# Thermal Tutorial

Presented at:

**HyspIRI Symposium**

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Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

# Outline

- Physical Basis
- Emissivity of Rocks and Minerals
- Atmospheric windows
- Field measurements
- Airborne measurements
- Wrap-up
  - What we covered, what we didn’t cover and what next!

# Planck's Formula

In 1894 Planck turned his attention to the problem of black-body radiation. He had been commissioned by electric companies to create maximum light from lightbulbs with minimum energy. The problem had been stated by Kirchhoff in 1859: "how does the intensity of the electromagnetic radiation emitted by a black body (a perfect absorber, also known as a cavity radiator) depend on the frequency of the radiation (i.e., the color of the light) and the temperature of the body?". - Source Wikipedia

where:

$M_\lambda =$ blackbody spectral exitance.

$\lambda =$ wavelength.

$T =$ absolute temperature.

$C_1 =$ first radiation constant.

$C_2 =$ second radiation constant.

$$M_\lambda = \frac{C_1}{\lambda^5\left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]}$$

# More Formulas

## Wien Displacement Law

The spectral exitance of a blackbody varies strongly with temperature. The wavelength of maximum spectral exitance at a given temperature can be obtained with the Wien Displacement Law

$$\lambda_m = C / T$$

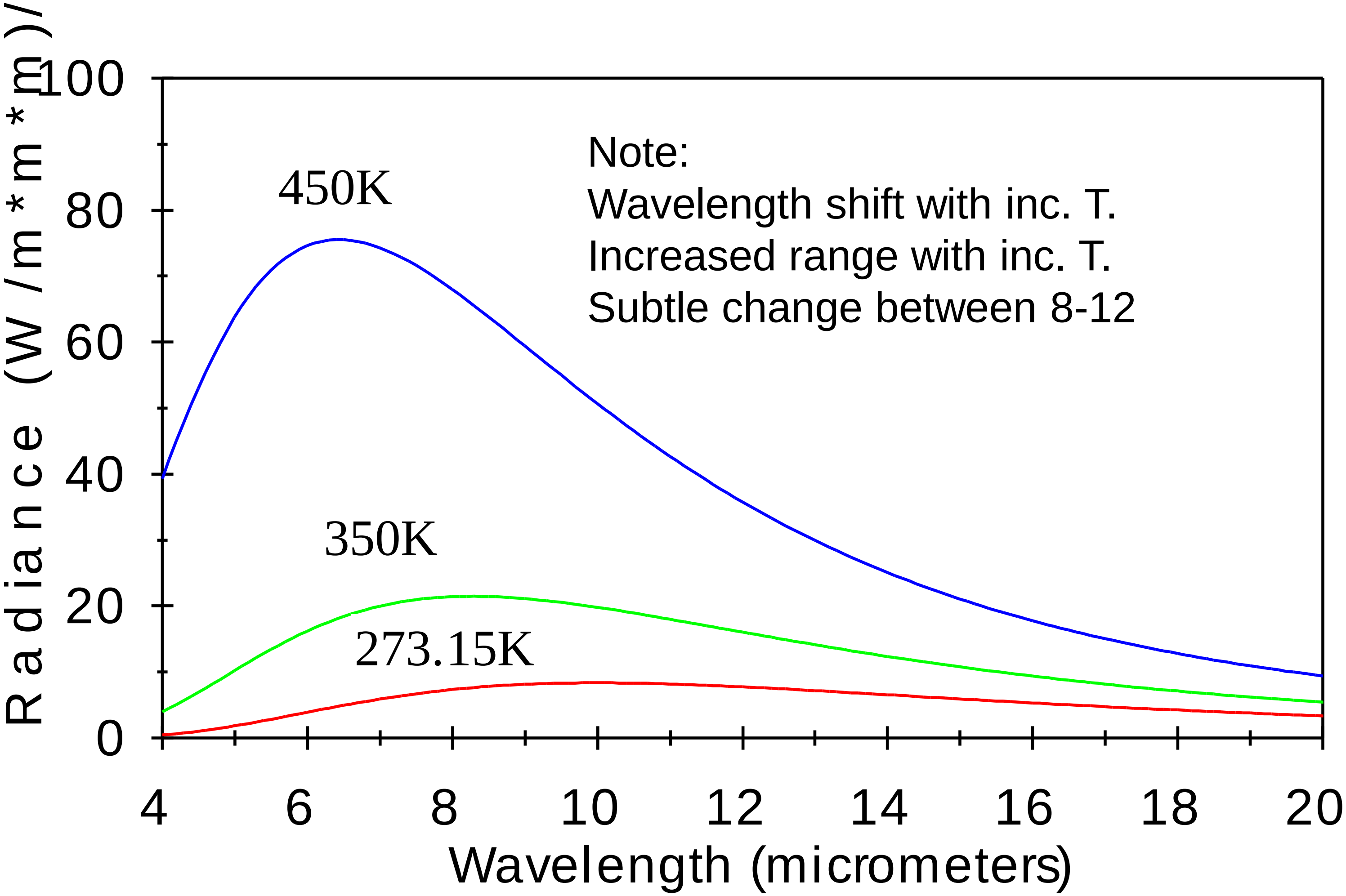
where C = 2.898 x $10^{-3}$ mK

## Spectral Exitance vs Spectral Radiance

A true blackbody surface is a Lambertian radiator and so the relation between spectral radiance and spectral exitance is:

$$L_\lambda = M_\lambda / \pi$$

# Blackbody (Planck) Radiance Curve

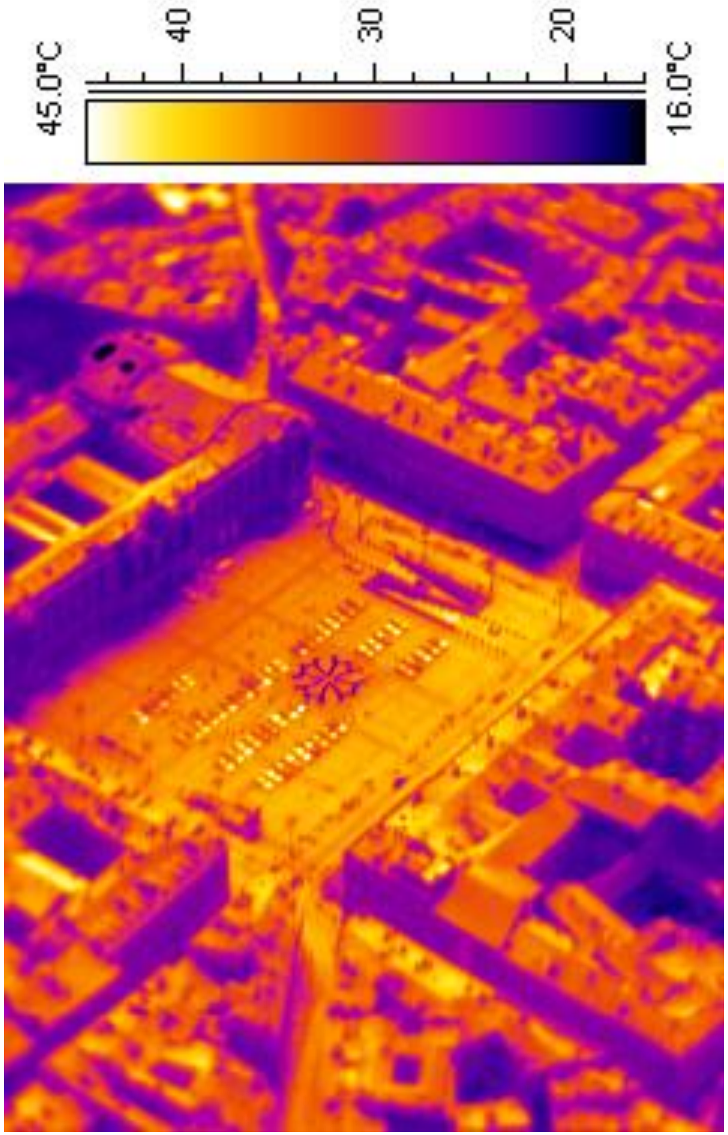


# Spectral Emissivity

Materials are not perfect blackbodies, but instead emit radiation in acordance with their own characteristics. The ability of a material to emit radiation can be expressed as the ratio of the spectral radiance of a material to that of a blackbody at the same temperature. This ratio is termed the spectral emissivity:

$$\varepsilon_\lambda = L_\lambda(\text{Material}) \ / \ L_\lambda(\text{Blackbody})$$

