Mid and thermal infrared remote sensing at the Jet Propulsion Laboratory

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Outline

Introduction

- HyspIRI Background & Earth Science

Airborne Earth Science: HyTES

- Hyperspectral pushbroom scanning
- QWIP and CBIRD

Space Based Earth Science: ECOSTRESS

- Push-whisk scanning
- MCT

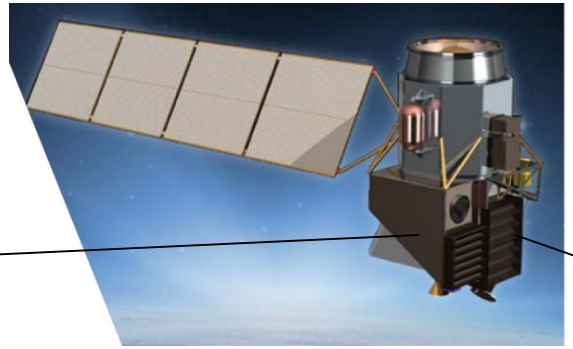
Beyond Earth Orbit: DIVINER

- Multi-band pushbroom scanning
- Thermopiles

- **Concluding Remarks**

HyspIRI Background

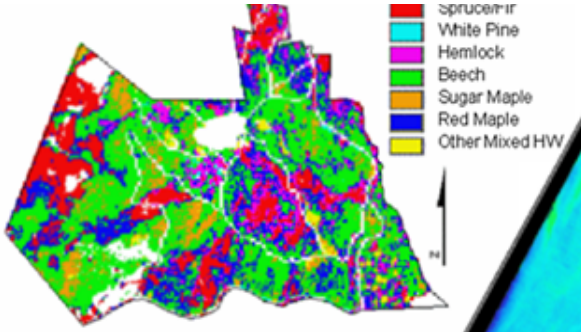
Visible ShortWave InfraRed (VSWIR) Imaging Spectrometer
+
Multispectral Thermal InfraRed (TIR) Scanner

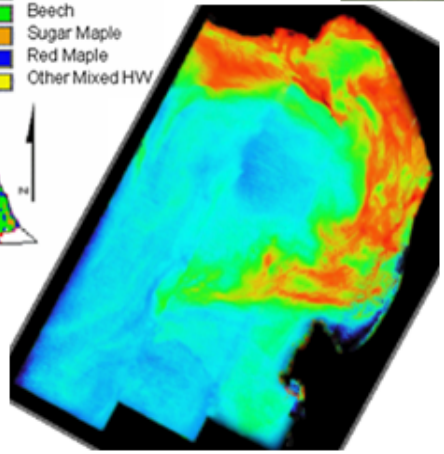


VSWIR: Plant Physiology and Function Types (PPFT)

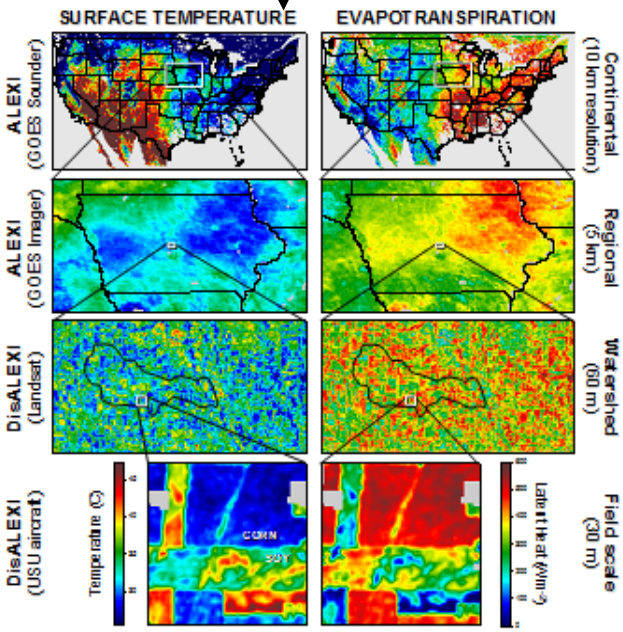
Multispectral TIR Scanner

Map of dominant tree species, Bartlett Forest, NH





Red tide algal bloom in Monterey Bay, CA

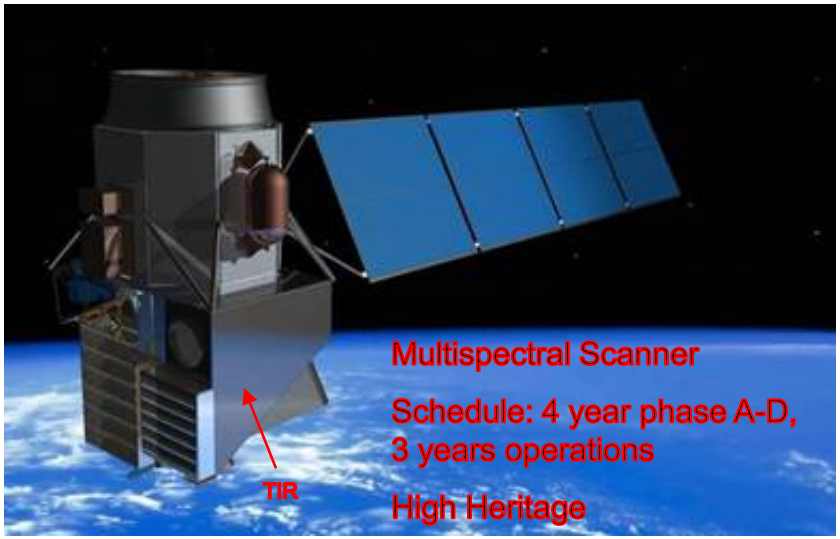


http://hyspiri.jpl.nasa.gov/

HyspIRI Measurement Requirements

PARAMETER	BASELINE	SCIENCE REQUIREMENT
Ground Resolution (m)	60	<100
Revisit (days)	5	<6
Noise equivalent delta temperature (K)	0.2	<0.3
Absolute accuracy (K)	0.5	<1
Saturation – low temperature bands (K)	500	>400
Saturation – high temperature band (K)	1200	>1100
Overpass time (hh:mm)	10:30am	10-3pm
Nighttime imaging	Yes	Required
Number of Bands (spectral range: 3 – 12 µm)	8	>=8
Coverage	Land and coastal regions	Land and coastal regions
Data latency	2 days	< 1 week

HyspIRI-TIR Objective



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)*

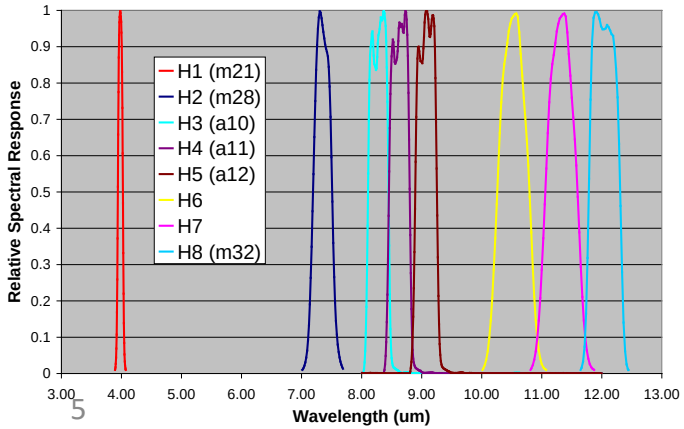
– How does urbanization affect the local, regional and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare?

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

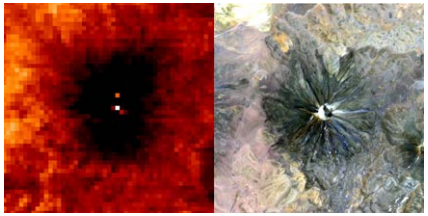
– What is the composition and temperature of the exposed surface of the Earth? How do these factors change over time and affect land use and habitability?

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

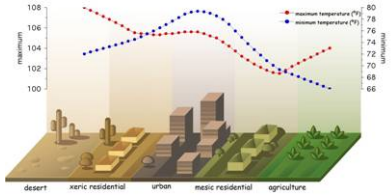


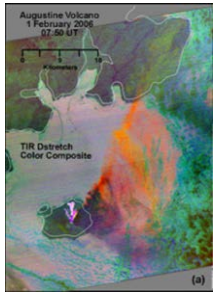
Andean volcano heats up



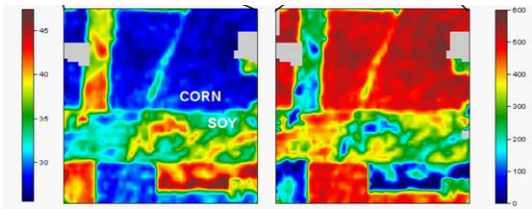
Volcanoes

Urbanization





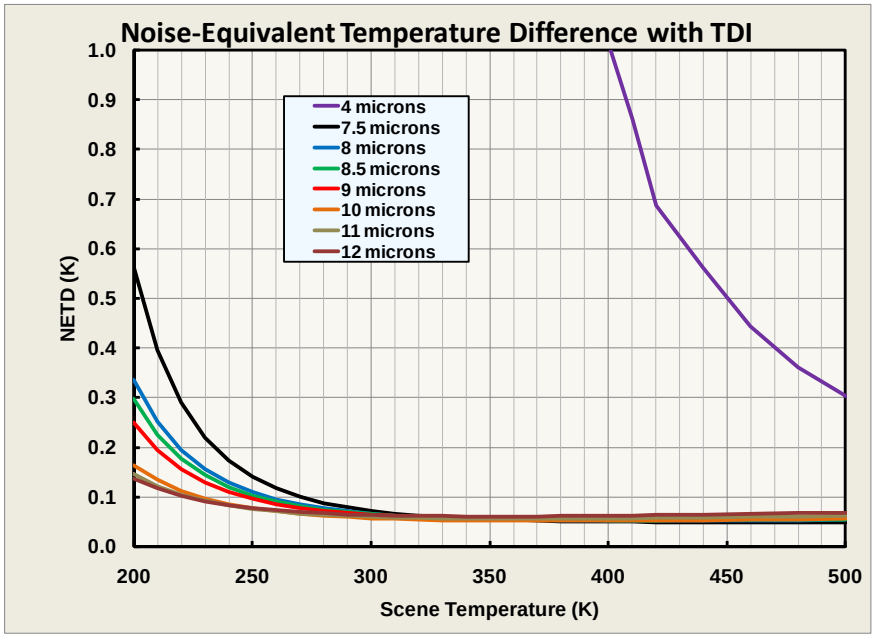
Water Use and Availability



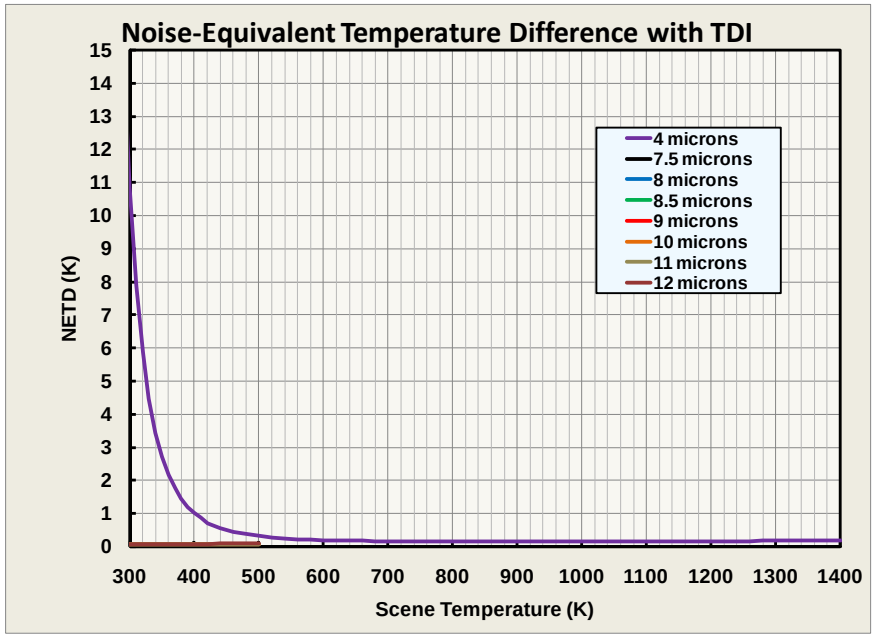
Surface Temperature

Evapotranspiration

HyspIR-TIR Radiometric Performance



Expected HyspIRI-TIR Sensitivity Metric expressed as Noise Equivalent Delta Temperature (NEDT)

