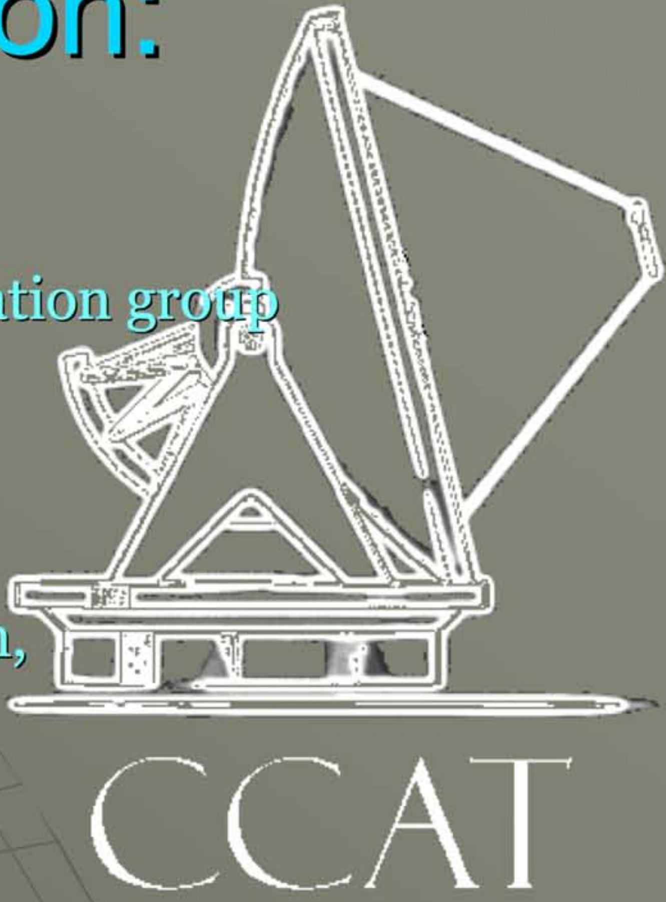
CCAT Instrumentation: SW-Cam



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Waterloo - July 18, 2007

Outline

- Our plans compared with the current state-of-the-art
- Instrument Requirements
  - Need to make compromising decisions that deliver science most efficiently
- Baseline Instruments ("White Paper")– first light
  - Submillimeter wave camera
  - Near millimeter wave camera
- Transferred, and future instrumentation
  - Extragalactic Spectrometer (e.g. Z-Spec and/or ZEUS)
  - Full FoV cameras
  - Heterodyne spectrometers

CCAT

- 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 (~ 5600 m) 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 19,456 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

Additional CCAT Instrumentation

- 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
- These instruments could be transferred, or developed later.

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 (@450 μm)
  - 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