# Thermal Cross in Toulouse, France



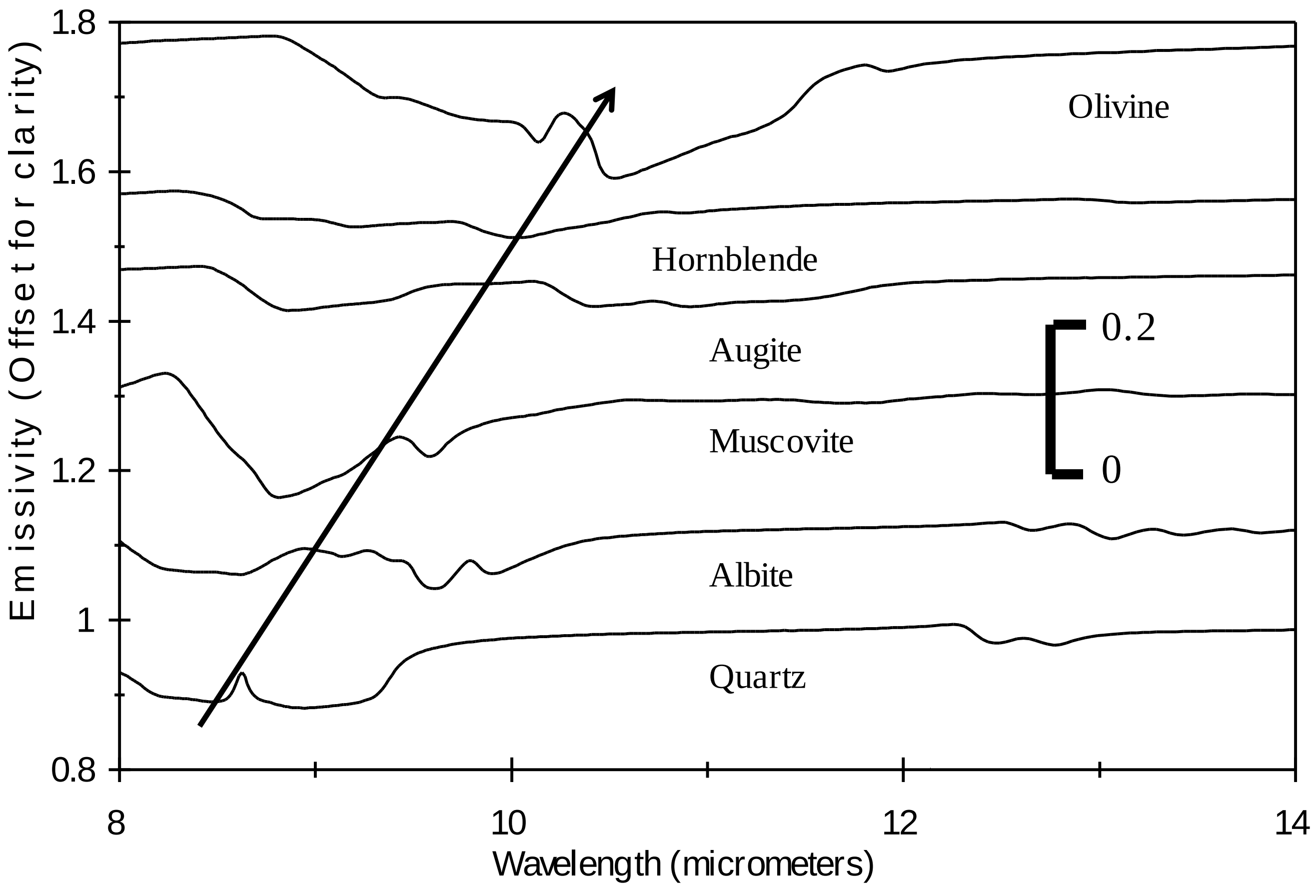

In the Thermal Infrared (TIR) we measure temperature and emissivity. Emissivity relates to the composition of the material

# Spectral Emissivity (cont.)

The most intense absorption features in the spectral of all silicates occur near 10 µm in the region referred to as the Si-O stretching region or reststrahlen band.

The emissivity minimum occurs at relatively short wavelengths (8.5 µm) for framework silicates (quartz, feldspar) and progressively longer wavelengths for silicates having sheet, chain and isolated SiO4 tetrahedra.

