Severe Environmental Conditions and Require Additional Anchorage.
- All of these Factors have a Direct Impact and Risk on the Project's Schedule and Costs. Construction Delays, due to Weather, Labor Availability, etc. are Additional Costs to the Contractor and Owner Extending the Overall Construction Schedule, Possibly into the Next Construction Season.

CCAT Enclosure

Nathan Loewen
AMEC Dynamic Structures
January 17, 2005

AMEC Corporate Profile

- AMEC Dynamic Structures Ltd:
  - Located in Vancouver, Canada
  - Design/build steel fabricating firm
  - Specialize in astronomy and entertainment industries





Scope

- Scope of enclosure: everything above the fixed facility building
- Scope of feasibility study:
  - Structural design
    - Structural shell design and analysis
    - Fabrication/construction considerations
  - Mechanical design
    - Calotte mechanical system
    - Azimuth mechanical system
    - Shutter
    - Crane

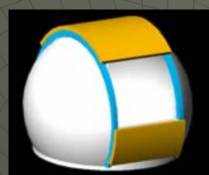
Requirements for Subsystem

- CCAT Enclosure Requirements
  - Dome diameter: 50m
  - Aperture diameter: 30m
  - Aperture zenith range: 0 – 75 degrees
  - Azimuth rotation: unlimited
  - Calotte rotation: 200 degrees
  - Key environmental loads:
    - Wind (survival): 65m/s
    - Snow Load: 100kg/m^2
    - Ice Load: 25kg/m^2
    - Seismic: 0.4g ground acceleration
  - General: simplify on-site construction due to the extreme altitude
    - Trial assembly at the manufacturer's site
    - Shipping via standard containers
    - Construction procedures that minimize field labor

Enclosure Type

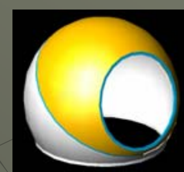
- Various enclosure types considered
  - Formal trade studies carried out for TMT, VLOT, GSMT

Dome-Shutter



Carousel

Calotte

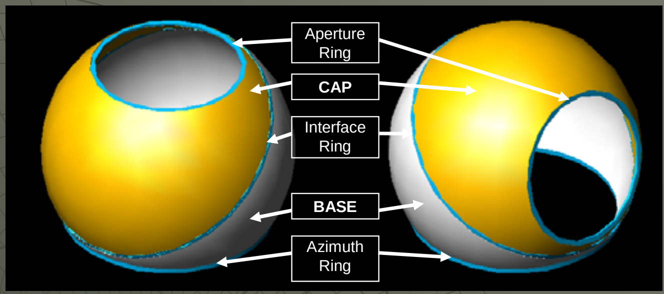


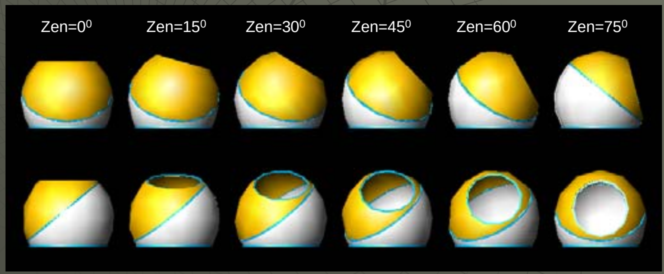
- "Calotte" selected as baseline design:
  - Continuous spherical form
    - Lighter structure = lower cost (structural, mechanical, construction)
    - Avoids concentrated loads on mechanical systems at arch girders
    - Reduces snow and ice accumulation
    - Reduces wind load on enclosure and turbulence
  - Requires minimum number of moving components (no windscreens/light screens)
  - Minimum aperture opening gives maximum wind protection

Enclosure Type

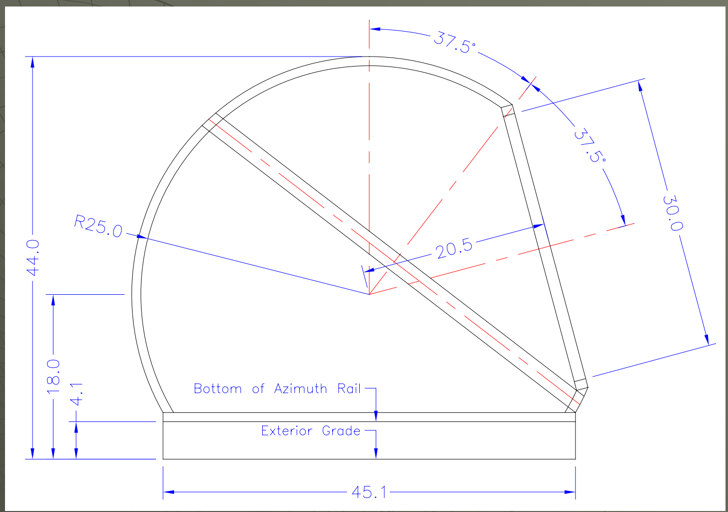
- Key aspects of TMT enclosure comparisons
  - Enclosure mass
    - Calotte: 2300 T
    - Dome-shutter: 2500 T
    - Carousel: 3600 T
  - Enclosure cost estimates
    - Dome-shutter: 20% higher than Calotte
    - Carousel: 45% higher than Calotte
  - Peak power requirements
    - Calotte: 400 kW
    - Dome-Shutter: 2600 kW
    - Carousel: 1000 kW
- Major drawback of Calotte for TMT was the possible venting limitations
  - Not an issue for CCAT

Enclosure Concept – "Calotte"





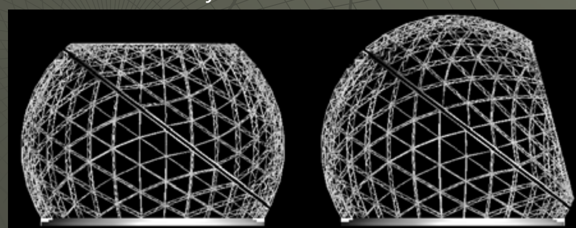
Enclosure Dimensions



Structural Design

- Structural design trades
  - Triangulation geometry (geodesic, rib & tie)
  - Beam vs. truss elements
  - Aluminum vs. steel
- Selected design for feasibility study
  - Steel triangulated truss structure, nominally 1.0m deep
  - Stiffened ring sections at mechanical interfaces
  - Shares similar components to existing enclosures (i.e. Keck I & II)

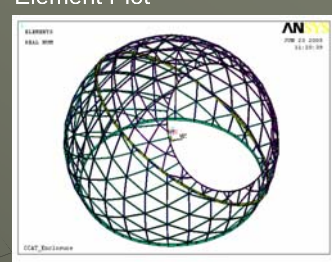
Geometry of rib & tie shell structure



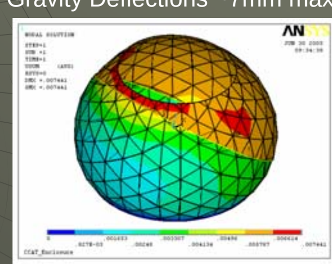
Structural Analysis

- Structural Analysis
  - Preliminary FEA of enclosure structure
  - Members optimized under survival load combinations (gravity, wind, snow, ice)
  - Mechanical elements modeled with equivalent spring elements

Element Plot

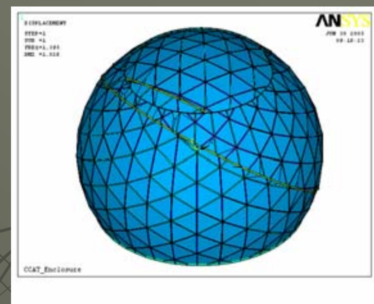


Gravity Deflections ~7mm max

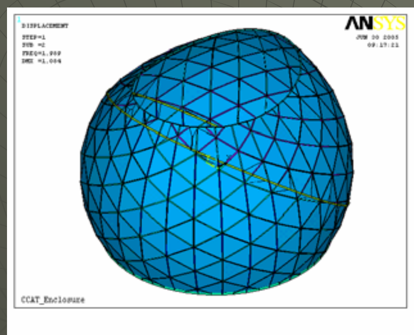


Mode Shapes

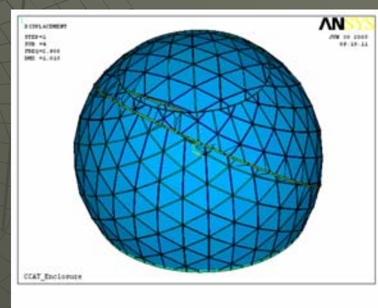
Mode 1: 1.4Hz



Mode 2: 2.0Hz (Mode 3 similar)



Mode 4: 2.9Hz



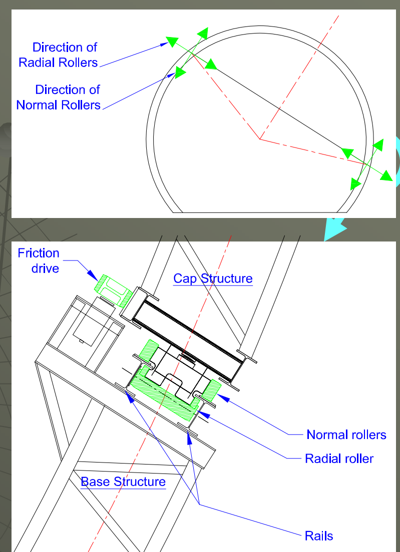
Interface Bearings/Drives

- The mechanical interface design (i.e. the bearings and drives at the inclined plane) are considered a high risk component of the Calotte enclosure design
  - Wear Issues
  - Over-constraint and Differential Thermal Expansion
- Interface design trades:
  - Continuous vs. discrete rolling elements
  - Bogie mount location (cap-mounted vs. base-mounted)
  - Bogie orientation (parallel to plane of rotation vs. parallel to structural shell)
- Several general concepts for the mechanical design have been developed; the preferred point design is presented here

CCAT Feasibility/Concept Study Review 17-18 January 2006

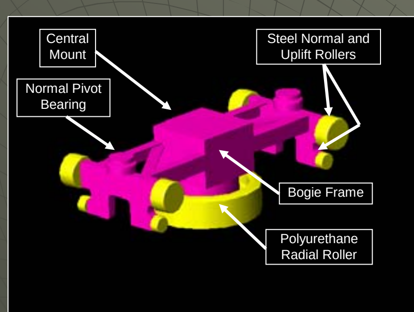
Interface Bearing Concept

- Bogies contain 2 roller sets:
  - *Normal rollers* oriented perpendicular to plane of rotation
  - *Radial rollers* oriented perpendicular to axis of rotation
- Bogies mounted to "cap", rails mounted to "base"
  - Allows bogies to be accessed from single location at lowest point of interface
- Drive assembly independent from bogie assembly
  - Several drive units mounted to base at lowest point of interface; allows redundancy and ease of access
  - 90 hp total input power required

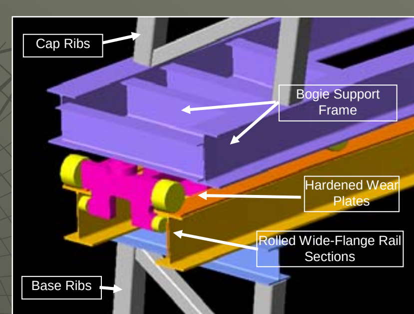


Interface Bearing Concept

Interface Bogie Assembly

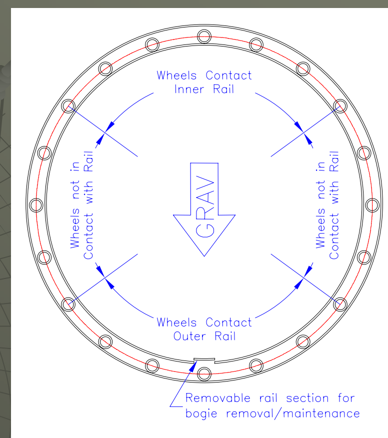


Interface Bogie/Rail Assembly



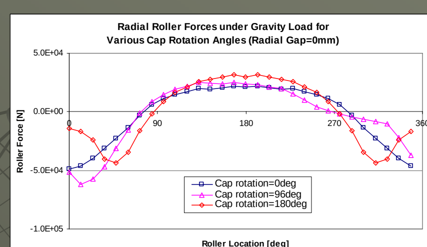
Interface Bearing Concept

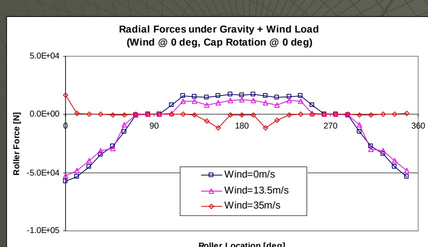
- Radial rollers contained within a double rail
  - Loading switches between inner/outer rail due to gravity load on inclined interface
- Gap between rollers and rails
  - Notionally 1” gap
  - Avoids over-constraint
  - Eases fabrication and assembly tolerances

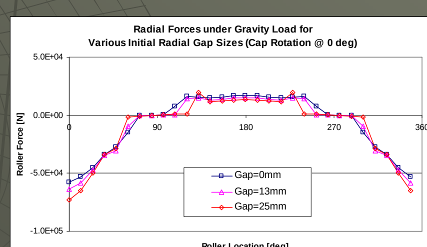


Interface Analysis

- Analysis have investigated load distribution at interface bogies
  - Analysis based on enclosure FEM
  - Load cases considered include gravity, wind, thermal, fabrication tolerances
    - Fabrication/construction tolerances found to a driving consideration
  - Sample results shown here







Azimuth Bearings/Drives

- Azimuth bearings/drives
  - Bogies are fixed to foundation, rail surface is mounted to enclosure
  - Drive system utilizes rubber-tire drive rollers, spring loaded to maintain friction force
    - Bearing and drive concept is similar to HET/SOAR concepts
    - 110 hp total input power required
  - Not considered a high-risk design issue due to experience with existing designs

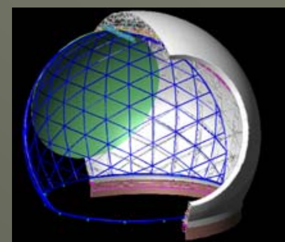
Shutter

- Shutter key design trades
  - Fixed vs. Movable
    - Movable structure required: fixed shutter blocks too much sky
  - Interior vs. Exterior
    - Interior structure preferred: minimizes wind/snow/ice loads on the shutter structure, resulting in lighter shutter structure
  - Azimuth mounted vs. interface mounted
    - Azimuth mounted preferred: minimizes load on enclosure structure, and does not require structure to be balanced about rotation axis

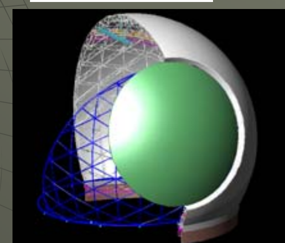
Shutter

- Selected shutter concept is movable, azimuth mounted, internal structure
  - Shutter closes w/aperture pointed to zenith=75^0
  - Shutter structure supported via bogie system on enclosure azimuth ring girder, rotates 180^0 to open/close shutter
  - Shutter structure does not require drive system:
    - In open or closed configurations, locking pins fix shutter rotation to enclosure rotation
    - In transition from open to closed configurations, locking pins or brakes fix shutter rotation to foundation, and enclosure rotates 180^0 in azimuth to open/close shutter
  - Shutter seals opening via a telescoping annulus ring and an inflatable seal

Shutter OPEN

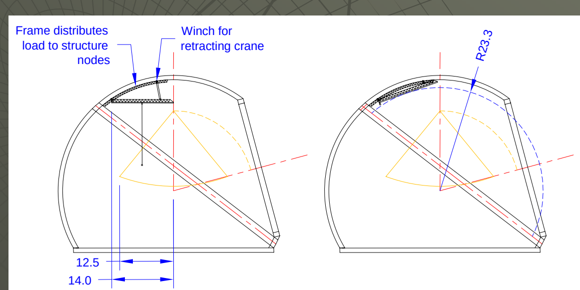


Shutter CLOSED



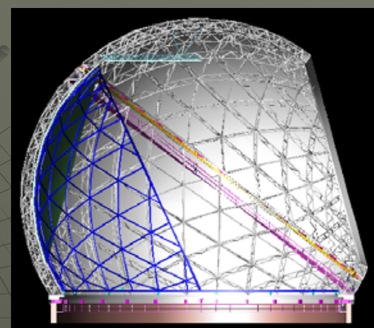
Enclosure Crane

- Enclosure requirements specify 2-tonne crane for telescope maintenance
- Alternate crane options have been considered:
  - An enclosure-mounted retractable gantry crane is currently the preferred option (see figure below)
  - Alternate concepts include vehicle-mounted jib cranes; access to telescope is either from interior of enclosure or from exterior through open aperture



Mass Estimate

Component	Mass [Tons]
Structural - Ribs	54
Structural - Ties	101
Structural - Azimuth Ring	21
Structural - Interface Ring-Base	24
Structural - Interface Ring-Cap	24
Structural - Aperture Ring	12
Structural - Shutter	50
Structural - Cladding/Insulation	81
Mechanical – Azimuth	76
Mechanical - Interface	38
Mechanical - Shutter	15
TOTAL	**496 tons**



Note: Gemini Dome: 36m Diameter 360 tons, Scaled to 52m=1100 tons

Keck Dome: 36 m Diameter 650 tons, Scaled to 52m=2000 tons

Critical Risk Assessment

- Critical issues identified:
  - Interface
    - Further detailed of design/analysis required; no potential showstoppers indicated in analysis to date
    - Development of fabrication and installation procedures
  - Structural mass
    - Structure fabrication/construction a large cost driver, potential to further optimize structure due to efficient structural form
    - Opportunity to utilize subcontractors specializing in manufactured domes

Telescope Mount Concept

CCAT

General Dynamics C4 Systems
Satcom Technologies
VertexRSI Controls & Structures

VertexRSI Profile

- Presenters:
  - David Finley, Mechanical
  - Ed Reese, Controls
- Our Telescope Projects Include:
  - Green Bank Telescope
  - Hobby*Eberly Telescope
  - SOAR
  - VISTA
  - Very Long Baseline Array (VLBA)

Scope of Design Task

- Design And Fabrication Of The Mount Structure
  - Azimuth Rotating Structure (Alidade)
  - Elevation Rotating Structure Except For The Primary Mirror And the Primary Mirror Support Truss
  - Establishing Panel Layout
- Design Of Elevation And Azimuth Drives
- Design Of Control System For The Mount

Requirements for Subsystem

- Alt-az mount
  - Azimuth motion — $\pm$ 270°
  - Elevation motion — +10° to +90° (mechanical travel)
- Velocities and Accelerations
  - Full Performance — 0° To 60° Elevation Angle
  - Scanning velocities — 0.2 deg/sec (slow); 1 deg/sec (fast)
  - Scanning accelerations — 0.2 deg/sec^2 (slow); 2 deg/sec^2 (fast)
- Pointing accuracy
  - Overall — 2 arc-sec, RMS
  - Offset, 1 to 5 deg — 0.5 arc-sec, RMS
  - Offset, < 1 deg — 0.1 arc-sec, RMS
- Open loop behavior
  - Nonguided image jitter — <0.1 arc-sec
  - Open loop drift — 0.1 arc-sec in 1 min
  - Open loop drift goal — 0.1 arc-sec in 10 min

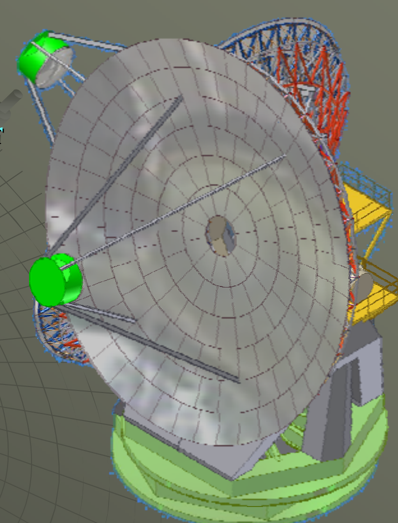
CCAT Feasibility/Concept Study Review 17-18 January 2006

Key Design Issues

- The Close Spacing Of The Optics Poses Challenges For Designing Support Structure.
- The Dynamics Of Scanning At High Elevation Angles Controls Drive Design And Required Structural Stiffness.
- Installation At A Remote, High Altitude Site Requires The Work To Be Organized To Minimize Time At The Site.

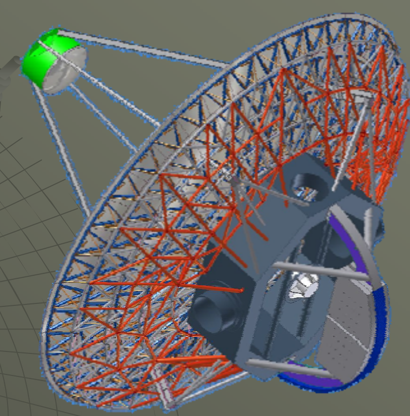
CCAT Mount Overview

- Mirror Truss and quadrapod support primary and secondary mirrors, respectively.
- Reflector Hub Supports Mirror Truss And Elevation Sector Gear
- Elevation Bearings Support Reflector Assembly
- Yoke Arms Support Elevation Bearings And Transmit Reflector Loads Into Azimuth Bearing
- Alidade Rotates In Azimuth, Supported By Hydrostatic Bearing



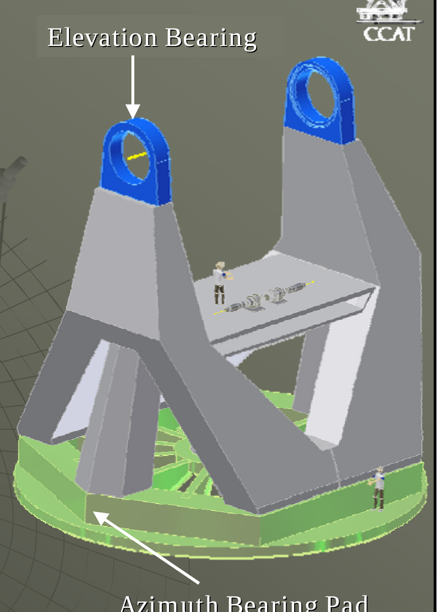
Reflector

- Quadrapod Provides Support For Secondary Mirror
- Quadrapod Legs Supported On Separate Load Path, So Its Loads Do Not Affect The Primary Mirror.
- Central Hub Supports The Mirror Truss And The Elevation Drive Gear
- Access In Central Hub For Tertiary Mirror
- Bent Cassegrain Port In Hub
- Reflector Assembly Supported On Elevation Bearings



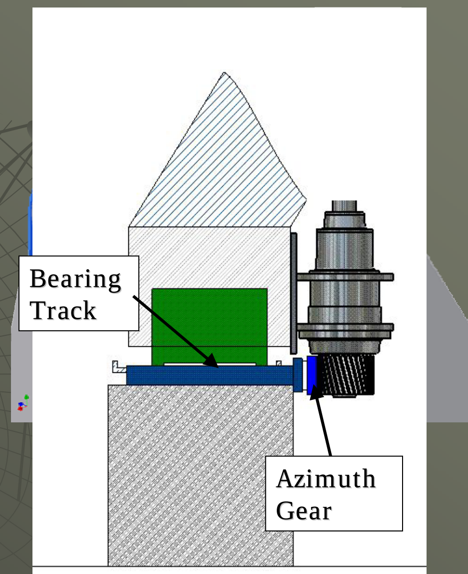
Alidade

- The Yoke Arms Provide A Direct Load Path Between The Elevation Bearings And The Azimuth Bearing Pads
- Elevation Drive Platform Between The Yoke Arms Support The Elevation Drive Motors
- The Platform Also Ties The Yoke Arms Together To Provide A Greater Stiffness In Sidesway
- Hexagon In The Base Supports The Yoke Arms And Ties The Bearing Pads Together



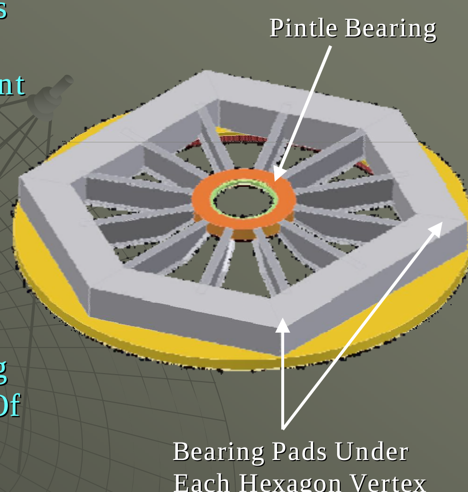
Elevation & Azimuth Drives

- Elevation Drive
  - Reflector Driven By Helical Sector Gear
  - Drive Motors, Driven Against Each Other To Remove Backlash
- Azimuth Drive
  - Helical Gear System
  - Stationary Gear Mounted On Inside Of Azimuth Bearing Track
  - Drive Motors, Gearboxes, And Pinions Located On Moving Structure



Alidade Base

- Hydrostatic Bearing Provides Both Azimuth Rotation And Support For The Entire Mount
- The Center Of Rotation Is Determined By A Rolling Element Pintle Bearing
- The Bearing Pads, Drive Motors, And The Pintle Bearing Are Connected By A Series Of Spokes, Minimizing Deflection Between Motion Of The Motors And The Mount.