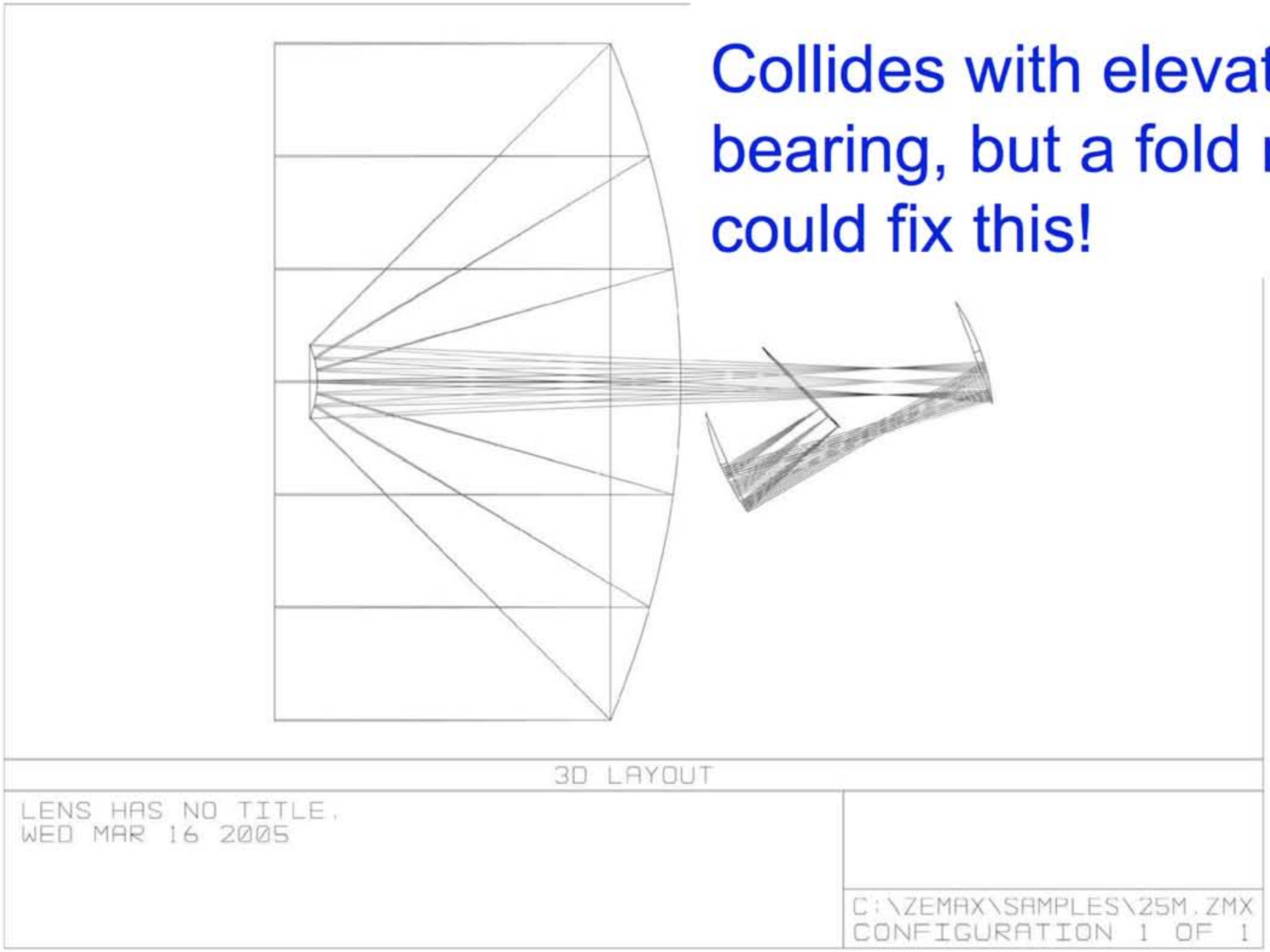
Two Designs Considered

- All reflective design
  - Maximizes throughput
  - Minimizes emissivity
  - Off-axis approach leads to BIG optics
- Transmissive design
  - Nice, compact design
  - Throughput and emissivity quite good
- Direct imaging
  - Would be fine at 200 um, over-sampled at longer wavelengths
  - Problems with stray light…

All Reflective Design

Works!- Full 17’ FOV

Collides with elevation bearing, but a fold mirror could fix this!



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3D LAYOUT
LENS HAS NO TITLE.
WED MAR 16 2005
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CONFIGURATION 1 OF 1
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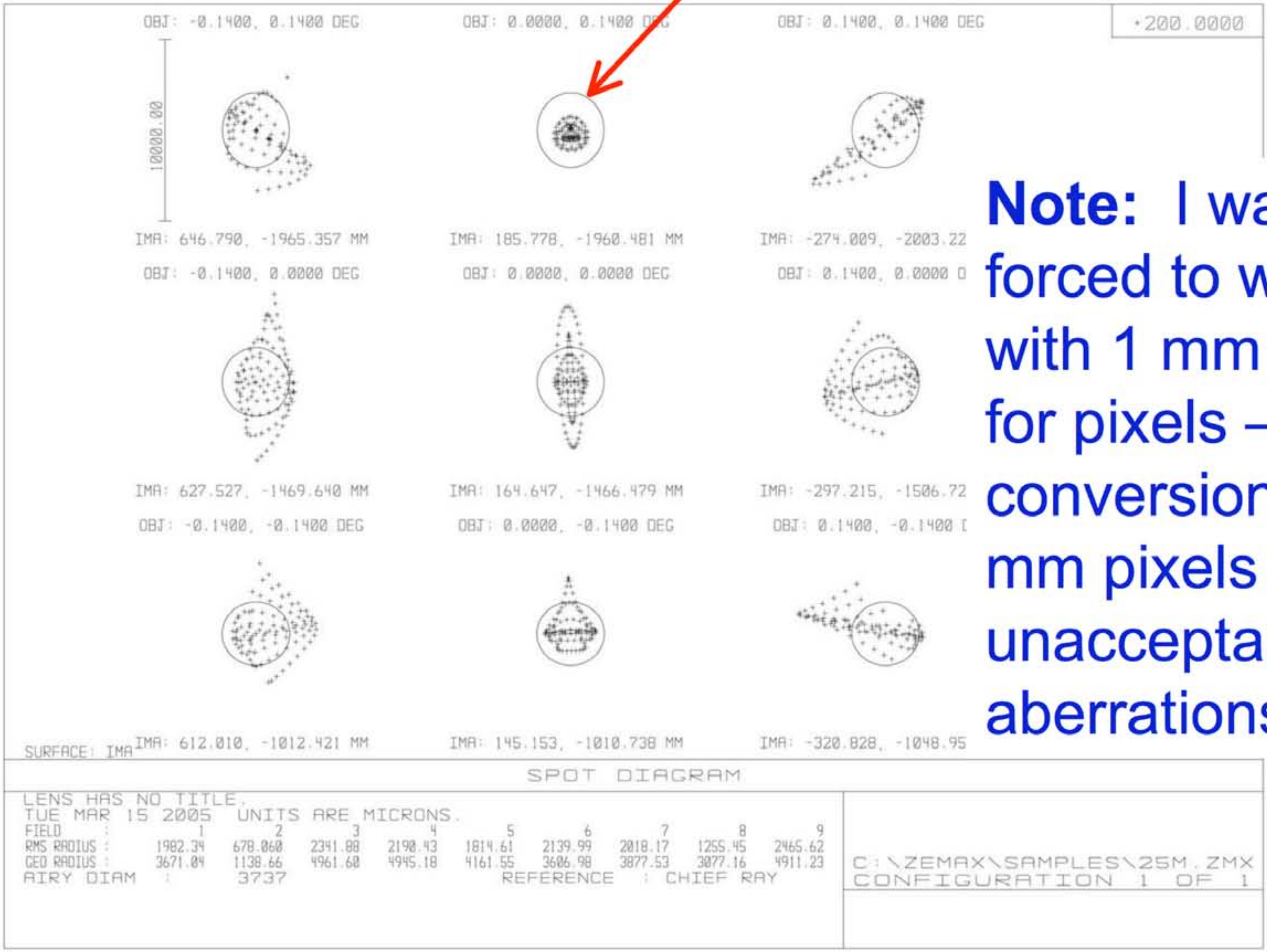
Marginally OK Spot Diagrams