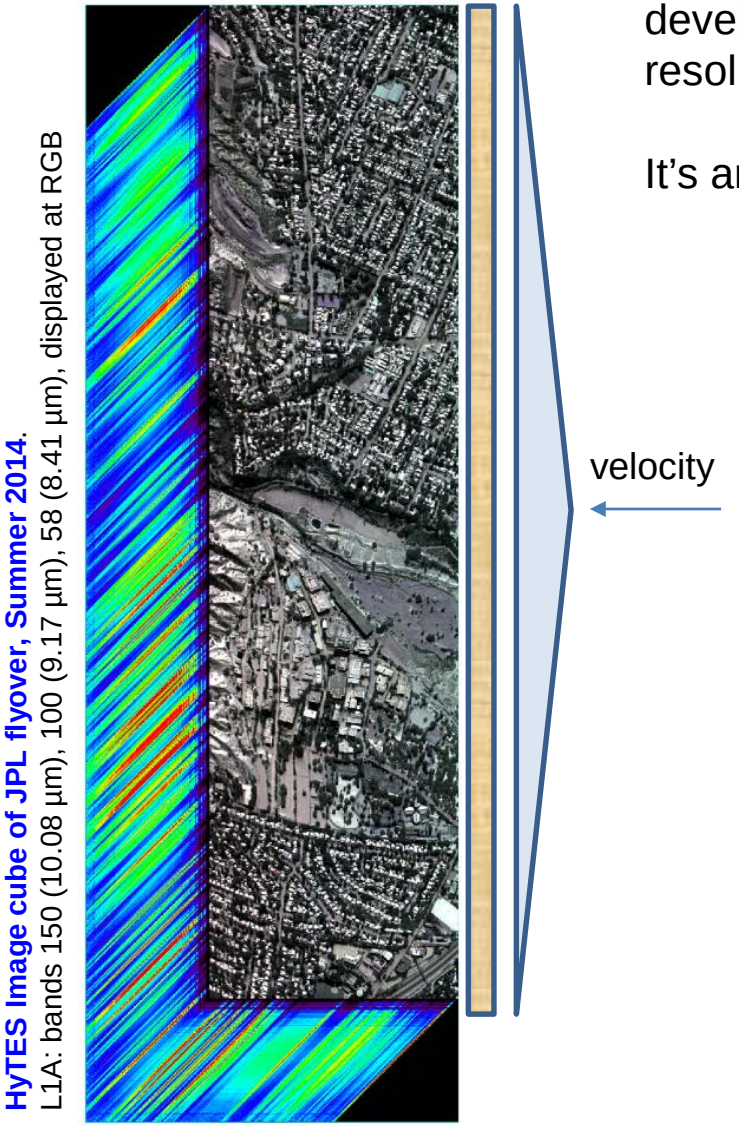


Expected HyspIRI-TIR Sensitivity Metric expressed as Noise Equivalent Delta Temperature (NEDT)

- Predicted sensitivity better than 0.2 K @ 300 K requirement.
- Good sensitivity in overlap region between channel 1 and channels 2-8.
- Expected saturation temperature of 1100K based on HyspIRI: Hot Target Saturation Subgroup (HTSS)

HyTES Instrument

Push broom imaging



HyTES Image cube of JPL flyover, Summer 2014.
L1A: bands 150 (10.08 µm), 100 (9.17 µm), 58 (8.41 µm), displayed at RGB

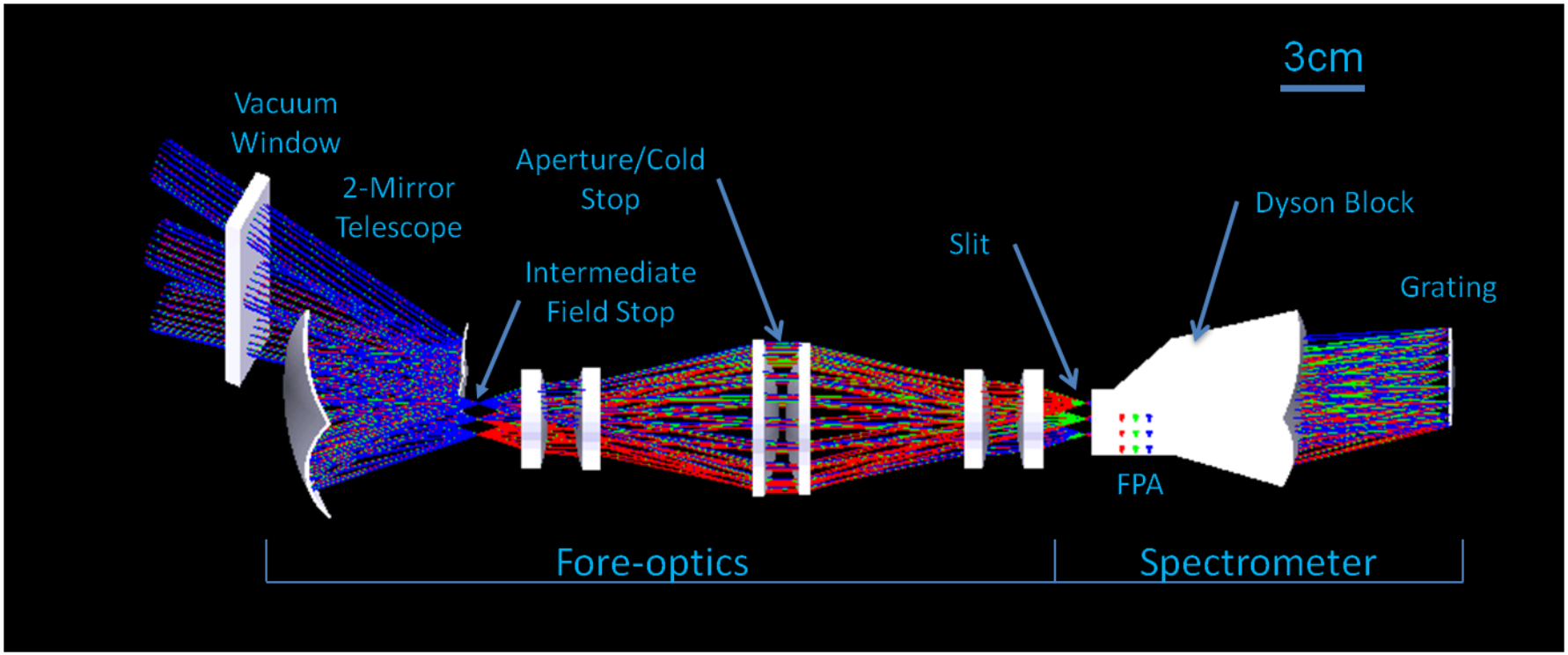
velocity

Hyperspectral thermal emission spectrometer (HyTES) was developed to support HyspIRI by providing higher resolution spatial and spectral science products.

It's an airborne sensor with the following parameters:

Volume (scan head)	0.6m x 0.4m + peripheral struts
Number of spatial pixels x track	512
Number of spectral channels	256
Spectral range	7.5 - 12μm
Frame Speed	35 or 22 fps
Total field of view	50deg
Calibration	Full aperture blackbody
Detector temperature	40K
Optics temperature	100K
NEΔT	200mK
IFOV	1.7066 mrad
Low Altitude pixel size/swath	2m/1Km
High Altitude pixel size/swath	20m/10Km

HyTES Optics

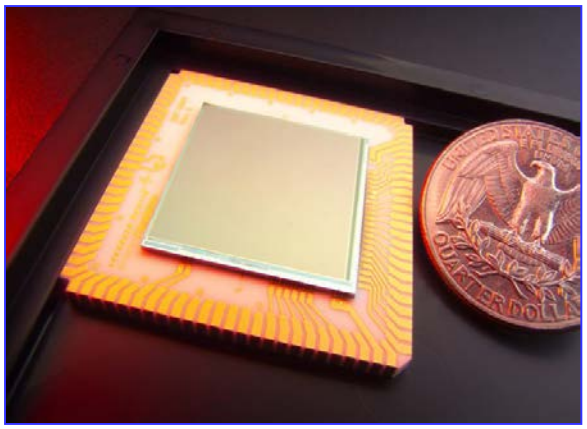


HyTES Optical Layout

QWIP Technology

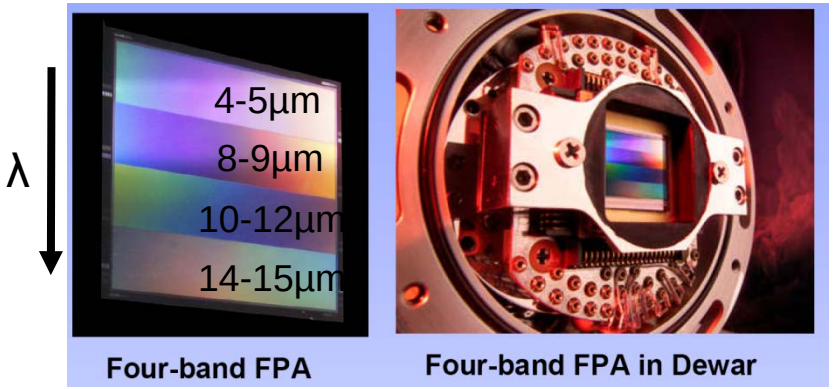
Quantum well infrared photodetector (QWIP)

- Detector Material - Spatially separated 2-color QWIP
- Array Size - 1024x1024 pixels
- Pixel Pitch - 19.5 microns
- Wavelength - 7.5-12 microns; three spectral bands
- Input Circuit - Direct Injection
- Integration Type - Snap Shot mode
- Integration Time - Adjustable integration time > 10 μs
- Integration Modes - Integrate-While-Read & Integrate-Then-Read
- Well Depth - 8.1×10^6 electrons



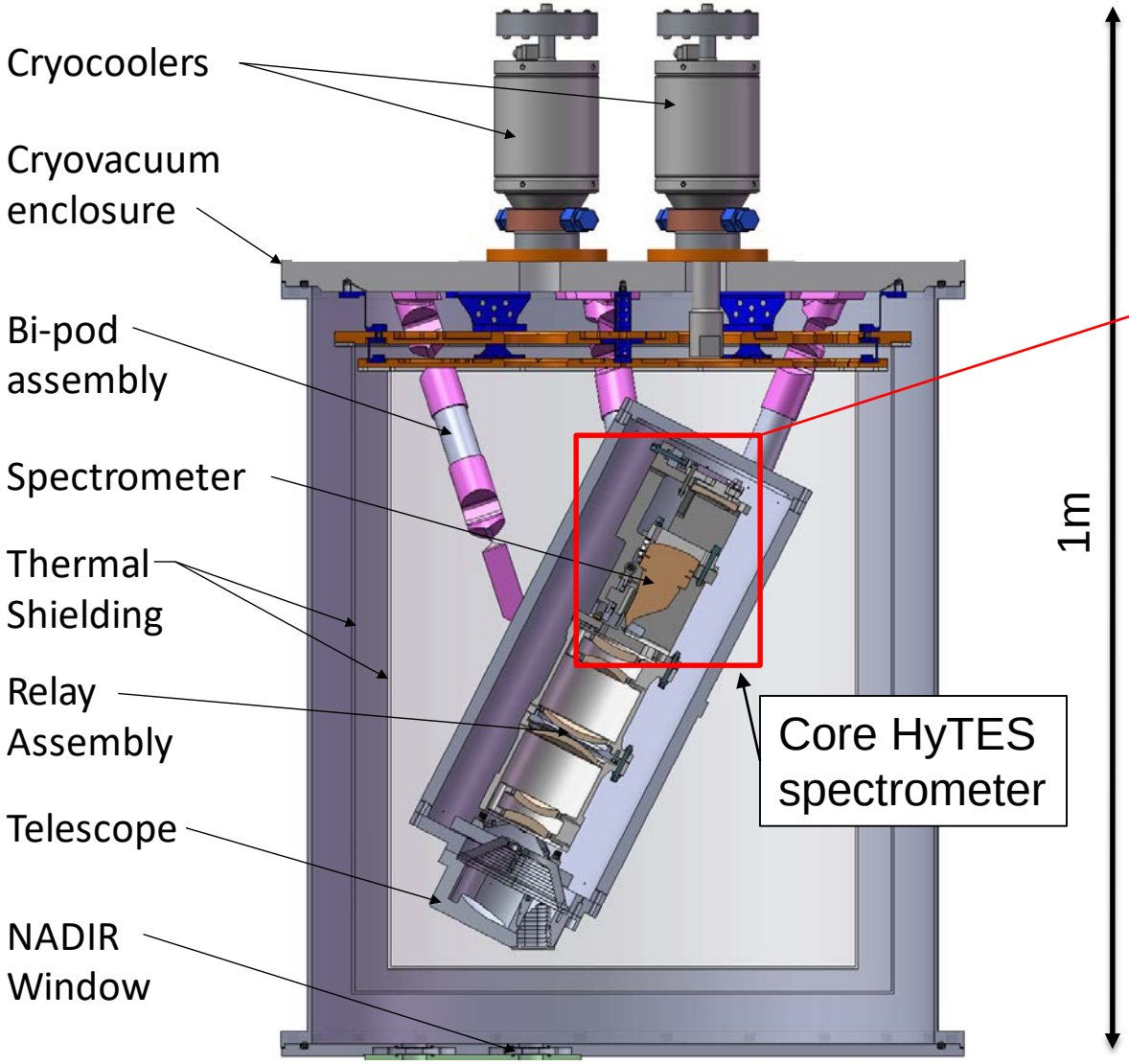
1024x1024 pixel single-band QWIP FPA

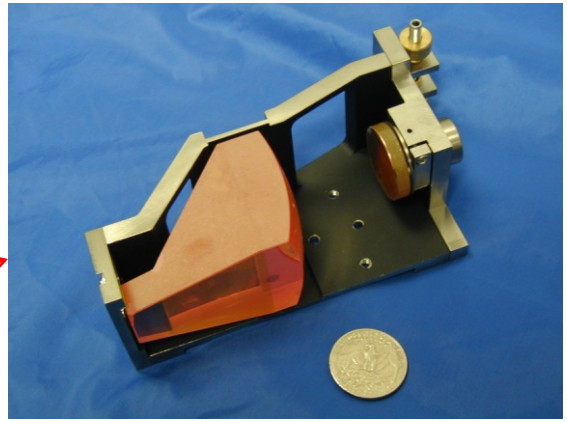
2-point corrected image of focal plane array used in HyTES.



