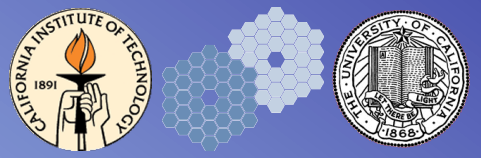


# AO Relay Optomechanical Mini-review
# Optical Design

Contributors: Reni Kupke, Chris Lockwood, Jim Bell

# Requirements

- Location:
  - The AO system will reside on the left Nasmyth platform. (SR-744)
- Wavelength Range
  - The AO relay shall transmit a wavelength range of 0.818μ - 2.4μ for the NIR imager (INT 157) and NIR integral field spectrograph (INT-382).
  - The AO relay shall transmit 1.16-1.77μ to the LOWFS (FR-175) and shall not preclude K-band
  - The AO relay shall transmit 1.1-4.1μ to the interferometer (SR-683).
  - The NGS WFS will require 0.4-0.8μ light (FR-140 and KAON 642).
  - THE LGS WFS will require 589nm sodium light (FR-523).
- Entrance Window
  - The entrance window shall provide a thermal seal between the cold enclosure of the AO system and the ambient room temperature. It shall consist of two windows to prevent condensation, and it shall be big enough to transmit the entire 120” field of view.

# Requirements

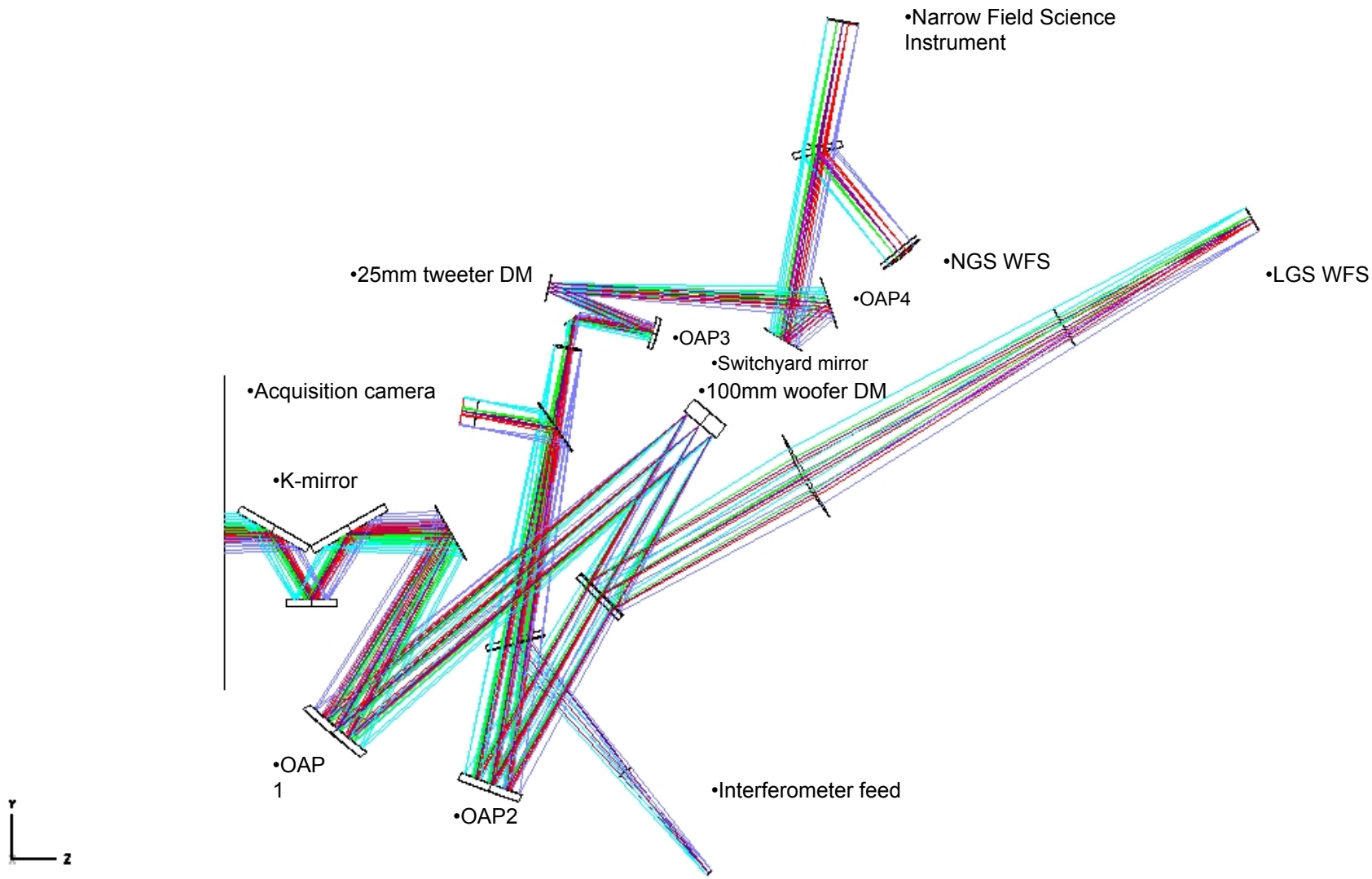
- Field of View:
  - A high Strehl science relay with an unvignetted field of view (FOV) of at least 20 arcseconds diameter with a goal of 40 arcseconds diameter. (FR 41)
  - A 120 arcsecond diameter field of regard (FOR) at the focal plane of the first relay, providing natural guide stars (NGS) for the low-order wavefront sensors (LOWFS ). (FR 40)
  - A 120 arcsecond diameter unvignetted FOR for guidestars from 80 to 120km in altitude to the LGS WFS.
  - There is currently no FOR requirement stated for the NGS WFS.
- . Output pupil location:
  - The exit pupil for the first relay will be telecentric to simplify design of the LOWFS pick-off mechanisms. (FR-1502)
  - The exit pupil for the entire relay will be telecentric to simplify design of the NGS WFS. (FR-1501)

# Requirements

- Field and Pupil Rotation:
  - The optical relay will have a K-mirror upstream of the science instruments and wavefront sensors that can pass the entire field of view.
- Deformable mirrors
  - The wide field relay shall contain a deformable mirror conjugate to the telescope pupil, with a pupil size of 100mm. The deformable mirror shall have 22 actuators across the pupil diameter. (FR-32 and FR-56). The requirements do not state whether this is circumscribed pupil diameter, maximum mirror diameter, active mirror area, or mirror area, so a primary mirror diameter of 10.949m circumscribed mirror diameter is assumed.
  - The narrow field relay shall contain a deformable mirror conjugate to the telescope pupil with a pupil size of 24mm. The deformable mirror shall have 63 actuators across the pupil diameter. (FR-33 and FR-57).

# Requirements

- Output focal ratio:
  - The output focal ratio of the first relay shall be the same as the input focal ratio of the telescope, and shall be made compatible with the input for the LOWFS, the second relay, the acquisition camera, and the interferometer. (F-1499)
  - The output focal ratio of the second relay shall be greater  than f/40 . (FR-1500)
- Optical Switchyard
  - The relay design should provide for a LGS WFS sodium dichroic (FR-67), a removable NGS WFS dichroic (FR-39), and a removable acquisition camera fold (FR-68). There are currently no requirements for alternate instrument selection.