2λ/d at 350 μm

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SPOT DIAGRAM

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TUE MAR 15 2005  UNITS ARE MICRONS.
FIELD      :       1        2        3        4        5        6        7        8        9
RMS RADIUS :  1982.34  678.060  2341.88  2190.43  1814.61  2139.99  2018.17  1255.45  2465.62
GEO RADIUS :  3671.04  1138.66  4961.60  4945.18  4161.55  3606.98  3877.53  3077.16  4911.23
AIRY DIAM  :     3737                    REFERENCE  : CHIEF RAY

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CONFIGURATION 1 OF 1
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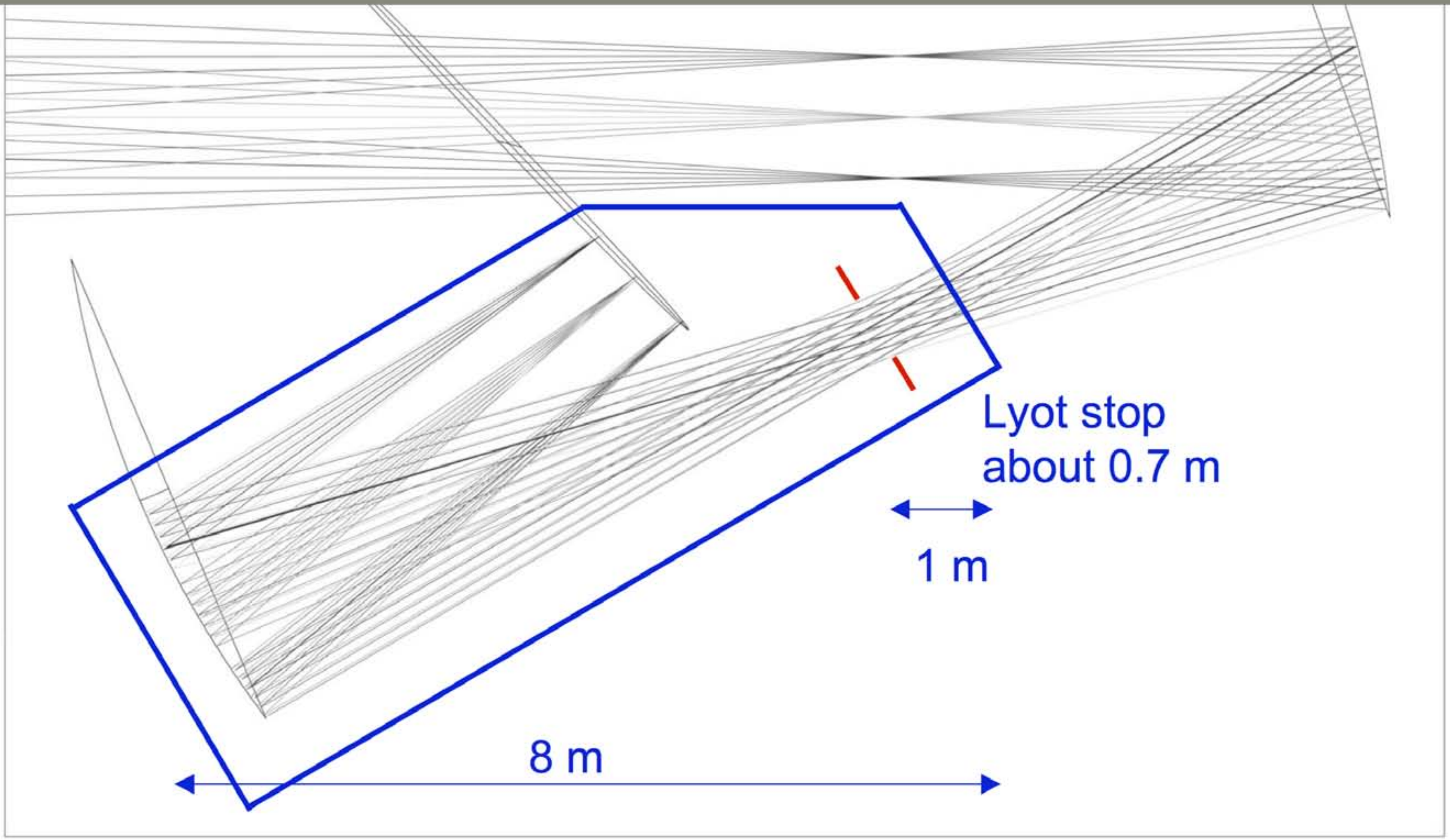
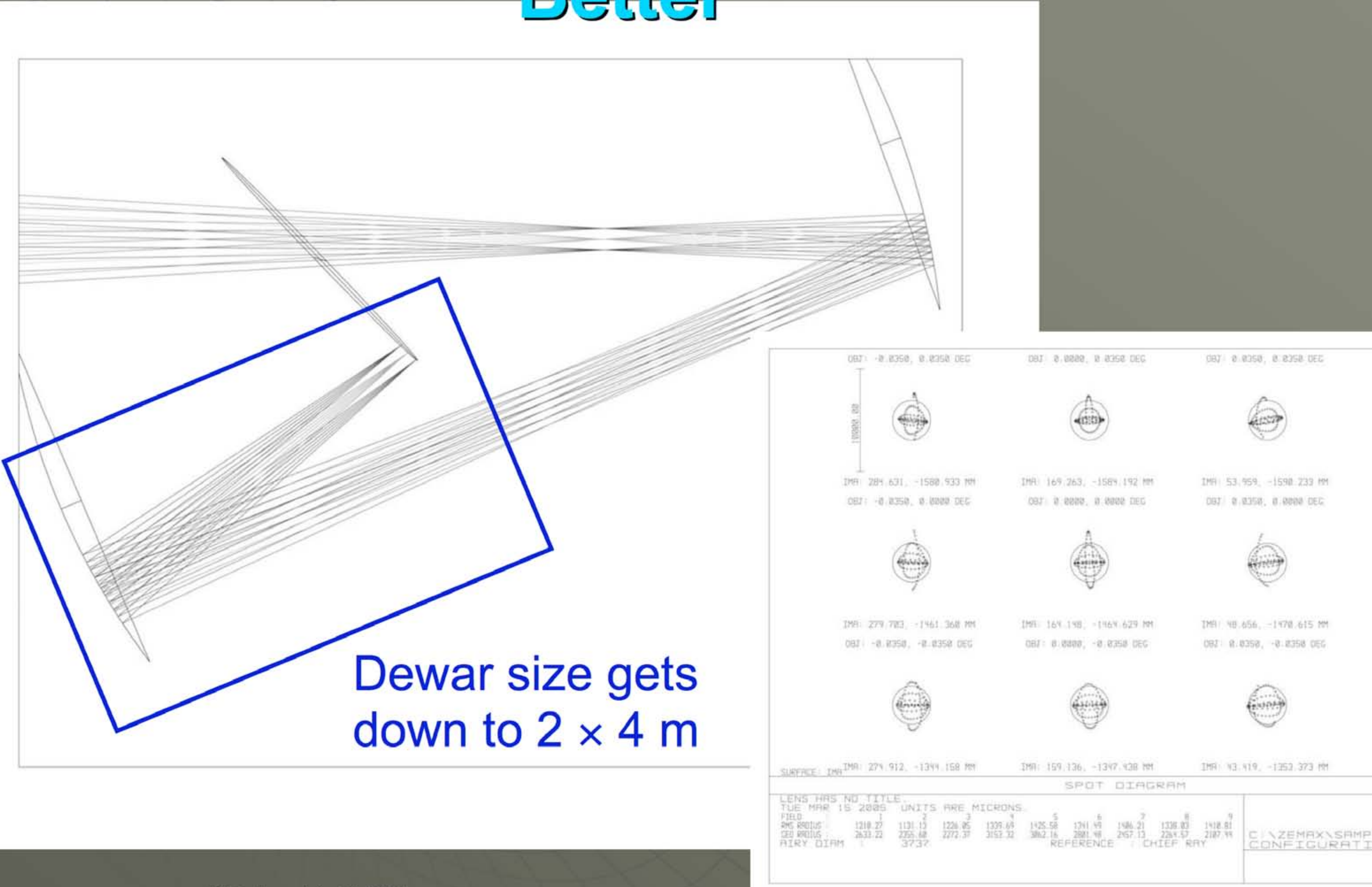
Note: I was forced to work with 1 mm pitch for pixels – the f/# conversion to 0.5 mm pixels lead to unacceptable aberrations

