QWEST and HyTES: Two New Hyperspectral Thermal Infrared Imaging Spectrometers for Earth Science

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Detectors: Sarath Gunapala, Cory Hill, David Ting
Gratings: Dan Wilson
Mechanical: William Johnson
Thermal: Chris Paine, Andy Lamborn
Science: Vince Realmuto, Simon Hook
Data recording and storage: Bjorn Eng

Outline

- Science goals and task objectives
- Technical developments to date
  - System design
  - Optics
  - Detectors
  - Mechanical
  - Thermal
  - Data recording and storage
- Radiometric analysis of QWEST
- Summary and Conclusions

Overall Science Goal and Objective

- Provide precursor high spectral and spatial resolution thermal infrared data for the NRC Recommended HyspIRI mission and for use in Earth Science Studies.

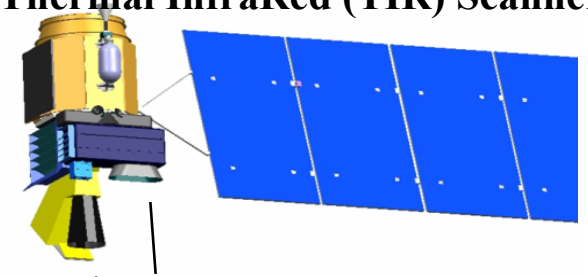
- Build and deploy an airborne Hyperspectral Thermal Emission Spectrometer (HyTES) with 512 pixels across track with pixel sizes in the range of 5 to 50 m depending on aircraft flying height and 256 spectral channels between 7.5 and 12 μm.

NRC Decadal Survey HyspIRI

Visible ShortWave InfraRed (VSWIR) Imaging Spectrometer

+

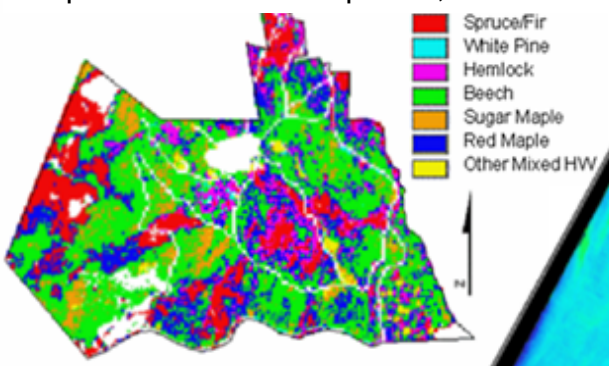
Multispectral Thermal InfraRed (TIR) Scanner

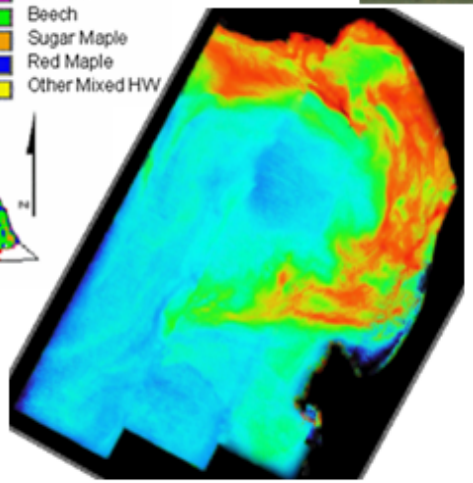


VSWIR: Plant Physiology and Function Types (PPFT)

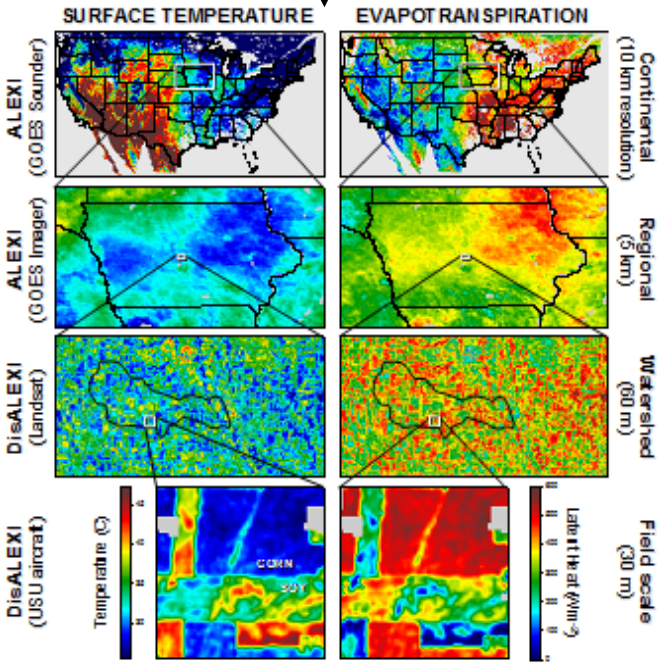
Multispectral TIR Scanner

Map of dominant tree species, Bartlett Forest, NH

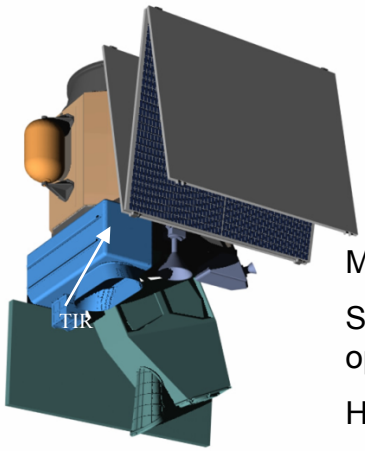


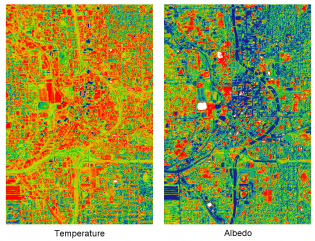


Red tide algal bloom in Monterey Bay, CA



HyspIRI Thermal Infrared Multispectral (TIR) Science Measurements





Atlanta, GA - May 1997

Multispectral Scanner

Schedule: 4 year phase A-D, 3 years operations

High Heritage

Science Questions:

TQ1. Volcanoes/Earthquakes (MA,FF)

– How can we help predict and mitigate earthquake and volcanic hazards through detection of transient thermal phenomena?

• TQ2. Wildfires (LG,DR)

– What is the impact of global biomass burning on the terrestrial biosphere and atmosphere, and how is this impact changing over time?

• TQ3. Water Use and Availability, (MA,RA)

– How is consumptive use of global freshwater supplies responding to changes in climate and demand, and what are the implications for sustainable management of water resources?

• TQ4. Urbanization/Human Health, (DQ,GG)

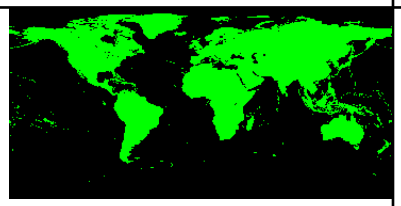
– How does urbanization affect the local, regional and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare?

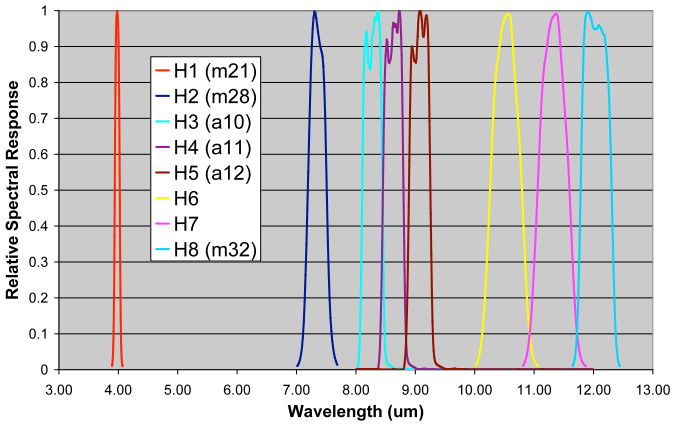
• TQ5. Earth surface composition and change, (AP,JC)

– What is the composition and temperature of the exposed surface of the Earth? How do these factors change over time and affect land use and habitability?

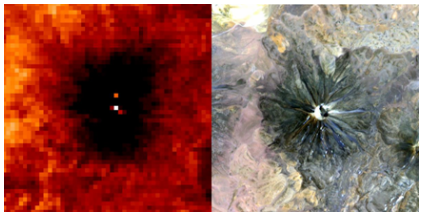
Measurement:

- 7 bands between 7.5-12 µm and 1 band at 4 µm
- 60 m resolution, 5 days revisit
- Global land and shallow water

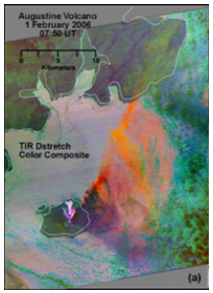




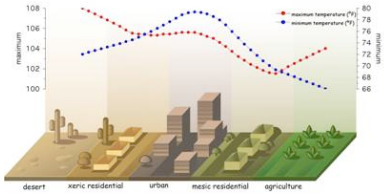
Andean volcano heats up



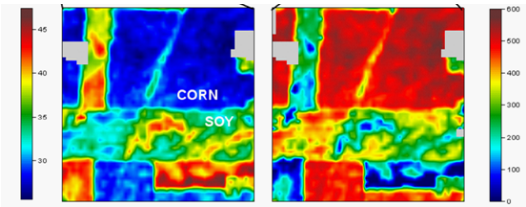
Volcanoes



Urbanization

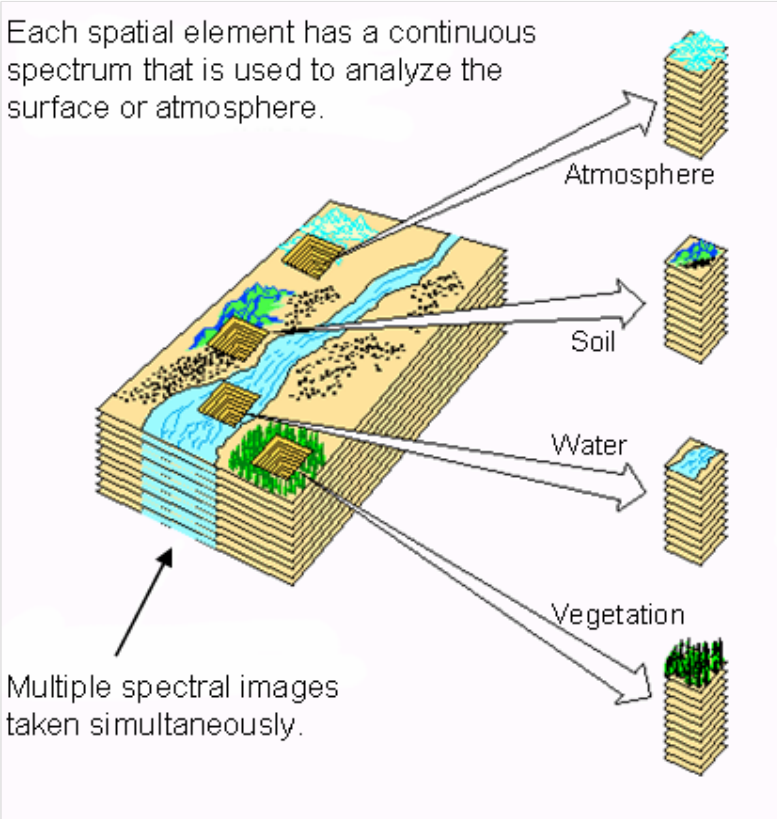


Water Use and Availability



Surface Temperature Evapotranspiration

Thermal Imaging Spectroscopy for Earth Science



Volcanoes

How can we help predict and mitigate earthquake and volcanic hazards through detection of transient thermal phenomena?

Wildfires

What is the impact of global biomass burning on the terrestrial biosphere and atmosphere, and how is this impact changing over time?

Water Use and Availability

How is consumptive use of global freshwater supplies responding to changes in climate and demand, and what are the implications for sustainable management of water resources?

Urbanization

How does urbanization affect the local, regional and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare?

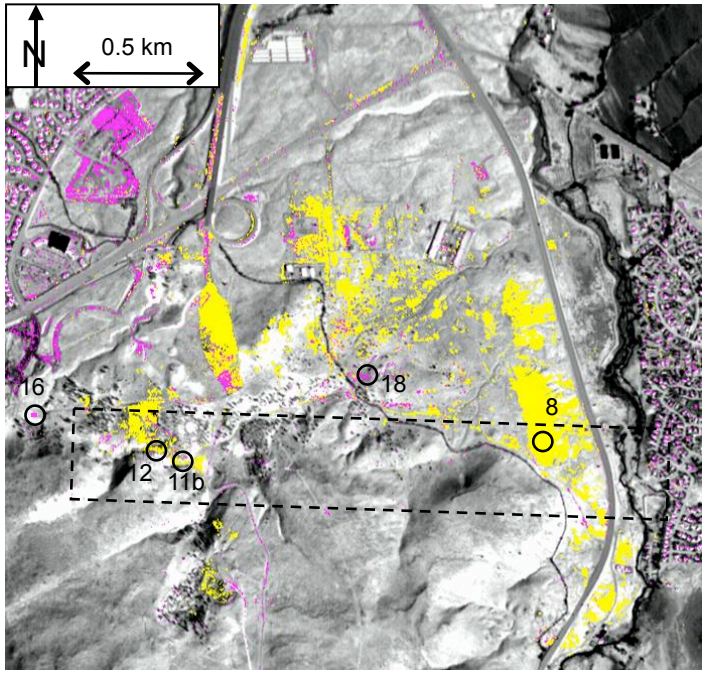
Land surface composition and change

What is the composition and temperature of the exposed surface of the Earth? How do these factors change over time and affect land use and habitability?

Thermal spectroscopy acquires both the emission from the target source object as well as reflected and/or transmitted emission from surrounding and/or foreground objects.