Control System and Dynamics

- Preliminary Error Budgets Were Derived, Based On:
  - Vendor Specification Sheets
  - Field Tests From Similar Systems
  - Preliminary Analysis
- Derived Budgets Included:
  - Offset Pointing
  - Tracking
  - Jitter
- Based On This Preliminary Work, The Specification Requirements Appear Achievable
- Performance Requirements Within Current Technology

Performance Requirements

Item	Requirement	Comment
Pointing Accuracy	2 Arcsec RMS	Values of 2-4 Arcsec Achievable
Offset Pointing 1º To 5º	< 0.5 Arcsec RMS	Reasonable Requirement for this Application
Tracking Dynamics	0.25 deg/sec 0.01 deg/sec^2	Achievable
Zenith Transit Outage	Nominal 8-10 minutes	Consistent With Tracking Dynamics
Nonguided Image Jitter	< 0.1 Arcsec	Consistent with Similar Designs. Wind Load Needs More Study
Open Loop Drift	0.1 Arcsec/Min	Realistic, SOAR meets this requirement

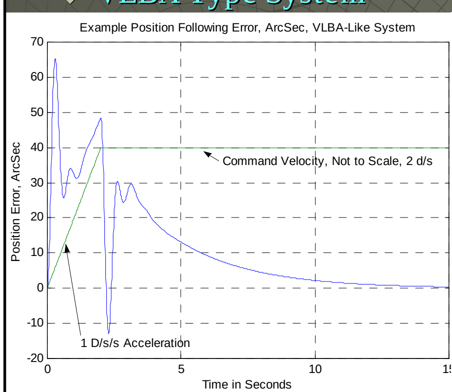
Performance Goals

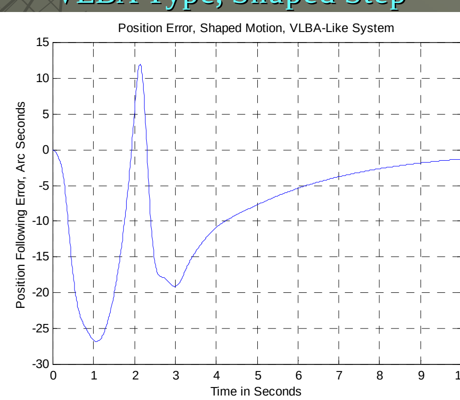
Item	Goal	Comment
Offset Pointing, $<1^o$	< 0.1 Arcsec RMS	Difficult To Analyze And Meet
Open Loop Drift	0.1 Arcsec In 10 Min	Analysis Suggests This Is Difficult To Meet, Yet Our Experience with SOAR Indicates It May Be Possible

Scan Pattern Performance

- Shaped Steps Reduce Following Error
  - Reduces Error Between Commanded Position And Position Vector
  - Shaped Steps Can Improve Peak Following Error, But Increase Mount Dynamics And/Or Increase Motion Time
- VLBA Type System

VLBA Type, Shaped Step





Control System and Dynamics

- Position Reporting Errors
  - Blind Pointing Errors Plus..
  - Errors Due To Dynamic Deflections
- Depends Upon As-Built Structure And Dynamic Requirements
- Some Example Values For Steady State Error Shown In The Table Below For Reference And Science Consideration
- Probable Structural Values In The 3-7 Hz Range

Acceleration =	$1^{o}/s^{2}$	$2^{o}/s^{2}$	$3^{o}/s^{2}$
Structural Resonance	Steady State Error, ArcSeconds		
2 Hz	23	46	69
3 Hz	10	20	31
4 Hz	6	12	17
7 Hz	2	4	6
10 Hz	0.9	1.8	2.8

Critical Risk Assessment

- Optical Layout Imposes Space Limitations For Structure Design
  - An Active Optical Surface Provides An Extra Design Degree Of Freedom
  - The Hub Design Balances Optical And Drive Needs
- Scan Pattern Expectations
  - Further Work With CCAT Program To Establish The Appropriate Pattern
- Installation at a Remote Site
  - We Must Design With The Installation In Mind
  - Confirm Performance Through Factory Testing Before Shipping

CCAT Primary Mirror Overview

T.A. Sebring

Recent Examples Radio/Optical

Telescope	Panel Shape	Material	Fabrication	Mounting	Figure (RMS µm)
Caltech Submm Obs	Hexagonal	Aluminum	Machined as Parent	Active, Open Loop. Kinematic	~15
H. Hertz Telescope	Radial	CFRP/Al Sandwich	Replication & Bonding	Passive & Overconstrained	~15
ALMA/APEX (VRSI)	Radial	Aluminum	Machined as Panels	Passive & Overconstrained	~20
ALMA Alcatel/EIE	Radial	Electro-Ni/AL Sand.	Replication & Bonding	Passive & Overconstrained	~20
Keck Telescopes	Hexagonal	Zerodur	Stressed Lap & Ion	Active, Closed, Kinematic	~0.03
Hobby Ebberly	Hexagonal	Zerodur	Planetary & Ion Figuring	Active, Closed, Kinematic	~0.045
SALT	Hexagonal	Sittal (Fused Qz)	Planetary & Ion Figuring	Active, Closed, Kinematic	~0.045

We Have Assumed that CCAT Must be Segmented…okay?

ALMA Approach: Not Adequate

CCAT

- Initial Error Budget Allocations
  - ALMA 2x Worse ½ Wavefront Error Than Required
  - ALMA 12 m Diameter vs. CCAT 25 m Diameter
- Mirror Mounting Strategy
  - ALMA: Panels Mounted on 5 Points to Structurally Rigid CFRP Support Structure
  - 25 Meter Structure Would Not be Sufficiently Rigid
  - Cost of CFRP PM Truss 5x Greater than Steel ($10m)*
- Opinion of Vertex ALMA Telescope Builders
  - "ALMA Technology Unlikely to Meet Requirements."

* Independent Estimates of MERO and ATK

Conclusions on General Approach

CCAT

- Active Panel Positioning Would be Required
  - Gravity Driven Deflection of Even CFRP Truss Too Large
  - Success of Optical Segmented Telescopes Illustrates Feasibility
- Use of Steel Truss Prohibits Overconstrained Mounting
  - Local Truss Deformations Would Degrade Panel Figure
  - Hence Panels Should Self-Determine Figure Like the Optical Telescopes
- Kinematic Panel Mounting via Bipod Flexures
  - Multi-Point Whiffle Tree Mounts a Challenge
  - Expense, Hysterisis, Part Count
  - Separate Axial/Lateral Load Bearing Difficult
  - Problems with Keck, HET, SALT Mounts

Panel Shape

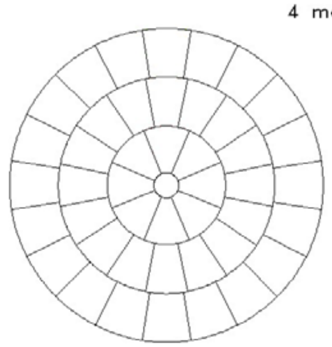
- Hexagonal Segments
  - Less Deflection for Kinematic 3 Point Mounting
  - Only 6 Identical of Each Type: (~35 Different Types)
  - Don't Regularly Tile Surface of Revolution
  - Don't Form Smooth Inner/Outer Edges (Wasted Area)
- Radial Segments
  - Not a Favorable Shape for 3 Point Support
  - Only 6-7 Different Types of Panels
  - Identical Perimeter Shapes for Each Type
  - Full Area of Panels Useable to Inner/Outer Edges

Conclusion: If Radial Panels Would Exhibit Acceptable Deformation on 3 Point Mounts Then Better In Other Regards

Segmentation

To 4 meter Panels

25 meter OD
2 meter ID
4 meter Nom. Panel Size

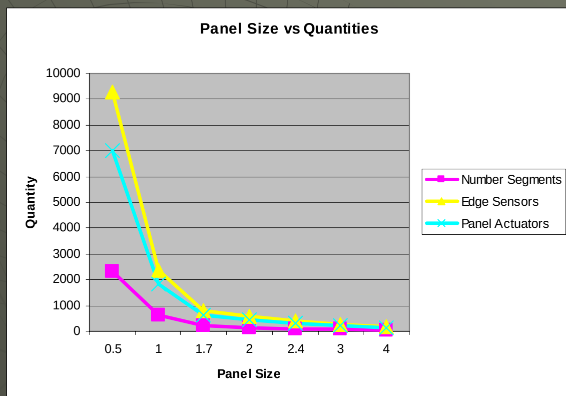


We Looked at Various Segmentation Schemes

AT 25
3NOV04
CHenderson

Assessment of Number of Panels, Edge Sensors, and Actuators

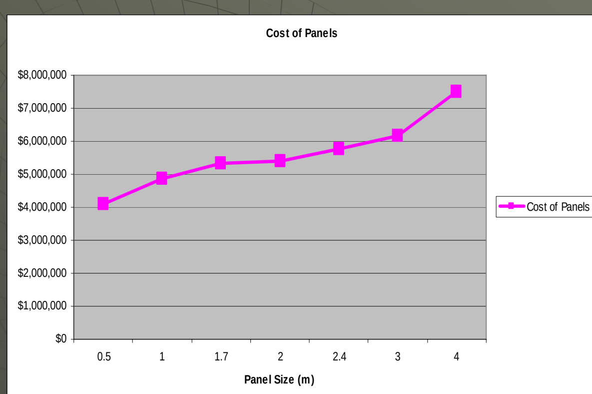
CCAT



- Total Number of Panels Grows Rapidly as Panels Get Smaller
- Number of Edge Sensors and Actuators Required Grow Even Faster

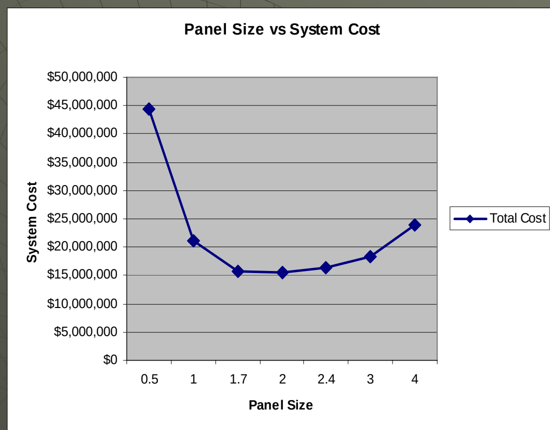
Total Panel Cost Scaled by Size

CCAT



- Using Estimated Cost for Replication of 1.7 m Panels as Baseline
- Panel Costs Scaled with Size $(D1/D2)^{2.2}$

When Adding Other Costs



- Includes:
  - Mandrel's Cost Scaled by Size (Ratio of Panel Size)$^{2.5}$
  - Edge Sensors
  - Actuator's Cost Scaled (Ratio of Panel Size)$^{0.75}$

Supports Usual Contention that There is a Range of Panel Sizes Over Which Number/Size/Infrastructure Roughly Cancel

Other Considerations in Panel Size

- Mandrels are Convex and Need to be Accurate to <1 μm RMS
- In Sizes Larger than 2m Only a Couple of US Fabricators Could Bid…Probably Very Expensive
- Initial Study Specified 2m Panel Sizes
- Based on Panel Study Results We Anticipate ~1.7m Panels

Panel Approaches Considered

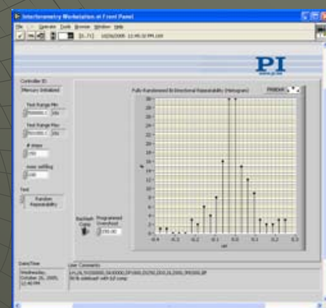
- Machined Aluminum
  - Large Thermal Errors & Warping Require Overconstrained Mounting...Not Compatible
- Ni/Al Sandwich (Media Lario)
  - Early Info from Media Lario Indicated Large Thermal Errors if Panels Were Made Thicker than ALMA's
  - Now Considered "In the Mix" Until Resolved
- CFRP/Al Sandwich (Several Possible Vendors)
  - Good Structural and Thermal Performance
  - "Easily" Replicated
  - Questions of Long Term Stability, Coating, Cost
- Precision Molded LW Borosilicate Glass (ITT)
  - Emerging Technology
  - "Inert" Material, One Stop Shopping wrt Mandrels
- SiC/Nanolaminate: Proven Too Costly

Primary Mirror Truss

Actuators

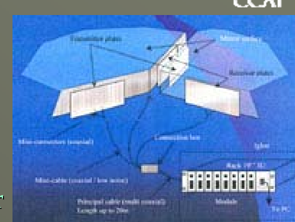
- 3 Actuators/Segment
- Intended to Take Lateral as Well as Axial Loads
- Studied by Polytec PI Pro Bono
- Actual Tests Validate Performance

•***Histogram still shows FWHM <0.2μm,***
•***And >70% better than 0.1um***
•***Tested with high radial load of 50lbs***



Panel Alignment & Control

- Edge Sensors: Several Approaches Possible
  - Fogale Nanotech (SALT) and Blue Line Engineering (HET) Commercial Solutions...~$1000-1500/sensor
  - TMT Developing Mark II Keck Edge Sensor
  - JPL to Investigate Lateral Effect Photodiode Approach
- Supplementary Sensors
  - Un-sensed or Low Sensitivity Modes Drive Need for Supplemental Sensors
  - Some Edge Sensors May Measure Dihedral Angle
  - Other Supplementary Sensors Under Consideration

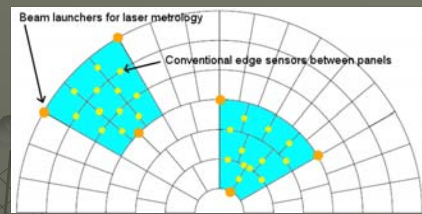


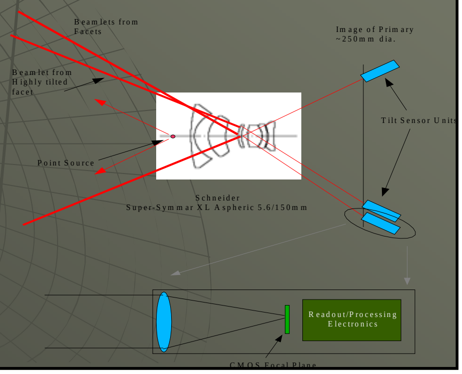
Fogale SALT Sensor

Proposed TMT Edge Sensor

Supplementary Sensors

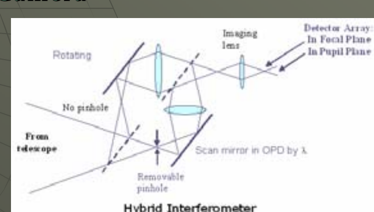
- Laser Absolute Distance Meas. Interferometry: JPL
  - Distributed as Required
  - Provide Absolute Start-Up Data
  - Provide M1/M2 Alignment
- Hartman Type Sensor: AOA
  - Senses Angles via Facets on Facesheets
  - Size Dictates 1 Sensor per Panel
  - Analysis Validates Precision
  - Low Cost ~$750k
- Wavefront Sensing Guider
  - Requires IR Panel Quality
  - May Yet Work





Initial Alignment via Interferometry

- Initial Alignment via Mechanical and Optical Gauging
  - Spherometer at Adjacent Panel Surfaces (~5 µm precision)
  - Hamar Laser & Probe Over Larger Areas (~5 µm precision)
- G. Serabyn JPL Has Identified Three Possible Interferometric Approaches Based on CSO Type Sensors
  - Shearing Interferometer
  - Point-Diffraction Interferometer
  - Pupil Plane Point-Diffraction Interferometer
  - Large and Expensive Instrument
  - Depends on Science Instrument for Camera



PM Issues for Next Phase

- Panel Analyses, Tests, Qualification
- Calibration Alignment Development
- Alignment Maintenance Development
- Optimize Segmentation/Sensors/Deployment

The CCAT Primary Mirror Appears Feasible and of Acceptable Risk…Further Definition of Concept and Cost Reduction Work Planned

System Engineering

CCAT

David Woody
Assistant Director of Instrumentation
Owens Valley Radio Observatory

Background and experience

CCAT

- Antenna experience
  - CSO (Caltech)
    - modeling and surface adjustment
  - OVRO millimeter array (Caltech)
    - production of second run of antennas
    - surface measurement and setting
  - ALMA (NRAO and ESO)
    - design concepts
    - analysis and review of prototype antennas
  - SZA (U. Chicago and Caltech)
    - conceptual design
    - responsible for construction (Vertex)
  - Consulted on several other antennas
    - SMA, SPT, ACT
- Extensive experience in radio astronomy instrumentation and system design

Scope and Approach

CCAT

- Interaction of components and systems
- Input: carefully defined
  - requirements
  - specifications
  - design goals
  - environment parameters
- Analyze design concepts
- Output: error budgets
- Want measurable engineering specifications in next phase

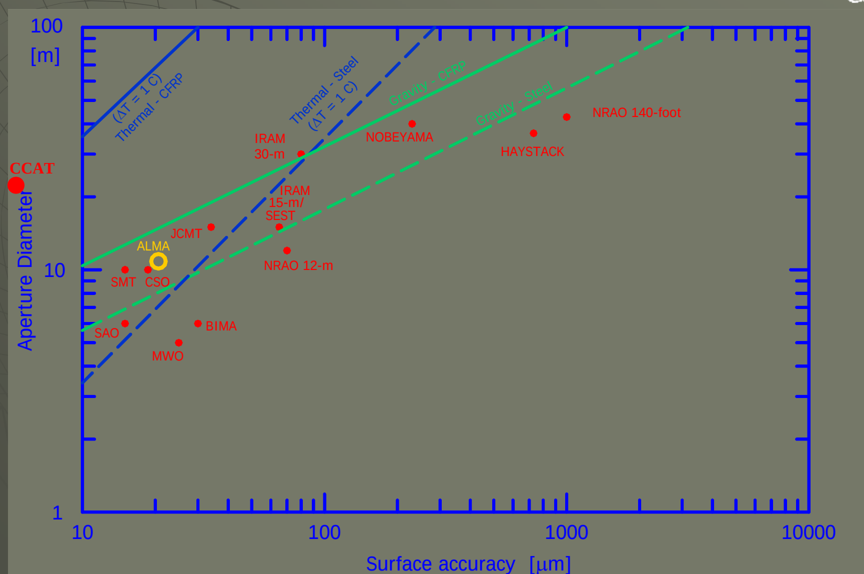
Major Issues

CCAT

- Wave Front Error (surface errors)
  - Primary, secondary and tertiary
    - Fabrication (panels)
    - Setting (measurement)
    - Maintenance (active control)
- Pointing and tracking errors
    - Mount distortions
    - Drive servo system
    - Atmosphere
- Image quality
    - Most image issues are encapsulated in the ½ WFE
    - Diffraction effects

Updated von Hoerner Plot

(Lamb ALMA memo)



Context for CCAT

- Physical limits shown in updated Von Hoerner plot
  - CFRP, etc.
  - Homology
  - Dome
    - No solar heating
    - Minimal wind
- CCAT will have an active surface
  - Passive would represent large risk at this point
    - Telescopes close to the limits on the plot already employ CFRP and high degree of homology
  - Active surface reduces risk and increases complexity
  - Can use steel support structure

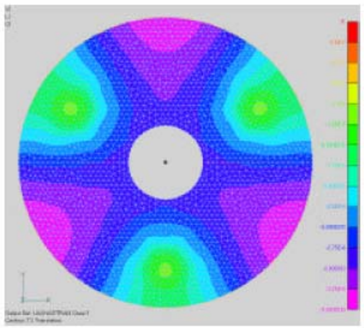
Top-Down error budget

1/2 Wavefront Error Budget			
	ALMA RFP	CCAT	
Panels	[microns]	[microns]	
Total Panel (RSS)	11.8	5.0	
Backing Structure			
Total Backing Structure	7.5	4.0	
Panel Mounting			
Total Panel Mounting (RSS)	5.4	4.0	Total Active Surface Control
Secondary Mirror			
Total Secondary Mirror (RSS)	8.4	3.5	
Total Tertiary Mirror (RSS)	0.0	3.5	
Total Measurement and Setting (RSS)	10.0	4.0	Astro. WFE & Holography
Other Errors not Included Above	2.0	1.5	
TOTAL (RSS)	20.0	10.0	

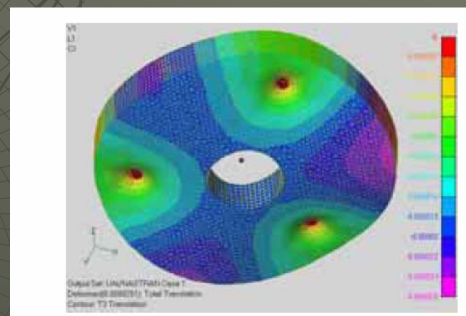
Panel analysis

- Generic parametric model
  - Plate-core-plate laminate
  - Materials
    - Al, CFRP high strength, CFRP low CTE, Ni, steel, Invar, Beryllium, Borosilicate glass, ULE glass, SiC
  - Geometry
    - Diameter
      - Round disk supported at optimal three points
    - Plate thickness
    - Core thickness and density

Three point support, fig. from SNAP 2m



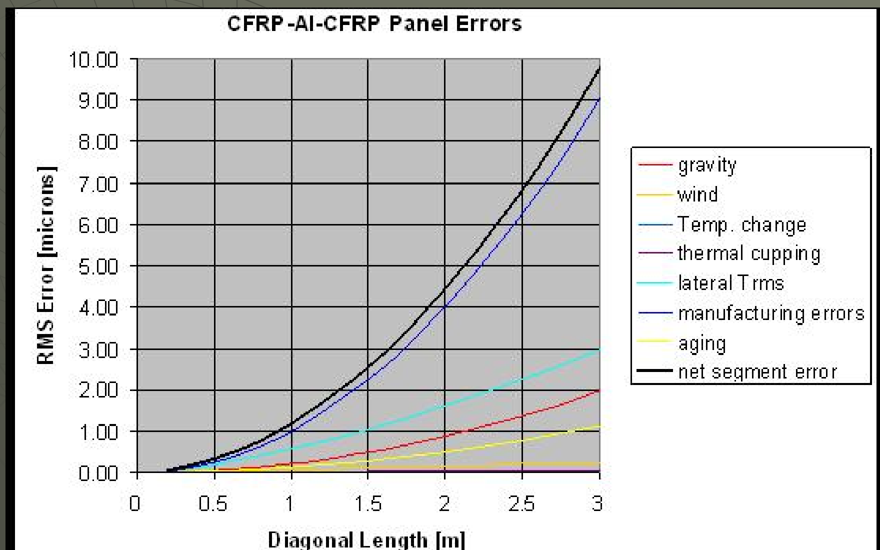
1g sag on 3pt support
vertical axis
P-P Z deflection = 2.3 μm



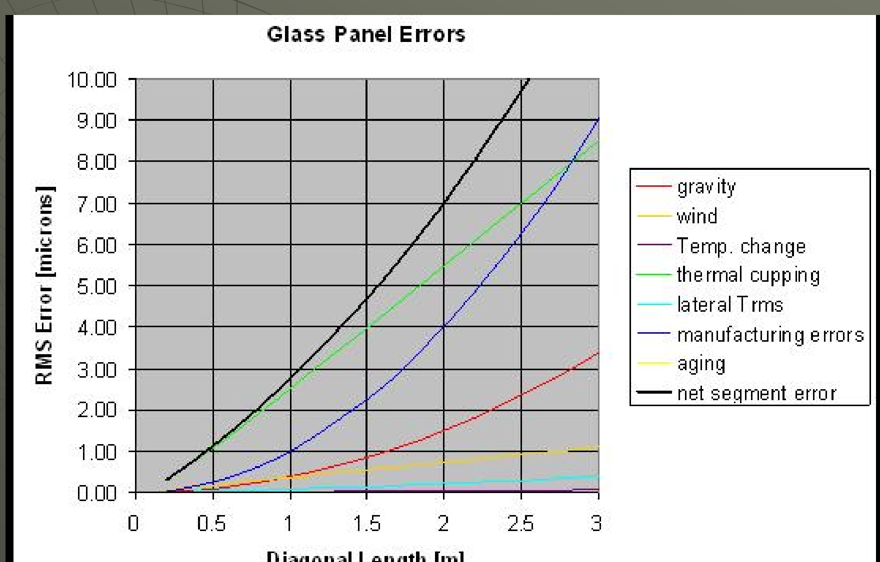
Panel errors

- Loads
  - Thermal: ΔT CTE
    - Uniform: D^2
    - lateral RMS: h
    - axial through segment: D^2/h
      - Radiative
      - Air and insulation
  - Gravity: $\rho\ t\ D^4 / Y\ h^2$
  - Wind: $v^2\ D^4 / Y\ h^2$
- Other errors
  - Fabrication: D^2
  - Aging: D^2
- Comparable to other detailed designs

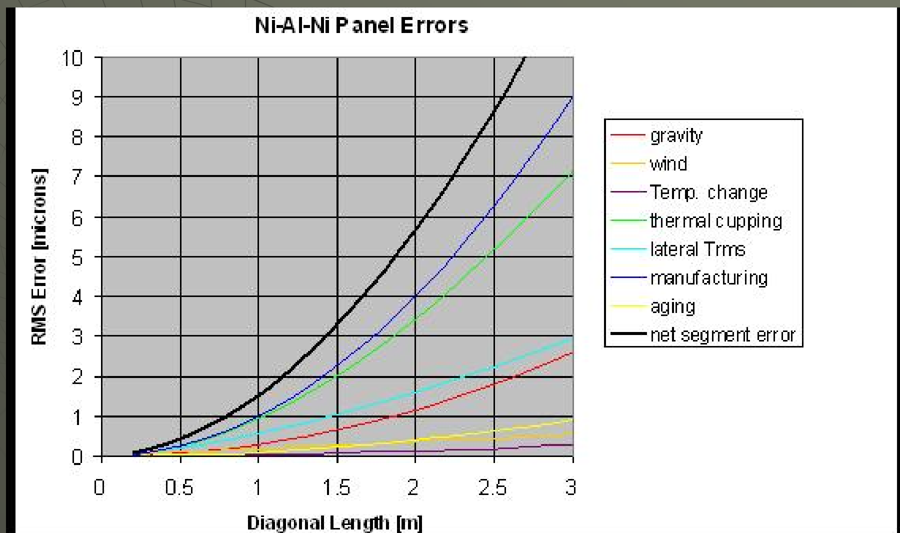
RMS surface error vs. effective diameter



RMS surface error vs. effective diameter



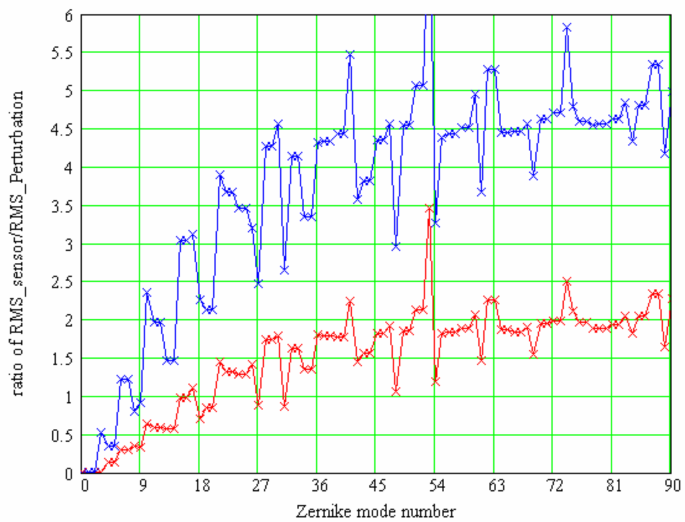
RMS surface error vs. effective diameter



Surface maintenance system

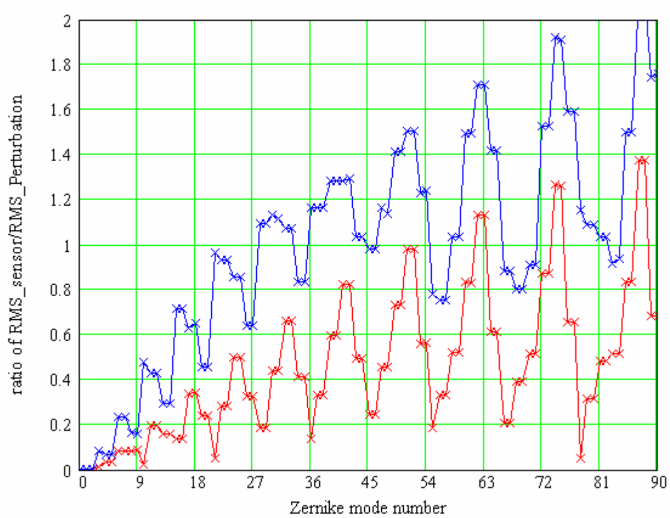
- Edge sensors
  - Continuity between panels
  - Dihedral angle between panels
- Large scale measurement
  - Absolute distance measurement from some panels to secondary
- Servo algorithm is critical
  - Can dampen or accentuate errors
- Have MathCad model of sensor reading for first 100 Zernike distortions
  - Explore configurations and number of panels
  - Use ratio of RMS_sensor/RMS_distortion

Edge sensor sensitivity, Keck



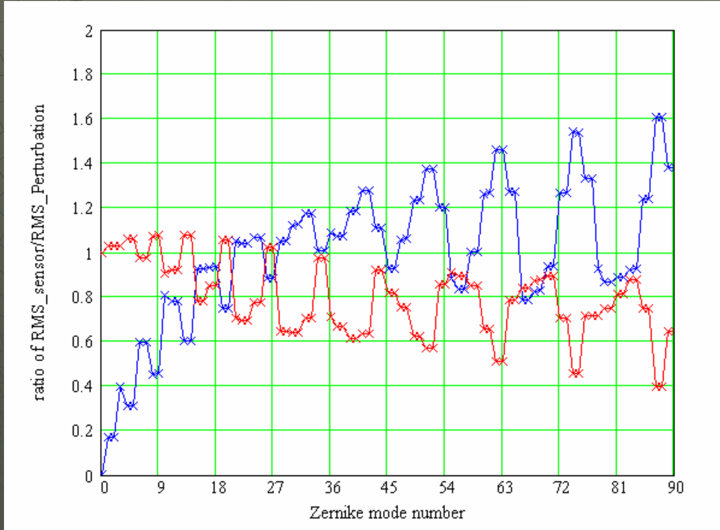
Sensitivity of edge sensors (red) and diahedral angle (blue) for a 36 hex segment surface. The diahedral sensitivity is in microradians_RMS/micron_RMS.