Soibel, Alexander, Ed Luong, Jason M. Mumolo, John Liu, B. Rafol, Sam A. Keo, William Johnson et al. "Multi-color QWIP FPAs for hyperspectral thermal emission instruments." In SPIE OPTO, pp. 86310R- 86310R. International Society for Optics and Photonics, 2013.

HyTES Instrument





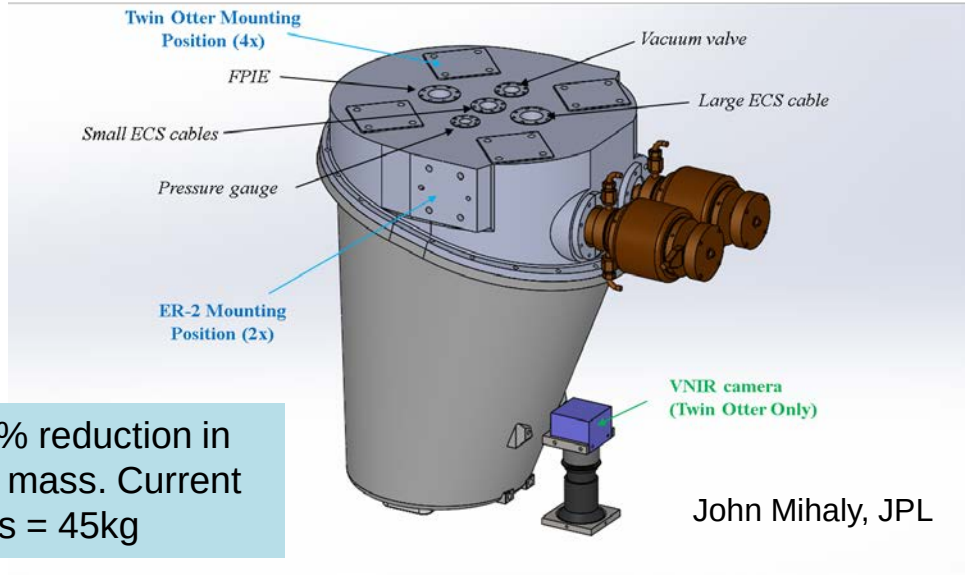
HyTES flew its last campaign with this cryovac configuration in January 2016.

It's being transition to an even smaller configuration for higher altitude deployment.

The new smaller design still works on the twin otter.

http://airbornescience.jpl.nasa.gov/hytes/

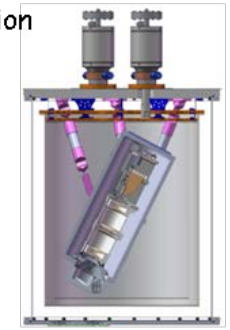
HyTES New ER-2 Platform

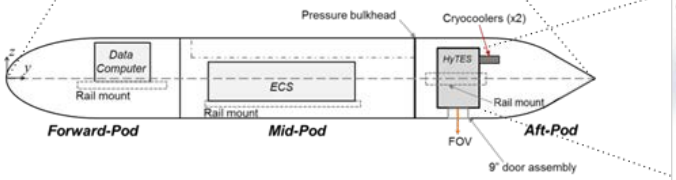


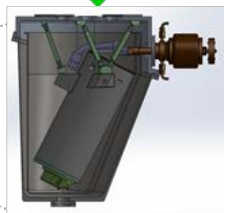
John Mihaly, JPL

Nearly 50% reduction in scan head mass. Current mass = 45kg

HyTES enclosure size reduction for accommodation in ER-2 wing pod



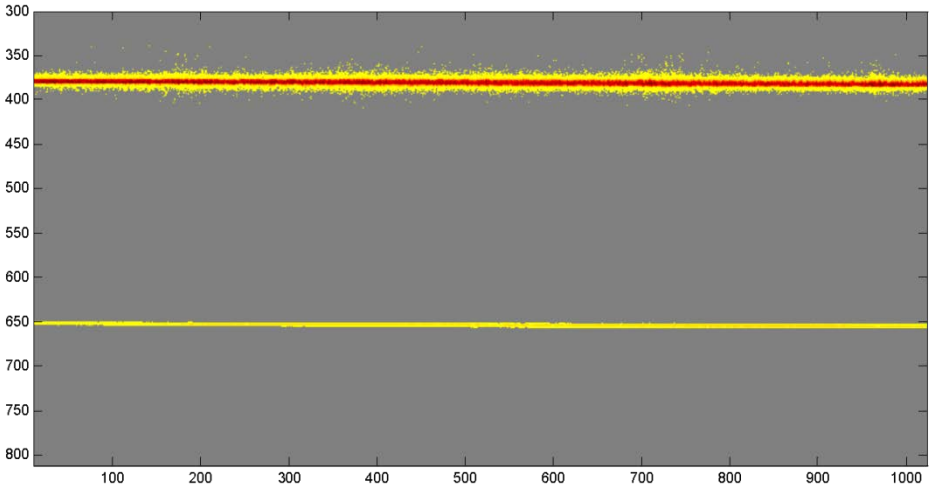




ER-2 HyTES scan head

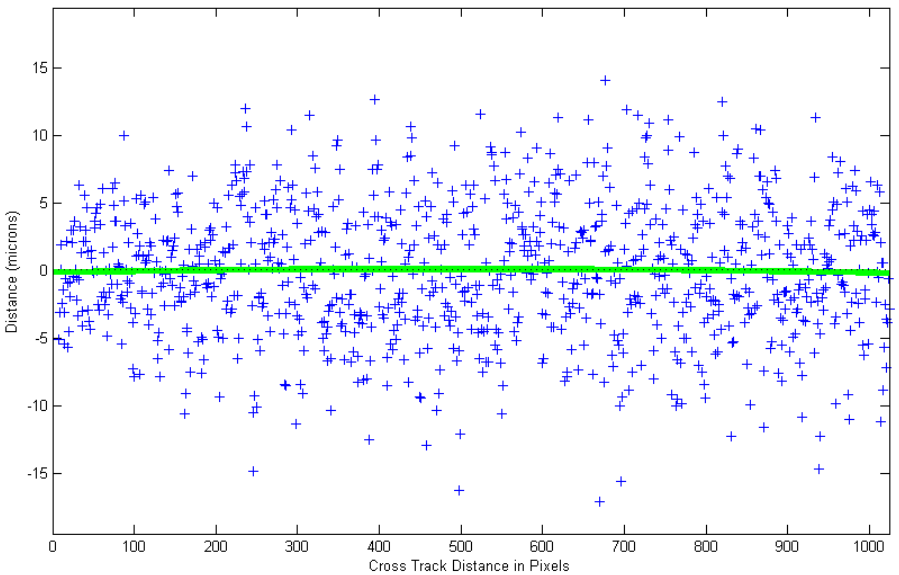
Pre-flight calibration: Distortion

Dual laser integrating sphere (8.18μm and 10.6μm diffuse output)

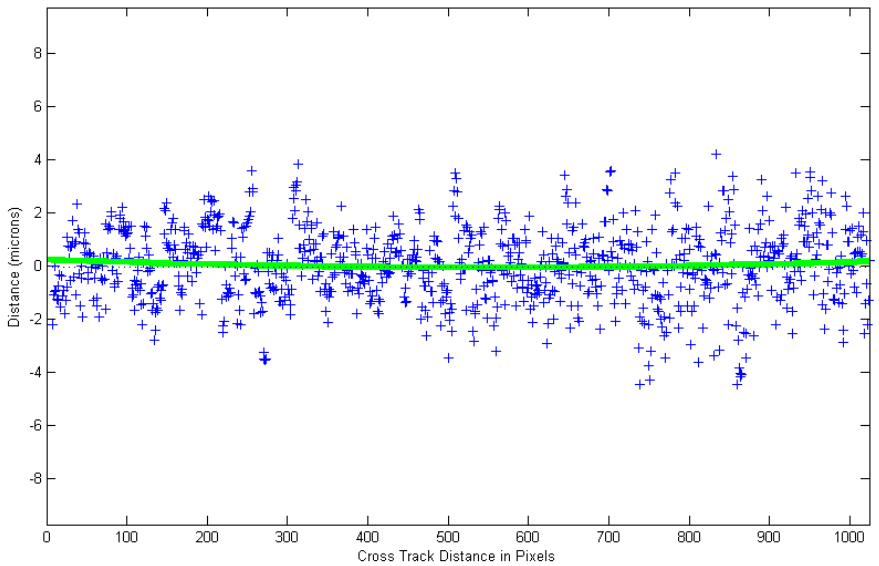


Raw detector output used for spectral/spatial characterization.

Pre-flight calibration: Distortion



Smile Distortion 8.18μm

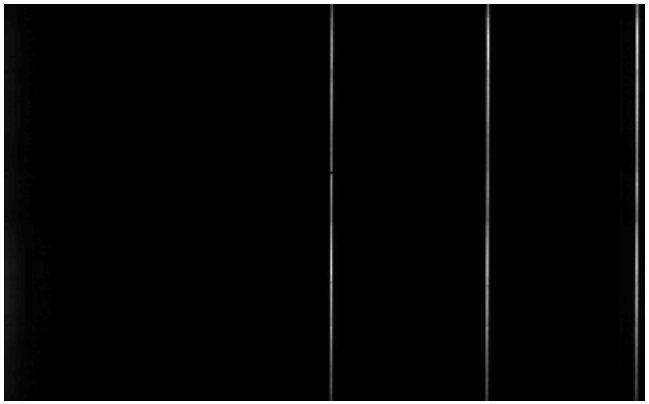


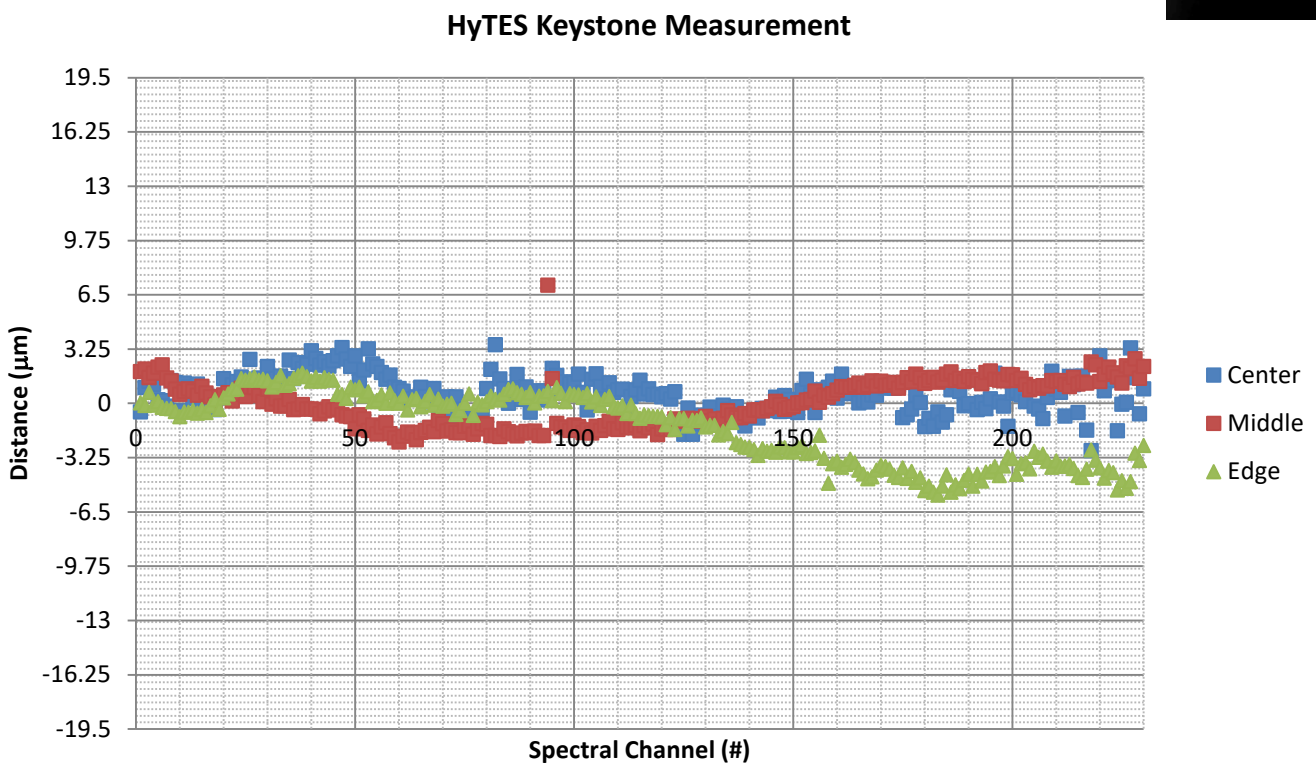
Smile Distortion 10.6μm

High performance spectral distortion observed. Final measurements made at the normal operating temperature (FPA at 40K, Optics at 100K).

