CCAT Instrumentation

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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

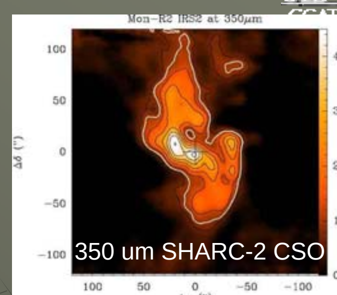
The Present

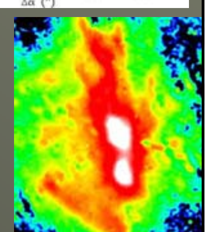
At present, there are a few 10 to 15 m class telescopes of very good surface quality (15 to 25 um rms) in very good submillimeter sites:

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

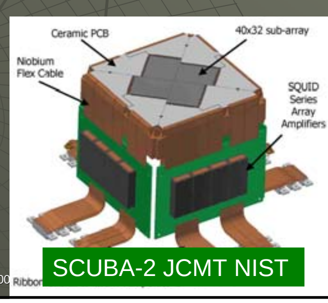
The Present

- 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 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 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

Submmm 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

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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

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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

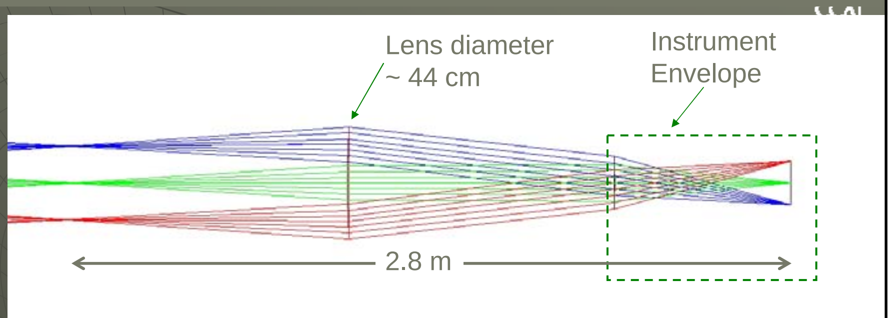
Fore-optics

- 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

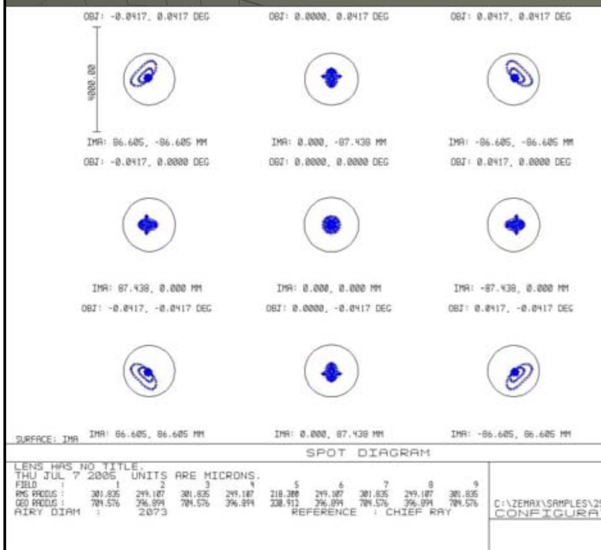
- System is much more compact
  - The instrument is ~ 0.7 x 1.0 m in size, with a 25 cm dewar window
  - However, selection of lens material is problematic – bulk absorption hurts both with transmission, and emission
- Found a variety of materials that will work (e.g. PE, Quartz, Sapphire, Silicon, Germanium)
- 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