Edge sensor sensitivity, CCAT



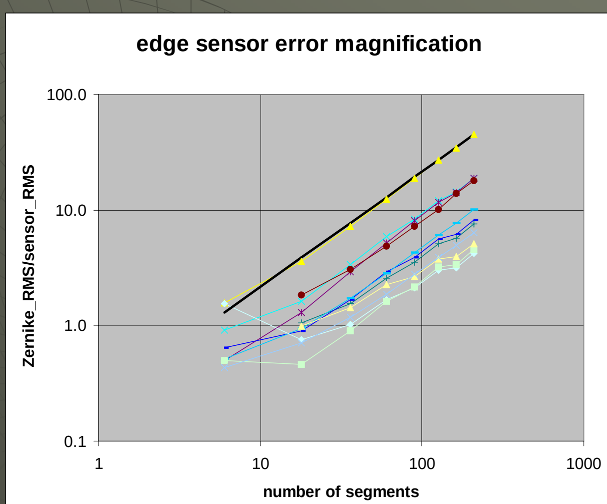
Sensitivity of edge sensors (red) and diahedral angle (blue) for a 162 pie segment surface. The diahedral sensitivity is in microradians_RMS/micron_RMS.

Distance & tip-tilt sensor sensitivity, CCAT



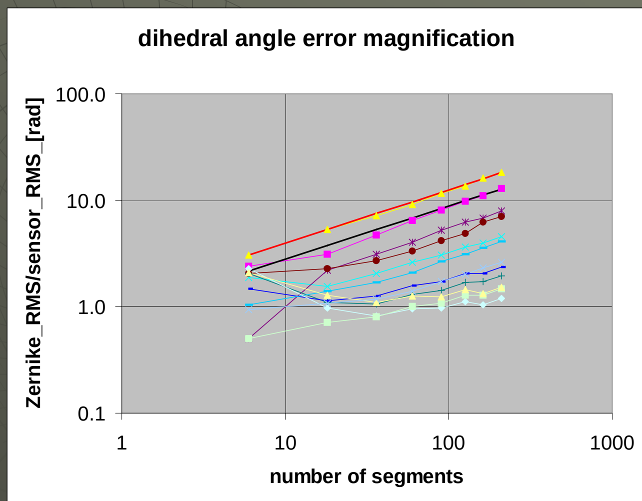
Sensitivity of distance sensors (red) and tip-tilt sensors (blue) for a 162 pie segment surface. The tip-tilt sensitivity is in microradians_RMS/micron_RMS.

Sensitivity vs. number of segments for low order Zernike modes



Mag ~ 0.2 N

Sensitivity vs. number of segments for low order Zernike modes



Mag ~ 1.3 $N^{1/2}$

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Error budget input parameters

- Panel design
  - dimensions: d, t, h, f
  - Materials
  - Fabrication errors for 1 m dia panel, typical value 1 micron
- Panel thermal environment
  - Change in average temperature
  - RMS air temperature over 1 m, $d^{1/2}$
  - Dome temperature
  - Insulation thickness
  - Thermal emissivity
  - Cold sky coverage
  - Boundary layer thickness
- Sensor configuration
  - Number of distance measuring devices and noise
  - Sensor noise
  - Number of panels (from panel dia)
  - (Panel errors feed into sensor errors)
- Misc. error sources
  - Panel location
  - Wind
  - Surface measurement map resolution
  - Vibration

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Typical thermal environment parameters

thermal surroundings	
average segment temperature [K]	273
temp. difference BUS to dome air [K]	5
foam thickness [m]	0.05
foam surface emissivity	1.00
effective air boundary thickness back [m]	0.05
thermal emissivity of back of segment	0.07
thermal emissivity of front of segment	0.07
effective air boundary thickness front [m]	0.05
fraction of cold sky seen by segments	0.50

CCAT 1/2 WFE from parameterized model				
segments	CFRP-Al-CFRP	Ni-Al-Ni	borosilicate	Aluminum
size, diagonal [m]	2.07	1.82	1.30	1.07
number of segments	147	190	370	542
areal density [km/m^2]	8.94	18.45	8.41	13.10
errors [microns]				
gravity	0.93	0.95	0.63	0.60
wind	0.16	0.32	0.48	0.29
thermal cupping	0.03	2.87	3.39	0.64
lateral Trms	1.68	1.39	0.11	0.63
manufacturing errors	4.26	3.29	1.69	4.61
aging	0.53	0.33	0.00	0.58
net segment error	4.71	4.70	3.87	4.78
primary figure maintence				
number of distance measurements	6	36	58	36
distance measuring error	1.00	1.00	1.00	1.00
surface error from edge sensors	10.32	3.80	4.89	4.46
surface error from angle sensors	3.48	10.46	14.91	6.78
net surface maintenance error	3.45	3.71	4.75	3.86
total primary 1/2WFE	**5.84**	**5.99**	**6.13**	**6.14**
other non-primary surface 1/2WFE				
primary support	4.91	4.72	4.50	4.46
secondary	3.49	3.49	3.49	3.49
tertiary	3.49	3.49	3.49	3.49
wavefront measurement	4.18	4.19	4.22	4.26
total other contrib. 1/2WFE	**8.12**	**8.0**	**7.90**	**7.90**
total telescope 1/2WFE	**10.00**	**10.00**	**10.00**	**10.00**

Feasible pointing error budget

Nonrepeatable Pointing and Tracking Errors			
	ALAM RFP template		CCAT
	day	night	
	[arcsec]	[arcsec]	[arcsec]
wind, steady component	0.20	0.45	0.04
wind, gusty component	0.10	0.10	0.02
structure temperature gradients	0.35	0.00	0.05
ambient temperature changes	0.20	0.00	0.05
inertial forces	0.15	0.15	0.10
encoder errors	0.20	0.20	0.10
servo error	0.10	0.10	0.10
bearing errors	0.20	0.20	0.05
other errors	0.19	0.19	0.05
Total RSS error	**0.60**	**0.60**	**0.20**

Risk assessment

- Large panels are the highest risk
  - Scaling processes to larger sizes
  - Achieving manufacturing tolerance
  - Thermal environment
  - Cost
  - Mitigation/Alternatives
    - Early prototype and full scale test production run
    - Smaller panels on CFRP sub-frames
- Active surface maintenance is a moderate risk
  - More complex than previous systems
  - Components must be much cheaper than previous systems
  - Mitigation/Alternatives
    - Accurate detailed simulation of the full system
    - Prototype large part of the system
    - Add more distance measuring devices
- Pointing accuracy is a moderate risk
  - Well beyond current performance for radio telescopes
  - Drive servo system is larger and more precise than existing systems
  - New sources of small pointing errors will be exposed
  - Mitigation/Alternatives
    - Optical offset guiding when possible
    - Fast tip-tilt corrector
    - Direct drive servo system

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Raft concept

- Risk mitigation
- Large CFRP sub-frames with many smaller panels
  - Better manufacturing and performance of small panels
  - Exploit excellent properties of CFRP
  - Fewer actuators
  - Panels have to be preset to high accuracy on sub-frames
  - Extra layer of structure
    - Weight
    - complexity

CCAT 1/2 WFE from parameterized model with rafts				
twice the panel manufacturing error				
segments	CFRP-Al-CFRP	Ni-Al-Ni	borosilicate	Aluminum
size, diagonal [m]	0.67	0.67	0.67	0.67
number of segments	1406	1406	1406	1406
areal density [km/m^2]	2.89	6.78	4.31	8.13
errors [microns]				
manufacturing errors	0.89	0.89	0.89	1.78
net segment error	0.95	1.05	1.80	1.86
sub-frames				
dia [m]	2.00	2.00	2.00	2.00
number of sub-frames	156	156	156	156
number of segments per sub-frames	9	9	9	9
areal density	16.20	16.20	16.20	16.20
errors [microns]				
gravity, including segment wt.	1.14	1.37	1.22	1.45
wind	0.09	0.37	0.37	0.37
Temp. change	0.00	0.00	0.00	0.00
thermal cupping	0.11	0.11	0.11	0.11
lateral Trms	0.01	0.01	0.01	0.01
adjuster temp & gravity	0.18	0.18	0.18	0.18
segment setting errors	1.20	1.20	1.20	1.20
aging	0.40	0.40	0.40	0.40
net subframe error	1.72	1.91	1.81	1.97
primary figure maintence				
number of distance measurements	6	6	6	6
net surface maintenance error	3.26	3.46	3.63	3.46
total primary 1/2WFE	3.80	4.09	4.44	4.39
total other contrib. 1/2WFE	8.08	8.08	8.08	8.08
total telescope 1/2WFE	8.93	9.05	9.22	9.20

CFRP Panel Study

Composite Mirror Applications
Tucson, AZ

CCAT

CMA Personnel Involved:
Robert Martin, Robert Romeo, Jeff Kingsley

CMA Profile

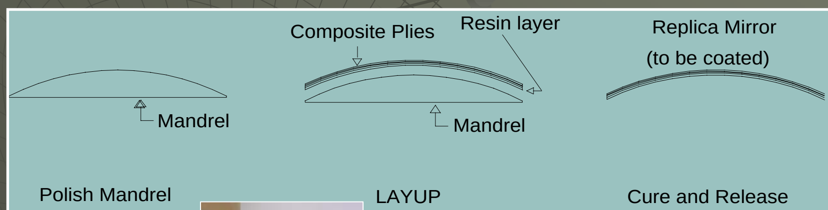
www.compositemirrors.com

- Composite Mirror Applications, Inc. (CMA) founded 1991
  - Design, prototype and manufacture custom lightweight optics
  - CFRP lightweight structures
  - Has developed and optimized processes for producing ultra-smooth, high precision lightweight mirrors
  - Applications in imaging, LIDAR, particle physics, astronomy
  - CMA is ***the*** industry leader in ultra-smooth, extremely lightweight precision composite reflectors.
- Previous CMA projects which are relevant to the CCAT Panel Study include
  - Secondary Mirrors for ALMA and APEX antennas
  - CFRP components for the ALMA and APEX chopping systems
  - CFRP/ Aluminum sandwich tertiary mirror for the SMTO
  - CFRP secondary mirrors for CBI dishes
  - CFRP 16" optical wave mirrors and OTA for ULTRA and NRL projects
  - 1 m CFRP optical wave mirrors and OTA for ULTRA (in construction)
  - 1.4 m CFRP optical wave mirrors and OTA for NRL (in construction)

Mirror Fabrication Surface Transfer

What are Composite Mirrors?

Carbon Fiber Reinforced Plastic Composite material Molded over an Optical Quality Mold



Scope of the CFRP Panel Study

Defined by contract from JPL to CMA:

- Review Technical specifications.
- Develop baseline panel design concept.
- Analyze concept performance under environmental loads.
- Optimize within rough boundary conditions supplied.
- Develop manufacturing plan.
- Critical risk assessment of all areas related to design & manufacture.
- Initial cost estimate and schedule.
- Recommend steps for further development and design of panels.
- Scope of work does not include detailed panel design nor a prototype.

Panel Requirements and Goals

- Optical specs defined by CCAT
  - 25m diameter, 3m central hole, f/0.6 primary.
  - 6 or 7 rings
  - Radial layout preferred
  - 3 point mount for panels
  - 5 µm rms surface under all loading conditions
  - “specular” surface on small scale
  - Panel gaps 5 mm or less
  - Panel areal density < 10 Kg/m^2
  - Panel cost < $10,000/$m^2$

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Feasibility of Approach

- Feasibility of meeting specs is proven by previous projects and current CMA development
  - Example 1: SMT panels 1.55m on side & 6 µm rms.
  - Example 2: Current CMA development of rigid 1.4m optical mirrors.
- Approach is of acceptable risk. Similar products have been field tested. Manufacturing technology is successful & cost effective.
- Challenge for CMA concept design is ***Value Engineering***. Our design process aims to
  - maximize performance
  - reduce cost
  - reduce overall weight

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Possible Panel Design Approaches

- All CFRP
  - Use for CMA Optical mirrors
  - Complex core structure
  - Stiff and stable
  - Costly in material & labor
  - Higher areal density
- Meniscus mirror bonded to stiff frame
  - Lightweight
  - Fairly labor intensive
  - Some further development worth considering
- CFRP face sheets and Aluminum honeycomb Core
  - Proven approach
  - Known costs

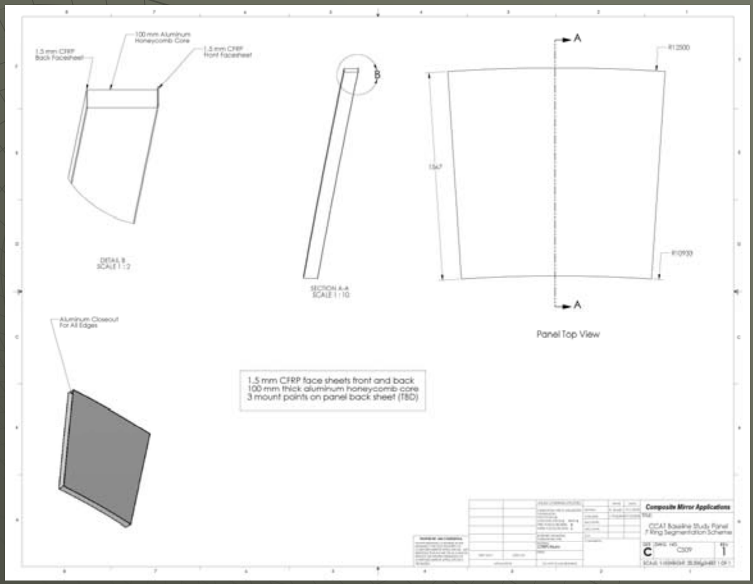
Baseline Panel Design

- Design:
  - Sandwich Panel construction
  - 1.5mm thick CFRP face sheets of high modulus fiber lay-up
  - Aluminum 5056 honeycomb core
  - 3 point mounting to backside
  - baseline panel is for 7-ring segmentation
    - 1.57 m radial side; < 1.5m in width
    - Good aspect ratio for panels
    - Tooling and handling less than 60” for all widths
  - Replication over glass mandrel

Composite Mirror Applications

Baseline Study Panel

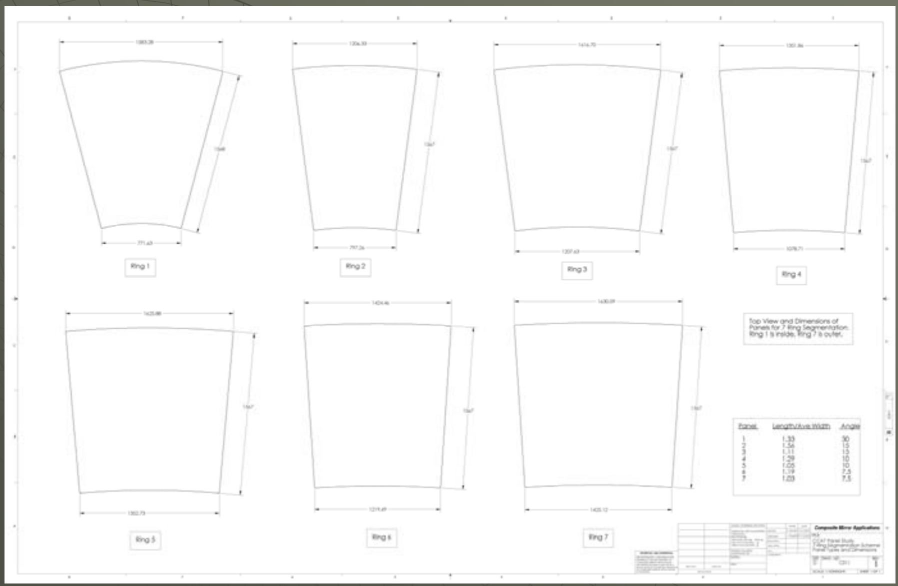
CCAT



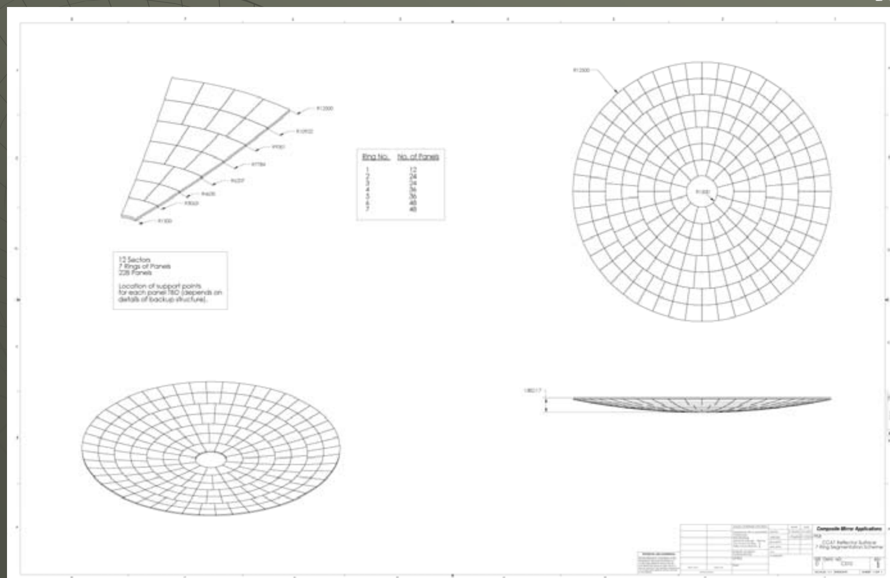
Composite Mirror Applications

Panel Set for 7-Ring Segmentation

CCAT



7-Ring Segmentation Scheme



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Analysis

- Analysis:
  - FEA study (using *Solidworks and Cosmos*)
    - Use material properties based on previous projects and supplier's specs.
    - optimize mounting locations and panel thickness
    - Evaluate for gravitational and wind loading
    - Thermal loading not in analysis (low CTE for CFRP)
  - Evaluated 6-ring segmentation and Hex panel shapes for comparison
  - Evaluated constraining panel at more than 3 points

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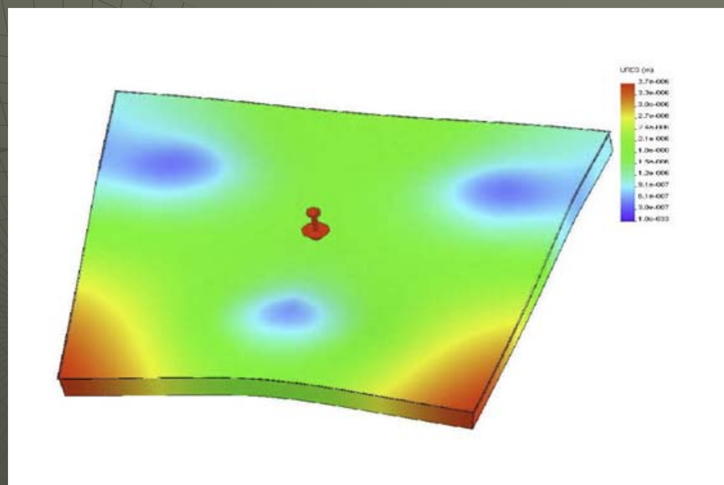
Panel Deformations under Gravity

6-ring Segmentation panel:

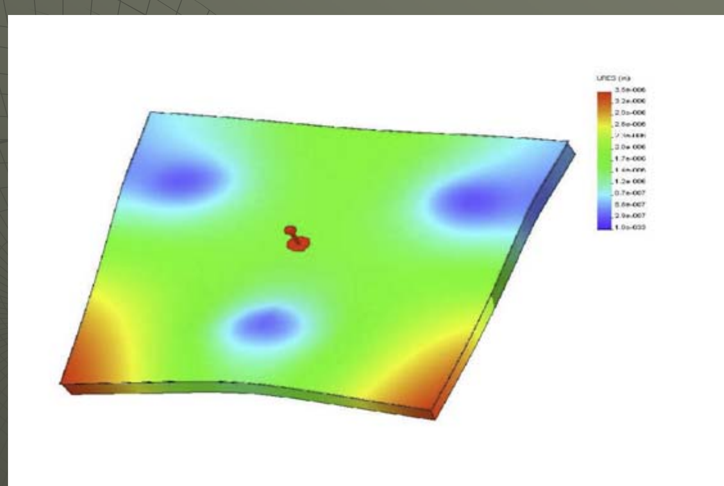
- 140 mm thick
- 1.83 m R side
- 9.8 Kg/m^2



Panel Deformations under Gravity

7-ring Segmentation panel:

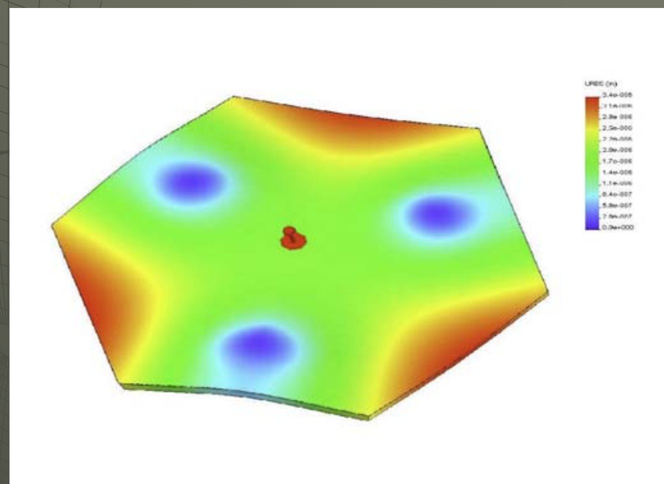
- 100 mm thick
- 1.57 m R side
- 8.3 Kg/m^2



Panel Deformations under Gravity

Hex Segmentation panel:

- 65 mm thick
- 1.67 m side-side
- 7.0 Kg/m²



Summary of Design Conclusions

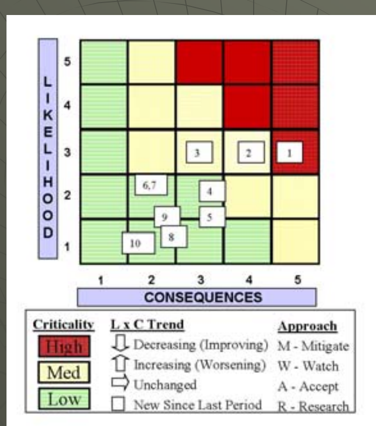
	6 ring trapezoidal	7 ring trapezoidal	Hexagonal
Number of panels	162	228	210
Areal density	9.8 Kg/m²	8.3 Kg/m²	7.0 Kg/m²
Total reflector mass	4740 Kg	4010 Kg	3390 Kg
Shape & aspect ratio	Worse	Acceptable	Good
Attachments *	Unnatural match to 3-point mount	Unnatural match to 3-point mount	Natural match to 3-point mount
Performance	Acceptable	Better	Better
Cost	Baseline + 20%	Baseline cost	Baseline – 10%

Panel Error Budget

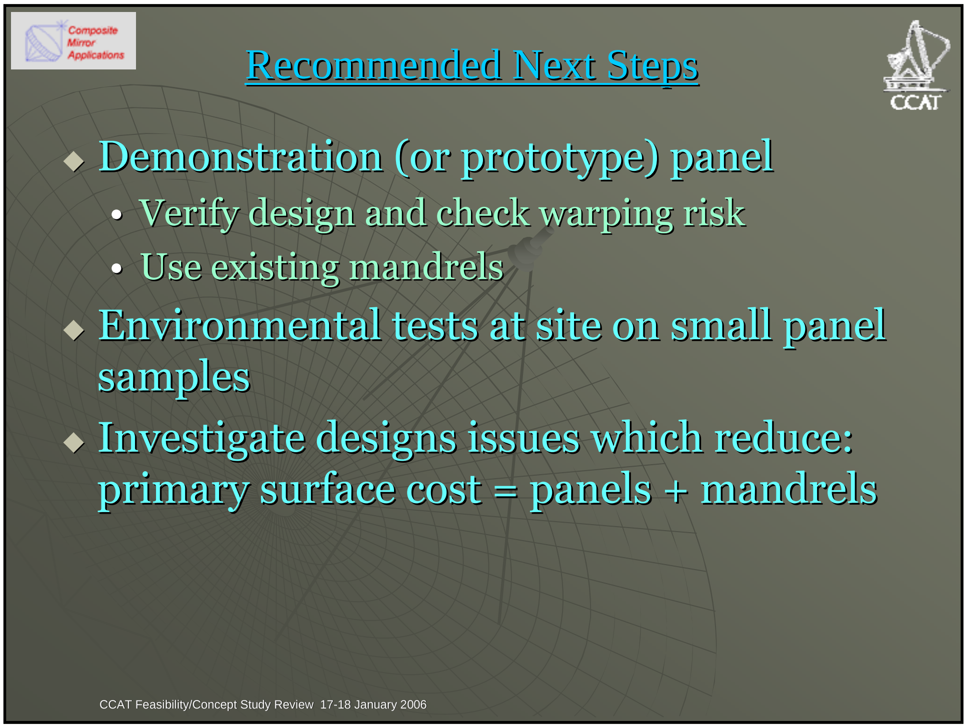
(for all panels, worse case)