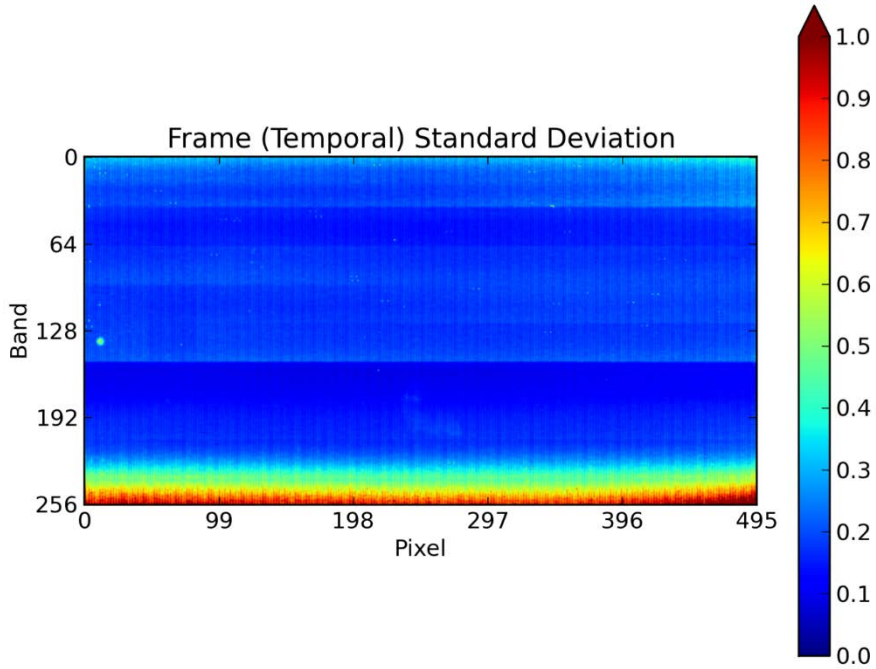
Pre-flight calibration: Distortion

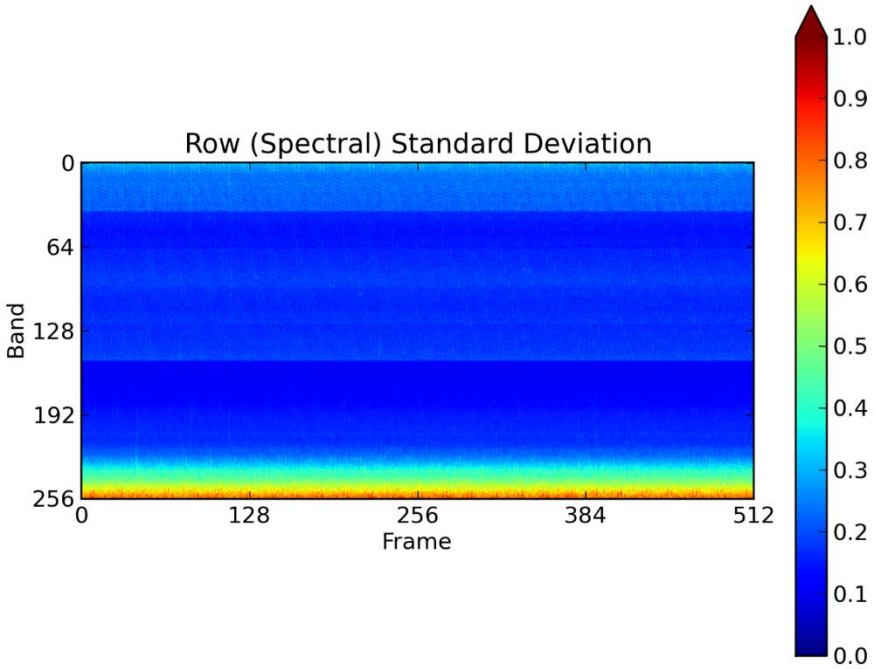
Broadband source posited at different field positions.





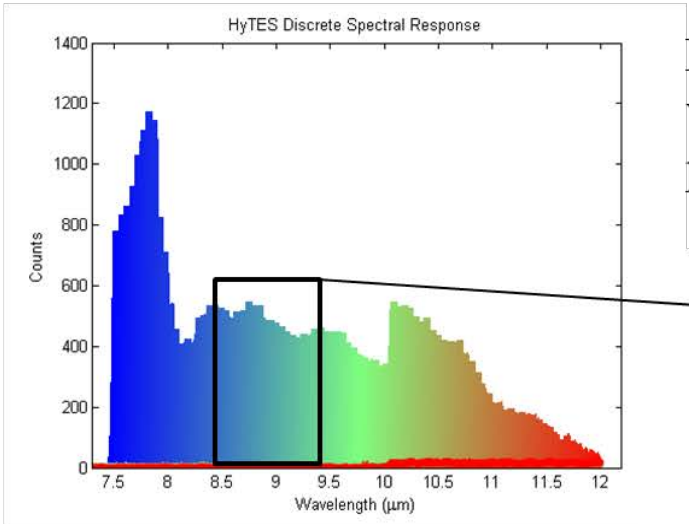
Pre-flight calibration: Radiometric



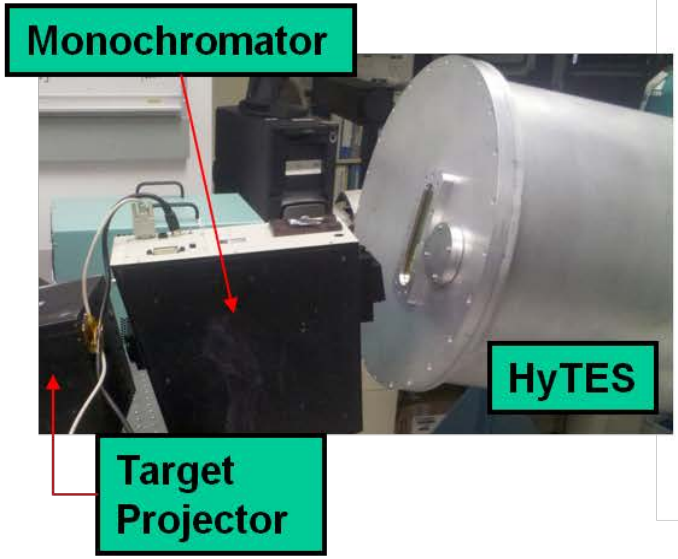


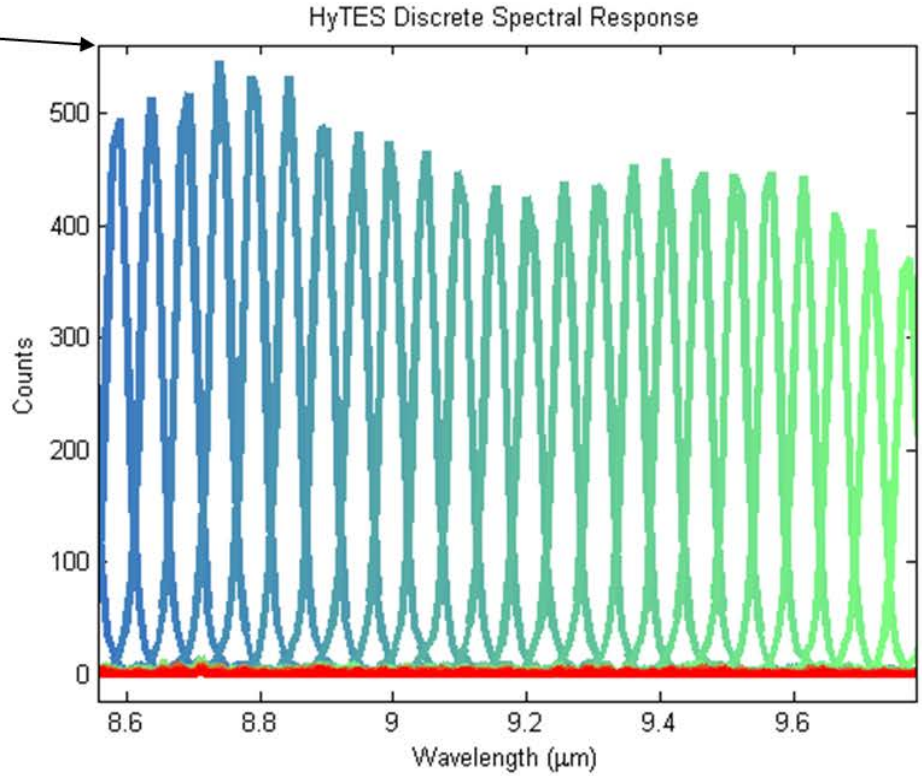
A key aspect of HyTES is the fact it doesn't use onboard calibrators. It also has remarkable sensor uniformity. A calibration is done before and after every flight to confirm stability (on approximately ~ 4 to 8 hr intervals).

Pre-flight calibration: Spectral

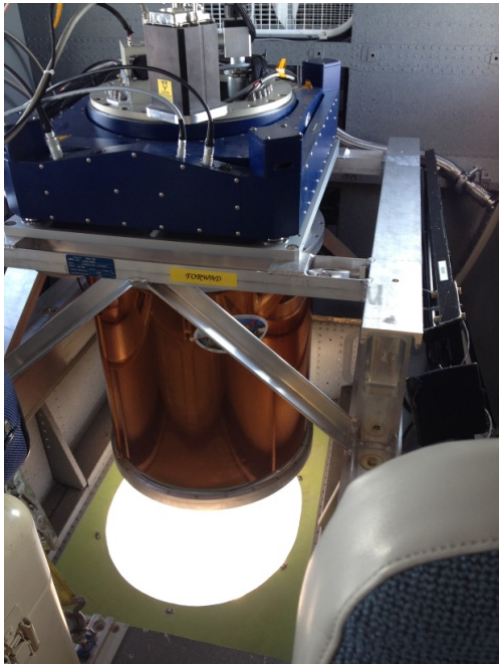


HyTES measured spectral response. A monochromator was cycled through each spectral band while positioned at the entrance aperture.





HyTES Flights



HyTES has flown 6 campaigns since 2012.

All flights have been out of Grand Junction Colorado on a low altitude Twin Otter aircraft.

HyTES is scheduled to have its first high altitude flight on NASA's ER-2 before summer 2016.

A suite of additional instruments are used to stabilize the system as well as to assist with pointing knowledge.