•Narrow Field Science Instrument
•NGS WFS
•LGS WFS
•25mm tweeter DM
•OAP4
•OAP3
•Switchyard mirror
•Acquisition camera
•100mm woofer DM
•K-mirror
•OAP 1
•OAP2
•Interferometer feed
Y
Z

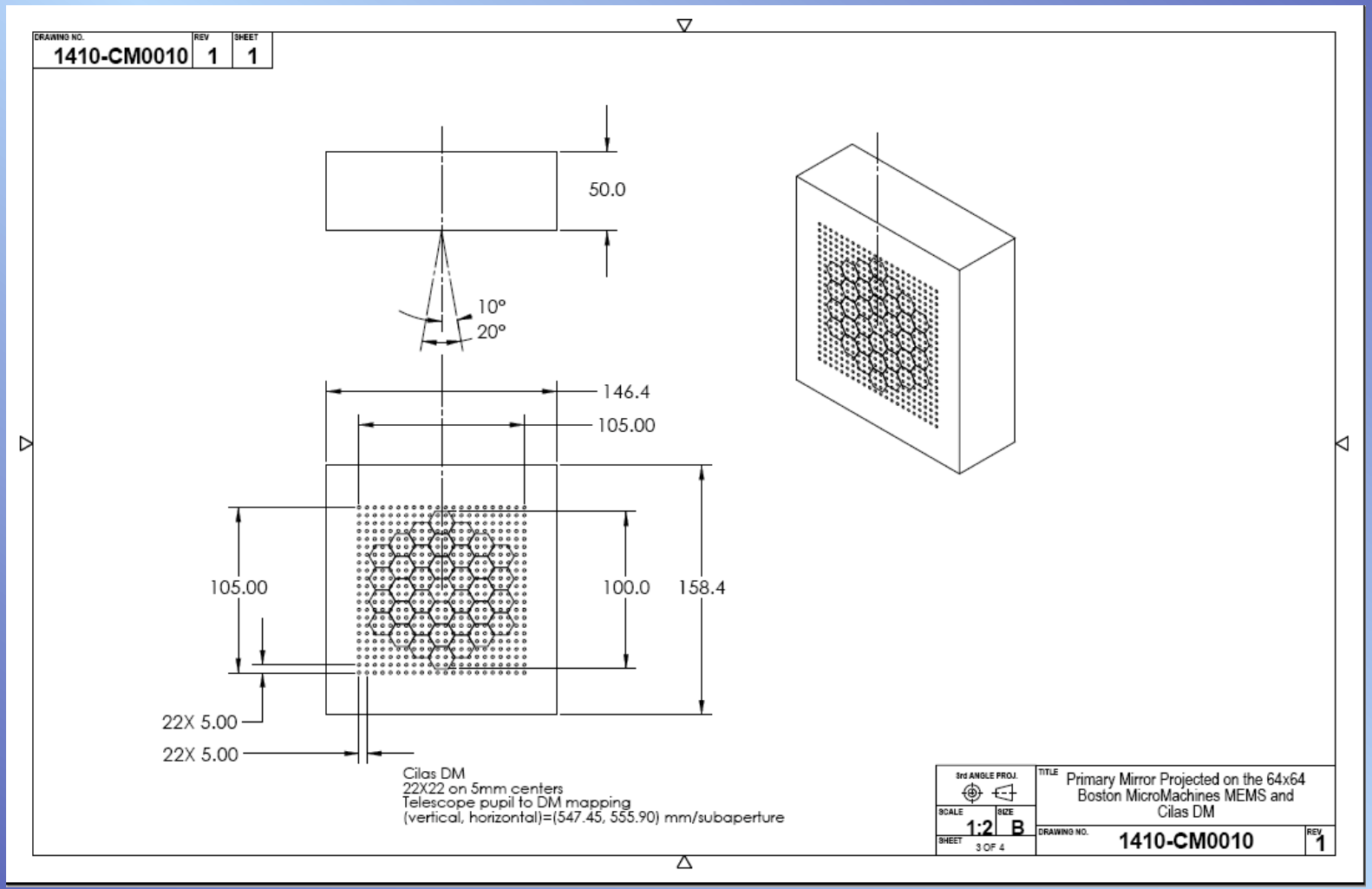
## K-mirror

- Location of telescope focus inside K-mirror, halfway between K1 and K2.
- Angles of incidence on K1 (60 degrees), K2, and K3 (60 degrees) are identical to existing Keck AO.
- Sizes of K1, K2, and K3 in design document are given as 90% clear aperture.
- Coating not yet specified. Will we recoat other Keck K-mirror to match?

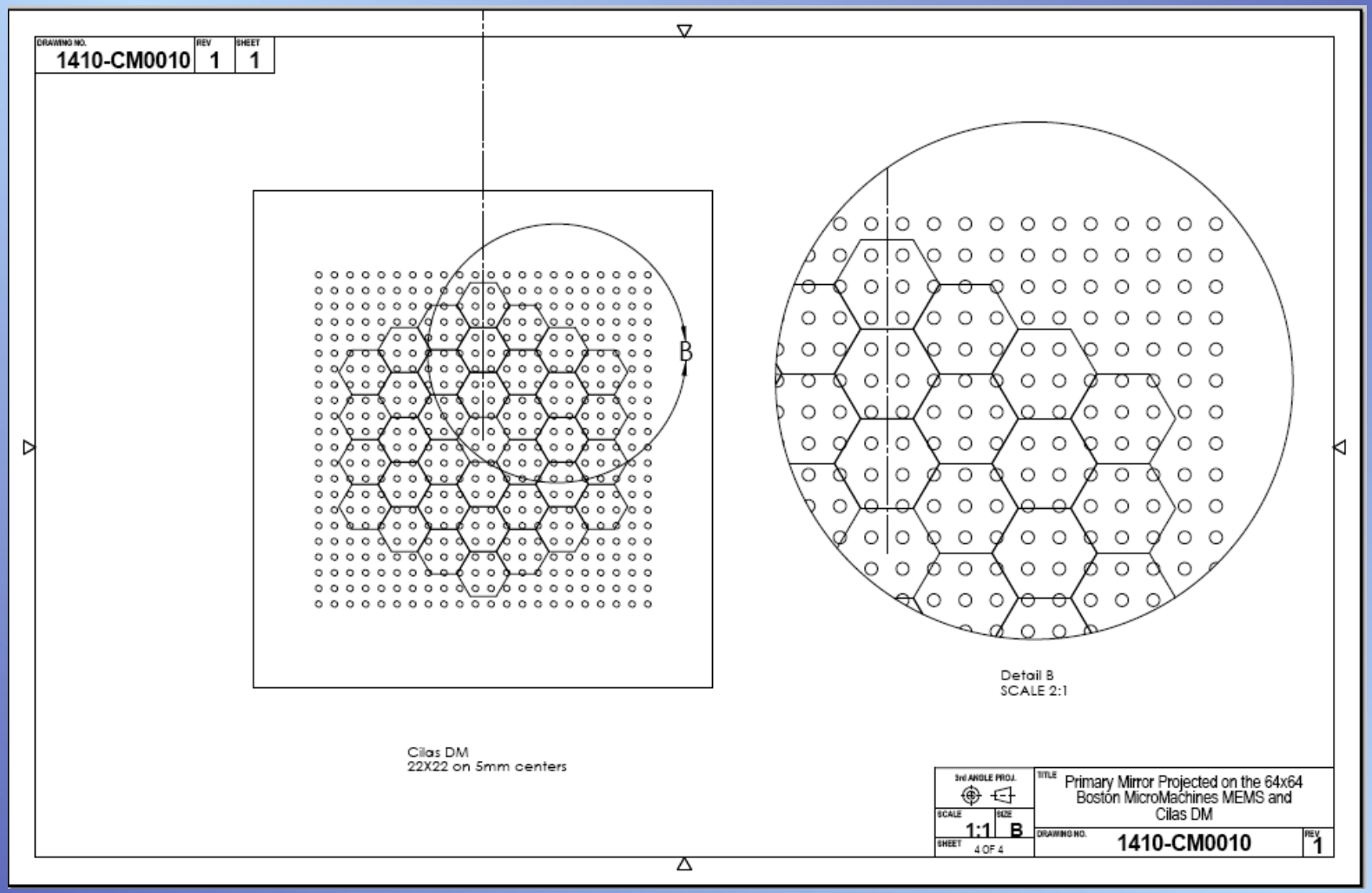
## Fold Mirror

- Needed for packaging.
- Angle of incidence, 30 degrees
- Conjugate height, 22km.