Thermal Imaging Spectroscopy for Earth Science

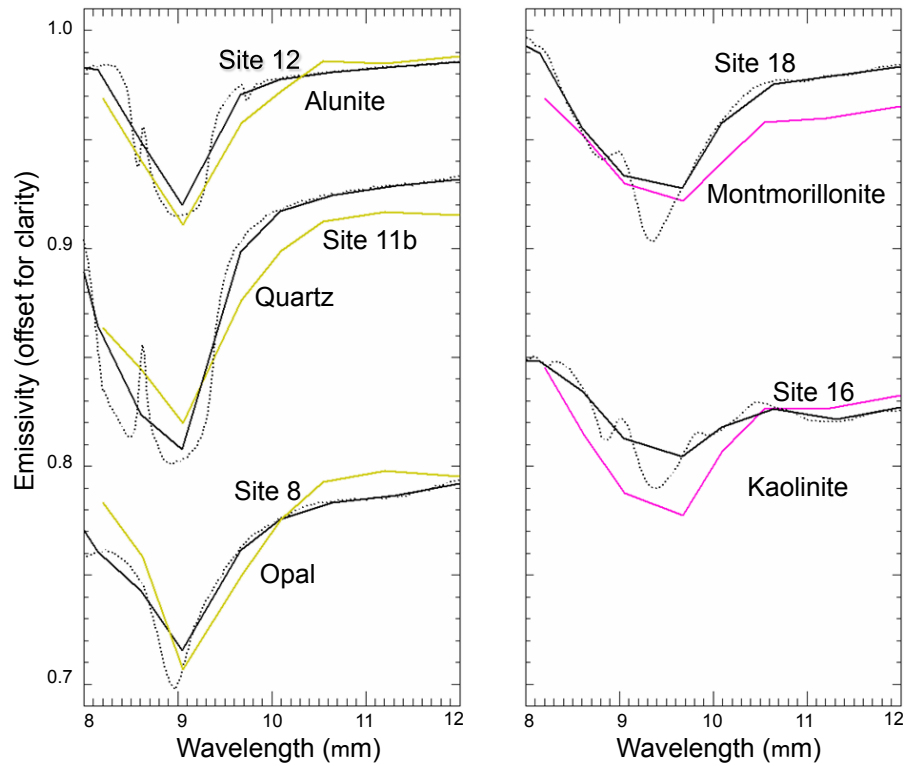
Steamboat Springs



Map Color Legend

Silica-rich (Opal, Quartz, Alunite)

Clay-rich (Kaolinite, Montmorillonite, Muscovite, Illite)



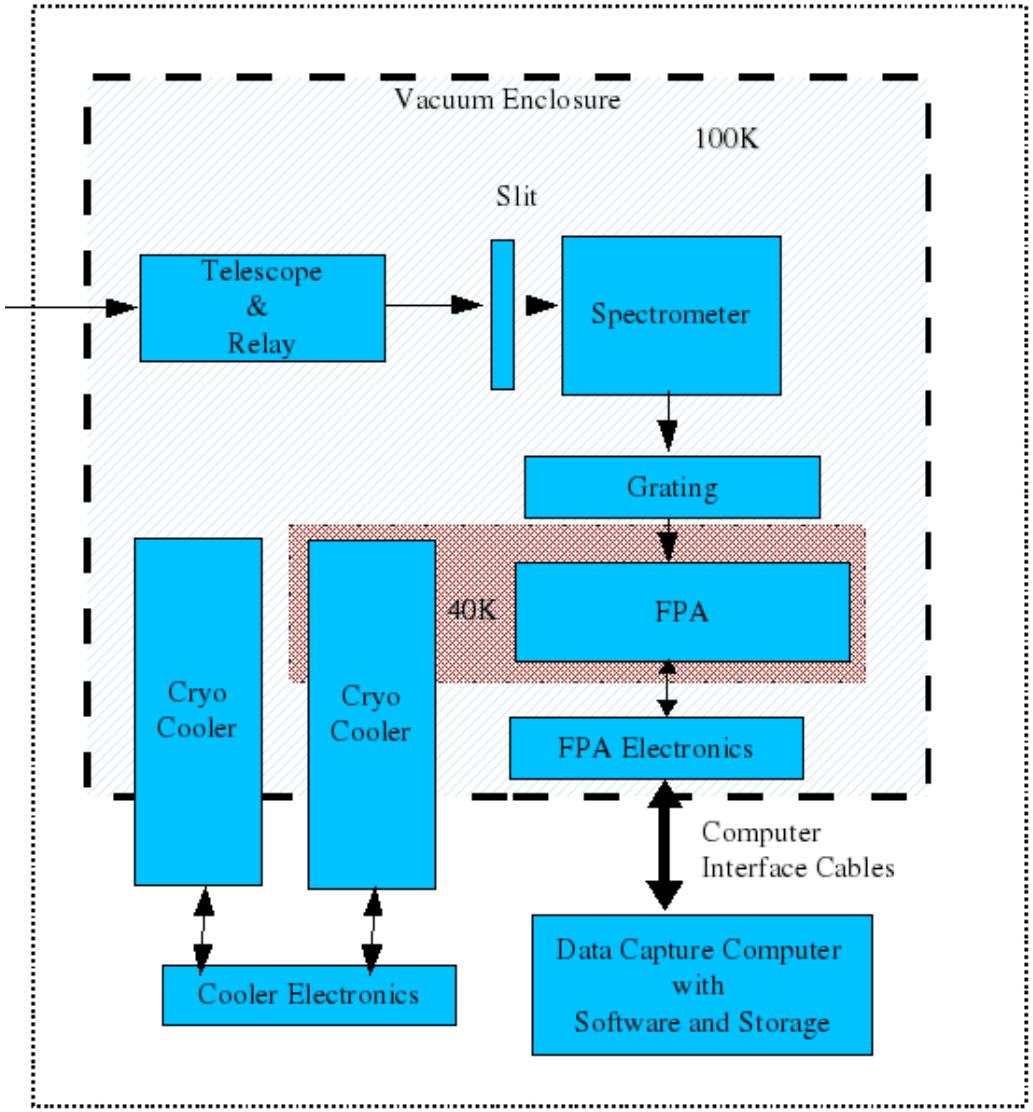
Emissivity plots derived from spectra

HyTES Task Objectives

- Develop a calibrated, airborne imaging spectrometer operating between 7.5 and 12 μm with 256 spectral channels
- Develop an initial overall system design
  - Optical design
  - Thermal/mechanical design
  - Data acquisition and recording system
- Evaluate key design elements using the existing JPL Quantum Well Earth Science Testbed (QWEST), in particular 7.5-12 μm QWIP FPA
- Design and fabricate:
  - Overall system, Optics, Detectors, Grating, Mechanical, Thermal, Data recording and storage
- Assemble, test and calibrate in the laboratory
- Complete aircraft-integration
- Deploy from an airborne platform over test sites in Western USA
- Provide data to HyspIRI Study Group

System Design

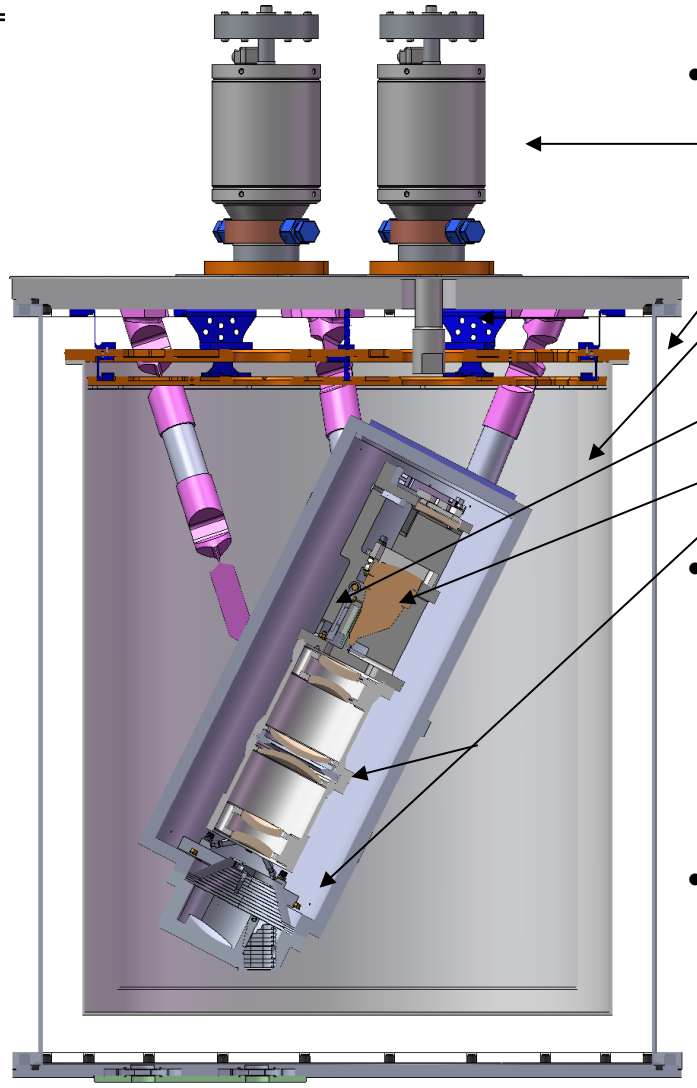
HyTES System Block Diagram



The HyTES airborne instrument is a mechanically cooled system consisting of a vacuum chamber, cryocoolers, thermal radiation shields, telescope/relay, and spectrometer

The mechanical coolers are a design change from the original proposal

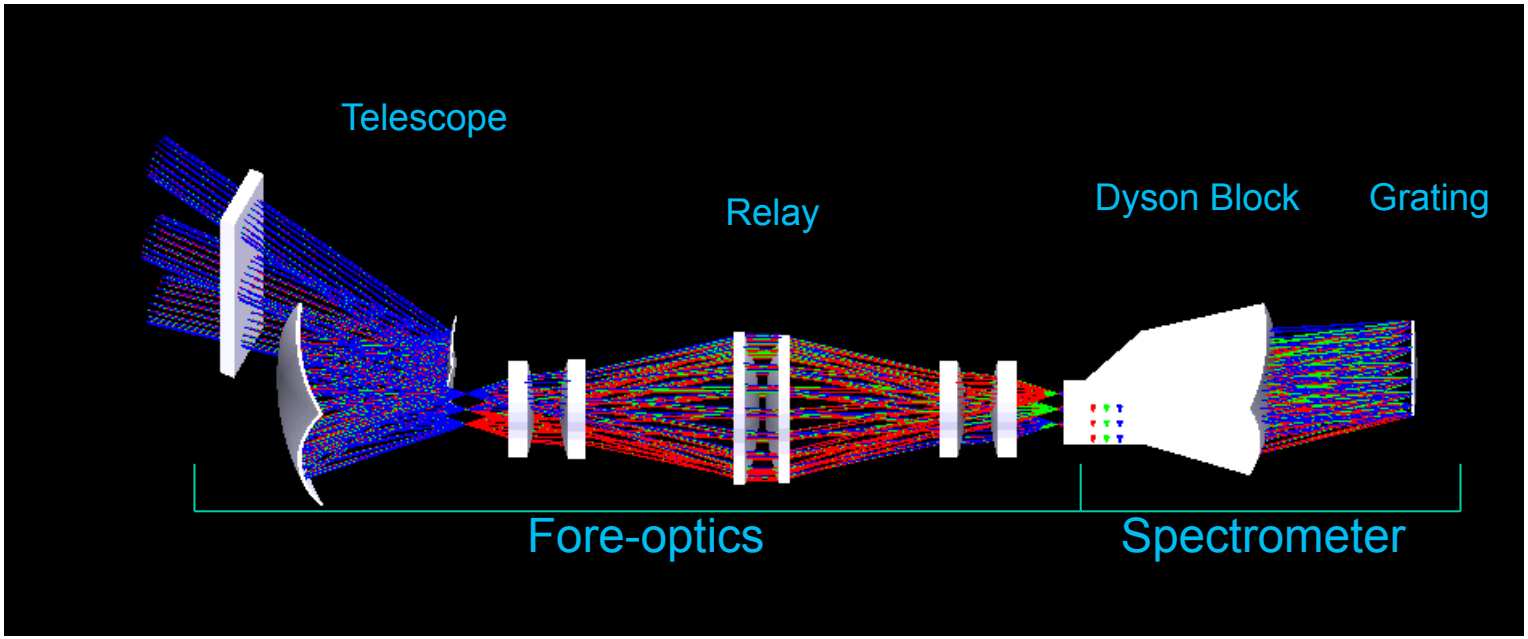
HyTES cryovacuum package



- Mechanical components:
  - mechanical cryocoolers (2)
  - vacuum enclosure
  - floating radiation shields (2)
  - thermal isolation struts
  - QWIP focal plane array with positioning assembly
  - spectrometer
  - telescope and relay optics
- Temperature requirements:
  - QWIP FPA ≤40 K for dark current supression
  - Spectrometer ≤100 K for background supression
  - Relay optics ≤250 K with stability restrictions
  - Telescope ~room temperature
- Chose to cool the optical instrument to 100 K
  - single mechanical assembly is highly desirable for alignment
  - cold relay eliminates temperature variation concerns