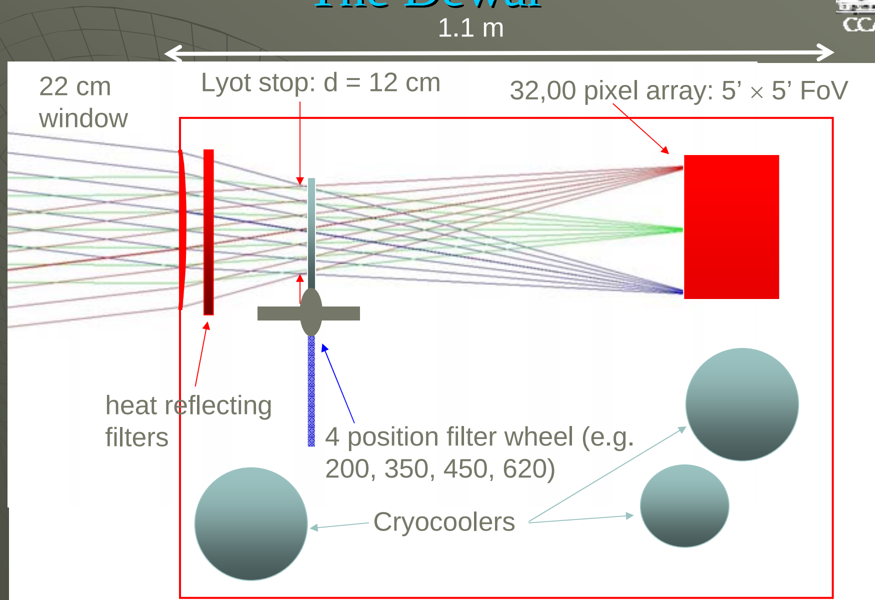
- 44 cm diameter first lens collimates telescopes f/8 beam at 13.5 cm
- Beam is transferred to a 22 cm diameter lens near the pupil which reimages to f/4.8 to Nyquist sample 1 mm square pixels at 350 μm
- Second lens serves as the dewar window (>0.64 cm thick)

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

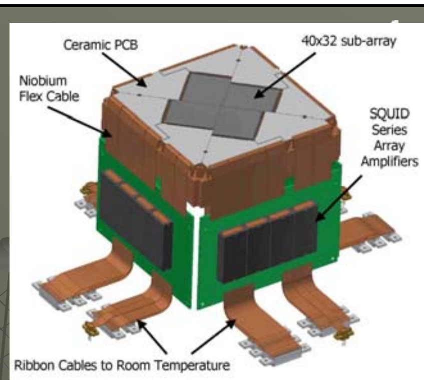
Low T Head

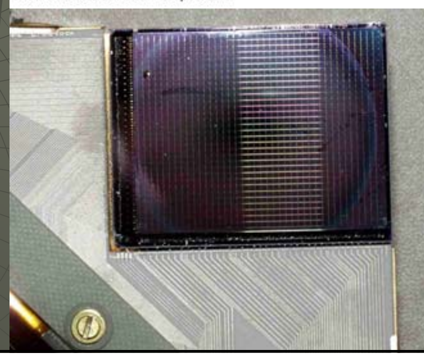
- "He-7" system (e.g. VeriCold):
  - Based on 4K pulse tube cooler (e.g.Cryomech)
    - Cooling power of 40 W at 45 K
    - 1 W at 4.2 K
    - Power consumption ~ 7 KW
  - Two stage ^{4}He and ^{3}He sorption coolers (e.g Chase Research)
  - 100 uW cooling @ 300 mK
- Can go to 225 mK with "He-10" system:
  - 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

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

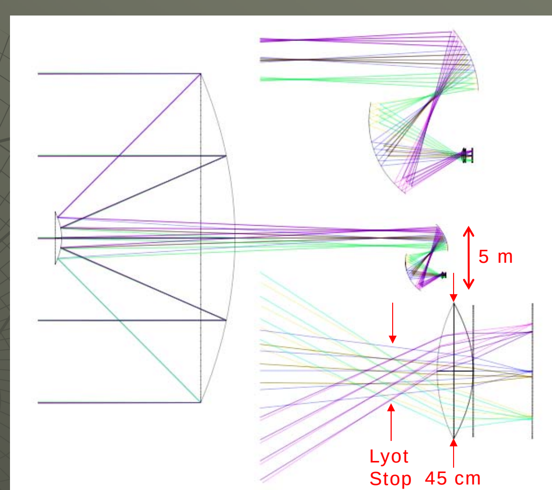
- The long-wavelength camera (LWCam) covers 5 bands from 740 μm to 2 mm
- Fore-optics will be mirror system, since for longer λ’s:
  - The background is much lower so that even the small emissivity of Germanium lenses is not sufficient
  - The beam is much larger, so the relatively poor PSF delivered 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



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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