But…, It's a bit LARGE!



AST/RO, SPIFI, and Steve Parshley

The Smaller (4’) FOV Works Much Better



Dewar size gets down to 2 × 4 m

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OBJ: -0.0350, 0.0350 DEG          OBJ: 0.0000, 0.0350 DEG          OBJ: 0.0350, 0.0350 DEG

IMA: 284.631, -1580.933 MM        IMA: 169.263, -1584.192 MM       IMA: 53.959, -1590.233 MM
OBJ: -0.0350, 0.0000 DEG          OBJ: 0.0000, 0.0000 DEG          OBJ: 0.0350, 0.0000 DEG

IMA: 279.703, -1461.360 MM        IMA: 164.148, -1464.629 MM       IMA: 48.656, -1470.615 MM
OBJ: -0.0350, -0.0350 DEG         OBJ: 0.0000, -0.0350 DEG         OBJ: 0.0350, -0.0350 DEG

SURFACE: IMA
IMA: 274.912, -1344.158 MM        IMA: 159.136, -1347.438 MM       IMA: 43.419, -1352.373 MM
                                 SPOT DIAGRAM
LENS HAS NO TITLE.
TUE MAR 15 2005  UNITS ARE MICRONS.
FIELD      :     1        2        3        4        5        6        7        8        9
RMS RADIUS :  1210.27  1131.13  1226.05  1339.69  1425.58  1341.49  1486.21  1338.03  1410.81
GEO RADIUS :  2633.22  2355.60  2272.37  3153.32  3062.16  2801.48  2457.13  2264.57  2107.94
AIRY DIAM  :     3737                         REFERENCE  :  CHIEF RAY
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Transmissive Optics

- System is much more compact
  - Instrument is then only ~0.7 × 1.1 m in size, with a 25 cm dewar window
  - However, selection of lens material is an issue – bulk absorption hurts both with transmission, and emission
- Found a variety of materials that will work (e.g. PE, Quartz, Sapphire, Silicon, Germanium)
- Selected Silicon primarily due to its small extinction coefficient