Optics

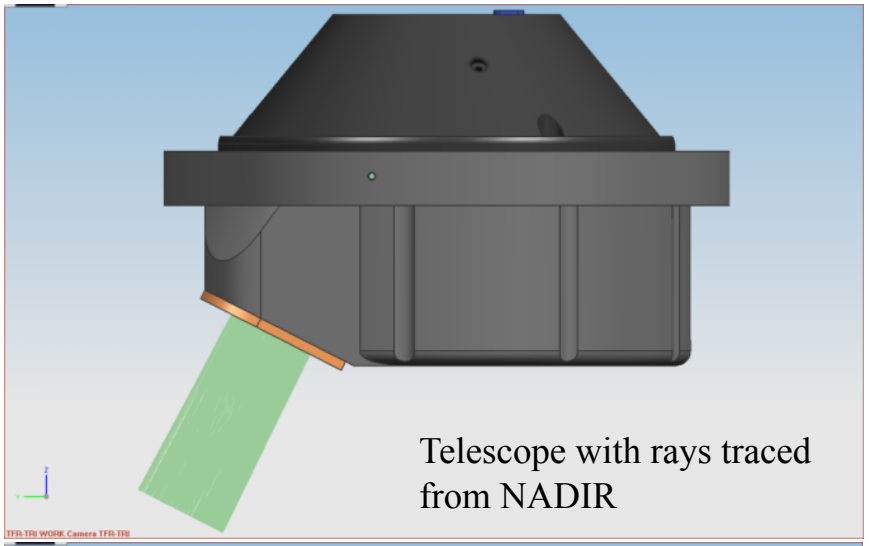
HyTES Optics

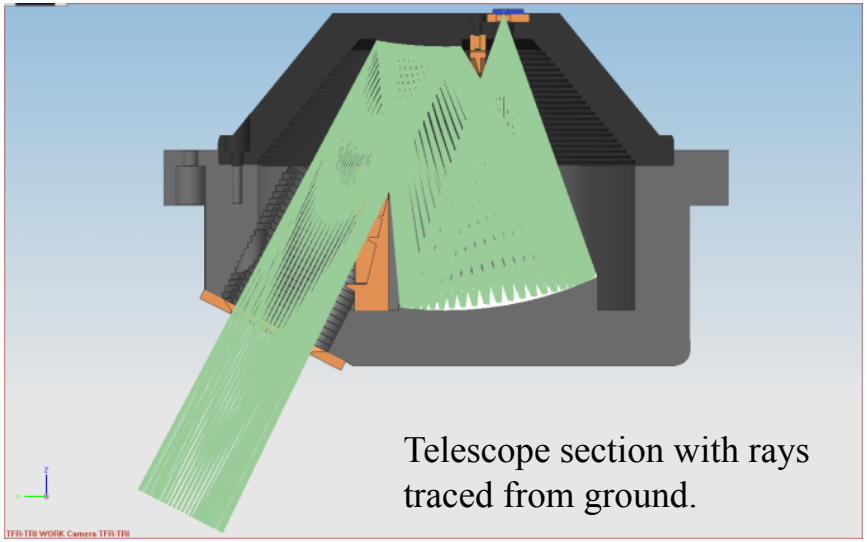


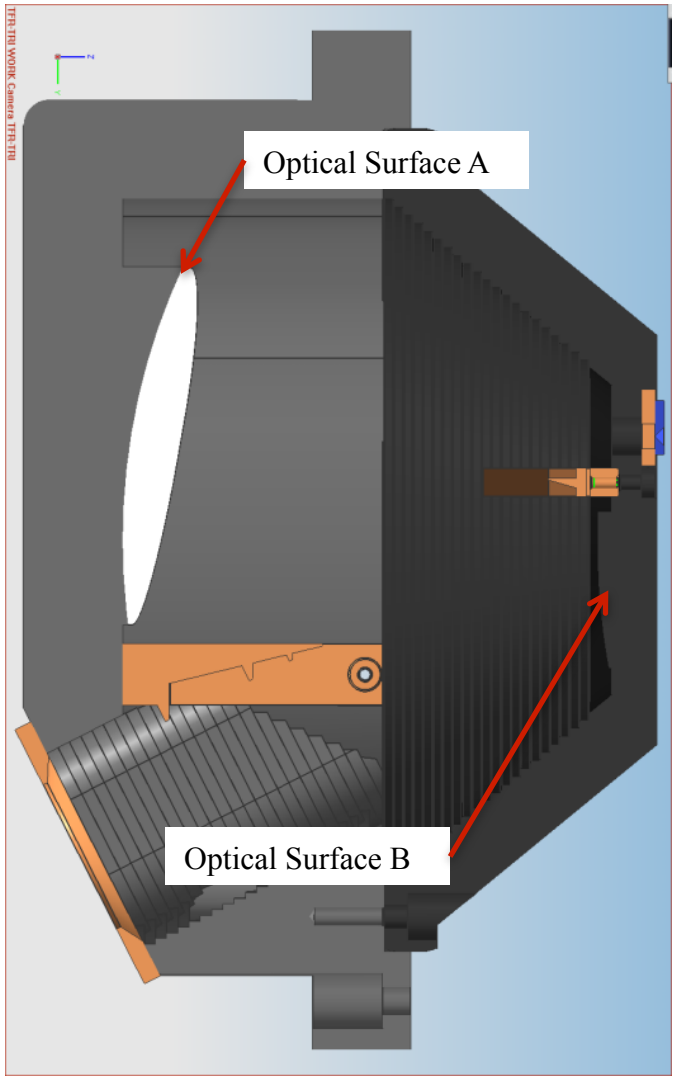
Parameter	Value
Spectral range	7.5-12 mm
Spectral channels (sampling)	256 (17.6 nm)
Field of view	48.3°
IFOV (pixel subtense)	1.44 mrad
Spatial elements	512

Telescope

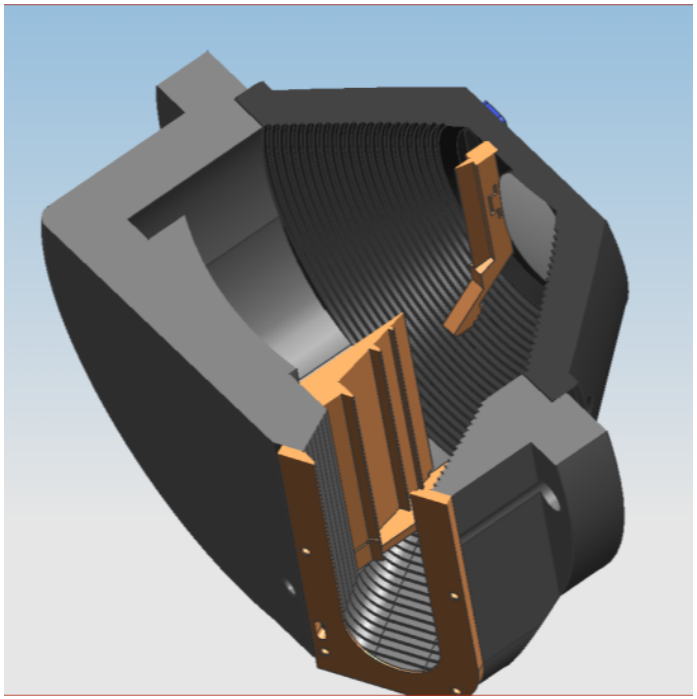
HyTES Telescope



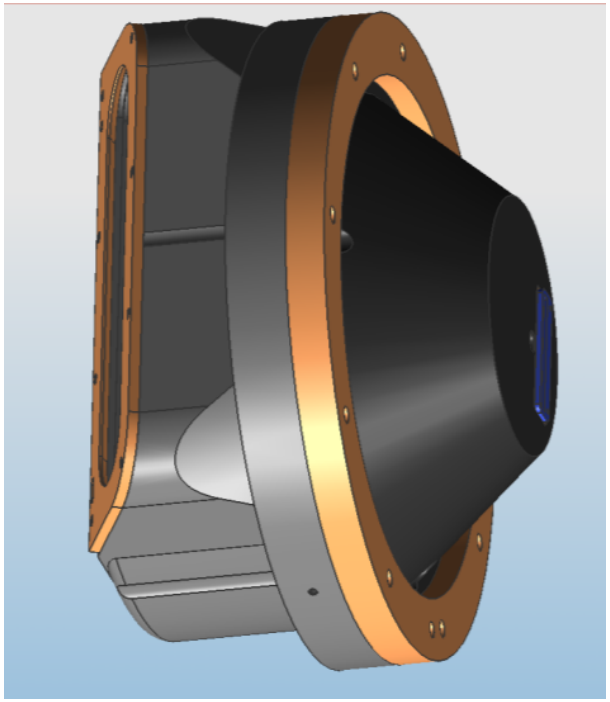




HyTES Telescope



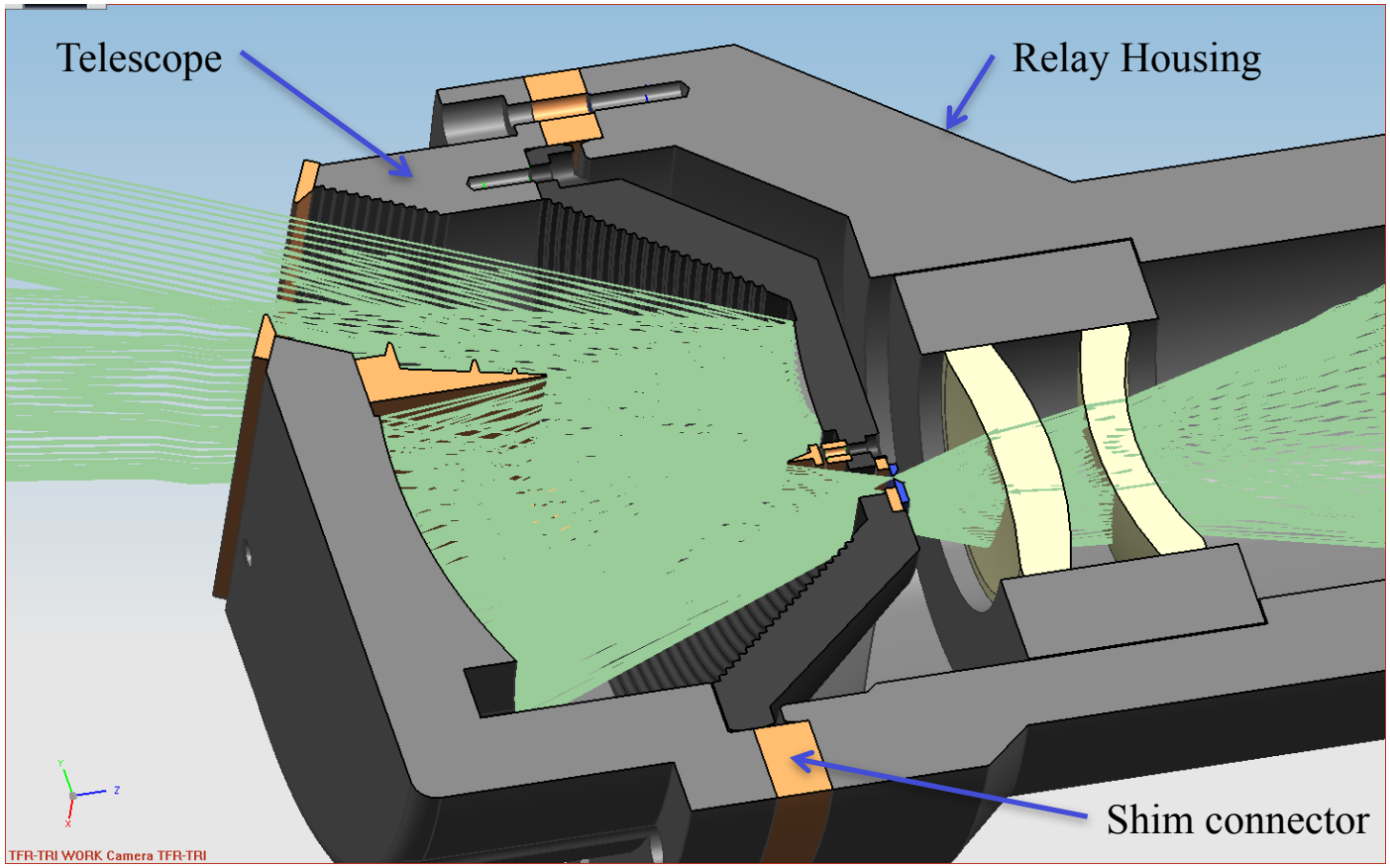
Section showing HyTES telescope. The telescope is all-aluminum, diamond-turned, athermal, “snap-together” design. No real technical hurdles. Diamond turning process is well defined.



Numerous accessories are also part of the design including:

- Aperture baffle
- 2 Internal baffles
- Rear slot baffle
- Precision made large shim

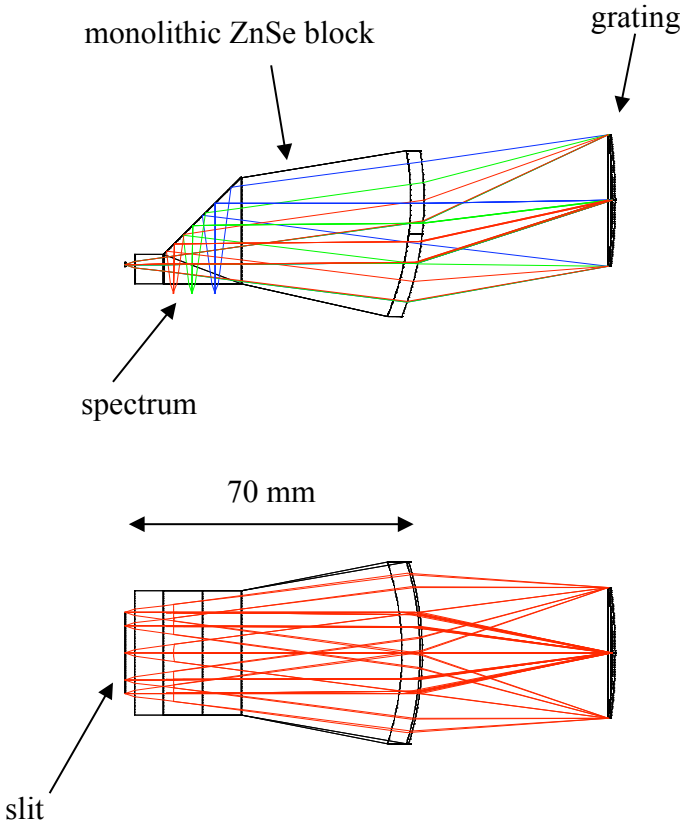
HyTES Telescope



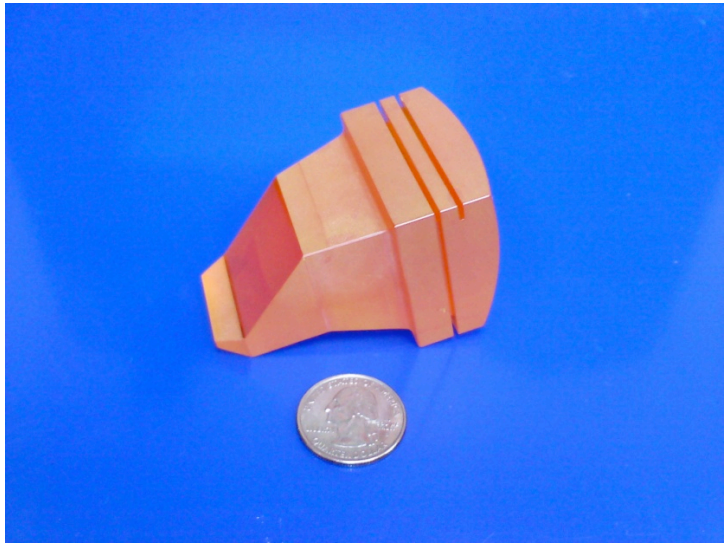
Telescope design provides a direct connection to the relay housing

Spectrometer
(Slit, Dyson Block and Grating)