# Keck primary on woofer



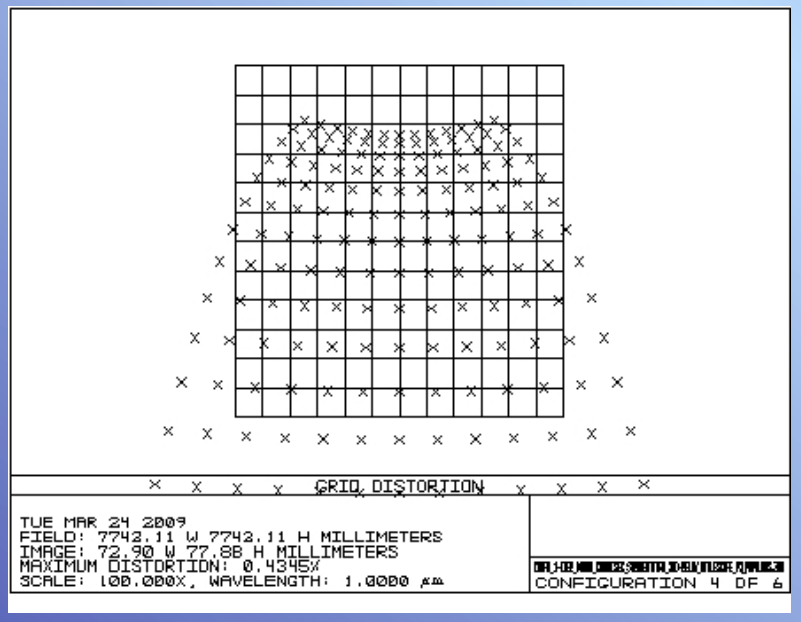
# Keck primary on woofer

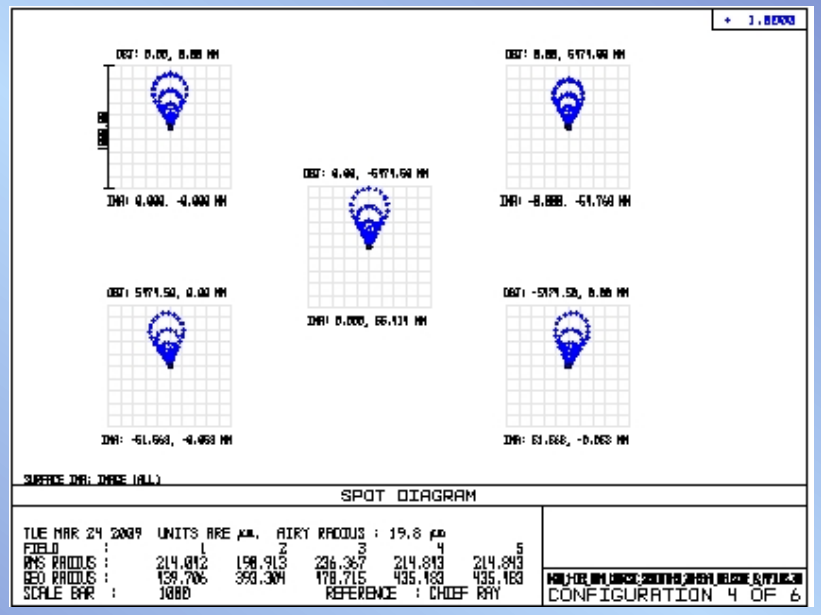


# First relay deformable mirror

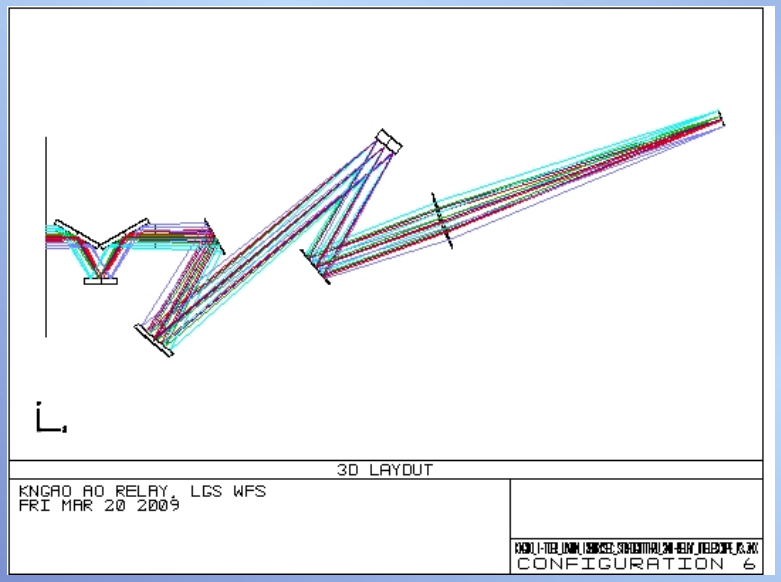
## 22x22 actuator, 5 mm pitch device

- Grid distortion of pupil 0.43% (requirement, 5%).
- Pupil aberrations (120 arcsecond field of view) produce 0.2mm rms radius, 4% of 5mm pitch.



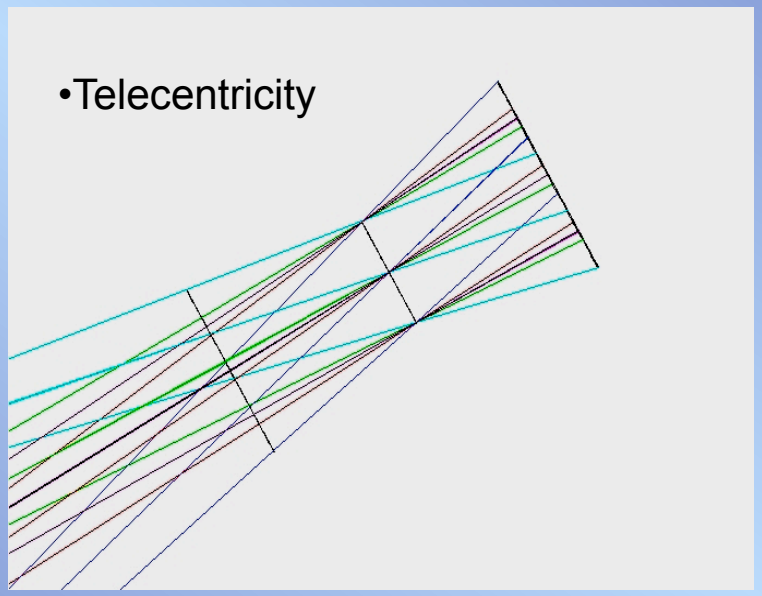



# Wide field Relay
# LGS WFS feed



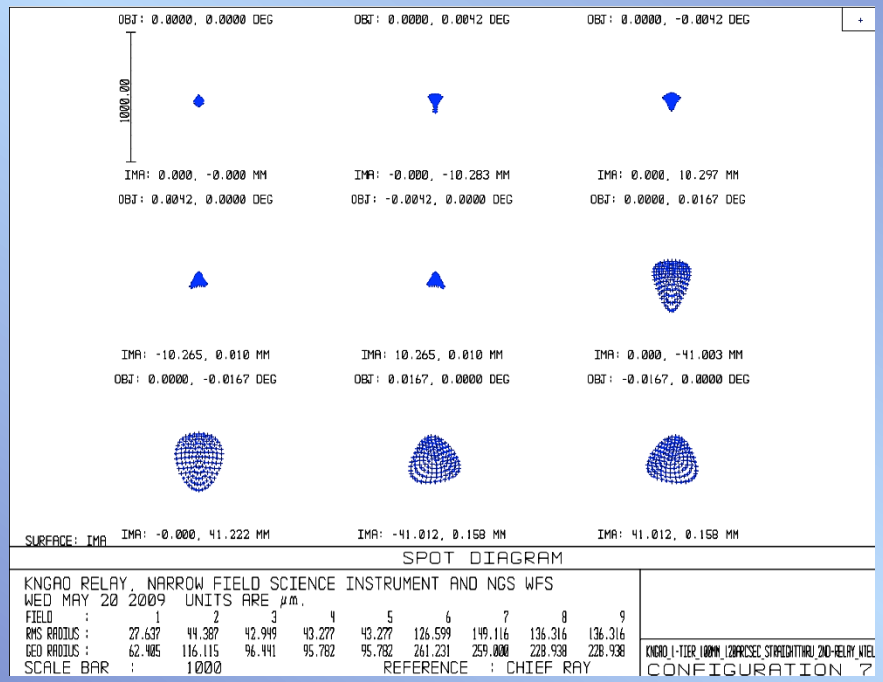

- LGS WFS notch dichroic reflects only Sodium light.
- Plano-parabolic lens forms image plane for LGS WFS.