# Silicate Minerals



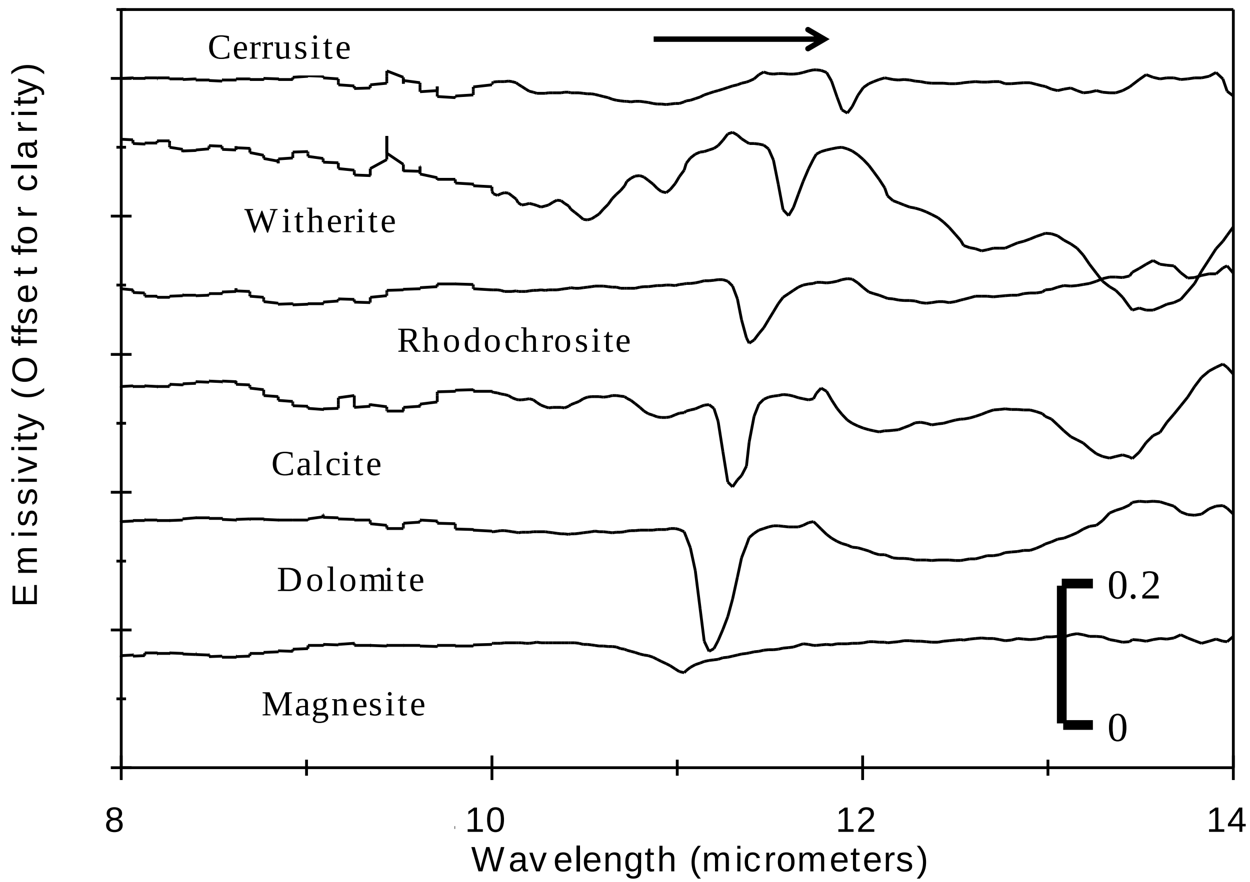

Note shift to longer wavelengths with Si-O bonding

# Spectral Emissivity (cont.)

Other non-silicate molecular units also give rise to spectral features in the thermal infrared. These include carbonates, sulphates, phosphates, oxides