HyTES Spectrometer-Block



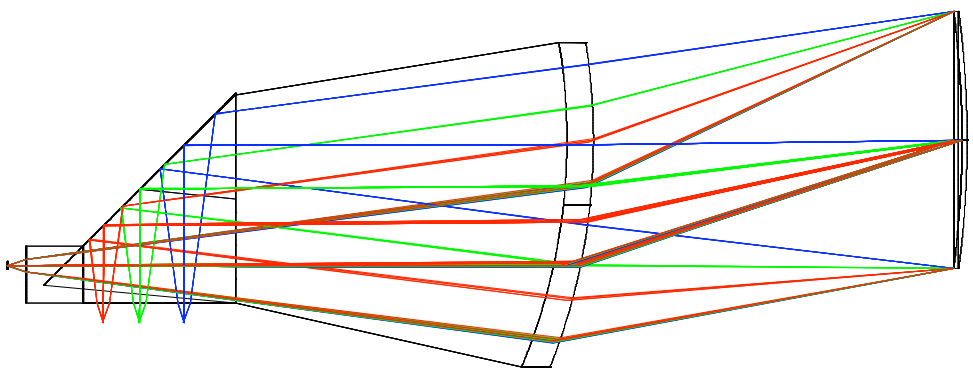
Optical prescription

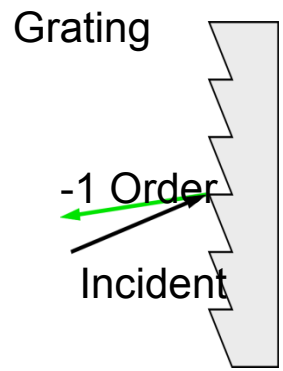


HyTES Spectrometer
delivered in May 2010

HyTES Concave Grating

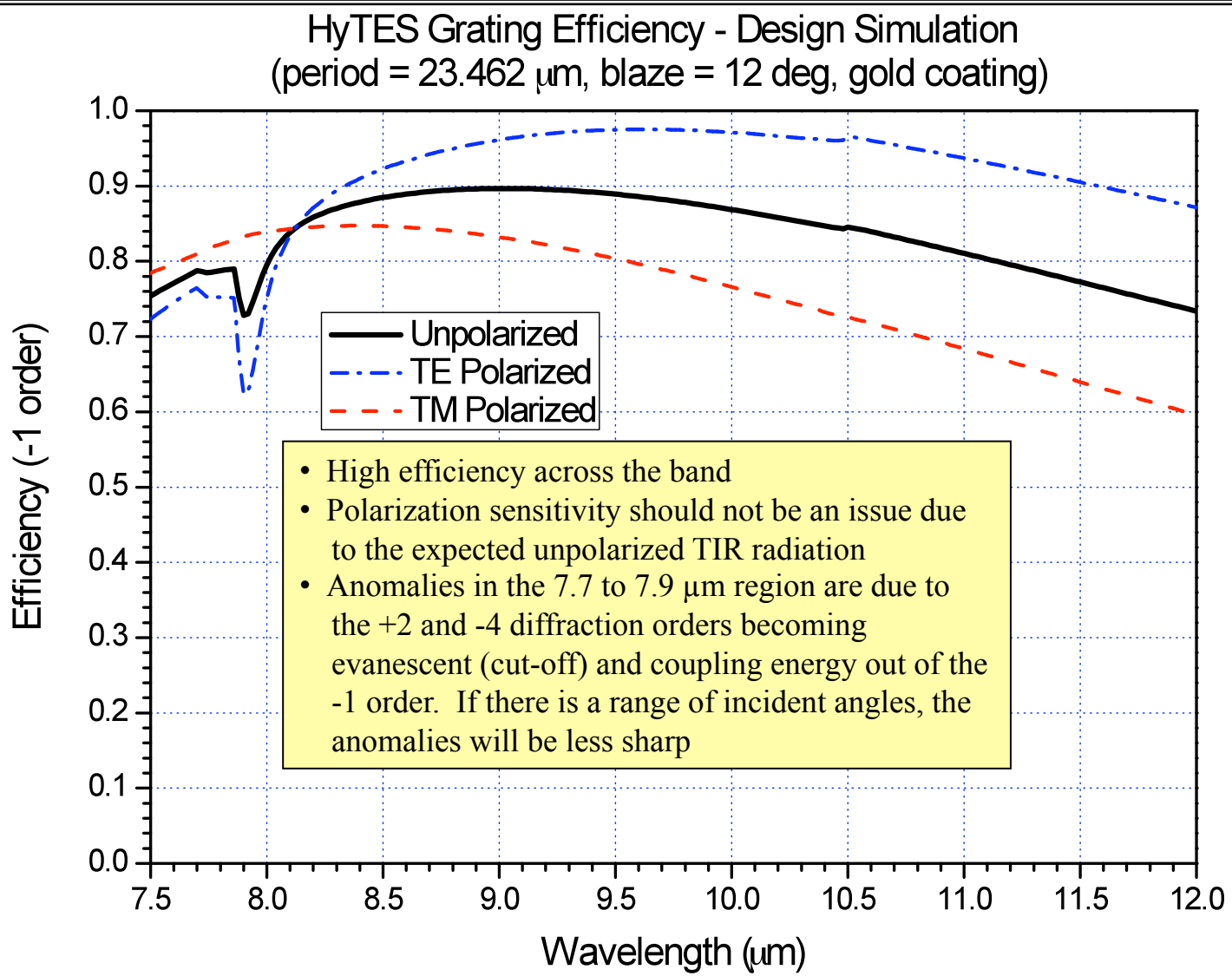
HyTES Spectrometer Ray Trace





Wavelength Range	7.5 - 12 µm
Incident angle	~17.9 deg
Diffraction order	-1

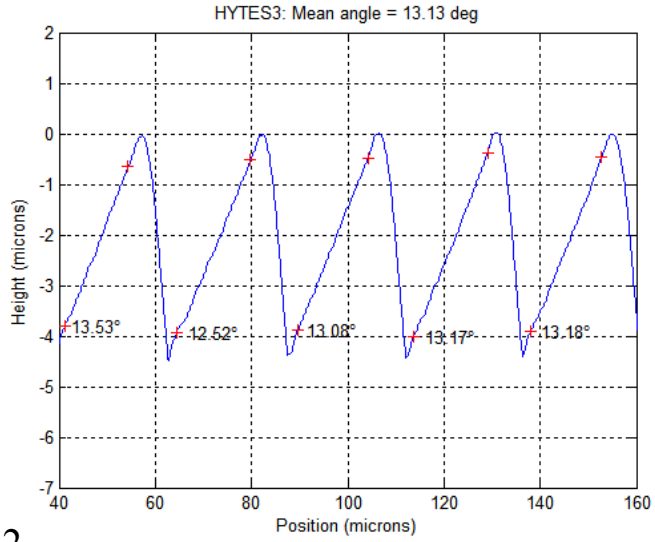
HyTES Concave Grating Design Simulation

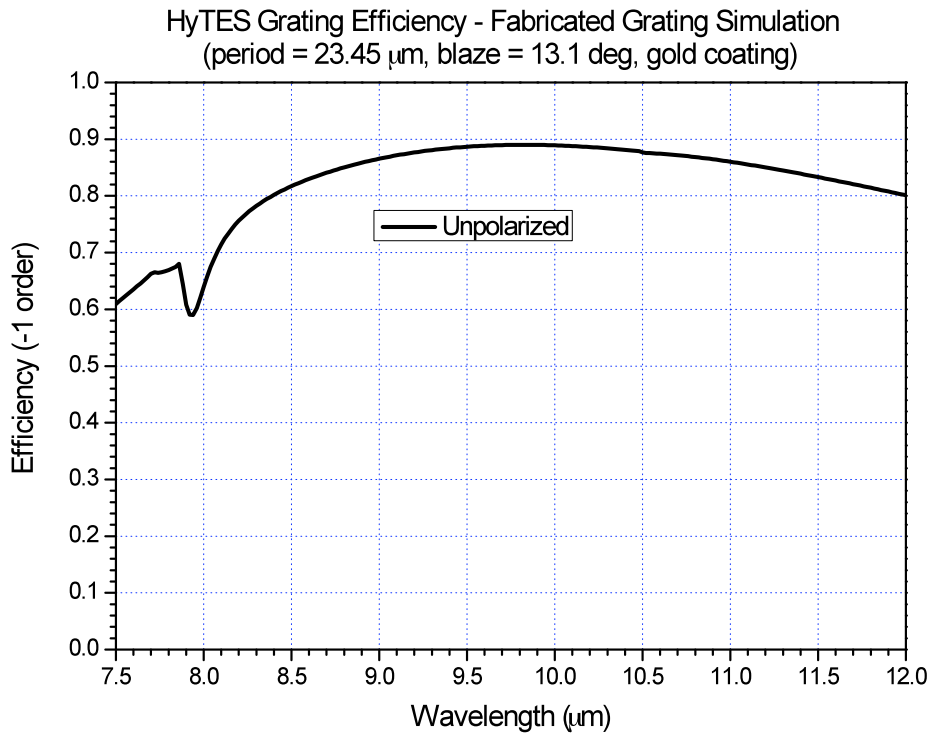


- High efficiency across the band
- Polarization sensitivity should not be an issue due to the expected unpolarized TIR radiation
- Anomalies in the 7.7 to 7.9 μm region are due to the +2 and -4 diffraction orders becoming evanescent (cut-off) and coupling energy out of the -1 order. If there is a range of incident angles, the anomalies will be less sharp

Fabricated 7.5 to 12 µm HyTES Grating

- Grating successfully fabricated (ZnSe substrate, grooves etched in PMMA resist, gold reflective coating)





- Measured blaze angle is ~13.1° (9% deeper than 12° design) – will decrease efficiency at 7.5 µm and increase efficiency at 12 µm as simulated above

HyTES Slit Design

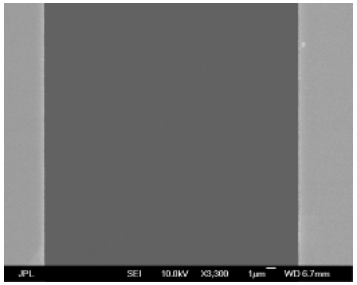
The slit was made using Reactive ion etching (RIE) of silicon nitride (Si3N4) films formed by low pressure chemical vapor deposition (LPCVD)

Usually, the silicon nitride is grown on a silicon wafer at a high temperature, 815 C or so. The recipe is adjusted so that when it comes down to room temperature, the nitride is under light tensile stress (50-100 Mpa).

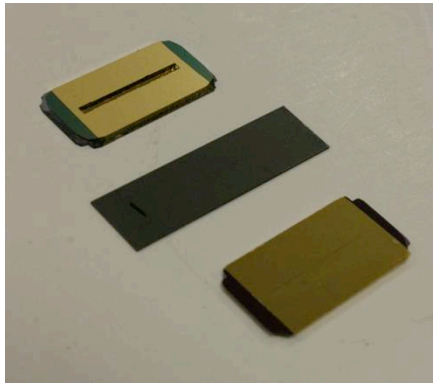
Thickness of substrate: 1mm

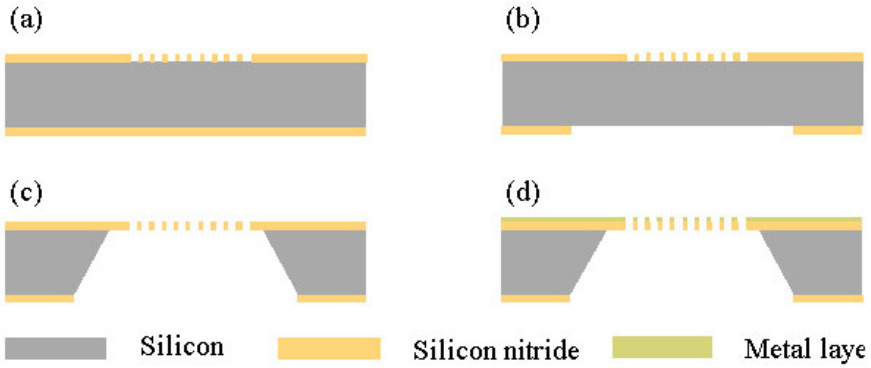
Outer dimensions: cut to 1.0” x 1.5”

Clear aperture: 20mm x 39µm



SEM of JPL slit shows high edge quality.

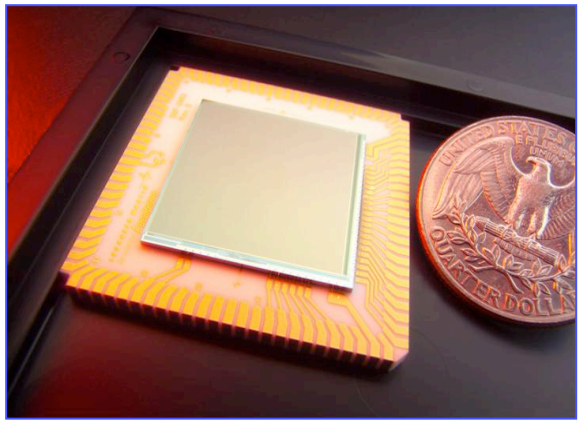




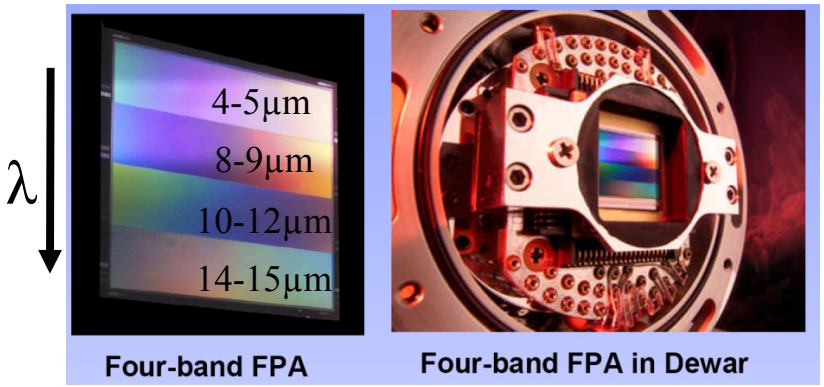
Detectors

Detector Array Plan

- HyTES will use a 1024x1024 pixel array covering the 7.5-12µm spectral band (typical array shown at top right)
- A two-band quantum well infrared photodetector (QWIP) array has been selected as the detector array material
- JPL has fabricated and delivered similar large area and multi-band (dual color, three color and four color) arrays in the past
- This is not a commercially available technology, and only JPL delivers large format, high performance multi-band QWIP arrays
- The detector array has the following requirements:
  - 1kx1k format, SBF 184 ROIC
  - Minimum operating temperature 40K
  - Performance such that in each of the 2-column averages in the 7.5-12µm band the NEDT is less than 200 mK