Item	general panel rms (micron)	sub-aperture use rms (micron)
Mold	1	0.05
Replication	1.5 (TDC)	0.10
Gravitational	2	n/a
Wind (5 m/s)	1	n/a
Absolute T change	1	n/a
T gradient	0.5	0.2
Aging	0.5	0.3
Total (RSS)	3.1	0.38
CCAT current spec:	5	

Critical Risk Assessment



ID	Risk Description
1	Potential trapezoidal warp
2	Handling of glass mandrel
3	Durability of surface
4	Production schedule
5	Long term stability
6	Material availability
7	Shipping
8	Handling in field
9	Galvanic corrosion
10	CFRP/honeycomb core technology


Composite Mirror Applications
Recommended Next Steps
CCAT
Demonstration (or prototype) panel
Verify design and check warping risk
Use existing mandrels
Environmental tests at site on small panel samples
Investigate designs issues which reduce: primary surface cost = panels + mandrels
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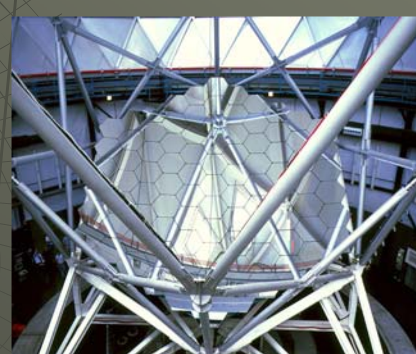
CCAT Panels
Corrugated Mirror Solution

CCAT

David Strafford,
R&D Manager
ITT

ITT Corporate Heritage

- Large segmented terrestrial telescopes
  - SALT, HET
    - Spherical primary mirror
    - 11.1 x 9.8 m
    - 91 1.0 m segments
    - ITT delivered:
      - PM segments + spares
      - Mounted, 1g corrected
  - KECK I & II
    - 10 m aspheric PM
    - 36 1.8 m segments
    - ITT final figured 81 PM segments

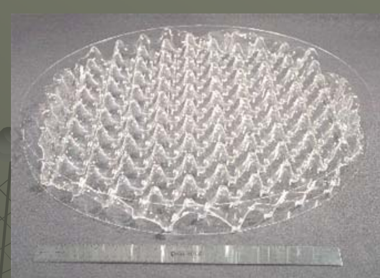


IIT Study Scope

- Primary Mirror Panel Manufacturing
  - Cost
  - Performance
    - Stiffness / 1 g sag
    - Thermal stability
    - Robustness
    - Segmentation
  - Manufacturability
    - Panels
      - material availability, design trades, process trades
    - Mandrels
      - process, metrology, material trades

ITT Corrugated Mirrors

- What are they?
  - Borosilicate glass
  - Stable, no hysteresis, no outgassing, no cure



- Formed core
- Fused facesheets

ITT Corrugated Mirrors

- Strong
  - 4.7 Kg/m^2 mirror
  - 72 Kg load

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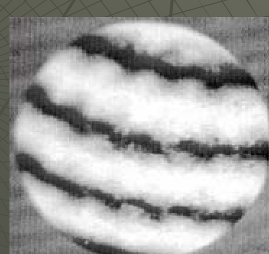
Visible Systems: 60 nm Mirror in 5 Days

Quality: 58 nm RMS / 310 nm P-V

Specs: <10 kg/m², 150mm diam, plano surface, borosilicate

Replicated surface ± 2um – minimal post processing

Ready for ion figuring



Sheet stock → Corrugate core → Fuse assembly → Replicate surface → Grind / Polish (for visible systems) → Final figure (for visible systems)

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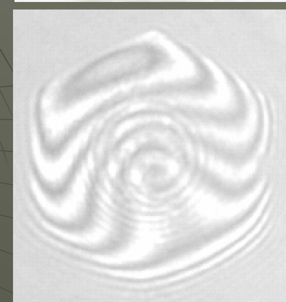
ITT Corrugated Mirrors

- Replicated
  - Geometry
    - 235 mm hexagonal part
    - 20 mm thick borosilicate glass
    - Replicated 5 m radius sphere
  - Figure:
    - <1.5 µm P-V surface error
    - Interferogram shown is at normal incidence, 632.8 nm wavelength



Rings are an interferometer artifact

Panel Requirements

- Materials and properties
  - Specific stiffness and areal density
  - Panel gravity deflection
  - Replication
  - CTE and thermal conductivity
  - Reflectivity and coatings
- Panel front surface requirements
  - RMS figure accuracy
  - Peak to valley
  - Surface roughness

Key Design Parameters

- Panel design parameters
  - Glass thickness
    - Robustness
    - Use existing LCD glass industry base
  - Corrugation spacing
    - Robustness
    - 3 vs 5 layer
  - Panel depth
    - 1 g sag
    - Manufacturability

Panel Design

- Specific stiffness and areal density
  - Trade
    - Glass thickness, corrugation spacing, panel depth
  - Changes
    - 1 g sag, robustness, manufacturability
- Point design – 1.8 m panels
  - 2 mm thick glass
  - ~85 mm deep panel
  - ~75 mm corrugation spacing
- 2 μm RMS gravity sag on 3 points
- Acceptable robustness, manufacturability

Panel Thermal Design

- CTE and thermal conductivity
  - First order analysis, recommend FEA
  - Thermal flow
    - Panels lose heat by radiating into the sky and dome
    - Panels gain heat from radiation from the ground
    - Heat moves within the panel by
      - Conduction (very inefficient)
      - Convection (efficient)
      - Radiation (efficient)
    - Convection to environment would decrease gradients
  - Full model shows 17 µm P-V / 3.5 µm RMS sag
  - Can be corrected by measuring temperatures or by insulating the back of the PM
  - 60% correction meets specification

Panel Design

- Reflectivity and coatings
  - SiO_2 protected aluminum
    - 95^{+}% reflectivity
    - 250µm to 3mm wavelengths
  - Borosilicate glass can be coated and stripped without surface degradation

Panel Design

- Panel front surface requirements
  - Error budget – total 5 µm RMS
    - Metrology – 2 µm RMS
      - OAGM <1 µm RMS accuracy
    - Surface error – 3.5 µm RMS
      - Mandrel as generated 2 µm RMS, grinding improves at small marginal cost increase
      - Replication demonstrated to 0.3 µm RMS in small scale
      - Balance scale-up
    - Gravity sag – 2 µm RMS
      - Designs meet this requirement
    - Thermal – 1.5 µm RMS
      - Panels meet this requirement with correction
    - Contingency – 1.5 µm RMS

Panel Front Surface Requirements

- Replicated panels will meet requirements
  - Roughness
    - 25-30 nm requirement (increases cost)
    - 1-2 nm demonstrated
  - RMS figure accuracy
    - 5 µm RMS total
    - 3.5 µm RMS allocated to the surface
      - 2 µm RMS mandrel - easy to fabricate
      - 2.75 µm RMS allocated replication
      - 0.3 µm RMS replication demonstrated in small scale, scale up risk should be addressed in follow-on work
  - Peak to valley
    - 15 µm P-V requirement, 1.5 µm P-V demonstrated
      - Scale-up to size, light weight must be demonstrated

Critical Risks Assessment

- Scale up to larger sizes
  - Glass material availability
    - Design for existing glass product lines
    - Some sizes require a custom glass run
  - Mandrel material availability
    - Demonstrate alternate, lower cost mandrel materials
  - Release from the mandrel
    - Size
    - Change in roughness requirements

Recommended next steps

- Additional analysis, design
  - Full panel design
    - Finalized segmentation, FEA (mechanical, thermal), mount locations, edge sensors, drawings, tooling quotes
- Subscale testing
  - 0.25 – 0.5 m solid parts
    - Verifies mandrel materials, assembly
    - Confirms release, surface figure and roughness
- Large scale demonstration
  - >1 m lightweight
    - Demonstrates full system
    - Lower NRE than full size demo piece
    - Confirms figure, roughness, release, scaling

Telescope Calibration & Alignment
or
Wavefront Sensing

Gene Serabyn

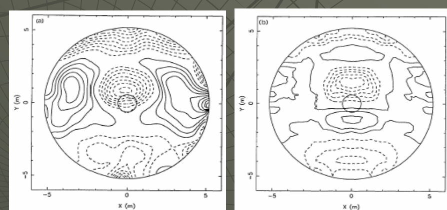
JPL

Profile

- Gene Serabyn
  - JPL
    - Senior Research Scientist 3/1998 –
    - Infrared interferometry, nulling, coronagraphy
  - Caltech
    - Visiting Associate 1/1987 –
    - Sub-millimeter wavefront sensing, spectroscopy, imaging

Scope

- Submillimeter Wavefront Sensing System
  - To optimize the telescope's main beam efficiency,
    - Need detailed knowledge of the telescope surface shape.
  - Metrology can hold a given shape,
    - but need to know what the shape is.
  - Mechanical models need to be calibrated.



  - Goal: Measure the wavefront reflected by the telescope, somewhere in the telescope's observing passband
  - Scope: Proof-of-concept design that meets the accuracy requirement

Scope

- Use of large-format submm arrays is assumed
  - Opens the door to "optical" techniques
- Wavefront quality (pupil plane) and image quality (focal plane) are Fourier conjugates
  - Not a vital trade at this point
- Proven CSO approach used as a sanity check
  - Previously, accuracy of 9 μm achieved

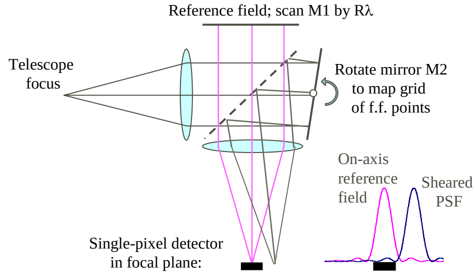
Requirements for Subsystem

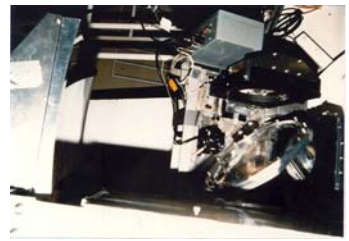
- Wavefront map of the combined primary/secondary reflector surfaces
  - Accuracy – small contributor to the error budget
    - a few (1-3) μm
  - Lateral resolution
    - – lo-res (gravitational flexure; ≈1 point per panel)
      - 16×16
    - – goal (panel shapes)
      - 32×32 to 48×48 pixels
  - Time resolution – small elevation angle range
    - 5-10° (under an hour)
  - Measurement interval – access “every few months”
    - (translates to source availability; number and flux)
  - Measurement wavelength – use a facility “submm” camera
    - 0.3 to 3 mm

Key Design Issues and Parameters

- Accuracy goal is a factor of 3 beyond current systems
- Small number of appropriate astronomical sources
- Examine:
  - Ultimate measurement accuracy
    - Dependence on source flux and thermal background noise
  - Optimal measurement wavelength

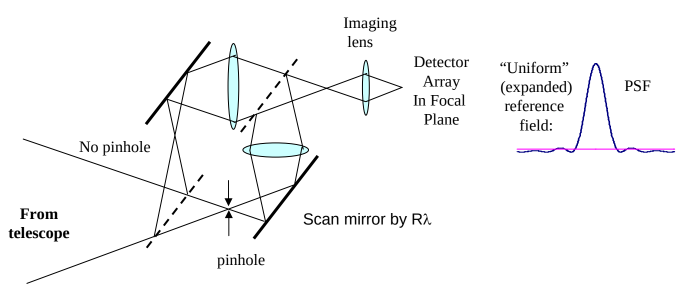
System Design: Option 1





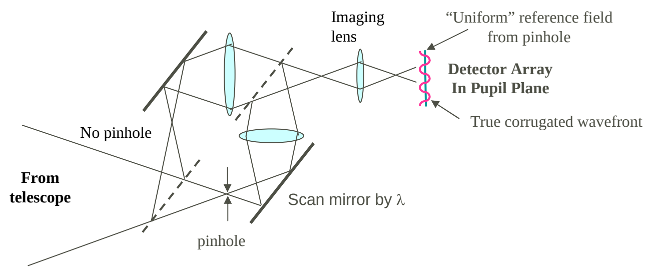
- Shearing interferometer: focal plane sensing with single pixel detector
- Proven at CSO:
  - 9 μm accuracy
  - 15×15 and 21×21 maps made
  - few hour measurement timescale achieved
- Can be improved significantly in terms of efficiency
- Point-by-point approach will always introduce systematic errors

System Design: Option 2



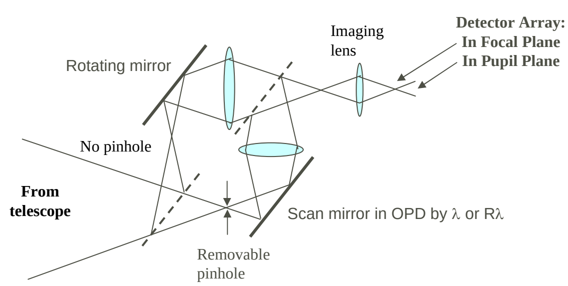
- Focal-plane Point Diffraction Interferometer
- Spreads out the energy of the reference beam
- Makes use of array detectors to instantaneously sense full focal plane field
- Lower instantaneous SNR per point
- Gains in the areas of stability and systematics

System Design: Option 3



- Pupil-plane Point Diffraction Interferometer
- Switch to pupil-plane sensing in this approach, as in the optical
- Only need to scan one mirror by 1-λ

System Design: Hybrid Option



Hybrid Interferometer: focal-plane and/or pupil-plane sensing

Supporting Analysis I

- FOV large:
  - $32F\lambda \approx 300\ \lambda \approx 0.1 – 1.0$ m
- Mirrors large:
  - Of order 1-2 m if long wavelengths are included

Supporting Analysis II

- Ultimate sensitivity of submm wavefront sensors depends on:
  - Phase measurement accuracy in the presence of long-λ background noise
- Start with pupil plane measurement case:
  - Phase accuracy: $\phi = 1/SNR = sqrt(N_{background})/N_{signal}$
  - Signal:
    - Source flux per subaperture
      - (only Mars, Uranus, Neptune are small and bright enough)
    - Atmospheric and instrumental transmission (T)
  - Noise:
    - Number of background modes transmitted by cold stop
    - Bose-Einstein statistics: $\Delta n = sqrt(n(n+1))$

Supporting Analysis III

- End with:
  - $\Delta x \approx \lambda/(100T\sqrt{t})$
  - Approximately proportional to λ
    - (Both signal and noise vary with λ differently)
    - Short wavelengths have higher accuracy (assuming reasonable atmospheric transmission)
  - Calculate time to reach 3-σ sensitivity of 3 μm (in a sq. m).
    - Assume $T_{inst} \approx 0.1$ (largely the pinhole)
    - Assume $T_{atm}(350) = 0.7$; $T_{atm}(1300) = 0.97$

λ (μm)	Time (sec)
350	25
1300	240

Critical Risk Assessment

- Fifteen years ago, the CSO shearing interferometry approach reached an accuracy of 9 μm with a less than optimized system.
- To reach better sensitivities, the choice is:
  - Improve a known technique, or try a new approach
- The hybrid system described allows both
- The new approaches can be tried at existing telescopes before CCAT (if funding is available)
- Theoretical sensitivity limits are quite good.
  - Feel confident that a factor of 3 can be gained.
- The main fundamental problem is thus the limited number of sources which are bright enough and small enough (< λ/D).
- Next phase concerns are then instrument-definition related: detailed throughput, sensitivity and aberration analyses, a diffraction analysis of the pupil plane approach,

Laser Metrology for Segmented Telescopes

Feng Zhao, Tom Cwik
Shanti Rao
Jet Propulsion Laboratory

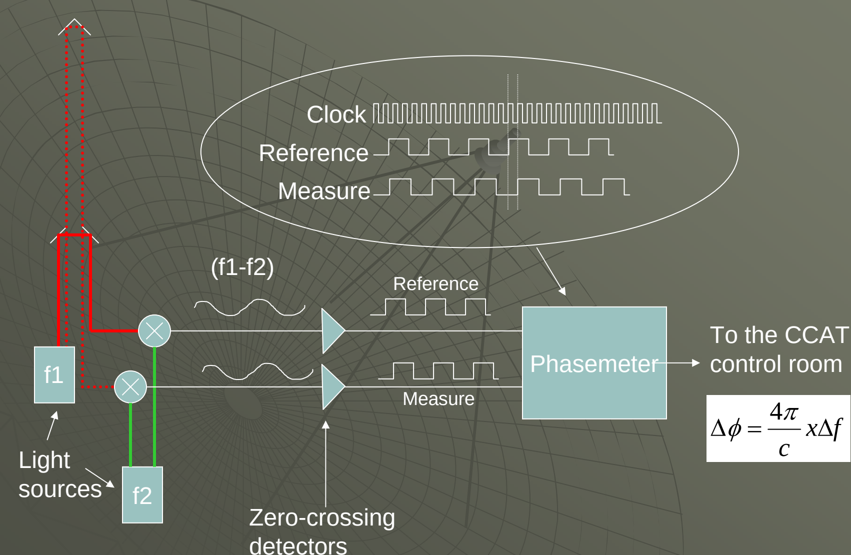
Laser Metrology at JPL

- Metrology enables
  - Stellar interferometry
    - Space Interferometry Mission
    - 10^{-12} m resolution, ~2 m range
- New designs
  - For next-generation segmented telescopes
    - Terrestrial Planet Finder
    - SAFIR, SMLS, …
    - CCAT
  - Absolute distance measurement

Faster, Better, and Cheaper Metrology

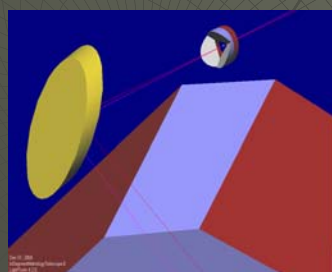
- Working prototypes
  - Hardware
    - Optics, mounts, electronics
  - Procedures
    - Assembly, alignment, calibration
- CCAT
  - Cost estimates and risk assessment
  - Integration
    - Software, implementation plan, manufacturing approaches

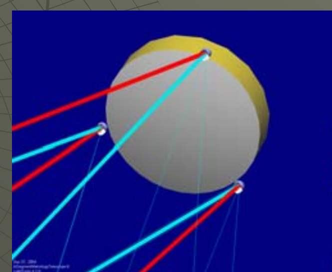
Relative Distance Measurement



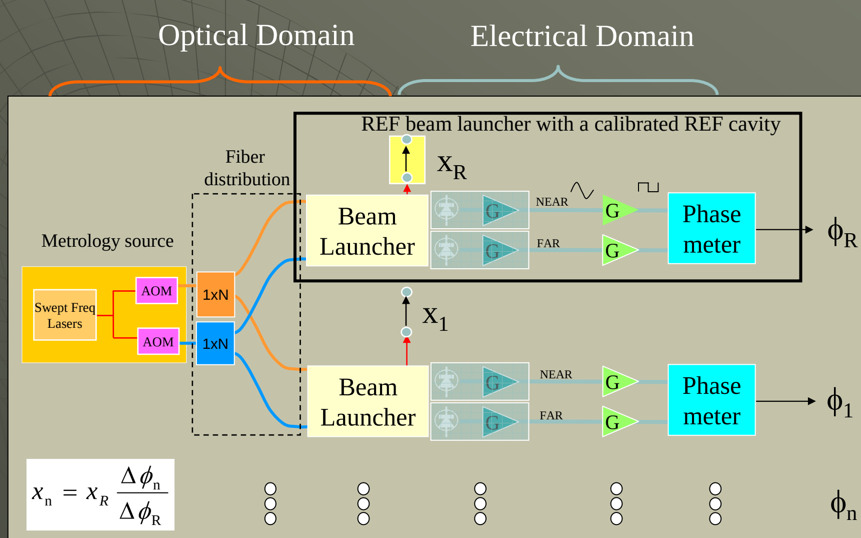
CoPHI for Accurate Differential Displacement

- Common Path Heterodyne Interferometer
  - Two concentric beams
    - "Near" reference point – outside, at the primary
    - "Far" reference point – inside, at the secondary
  - Drill a hole in a corner cube on the primary mirror
  - Reflect off a corner cube on the secondary mirror



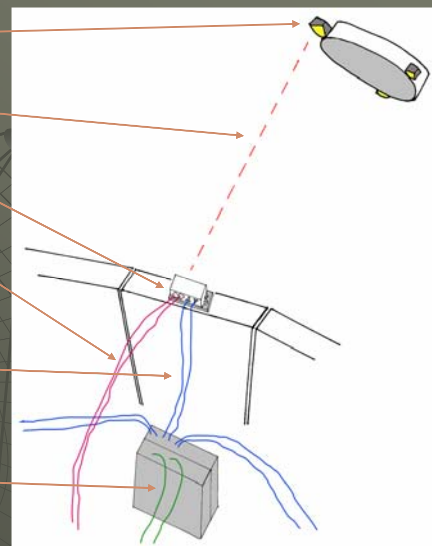


Swept Frequency Laser for Absolute Distance



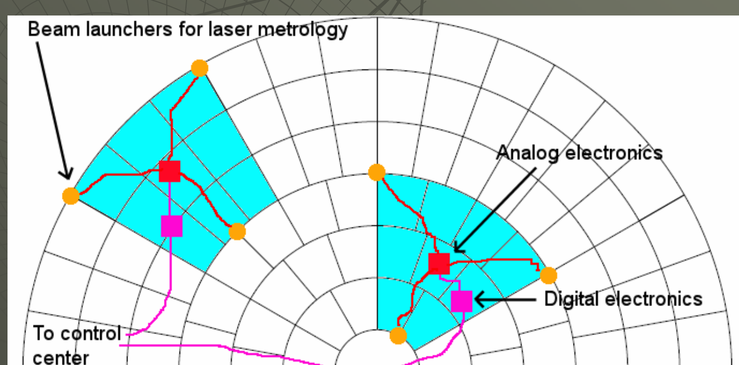
Concept Design

- Three corner cubes attach to the secondary mirror.
- The collimated visible beam doesn't interfere with astronomy.
- Beam launchers attach to the primary mirror segments.
- Each beam launcher needs two fiber optic cables. Light comes from a laser in the control room.
- Photodiodes are powered by low-power phasemeter boxes throughout the telescope truss.
- Minimal cabling connects the phasemeter boxes with the control room.



Concept Deployment

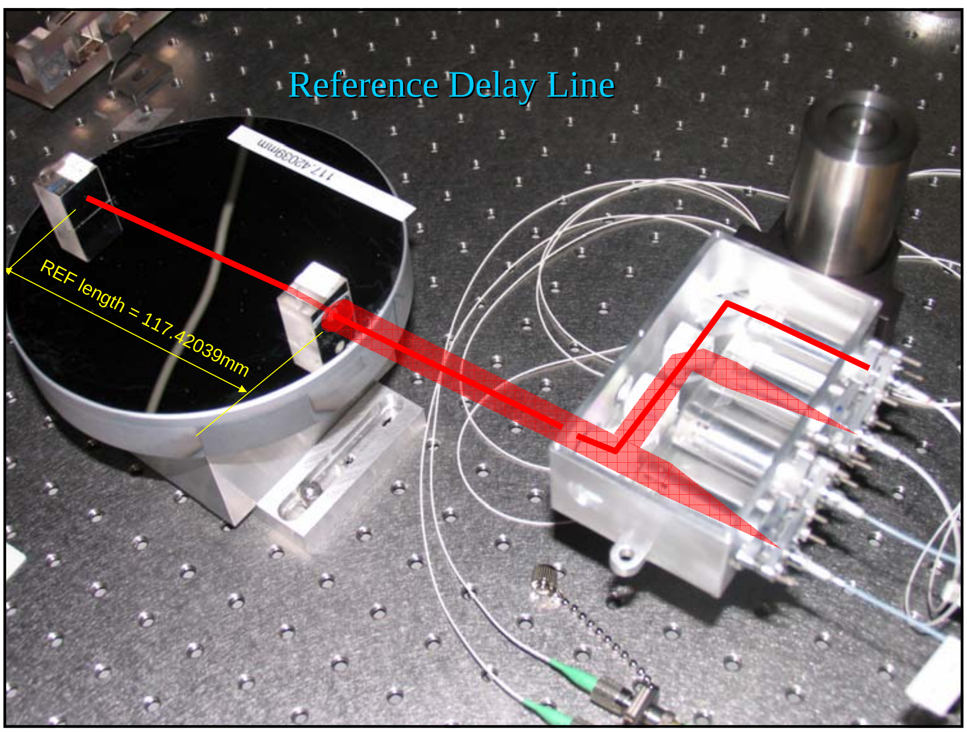
- How many beams?
  - Probably between 6 and 120

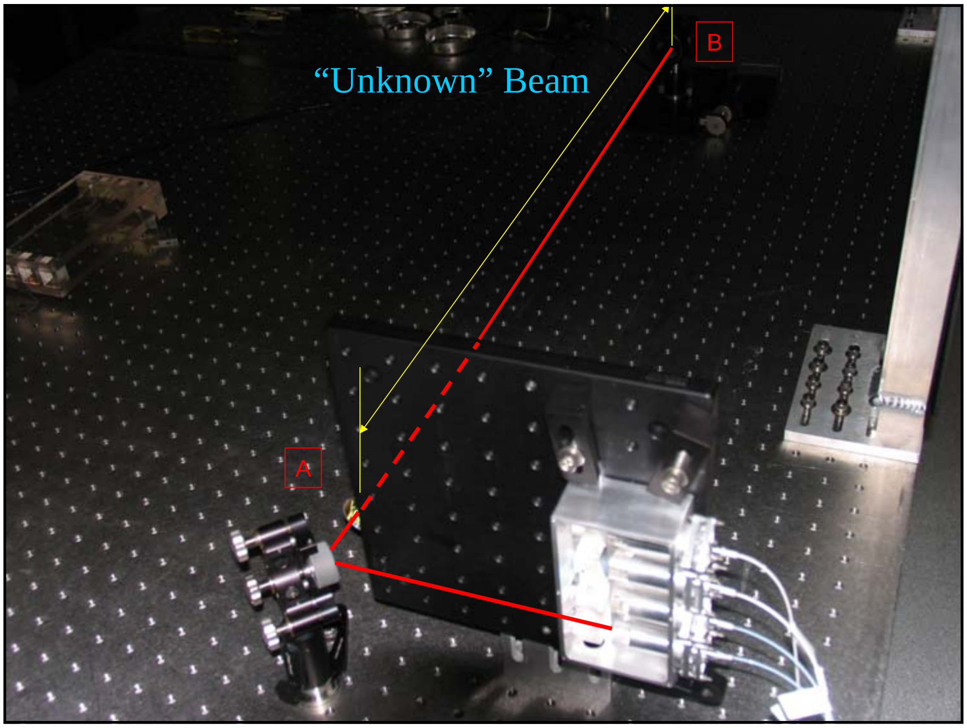


Key Tradeoffs

- How many beam launchers?
  - Trade with edge sensors.
- Beam launcher manufacturing
  - Assembly is difficult. Can JPL teach CCAT how to do it?
- Beam launcher pointing
  - Toleranced interface plates or adjustable fold mirrors?

