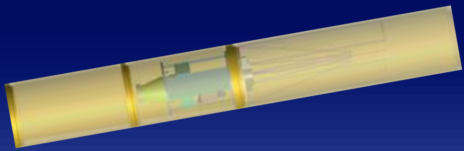
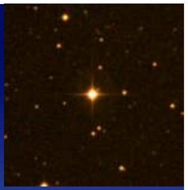




ACCESS

Absolute Color Calibration Experiment for Standard Stars

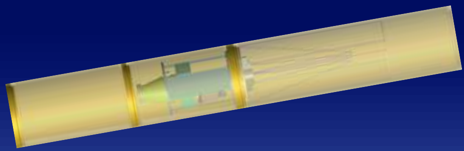
Design, Sub-system Performance, and Calibration Strategy

M.E. Kaiser & the ACCESS Team

CALCON

Conference on Characterization and Radiometric Calibration for Remote Sensing

29 August 2012



ACCESS

- Mary Elizabeth Kaiser (PI) – JHU
- Stephan McCandliss – JHU
- Jeffrey Kruk – GSFC
- Bernard Rauscher (Institutional PI) – GSFC
- Randy Kimble – GSFC
- Ned Wright – UCLA
- David Sahnow – STScI
- Dominic Benford - GSFC
- Ralph Bohlin – STScI
- Susana Deustua – STScI
- W. Van Dyke Dixon – STScI
- Paul Feldman – JHU
- Jonathan Gardner – GSFC
- Robert Kurucz – CfA
- Michael Lampton – SSL
- H. Warren Moos – JHU
- Saul Perlmutter – UCB/LBNL
- Adam Riess – JHU/STScI
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- Matthew Morris – JHU

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- Brent Mott – GSFC
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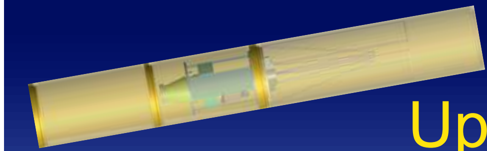
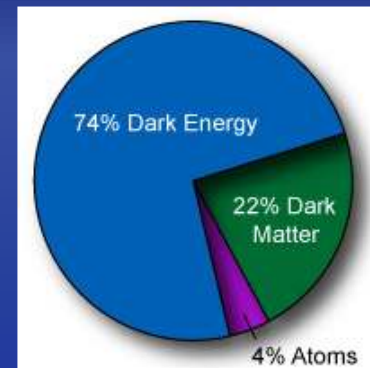
- Jeff Gum - GSFC
- Manuel Quijada - GSFC
- Yiting Wen – GSFC
- Robert Barkhouser – JHU
- Randy Hammond - JHU
- Joe Orndorff – JHU
- Steve Smee – JHU

Contributions & Infrastructure:

- Telescope Optical Bench
- Primary mirror
- Secondary Mirror
- HgCdTe 1024x1024 detector array
- Collimator
- JHU lab facilities/equipment
- JHU IDG engineers
- GSFC Detector Character. Lab
- GSFC engineering facilities



Fundamental Questions in Astrophysics Depend Upon our Ability to Precisely Measure Astrophysical Sources.



Evidence for Dark Energy (DE) *(HZT & SCP)*

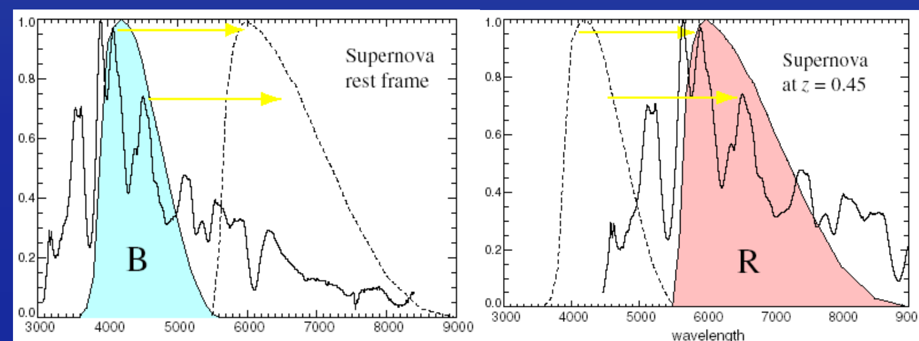
A decade ago, distant SNe Ia were discovered to be fainter than expected

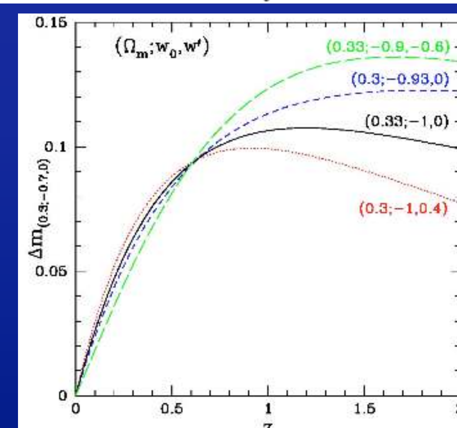
the expansion of the universe is accelerating,

rather than decelerating as would be expected

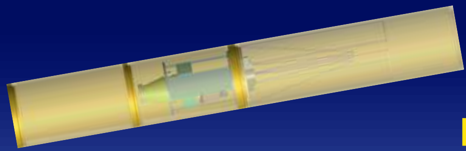
due to the gravitational attraction of matter

- DE parameters are determined from the shape, not the absolute normalization, of the Hubble brightness-redshift relationship
- z is plotted against the rest-frame B-band flux for each SN Ia
- Relative zero-points of all bands (0.35 - 1.7μm) must be cross calibrated to trace SNe Ia from z = 0 - 1.5.





A total uncertainty of <1-2% in the SNe Ia magnitude at z~1.5 (λ~1.4μm) is required to distinguish between the DE models shown .



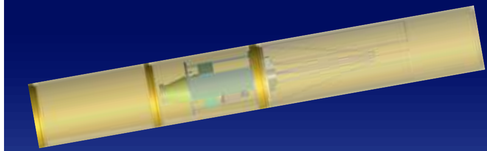
Photometric calibrations of 1% precision are relevant across the visible and NIR bandpass for current astrophysical problems.

Uncertainties in the astrophysical flux scale exceed 1% in the UV - NIR.

Technological advances in detectors, instrumentation, and the precision of the fundamental laboratory standards used to calibrate these instruments have not been transferred to the fundamental astrophysical flux scale.

The current astrophysical flux scale is transferred to absolute laboratory standards using observations of Vega, a star too bright to be observed with today's premier telescopes in the UV - NIR.

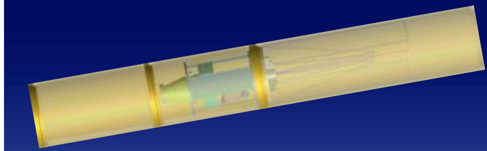
- Employ a detector based metrology
- Transfer this fundamental metrology, established in physical units,
- To a small number of standard stars,
- Establishes an absolute calibration that
- **enables the existing networks of standards to be placed on an improved absolute scale and makes them available to all telescopes.**



Strategy for an Improved Calibration

ACCESS's strategy to reduce uncertainties in the current standard star calibration system:

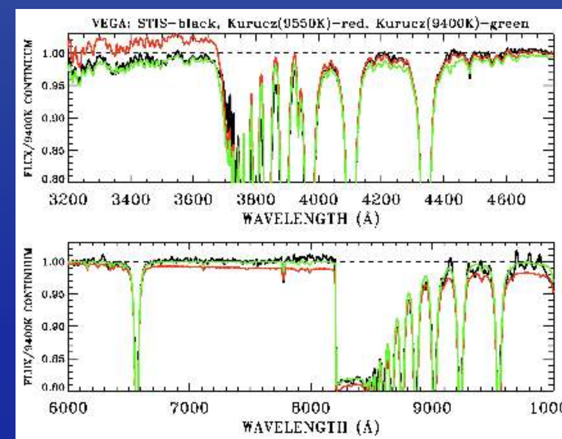
- ***Judicious selection of standard stars***
  - Observe existing (known) standard stars
  - Minimize spectral features & enable robust modeling
  - Flux level chosen to eliminate additional calibration transfers
- ***Observing above the Earth's atmosphere***
  - avoids uncertainties due to the Earth's atmosphere at λ > 8500 Å
- ***Using a single optical path and detector***
  - eliminates cross-calibration systematic errors
- ***Establishing an a priori error budget***
  - estimate, then measure and track, calibration uncertainties
- ***Performing NIST traceable sub-system & end-to-end payload calibrations***
  - Yields absolute calibration in addition to relative calibration
  - Establishes calibration system in fundamental physical units
- ***Monitoring and tracking payload performance***
  - on-board calibration monitor
  - re-calibrate payload between flights



Current Standard Star Uncertainties

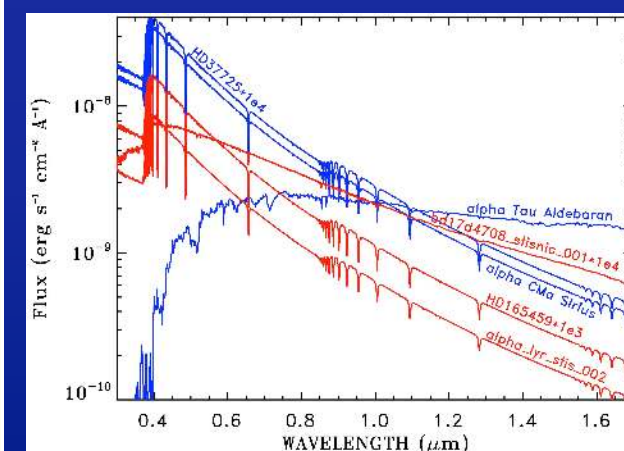
Uncertainty floor (circa 2007) in the fundamental stellar standards is 2%.
across the 0.35 - 1.7 μm bandpass (Bohlin 2007, Cohen 2007)

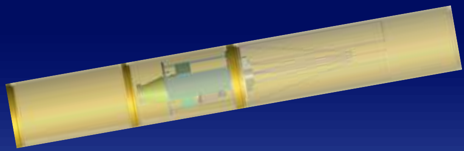
Major uncertainty contributors:
- Earth's atmosphere
  Sol'n:dedicated monitoring or observe above the atmosphere
- Stellar models: describe & extend the data
  Sol'n: Improved stellar models - need data constraints
  & test wrt NIST at the 1% level



Judicious selection of standard stars

- Observe existing (known) standard stars
  - **Vega** A0V) **- absolute VIS NIR std,** bright (V=0.026),
    pole-on-rotator => variety of thermal zones, complex
  - **Sirius** (A1V) **- IR std,** bright (V=-1.47)
  - **BD +17°4708** (sdF8) **simpler spectra, SDSS std,** fainter
  - **HD 37725** (A3V) - **absolute calibrator for IR satellites,**
    possible alternate target: **HD84937** (F5V)
- Minimize spectral features & - Flux level chosen to minimize calibration enable robust modeling transfers





Observe above the Earth's Atmosphere

Sounding Rocket observes completely above the Earth's atmosphere

- eliminates problem of measuring residual atmospheric abs'pn seen by balloons
  - OH arises at 70 km; typical balloon altitude: 39 km, rocket altitude: 300 km
  - OH airglow emission lines are 10-100X stronger than 13th mag star
- continuous spectral calibration across the 0.35 - 1.7 μm bandpass

Balloon: OH introduces additional complexity

- increased statistical noise & systematics from bkrnd subtraction
- increased instrument costs to avoid scattered OH airglow

Rocket disadvantage:

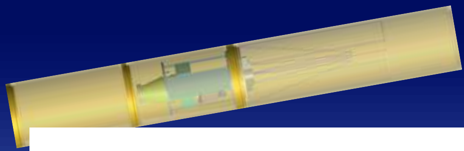
Flight times are short (~400 sec)

→ Limits faintest standard to ~ 9^{th} magnitude (BD+17°4708) with <1% uncertainty

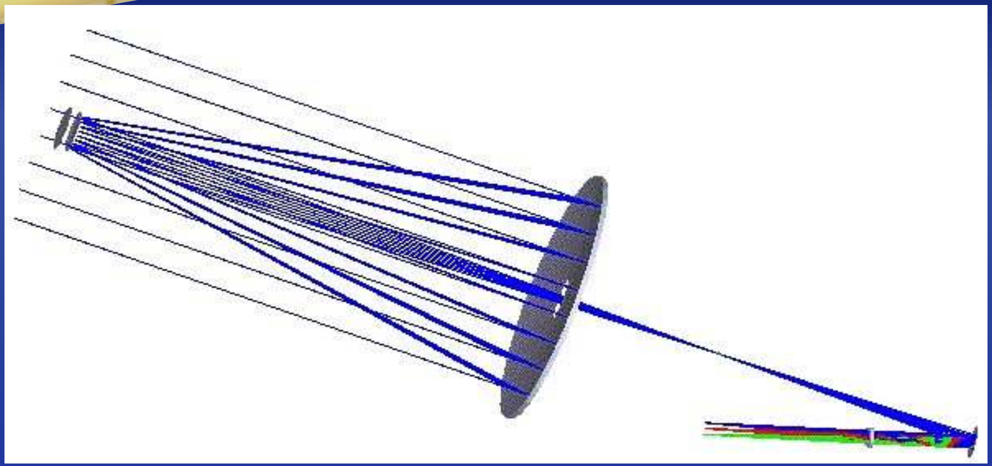
Establish repeatability:

Two flights per target

- Vega & Sirius 12h apart
- four flights of 2 targets each



ACCESS: Optical Design



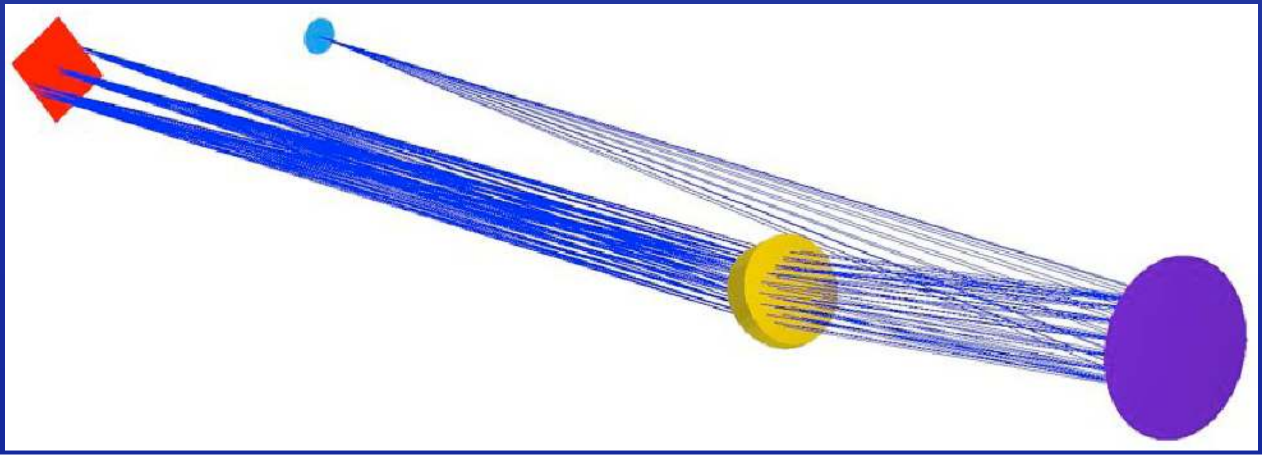
Telescope: F/15.72 Dall-Kirkham

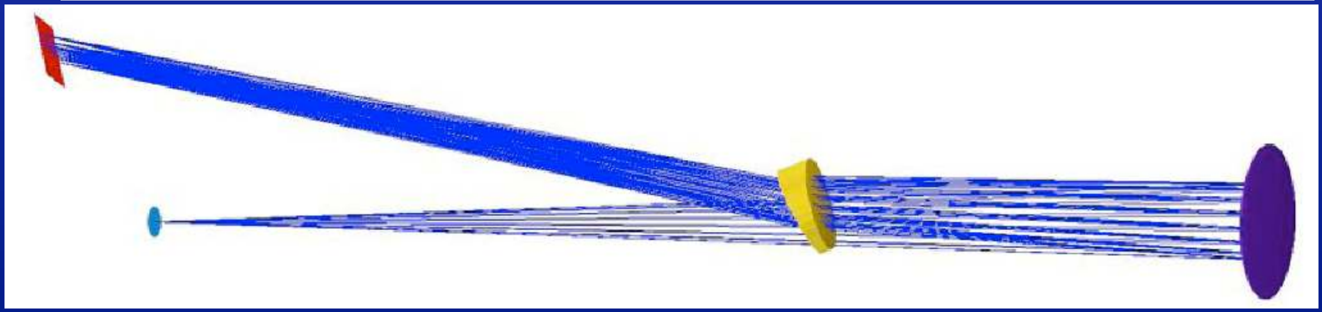
Primary figure: ellipse

393 mm (15.47in) diameter

Secondary figure: sphere

Coatings: MgF_2 over Al





Spectrograph:

Slit: 1mm (33 arcsec/mm**)**

Grating: Concave,

Blaze angle:1.65°

Utilize multiple orders

1st : 0.9 – 1.9 μm

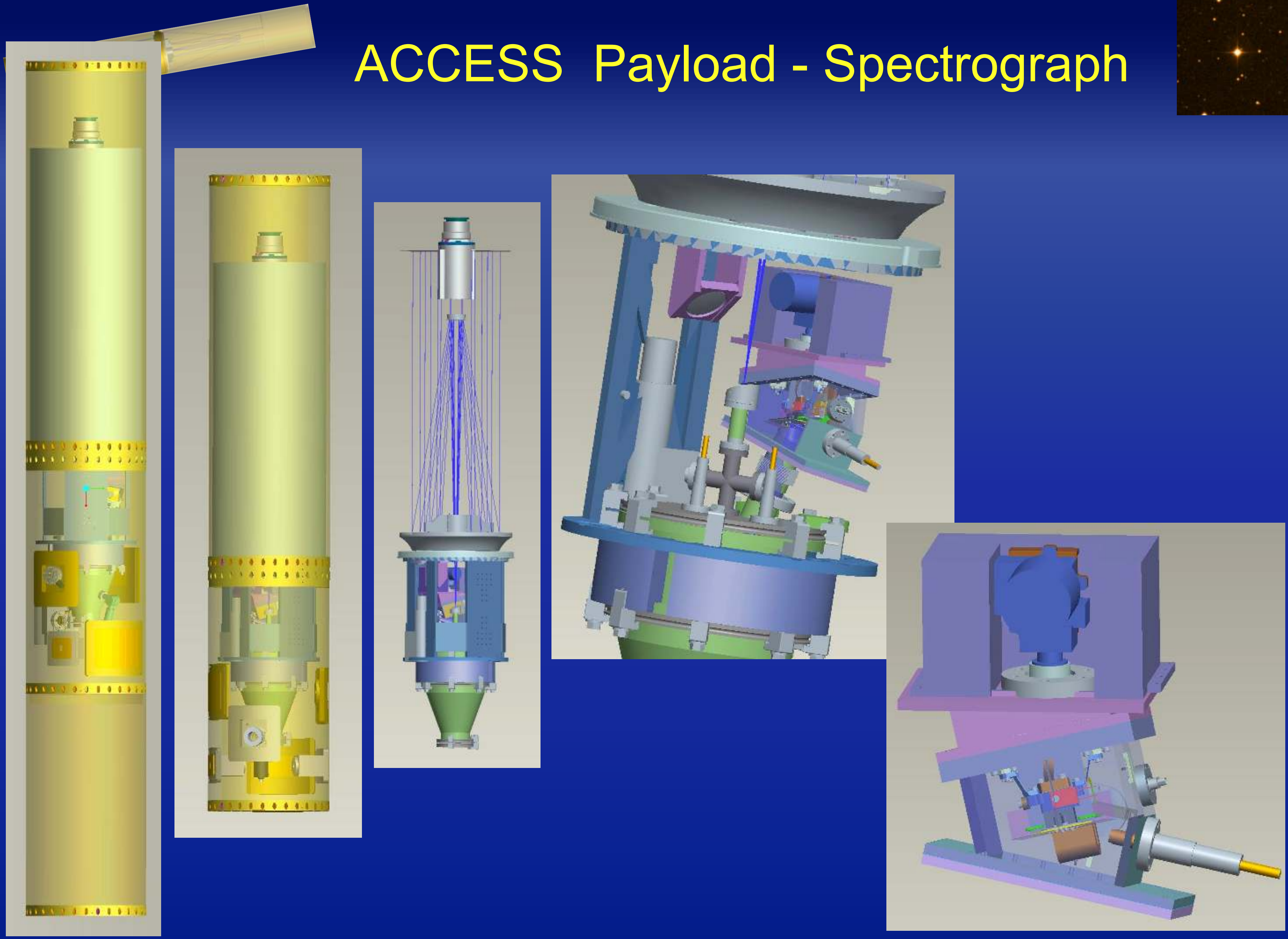
2nd : 0.45 – 0.95 μm

3rd : 0.30 – 0.63 μm

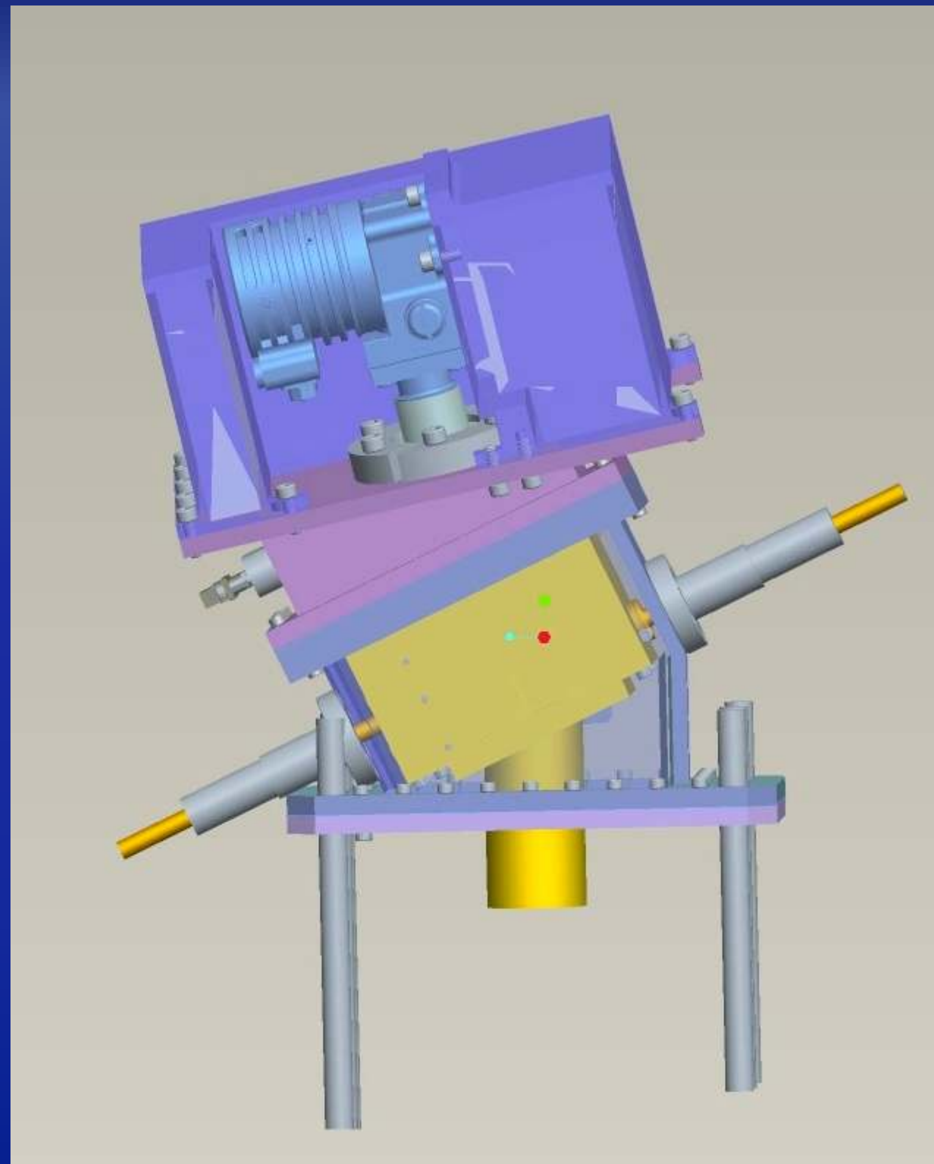
Cross disperser:

Prism spherical figure

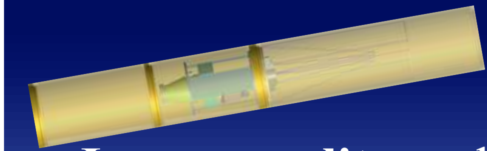
ACCESS Payload - Spectrograph



Detector Flight Assembly



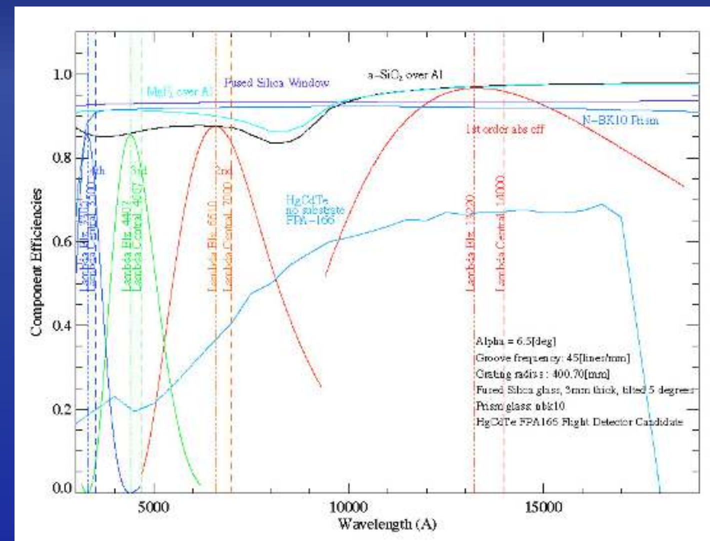
Detector flight system.

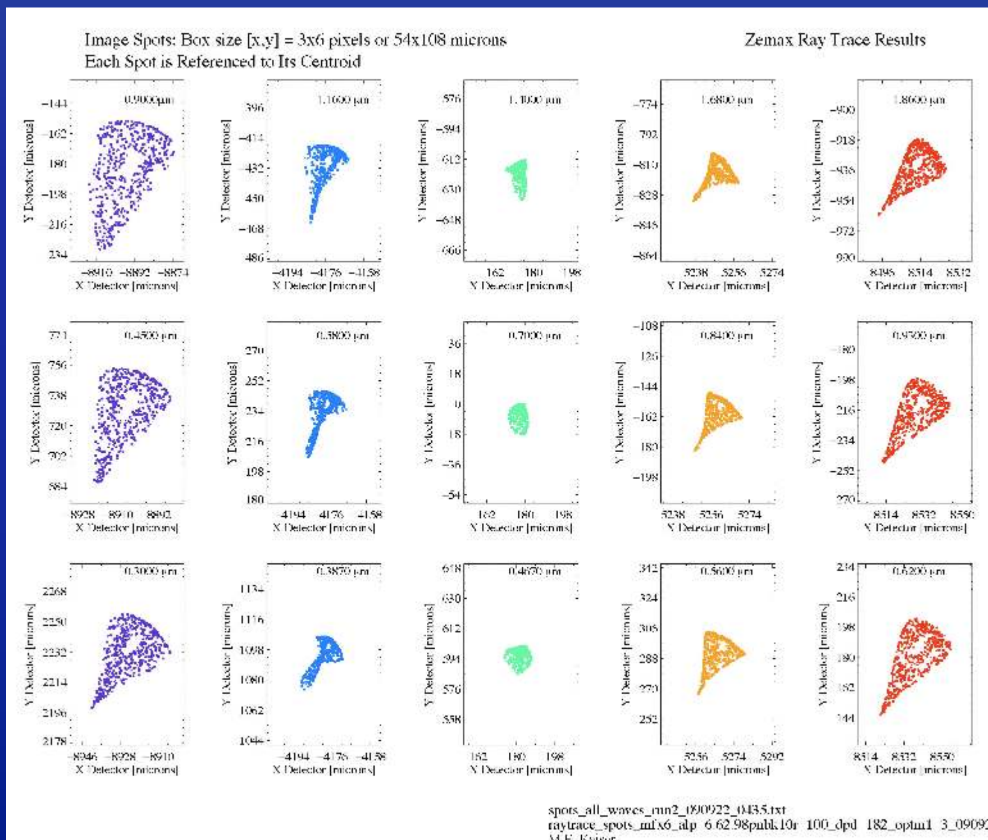


ACCESS Performance

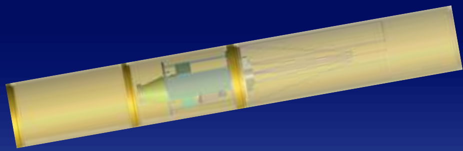
Image quality at the detector focal plane:

- Spot diagrams from a geometric raytrace
- Minimum separation between orders ~1 mm
- **Astigmatism** partially corrected by the prism
  ~ 4 pixels in **cross-dispersion direction**
- **General width of the image is < ~2 pixels**

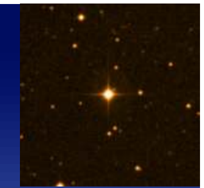


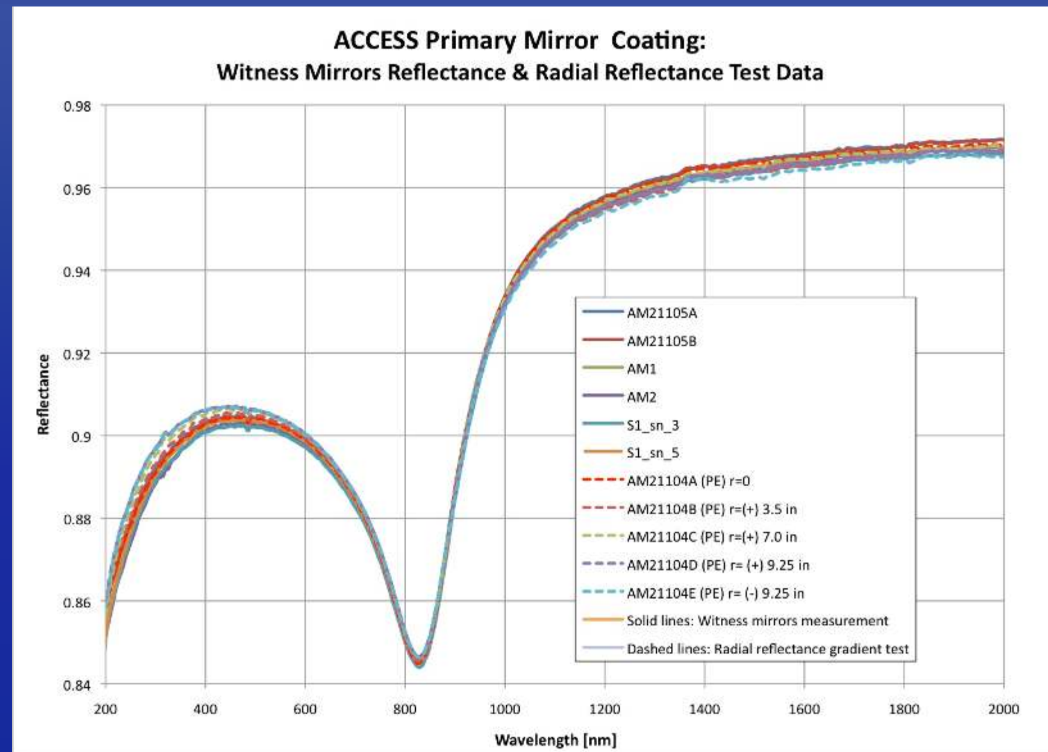


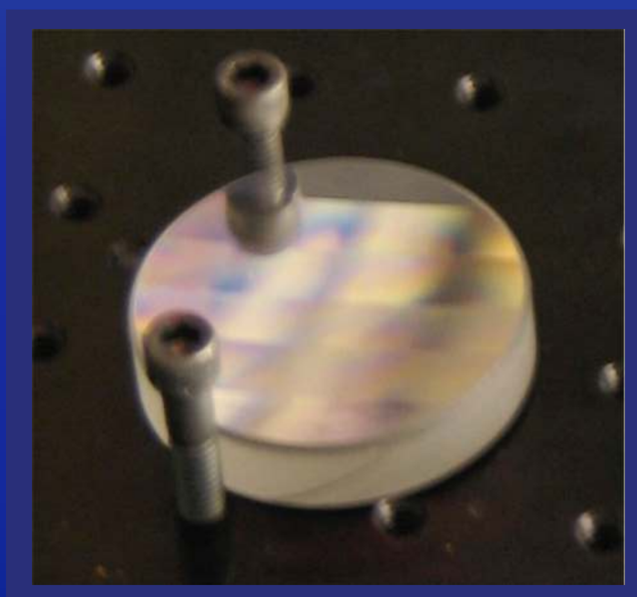
order	wavelength	2 pix resol
1st	0.9 – 1.9 μm	19.9 Å
2nd	0.45 – 0.95 μm	9.9 Å
3rd	0.30 – 0.63 μm	6.6 Å