- EXPP is not valid for decentered systems.
- Paraxial lens at image plane to check for telecentricity.



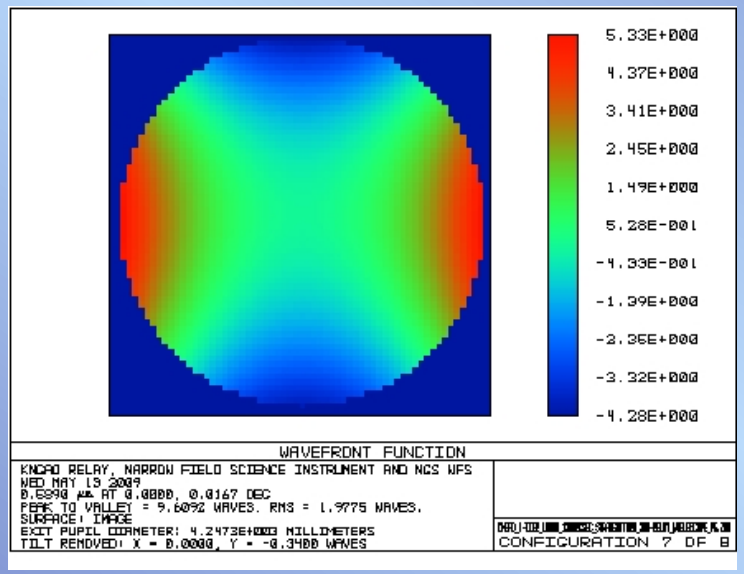
# LGS WFS Performance

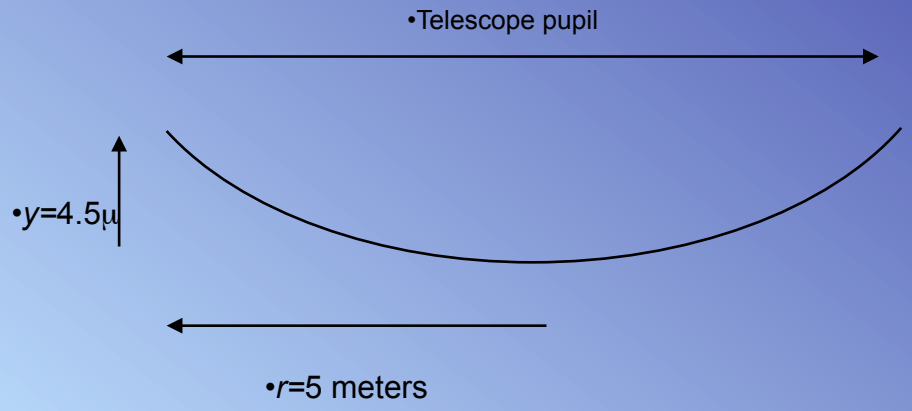
- With plano-parabolic imaging lens, LGS WFS reaches performance requirement of 250mas spot size.




| Conjugate height | FOV, arcsec | Field Curvature (mm) | RMS WFE (μ) | RMS Spot Radius (milli-arcseconds) |
|---|---|---|---|---|
| 90km | 120 | 883.205*1.4 | 1.4 | 233 |
| 180km | 120 | >2000* | 1.6 | 265 |

# •LGS WFS Hartmann spot displacement due to static aberrations.




**•The wavefront error on the extreme field points of the LGS WFS is dominated by astigmatism.**

**•Use the slope of the wavefront to determine the maximum spot displacement on the wavefront sensor:**

$$y = ar^2 \rightarrow 4.5 \times 10^{-6}\,\mathrm{m} = 25\,\mathrm{m}^2 a$$

$$a = 1.8 \times 10^{-7}\,\mathrm{m}^{-1}$$

**•where *y* is the 0 to peak wavefront error across the pupil, and *r* = 5m is the pupil radius.**

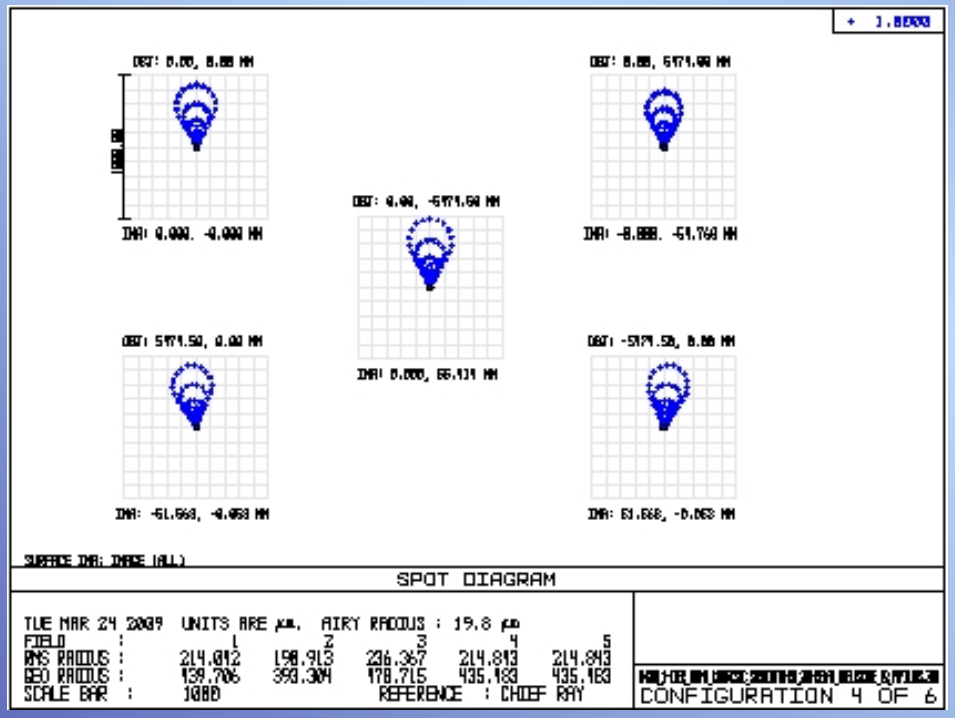
$$\frac{dy}{dr} = 2ar = 3.6 \times 10^{-7}\,\mathrm{m}^{-1}(5\mathrm{m}) = 1.8 \times 10^{-6}\ \text{radians}$$

$$= 0.37\ \text{arcseconds}$$

**•LGS WFS detector has 1.5 arcsecond pixels, 4x4 subapertures, so maximum spot movement is ~6% of a subaperture.**

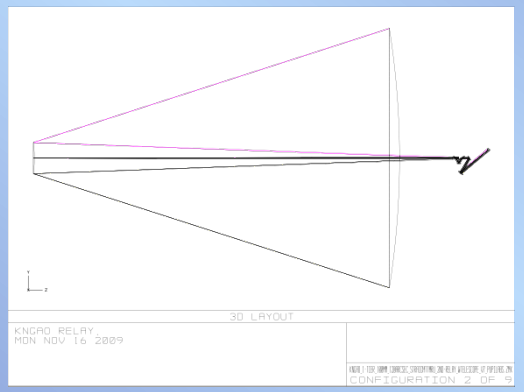
# LGS WFS pupil aberrations

•Pupil aberrations on woofer DM over 120 arcsecond field are significant compared to size of lenslet when sampling at 64x64.