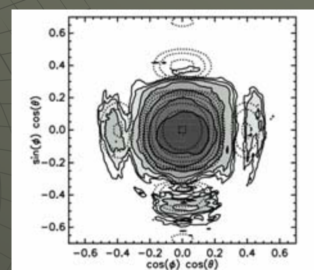
Antenna coupled arrays – 1

- 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 $\sqrt{\varepsilon}$·(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·f·λ pixel
  - Subset of 8^2= 64 slots summed for λ = 740 μm band: 0.7·f·λ 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

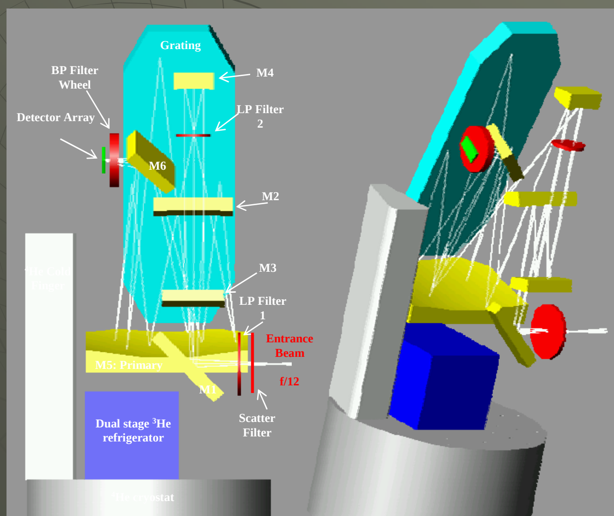
ZEUS – 1

- Redshift (z) and Early Universe Spectrometer (ZEUS)
  - Long slit echelle grating spectrometer
  - Designed for use in the 350, 450, 610 μm telluric windows in 5^{th}, 4^{th}, and 3^{rd} 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

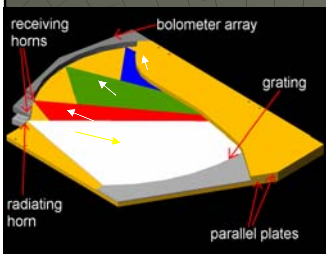
ZEUS mounted on the JCMT

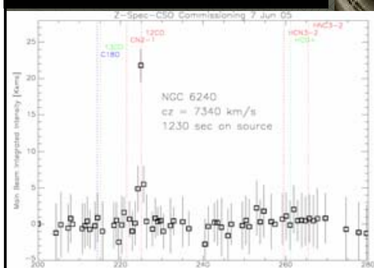
Z-Spec

- 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)

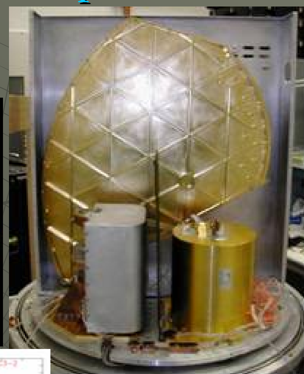
Z-Spec – 2

WaFIRS Spectrometer architecture





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



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

Radiating horn and focal plane

Heterodyne Receivers

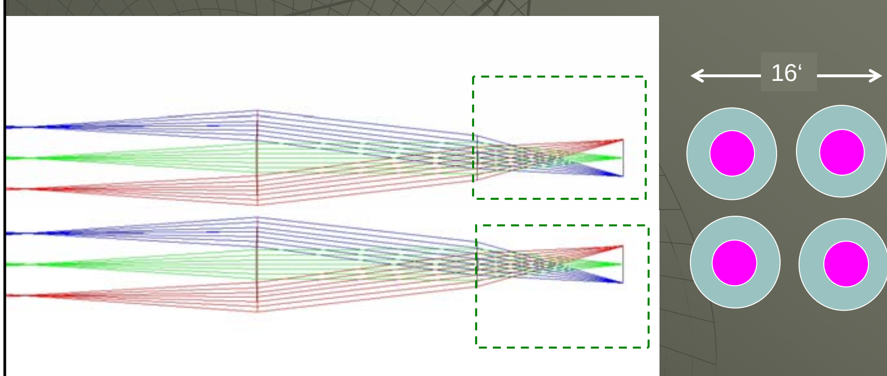
- Heterodyne receivers currently at the CSO allow access to every CCAT telluric window except the 1.5 THz window.
- These receivers have excellent sensitivity – typically within a factor of 5 of the quantum limit
- These are clearly the receivers of choice for high resolution spectroscopy, e.g. for protostars
- 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



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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