Primary & Secondary Mirror Reflectivity

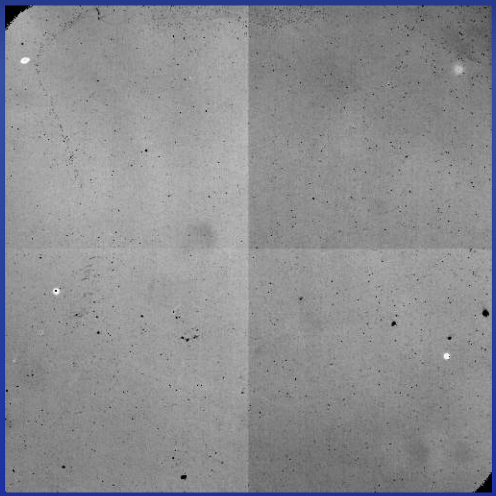




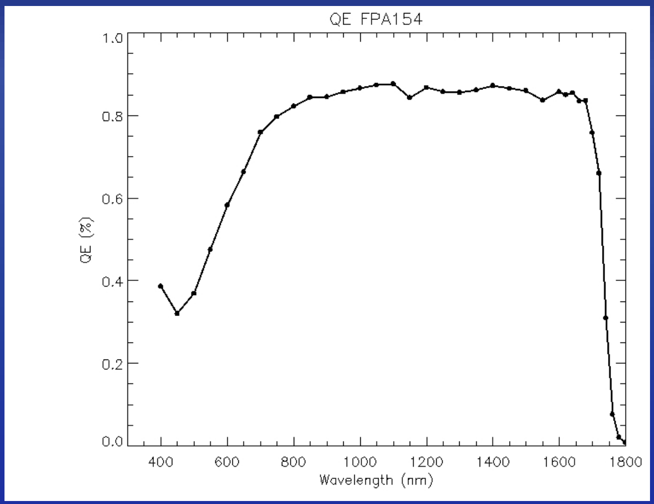


Flight Grating: Quad-partite, concave
nm

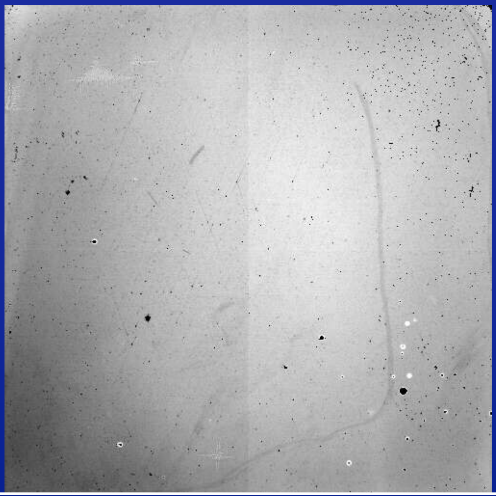
Detector Performance – FPA154 & 166



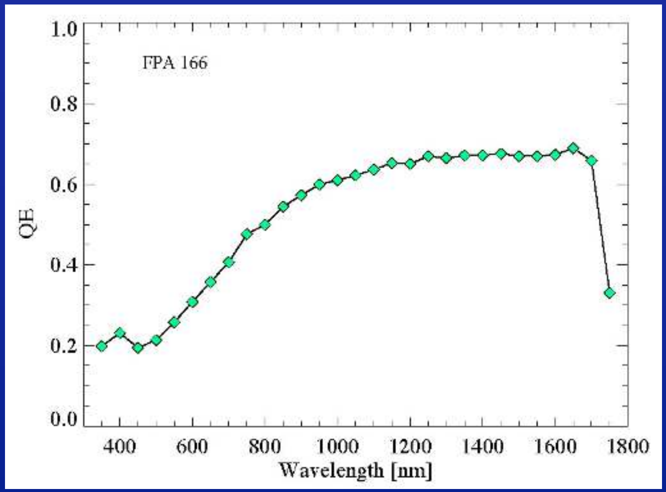
FPA 154: Flat Field at 1500 nm



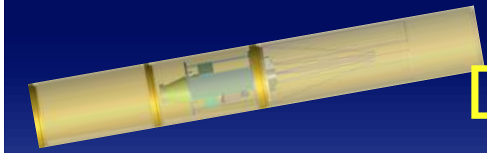
FPA 154: Quantum Efficiency



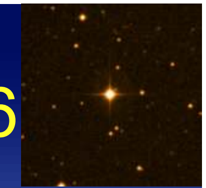
FPA 166: Flat Field at 1500 nm



FPA 166: Quantum Efficiency

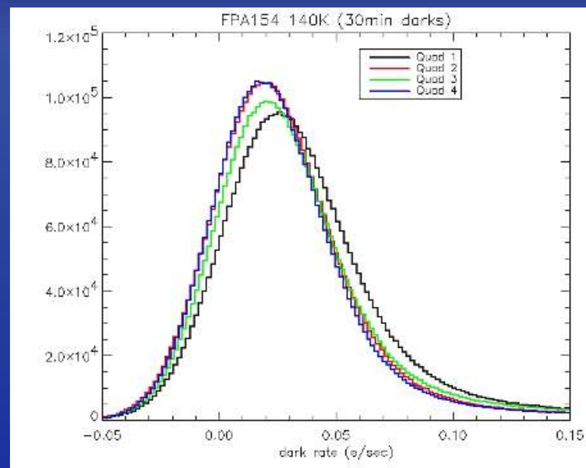


Detector Performance – FPA154 & 166

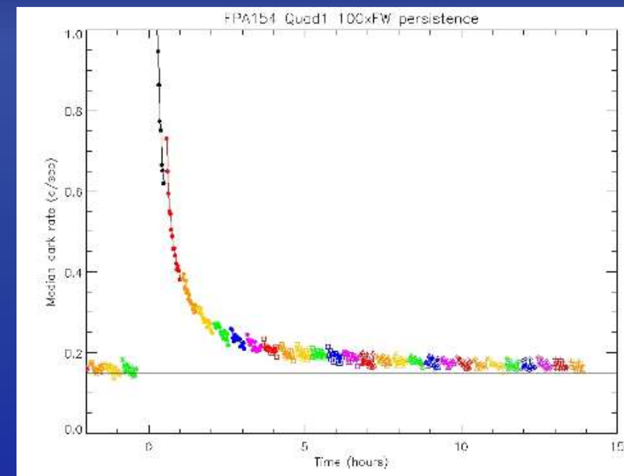


	Read Noise (e-/pixel)
Quad 1	29.06
Quad 2	27.81
Quad 3	27.47
Quad 4	26.62

FPA 154: Read Noise



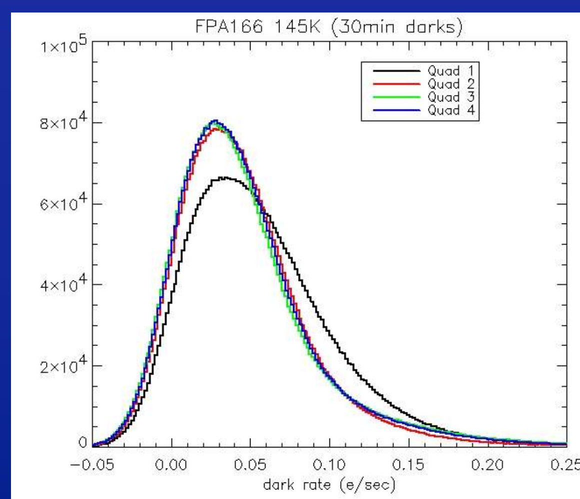
FPA 154: Dark Current at 140K



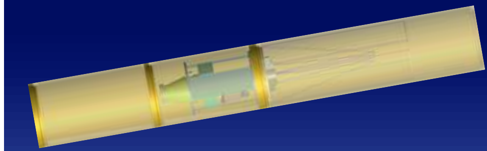
FPA 154: Persistence

	Read Noise (e-/pixel)
Quad 1	27.56
Quad 2	27.73
Quad 3	28.69
Quad 4	28.71

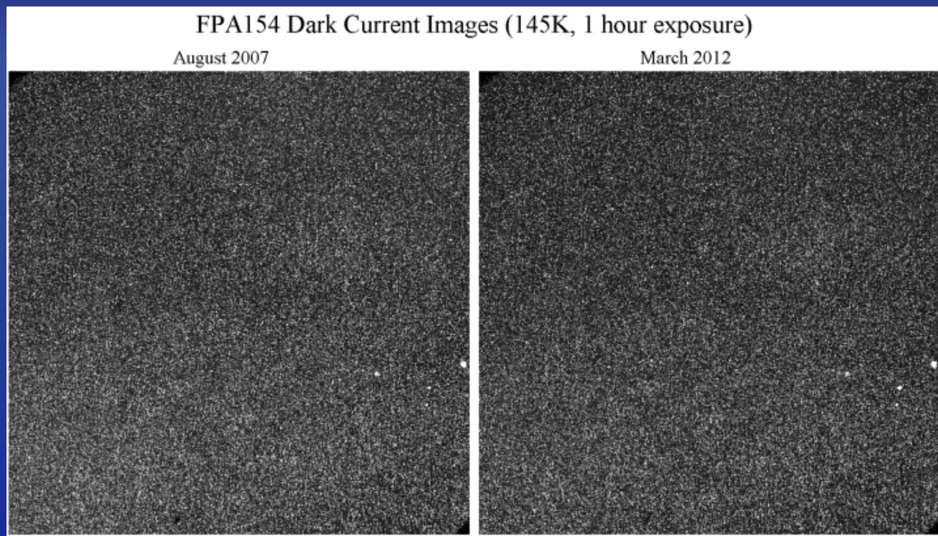
FPA 166: Read Noise

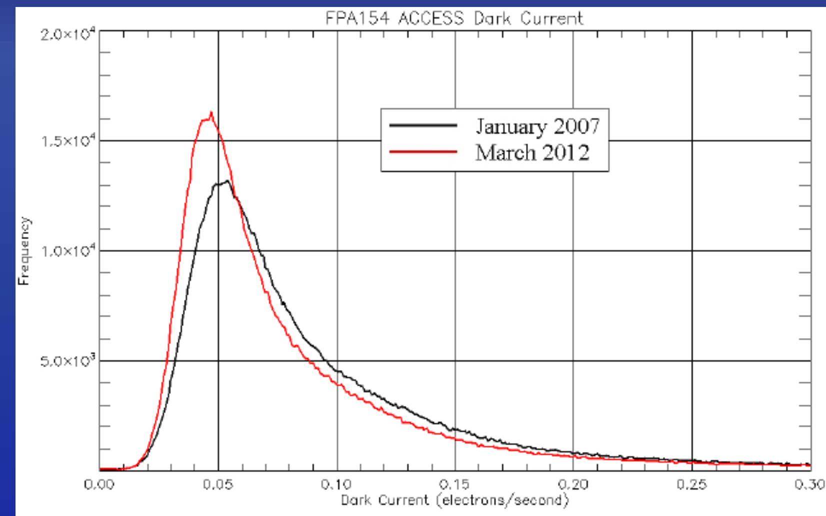


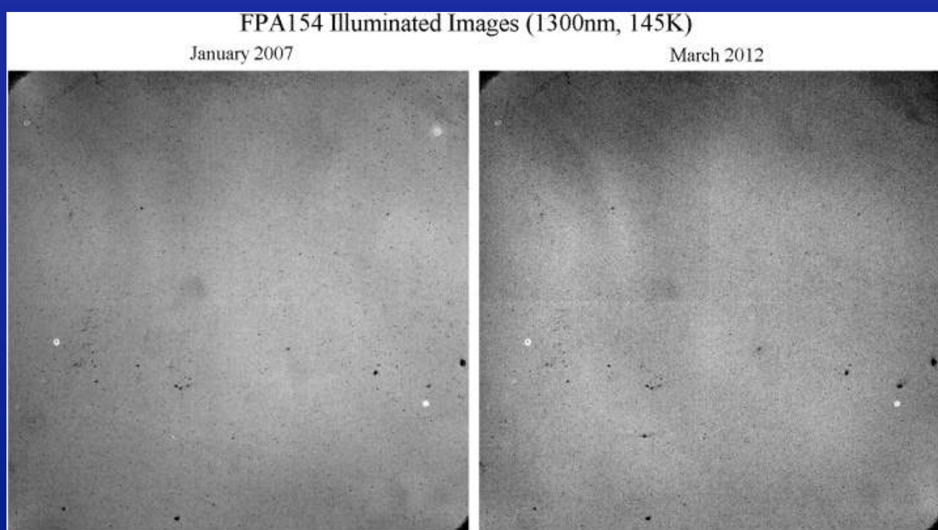
FPA 166: Dark Current at 140K

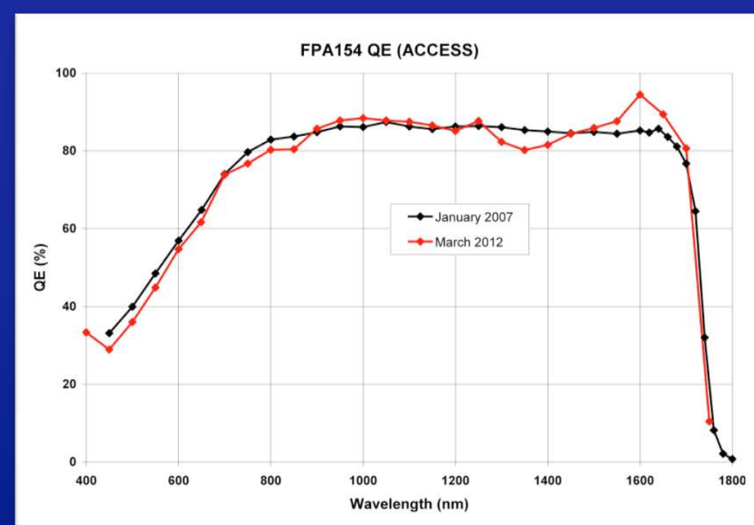


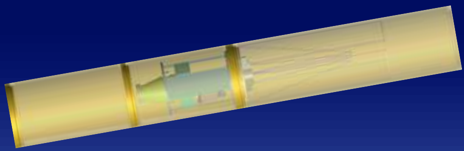
Detector Performance – Temporal Baseline



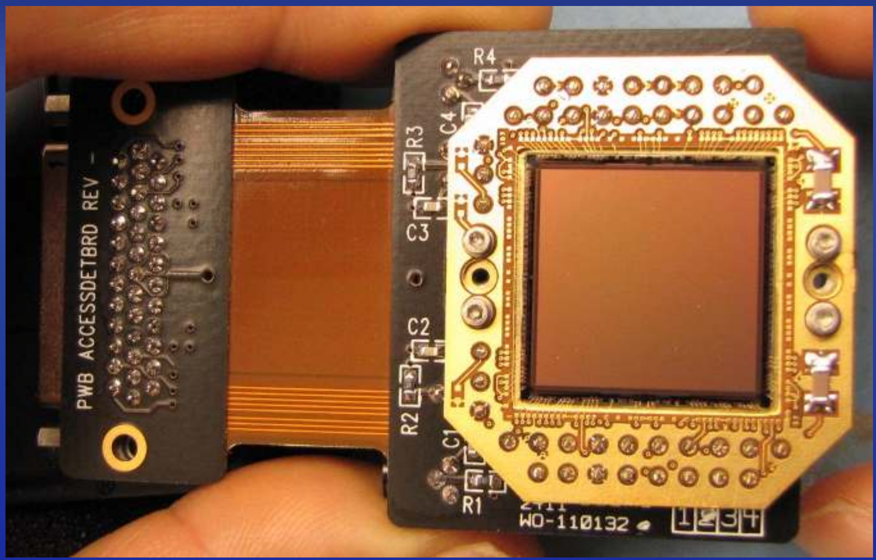


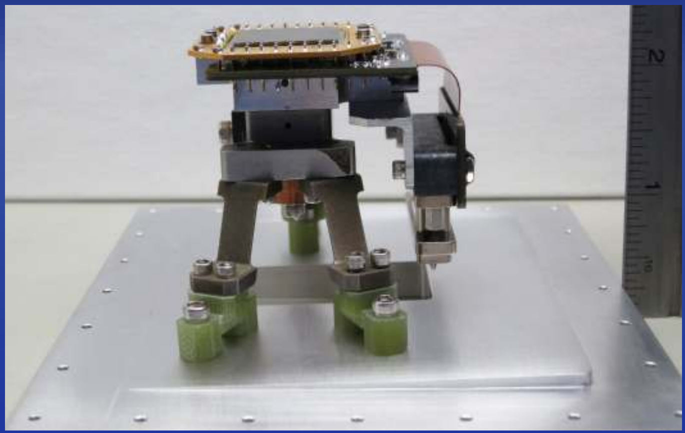




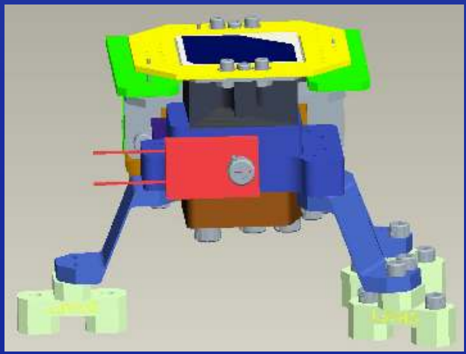


ACCESS Detector Mount





ACCESS FPA Mount



1Kx1K HgCdTe device

18 mm x18 mm pixels

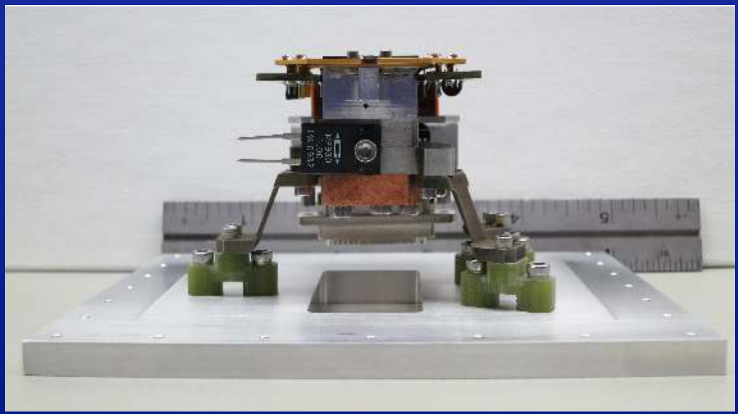
Full well: 60,000 e- -> 10^5 e- (5% non-lin)

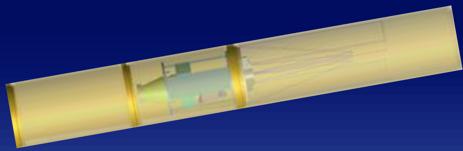
Bandpass: 0.35 < l < 1.7 mm

CdZnTe substrate removed

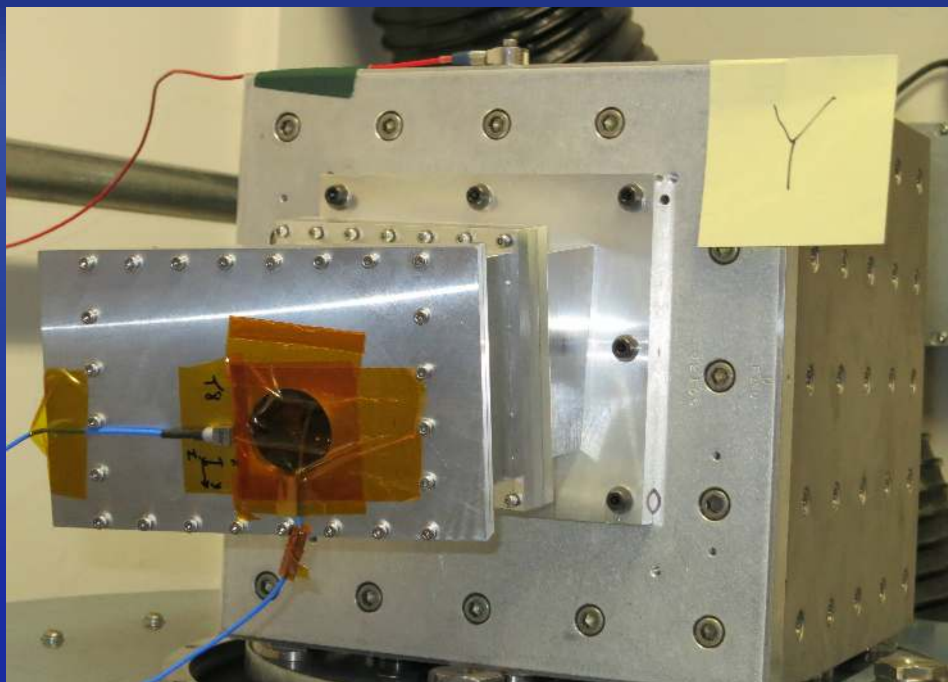
Low i_d ~0.02 e-pix^{-1}s^{-1} at 150K

Launch with detector cold and powered to mitigate transient response in i_d.