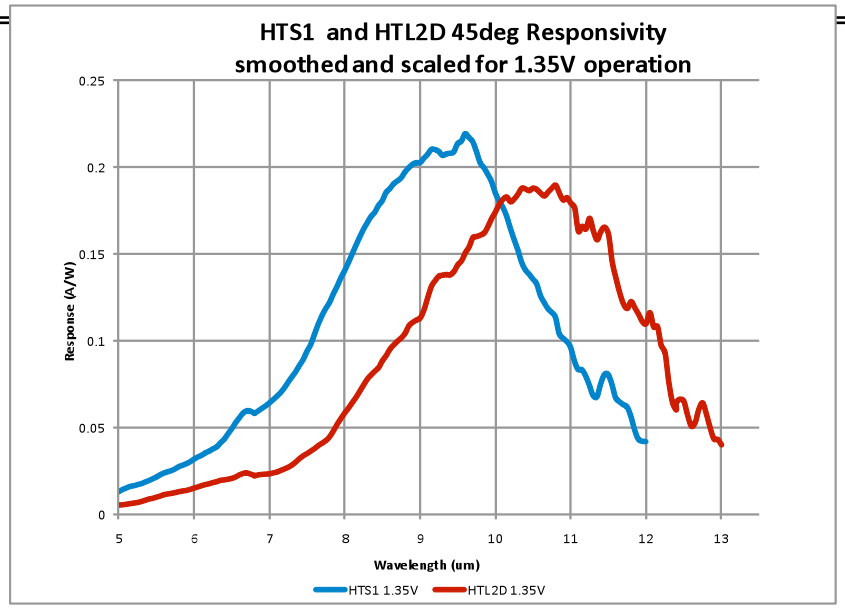


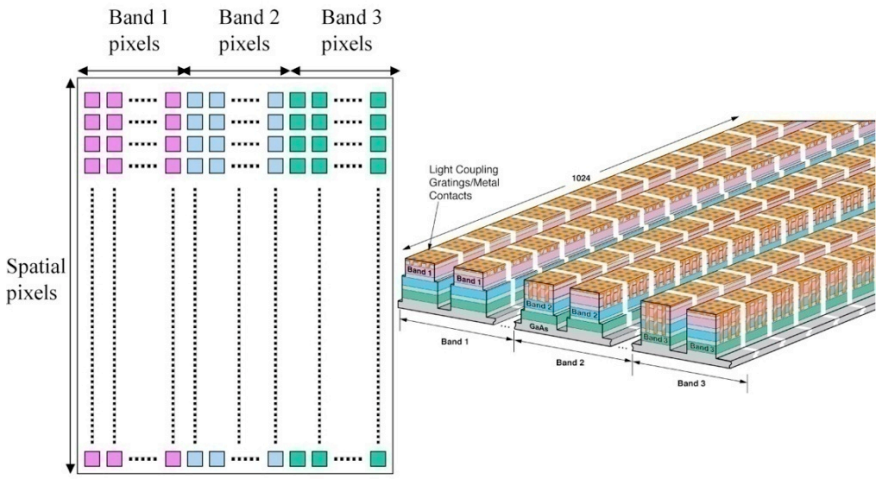
1024x1024 pixel single-band QWIP FPA



Detector Array Design

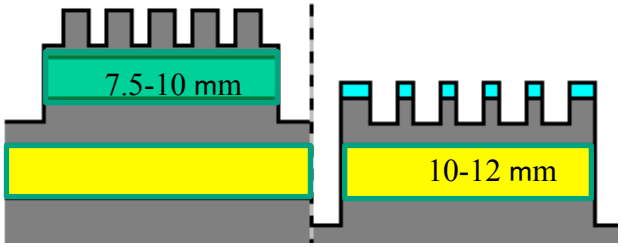
- The detector array will be processed as two separately optimized spectral bands, which together cover the entire 7.5-12µm spectral range
- This is the **first** time a high-performance QWIP array has been used in a hyperspectral application
- The spectral responsivity for the two bands designed for HyTES are shown here and together cover the 7.5-12µm band
- This customized array response is made possible by a design and fabrication method which allows many separate bands to be grown and processed monolithically on the same semiconductor wafer (an example with multiple bands is shown on the right)



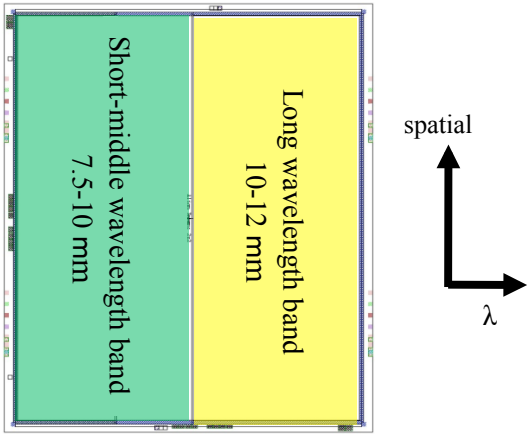


FPA Fabrication

- A cross section of the two-band quantum well infrared photodetector (QWIP) used as the detector material is shown below
- This is similar to the previous three-band design but much simpler to process
- Roughly half of the array will respond in the 7.5-10μm range, and the other half will cover the 10-12 range



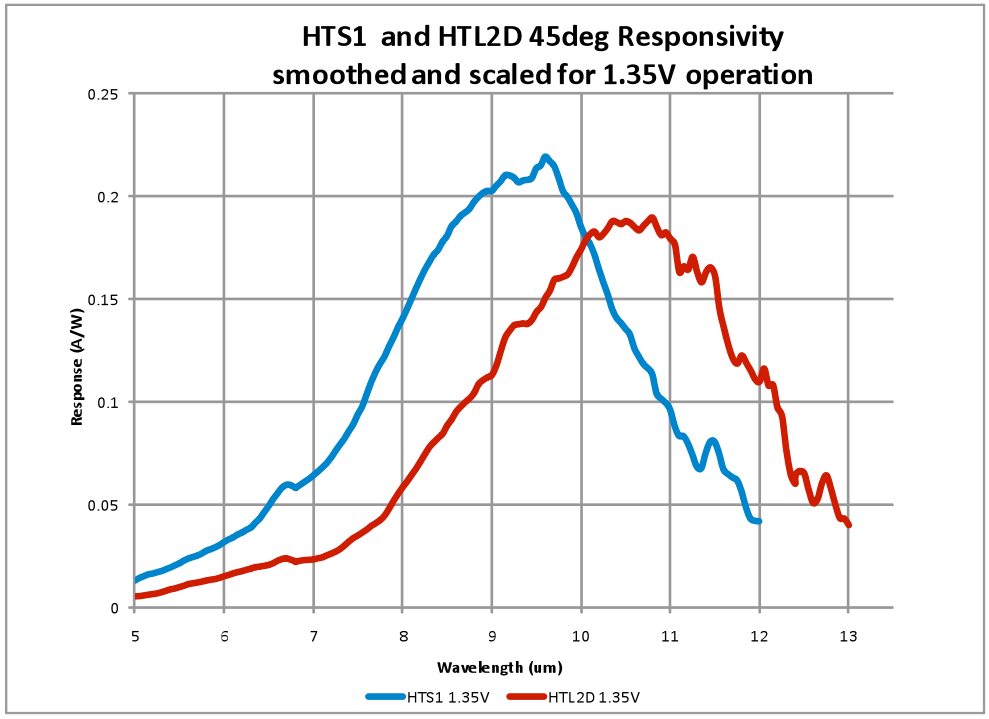
HyTES pixel design – cross-sectional zoom at the transition point, showing two bands with ¼ lamda gratings on each



Top-down view of FPA

Detector Design Status

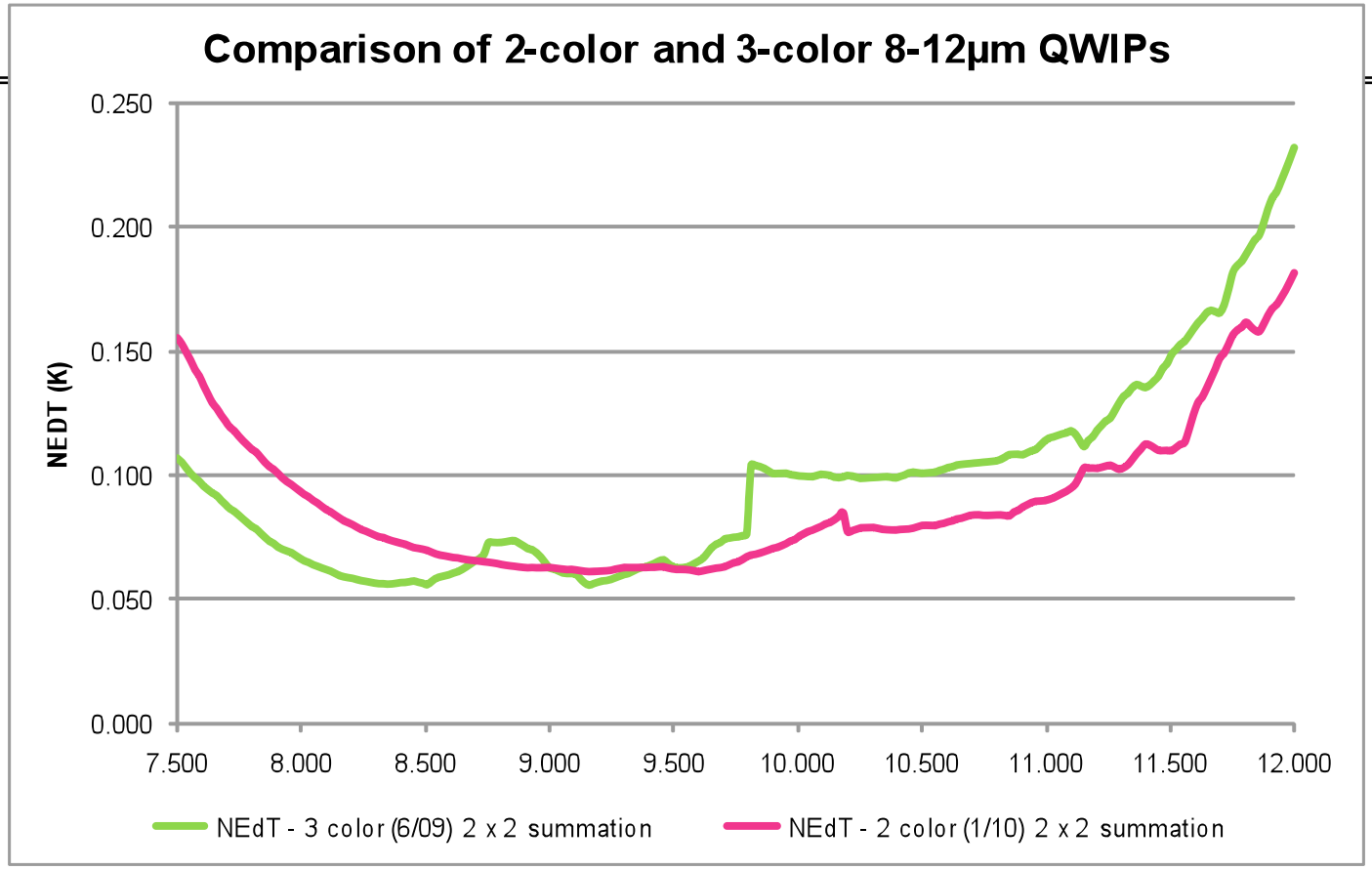
- The measured dual band response is shown at right
- The measured spectra meet specifications
- Several samples were optimized in the November 2009 -January 2010 time frame to optimize the detector performance and balance the response for a single bias
- These experimental results were used to model the system performance using a QWIP detector array
- Initial wafers were grown at JPL and eight additional 100mm wafers have been delivered to JPL from an outside vendor



Experimental data on final test detectors

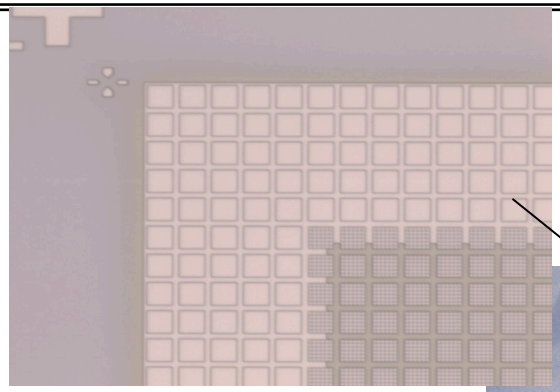
Bias 1.35V, 40K operation, 200x200µm squares

System Modeling

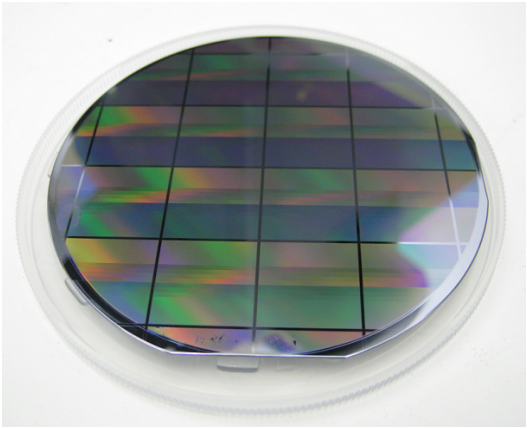


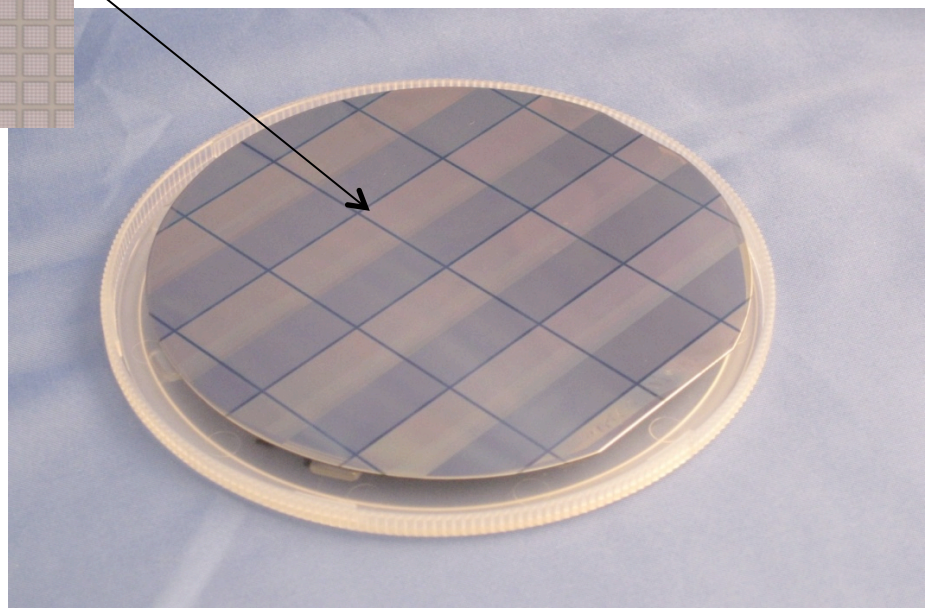
- Modeling shows the system with a QWIP array based on this design meets specifications in the 7.5-12µm band
- The new, optimized two-color version exhibits a smoother transition between bands than the original three-color version and meets spec (NEDT < 200mK) throughout the 7.5-12µm band