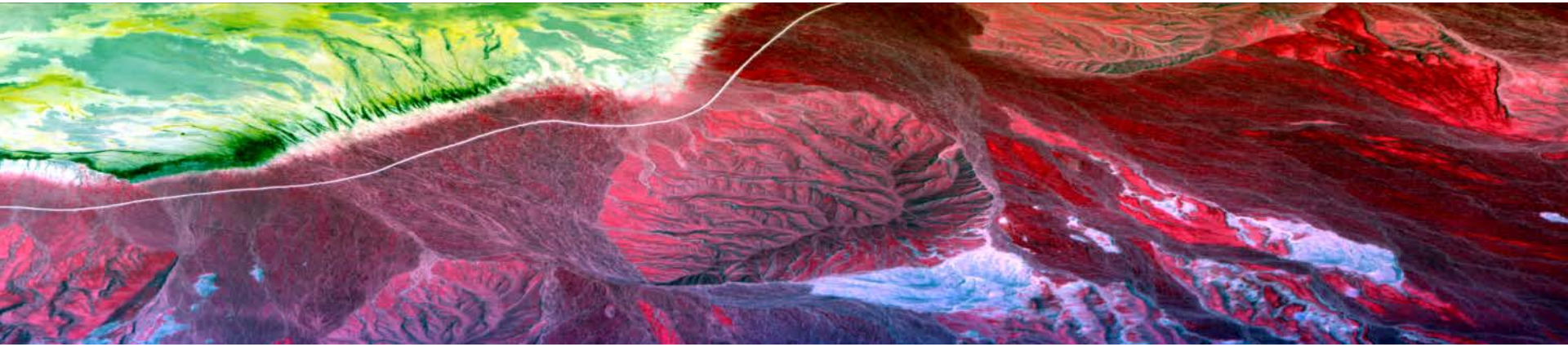
HyTES instrument team

HyTES Imagery from campaign

Death Valley, CA

Carbonate

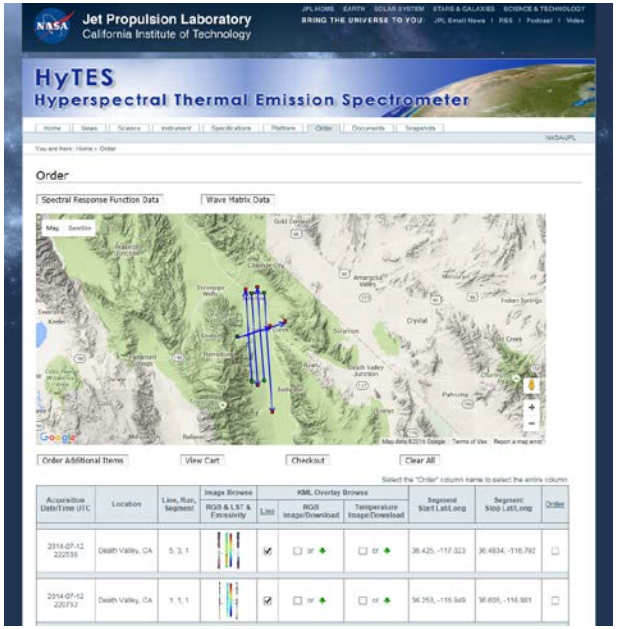
Quartz alluvial fan



L1A: bands 150 (10.08 µm), 100 (9.17 µm), 58 (8.41 µm), displayed at RGB

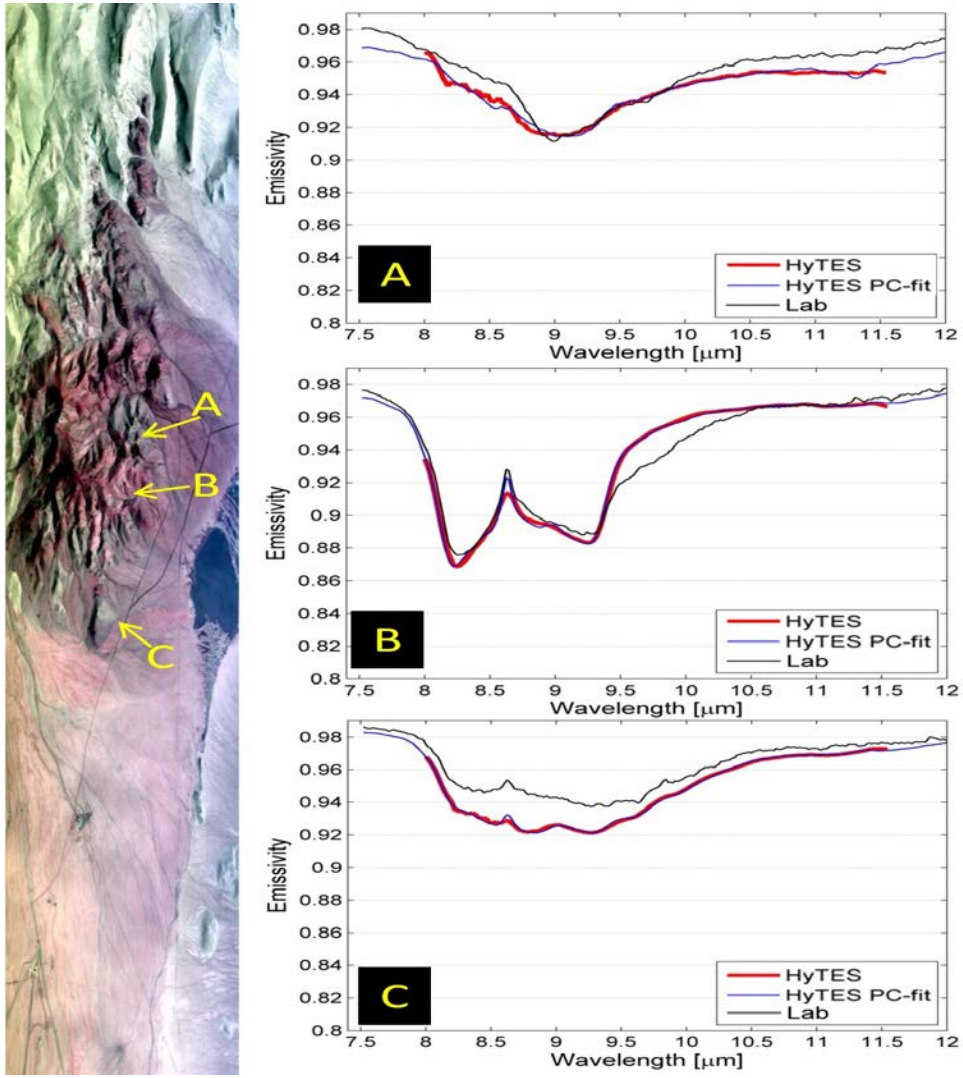
Basalt

- Data from nearly all previous flights can be found at the web portal shown to the right.
- There one can browse quick looks and order higher level products.



Web portal at *hytes.jpl.nasa.gov*

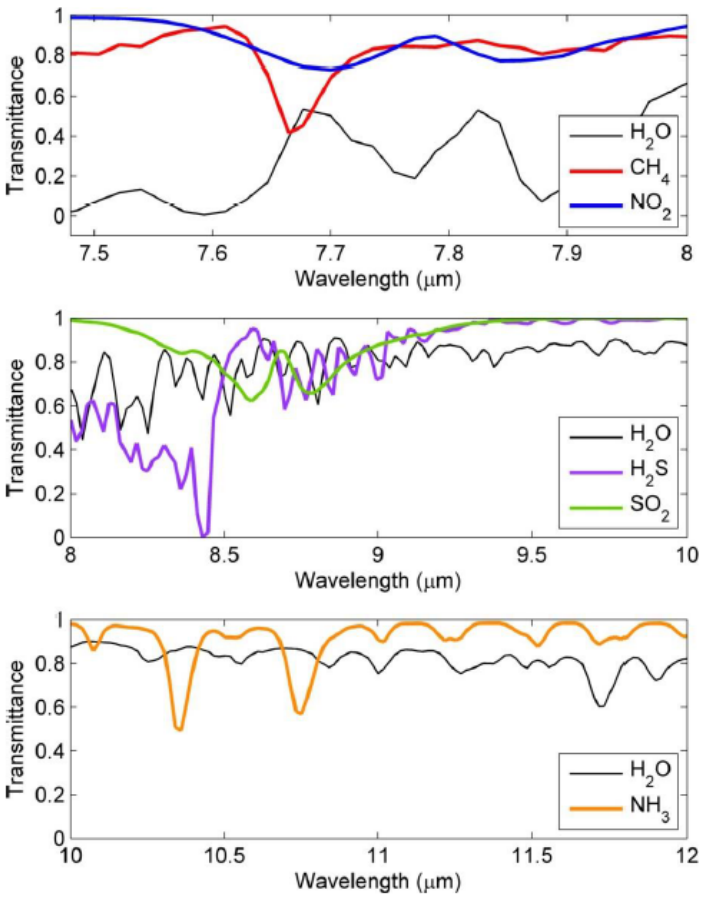
Spectral retrievals from calibration sites



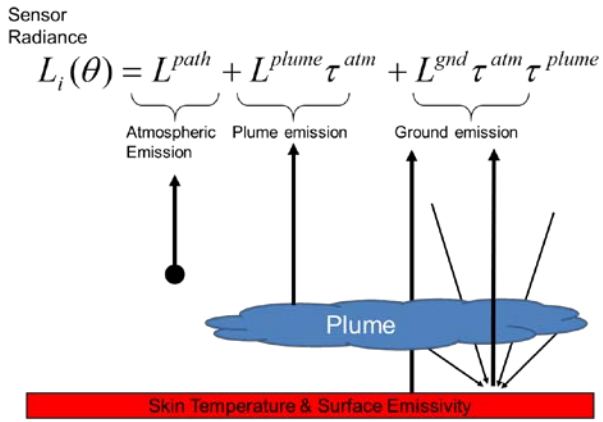
HyTES Radiance image over Cuprite, Nevada with bands 150, 100, 75 displayed as RGB and retrieved emissivity spectra over areas consisting of Alunite (A), Quartz (B), and Kaolinite (C). TES retrieved spectra for the window bands are shown in red, a Principal-Component (PC) regression fit to the TES data covering all wavelengths are shown in blue, and lab spectra of samples collected in these areas are in black.

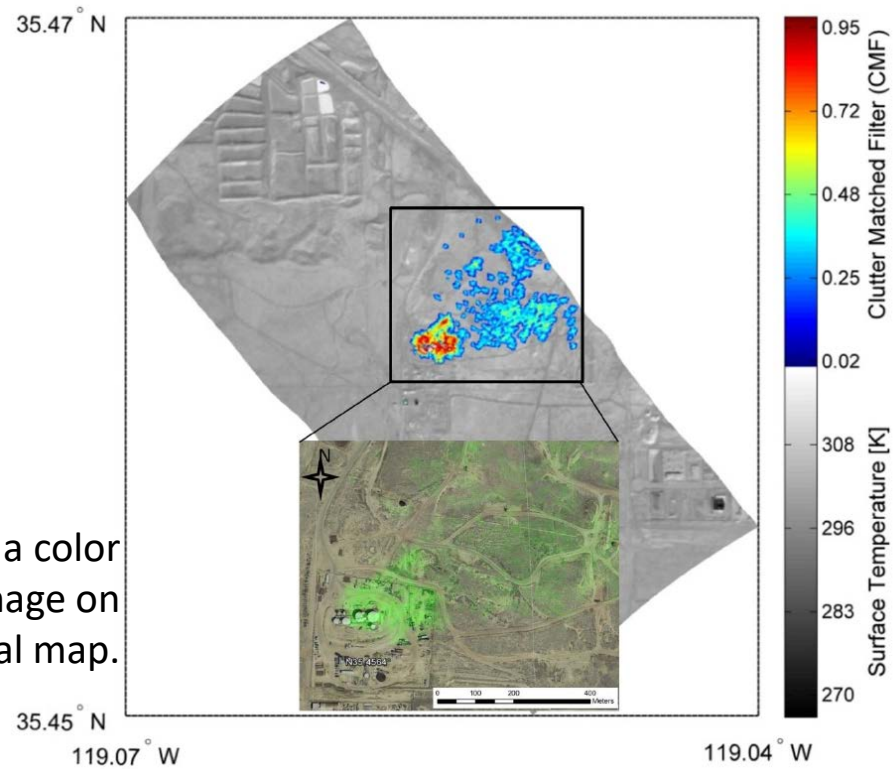
TES Algorithm: (Gillespie et al. 1998; Hulley and Hook 2009; Hulley et al. 2009; Tonooka 2005).