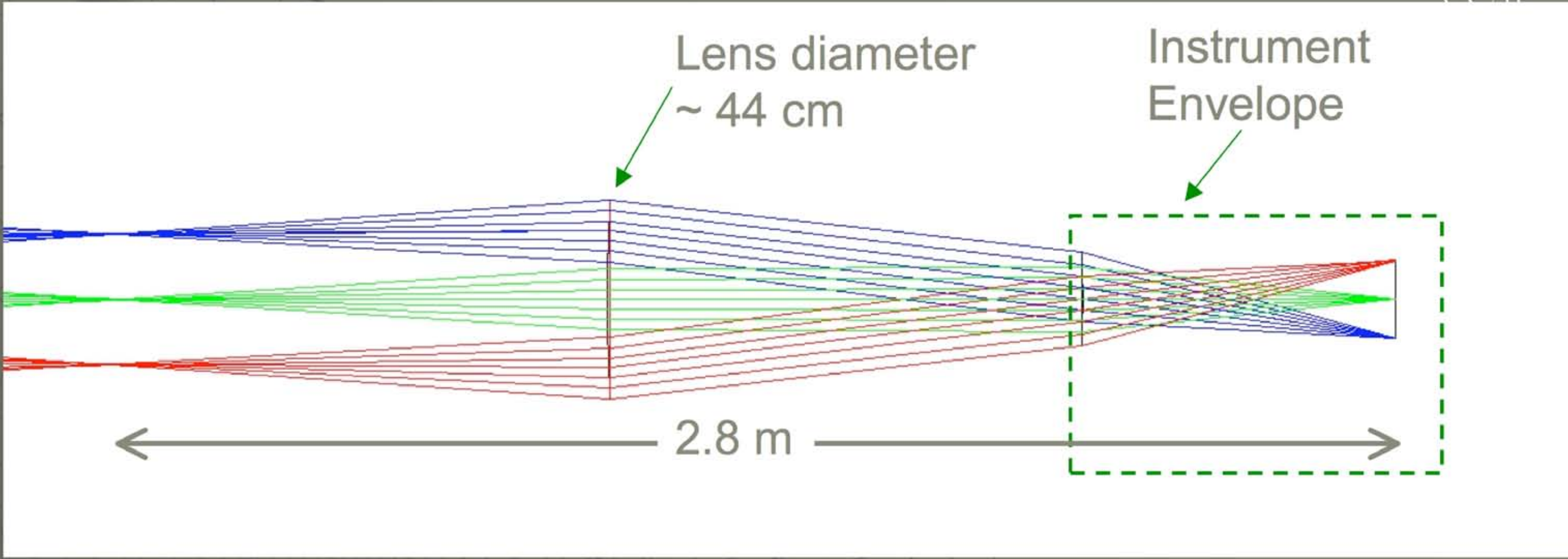
Lens Materials Considered

Material	Index	Extinction Coefficient	Radius of Curvature (cm)	Thick-ness (cm)	Trans-mission
Polyethylene	1.506	0.126	50.6	10.3	69%
Sapphire	3.2	0.91	220	2.13	38%
Fused silica	1.81	0.179	81	6.0	59%
Quartz	2.113	0.089	111	4.28	83%
Germanium	4.006	0.073	300	1.56	**93%**
Silicon	3.416	0.040	242	1.94	**96%**

Transmissive Optics

- Other important selection criteria
  - Material properties – environmental (H_2O), structural (window)
  - Cost and availability
  - AR coating
- Design is based on Silicon lenses.
  - Broad band (200 to 650 um) A/R coating achieved by tapering the index of the surface
    - Micro-machine pyramid-like structures
    - Under investigation at Caltech/JPL (Golwala)
  - These A/R coatings ⇒ transmissions > 90%

Silicon Lens Design: 5' FOV



Lens diameter
~ 44 cm

Instrument
Envelope

2.8 m

- 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 onto 1 mm square pixels (Nyquist sampled at 350 μm)
- Second lens serves as the dewar window (>1 cm thick)