and hydroxides, which typically occur in sedimentary and metamorphic rocks.

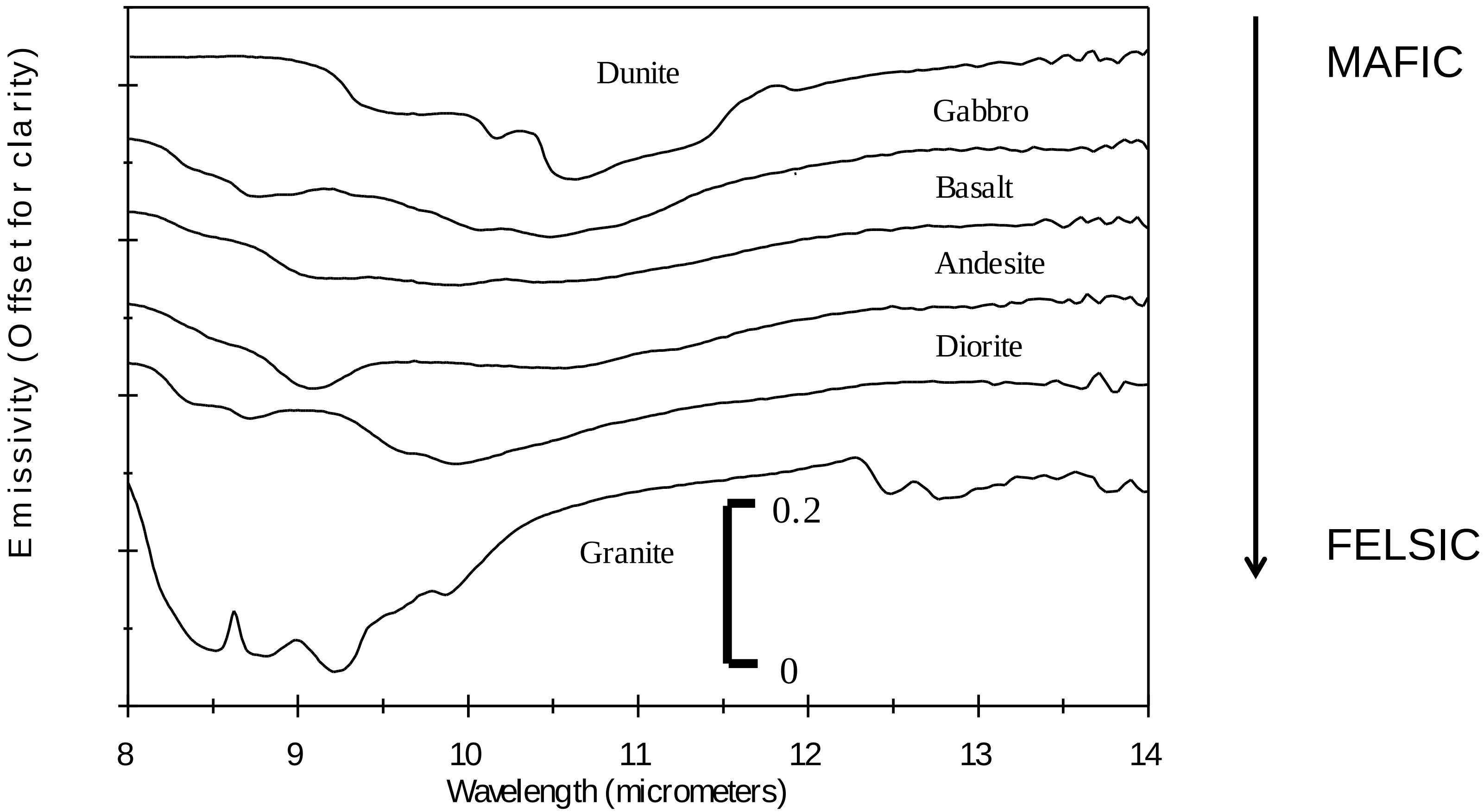
For example carbonate minerals have a diagnostic sharp feature around 11.2 $\mu m$ which moves to slightly longer wavelengths as the atomic weight of the cation increases.