Initial HyTES wafer



Twelve 1kx1k HyTES arrays on 4” GaAs wafer

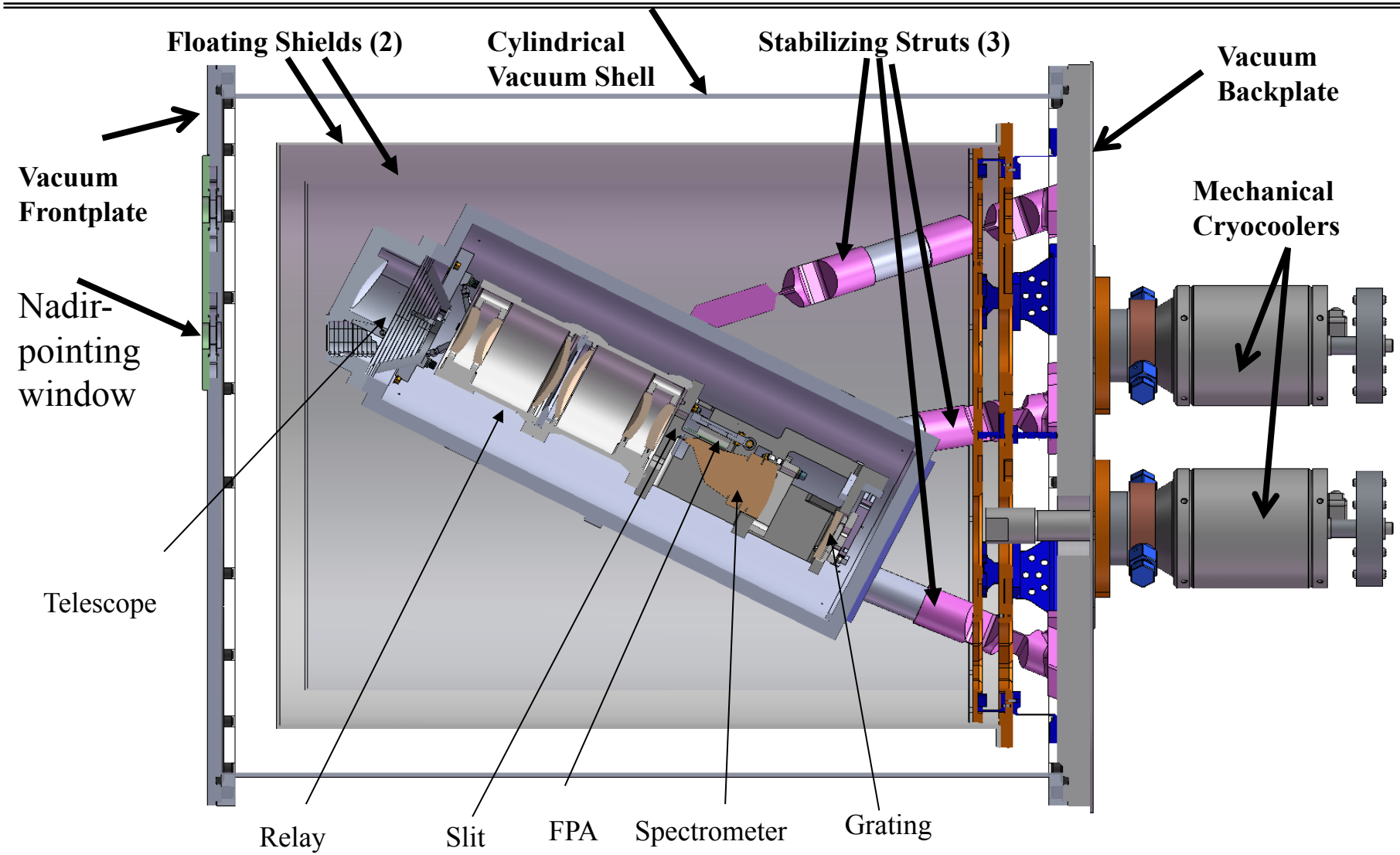




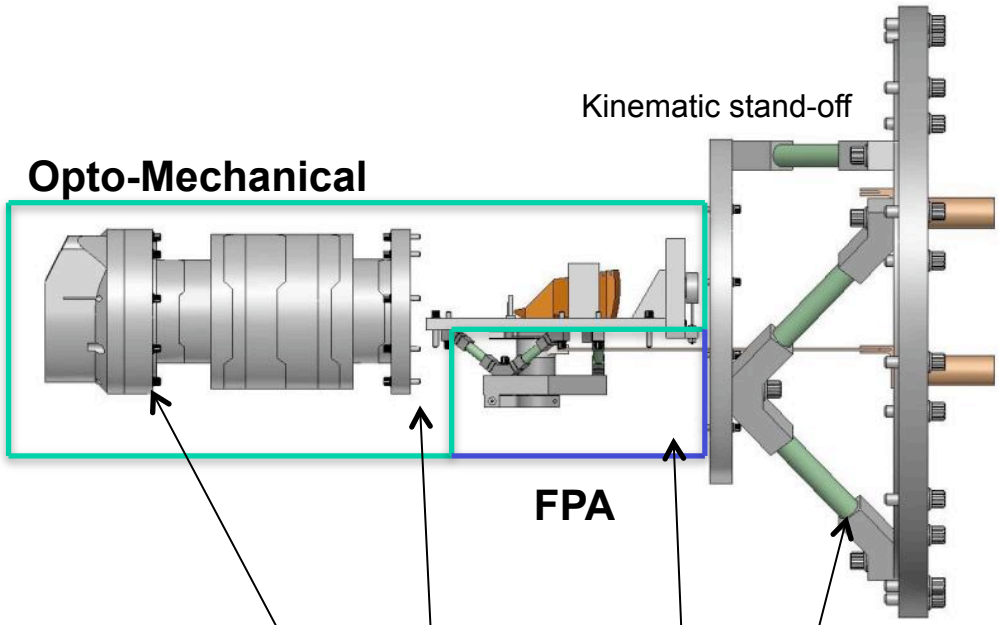
- This wafer was competed at the end of May and shipped for hybridization. All layers met processing design spec and should yield excellent arrays

Mechanical

HyTES Mechanical



HyTES Mechanical



Telescope Housing

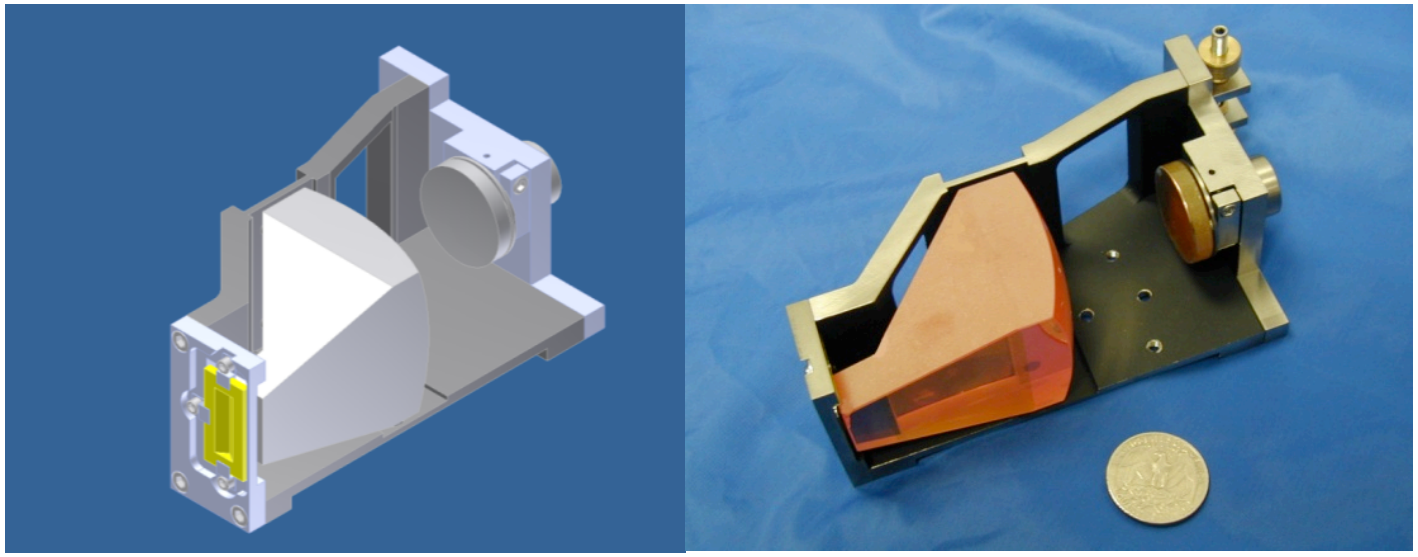
Relay Housing

Spectrometer Housing

Kinematic struts

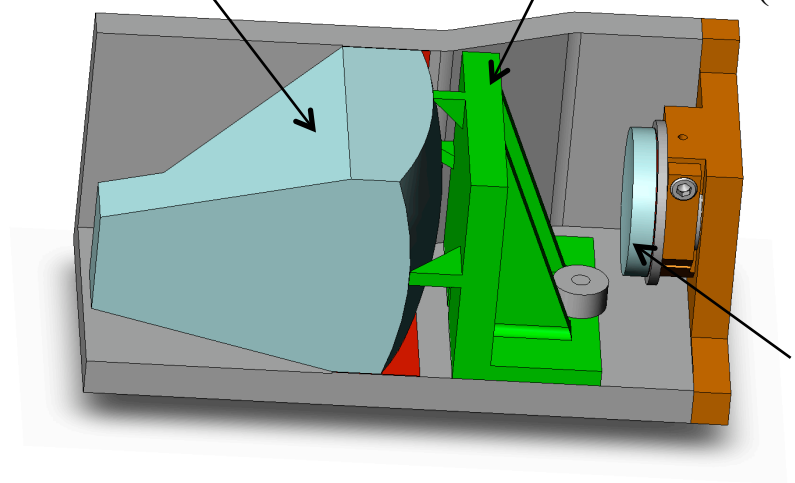
- Matching coefficient of thermal expansion (CTE) between optics and mechanical components to minimize inherent stresses caused by thermal soak
- Kinematic mounting allows minimization of stress in optical and mechanical members in all degrees of freedom
- Kinematic mounting used whenever possible to compensate for low to high CTE metal materials.

HyTES Spectrometer Heritage Mechanical Design



Existing QWEST mechanical housing

Spectrometer Alignment



Successful QWEST alignment technique to be reused for HyTES.

Alignment mechanism utilizes in a warm environment the spherical surface on both Monolithic ZnSe block and grating

Thermal

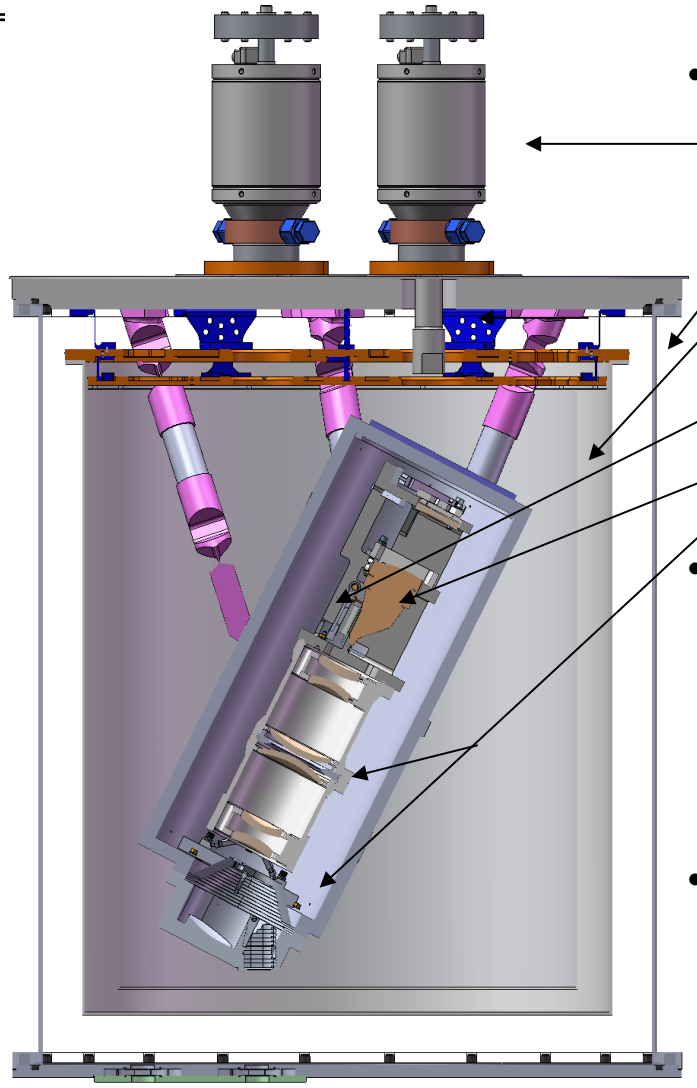
Thermal system design

- HyTES flight design will use two identical CryoTel GTs
  - one cooling only the QWIP array at 40 K
  - one cooling the Dyson spectrometer, relay optics, and telescope at ~100 K, and intercepting radiated and conducted parasitics to 40 K

- Heat rejection from cryocoolers via circulating-fluid chiller (as is being done on other JPL airborne instruments)

- HyTES will be designed for easy replacement of a cryocooler, should one fail during the instrument lifetime
  - these are commercial, not long-life space, cryocoolers, as appropriate for an airborne developmental program