Silicon Lens Design: 5’ FOV

λ/d at 350 μm

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LENS HAS NO TITLE.
THU JUL 7 2005  UNITS ARE MICRONS.
FIELD      :       1        2        3        4        5        6        7        8        9
RMS RADIUS :    301.835  249.107  301.835  249.107  218.300  249.107  301.835  249.107  301.835
GEO RADIUS :    704.576  396.894  704.576  396.894  330.912  396.894  704.576  396.894  704.576
AIRY DIAM  :     2073                        REFERENCE  : CHIEF RAY
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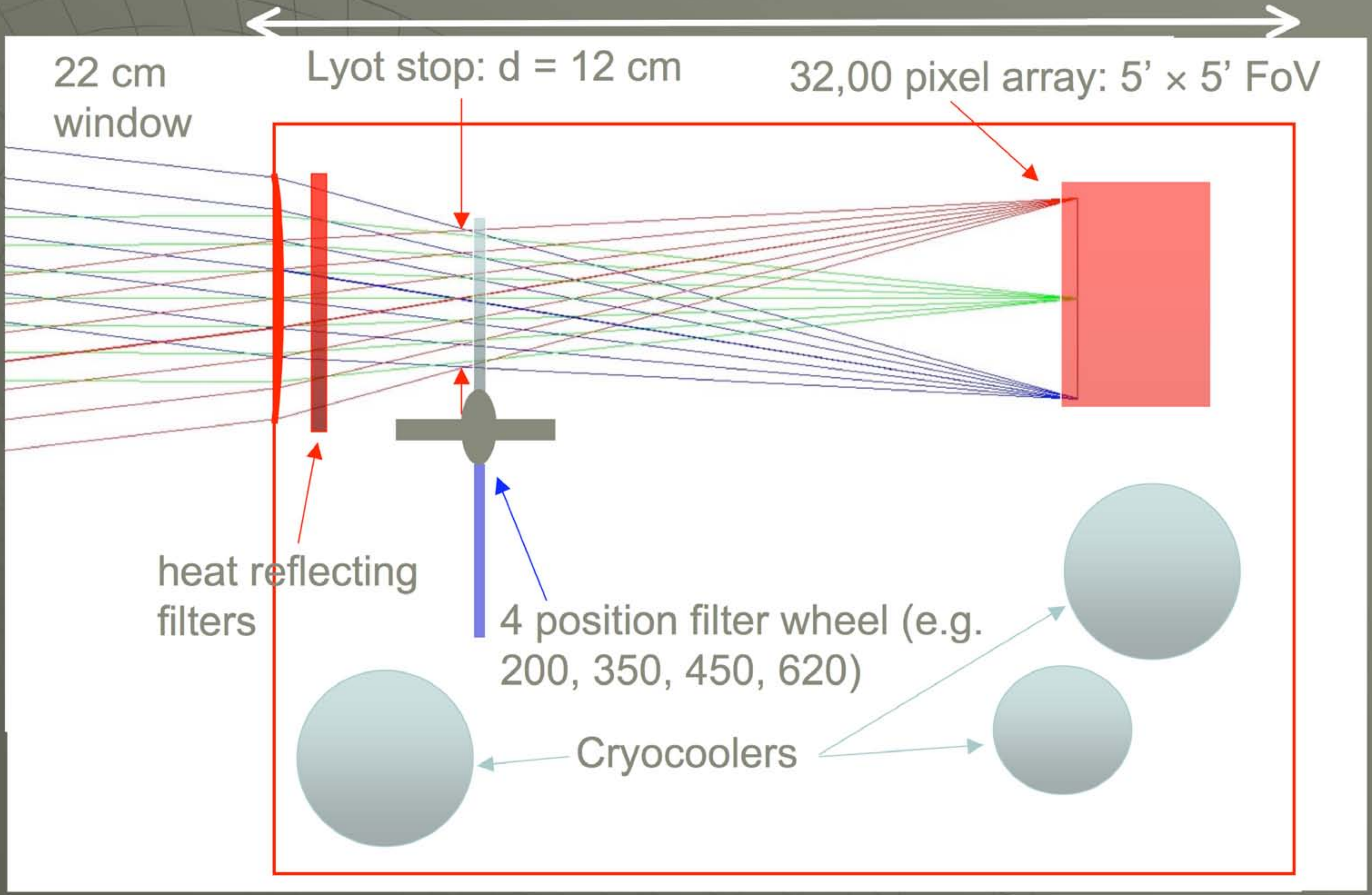
- Spot diagram is *excellent* – circle is λ /d at 350 μm
- Image plane is curved so can do better with curved focal plane
- Can do significantly better with somewhat larger lenses, but this is not deemed necessary

The Dewar



1.1 m

22 cm window

Lyot stop: d = 12 cm

32,00 pixel array: 5’ × 5’ FoV

heat reflecting filters

4 position filter wheel (e.g. 200, 350, 450, 620)

Cryocoolers

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/dual ^{3}He ("Helium-10") system cools detector package to 240 mK
  - For the baseline camera, requisite NEP is achievable with a head temperature of 240 mK
  - We get NEPs ~ 3×10^{-17} W/Hz with Zeus at 240 mK
- For margin, can use ADR to cool detector to 60 mK
- The end stage coolers are closed cycle ^{3}He systems or ADRs that are temperature stable, and vibration free

