Strawman Design of a Long-Wavelength Camera for the Cornell-Caltech Atacama Telescope

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Abstract

The initial suite of instruments for the Cornell-Caltech Atacama Telescope (CCAT) will likely include a wide-field, long-wavelength continuum camera (LWCam), covering frequencies from 150 GHz to 405 GHz (740 um to 2 mm) over a field-of view (FoV) as large as 20' diameter. Such a camera would contribute to many of CCAT's science goals and make use of time when poor weather renders short-wavelength (200-620 um) observations unfeasible. A strawman design for such a camera is presented here, including an assessment of the current status of various necessary technologies.

Motivation

CCAT will revolutionize submm astronomy by providing unprecedented wide-field survey and wide-bandwidth spectroscopy capabilities in the 200 to 620 μm submillimeter bands.

An important complement is a long-wavelength camera covering the atmospheric windows from 740 μm to 2 mm.

Science impact:

- **Submm galaxy observations**
  - No facility planned that will go as deep at 740 μm and 850 μm
  - Confusion limit in these bands is 2X deeper vs. JCMT.
  - These bands important for filling in SEDs between CCAT 200-620 μm and LMT 1-3 mm bands
- **Sunyaev-Zeldovich effect science**
  - SZ observations of galaxy clusters require coverage from 1 mm to 2 mm and also need the higher-frequency bands for submm-galaxy confusion removal
  - See poster 91.18 *Sunyaev-Zeldovich Effect Science with CCAT.*
- **Galactic protostellar regions**
  - Confusion not an issue for nearby sources.
  - Rayleigh-Jeans tail is necessary constrain dust T and spectral index.
  - With coverage to 2 mm, CCAT survey of galaxy would be *definitive*.

Observatory Efficiency:

- ~70% of the time is optimally used for observations at 740 μm and longer
  ~50% at 1.1 mm and longer
  LWCam would make use of these periods.
- Recently available technologies enable a camera that covers ***all*** bands from 740 μm to 2 mm ***simultaneously***.

Design Principles

Maximal use of CCAT 20' field of view
- Maximize mapping speed
- Minimize sky-noise removal artifacts

Maximal frequency coverage, simultaneous if possible
- Maximize source SED coverage
- Improve observatory efficiency
- *Spectral sky noise subtraction*

Antenna-coupled optical design
- Feedhorn coupling not feasible at largest pixel counts (>10^4 pixels)
- Bare absorbers
  - Pros:
    - Simple
    - Relatively easy photolithography
  - Cons:
    - Multi-color design difficult (beamsplitters) or inefficient (divided FoV)
    - Filter wheels render array non-optimal in some bands
    - Beam definition and stray light abatement challenging at lowest frequencies (Griffin, Bock, Gear, 2002)
- Antenna-coupled designs naturally eliminate above problems

Highly multiplexable bolometer technology
- Pixel counts (>10^4 pixels) large enough that multiplexed readout critical
- Superconducting transition-edge sensors (TESs) and microwave kinetic inductance detectors (MKIDs) good candidates

Optical train with low optical loading (at the longest wavelengths)
- Atmospheric opacity in the 1-2 mm bands is 10% or lower
- Telescope emissivity of 5-10% needed

⇒ Warm optics must be reflective and low roughness, stops and transmissive optics must be cold