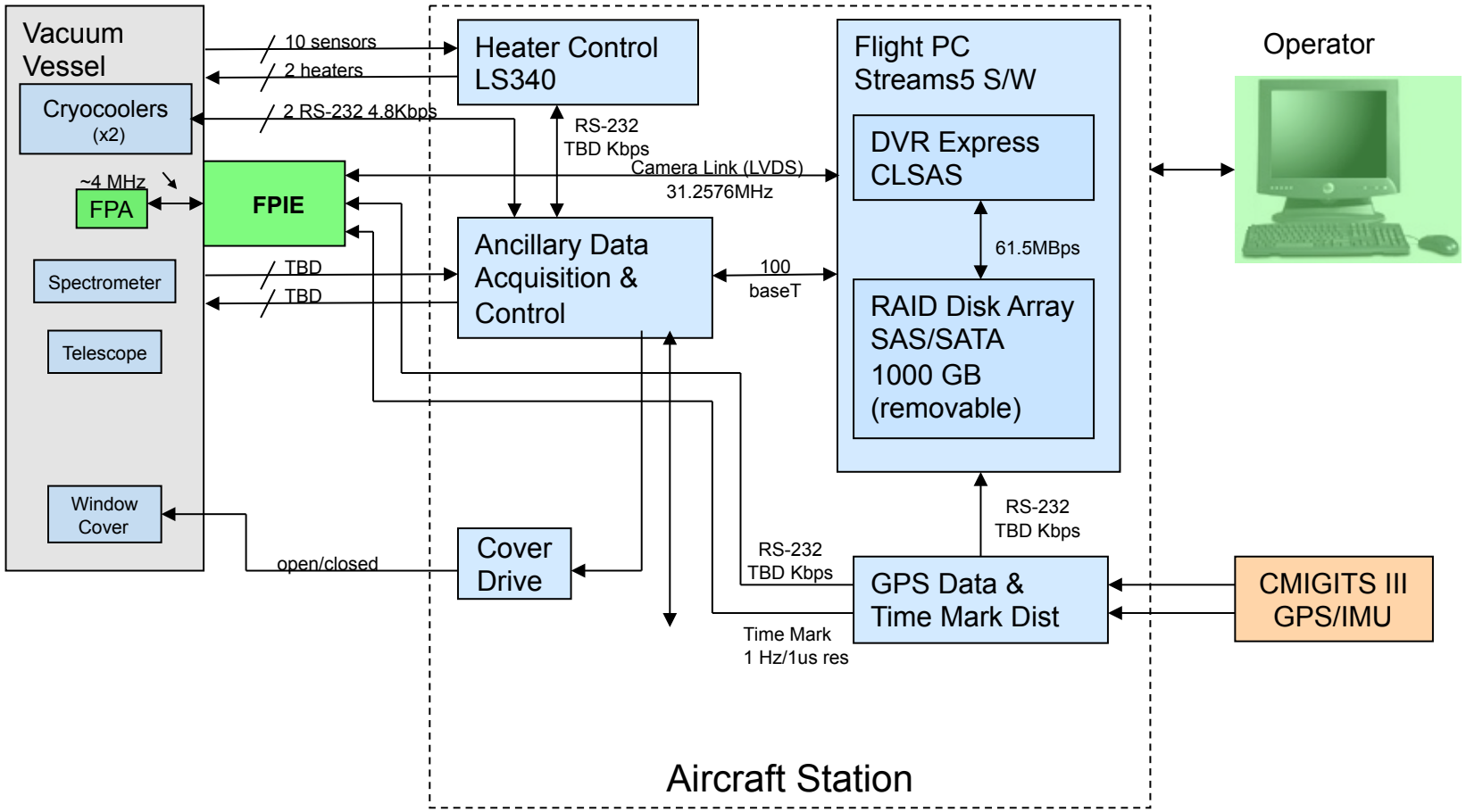
HyTES cryovacuum package



- Mechanical components:
  - mechanical cryocoolers (2)
  - vacuum enclosure
  - floating radiation shields (2)
  - thermal isolation struts
  - QWIP focal plane array with positioning assembly
  - spectrometer
  - telescope and relay optics
- Temperature requirements:
  - QWIP FPA $\leq$40 K for dark current supression
  - Spectrometer $\leq$100 K for background supression
  - Relay optics $\leq$250 K with stability restrictions
  - Telescope ~room temperature
- Chose to cool the optical instrument to 100 K
  - single mechanical assembly is highly desirable for alignment
  - cold relay eliminates temperature variation concerns

Data Recording and Storage

System Electronics - Data and Control

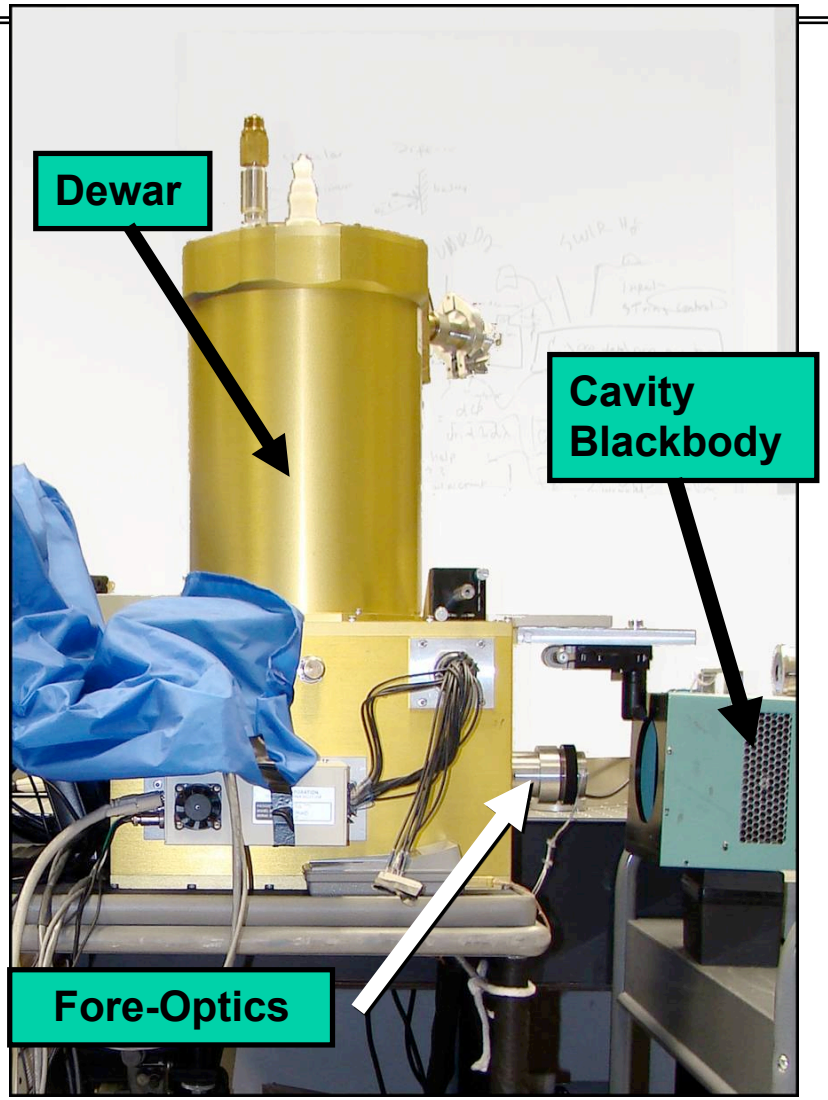


Data Products

- Raw data from FPA with interleaved GPS and engineering data (L0)
- Geo-located Radiance at sensor (L1)
- Future derived products
  - Surface Radiance
  - Surface Emissivity
  - Surface Temperature

Radiometric Analysis of QWEST

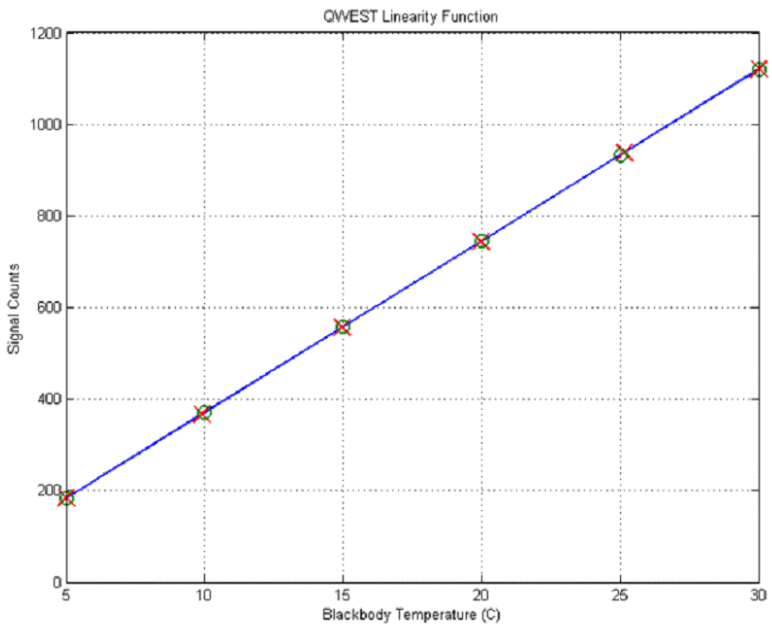
QWEST Lab Setup



Lab Test Procedure

- Cycle Blackbody Through Temperatures of 10, 25, and 30 °C
- Blackbody DN's at 10 and 30 °C used to Calculate 2-Point Calibration Coefficients
- Calculate Radiance and Brightness Temperature for Blackbody at 25 °C

QWEST Temperature Linearity

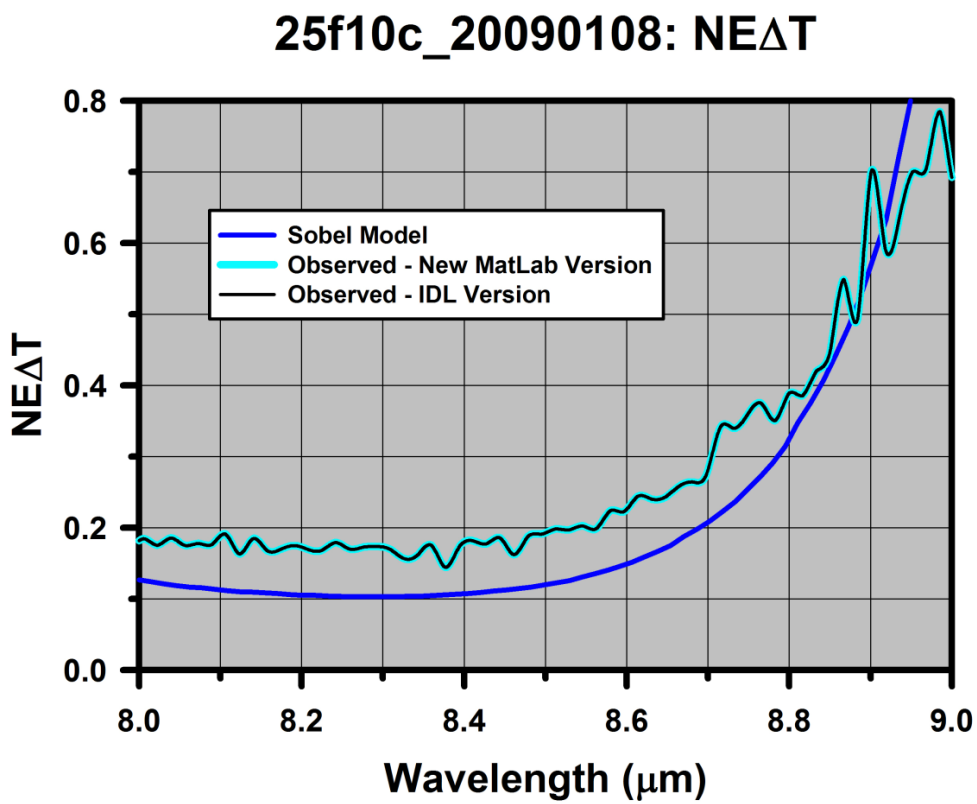


Actual T	Measured T	Abs. error T
5	5.00	0
10	9.90	-0.1044
15	14.96	-0.0445
20	19.98	-0.0213
25	25.14	0.1354
30	30.00	0

QWEST NEdT of 8-9 um QWIP

Lab Test Results
<u>8 January 2008</u>

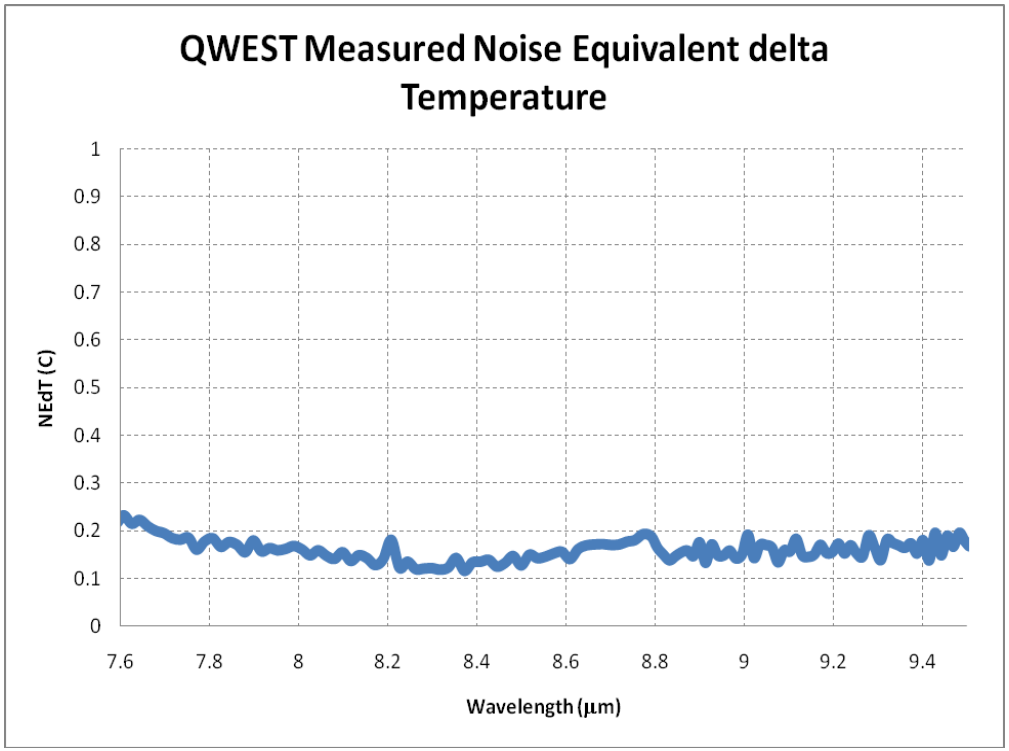
- **Brightness Temperature Within 1 °C of 25 °C (Black-body Set Point)**
- **Sensitivity (NEDT, Modeled as Standard Deviation) Better than 0.2 °C Between 8.0 – 8.6 µm**
- **Single-Layer QWIP Detector Array: Substantial Drop in Sensitivity for λ > 8.75 µm**