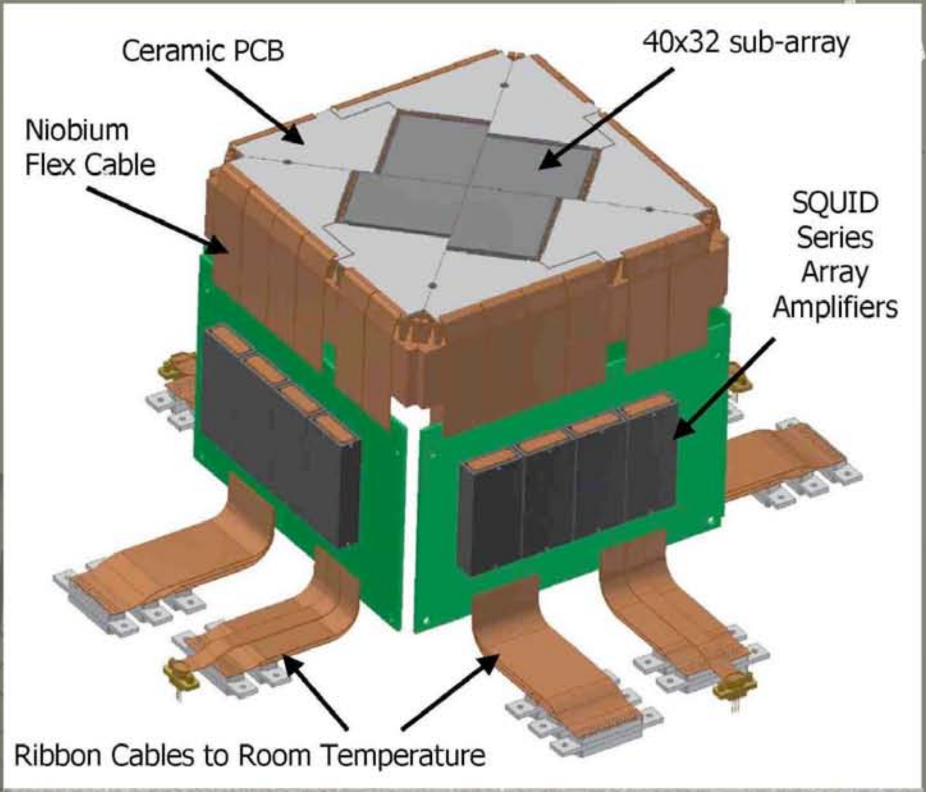
Sensitivity

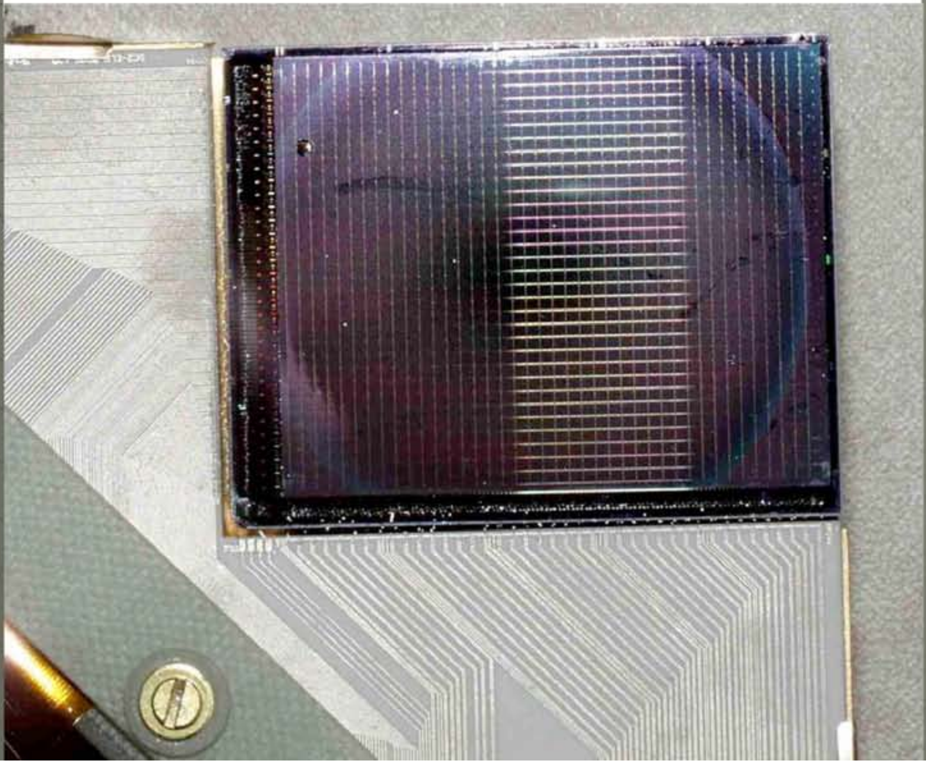
- Sensitivity ~ 1 mJy (5 σ in 1 hour) @ 350, 450, & 620 μm – 20 times worse at shorter wavelengths
- Confusion limits are about the same at 350 μm and about 20% higher at 450 and 620 μm

Band	5σ, 1 hour (mJy)	Conf. Limit (mJy)	Time to Conf. Limit (sec)	Conf. Limit src density (#/sq-deg)
200	22.7	0.36		116000
221	18.8	0.53		89400
298	17.6	0.93		54700
350	1.20	1.29	3100	37900
450	0.95	1.45	1540	22900
620	1.07	1.28	2500	12100

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: “spider-web” arrays
  - GSFC pop-up and BUG arrays (e.g. SHARC-2, ZEUS, & GISMO)
  - NIST arrays SCUBA-2/ZEUS-2
- These arrays easily deliver the requisite sensitivities ($< 10^{-16}$ $W/Hz^{-1/2}$) for SWCam with milli-Kelvin cold heads