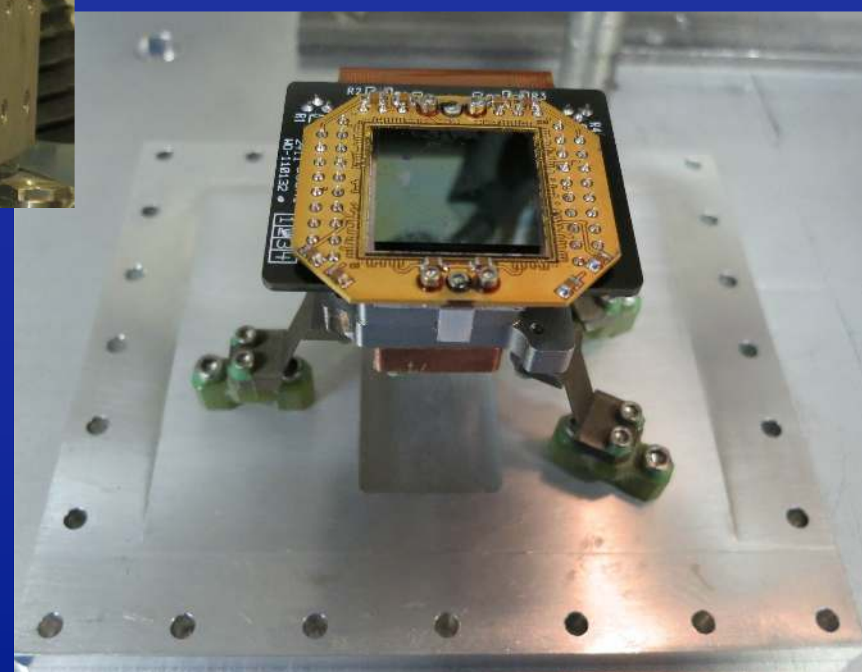


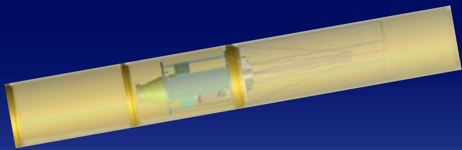


ACCESS Detector Vibration Test

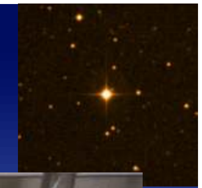


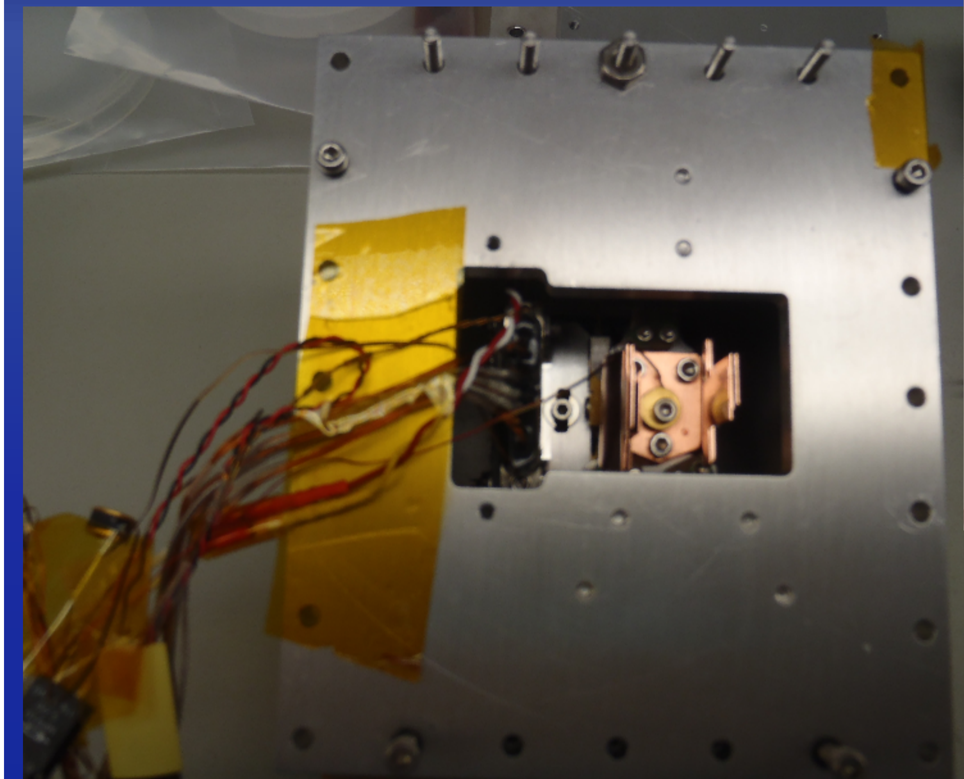
ACCESS FPA Mount

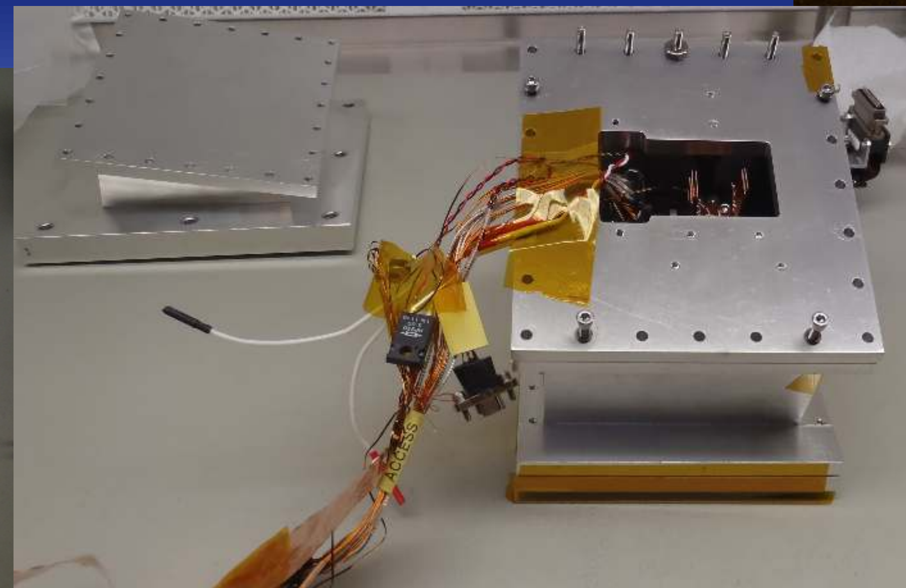


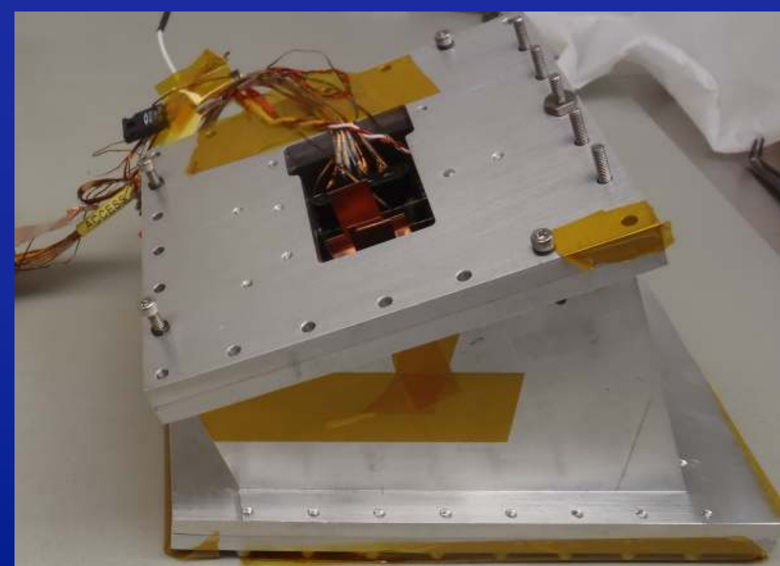


Detector Flight Housing & Mount



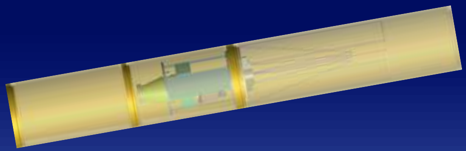






View of detector flight mounting plate, flight housing, and modified cooler housing for vibe test.

Detector cold block attachment for flight thermal link, flight detector controller, thermal harnesses, and dewar harness visible.



Test & Characterization Facilities

Four associated test and characterization facilities are being developed to enable flight qualification and testing of key components of the experiment and payload

Auxiliary small vacuum test facility:

- Leach controller detector electronics and fiber optic communications qualification
  - thermal and vacuum qualification

10-inch cryogenic dewar:

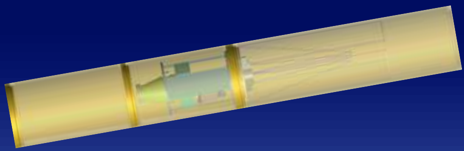
- Detector characterization

Reflectometer:

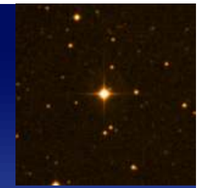
- 18-inch collimating flat mirror reflectivity measurement
- The first step in generating the artificial star

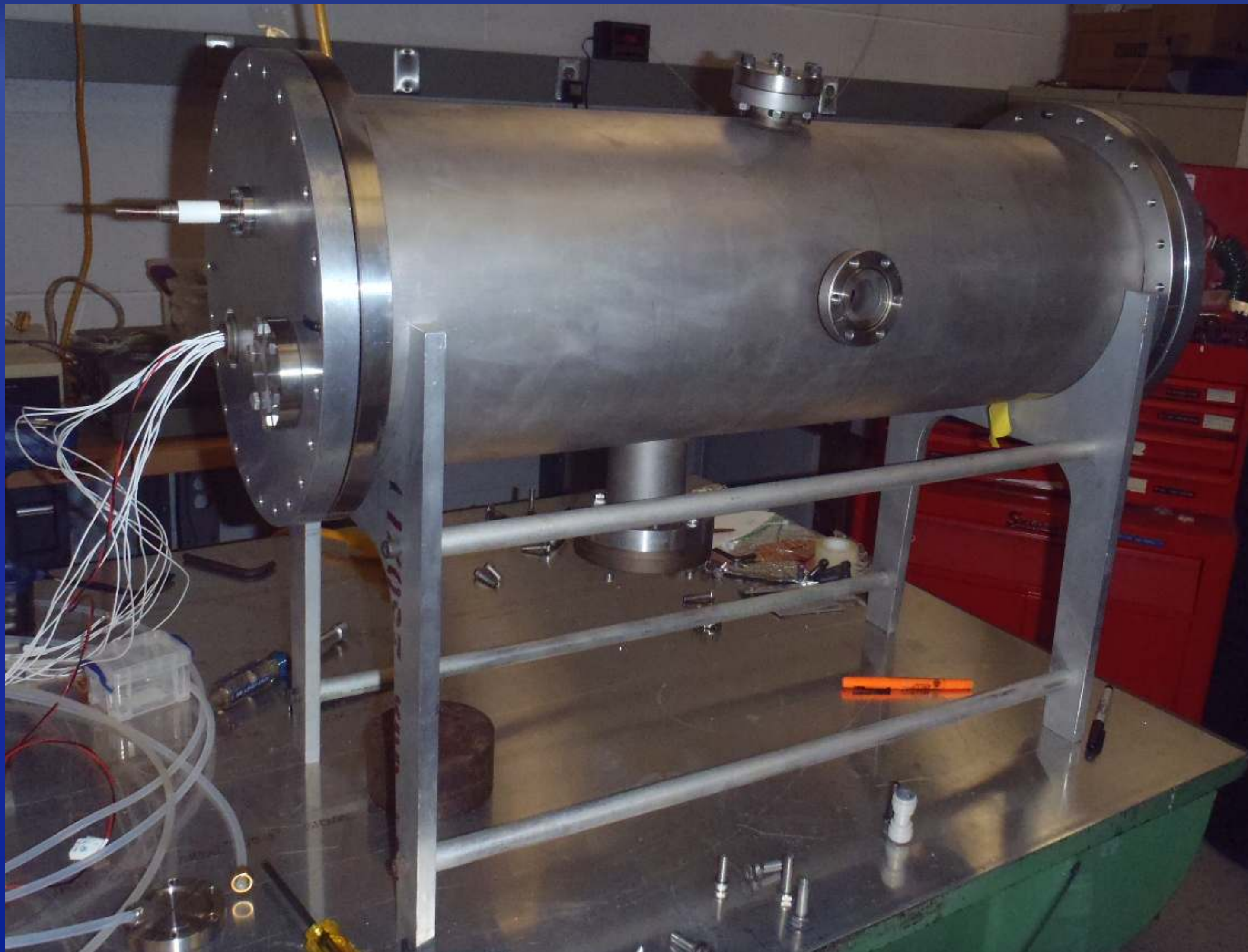
Artificial Star:

- Generation, characterization and absolute calibration of a collimated source input to telescope for absolute calibration of the telescope and spectrograph



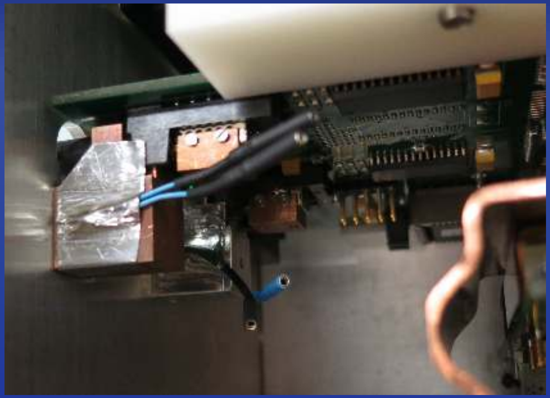
Vacuum Chamber for component qualification





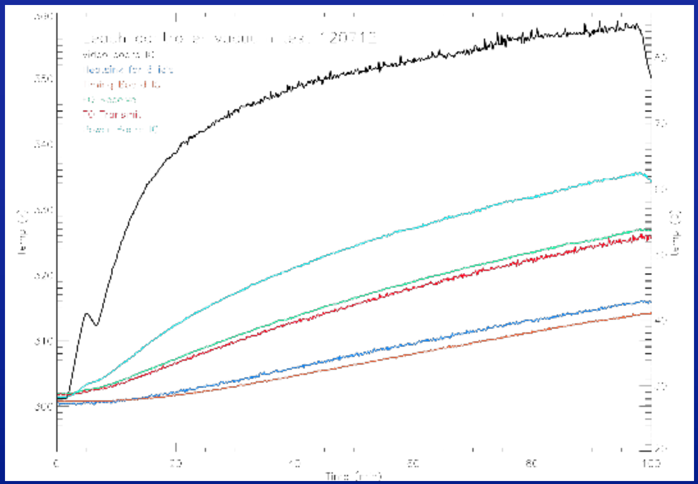
Small Vacuum chamber for component testing

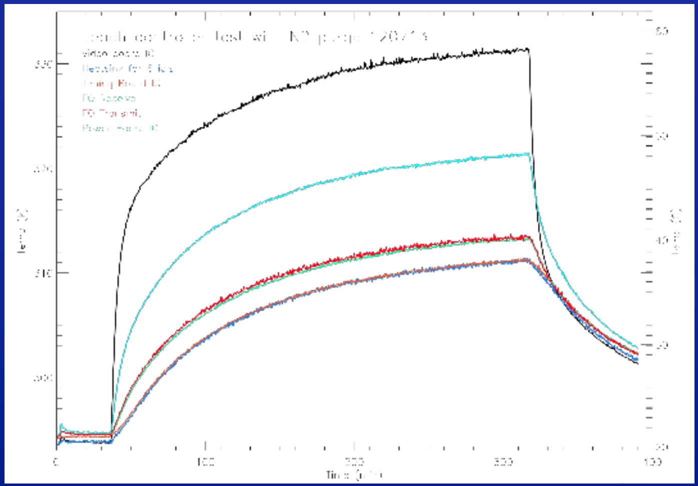
Detector Controller Ruggedization & Qualification

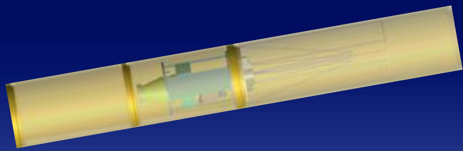


Leach controller detector electronics heat sinking for vacuum operation during flight.