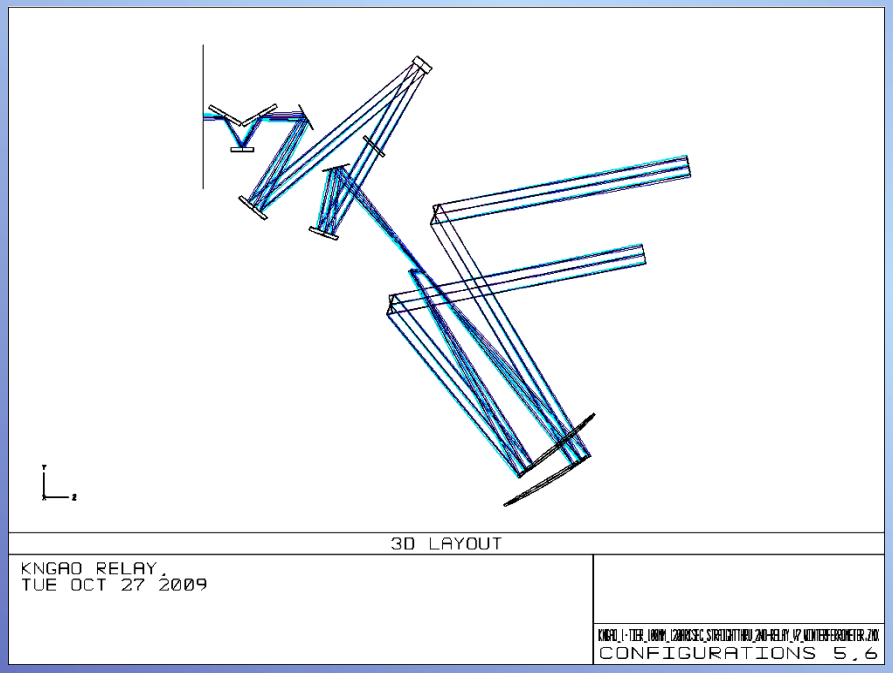



•Primary mirror as imaged onto woofer DM.

•RMS radius of 0.2mm small compared to 5mm DM pitch, but large compared to 64x64 sampling at LGS WFS (13% of a subaperture).



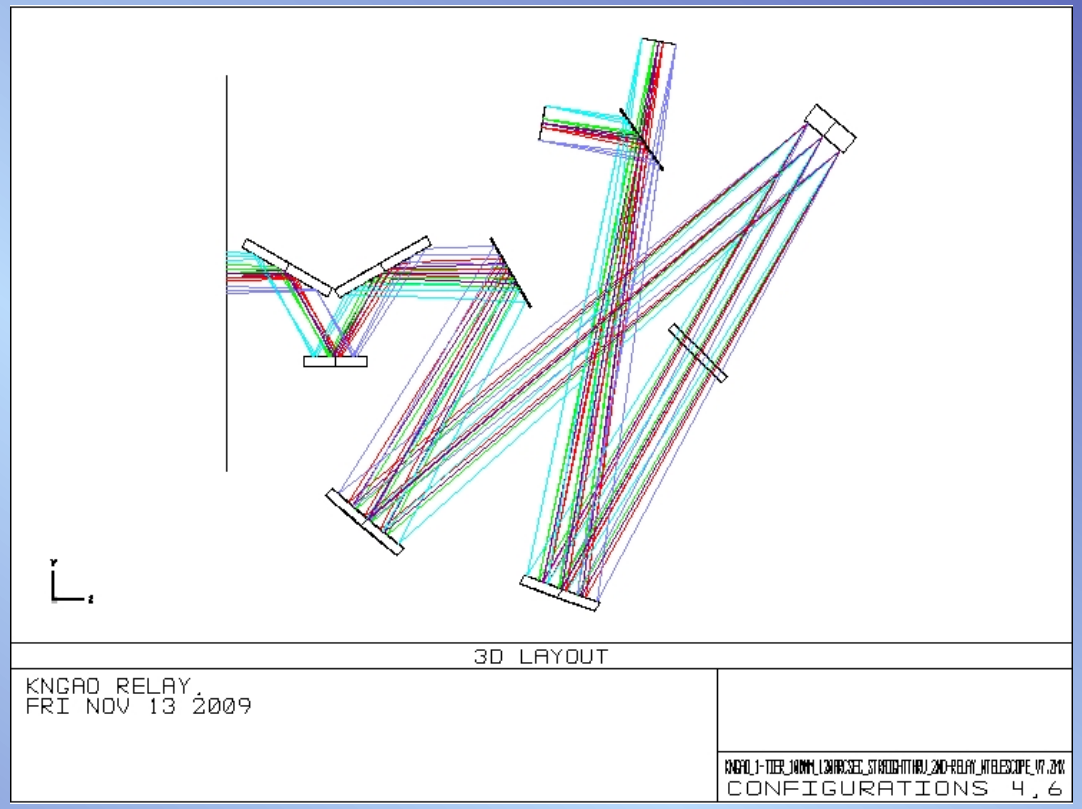
# Interferometer feed




- Removable dichroic at 25 degree incident angle, must transmit J,H,K, up to 4.1μ. <u>LOWFS must operate at shorter than 1.1μ.</u>
- FSM at focus, lies outside cold enclosure
- Identical OAPs to existing DSM

## Wide-field Relay

- Removable fold mirror before LOWFS focus directs entire 120 arcsecond field of regard to acquisition camera.
- Acquisition camera can be used for natural guide stars (LOWFS) and laser guide stars (assuming 0.5% leakage through LGS dichroic).
- Mechanical envelope assumed a design similar to MAGIQ camera, modified to image 120 arcsecond field (MAGIQ images 3 arcminutes).
- LOWFS pick-offs lie at focal plane of second relay.



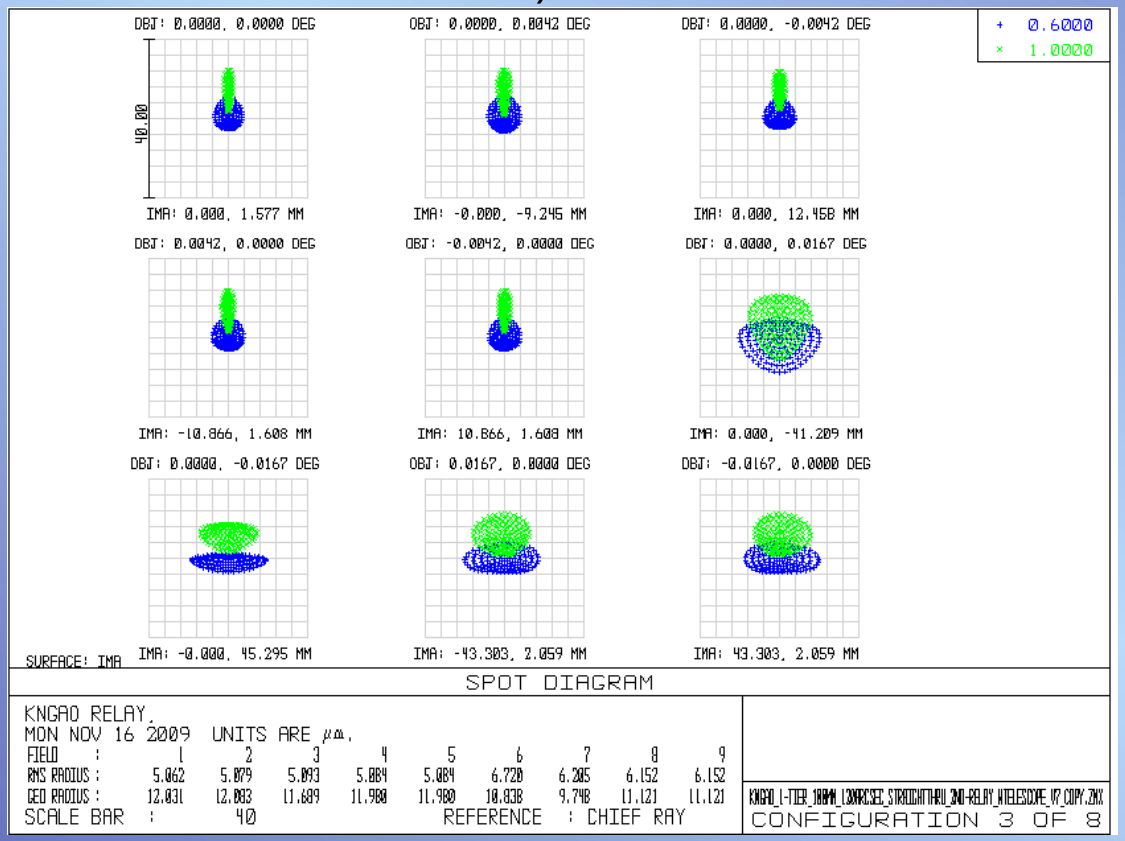
# Performance of Wide field relay

- MEMs devices in each path of the LOWFS will correct field -dependent aberrations for each natural guide star.
- The interferometer dichroic will have a wedge to correct lateral color for the LOWFS and acquisition cameras.