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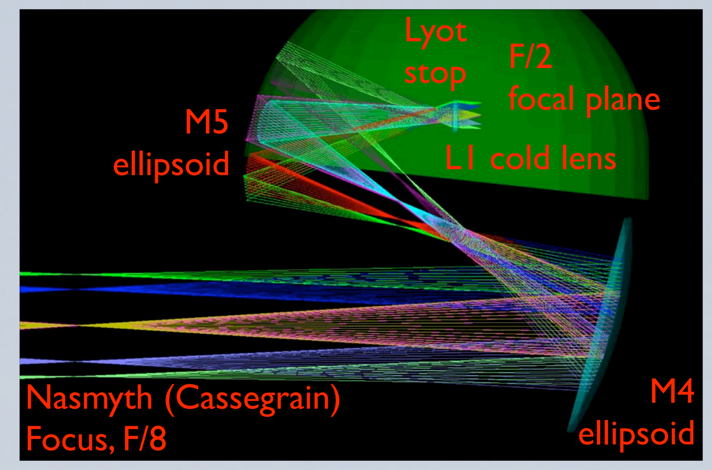
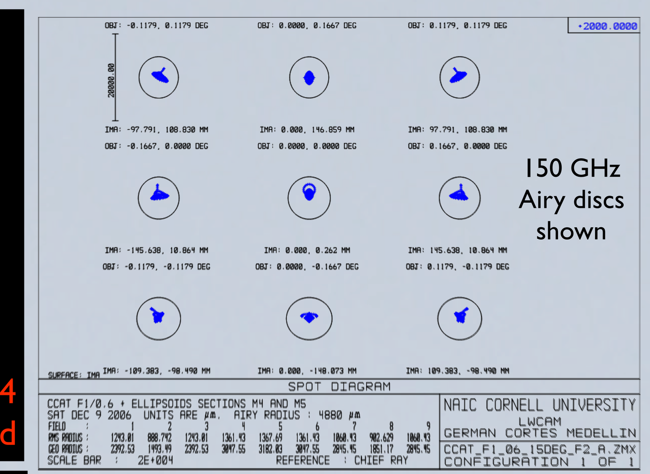
Optical Design

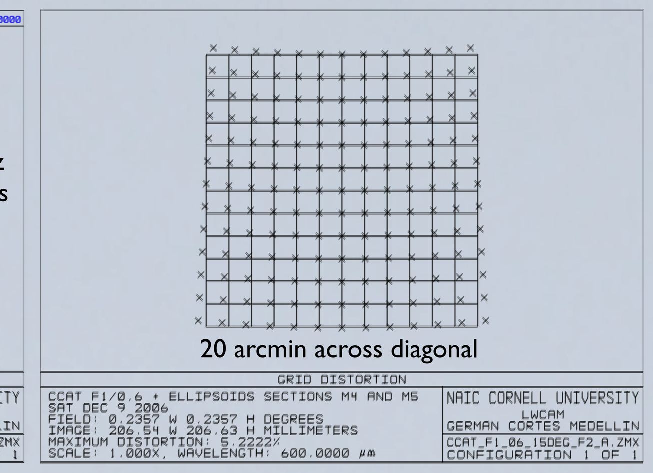
Constraints:
- CCAT primary is ∅25 m and F/0.6.
- CCAT will provide two F/8 Nasmyth foci.
- Reimage to ~ F/2 to yield reasonable pixel sizes (9.2 mm at 150 GHz).
- Need image of the primary for cold Lyot stop.
- Want low optical loading and high throughput; necessitates reflective elements for large reimaging optics; transmissive optics must be cold and therefore small.
- Need flat focal plane to make use of focal plane arrays.

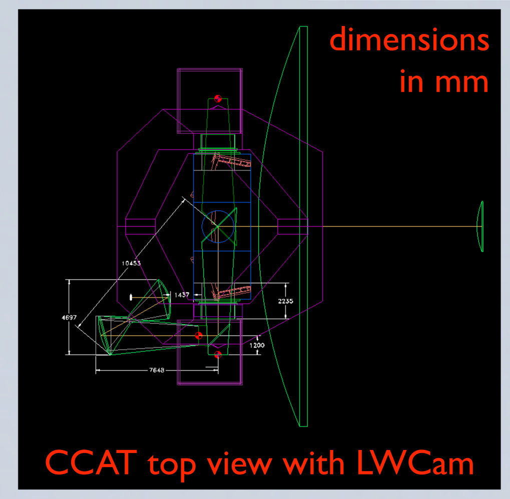
Resulting design
- Two ellipsoids (∅2.5m) and a final cold lens (∅30cm)
- ~∅30-cm cold Lyot stop between second ellipsoid and cold lens
- Bend angle at each ellipsoid = 15 degrees
- 5.2% distortion at edge of 20' diameter FoV
- Strehl ratio > 90% at 2 mm across full 20' diameter FoV
- Strehl ratio > 80% at 850 μm across 14.6' diameter FoV
- Further improvements to design in the works!