Plume retrievals and spectra



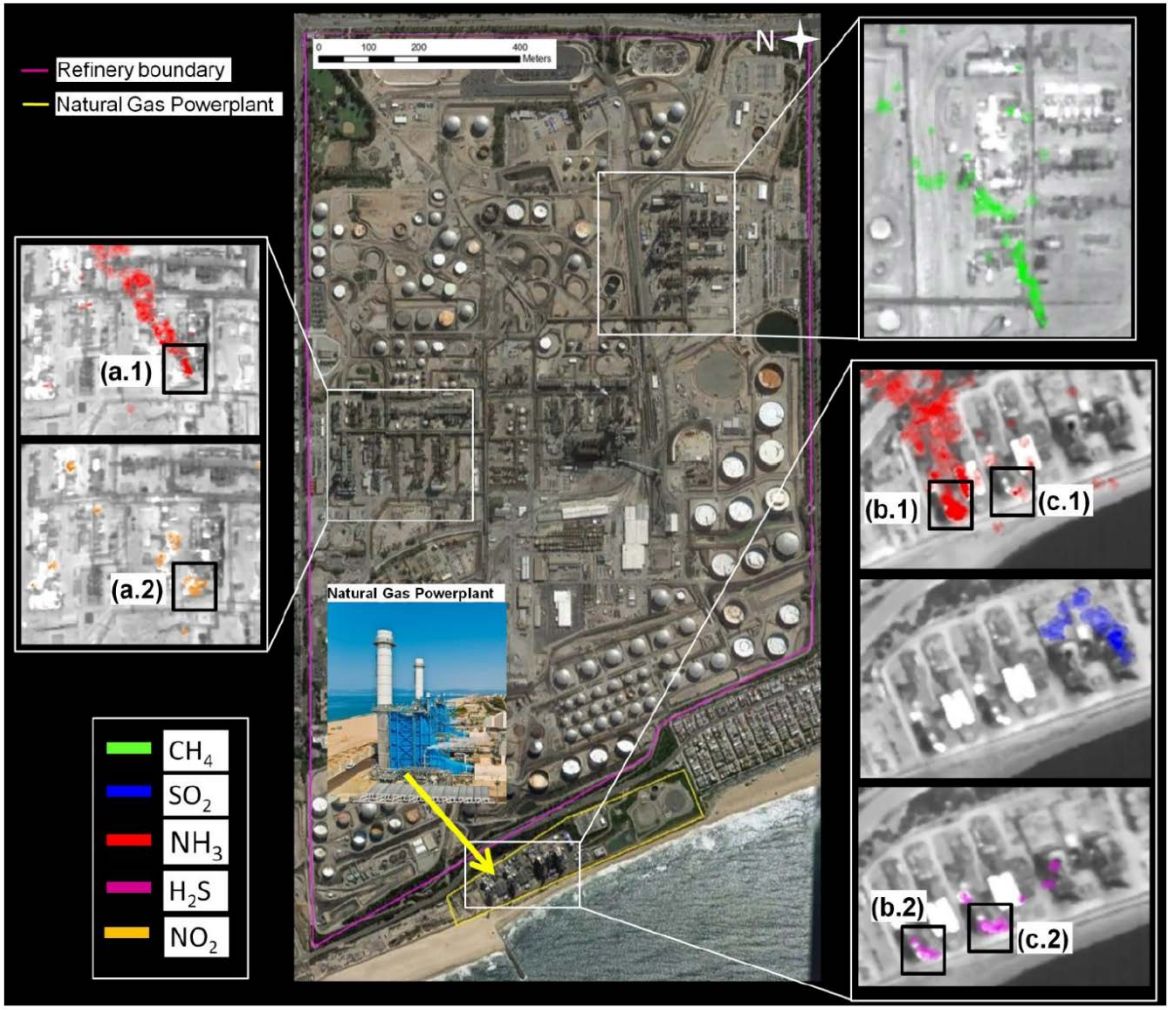
Spectral retrieval of various trace gas species





Higher-level plume visualization images showing a color CMF overlay on grayscale surface temperature image on a geospatial map.

Multi-species



A HyTES Multi-species gas detection example showing a Google Earth image (center) of the area covered by a HyTES flightline over a refinery (magenta outline) and a natural gas powerplant (yellow outline) near El Segundo, CA. The insets show HyTES imagery of five detected trace gases (CH4, NO2, NH3, H2S, and SO2) highlighted in different colors and overlayed on retrieved surface temperature data in grayscale. Three examples are indicated where two different gases were detected 25 simultaneously within the same plume consisting of several contiguous pixels; NH3 and NO2 were detected over the refinery at the location **a.1**,/**a.2**, while at the natural gas powerplant, NH3 and H2S were detected at location **b.1**/**b.2**, and **c.1**/**c.2** respectively. Small plumes of SO2 (blue) can also clearly be seen being emitted from areas of the power plant (inset photograph).A distinctive CH4 plume was detected in the southeastern region of the refinery.

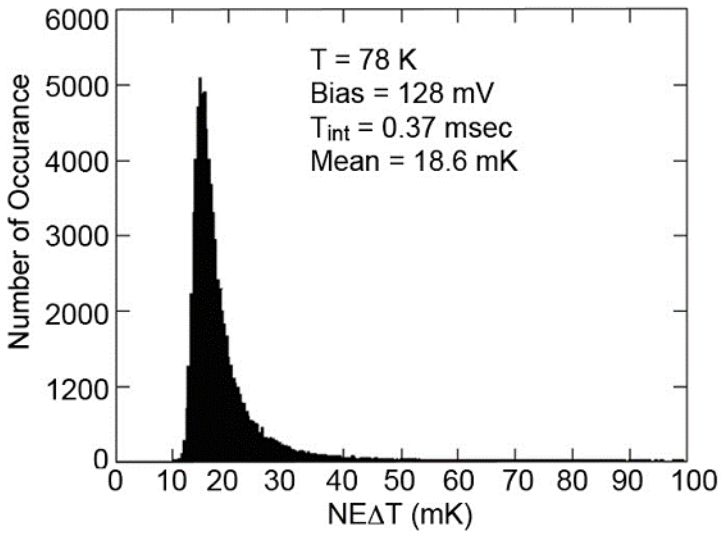
Hulley, G. C., et al. "High spatial resolution imaging of methane and other trace gases with the airborne Hyperspectral Thermal Emission Spectrometer (HyTES)."

CBIRD Technology

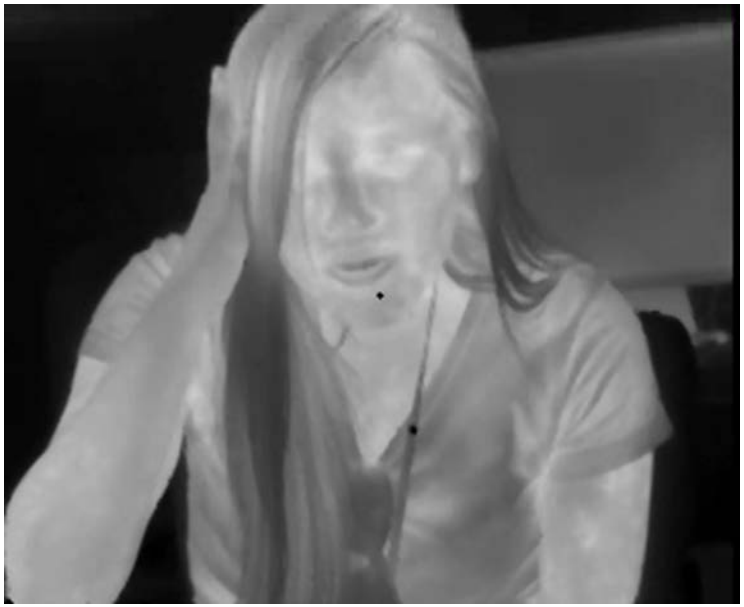
New potential detector technology for future pushbroom hyperspectral sensors:

- Antimonide superlattice based long-wavelength infrared photodetectors using a complementary barrier infrared detector (CBIRD) design offers the possibility of stabilized, uniform arrays with low dark current, higher operating temperature than QWIP and higher QE.

- Antimonide-based superlattice infrared absorbers can be customized to have cut-on wavelengths ranging from the short-wave infrared (SWIR) to the very long-wave infrared (VLWIR).



Format	– 320x256
Pixel pitch	– 30 μm
ROIC	– ISC 0903 DI
Pixels	– Fully reticulated
Pixel Size	– 26x26 μm^2
Polarity	– N on P
Cutoff wave.	– 10 μm
Oper. temp.	– 78 K
QE (8-9.2 μm)	– 54% (without A/R)
NEΔT	– 18.6 mK with f/2 300K
Substrate	– Removed
Temp. Cy	– 29



ECOSTRESS Project Overview

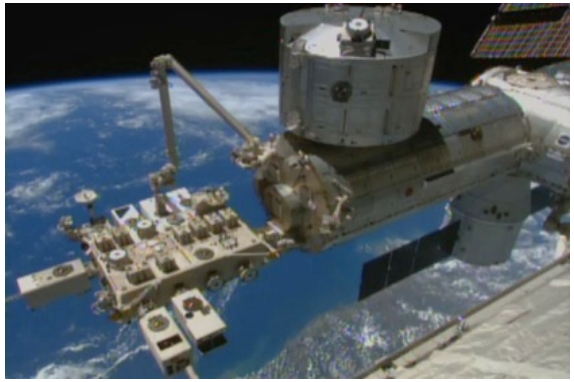
ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) is an Earth Venture Instrument-2 on the ISS

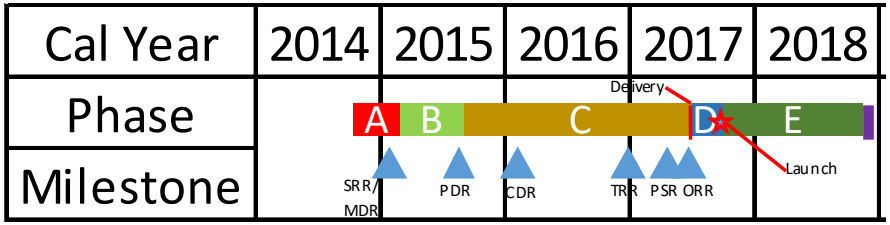
Primary Science Objectives

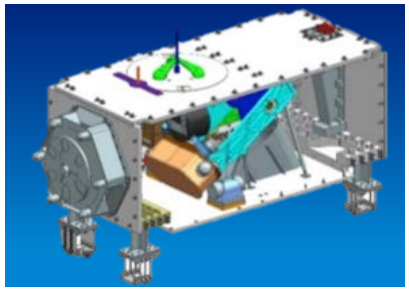
- Identify critical thresholds of water use and water stress in key climate-sensitive biomes
- Detect the timing, location, and predictive factors leading to plant water uptake decline and cessation over the diurnal cycle
- Measure agricultural water consumptive use over the contiguous United States (CONUS) at spatiotemporal scales applicable to improve drought estimation accuracy

Features:

- class D
- 8–12.5 µm Radiometer with a 400km swath
- 2017 Payload delivery date
- Deployed on the ISS on JEM-EFU 10
- Measure brightness temperatures of Earth at selected locations
- Operational life: 1 year after 30 days on-orbit checkout



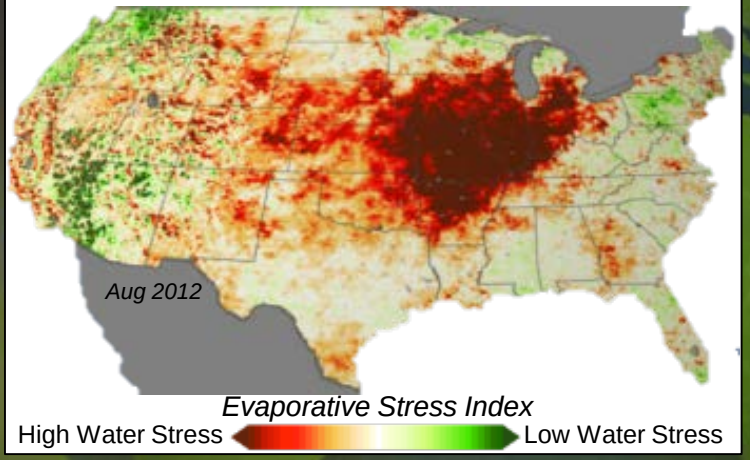




ECOSTRESS Science Overview

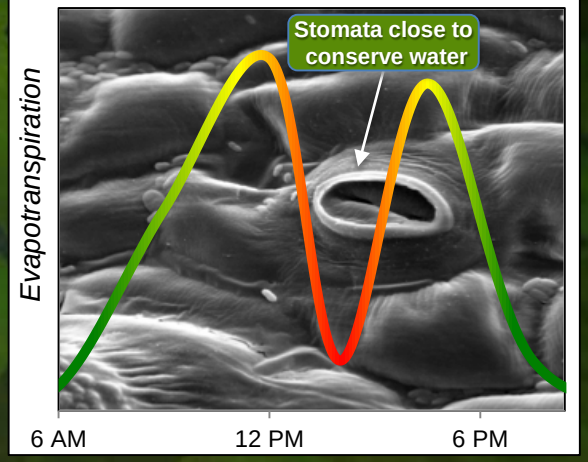
*ECOSTRESS will provide critical insight into **plant-water dynamics** and how **ecosystems change with climate** via **high spatiotemporal** resolution thermal infrared radiometer measurements of evapotranspiration (ET) from the International Space Station (ISS).*

Water Stress Threatens Ecosystem Productivity



Water stress is quantified by the Evaporative Stress Index, which relies on evapotranspiration measurements.