| Instrument (mode) | λ (μ) | F/# | FOV ″ | Fld curv. (mm) | RMS WFE (nm) | RMS Spot Radius (μ) | RMS Spot Radius (milli-″) | Airy radius (μ) at 1.17μ | Lateral color (μ) | Chrom. Focal shift (μ) | Depth of focus* (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **LOWFS** | **1.17-1.78** | **1513.66** | **120** | **1200** | **35** | **4** | **5.5** | **19.5** | **0** | **0** | **0.9** |
| **LOWFS with interferometer** | **1.17-1.78** | **1513.66** | **120** | **1200** | **45** | **5** | **7** | **19.5** | **1.3** | **91** | **0.9** |

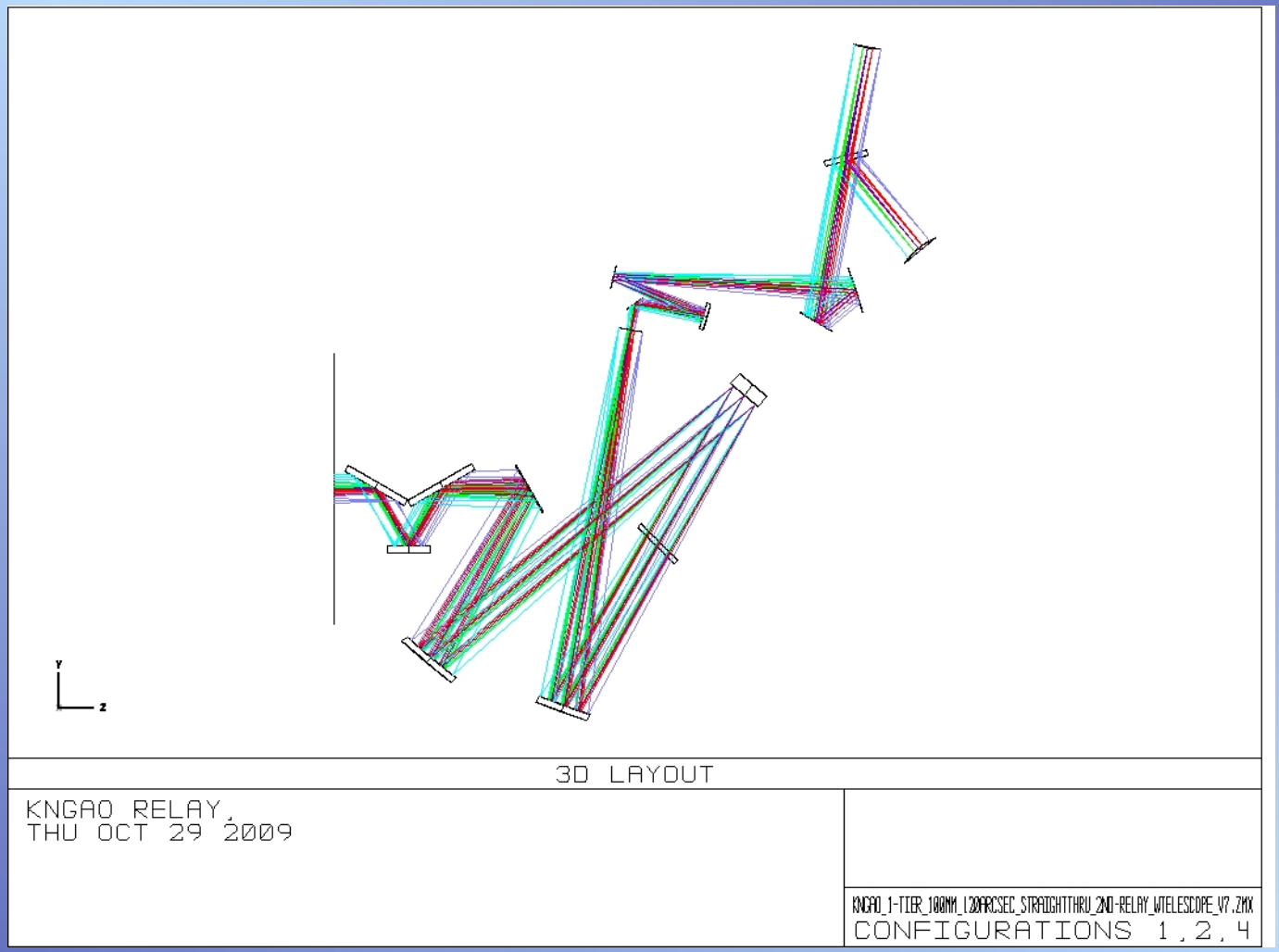
# Acquisition Camera

- The acquisition camera is assumed to have 117 mas pixels (120 arcseconds divided by 1024). Spot sizes on acquisition camera when interferometer dichroic in place ~10mas (depends on λ range, which is not well defined).