Reference Delay Line

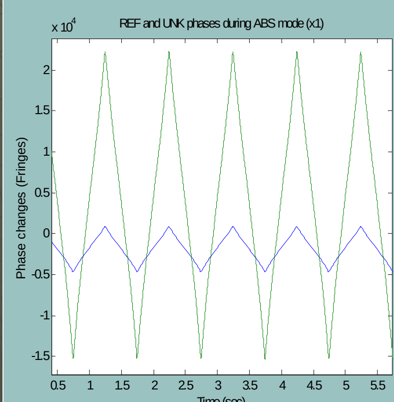




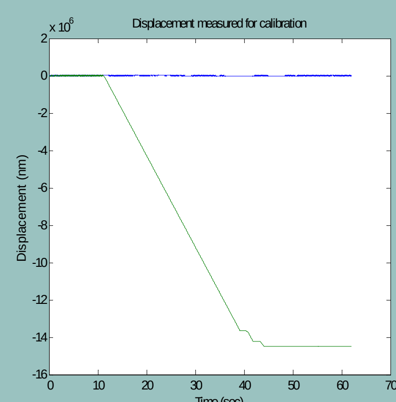
Phase Measurement

CCAT

Absolute Mode



Relative Mode



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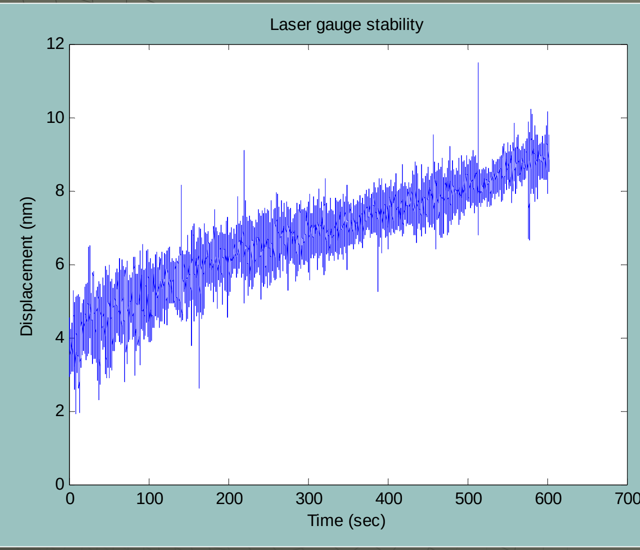
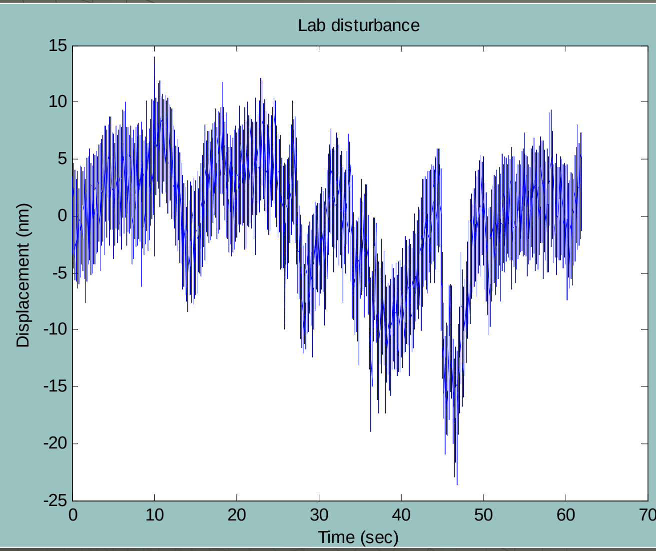
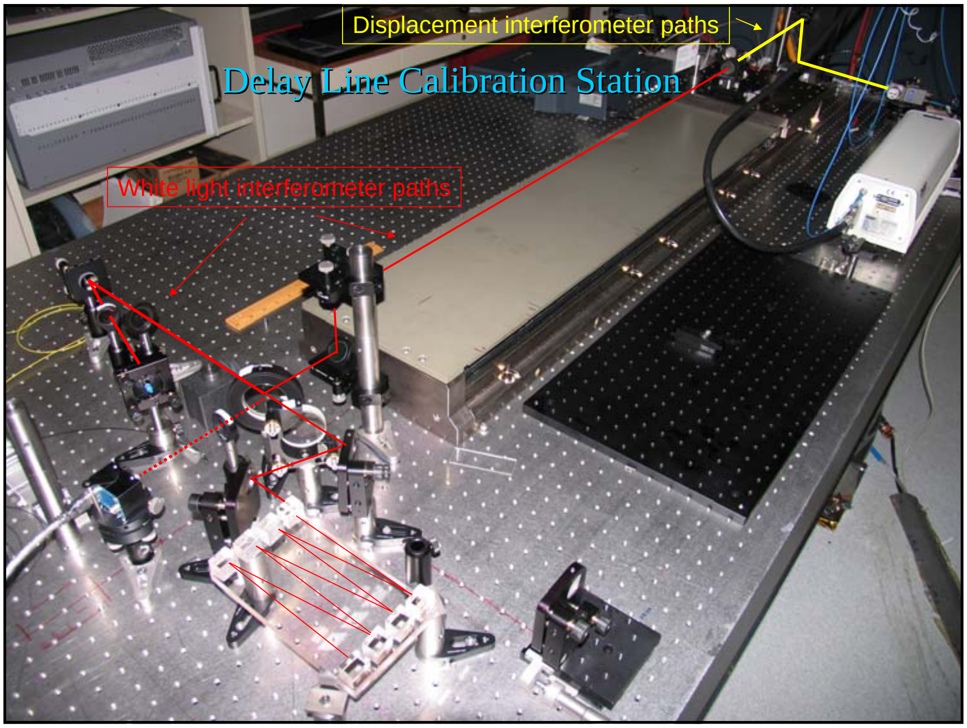
Background Noise



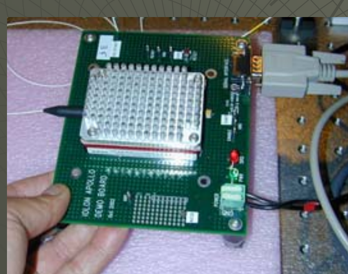
Background Noise (linear fit subtracted)





R&D Progress

- Working testbed.
  - 10^{-7}m resolution.
- External cavity controlled laser.



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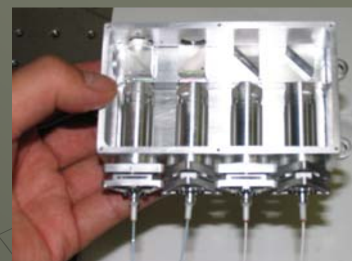
R&D Progress

- Beam launchers
  - Fiber-fed
  - COTS optics
  - Thermally stable mounts and housing
- Detector circuits
  - Line noise filters
  - Automatic gain control

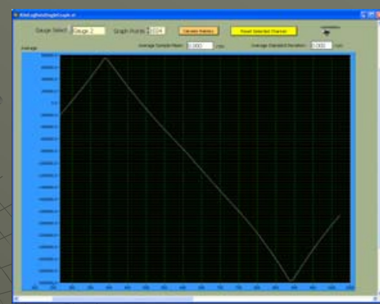


R&D Progress

- Phasemeter
  - Re-implement SIM algorithms in low-cost FPGAs.
  - Communicate via ethernet.
- Reference cavity
  - Calibrated with white light to 10^{-6}.

R&D Progress

- Software
  - LabView panels track a phasemeter as the laser frequency sweeps
  - Wrote C code for listening to next-generation ethernet-based phasemeters



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Moderate Risks

- Thermal stability
  - Needs further study
- Beam launcher assembly
  - Need more practice
- Software development
  - Integration into the CCAT servos
- Calibration
  - Define calibration requirements
- Air turbulence?

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Hartmann Type Segment Position Sensing

Concept Provided by Alan Wirth

Adaptive Optics Associates

Cambridge, MA

General Approach

- Based On Hartmann Type Sensing of Panel Tilt Angles
- Similar to System Provided to SALT
- Additional References Available in SPIE Vol 5489, p.892, 2004

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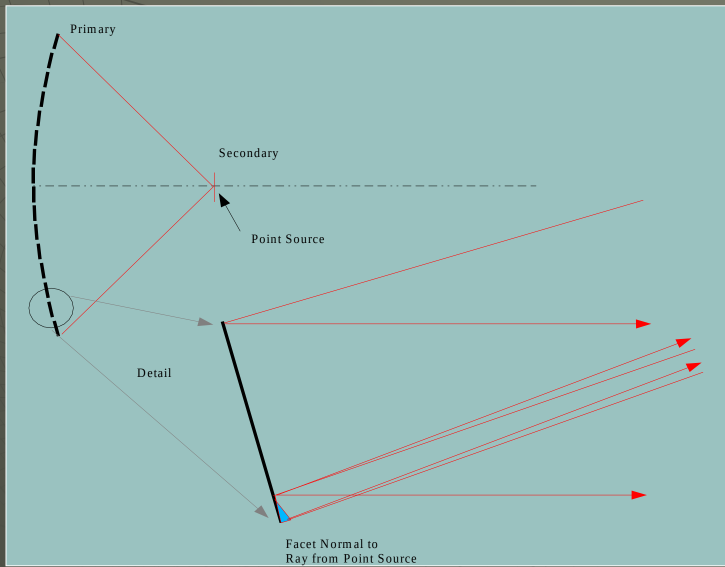
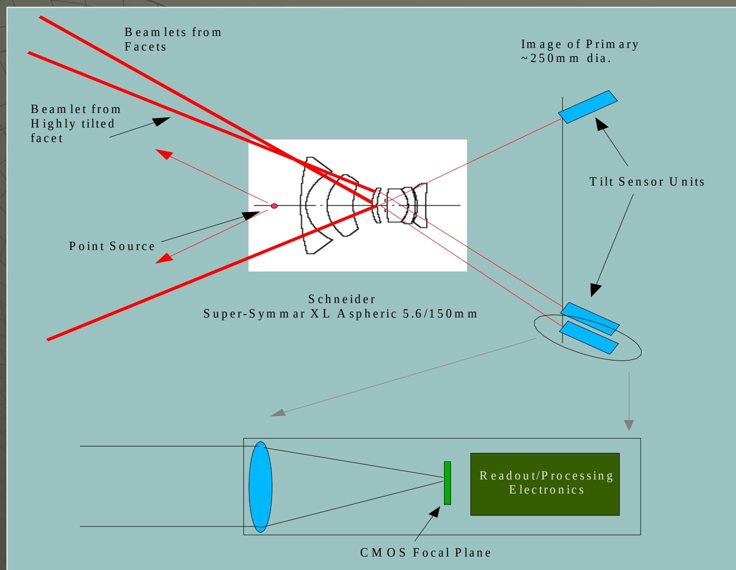
General Configuration



General Precepts

- Point Source Near or at Center of M2
- Small "Facet" Mirrors Attached to Segments
- Facets Aligned to Provide Returns from Point Source to Sensor
- Facets Adjusted When Panels are Aligned and Then Fixed

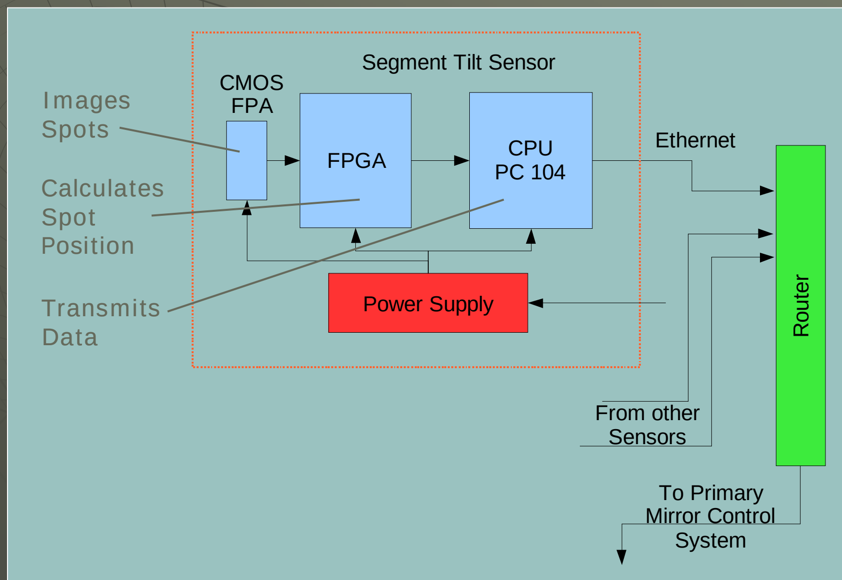
Sensor Configuration Concept



Initial Analysis

- Tilt Sensitivity: Noise <1 µrad
- Areal Fill of Facets 1/40,000: High Brightness LED Provides Sufficient Illumination
- SNR >50:1 for Anticipated Detector Noise & Integration Time

Detector Electronics



Summary

- Relatively Simple and Low Risk
- Access to Center and Region Behind M2 a Question
  - Standing Wave Issue Needs Consideration
- Additional Design/Analysis Required
- Total System Cost ~$1 Million…Could be an Excellent Value

Wavefront Sensing Guider

James Lloyd
Cornell University

Scope

- Guiding is ubiquitous with optical telescopes
- CCAT large aperture and short wavelength may require active guiding
- CCAT mirrors may be reflective in the O/IR
- What are the options for "optical" guiding with CCAT if required/desired?

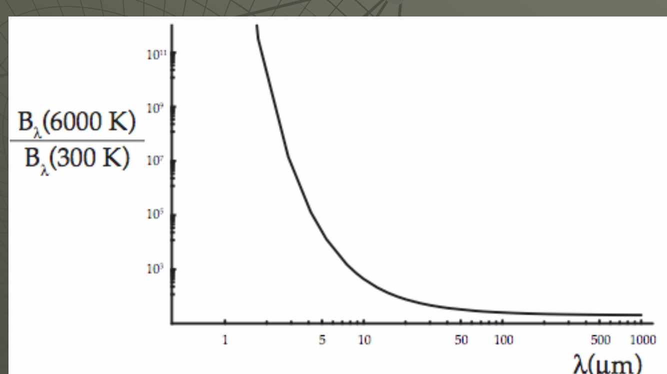
Edwin Hubble guiding the Mt Wilson 100" telescope

Requirements

- Guidestars within field of view
- Sensitivity to guide at 0.1-20 Hz
- Goal to guide in common mode with science starlight, avoiding additional non-common path concerns of a side-mounted guide telescope

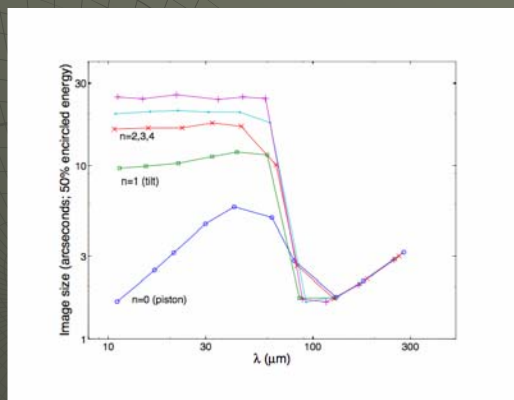
Key Design Issues

- Sensitivity requires λ<2.5 μm, for bright stars and dark sky



Key Design Issues II

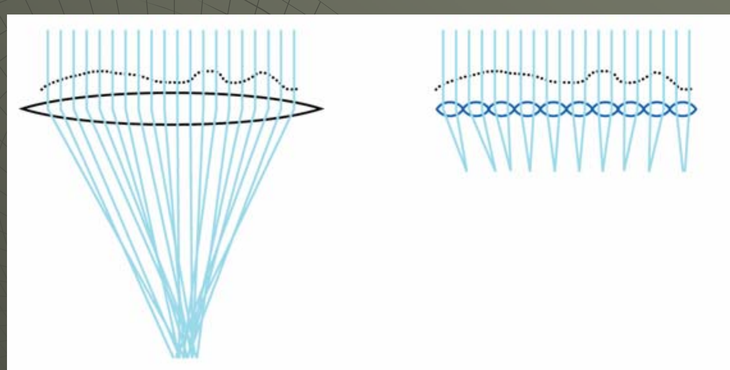
- PSF quality at short wavelengths



5 μm RMS segment aberration calculation by J. Zmuidzinas

System Design

- Consider subapertures on the primary



Sufficiently small subapertures will have low enough WFE for a compact PSF

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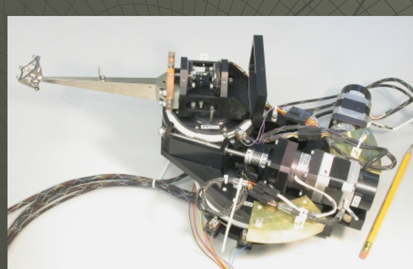
System Design

- For subapertures small enough for a good PSF and large enough to avoid excessive diffraction, guiding signal (global tilt) is recovered without significant SNR penalty by averaging
- Can be considered as a parallel set of small guide telescopes, each using only a small piece of the optics
- Additional benefit is wavefront sensing
- Coarse alignment will require additional modes (e.g. Curvature/Phase Diversity) to sense segment edge discontinuities, as used for Keck mirror alignment, which can be implemented in same guider

System Design

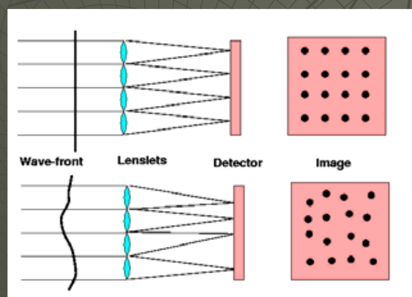
- Similar conclusions reached with optical telescopes, e.g. Gemini, TMT employ full time wavefront sensing guiders



Gemini Flamingos-2 OIWFS (NRC/HIA)

Shack-Hartmann Wavefront Sensing

- Most common form of wavefront sensing in Adaptive Optics; also used in optical metrology



Risk Assessment

- Requires specular reflectivity at short wavelengths
- FPA and optics technology is mature and available
- May require additional spec on small scale wavefront error (e.g. $<1\ \mu m$ RMS on scales $< 30cm$)
- May require additional maintenance of mirror surfaces
- Mitigates risks of mirror alignment and maintenance

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Conclusion

- Wavefront sensing/guiding can be implemented at λ~2 μm
- There is a very large advantage in SNR available from astronomical objects by going to these wavelengths
- If the choice of panel technology supports these wavelengths, then an IR wavefront sensor can be a solution to initial calibration and maintenance of segment and telescope alignment

M2 & M3 Positioning Systems

Mike Cash
CSA Engineering, Inc.
mfc@csaengineering.com

Introduction to CSA Engineering

An Employee–Owned Company

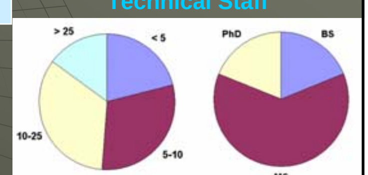
Founded in 1982 around core competencies in structural dynamics and vibration

Engineering services, R&D and custom products for
Vibration suppression
Precision motion control

Application Areas

Launch vehicles
Ground test systems
Spacecraft
Directed energy
Optics
Aerospace structures
Semiconductor equipment
Medical, automotive, etc.

Technical Staff



50 employees

Hexapods for Motion and Vibration Control

Functions: precision positioning, vibration isolation or motion simulation

Actuation: piezoelectric, electromagnetic, and motor-driven screws

Electronics and control: customized interfaces to user specifications

Scope of Work

- M2 Positioner Concept Design ("Baseline")
- M2 Integrated Positioner Concept Design
  - Positioner, Alignment System, and Nutation all in one system
- M3 Positioner Concept Design
  - Relative mirror alignment
    - Likely passive, one-time adjustment
    - Gravitational load constant
  - Beam direction to Naysmyth/Cassegrain foci
    - Active motion to any of four locations
- Investigation & Optimization of Hexapod Geometry for Best Resolution
- Reactionless Gimbal Support Design

Requirements for M2 Positioner

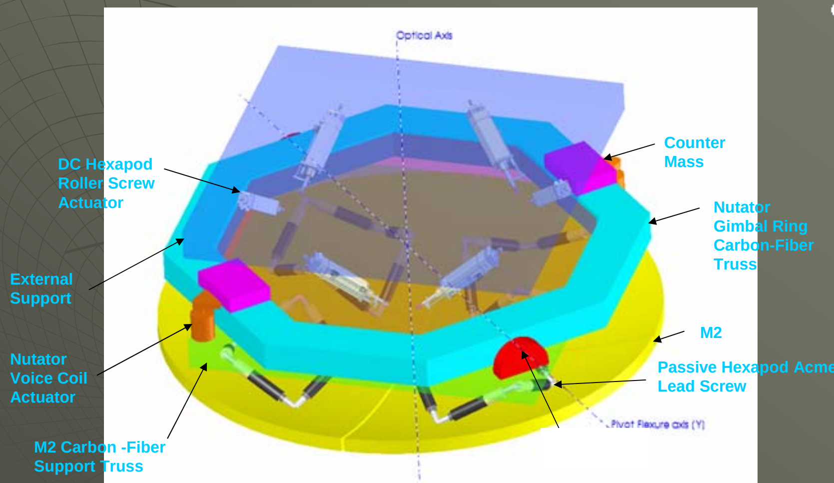
	Range	Precision	Speed
Focus	± 20 mm	18 µm	300 µm s^{-1}
Translation	± 10 mm	65 µm	150 µm s^{-1}
Tilt	± 0.5°	4.85 µrad	15°/hr

- 80kg mirror, Ø3.3m, 4 segments, "X" configuration
- +/-2.5 arcmin nutation @ 1 Hz; 100ms transitions
- Gravitational loading changes

Key Design Issues & Parameters

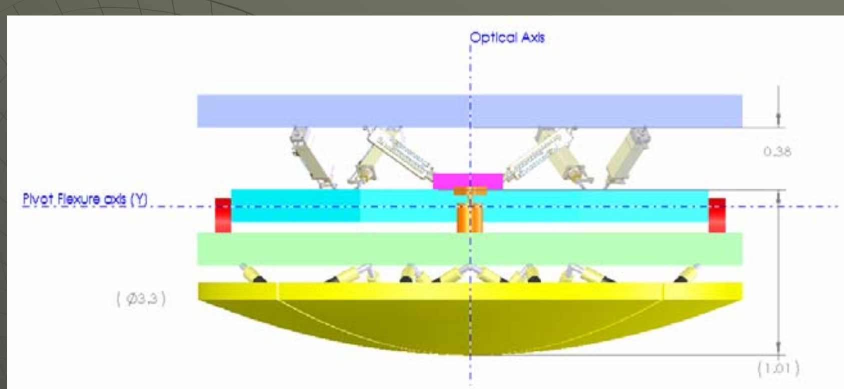
- Actuator Type & Resolution
- Geometry/Nodal Positions
- Reactionless Design
- Passive Alignment of 4 Segments
- Nutation Actuators
- Athermal or Zero-CTE Design

Baseline M2 Positioner Design



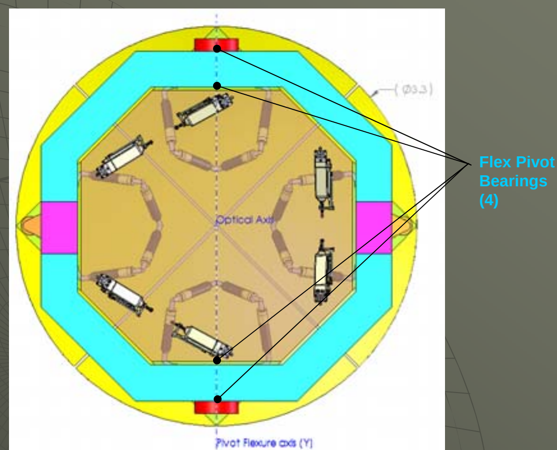
- Low bandwidth positioning hexapod (sub-Hertz) w/ roller screw actuators
- Nutation achieved with voice coil actuators (2 per nutation axis)

Baseline M2 Positioner Design – Side View



- Passive hexapods used for initial alignment of each mirror segment
- Reactionless design using gimbal ring (1 axis shown, 2 axis possible)

Baseline M2 Positioner – Top View



Baseline M2 Positioner: Estimated Resolution

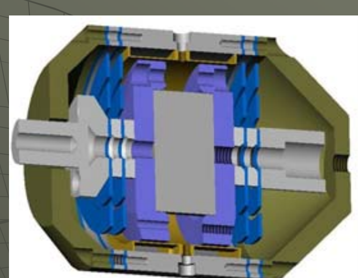
Axes – Resolution Spec µm / µrad	Average Resolution µm or µrad	Standard Deviation µm or µrad	Maximum Step µm or µrad
X - 65.0	65.0	1.66	67.6
Y - 65.0	65.0	1.86	69.4
Z - 18.0	18.0	1.36	18.6
Ox - 4.85	4.84	0.567	7.29
Oy - 4.85	4.84	1.26	8.41
Oz - N/A	9.60	2.84	11.7

- Assumes 3-micrometer resolution actuators and a commanded step equal to the resolution specification
- 40 simulated moves using MATLAB
- 80mm stroke roller screw actuators
- 1 µrad is approximately 0.2 arcseconds