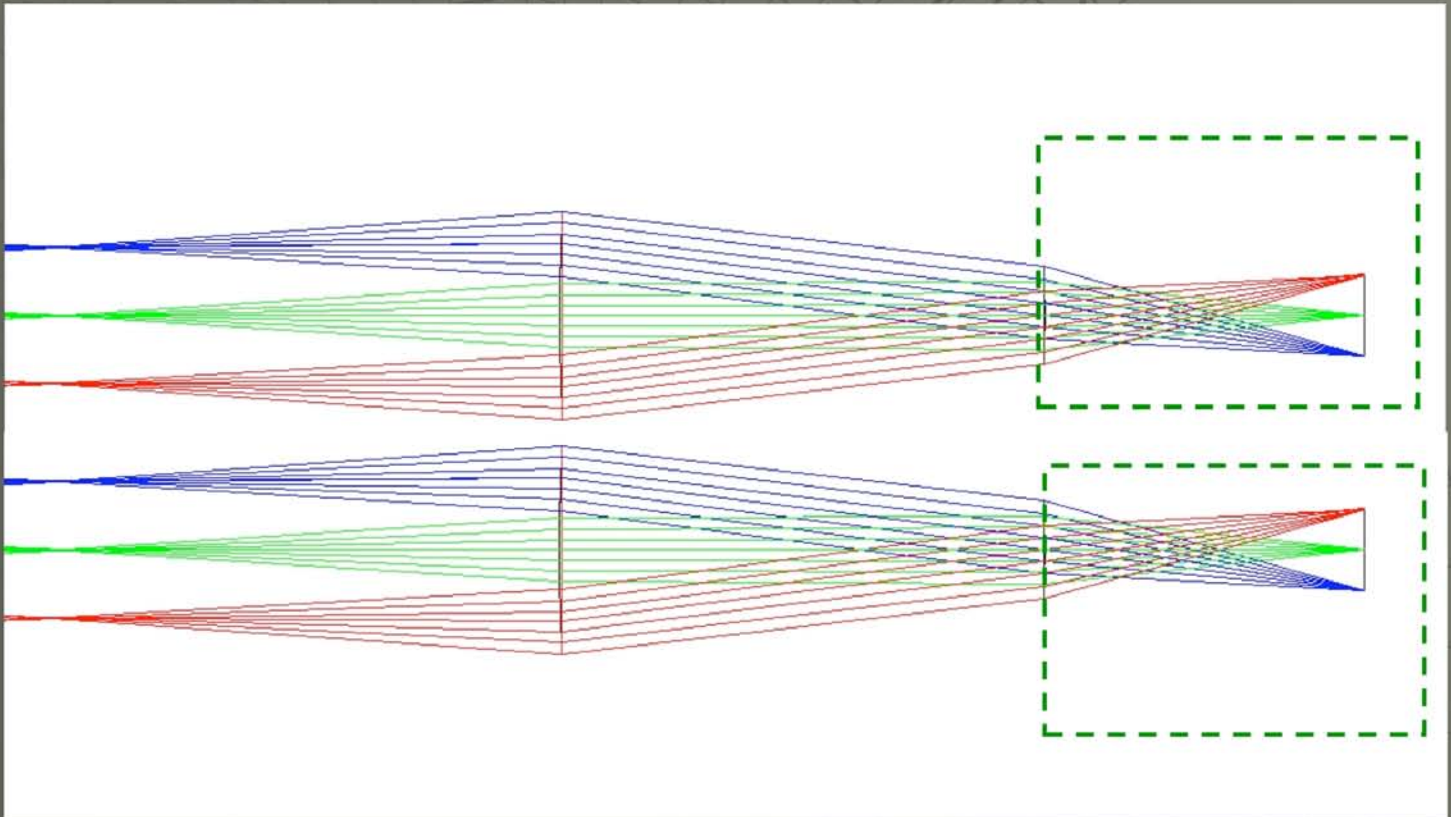


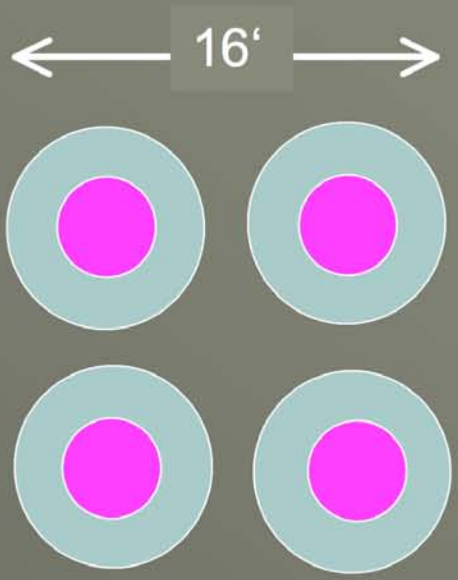
Future Instruments for CCAT

- 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 imager

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 1/4 the available FoV

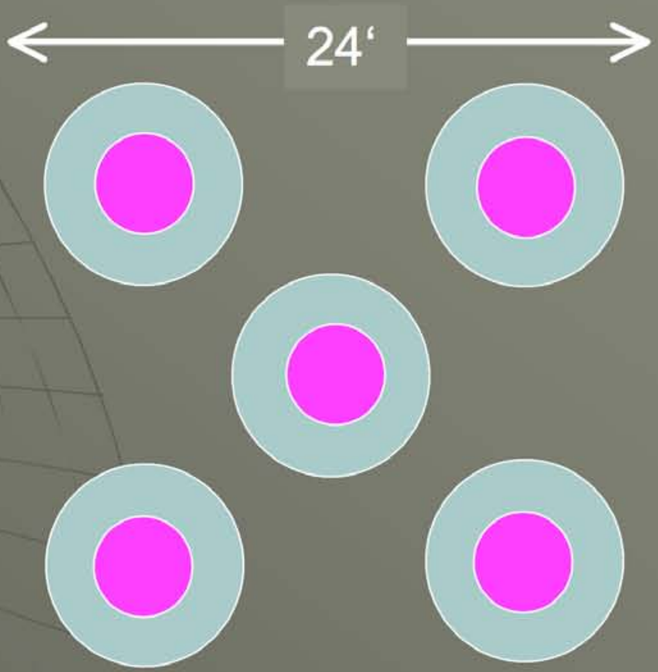




SWCam

- 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 1/4 the available FoV

"Saturn V" configuration covers 127 square arcminutes, or 32% of the available FoV



Summary

- 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
- Spectrometers -- Current Plan: Employ "borrowed" direct and heterodyne detection spectrometers
  - Likely upgraded to include multi-object capabilities
- Second generation instruments include dedicated multi-object spectrometers and a far-IR (40 μm) camera