# Narrow field relay

IR Science, NGS WFS



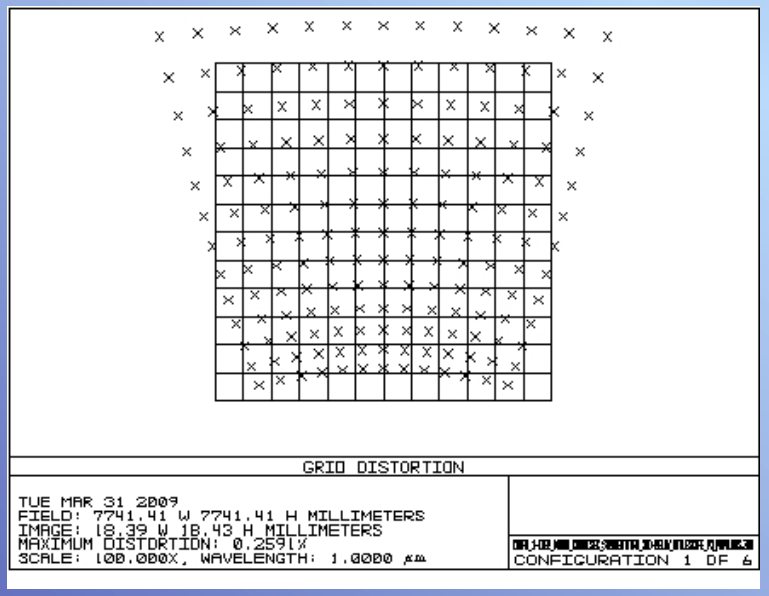
# Narrow field relay

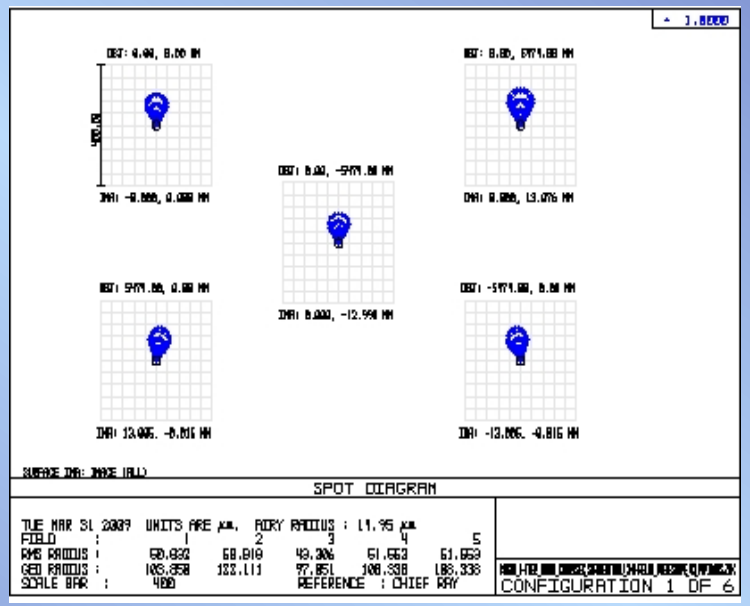
Science, NGS WFS

- Field of view requirement is 20 arcseconds diameter, with a goal of 40 arcseconds diameter.
- MEMs deformable mirror provides high order wavefront correction in open loop.
- MEMs will be mounted on slow steering platform.
- Field of regard for NGS WFS has goal of 40 arcseconds by 60(?) arcseconds, not a functional requirement.
- Unmatched OAPs provide output focal ratio of greater than f/40 (f /40.98).
- Science instruments are NIR imager and integral field spectrograph.
- Second relay OAP focal lengths must be modified to accommodate 24mm pupil.

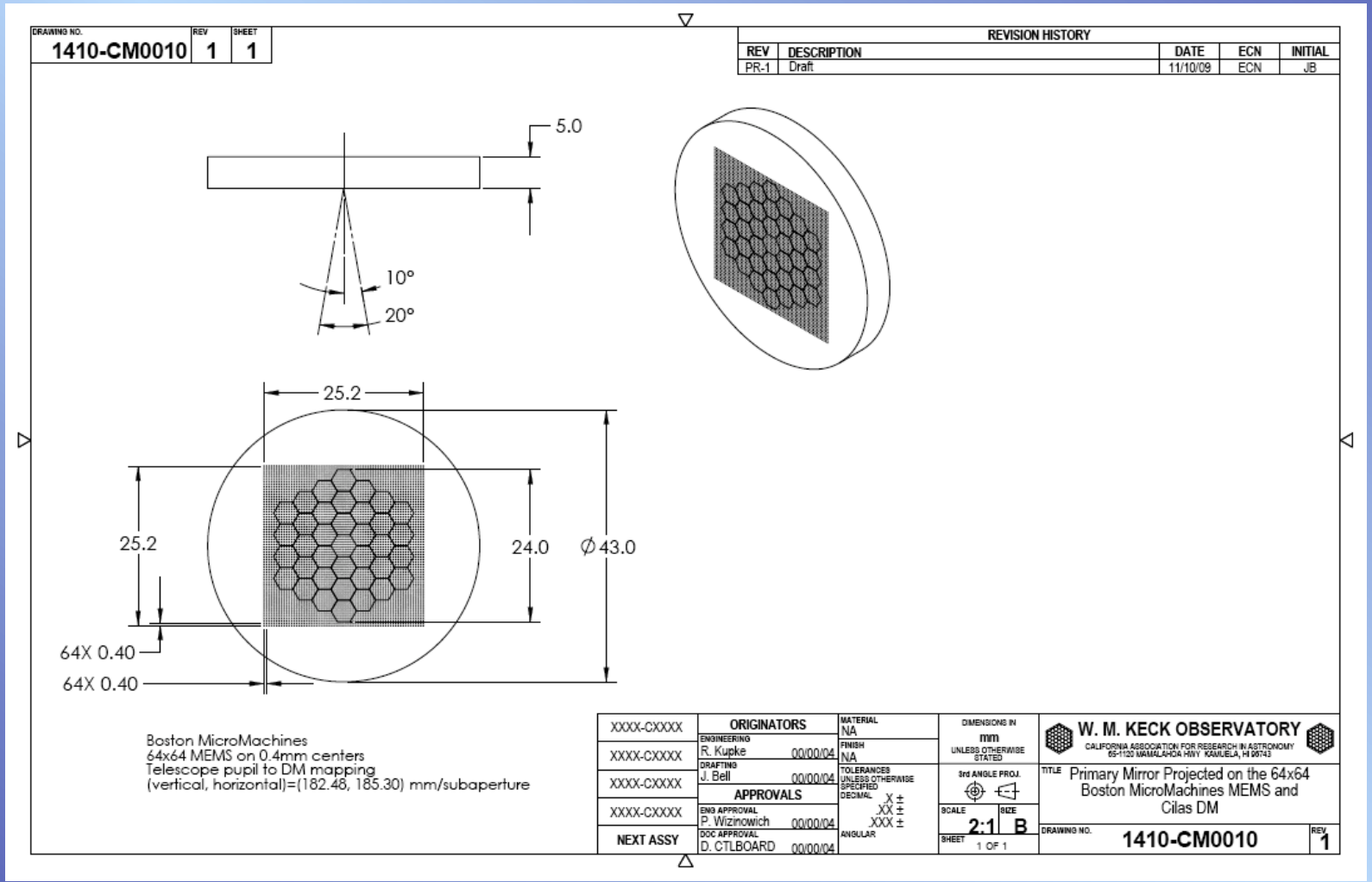
# High order deformable mirror

- 64x64, 0.4mm actuator pitch, Boston Micromachines MEMs device
- Grid distortion equal to 0.26%. Does not meet requirement of grid distortion < 0.2%. This will increase with new focal length.
- Pupil aberration equal to 58μ, or 15% of a 0.4mm subaperture. Does not meet requirements.