Baseline M2 Positioner: Alignment Hexapod

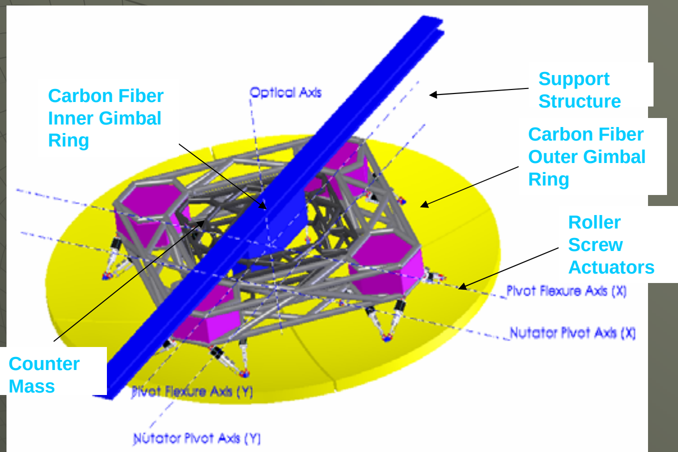
- ACME lead screw struts are manually adjusted
- 20 TPI effective pitch
- Up to 1.3 micron resolution
- 8.3 kg
- Flexure kinematic joints

Baseline M2 Positioner: Nutation



- Voice coil actuator (2 units per nutation axis)
- Flexure-based return spring
- +/-1.5mm stroke
- +/-50N force
- CSA “SA10” or similar is adequate

Integrated M2 Positioner Design



- 4 active hexapods replace 1 active + 4 passive hexapods
- Lighter payloads correspond to smaller struts, faster motion
- 2 axes of nutation using inner and outer carbon fiber gimbal rings

Integrated M2 Positioner: Resolution

Axes – Resolution Spec µm / µrad	Average Resolution µm / µrad	Standard Deviation µm / µrad	Maximum Step µm / µrad
X - 65.0	65.0	0.86	66.7
Y - 65.0	65.0	1.25	66.6
Z - 18.0	18.0	0.90	19.3
Ox - 4.85	4.84	0.95	6.71
Oy - 4.85	4.84	1.86	8.67
Oz - N/A	4.86	0.53	5.32

- Assumes 1 micrometer resolution actuator
- Uses similar analysis to baseline design

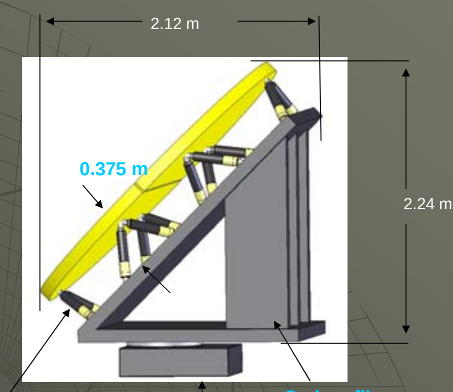
Baseline vs. Integrated M2 Positioner

	Baseline	Integrated
Actuator Count	8-10 Active, 24 Passive	24 Active
Actuator Mass	300 kg	60 kg
Kinematic Joints	60	48
Axes of Nutation	1, or 2 with add'l gimbal ring	2, relatively simple
Hex Actuator Resolution	3 micrometer	1 micrometer
Hex Actuator Force	1230 N	120 N
Hex Actuator Stroke	79 mm	70 mm
Hex Actuator Speed	~0.5 mm/s	75 mm/s
Support to Vertex Length	1.39 m	0.85 m
Alignment	6 manual mechanisms/panel	6 active actuators per panel
Risks	Accessibility, number of actuators & joints	Localized Actuator Wear, Coordinated Control of Segments

Requirements for M3 Positioner

- Support mirror segments
- Maintain Optical Alignment
- Rotate to direct telescope beam in any of 4 directions
- 10mm adjustment range
- 0.2 arcsec alignment with sky (5 arcsec rotation alignment)
- 180° rotation in 2 min
- 10^5 mirror rotations (lifetime)

M3 Positioner Design



Critical Risks/Cost Drivers

- Tip/Tilt resolution requirements require 1-3 micron actuator resolution
  - Mitigation: Single-strut qualification testing
- Nominal M2: Accessibility to passive hexapod for alignment
  - Mitigation: Additional development of installation/maintenance procedures
- Nominal M2: Large number of kinematic joints introduce compliance & deadband
  - Mitigation: Test program or opt for Integrated design
- Integrated M2: High frequency, low amplitude motion may cause actuator lubrication issues
  - Mitigation: 2-stage actuator or maintenance scheduling
- Integrated M2: Control of alignment of four mirror segments
  - Mitigation: Global control method
- 2 axes nutation may cause compliance, increase complexity
  - Mitigation: Additional design and review, or single-axis nutation

CCAT Instrumentation

Gordon Stacey representing the instrumentation group

Darren Dowel, Sunil Golwala,
Thomas Nikola, German Cortes,
Matt Bradford, Simon Radford,
Jonas Zmuidzinas, Paul Goldsmith,
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Don Campbell, Paul Harvey

Outline

- Where we are: the current state-of-the-art
- Instrument Requirements
  - Need to make compromising decisions that deliver science most efficiently
- Baseline Instruments – first light
  - Submillimeter wave camera
  - Near millimeter wave camera
- Second light and future instrumentation

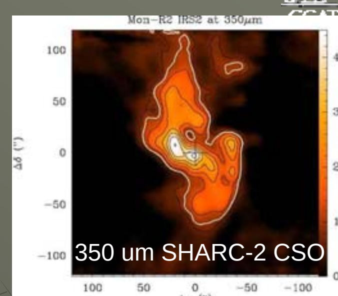
The Present

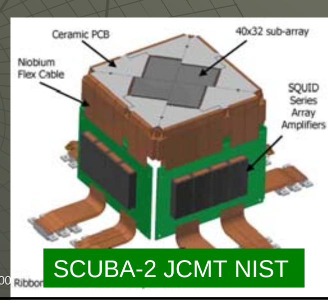
At present, there are a few 10 to 15 m class telescopes of very good surface quality (15 to 25 um rms) in very good submillimeter sites:

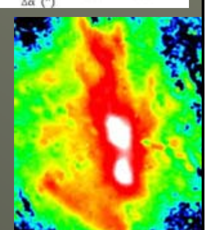
- 10.4 m CSO: Mauna Kea
- 15 m JCMT: Mauna Kea
- 10 m HHT: Mount Graham
- 12 m APEX: Chajnantor

The Present

- These telescopes have delivered high sensitivity and ground breaking science with relatively modest arrays
  - CSO: SHARC – 40 pixels
  - JCMT: SCUBA – 128 pixels
- New larger format arrays promise exciting new science
  - SHARC II – 384 pixels – *now in use!*
  - SCUBA II – 5000 (×2) pixels – very soon!







SCUBA JCMT Johnstone & Bally

The Future

- We plan to build a very high quality (10 µm surface) 25 m class telescope at the best known mid-latitude site: the high peaks above the Atacama plain in Chile
- Our baseline instruments will have at least 6 times as many pixels as the best near future instruments
- The combination of better site and larger dish should deliver ~ 10 to 40 times better sensitivity in the short submm bands
- Combination of sensitivity gain plus array size results in factors of thousands gains in mapping speed

CCAT

CCAT First Light Instruments

- Primary science
  - Exploration of the Kuiper Belt
  - Star and planetary system formation
  - Survey of distant star forming galaxies
  - Sunyaev-Zeldovich Effect
- These science topics emphasize wide-field imaging – hence our first light instruments will be cameras

CCAT

CCAT First Light Instruments

- Short wavelength camera
  - 200 μm, 350 μm, 450 μm, 620 μm windows
  - Bands selected by a milli-Kelvin filter wheel
  - 32,000 pixel TES silicon bolometers
  - 5’ × 5’ FoV
- Long wavelength camera
  - 740 μm, 870 μm, 1.1 mm, 1.4mm, and 2.0 mm windows
  - Slot dipole antennae coupled bolometers – bands separated by microstrip bandpass filters
  - 1024 to 16,384 pixels depending on wavelength
  - 10’ × 10’, and 20’ × 20’ FoV
- These two instruments will occupy the two Nasmyth foci so that all continuum science goals can met without instrument changes

Instrument Transfers to CCAT

- The primary science is enhanced through additional instrumentation
  - Spectroscopy of nearby and distant galaxies
    - Direct detection spectrometers
  - Spectroscopy of Galactic star formation regions and protostars
    - Heterodyne spectrometers
  - Studies of magnetic fields Galactic star formation regions and protostars
    - Polarimetry through rapid polarization modulation
  - High resolution far-IR imaging of AGN, starformation regions and debris disks
    - Sparse aperture imaging with a 40 μm camera

Submm Camera Decision Tree – Field of View

- The telescope delivers a 20’ FOV – why are we designing to a 5’ FOV?
  - Science: The initial science can be delivered with 5’ FOV cameras
  - Image Scale: The telescope delivers a 1.17 meter image for a 20’ FOV – this is quite challenging to couple into a background limited camera
  - Technology: Current, and near future technology suggests 32,000 pixels is a reasonable goal for the array – this can deliver Nyquist sampled images over a 5’ x 5’ FOV at 350 μm
    - tiling a 20’ FOV requires ***500,000 pixels*** at 350 um, -- extremely expensive using today’s technologies
    - Future developments will greatly reduce the costs – therefore mega pixel cameras are postponed

Decision Tree: Dichroic Operation?

- Why not build a dichroic instrument that simultaneously images in two bands, e.g. 350 and 850 μm in a single cryostat?
    - Excellent spatial registration – benefits SED science
- However:
  - Sensitivities, and SEDs are not well matched – the confusion limit is reached 3 times faster at 850 μm than at 350 μm
  - Technology: An optically coupled (SCUBA-2) array is best in the short submm, while antenna coupled arrays have better promise at the longer wavelengths
  - Fore-optics: Lenses or mirrors?
    - Lenses deliver the image quality and sensitivity for the submm camera, but have unacceptable emissivity for the mm camera
    - Mirrors achieve adequate image quality over large FOV for the mm camera, with very low emissivity
  - Costs: the arrays are the largest single capital item for an instrument. Folded into the different array technologies, it is logical to construct separate instruments

Submm Camera Design

- First light instrument
  - FOV is 5’ x 5’
    - For Nyquist sampling at 350 μm this requires a 170 × 170 pixel array
    - 32,000 pixels, or 6 times that of SCUBA-2
  - Primary bands are
    - 200, 350, 450 μm and 620 μm
    - Driven by similar backgrounds and adequate sampling requirements
    - Filter wheel to change wavelengths
- Future instrument will take advantage of the entire FOV

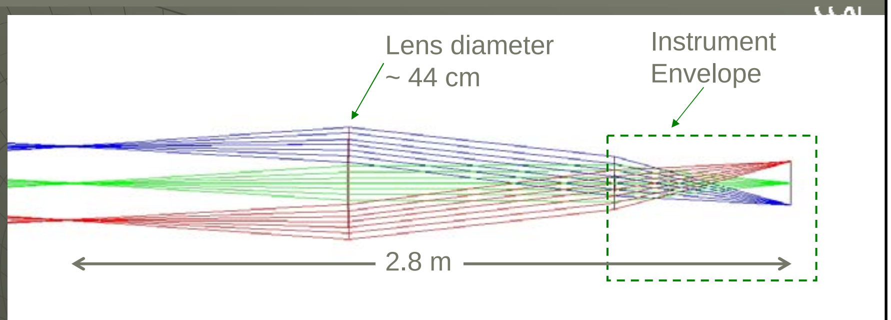
Fore-optics

- Investigated both mirror and lens designs
  - Mirror design maximizes through-put
  - Aberrations kept under control
  - However to obtain a 20’ FOV…
    - Mirror design requires 4 m class off-axis paraboloids
    - Dewar would likely 8 m × 3 m in size
  - For 5” FOV, the design is more modest
    - 3 m class off-axis paraboloids
    - Dewar could be more modest 3 m × 1.5 m in size

Transmissive Optics

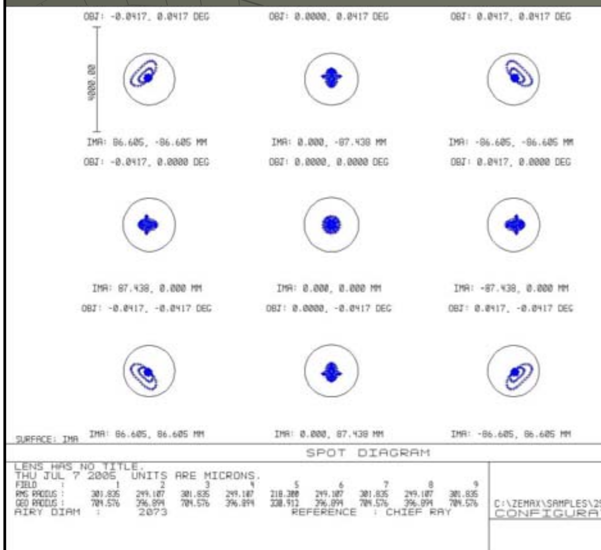
- System is much more compact
  - The instrument is ~ 0.7 x 1.0 m in size, with a 25 cm dewar window
  - However, selection of lens material is problematic – bulk absorption hurts both with transmission, and emission
- Found a variety of materials that will work (e.g. PE, Quartz, Sapphire, Silicon, Germanium)
- Selection criterion was essentially the extinction coefficient
- Other important features
  - Material properties – environmental (H_2O), structural (window)
  - Cost and availability
  - AR coatable?
- Design is based on Germanium lenses A/R coated with diamond and expected transmissions > 90%

Germanium Lens Design: 5' FOV



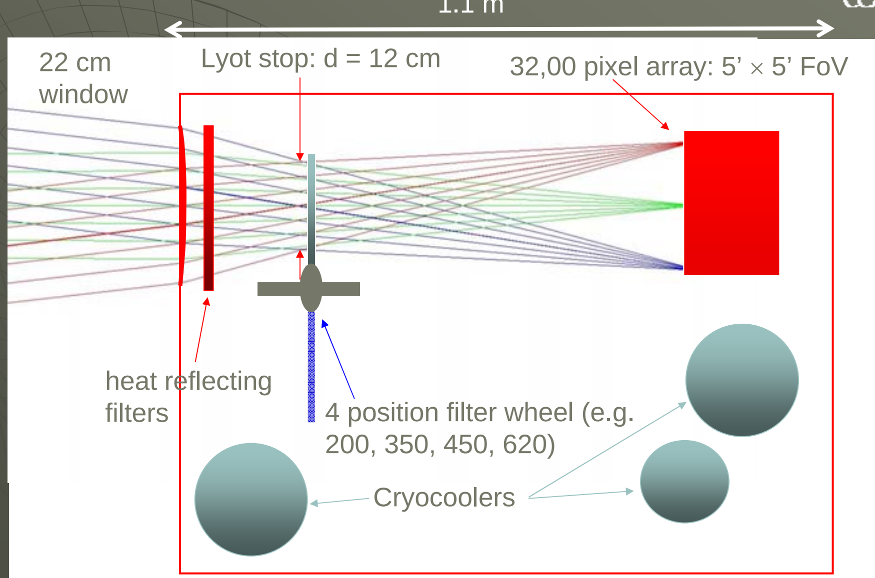
- 44 cm diameter first lens collimates telescopes f/8 beam at 13.5 cm
- Beam is transferred to a 22 cm diameter lens near the pupil which reimages to f/4.8 to Nyquist sample 1 mm square pixels at 350 μm
- Second lens serves as the dewar window (>0.64 cm thick)

Germanium Lens Design: 5’ FOV



- Spot diagram is very good – circle is λ/d at 350 μm
- Image plane is curved so can do better with curved focal plane
- Can do significantly better with somewhat larger lenses, but this is not deemed necessary

The Dewar

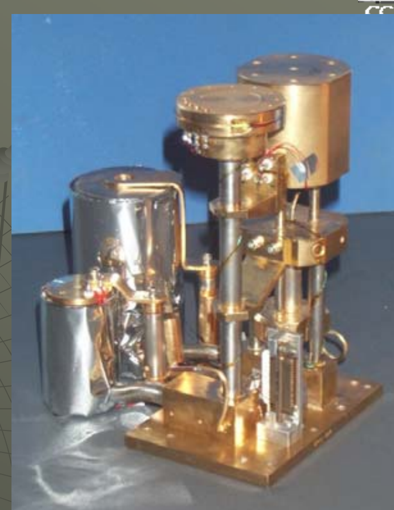


Cryo-coolers

- We are base-lining closed cycle refrigerators for all CCAT instrumentation
- Pulse tube coolers cool down instrument to 4.2 K
- Closed cycle ^{4}He system cools detector package to 2 K
- Closed cycle ^{3}He system cools detector package to 250 to 300m K
  - For the baseline cameras, requisite NEPs are achievable with a head temperature of 225 mK
  - We get NEPs ~ 10^{-16} W/Hz with Zeus at 250 mK
- If necessary, ADR can cool system further (60 mK)
- The end stage coolers are closed cycle ^{3}He systems or ADRs that are temperature stabile, and vibration free

Low T Head

- "He-7" system (e.g. VeriCold):
  - Based on 4K pulse tube cooler (e.g.Cryomech)
    - Cooling power of 40 W at 45 K
    - 1 W at 4.2 K
    - Power consumption ~ 7 KW
  - Two stage ^{4}He and ^{3}He sorption coolers (e.g Chase Research)
  - 100 uW cooling @ 300 mK
- Can go to 225 mK with "He-10" system:
  - Dual stage ^{3}He sorption cooler
  - 50 uW cooling @ 250 mK as in our ZEUS spectrometer
- Can go to 60 mK with an ADR
  - Typically has ^{3}He thermal shield
  - Provides ~ few uW cooling @ 60 mK

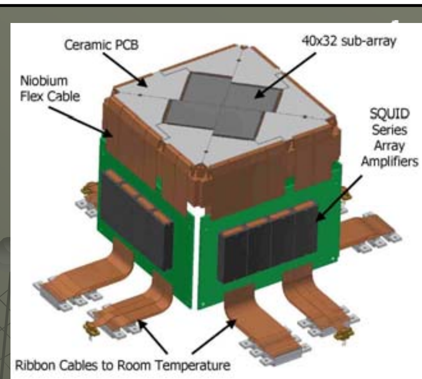


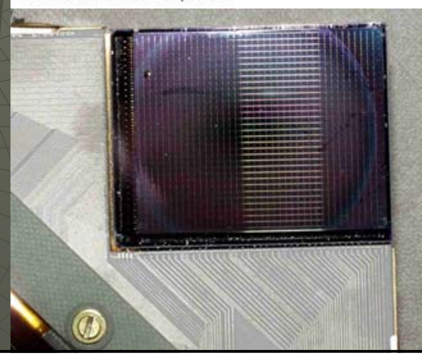
Dual stage ^{3}He cooler used in ZEUS/SPIFI

CCAT Feasibility/Concept Study Review 17-18 January 2006

Array

- Baseline is extension of SCUBA-2 array from NIST
- 4 × (32 × 40) pixel subarrays to make 5120 pixels – extend to 32,000 by using 25 edge-butted arrays
- Heritage with similar technologies
  - JPL/Caltech group manufactures sensitive "spider-web" arrays
  - CCAT members also have great experience with arrays from GSFC (e.g. SHARC-2)
- These arrays easily deliver the requisite sensitivities ($< 10^{-16}$ W/Hz$^{-1/2}$) for SWCam with milli-Kelvin cold heads





Long-Wavelength Camera

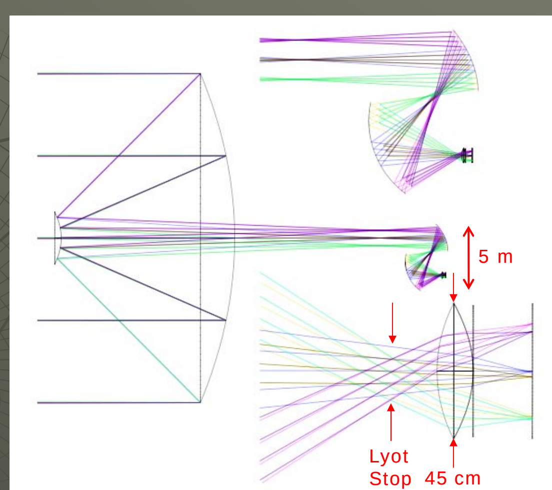
- The long-wavelength camera (LWCam) covers 5 bands from 740 μm to 2 mm
- Fore-optics will be mirror system, since for longer λ's:
  - The background is much lower so that even the small emissivity of Germanium lenses is not sufficient
  - The beam is much larger, so the relatively poor PSF delivered by the off-axis mirror design is sufficient
  - A larger FoV is populated with the same number of pixels. Lenses that would be required to image a 20' FoV become unaffordably large.
- Antenna-coupled bolometer arrays are feasible
  - Enable multifrequency coverage using a single focal plane array
  - Phased array antennae provide accurate beam definition – especially important with lower sky emissivity at these wavelengths

LWCam Optical Design

- Practical concerns lead to a final f-ratio of f/2:
  - Pixel Size: At 2 mm we wish to use $2f\cdot\lambda$ = 8 mm pixels for good beam definition – this is a very reasonable size (single pixels exist) for antenna coupled pixels at 2 mm.
  - Focal plane size: f/2 yields a plate scale of 4”/mm so that the 20’ FoV corresponds to a 30 cm diameter focal plane – 16 tiles produced on 4” silicon wafers can fill this focal plane
- All reflective optics reduce f/8 from telescope to f/2 for the array
  - Preliminary design is twin conjugate ellipsoidal mirrors
  - Image of primary just inside dewar window to provide a cold stop to terminate the sidelobes of the beam from the phased-antenna array
- Since the re-imaging optics are warm, they may be large
  - Large mirrors less of a concern at longer wavelengths
- All transmissive optical elements need to be AR coated so as to be reasonably efficient over the 740 μm to 2 mm band…

Long wavelength Camera Layout

- Off-axis ellipsoids deliver Strehl ratios > 90% over the 20’ FOV excepting 2 extreme corners
- 15% distortion at corners of FoV is an issue to be addressed
- Image brought to appropriate f/2 focus by cold polyethylene lens (45 cm diameter)
- Modest 20 cm Lyot stop and 40 cm dewar entrance window
- Dewar length ~ 1 m
- Mirrors are large: 2 and 3 m diameter



Focal Plane Detectors

The detection process is more formally split into two steps with the LWCam arrays

- How light is routed from free space to detectors

  Antenna coupled arrays

- What kind of detectors will be used?

  TES of MKID detectors

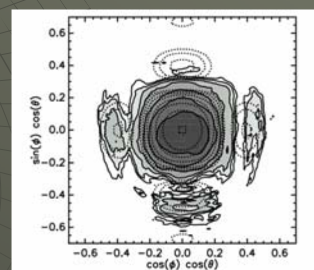
Antenna coupled arrays – 1

- Caltech-JPL are developing antenna coupled arrays using a slot dipole architecture
- The phased array is sensitive to a single polarization for λ's between $\sqrt{\varepsilon}\cdot$(tap spacing) and the slot length {ε = substrate dielectric constant = 11.5 for silicon)
- Device is broad bandwidth: can cover 740 μm to 2 mm
  - Slots of length 8 mm with 64 taps (spaced at 125 μm)
  - 64 slots across a single 2 mm pixel
- Bands are separated using microstrip bandpass filters placed at the ends of a binary summing tree
  - All 64^2= 4096 slots summed for λ = 2 mm band: $2\cdot f\cdot\lambda$ pixel
  - Subset of 8^2= 64 slots summed for λ = 740 μm band: $0.7\cdot f\cdot\lambda$ pixel
  - Therefore, each 2 mm square is one pixel at λ = 2 mm, or 8^2= 64 pixels at λ = 740 μm

    "multi-scale pixellization"

Antenna Coupled Arrays – 2

- Antenna coupled focal plane prototype device
  - Vertical lines are slots
  - Pie shaped structures connect to the microstrip taps that cross over the slots
- Demonstrated to work in the lab
  - Beam maps at 110 GHz meet expectations
  - Expected bandwidth confirmed
  - Cross polarization is modest 1%
- 16 pixel, 4 color (220, 270, 350, and 420 GHz) array in development using microstrip filters



Antenna coupled Arrays – 3

- Filling the entire 20' FoV with multi-scale pixels requires about 140,000 pixels which is quite a challenge at present
- However, the pixel count is reduced by including high frequency pixels only in the central parts of the array:
  - 16 tiles cover entire FoV
  - Central 4 (10' × 10' FoV) have multi-scale pixels operating at 740 and 865 µm with 16,384 pixels
  - The remaining 12 tiles can form large pixels at the shorter wavelengths

LWCam Parameters			
Band GHz (µm)	Δν (GHz)	Pixel Size f·λ	Number of Spatial Pixels
150 (2000)	30	2.3	16 tiles × 64 = 1024
220 (1400)	40	3.2	16 tiles × 64 = 1024
275 (1100)	50	2.1	16 tiles × 256 = 4096
350 (870)	40	0.7 2.8	4 tiles×4096 = 16384 12 tiles × 256 = 3072
405 (740)	30	0.8 3.2	4 tiles×4096 = 16384 12 tiles × 256 = 3072
Total			45,056 detectors

Detectors

- The best candidates for detectors at the ends of the microstrip are:
  - Superconducting Transition-edge sensors (TESs)
  - Microwave kinetic inductance detectors (MKIDs)
- Each has its advantages and disadvantages
  - Sensitivity: currently TES, but MKIDs progressing
  - Degradation under optical loading: slight advantage to MKIDs
  - Fabrication: Advantage to MKIDs
  - Multiplexing: Advantage to MKIDs
  - Cold Electronics power dissipation: Advantage TESs
  - Microphonics Susceptibility: Advantage MKIDs

Detectors

- Antenna coupled TES and MKID arrays both are under development by the Caltech/JPL group
- If successful, the only technical challenges for LWCam are multiscale antenna-coupled pixel design and very wide band optics

Existing Instruments for CCAT

- Budget and schedule limit us to SWCam and LWCam at first light

These cameras deliver most of the fundamental goals of the project

- The addition of spectroscopic capabilities, however, clearly enhances the science return
- At modest R, suitable for extragalactic work, direct detection spectrometers are the instruments of choice
  - Large instantaneous bandwidths
  - Operate near photon limit
- At high R, such as that required for protostars ($R > 10^5$) heterodyne spectrometers are the natural choice
- Consortium members have constructed a wide variety of direct and heterodyne spectrometers transferable to CCAT
- These instruments continue to "evolve" and be replaced by better instruments as technology improves