# Carbonate Minerals



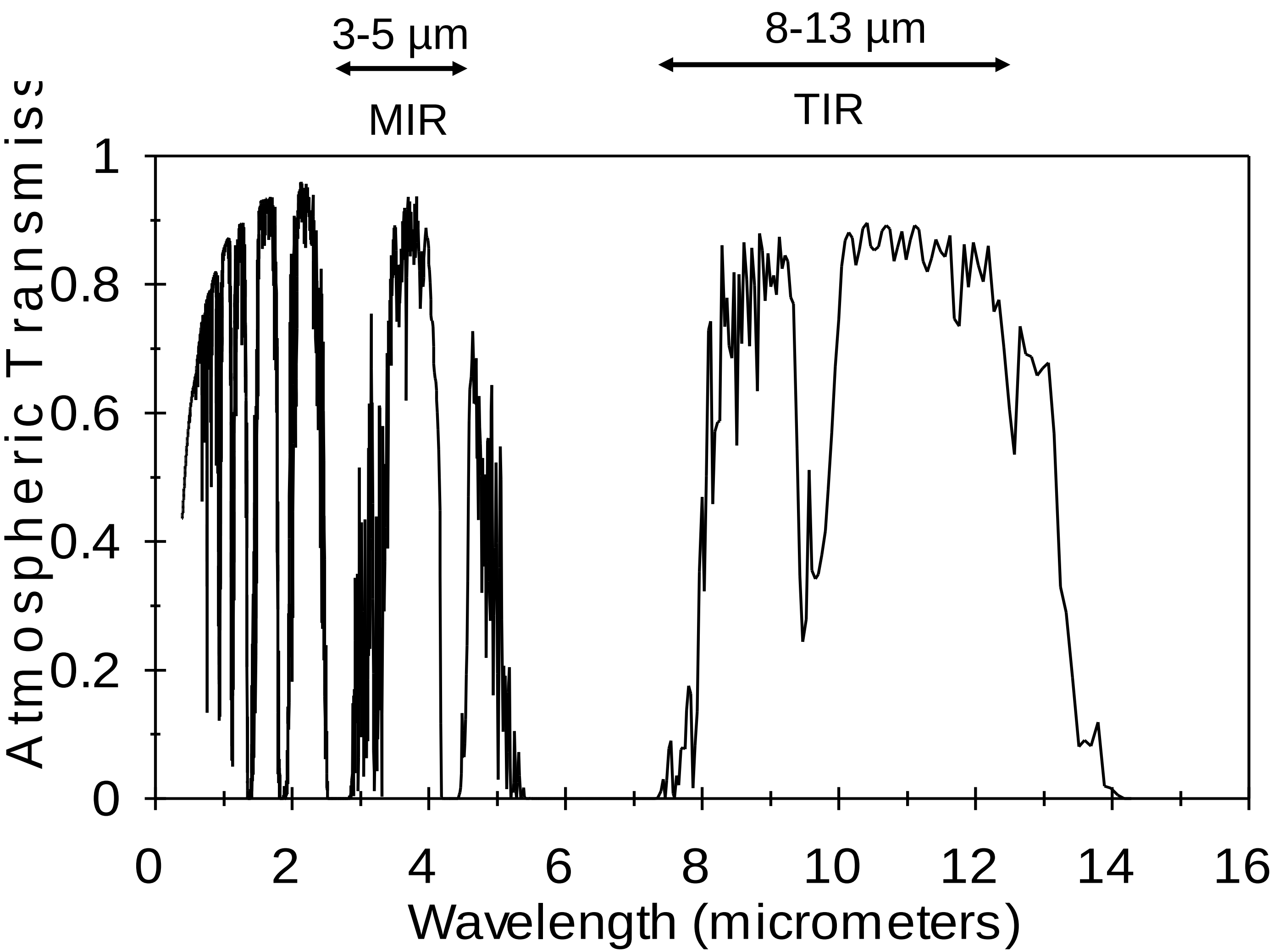

Note shift to longer wavelengths as size of cations increases

# Igneous Rocks




Rocks are classified based on mineralogy from felsic to mafic. Felsic rocks have more framework silicates so minimum at shorter wavelengths – use for mapping

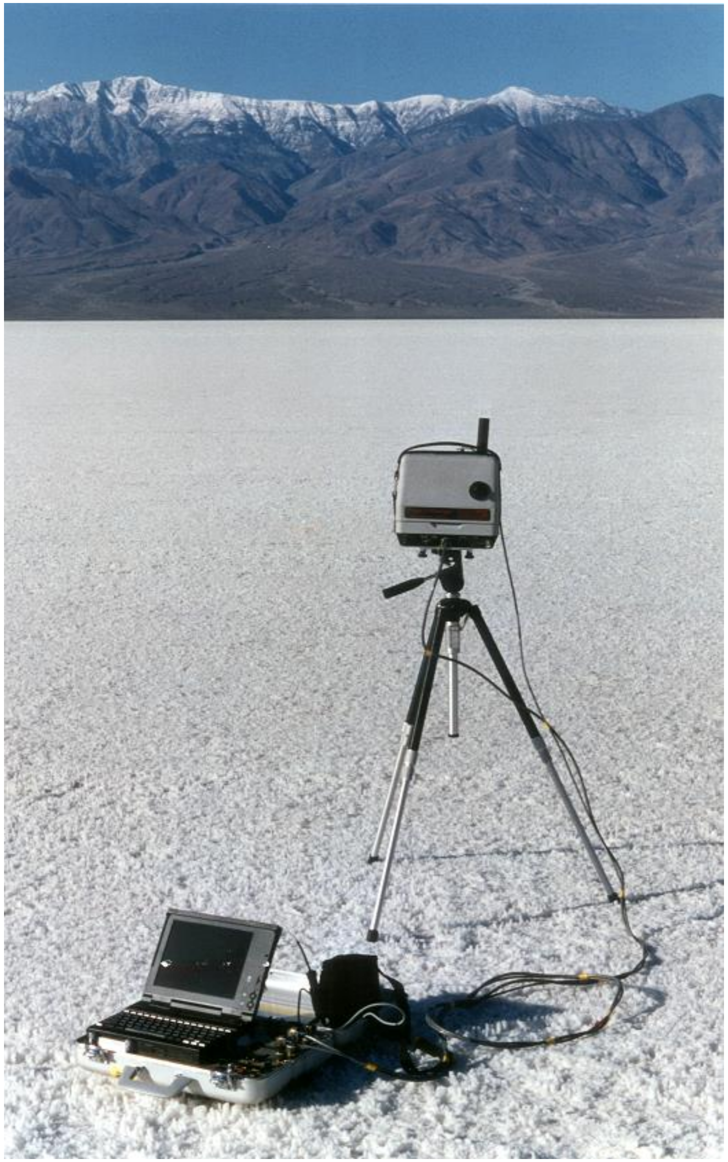
# Atmospheric Windows




Since neither the MIR or TIR is defined you should start your papers by defining them

# Field Measurements

- Refractively scanned interferometer.
- Lightweight. (16 kg)
- Compact.
- Simultaneous acquisition between 3 and 14 um.
- 6 wavenumber spectral resolution.
- 1 wn spectral calibration.
- External BB for radiometric calibration.
- 8 hr dewar or sterling cycle cooler.