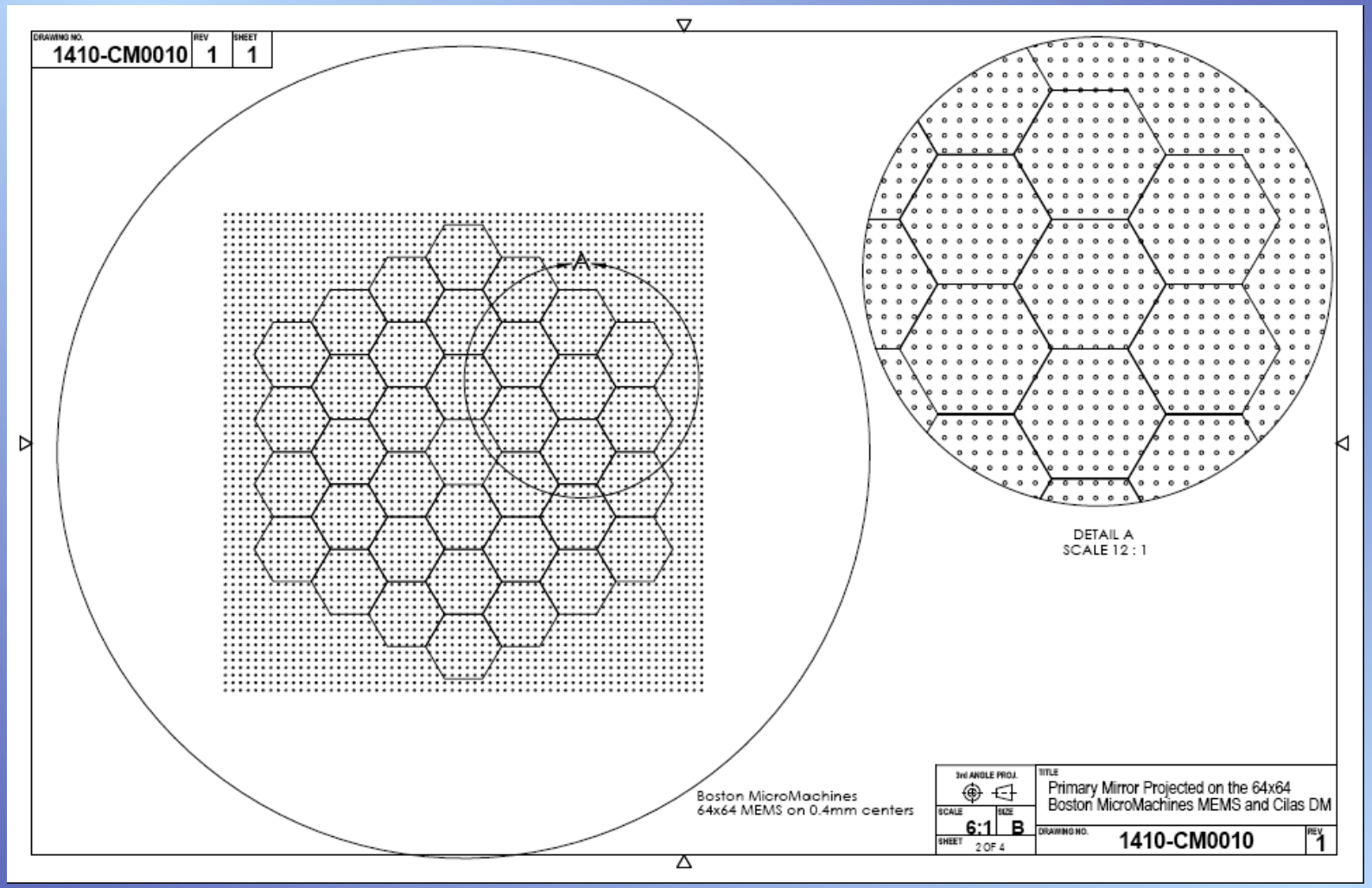


# Keck primary on high order DM



# Keck primary on high order DM



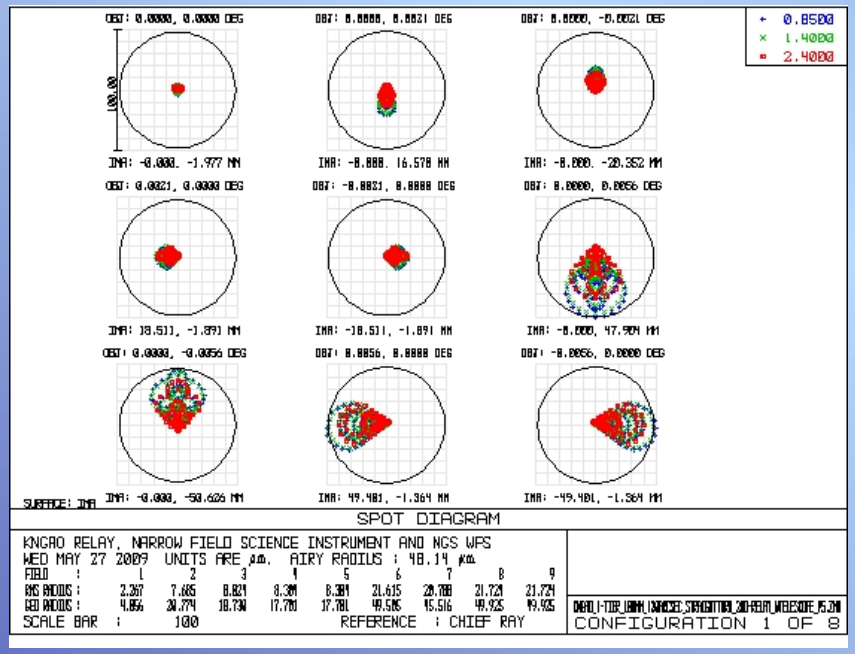
# Pupil characteristics at DMs

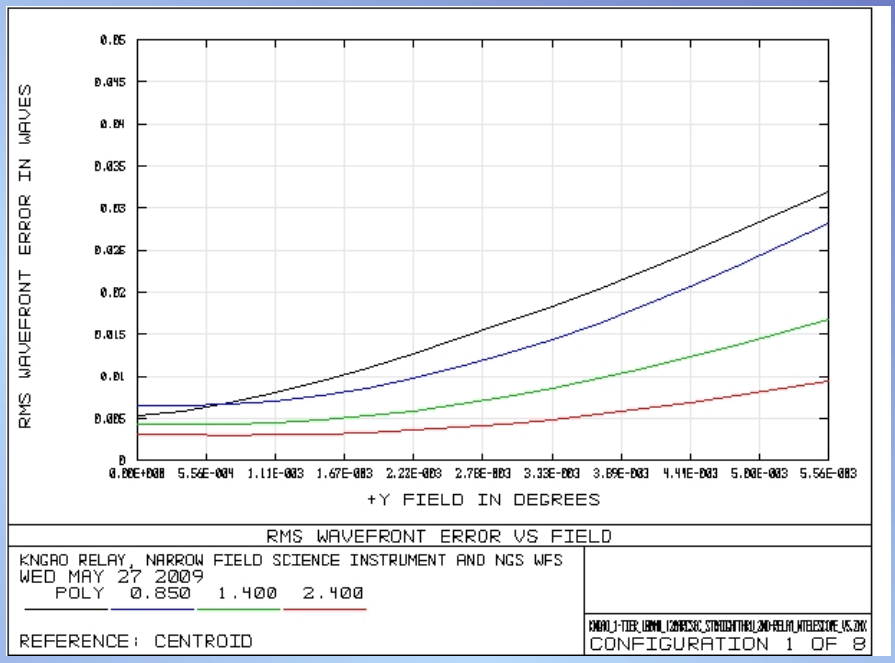
| | Diameter (mm) | Field (″) | # actuators | Tilt (meters on sky, peak) | Curvature (mm) | Max Grid Distortion | Pupil PSF, (μ) |
|---|---|---|---|---|---|---|---|
| **DM1, woofer** | 100 | 120 | 20x20 | 59 | 3000 | 0.4% | 240 |
| **DM2, tweeter** | 25 | 40 | 64x64 | 225 | 328 | 0.26% | 58 |

# Narrow-field relay

| Observing band | λ (μ) | F/# | FOV ″ | Fld curv. (mm) | RMS WFE (nm) | RMS Spot Radius (μ) | RMS Spot Radius (milli-″) | Airy radius (μ) | Lateral color (μ) | Chrom. Focal shift (μ) | Depth of focus (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **z-band** | **0.85-1.05** | **40.98** | **40** | **300** | **25** | **22** | **9** | **42** | **2.9** | **28** | **5.7** |
| **Y-band** | **0.97-1.07** | **40.98** | **40** | **300** | **25** | **22** | **9** | **48.5** | **0.7** | **11.8** | **6.7** |
| **J-band** | **1.17-1.33** | **40.98** | **40** | **300** | **25** | **22** | **9** | **58.5** | **1.2** | **17** | **7.9** |
| **H-band** | **1.49-1.78** | **40.98** | **40** | **300** | **25** | **22** | **9** | **74.5** | **1.9** | **34** | **10** |
| **K-band** | **2.03-2.37** | **40.98** | **40** | **300** | **25** | **22** | **9** | **105** | **2.9** | **53** | **13.6** |
| **NGS** | **0.6-1.0** | **40.98** | **40x60 patrol** | **300** | **24** | **22** | **9** | **30** | **0** | **0** | **4.0** |

# Narrow-field performance



# Optical Tolerancing

- Preliminary tolerance analysis was done in Zemax for the first and second relays.
- Values for mounting and fabrication tolerances were obtained. Nothing alarming was suggested by the analysis
- On the suggestion of Peter, an analytical tolerance analysis will also be performed to confirm values obtained in Zemax.
- Rich would like the tolerance analysis to be performed without compensators, as those will adversely effect optical systems downstream (WFS, Science instruments, etc).

# Remaining work for PDR

- Design science instrument ADC to work in science bandpasses from 0.85-2.4μ.
- Perform analytical tolerancing for optical system.
- Specification of substrates and coatings for windows.
- Polarization analysis for interferometer feed.