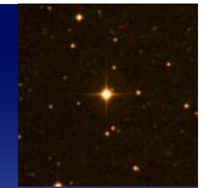
Component	Tmax_spec	T_init t=0	T_final t=90 min	T_margin at t=90 min
Video Board (U35: hottest video board IC)	398	301	358	40
Clock Driver Board (6 ICs sunk)	398	301	316	82
Timing Board (U35: ARC22)	398	301	315	83
Fiber optic receive (Timing Board)	343	302	327	16
Fiber optic transmit (Timing Board)	343	302	326	17
Power Board IC U2 (LM317 V regulator)	398	302	336	62

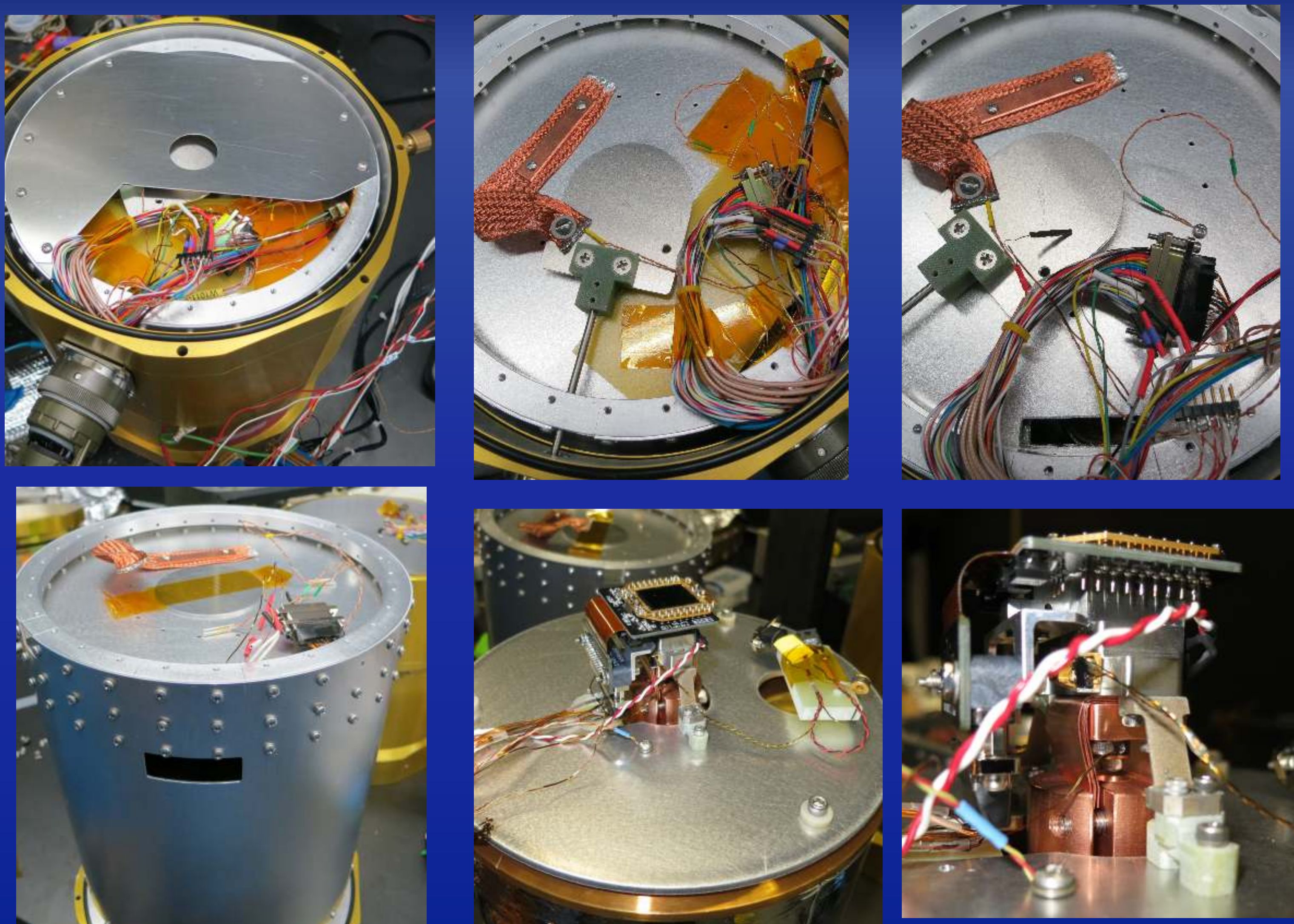




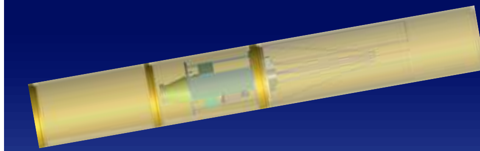


Detector Cryogenic Dewar



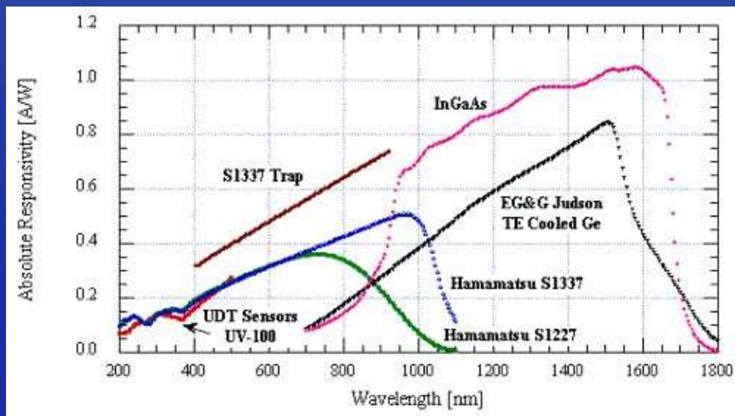


Detector10-inch dewar for characterization tests.



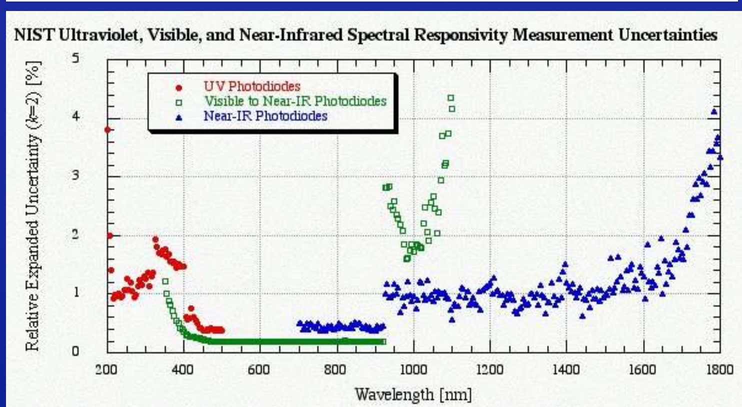
NIST Cal Photodiode Spectral Responsivity

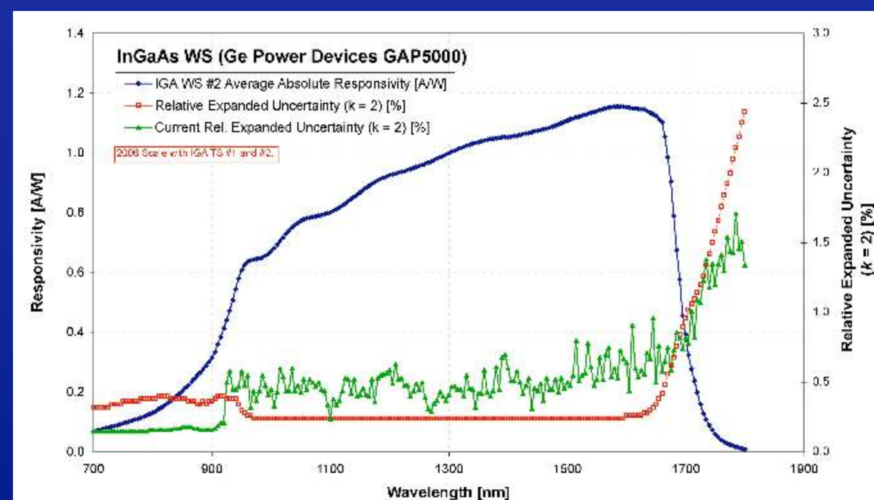
Standard Detectors − not standard sources − are the calibrator of choice
- increased precision in the photodetector calibration,
- ease of use,
- repeatability of standard detectors relative to standard laboratory sources



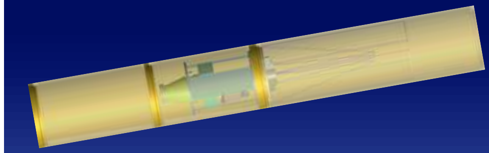
NIST photodiode responsivity measurements
- InGaAs spectral responsivity
  uncertainty of 0.1% (1**s**) for $1.0<\lambda<1.7$ **m**m

Photodiode detectors extremely stable over time
- Si stability exceeds 15 years, thus far
- InGaAs stability exceeds 10 years, thus far





Eppeldauer, Metrologia 2009
updated InGaAs figure: courtesy Keith Lykke (NIST)



Absolute Color Calibration:
The 5 Step Plan

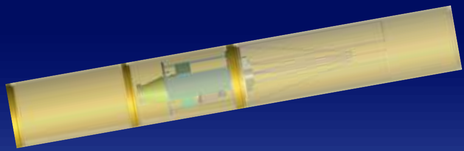
1. **Establish a standard candle**
   - transfer NIST calibration standard to the source input to telescope

2. **Transfer NIST calibrated standard to the ACCESS payload**
   - calibrate ACCESS payload with NIST certified laboratory irradiance standards

3. **Transfer NIST calibrated standard to the Stars**
   - Observe Standard Stars with the calibrated ACCESS payload

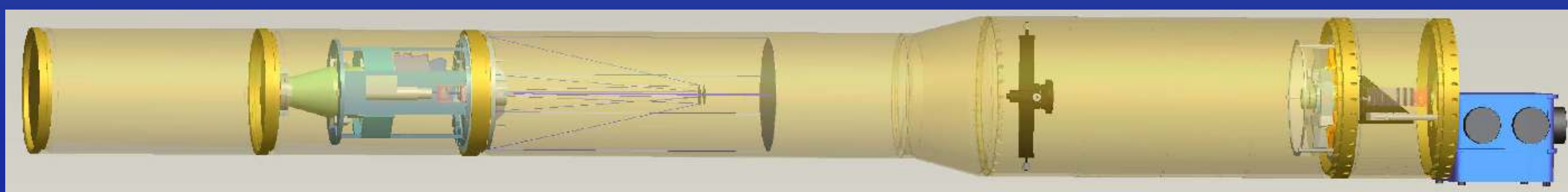
4. **Monitor ACCESS sensitivity**
   - NIST calibrated on-board lamp tracks sensitivity throughout the program

5. **Fit Stellar Atmosphere Models** to the flux calibrated observations
   - confirm performance; refine and extend Standard Star models

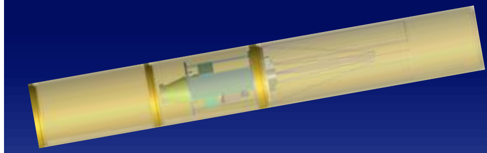


ACCESS End-to-End Calibration: The Artificial Star at Infinity

System in vacuum housing with N_2 gas purge capability, to :
- reduce background light,
- maintain cleanliness, &
- thermal stability

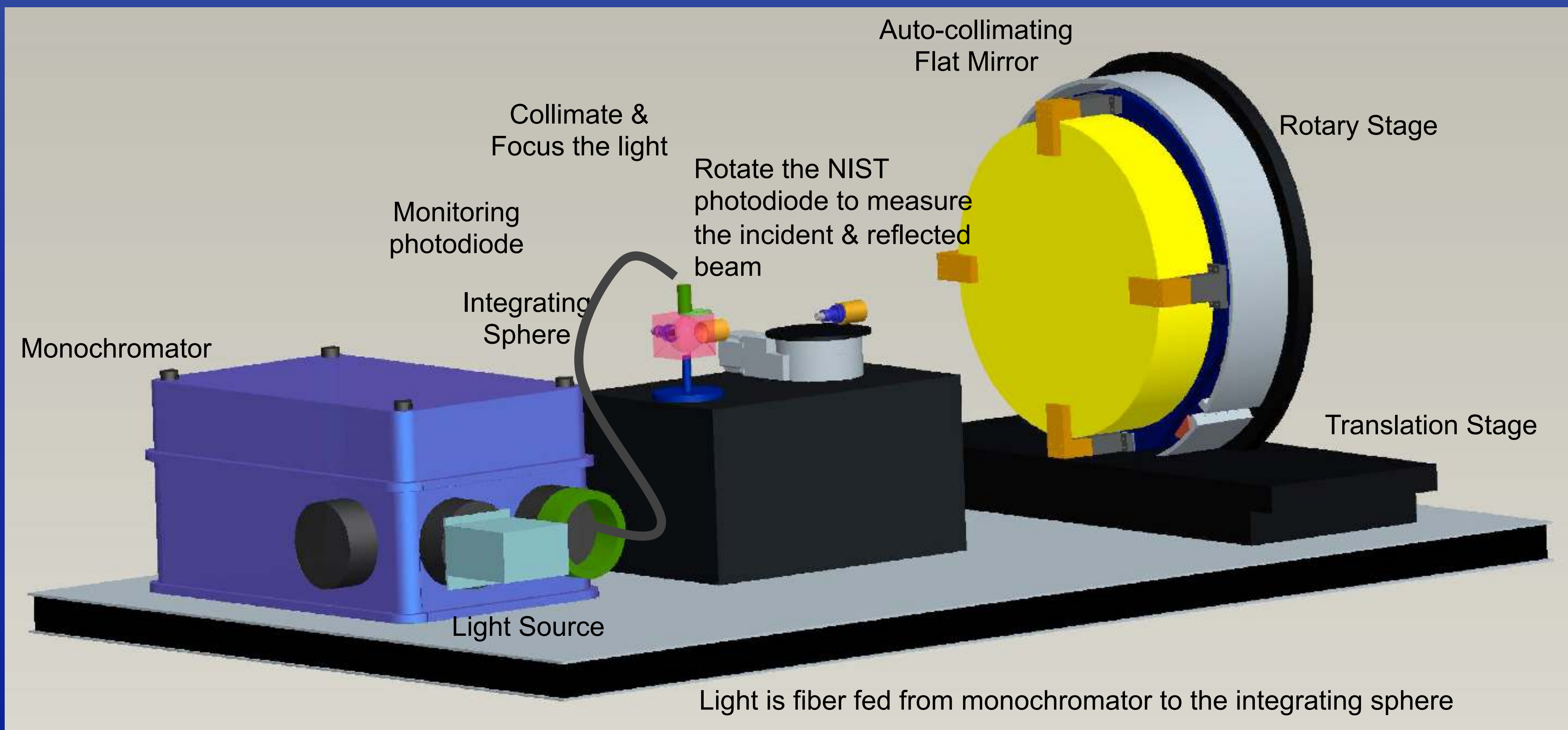


Measurement of the input beam to the telescope requires knowledge of the artificial star flux at the collimator output
- Measure the reflectivity of the autocollimating flat
- Measure the reflectivity of the collimator primary & secondary product
- Need to under fill the telescope → Insert aperture stop prior to flat, measure beam