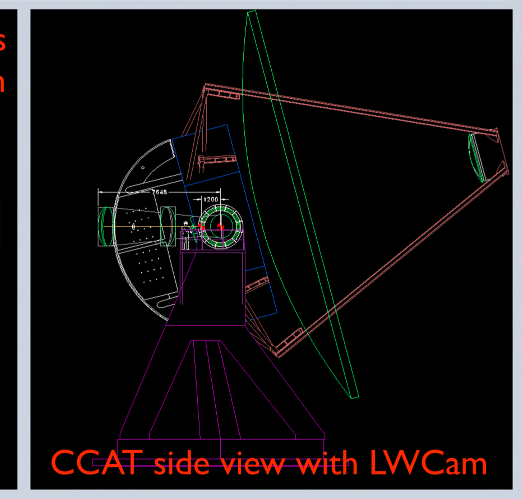
SCUBA2 may be mounted at other Nasmyth
Successor SWCam may share ellipsoids with LWCam

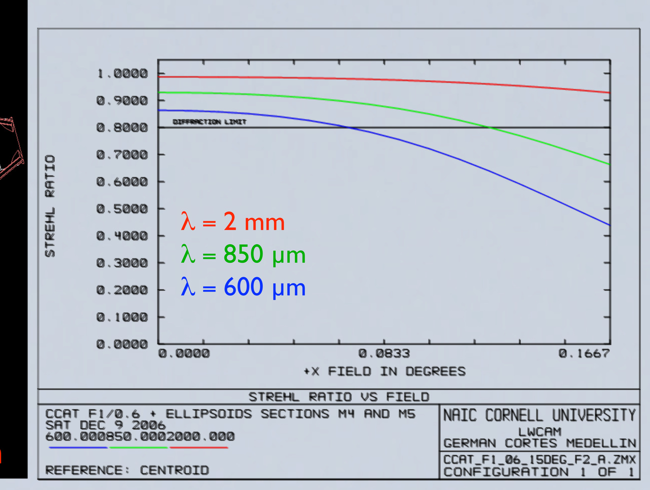


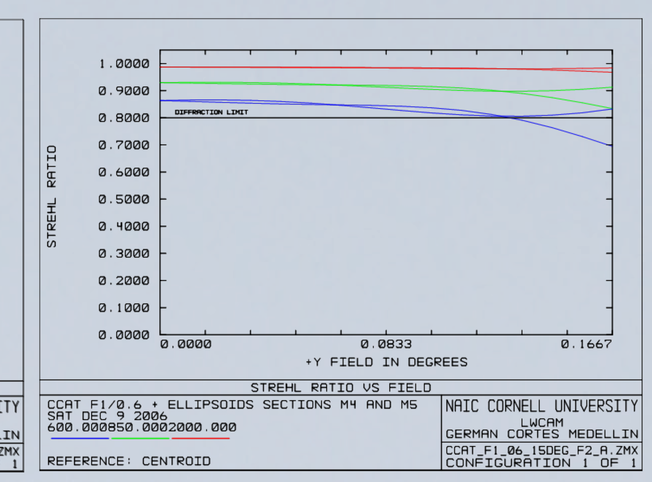












CCAT LWCam Summary

Summary of LWCam bands and sensitivities. Due to the high pixel count, we assume that only the inner 10' of the FoV is populated with Nyquist sampled 740 μm and 850 μm pixels; the outer 5' annulus of the FoV will use the same size pixels in these bands as at 1.1 mm, resulting in poorer angular resolution but still allowing their use for sky-noise removal. A future upgrade of the instrument would populate the entire FoV with small 740 μm and 850 μm pixels.