Water Stress Drives Plant Behavior

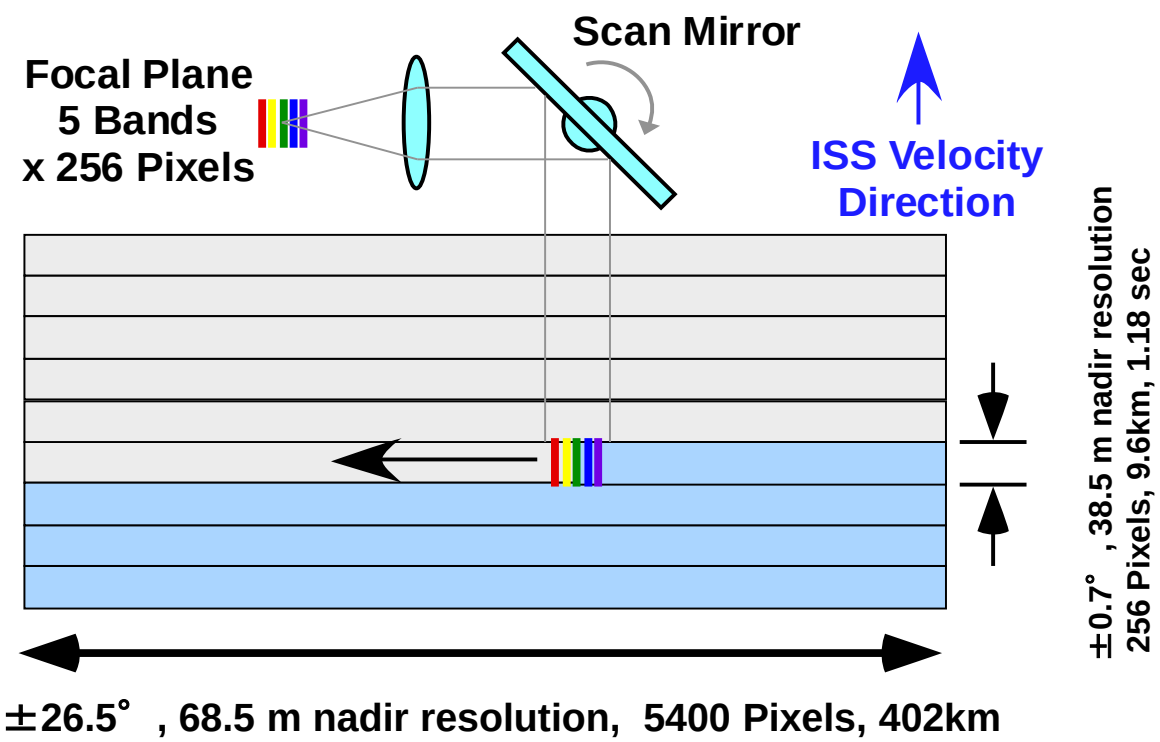


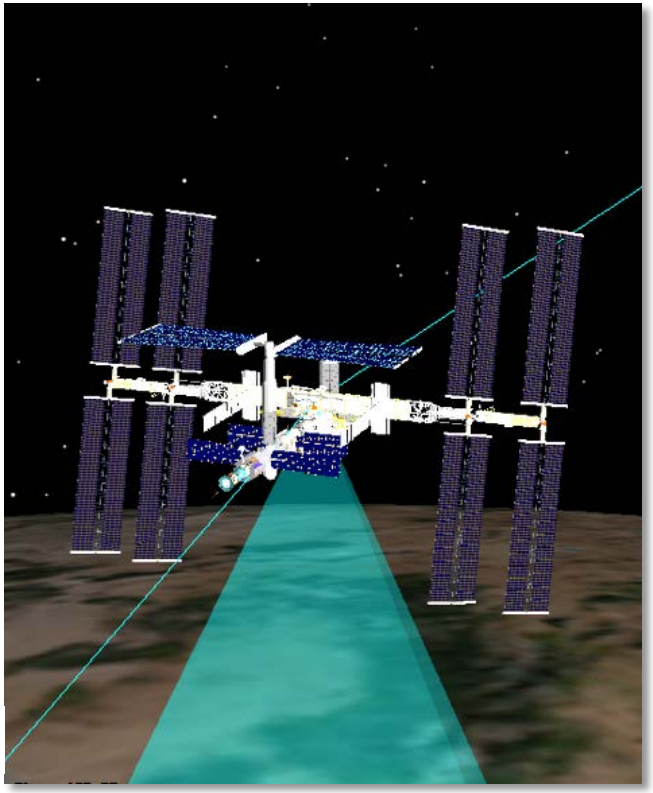
When stomata close, CO_2 uptake and evapotranspiration are halted and plants risk starvation, overheating and death.

Science Objectives

- Identify **critical thresholds of water use and water stress** in key climate-sensitive biomes
- Detect the timing, location, and predictive factors leading to plant **water uptake decline** and/or cessation over the **diurnal cycle**
- Measure **agricultural water consumptive use** over the contiguous United States (CONUS) at spatiotemporal scales applicable to improve drought estimation accuracy

Instrument Concept





- 402 km swath width at 400 km altitude *(Requirement is ≥ 360 km)*
- 38.5 x 68.5 m Pixel Footprint at Nadir *(Requirement is ≤ 100 m)*
- Scan Mirror rotates to enable overlap between successive scans
- Pixel Dwell Time 32 microseconds

ECOSTRESS Sensor Rational

Science Requirements
60 m Resolution
Wide swath

→

Instrument Requirements
~10,000 pixels cross track
~400 km swath
53° Cross-track swath

Whiskbroom (Push-Whisk)
- Single telescope with scanning mirror
- Single detector array with 256 pixels per band

✓

Pushbroom
- ~10 detector arrays, each with ~1,000 pixels per band
- ≥3 telescopes

✗

Science Requirements
0.5% Radiometric accuracy for 300 K scenes

→

Instrument Requirements
Frequent 2-point calibrations (space and blackbody)

Whiskbroom (Push-Whisk)
- Scanning mirror allows easy and frequent 2-point calibrations
- No mapping gaps

✓

Pushbroom
- Calibration mechanism required – must enable multiple telescopes to view space and blackbody
- Gap in mapping during calibration

✗

ECOSTRESS Sensor Rational

Science / Instrument Requirement
0.2 K resolution for 300 K scene

QWIPs
- Quantum efficiency ~low
- > 0.3 K resolution at 40 K

MCT Detectors
- Quantum efficiency ≥ 70%
- 0.06 K resolution at 60 K

Uncooled Microbolometers
- Too slow for push-whisk method
- Even with pushbroom, resolution ~0.5 K

Science / Instrument Requirement
8 spectral bands 4-12 μm

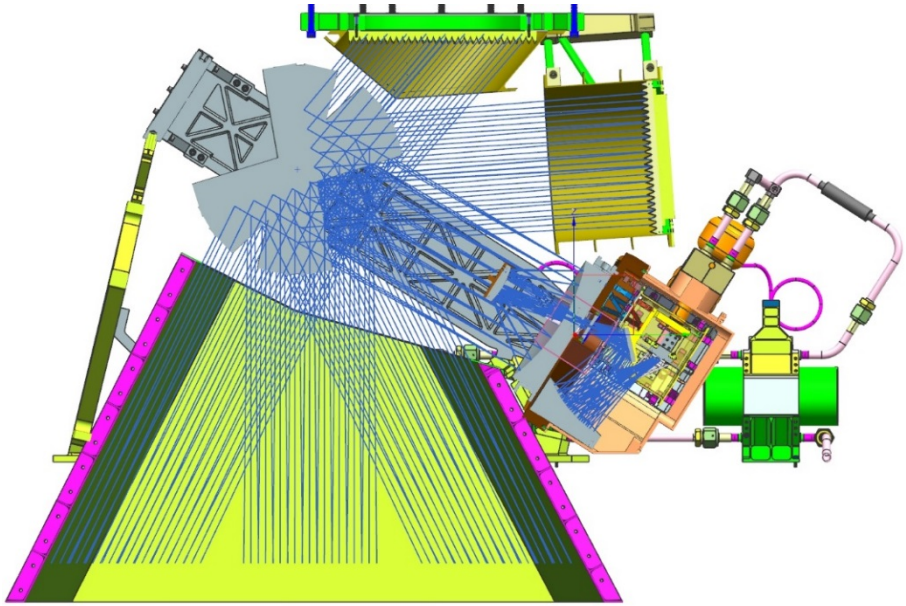
QWIPs
- Multiple arrays required to cover all bands

MCT Detectors
- Single band-gap material can cover full spectral range

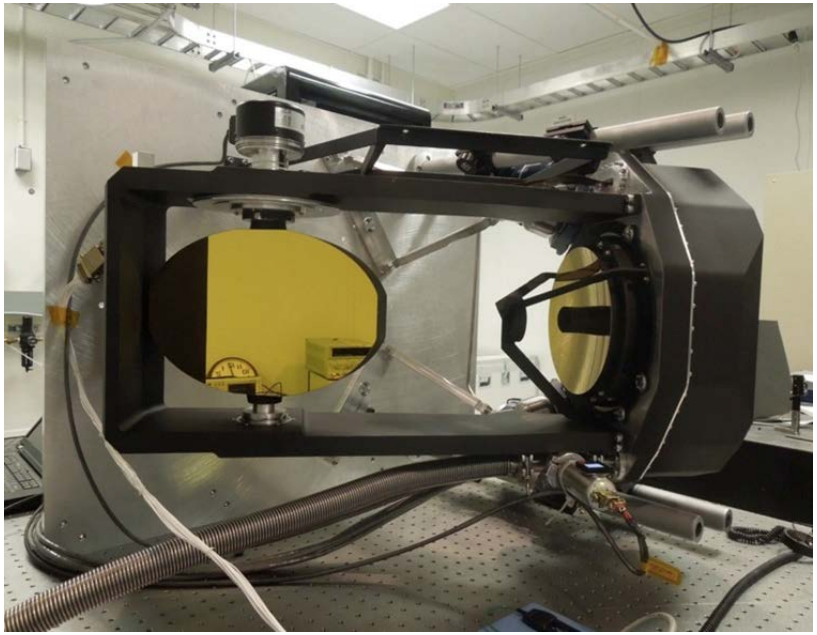
Uncooled Microbolometers
- Not sensitive to <4 μm band

ECOSTRESS Optics

- Design: Three mirror anastigmatic (TMA) with accessible Lyot stop
- Cold focal plane filter array (Butcher-block design)
- Continuously rotating scan mirror (constant scan rate)
- Two on-board blackbodies (295K, 325K)



Graphical depiction of ECOSTRESS

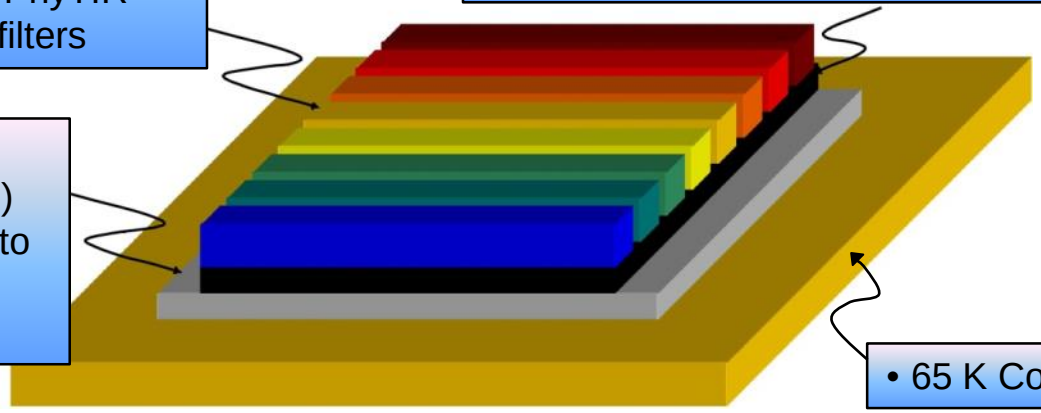


Existing hardware under test

ECOSTRESS Detector Technology

- Butcher-Block Filter Assembly
- Baffles to Prevent Crosstalk Between Spectral Channels
- HyspIRI will have 8 filters, PhyTIR demonstration will have 3 filters

- MCT Detector Array – 256 elements cross-sweep
- 1 Bandgap to Cover Full Spectral Range
- ≥ 4 Detector Columns per Spectral Channel to Allow Time Delay and Integration (TDI)