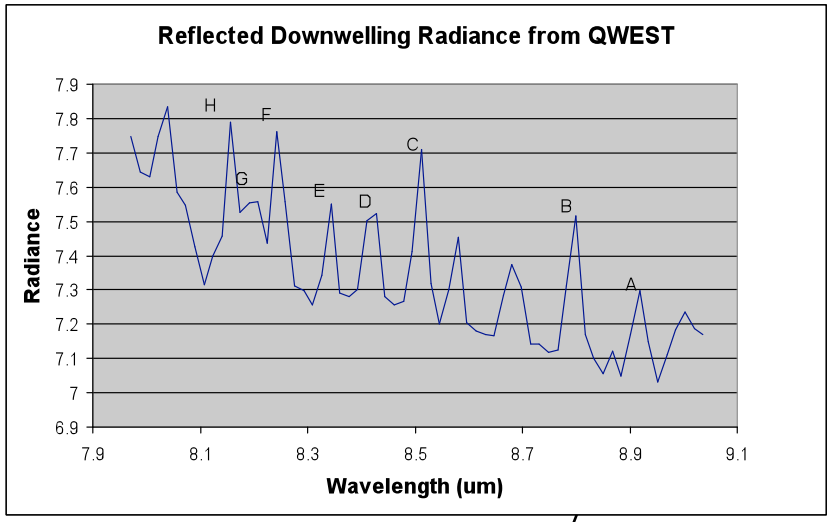
QWEST NEdT of 3-color QWIP

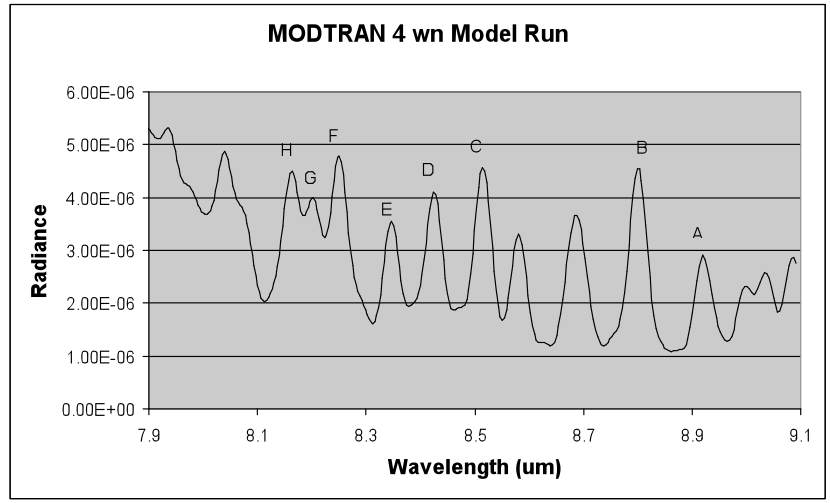
Lab Test Results
Using 7.5-9.5µm portion of 3-color QWIP

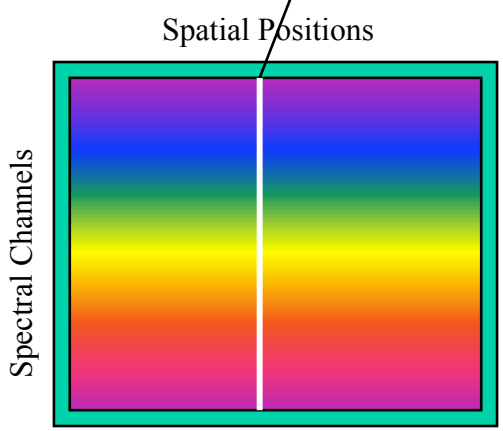
Noise equivalent temperature difference. The distribution is shown for all spectral channels irrespective of blackbody temperature measured. Measurements were made for a calibrated blackbody between 5C and 40C.



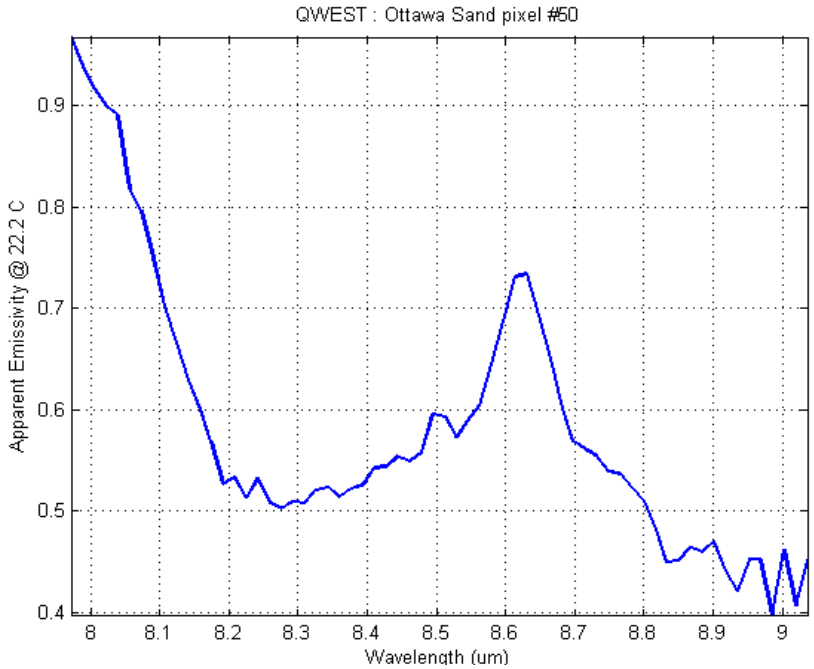
QWEST Spectral Accuracy

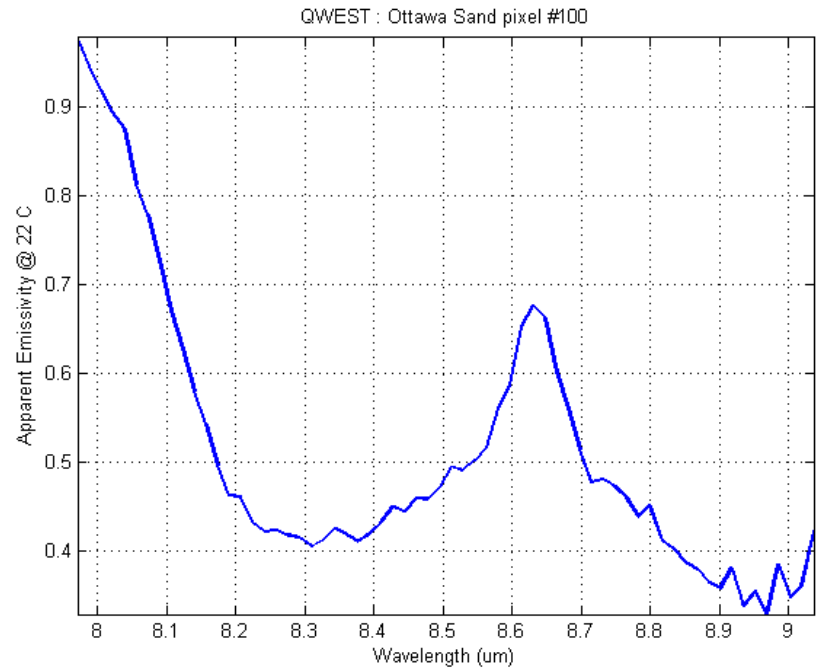




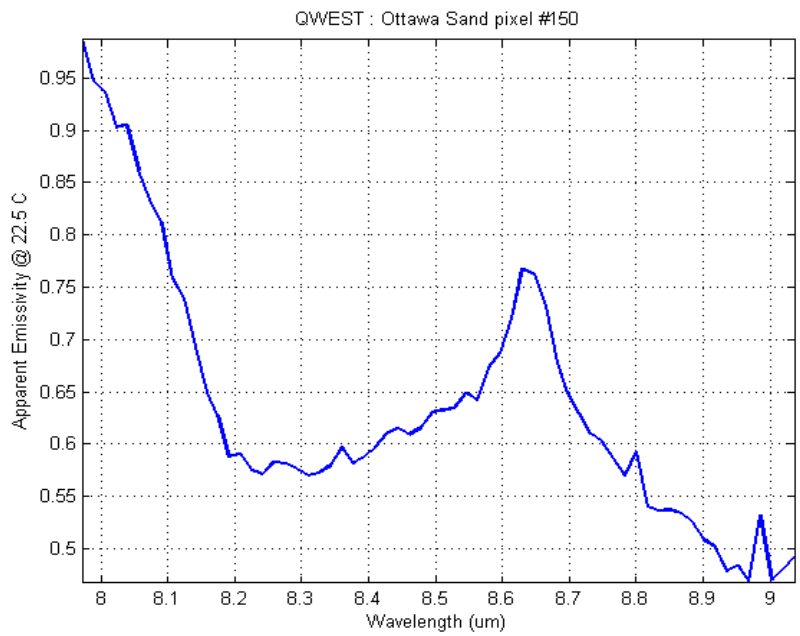


	Model	QWEST	Delta
A	8.92061	8.9179	0.00271
B	8.79894	8.7995	-0.00056
C	8.51426	8.5121	0.00216
D	8.4246	8.4276	-0.003
E	8.34725	8.3431	0.00415
F	8.25082	8.2418	0.00902
G	8.20345	8.208	-0.00455
H	8.16327	8.1573	0.00597

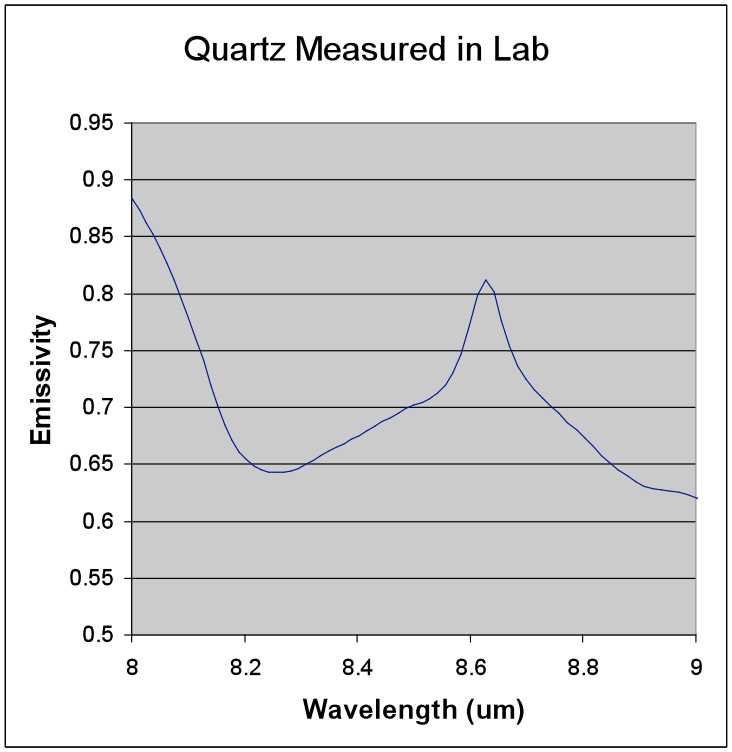




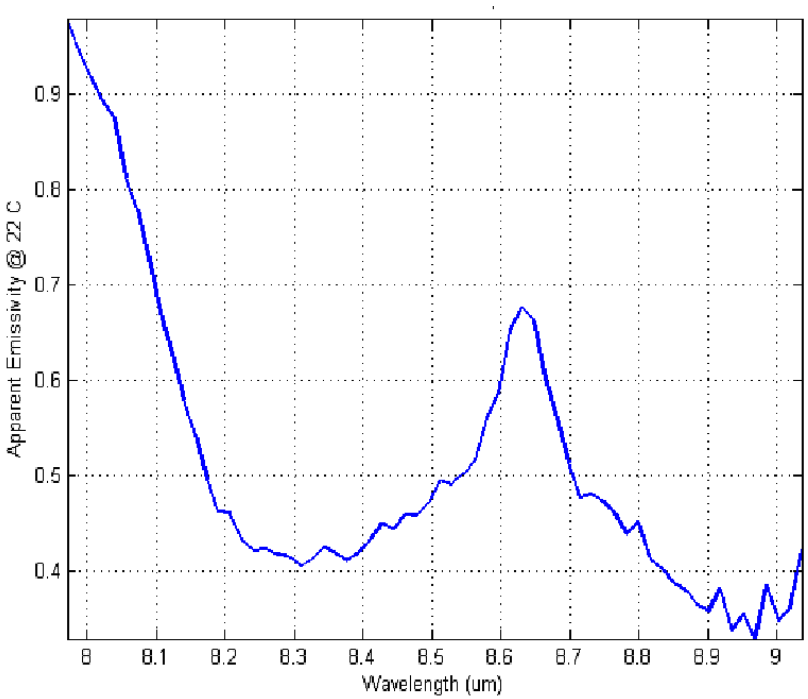
$$\frac{L_\lambda - L_{skybkg}}{L_{surface} - L_{skybkg}}$$



Lab versus QWEST



Emissivity of a sample of Quartz measured in the lab.



Apparent emissivity of quartz as measured by QWEST in direct sunlight.

Summary

- The QWEST testbed has demonstrated the utility of QWIP technology for Hyperspectral TIR measurements.
  - Two arrays have been tested, a single-color 7.5-9 μm device and a 3-color 7.5-12 μm device
- HyTES implements the technology from QWEST in a cryo-cooled airborne instrument
  - HyTES 1Kx1K FPA expected in June 2010
  - Completed Optical and Mechanical/Thermal Design and reviews
  - Procured cryo-coolers, masks, wafers, vacuum chamber
  - Procurements of Dyson block and fore-optics complete
- Established key component performance with QWEST
- Developed test and alignment procedures from QWEST