Band Center		*Bandwidth [Δν/ν]*	*Beam FWHM [arcsec]*	*Single-Pixel Sensitivity*		*Pixel Size*		*Pixel Count*		*Mapping Speed*	
Wavelength [μm]	*Frequency [GHz]*			*mJy √sec*	*μK$_{CMB}$ √sec*	*inner 10'x10' square*	*outer 5' annulus*	*inner 10'x10' square*	*outer 5' annulus*	*deg^2 / mJy^2 / hr*	*deg^2 / (10 μK$_{CMB}$)^2 / hr*
740	405	0.07	8	7	–	0.8	3.2	16384	3072	6.7	
865	350	0.11	9.5	4	–	0.7	2.8	16384	3072	29.1	
1100	275	0.18	14	2.5	1000	2.1		4096		40.4	0.03
1400	215	0.19	18	2.2	530	1.6		4096		86.3	0.15
2000	150	0.20	26	2.3	310	2.3		1024		41.2	0.23
3000	100	0.30	40	2.7	270	1.5		1024		70.7	0.71

Pixel Distribution over FoV

H = high pixel density in high-frequency bands
L = low pixel density in high-frequency bands

20 arcmin
10 arcmin

L	L	L	L
L	H	H	L
L	H	H	L
L	L	L	L

Critical Technologies

Antenna-coupled pixels
- *Phased array* of long slot dipole antennae tapped by microstrip defines reasonable beam (Goldin 2002, 2003, Kuo et al 2006a, 2006b, Vayonakis et al. 2002)
- Optical bandwidth set by phased-array physical parameters
  - Slot length, extent of array ⊥ to slots:
    ⇒ max λ
    ⇒ size of pixel in (F/#) λ
  - Tap spacing along a single slot, slot spacing: ⇒ min λ.

Status:
- *slot-dipole antennae demonstrated in lab (figure) and prototype camera (poster 101.02, Schlaerth et al. 2008, Vayonakis et al. 2008)*
- *Coupling efficiency, absorption spectra not fully understood, but good (60-70%) for narrow-bandwidth antennae w/short slots*

On-chip in-line bandpass filters
- Long-slot antenna design covers wide bandwidth; need to define bands matched to atmospheric windows
- Use bandpass filters in-line with microstrip to define multiple colors for a single pixel
  - Filters use lumped element capacitors and lumped-element or microstrip inductive elements
  - Filters can be matched to microstrip in-band and have high impedance out of band, many can be used in parallel, outputs feed to independent detectors.

Status: Bandpass filters demonstrated in two varieties and for five of the six nominal bands (poster 101.02, Schlaerth et al. 2008, Vayonakis et al. 2008)

Multi-Scale Pixels
- Want pixel size to scale with λ:
  - too small: poor optical efficiency, too many pixels
  - too large: poor instantaneous sampling of sky
- Binary nature of phased-array antenna summing tree naturally allows factor-of-2 steps in pixel size
  - Output of a pixel of size *L* high-pass-filtered to define high-frequency pixel of size *L*
  - Reflected low-frequency power summed with adjacent pixels to define pixels of size 2*L*, 4*L*, etc.

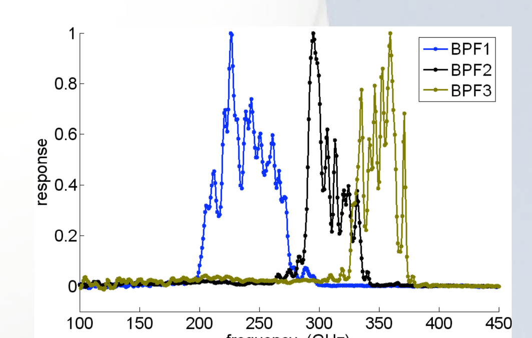
Status: To be demonstrated. Expected difficulties are with photolithography, which may require microstrip crossovers. Low-pass and high-pass filters are similar to demonstrated bandpass filters.