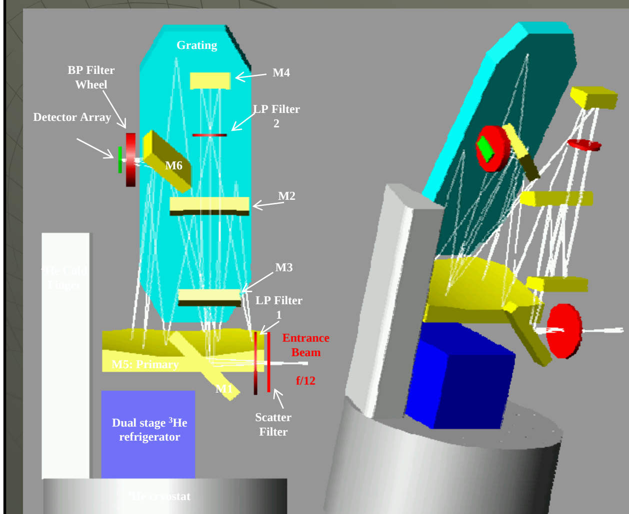
ZEUS – 1

- Redshift (z) and Early Universe Spectrometer (ZEUS)
  - Long slit echelle grating spectrometer
  - Designed for use in the 350, 450, 610 μm telluric windows in 5th, 4th, and 3rd order of the echelle
  - Employs a 1 × 32 pixel thermister sensed bolometer array yielding 3.2 % BW at R = 1000
  - Upgradeable to 12 × 64 pixel TES array to extend coverage to 6.4%, and 12 beams on the sky – well configured for resolved nearby galaxies
- Low cost future improvements
  - Cover more windows: Open up 8 orders of the echelle with a filter wheel
  - Convert to a multi-object spectrometer: Can implement "fiber optics" system feeding multiple point sources to the long slit

ZEUS Properties

Echelle Order	Spectral Range (μm)	Resolving Power R
9	185 to 211	1280 to 2700
8	208 to 237	1140 to 2400
6	278 to 316	850 to 1800
5	333 to 379	710 to 1500
4	416 to 474	570 to 1200
3	555 to 632	430 to 900
2	832 to 948	285 to 600

ZEUS – 2



Two views of the optical layout for ZEUS

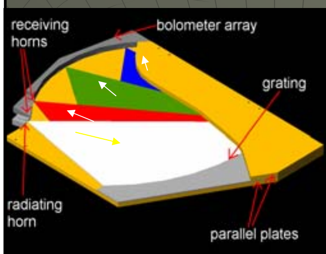
ZEUS mounted on the JCMT

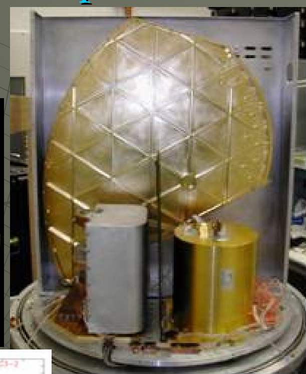
Z-Spec

- Z-Spec is an alternative to long slit grating spectrometers
  - Curved grating inside a parallel plate waveguide
  - Provides nearly an octave of instantaneous bandwidth in an especially compact configuration
- Light from a single spatial mode propagates through the waveguide to the curved grating which both focuses and diffracts the light to the detector array
- Developed in both a far-IR version (WaFIRS) and mm wave versions (Z-Spec), which recently had first light on CSO
- Each WaFIRS module provides an instantaneous BW of at least 1.7 for a single beam on the sky
  - The compact 2-d geometry permits stacking of modules
  - Perhaps half a dozen could be stacked within a 1 m cryostat providing:
    - Spatial multiplexing – again could be “fiber fed”
    - Spectral multiplexing (cover other telluric windows)

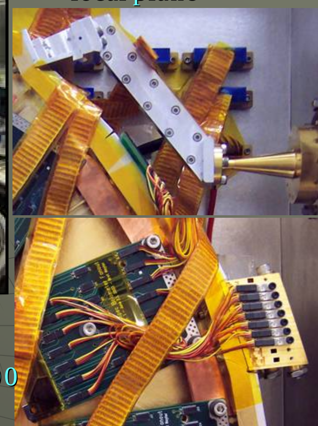
Z-Spec – 2

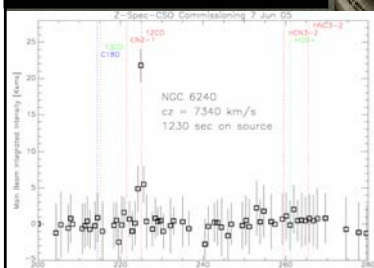
WaFIRS Spectometer architecture





Radiating horn and focal plane





Z-Spec instrument covering 190 to 310 GHz at R ~ 250 to 400

Z-Spec first light spectrum obtained on the CSO in June 2005

Heterodyne Receivers

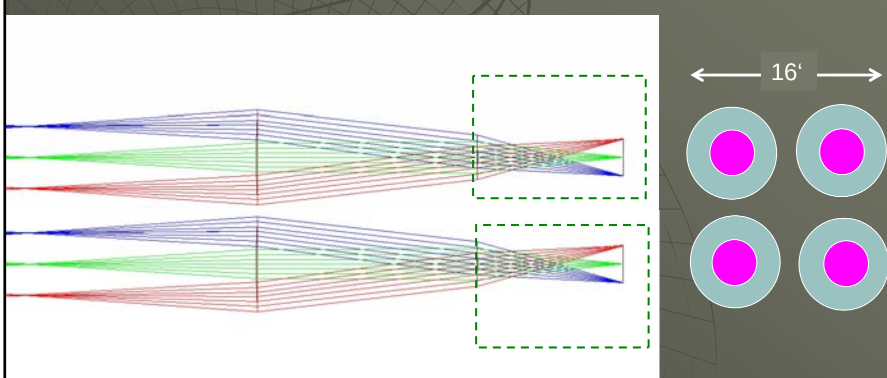
- Heterodyne receivers currently at the CSO allow access to every CCAT telluric window except the 1.5 THz window.
- These receivers have excellent sensitivity – typically within a factor of 5 of the quantum limit
- These are clearly the receivers of choice for high resolution spectroscopy, e.g. for protostars
- Very high sensitivity HEB terahertz devices exist and have been used in receivers at the South Pole and at Atacama sites with good success
- Heterodyne receivers are compact, and easily transportable to the CCAT facility
- Backends will be shared
- Near future developments include muli-pixel arrays at all frequencies

Future Instruments for CCAT

- There are significant upgrade paths for both SWCam, and LWCam
- High priority is the implementation of multi-object spectrometers
- We also are investigating a 40 μm diffraction limited imaging

SWCam

- SWCam can be "multiplexed" either spatially, or spectrally
- 4 instruments cover 16' FOV, or up to 4 bands
- The total areal coverage is 102 square arcminutes, or 1/3 the available FoV



LWCam

- Upgrade paths:
  - Cover the entire FoV with Nyquist sampled pixels at 740 and 865 μm – a total of 137,216 pixels!
    - Or, more modestly, upgrade from 3f·λ pixels to 1.5f·λ pixels: "only" 63,488 pixels total
  - Cover the entire FoV with Nyquist sampled pixels at 620 μm resulting in 262,144 pixels in addition to the 137,216 pixels in the first upgrade
    - Or, more modestly, employ "two tier" system for an addition of 77,824 or 114,688 pixels total
    - Extension to 620 μm will be challenging due to issues with SQUID packing density (TES), and heat-loads with HEMTs (MKID)
  - There may be issues with image quality at the shorter wavelengths for the larger FoV
  - 620 μm band already covered with SWCam…

Far-IR Camera

- Some of the panels discussed for CCAT could support far-IR imaging in the 40 μm telluric window
- The 10 μm overall wavefront error is much smaller at the scale of individual panels ⇒ diffraction limited imaging is possible in a sparse aperture imaging mode
- As with the non-redundant aperture masking done at the Keck telescope, one could combine beams from selected subapertures to achieve diffraction limited imaging
- At 40 μm, 5 μm rms panels are λ/8 so that we could achieve diffraction limited imaging there: θ ~ 0.4"
- This unique high spatial resolution imaging capability in the short far-IR is well suited to studies of galactic nuclei, starformation, and debris disks.
- This may turn out to be an exciting and important bonus of the CCAT figure, and low PWV location

Summary

- The CCAT consortium has extensive expertise in submillimeter instrumentation
- The first light instruments are substantially more powerful than other current or near future instruments:
  - 32,000 pixel 200 to 620 μm TES optically coupled bolometer camera
  - 45,056 pixel 720 μm to 2.0 mm slot dipole antennae coupled bolometers camera
- Each of these is likely to have polarimetric capabilities using rapid polarization modulation techniques
- Both of these cameras have significant upgrade potential
- Early on, we will employ existing instruments constructed by consortium members for spectroscopy including both direct detection and heterodyne systems
  - These systems will likely be upgraded to include multi-object capabilities
- Second generation instruments include dedicated multi-object spectrometers and a far-IR camera

Observatory Control System & Electronics

CCAT

Simon Radford &
Tom Sebring

Control System Scope

- All software and hardware
- Timing and communications
- Architecture includes embedded systems
  - Controls for major subsystems supplied by vendors
- Safety systems autonomous
  - Only monitored by observatory system
- Common instrument interface
- Support data reduction packages

Control Functions

- Telescope Control
- Enclosure Control
- Environmental Monitoring
- Instrument Control
- Observation Control
- Data Management
- Communications

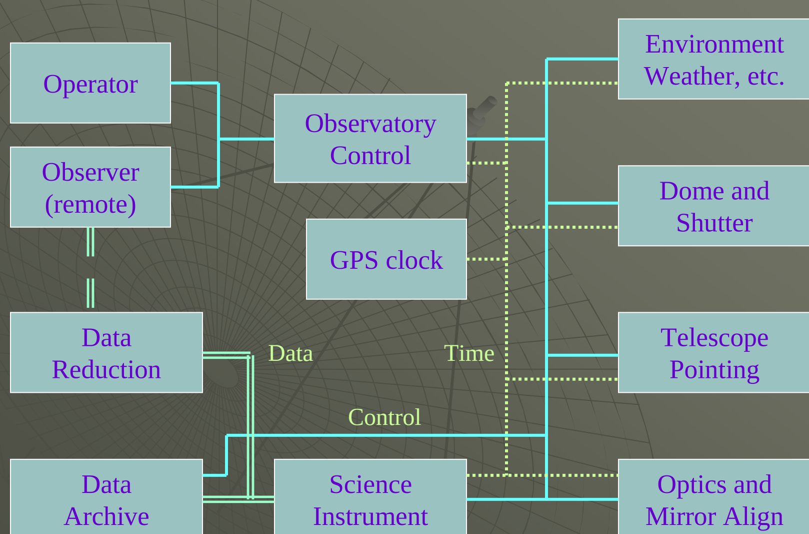
Controls/Software Design Guidelines

- Existing solutions when practical
- Transparent support for remote operations
- Efficient user interfaces - direct and scripted
- Include instrument and subsystem developers
- Mostly homogenous, but not draconian
- Commodity hardware and OS
- Well supported applications environments
- Adequate communications bandwidth

Strawman Control System

- As available subsystems from existing telescopes (CSO, Arecibo, etc.)
- Pointing kernel from P. Wallace
- PC hardware with Linux (mostly)
- LabVIEW applications environment supports legacy code
- Ethernet, separate control and data
- Separate timing bus (IRIG-B)

Control System Conceptual Design



CCAT Feasibility/Concept Study Review 17-18 January 2006

Control System Design Approach

- Hire experienced software engineer
- Define use cases and requirements
- Detailed functional specifications
- Interface identification and spec.
- Choose development tools and stds
- Identify hardware capacities

Electronics Scope

- Power Sources, Distribution and Protection Strategy
- Lighting and Emergency Lights
- Safety and Security Equipment
- Communications Network
- Control System Implementation
- System Specific Equipment
- Computer System Approach
- Dome and Shutter Controls
- Optical Systems Electronics
- Instrument Interface Electronics
- Coating Plant Controls

Electronics for Major Subsystems Included in Contractor's Scope of Work

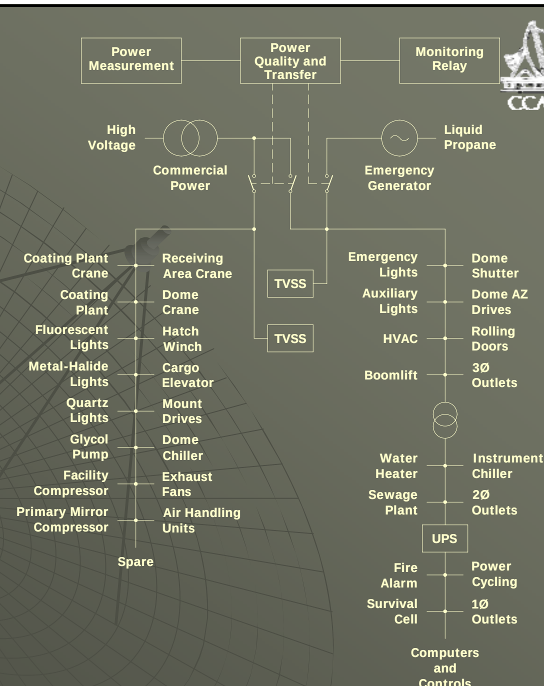
We Will Need Electric Power Budget
Preliminary Estimate by M3

Load		Power [kVA]					Classification		
Item	Description	Total	RAW	Total	ATS	UPS	SHR	OBS	SDN

- Total Raw Power
- Raw Power
- Total Automatic Transfer Switch Power
- Automatic Transfer Switch Power
- Uninterruptible Power Supply Power
- Shared Loads
- Observation Loads
- Shut Down Loads

Electric Power Distribution

- Provides Appropriate Power to Subsystems
- Compatible with Emergency Switchover
- Central UPS for All 110 VAC Power (Computers & Network Equipment)



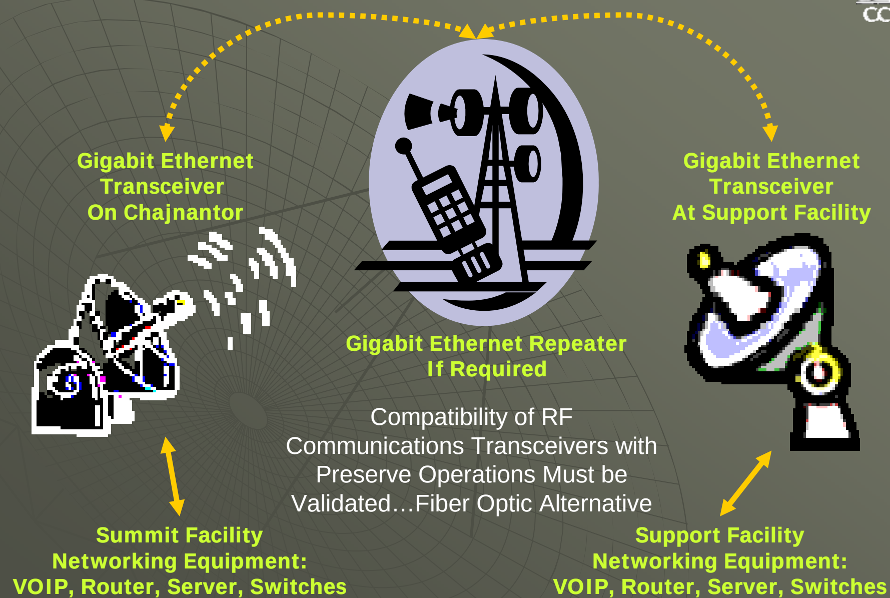
Emergency Stop System

- Normally Closed Double Loop Around the Facility and Mount
- Any Switch Interrupts the Loop and Stops all Dome, Shutter and Telescope Motion
- "Intelligence" always Remains Alive
- Large Illuminated Mushroom Switches, Lockout as Reqd.
- Electrical Panel in Control Room Shows E-stop Status
- Integrated with Contractors' and Third Party Subsystems

Telescope Surveillance System

- Automatic Iris Low Light Video Cameras w Ethernet Interface
- Coverage Angles Throughout Facility Required for Remote Operations
- Microphone and Two-way Intercom Incorporated on Each Camera
- Provides Remote Monitoring of Personnel for Safety
- Integrated with TCS

Data Transfer & Communications



CCAT Feasibility/Concept Study Review 17-18 January 2006

Summary of Electronics

- Electronics as Defined are Not Technically Challenging
- Cost of Electronics is Not an Issue
- Appropriate Engineering Practice and Implementation Important
- Next Phase of Work Will Include Further Definition and Specification of Electronics Subsystems

CCAT Feasibility/Concept Study Review 17-18 January 2006

Site Selection

Simon Radford

CCAT

Project Goals for Site

- Consistently superb obs. conditions
  - Suitable for submm most of the time
  - Suitable for THz much of the time
  - Better than Mauna Kea (requirement)
  - Better than ALMA (goal)
- Feasible logistics
- Proximity to other observatories

South America

CCAT

Atacama

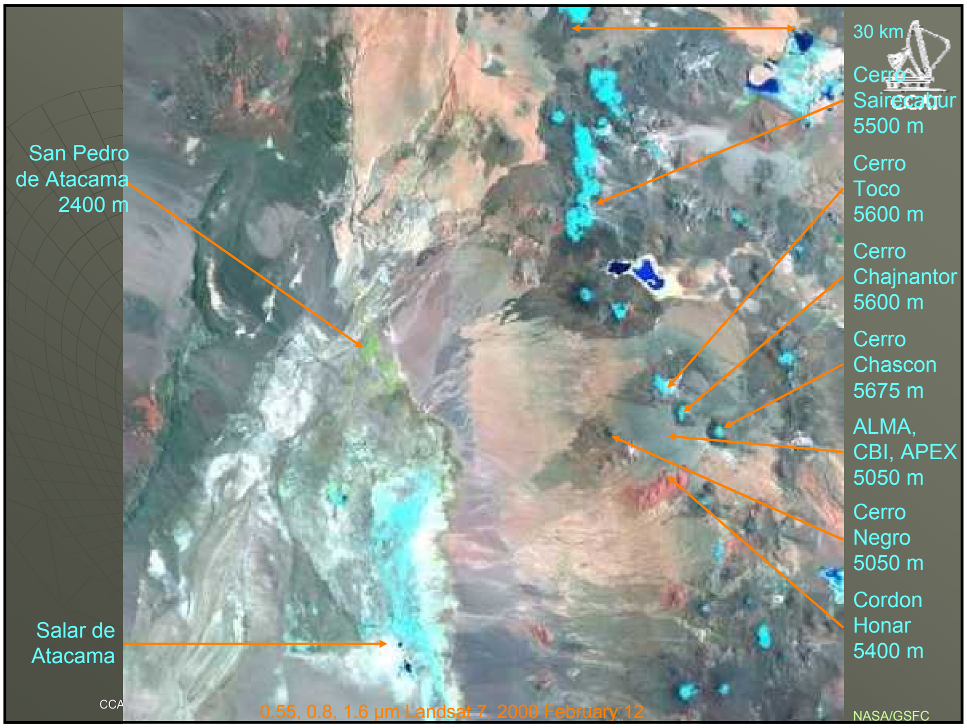
Living Earth

Chajnantor Plateau (5000 m)

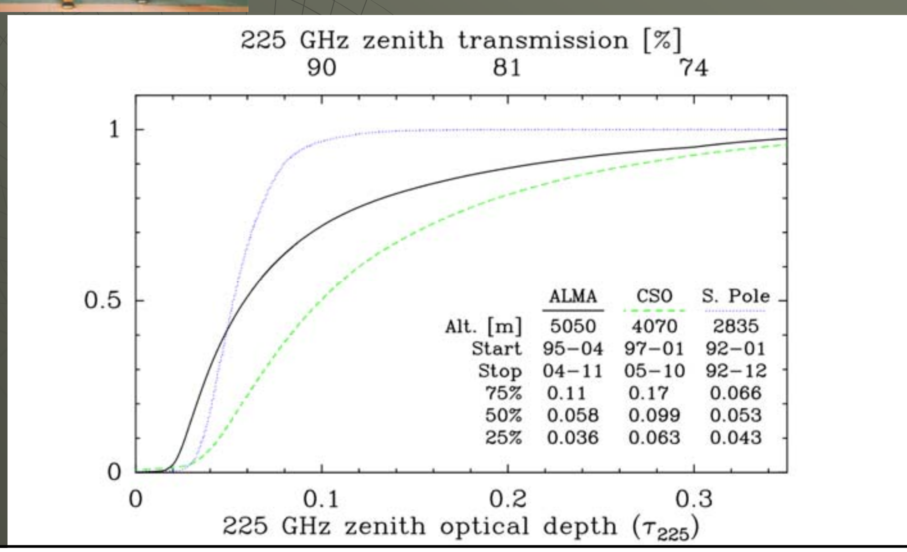
CCAT

CBI APEX ALMA Co. Chajnantor

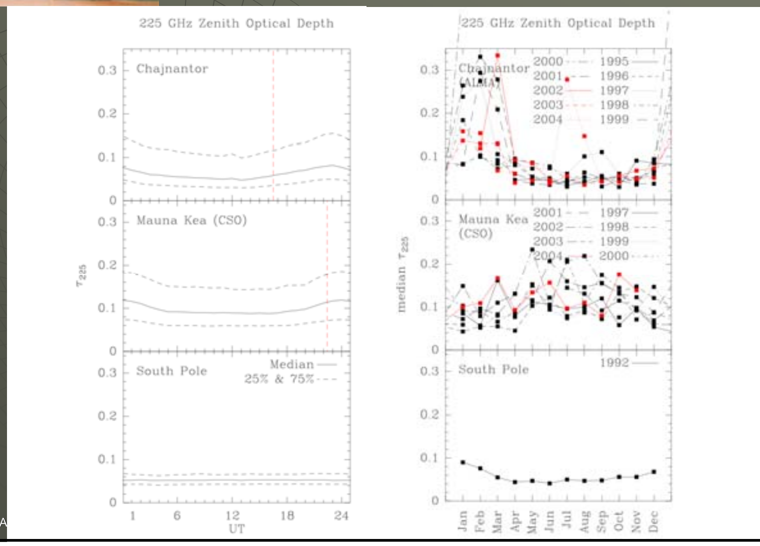
Dietrich/Caltech



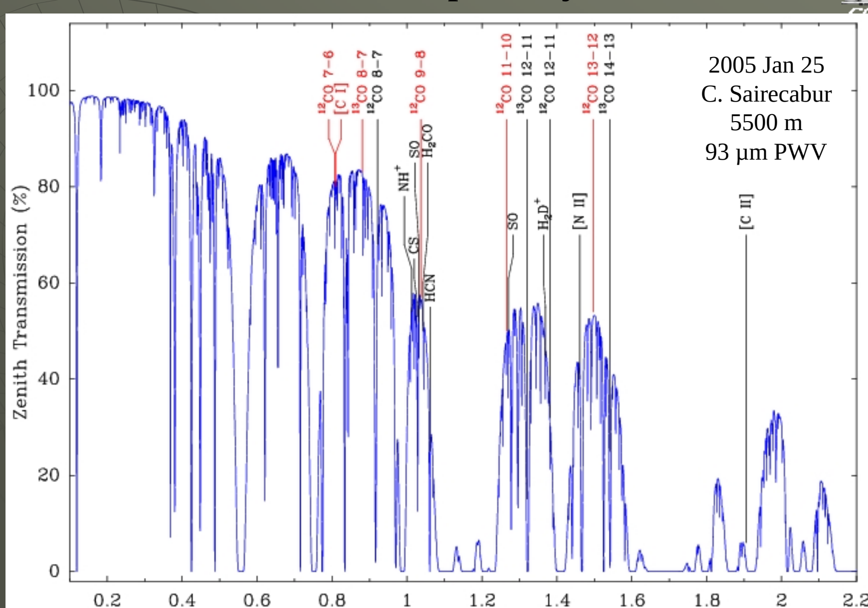
225 GHz Transparency Global Comparison



225 GHz Transparency Variations

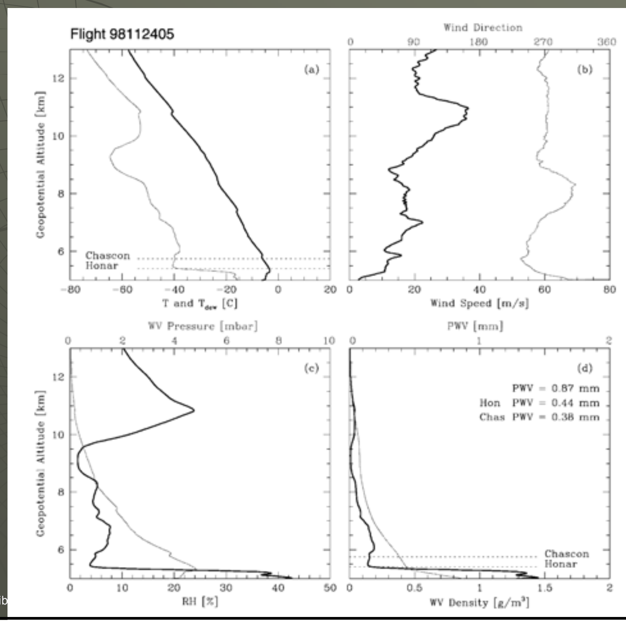


Submm Transparency



Marone et al. 2005

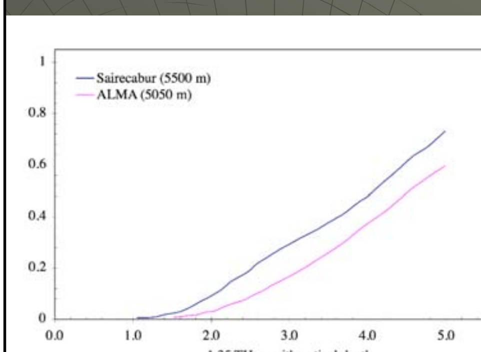
Site altitude: Radiosondes

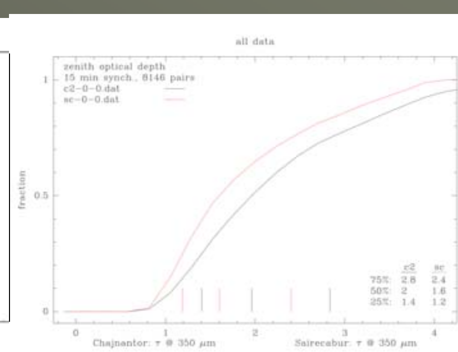


CCAT Feasib

Site Altitude: Transparency

Sairecabur (5500 m) vs. ALMA (5050 m)

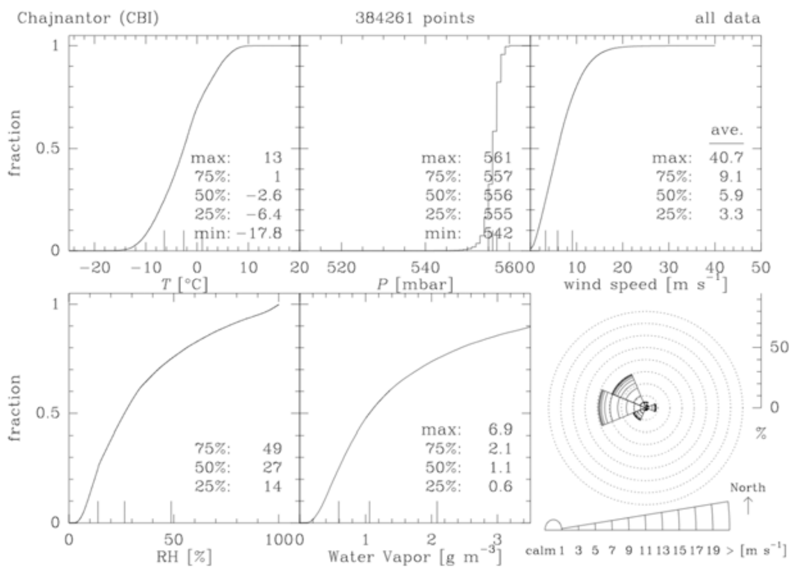




τ @ 1.35 THz

τ @ 350 μm

Meteorology: CBI



Cerro Chajnantor (5600 m)

- Expected conditions similar to Sairec.
- 1 ha ENE and 50 m below summit
- Inside science preserve
- No archaeology, flora, fauna concerns
- Close to ALMA (5 km)
- Share road with Japanese(?)
- Selected candidate site

Cerro Chajnantor (5600 m)

1994 November

CCAT Feasibility/Concept Study Review 17-18 January 2006

Cerro Chajnantor: Site Visit

2005 December 12

CCAT Feasibility/Concept Study Review 17-18 January 2006

Cerro Chajnantor: CCAT site

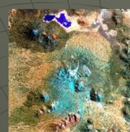
2005 December 12

Site Measurements

- Broadband 350 µm transparency
  - Tipping radiometers (NRAO/CMU)
  - Units also at Mauna Kea and South Pole
- Simultaneous comparison
  - Cerro Chajnantor candidate (5600 m)
  - Chajnantor plateau (CBI; 5050 m)
- Assume relative conditions are stable
  - Short term comparison proxy for long term
- Direct measurements in 2006
  - Bureaucratic path difficult in 2005

CCAT Equipment

Corndon Honar (5312 m)



A Few Considerations About Operating in Chile

Riccardo Giovanelli

The Astronomy Record in Chile

•Foreign Observatories have successfully operated in Chile for nearly half a century, through democratic and authoritarian regimes.
• Chilean governments have shared a common policy of welcoming the establishment of world class foreign observatories, recognizing them as agents of scientific and technical fallout in the country.
• Chile has one of the soundest property and labor law environments in Latin America, open to foreign investment and operation.
• Astronomy initiatives have "diplomatic status" and they can import goods free of taxation, be exempt from value added tax, among other exceptional privileges.
• Quality of infrastructure, technical and banking services and "modernizing trends" are the best in the region.
• National and local administrations are affected by extremely low levels of corruption and only moderate amounts of red tape.
• Relationships between foreign observatories and Chilean astronomical institutions are very friendly and they operate in a mutually "altruistic" mode.