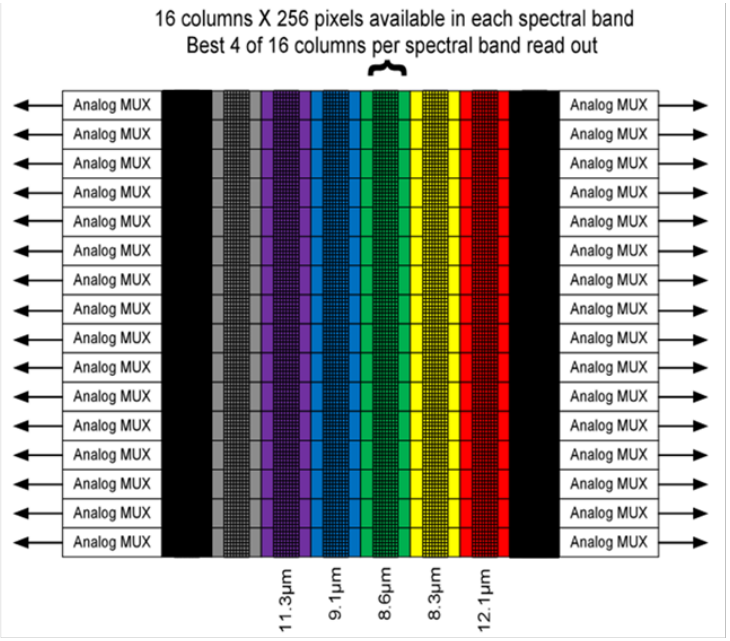
- CMOS Read-Out Integrated Circuit (ROIC)
- 32 Analog Output Lines to Enable Necessary Pixel Read Rate

- 65 K Cold Tip of Cryocooler

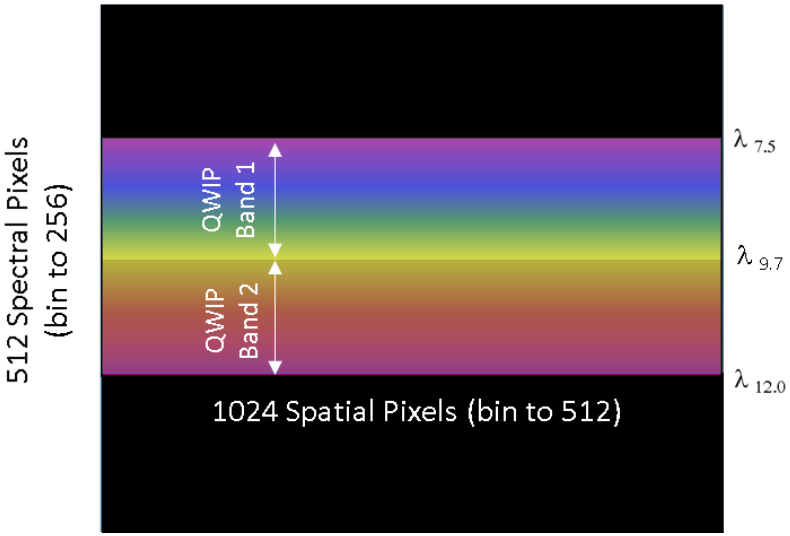
- JPL now has focal plane detectors and readout electronics.
- Digitization in off-chip ADCs
- TDI performed after digitization

ECOSTRESS Detector Compared to HyTES

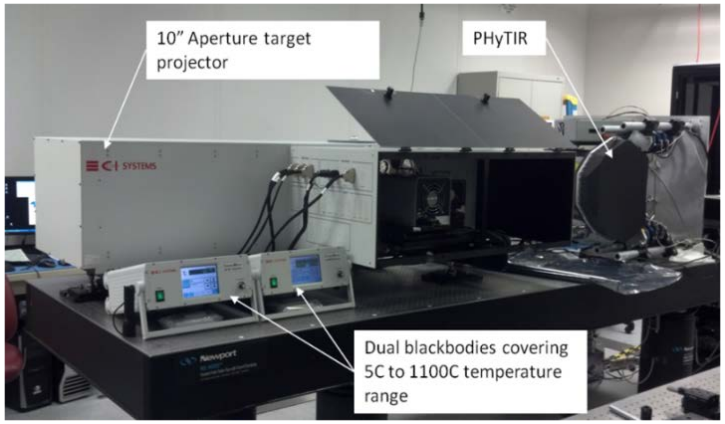
Operation Mode: Push-Whisk Multi-band
Detectors: Mercury Cadmium Telluride (HgCdTe)
Wavelength sensitivity: 8 – 12µm
Wavelength capability: 4 – 12µm
Pixel geometry: square, 40µm pitch
Array size: 256x256, 40µm pixels
Along track: 256 spatial pixels
Cross track: 4 spatial pixel TDI per spectral channel
Spectral channel: 5 (limited by # of filters)
Nominal dwell time ~ 32µs



Operation Mode: Pushbroom Hyperspectral
Detectors: Quantum Well Infrared Photodetector (QWIP)
Wavelength sensitivity: 7.5 – 12µm
Wavelength capability: 7.5 – 12µm
Pixel geometry: square, 39µm pitch (binned)
Array size: 1024 x 1024, 19.5µm pixels
Along track: 256 binned spectral pixels
Cross track: 512 binned spatial pixels
Spectral channel: 256
Nominal dwell time ~ 44ms

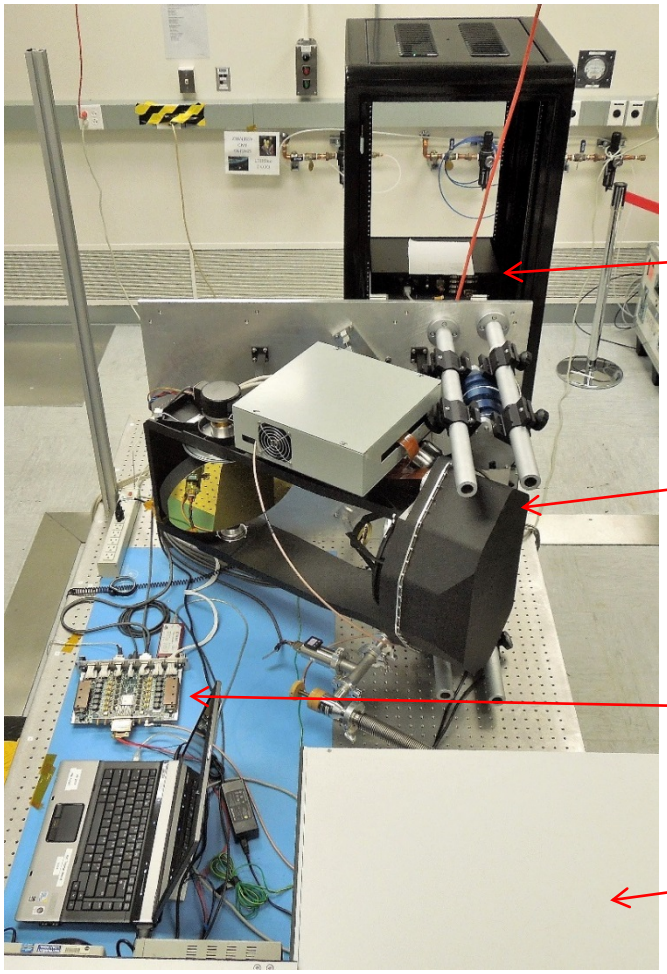


ECOSTRESS Sensor Calibration



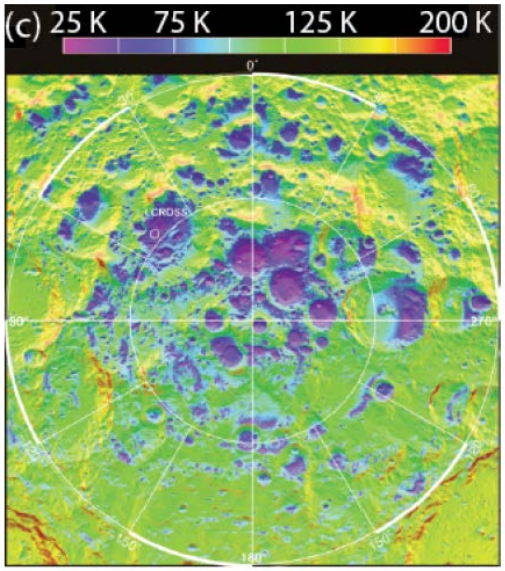
Radiometer calibration during I&T consists of the following system level measurements:

- Noise equivalent delta temperature (NEΔT) per spectral channel
- Absolute radiometric accuracy (linearity) per spectral channel
- Modulation transfer function (X and Y track)
- Saturation temperature
- In-band and out-of-band spectral response function (SRF).
- Radiance versus angle
- NIST traceability of blackbodies using transfer radiometer.
- Out-of-field rejection to confirm stray light rejection
- Geometrical field of view distortion map



Thermopile Sensors

Mars Climate Sounder (MCS) flying on Mars Reconnaissance Orbiter (MCS-launch 2005) and Diviner flying on Lunar Reconnaissance Orbiter (LRO launch 2009) are two examples of high fidelity thermopile based imaging sensors. MCS and Diviner are currently the gold standard for accurate thermal radiometry flying beyond Earth orbit and provide breakthrough science by measuring the infrared/far-infrared (1 to 100 μm) properties of the Martian atmospheric and the lunar surface, respectively.



DIVINER scan head

Polar image of Moon

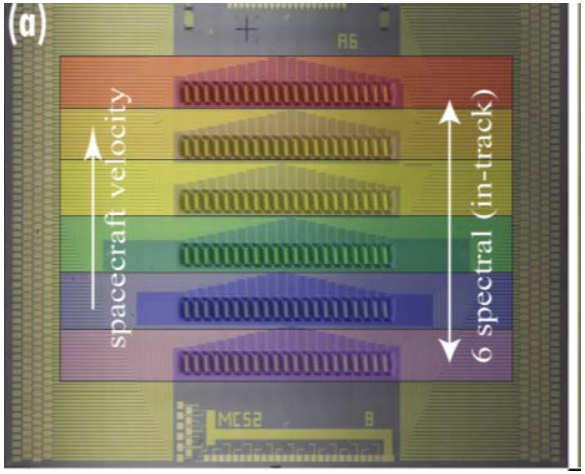
Thermopile Comparisons

While photon detectors are typically very sensitive compared to thermal detectors, photon detectors require extreme cooling to operate at long wavelengths because they low sensitivity as the thermal energy of the carriers approach the bandgap energy.

Thermal detectors, on the other hand, (bolometers, pyroelectric detectors, and thermopiles) can operate uncooled at long wavelengths, making them well suited for spaceborne missions where mass and power resources are scarce.

Thermopiles fill a measurement gap over some of the other uncooled thermal detector technologies:

- Pyroelectric detectors require a chopper and are not available in array formats.
- Microbolometer arrays developed for night vision are commercially available and have been used on two space instruments (THEMIS on Mars Odyssey and the ISAR shuttle instrument) and selected to fly on the New Frontier mission OSIRIS-REx and Europa Clipper.



Thermopile focal plane array with spectral filters defined.

Thermopile Sensor Advantages

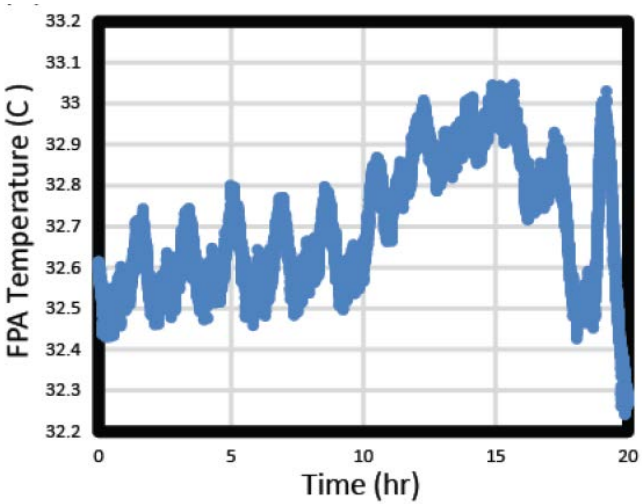
Thermopiles:

- Have broadband (λ= 0.1 to 100 μm) sensitivity. Micro bolometers are designed for 300 K and are tuned to measure = 10μm.

- They have negligible excess 1/f noise so the SNR can be improved by frame averaging and time-delay and integration (TDI). Thermopiles are completely passive devices and require no bias voltage. Conversely, micro bolometers are biased and, consequently, suffer from 1/f noise so they do not realize a sqrt(N) increase in SNR where N is the number of frame averages. Therefore, TDI is ineffective with micro bolometers

- They are insensitive to instrument temperature drifts which is important when radiometric accuracy is critical to success (micro bolometers temperatures must be highly controlled while thermopiles can be controlled to kelvin)

- They are highly linear to incident radiation (50x more linear than micro bolometers)



Concluding Remarks

Over the past few decades, the Jet Propulsion Laboratory has been building up a portfolio of technology to capture the MTIR for various scientific applications. This presentation is by no means an exhaustive examination of the sensors but does hit on three very distinctive existing detection technologies:

- QWIP and CBIRD technology for large format pushbroom sensing
- MCT for high speed push-whisk platforms
- Thermopile arrays for outer planetary, extended wavelength examination of cold objects.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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