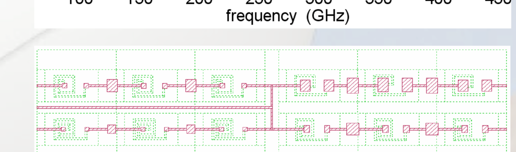
Highly multiplexable bolometric sensors

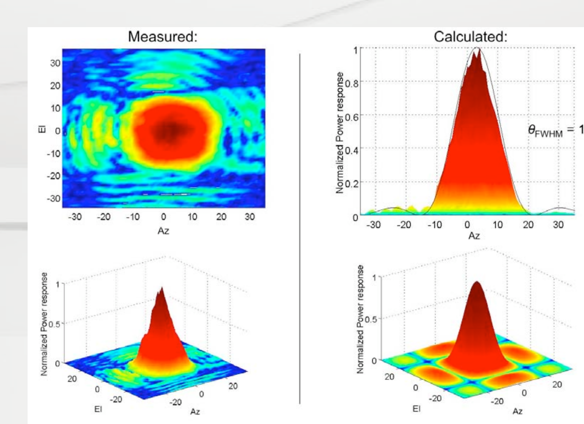
Two good options, both photolithographically compatible with phased-array antennae and in-line filters:
- *Superconducting Transition Edge Sensors (TESs)* (Irwin 1995, Hunt et al. 2002)
  - Demonstrated noise-equivalent powers (NEP) sufficient for background-limited performance in all bands
  - In use/planned for APEX-SZ, ACT, SPT, SCUBA2, CLOVER, BICEP2/SPUD, SPIDER
  - Kpixel-scale time-division-multiplexed SQUID-based readout developed by NIST and UBC, in use by SCUBA2, ACT, CLOVER, BICEP2/SPUD, SPIDER (deKorte et al. 2003, Reintsema et al. 2003)

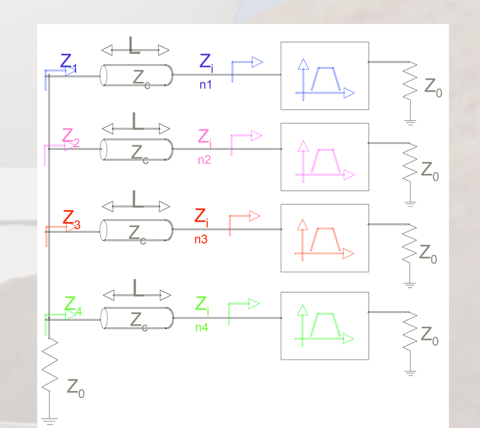
Status: Sensitivity is sufficient. Fab of focal planes of sufficient size and yield at reasonable cost to be demonstrated (in process). Multiplexing at kpixel scale has been demonstrated, probably insufficient for 10s of kpixels. RF SQUID-muxed readout may be needed, is under development at NIST (Irwin and Lehnert 2004)
- *Microwave Kinetic Inductance Detectors (MKIDs)* (Day et al. 2003, Zmuidzinas et al. 2003, Mazin 2004)
  - 1/4-wave notch resonators incorporating MKIDs are easily multiplexed at few GHz RF frequencies (Mazin et al 2006)
  - Not yet demonstrated sufficient performance to be background limited at CCAT site, within a factor of a few, near-term improvements may be sufficient
  - Demonstrated in astronomical observations in a protoype camera (see poster 101.02, Schlaerth et al. 2008, Vayonakis et al. 2008)

Status: X few sensitivity improvement needed, being actively worked on. Control and reproducibility of resonator frequencies to be demonstrated. RF multiplexing demonstrated for small arrays (tens of MKIDs), simultaneous readout of 100s to 1000s of MKIDs to be demonstrated.









Upper left: A portion of a 16-slot, 256-tap slot-dipole phased-array antenna. The slots are red. The pie-shaped objects are capacitors that terminate the microstrip slot taps. The binary summing tree that combines the power from the taps is visible. Figure courtesy of H. G. LeDuc (JPL).
Bottom left: Empirical and theoretical beam maps of a phased-array slot-dipole antenna coupled to a SIS mixer detector, measured at 110 GHz. Figure courtesy of A. Vayonakis (CIT).
Top right: Bandpasses for three in-line bandpass filters measured in the lab by Fourier Transform spectroscopy. Figure courtesy of A. Vayonakis.
Middle right: Photolithographic layout of four parallel lumped-element bandpass filters. Figure courtesy of S. Kumar (CIT).
Bottom right: Schematic of parallel arrangement of in-line bandpass filters. Figure courtesy of S. Kumar.