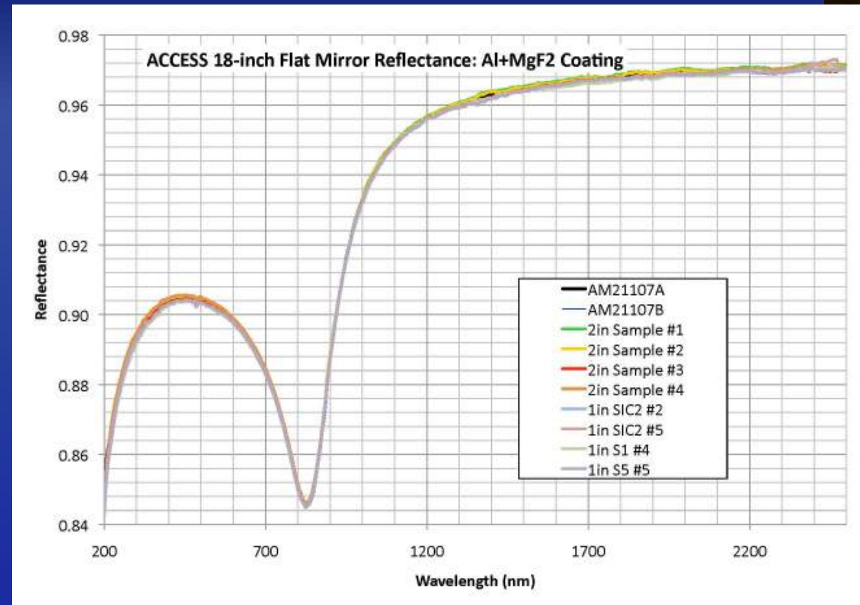
Establish a Standard Candle

Measuring the Absolute Reflectivity of the Auto-collimating Flat Mirror

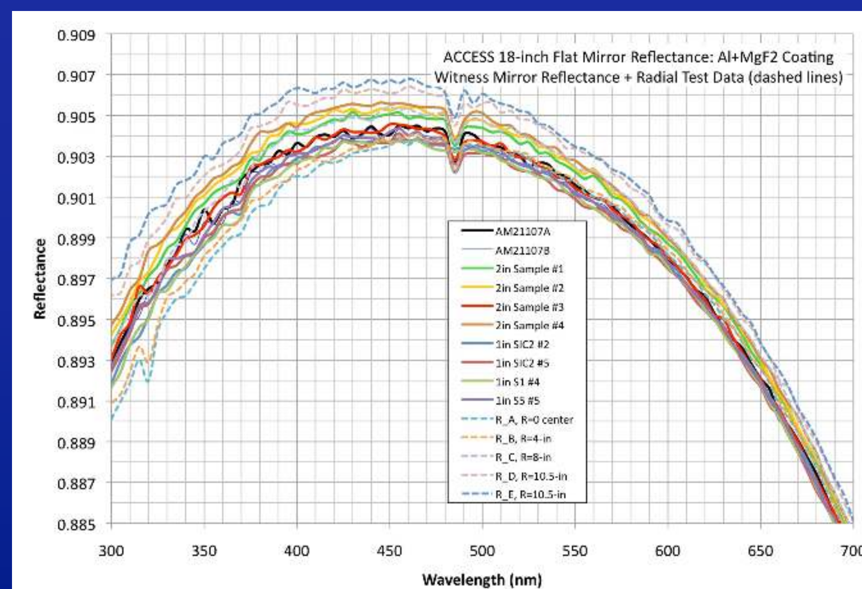


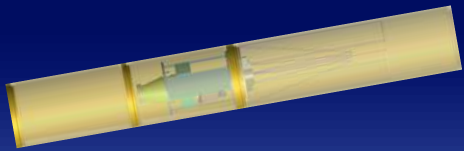
Auto-collimating Flat Mirror Reflectance

Optical Flat prior to entering coating chamber



Reflectometer: Closed configuration

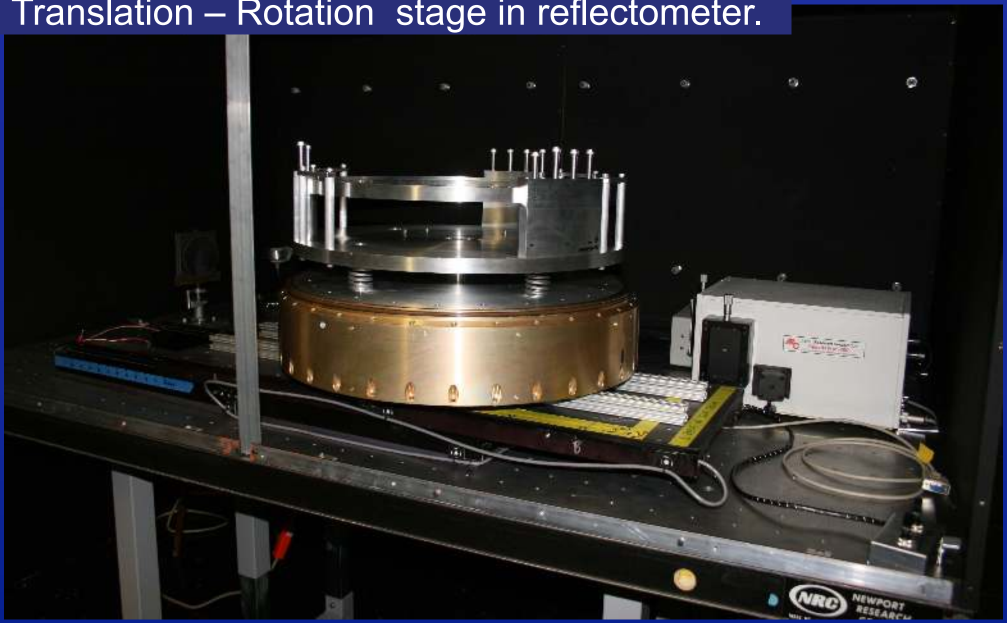


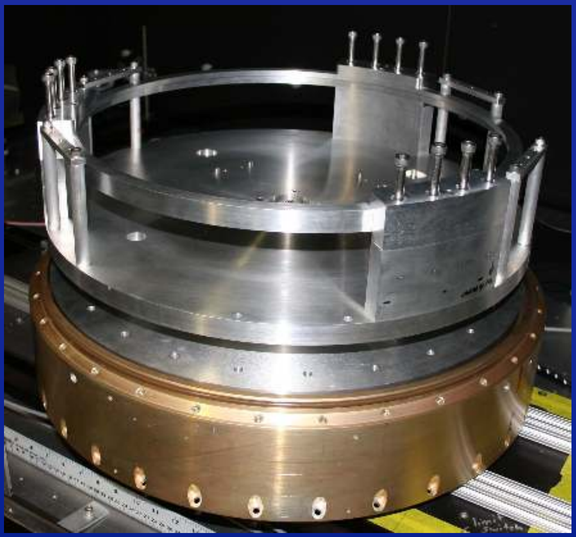


ACCESS Reflectometer

Translation – Rotation stage in reflectometer.

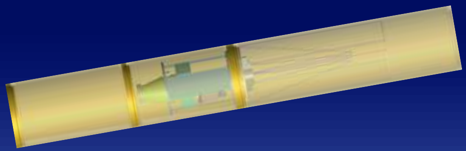
Flat mirror mount adjustment detail.



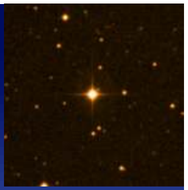


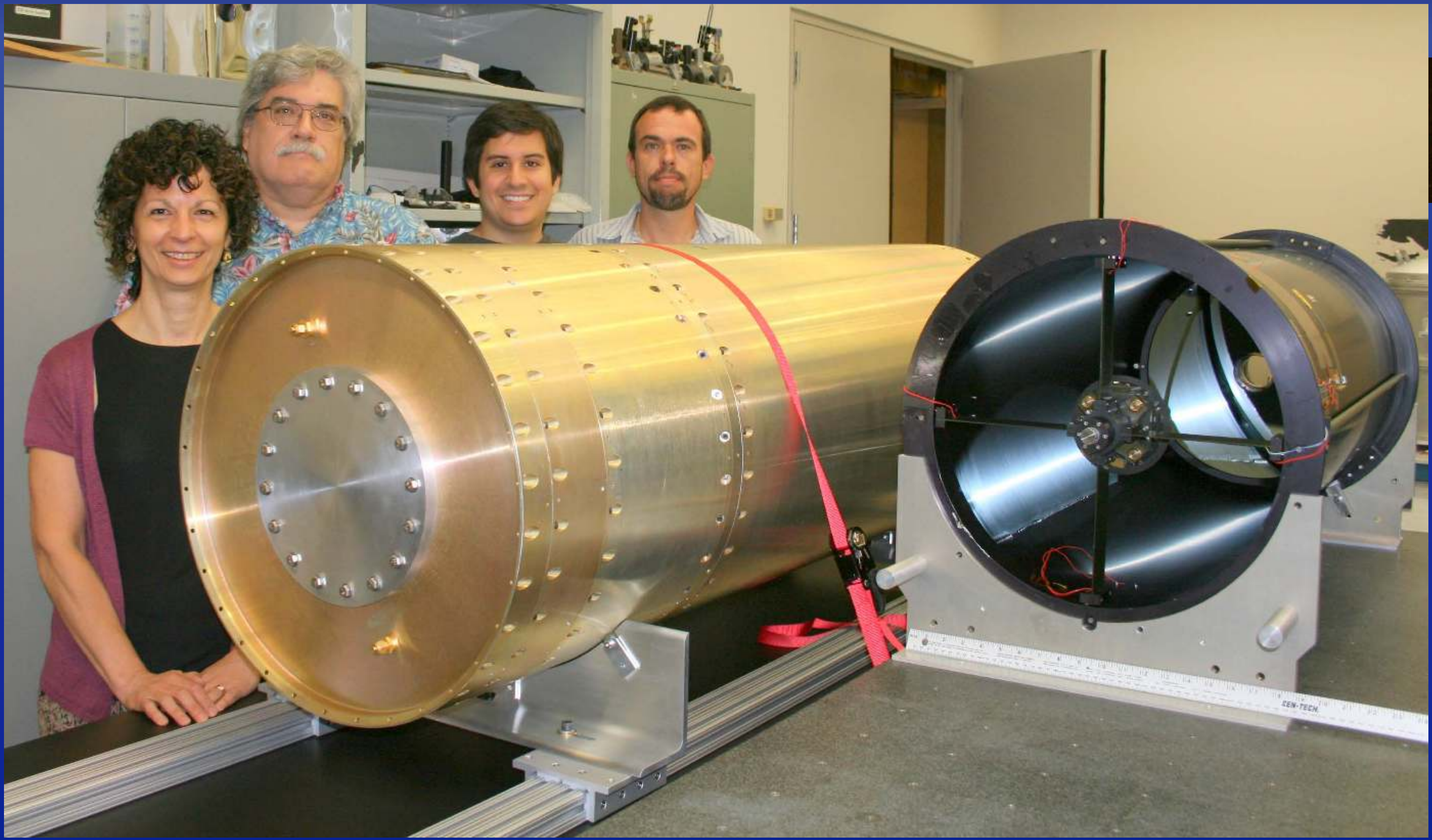
Mirror mount on translation–rotation stage.

Mirror mount with mating vacuum mount.

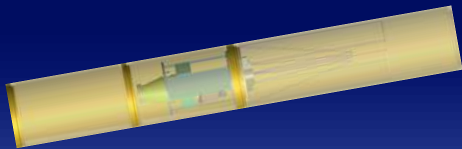


ACCESS (Auto) Collimator

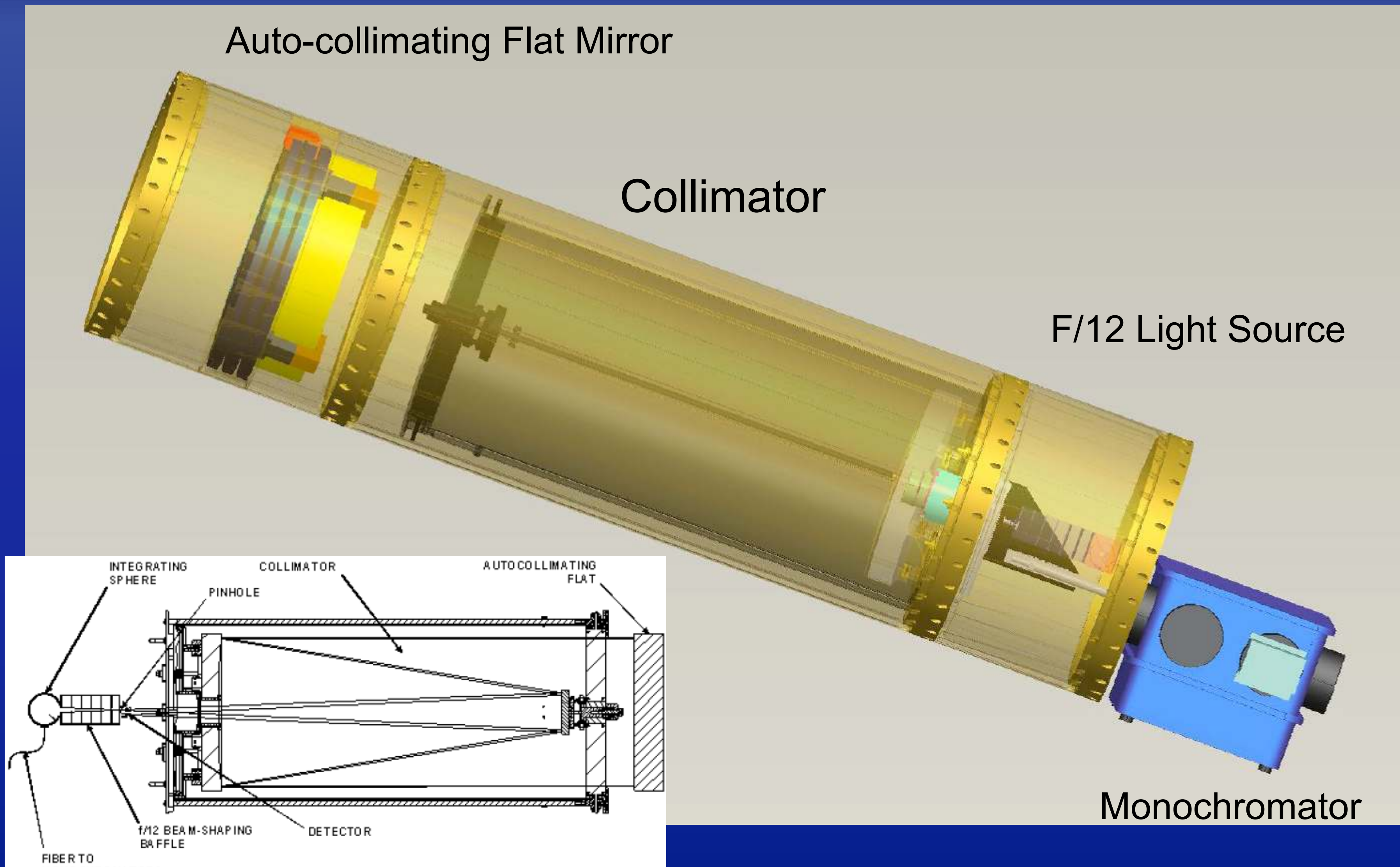


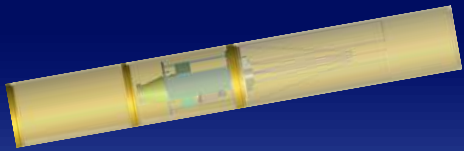


"Artificial star" vacuum housing (left) and collimator component (right).