# Field Data Reduction

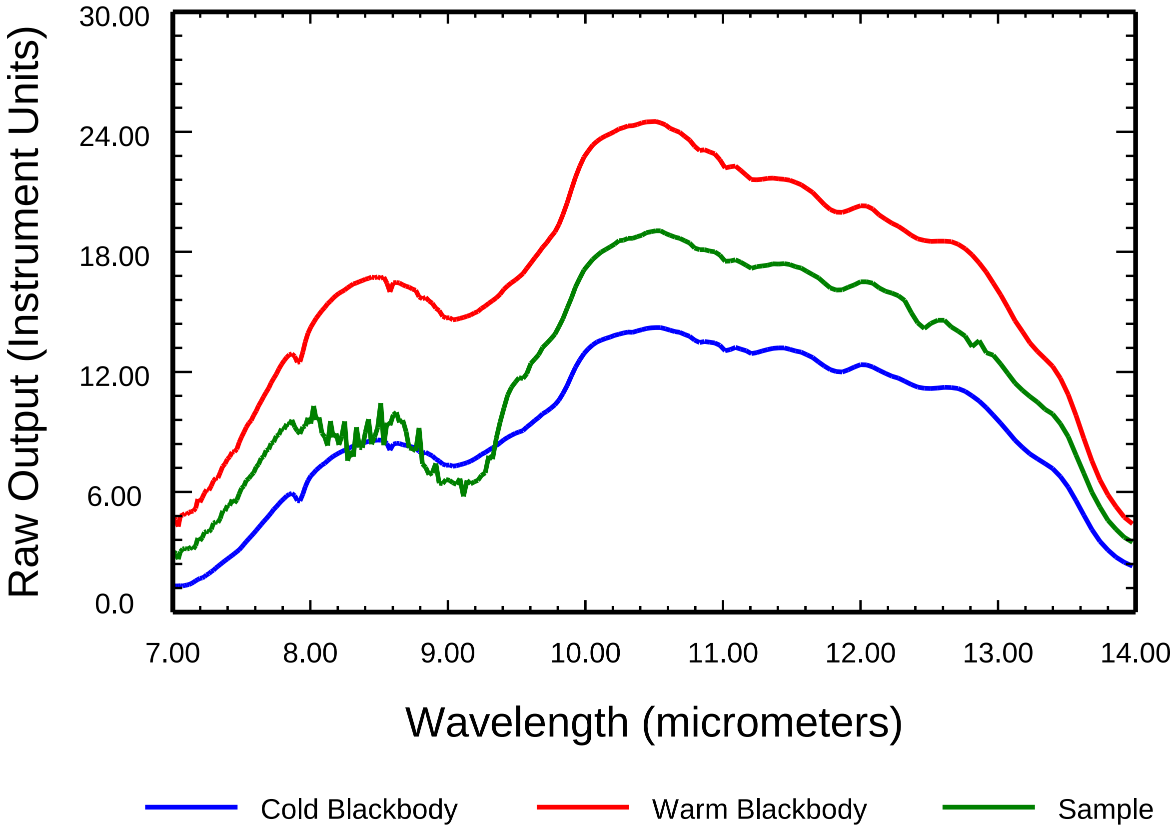
1. Calibration (with blackbodies)
2. Derivation of apparent emissivity