Operating Modes of Foreign Observatories in Chile

•Establishment of foreign observatories in Chile takes place under guidelines contemplated in the "Astronomy Law", nr 15172.

• A foreign, non-profit organization (such as AURA, AUI or Carnegie) establishes legal presence in Chile and enters a cooperative agreement with a Chilean academic institution (such as Universidad de Chile or P. Universidad Catolica).

• That partnership requests recognition as recipient of the privileges described in the Astronomy Law and operation of the observatory takes place under that legal umbrella.

• The Chilean partner administers the 10% of the telescope time allocated, by law, to scientists at Chilean institutions.

Options for Establishing CCAT in Chile

•One of the existing partners, already endowed with legal standing, establishes a partnership with a Chilean institution and jointly with that partner applies for the benefits of the law 15172.
• A new legal entity is formed, and it will represent CCAT in Chile.

Note:

A revision of the Law nr 15172 lies dormant in the Chilean Congress. It will have an impact on the way the Astronomy business is conducted in Chile, if passed.

Site Issues and New Political Paradigms

In the last year, the bureaucratic path to obtaining permits for astronomical site activities has become much more complex and slower.

This reflects a political shift towards increased recognition of the rights of indigenous populations, higher sensitivities towards the value of the historical record found in the field and increased protection of the physical and biological environment.

Requests that until recently were processed by CONICYT (National Committee for Science and Technology) within a matter of days now require clearance by CONADI (National Committee for indigenous affairs) and by local committees. While these new practices enhance the protection of the environment, preserve the historical record and protect local rights, they also increase the scheduling burden for initiatives that require agile implementation, such as site surveying.

Practicalities and CCAT Operation Modes - 1

- It will be necessary to hire the services of a legal office in Santiago, to process the implementation of the Astronomy Law protection and to monitor legal issues. This could be one of the offices already serving AUI, AURA, Carnegie.
- During normal operation of CCAT, instruments and other hardware will enter Chile by air through Santiago. It will be necessary to hire shipping and customs clearing personnel. This may be better done by contracting such services from AUI/ALMA.
- However, the maintenance of a close contact with the national agencies is desirable. In the possible absence of a CCAT facility in Santiago, that may be best achieved by establishing close collaborations with Chilean academic institutions, as their senior faculty can act as effective links to the government agencies.

Practicalities and CCAT Operation Modes - 2

• The baseline paradigm for the CCAT operation contemplates independent facilities, staff and services.

• This does not reflect any final decision on the observatory operational mode, but rather the easiest way to estimate a costing profile.

• Operation of an independent support facility at the lower altitude near San Pedro is part of the baseline operations paradigm. It may also be the most likely to be reconsidered. The most important reason is that it will be difficult to maintain good quality of services: a 20 person operation may not have critical mass to achieve that goal (power, water, gasoline, food, contracting with remote providers of services and manpower).

• Possible alternatives:
- join forces with another operation of comparable size (e.g. APEX)
- contract space and services with ALMA
- rent space at a local hotel (e.g. CBI mode)

Timescales

• The process of establishing legal presence in Chile will require 6-9 months.

• The CCAT schedule contemplates start of site development activities in the first half of 2007. By then, we need to have selected a site, fulfill environmental-etc. impact studies, obtain permissions from various agencies.

• The current schedule for site selection activities projects a decision on the Cerro Chajnantor site, at the very earliest, by the middle of 2006.

• The CCAT schedule is tight, but possible, provided that legal measures to establish partnership and legal presence in Chile are initiated as soon as the go ahead for the next phase of the project is obtained.

Integration & Commissioning

T.A. Sebring

Integration Challenges

- Remote Site & Challenging Access
  - Ability to Get Equipment, Systems, Materials On-Site
  - Logistics for Labor Force and US Based Project Team
  - Distance to System Providers
  - Emergency Preparedness and Response
  - Self Sufficiency wrt Roads, Site, Lodging, Food, etc.
- Altitude (Hypoxia)
  - Personnel Safety & Efficiency
  - Complexity of Integration Tasks
- Scale of Telescope and Facility
  - High Work, Large Components and Systems
  - Access & Crane Capacity
  - Personnel Safety

Major Integration Phases & Stages

- Site Preparation & Road Development
- Base Support Facility Construction
- General Construction of Summit Facilities
- Dome and Mount Integration
- Controls and Electronics Installation
- Mirror/Reflector Assembly and Alignment
- Engineering 1st Light Activities
- Instrument Installation
- First Light
- Commissioning

Safety

- Altitude: Poses Significant Health and Efficiency Risk
  - Oxygen Use Will Probably be Mandated for Project Personnel and Contractors
  - Personnel Medical Exams Required
  - Buddy System & Personnel Safety Systems/Processes Carefully Implemented and Maintained
- Remote Location
  - Must Have Good Emergency Plan in Place
  - Transport, First Responders, Equipment at Site at All Times
  - Evacuation Plan and Communications with Emergency Services

Preparation for Integration

- Subsystem Design & Requir
  - Modular Design: Allows Trial ... bly, Complex Modules to Remain ... ing
  - Trial Assembly and Fit Check ... jor Subsystems Before Leaving M
  - Alignment: Use of Pinning & Metrology & Adjustment on S

- Shipping and Handling
  - Modules to Fit Standard R
  - Minimum Deck Load to Re
  - Contractors Responsible O Port...Most Have Limited E

Preparation for Integration (cont.)

- Manufacturers Provide Assembly/Test Plans
  - Step-by-Step, Delivered Pre Final Acceptance Test
- Manufacturers Provide Technical Support to Integration
  - May Be More Than One Person at Different Stages
  - Contracts Do Not Include Full Installation
  - Allows Use of One Labor Force Under Project Direction
- Control System Interfaces Validated at Mfg
  - Project Supplies Telescope Control System Software
  - Interface Validated at Final Acceptance Testing
  - Should Re-Create Easily On-Site

Preparation for Integration (cont.)

- Facility Inventory
  - Inventory Identified via Survey of Existing Telescopes
  - Full Equipment/Materials Lists Prepared
  - Procurement in US, Shipped in One Container
  - Enables Full Population of Facilities When Completed
- Supplementary Tools for Integration
  - Contractors Supply Many of Their Own Tools
  - Rental or Purchase of Others Required as Appropriate
  - Special Tools Either Project Purchase or as Part of Contracts for Major Subsystems

Support to Integration

- Manlifts, Cranes, Hoists, Scaffolding
  - CCAT Will Purchase Large Manlift (~125 foot)
  - Investigation of Construction Cranes in Next Phase
    - Possible That a Large Hammerhead Crane May be Used
  - CCAT Will Purchase Required Materials Handling Equipment & Small Crane
- Housing & Meals for Workers
  - Investigation of Support via ALMA Facilities
  - Use of Rented Trailers & Catering Alternative
  - CCAT Personnel Transferred to Chile Will Adhere to Operations Plan...Work Turno from Residences
  - Support Facility to be Completed Early in Process

Labor for Integration

- CCAT Personnel Hired in Chile
  - Facility Manager, Administrative Manager
  - Others May be Repatriates from Project Team
- CCAT Personnel Transferred to Chile
  - Majority of Technical Staff Will Spend Time in Chile
  - Permits Continuity of Management from Design Through Manufacturing, Shipping, and Integration
- Majority of Labor Provided Under Contract
  - Likely to be Extension of General Construction or Steel Erection Contracts
  - Enables Selection of "Best" Workers to Continue on Beyond General Construction

Labor for Integration (cont.)

- Local Trades
  - Hired as Necessary to Support
    - Wiring, Cabling, Conduit, Termination
    - Plumbing, Equipment Installation
- Contractor Support to Integration
  - Assembly Plans Required as Deliverable Item
  - Contracts Include Technical Support to Integration
    - Same Personnel as Directed Trial Erection and Testing
    - May Vary at Different Stages of Integration
    - Provides for Retention of Corporate Knowledge

Stages of Integration

- Site Preparation & Support Facility Construction
  - Developed in Parallel
  - Objective: Have Support Facility Available Part-way Through General Construction of Summit Facility
- Complete Summit Facility
  - Provides Infrastructure to Support Integration
  - Facility Includes Interface to Dome and Mount
- Integration of Dome & Mount
  - Actual Sequence TBD…Likely in Parallel
  - Use Same Crane
  - Rotation of Dome & Mount Enabled Early to Support Follow On Integration

Stages of Integration (cont.)

- Primary Mirror Truss
  - Assembled in Sections on Ground?
  - Lifted Into Place When Mount is Sufficiently Completed

Dome

el (Hamar)

on

ls

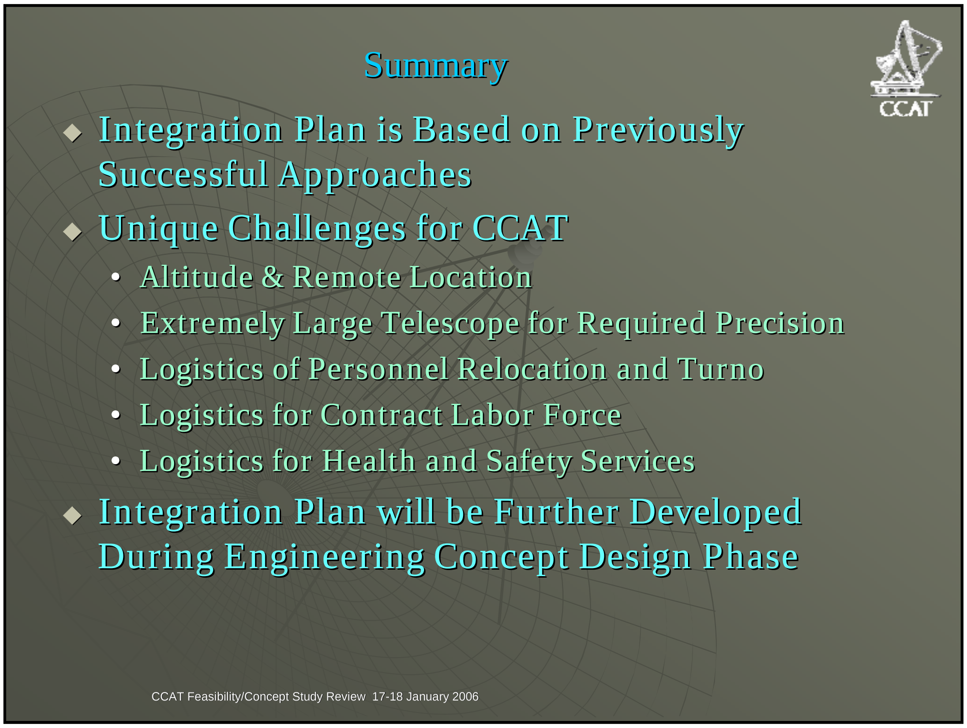
1st Light

Control System Integration

- TCS Software Provided to Subsystem Contractors Early in Development
- Interface to and Operability with TCS Part of Final Acceptance Test During Trial Assembly
- Control Integrated at Telescope as Each Subsystem is Added
  - Facility Components: e.g. Environmental Controls, Power Monitoring, Weather, Emergency Systems, etc
  - Dome Control & Mount Control
  - PM Segment Control
  - M2 & M3 Control
  - Sensors & Instruments

Commissioning

- Project Team Includes Personnel Who Will Transition to Operations
- Early Hiring of Operations Personnel During Integration
- Project Team Retained for 1 Year After 1st Light
- Monitoring of Operational Statistics Inherent Capability of Control System
- Commissioning Culminates in Final Acceptance Testing


Summary
Integration Plan is Based on Previously Successful Approaches
Unique Challenges for CCAT
Altitude & Remote Location
Extremely Large Telescope for Required Precision
Logistics of Personnel Relocation and Turno
Logistics for Contract Labor Force
Logistics for Health and Safety Services
Integration Plan will be Further Developed During Engineering Concept Design Phase
CCAT Feasibility/Concept Study Review 17-18 January 2006

Operations Concept

Simon Radford
R. Brown, D. Campbell,
T. Phillips, & A. Readhead

Starting Points

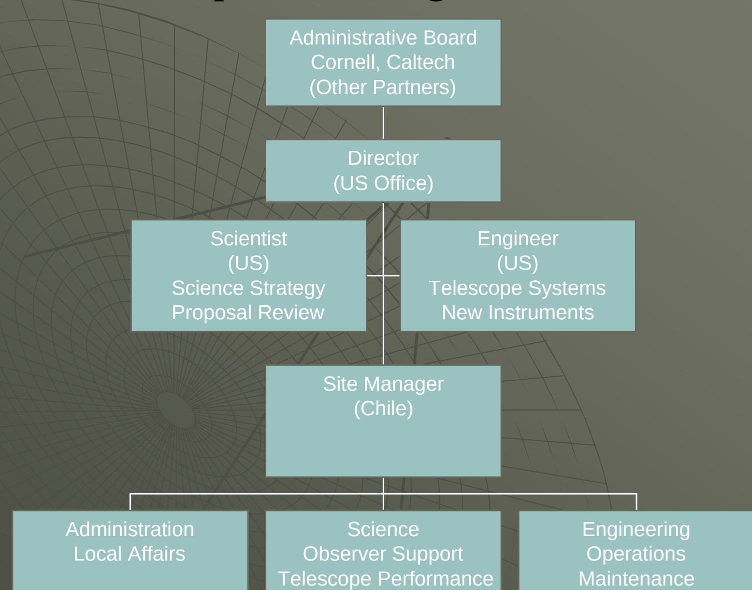
- CCAT serves scientific interests of partner faculties
- Provides both educational and research opportunities
- Initial programs are surveys with bolometer cameras
- Flexible design supports future instrument development

- Operation is a cooperation between
  - academic staff at partners and
  - local (Chile) support staff
- Only do tasks in Chile when necessary
- Only do tasks at high altitude when essential
- Goal of remote operation from San Pedro support facility

Operations Plan Development

- Initial model draws on previous experience
- CSO (Mauna Kea)
  - Offshore operation, user services, instrument development
- CBI (Chajnantor plateau)
  - Chilean operation and staffing, high altitude issues
- APEX, ALMA, etc.
  - Observe and learn from experience
- Continue plan development as project progress

Initial Operations Organization



Operations in Chile

- Similar to CBI, APEX, and other observatories
- Support facility near San Pedro de Atacama
- *Turno* work shifts with weekly commute
  - San Pedro is a *very* small town; 8 d x 10 h on, 6 d off
- ≈ 20 local staff, mostly Chilean recruits
- Installation & commissioning help from partners
- No (large) facilities in Santiago
- Contract services when possible
  - Administration (HR, purchasing, accounting, import/export)
  - Housekeeping, catering, etc.
  - Vehicle and equipment (e. g., generator) maintenance

Observing Concepts

- University based facility
  - Range of science interests and objectives
  - Training ground for students and young scholars
- Initial science objectives are surveys
- Observing responsibilities
  - Local staff responsible for telescope operation
  - Academic investigators responsible for science, instruments
  - Goal of remote operation from San Pedro support facility
- Flexible scheduling
  - Necessary to accommodate weather critical programs
  - Short list selected from approved proposals
  - Short list observers on call for remote observing
  - Active program selected by local staff based on weather

CCAT Feasibility/Concept Study Review 17-18 January 2006

Observing Modes

- On site 20 %
  - Commissioning, etc., of telescope or instruments
  - Instrument team and local staff at telescope
- Remote 40 %
  - Routine observing method in mature operations stage
  - Local staff at support facility control telescope
  - Academic investigator directs observations over internet
- Service 40 %
  - Fully specified programs: Surveys or observer unavailable
  - Local staff at support facility carry out program

- Surveys 60 %
  - Extended periods of uniform observations
  - Remote or service observing

High Altitude Issues and Mitigation

- Altitude Induced Hypoxia (Telescope ≥ 5000 m)
  - Reduced mental and physical capacity
  - Acute disorders: HAPE, AMS, HACE
- CBI, other telescopes show successful mitigation
  - Limit staff at high altitude to essential work
  - Oxygen enrich selected spaces in facility
  - Provide portable supplemental oxygen
  - Remote operation when feasible
  - Engage contractors
- Mitigation strategy part of operations plan

- Physiology consultant:
  John West, MD, UCSD

Personnel

- Predominantly Chilean staff
  - Engineers and technicians available
  - On-job training necessary for specialties
  - Scientists, senior managers may be US expats
  - CCAT will compete with mines, other obs.
- *Turno* system
  - San Pedro *very* small
  - Weekly commute from residences
  - System common at mines, other observatories

Initial Operations Staff in Chile

Position	Number	On [d]	Off
Site Manager	1	8	6
Administrator	1	8	6
Astronomer, telescope	2	8	6
Astronomer, survey	2	8	6
Engineer, instrument	2	8	6
Engineer, telescope	2	8	6
Engineer, software	2	8	6
Operator	6	8	6
Technician	2	5	2
Total	20		

Legal Model

- Partnership forms legal entity in Chile
- Establish cooperative agreement
  - Chilean academic institution
  - Univ. de Chile or Univ. Catolica
- Request privileges
  - Astronomy Law (nr. 15172)
  - Tax and duty exemptions
  - Entry of project personnel

Operations Budget

Category	(millions)
Telescope Operations	$ 3.83
US Support	$ 0.62
Instrument Upgrade	$ 0.80
Total	$ 5.25

Telescope Operations

CCAT

Category	(thousands)
Staff	$ 1608
Transportation	$ 519
Housekeeping	$ 100
Utilities	$ 250
Services	$ 35
Materials	$ 100
Land use	$ 125
Subtotal	$ 2738
Contingency (40%)	$ 1095
Total	$ 3833

US Support

CCAT

Staff		$ 315
Observatory Director	0.25	
Telescope Scientist	0.25	
Telescope Engineer	0.25	
Survey Astronomer	2	
Assistant	1	
Travel		$ 200
Matls. & Services		$ 100
Total (thousands)		$ 615

CCAT Feasibility/Concept Study Review 17-18 January 2006

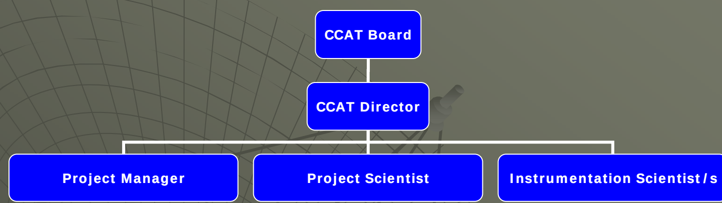
Project Management

T. A. Sebring

Phases of Development

- Feasibility/Concept Design Study
  - ~1 Year Culminating in This Review (17-18 Jan 06)
  - Objectives Defined by Cornell/Caltech MOU
- Engineering Concept Design
  - Start June 2006 Duration: 1 Year
  - Provide Full Concept Definition and Enabling Analysis
- Development Phase
  - Start: June 2007 Duration: ~5 Years at 1st Light
  - Major Contracts, Construction, Integration
- Commissioning
  - Duration 1 Year
  - Optimize Telescope Performance, Handover to Ops

Project Organization



- CCAT Board
  - Representatives from Each Partner
  - Scientific, Technical, Financial, Legal Expertise
- CCAT Director
  - Responds to Board, Non-Voting Member of Board
  - Coordinates Activities of Project Manager & Scientists
  - Interface Between Partners and Project Activities

Project Manager

- Define & Implement Program Plan
- Define Tasking & Assign
- Project Team Definition & Development
- Cost Estimation and Control Practices
- Implement Technical Development & Review Process
- Maintain Constant Vision and Foster Team Spirit and Ethics

The Project Manager is Responsible for Initiating and Maintaining all Required Activities En Route to Success

Project Scientist

- Ensure Scientific Quality and Efficacy of Project
- Interface and Ombudsman to the Partner Scientific Community
- Leads the Science Committee and Others as Required
- Leads Efforts in Commissioning Telescope wrt Astronomical Observation & Quality
- Represents CCAT to the Astronomical Science Community in General

Instrumentation Scientist/s

- Lead Development Activities for the Major Science Instruments Developed for CCAT
- Responsible for Performance of Science Instruments
- Manages Instrument Development to Meet Constraints of Budget and Schedule
- Maintains Cognizance of Relevant Technology Development Congruent with Instrumentation

Project Staffing

Skill	Number	US Office	Chile
Project Manager	1	*	>
Deputy Project Manager	1	*	>
Administrative Assistant	1	*	
Project Engineer	1	*	>
Site Manager	1		*
Administrative Manager	1		*
Optical/RF Engineer	1	*	>
Electrical Engineer	1	*	>
Mechanical Engineer	2	*	>
Control Engineer	1	*	>
Software Engineer	1	*	>
Mechanical Technician	2		*
Electronic Technician	2		*
Software Technician	1	*	>
Scheduler/Planner	1	*	
Administrative Specialist	1	*	
	19	12	13

- Initial Definition
- ">" Means Moves to Chile
- Effort Made to Hire Chileans Who Can Return and Stay
- Desirable to Hire Some Who Will Transition to Ops
- Lean/Mean Team
- Contracts for Other Labor

Business Model

- Partners Form Not-For-Profit Corporation
  - Legal Operating Entity in Chile
  - Insulates Partners from Liability
- Operate Project from Within a Partner Organization
  - Project is Too Small to Provide All Services
    - Legal, Personnel, Purchasing, Payroll, etc.
  - Provides Infrastructure Necessary During Initial Development (Offices, Meeting Rooms, etc.)
- Graduate to More Self Sufficient Stage During Operations

Integrated Product Teams

- Formed Within Project Organization to Address Subsystems and/or Tasks
  - Leaders Chosen from Within Team
  - Constituency Consistent with Technical Content
  - Everyone Gets to Lead Sometimes & Follow Some Times
- Project and Deputy Project Managers Mentor Teams
  - Remain Cognizant of All Activities
  - Participate to Adjust Course and Support Teams
  - Coordinate Tasks, Schedules, Manpower

Design Development Process

- Standard Aerospace Format
  - Concept, Preliminary, Critical Design Stages
  - Formal Reviews at Each Stage
  - Mandated by Statements of Work for Contracts
- Science Involvement with Design
  - Review of Requirements & Documentation
  - Participation in Source Selection Activities
  - Participation in Design Reviews

Contracting

- Approach
  - Firm Fixed Price Contracts
  - Competitive Procurements When Possible and Practical
  - Adherence to Federal Acquisition Regulations
    - Not Required if No Federal Funding
    - A Good Process for a Level Playing Field
  - Sole Source Justifications Developed for Non-Competitive Awards
- Contract Statements of Work
  - Include Stages at Which Formal Approval by Project is Required
  - Define Process by Which Work Will be Done

Cost Estimation

- Initial Estimate Provided During this Review
- Final and Accurate Estimate at Conclusion of Engineering Concept Design Phase
- Requirements
  - <90% of Estimated Costs Supported by:
    - Contractor Letter Quotes or Estimates
    - Catalogue Prices
    - Formal Estimating Processes
    - Extrapolation from Recent Similar Components/Subsystems
  - Final Estimate Must Include 10% Contingency
  - $20m Preserved for Science Instruments
    - Includes Contingency for Instruments

Cost Tracking and Planning System (CTPS)

- A Spreadsheet System Previously Developed and Used Successfully
  - Organized by Month of the Project and WBS Area
  - Provides Format for Initial Allocation of Funds
  - Updated Quarterly to Reflect Actual Expenditures
  - Revised Quarterly to Allow Completion Within Budget
- Provides Cost-to-Complete Estimate Within Hours at Any Time in Project
- Reconciled Quarterly with Host Institution's Accounting Department
- Status Reported 2x/Year to Partnership

Summary

- Management Process Previously Successful
- Staffing is Aggressively Light but Adequate
- Development Process is Straightforward
- Several Questions for Next Phase
  - More Accurate Cost Estimation
  - Issues of Partnership & Business Approach
  - Development of Project Office & Staffing