Establishing the Artificial Star



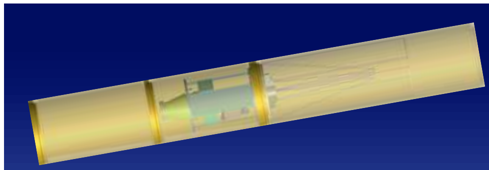


Integrated Collimator & Payload

- Light source: 100 W QTH continuum lamp
  radiometric power supply
  shuttered, thermally controlled housing
  fiber fed to monochromator
- Monochromator: blocking filters
- Spectralon coated integrating sphere (IS)
- Source monitoring diode on IS
  checks source stability near
- f/12 baffle box with pinhole
- NIST calibrated photodiodes

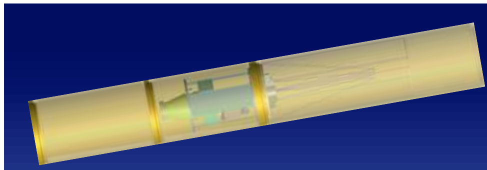
System in vacuum housing:

- eliminates atmosphere,
- reduces background light,
- maintains cleanliness, &
- stability



Transfer NIST standard to ACCESS: Flow down

- Check uniformity of input beam.
  Scan subaperture mask at collimator in autocollimated config
- Characterize collimator to telescope pupil match.
- Measure slit losses. Slit-in, slit-out method.
  Direct characterization of PSF with array detector in focal plane (expect ~1.2 arcsec diameter)
  Measure PSF of telescope & spectrograph at spectrograph focal plane.
- Characterize flat-field response of spectrograph detector.
- Characterize linearity of spectrograph (HgCdTe) detector.
- Characterize the detector count-rate non-linearity
- Characterize linearity of absolute calibration standards.
- Characterize read noise of the detector.
- Characterize readout properties of the detector
- Check end-to-end calibration with NIST facilities
  - Spectral Light Engine: Feed simulated stellar SED into ACCESS
    → standard continuum source (Brown et al., 2006, Jnl NIST 111)
  - SIRCUS: calibration of ACCESS (Brown et al., 2006, App Opt, 45, 8218)



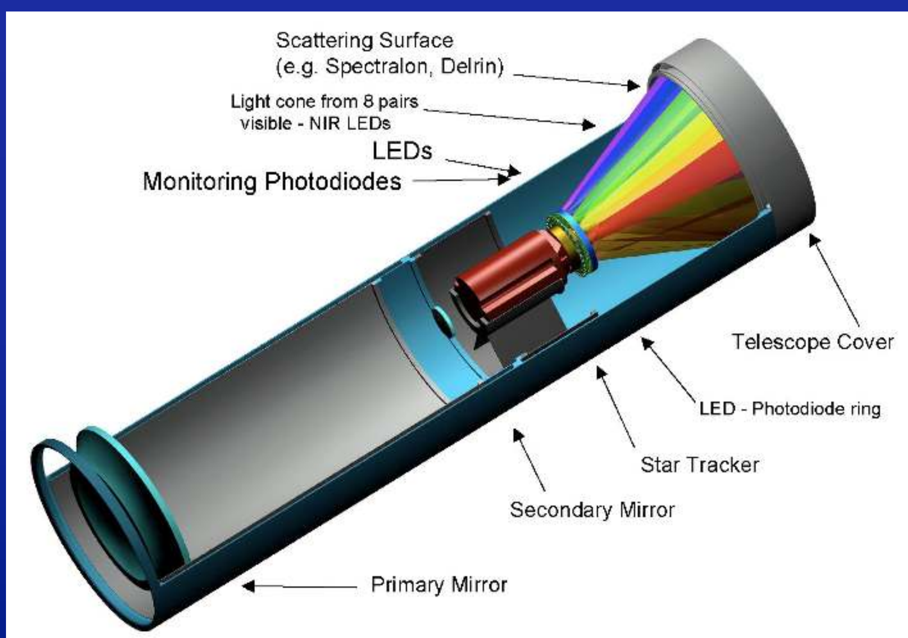
4. Monitor ACCESS Sensitivity

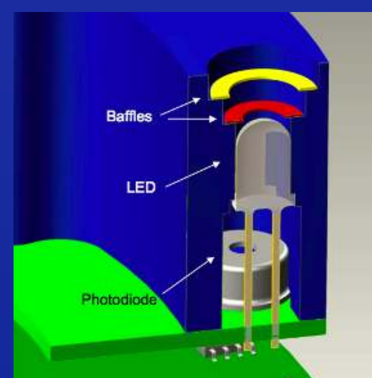
Key to a successful calibration is:

Knowledge of the absolute instrument sensitivity at the time the targets are observed.

ACCESS sensitivity is monitored before & after stellar observations with the On-board Calibration Monitor (OCM) a LED based stabilized light source on-board

- cross-calibrated to NIST standard
- characterizes ACCESS response, tracks & monitors sensitivity throughout program
  - in the lab, in the field at WSMR, while parachuting to the ground post-observation

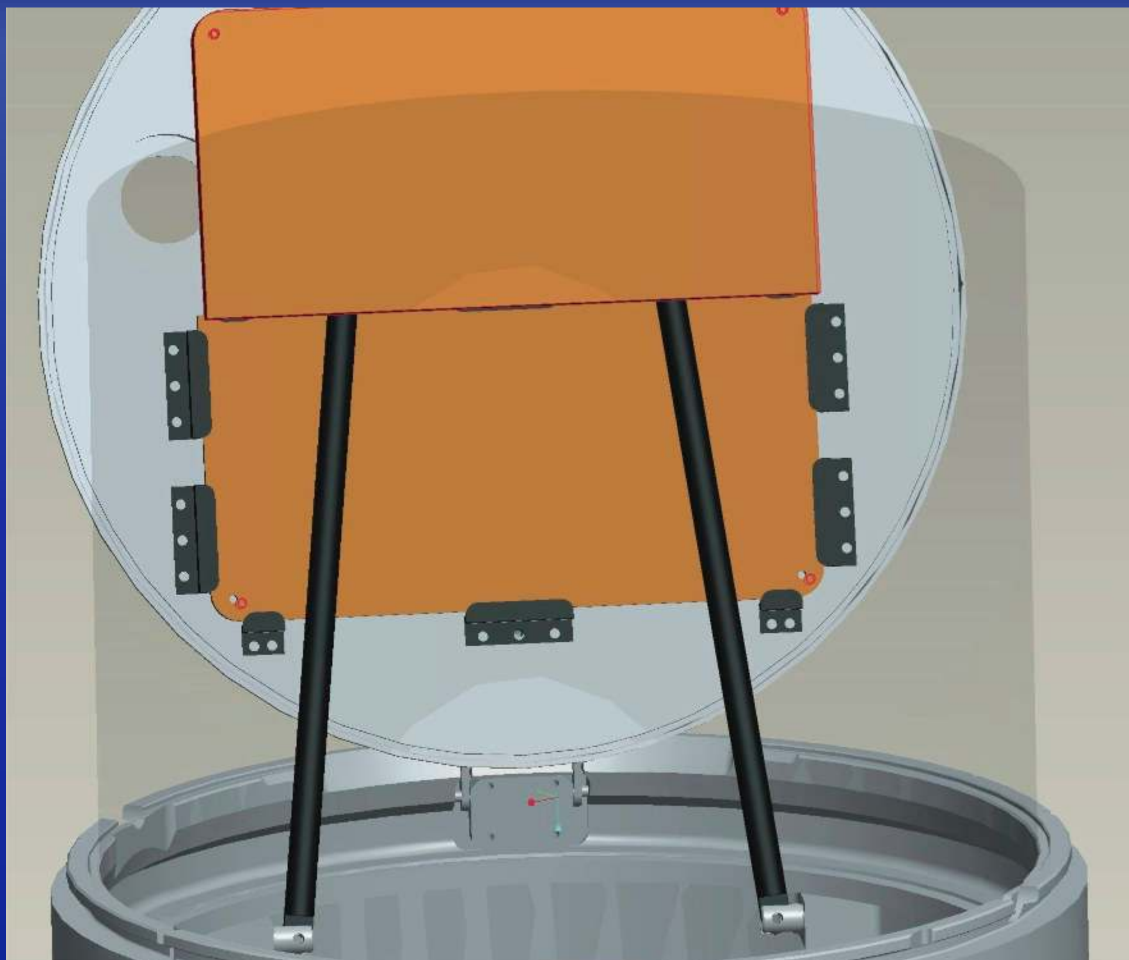




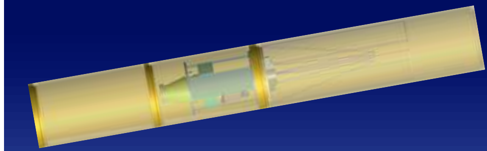
Witness mirrors as contamination monitor

LEDs (ring of 8 pairs):
- illuminate diffuser on telescope cover
- each controlled by a independent photodiode feedback circuit
- constant brightness by adjusts current

OCM Spectralon Diffuser



OCM diffuser screen mount design
The spectralon diffuser is mounted on the telescope door



ACCESS: Key Points

Summary of *Key Points:*

- ACCESS will enable a ***fundamental spectrophotometric calibration*** with spectrophotometry ***tied to multiple NIST calibrators***

- ACCESS **calibration to 1% is relevant** for current science

- **Single detector** & **optical path** span the 0.35-1.7μm wavelength region
  - reduces cross-calibration systematic errors

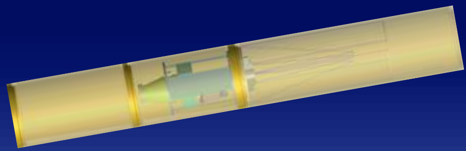
- **On-board Calibration Monitor to track system response** throughout experiment/mission lifetime. Tied to NIST calibration.

- **Errors identified, estimated & manageable**

- **Two observations** of each standard star to confirm/ensure repeatability

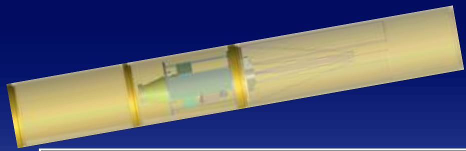
- **ACCESS recalibration with photodiode standards after each flight** NIST recalibration as warranted

- **Validation of high resolution models** for *fundamental standard stars*
  - for use by space and ground based observatories



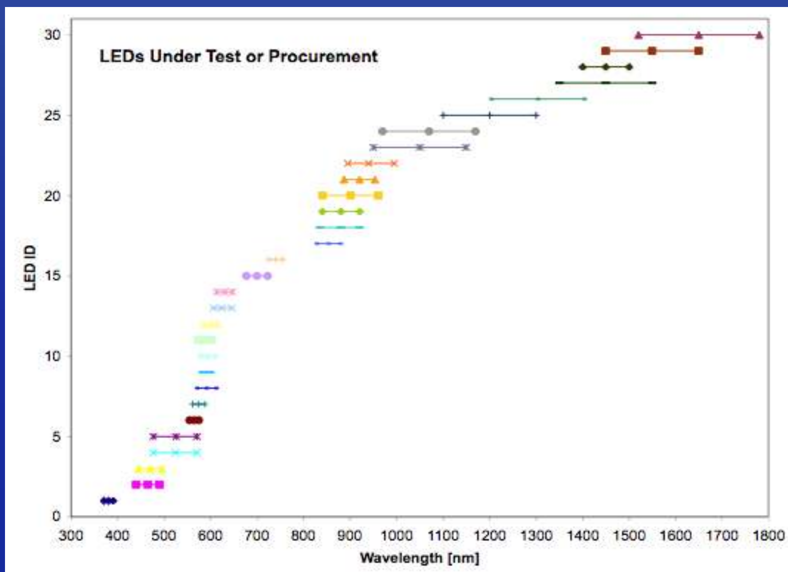
ACCESS

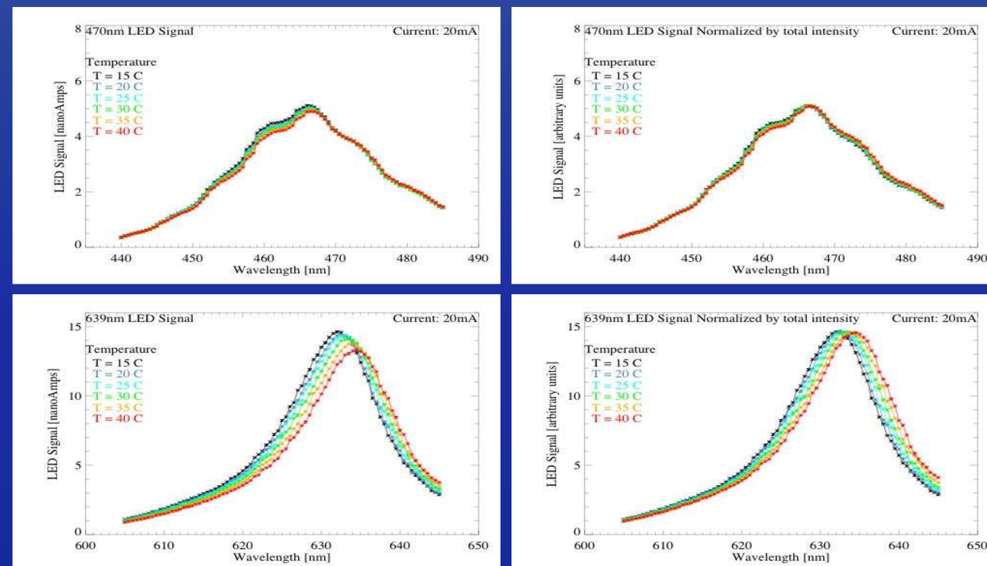
This work supported by NASA grant NNX08AI65G



LED selection & SED variation w/ Temperature

LED selection is driven by several characteristics:
- Brightness
- Bandwidth of the Spectral Energy Distribution (SED)
- Stability of the brightness and SED under variations in temperature





Left: Set of LEDs under test.

Center: Variation in LED output (brightness & SED) with temperature for a fixed current. The InGaN LEDs (top) are fairly stable, while active thermal control is preferred to minimize wavelength shifts & to stabilize the SEDs of the AlINGaP (bottom) LEDs.

Right: variation in LED output with the total intensity normalized to a common value. This represents the effect of photodiode feedback control.

Funding: DOE DE-PS02-07ER07-08 NASA NNX08AI65G