    simply fitting a planck curve

3. Derivation of "True" emissivity

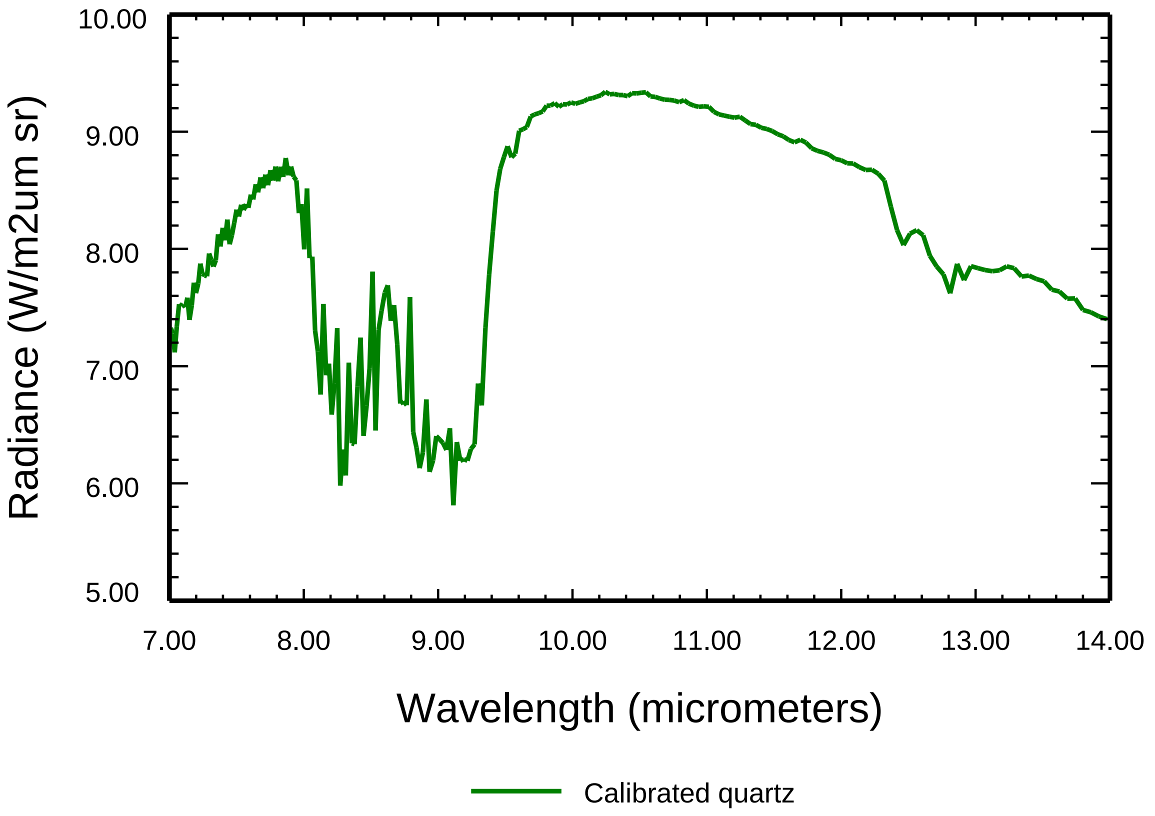
    atmospheric correction

# Raw Data

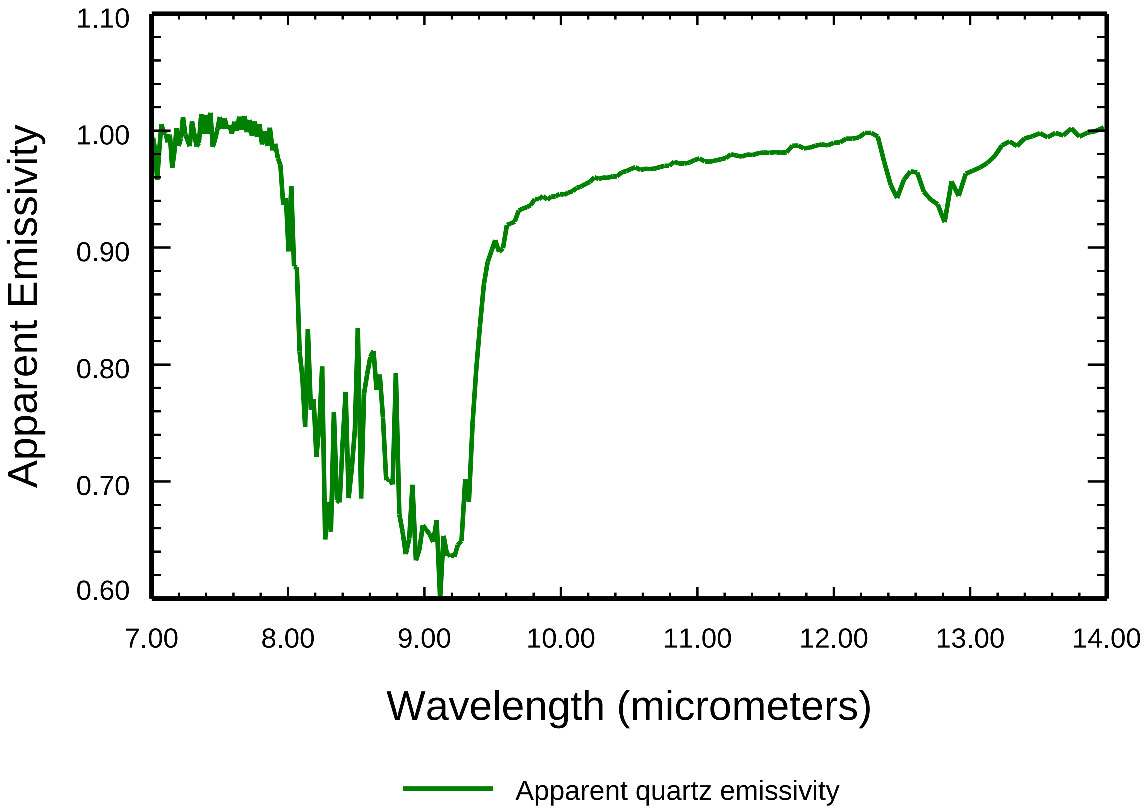


Raw Output (Instrument Units)
30.00
24.00
18.00
12.00
6.00
0.0
7.00
8.00
9.00
10.00
11.00
12.00
13.00
14.00
Wavelength (micrometers)
Cold Blackbody
Warm Blackbody
Sample

# Calibrated Data

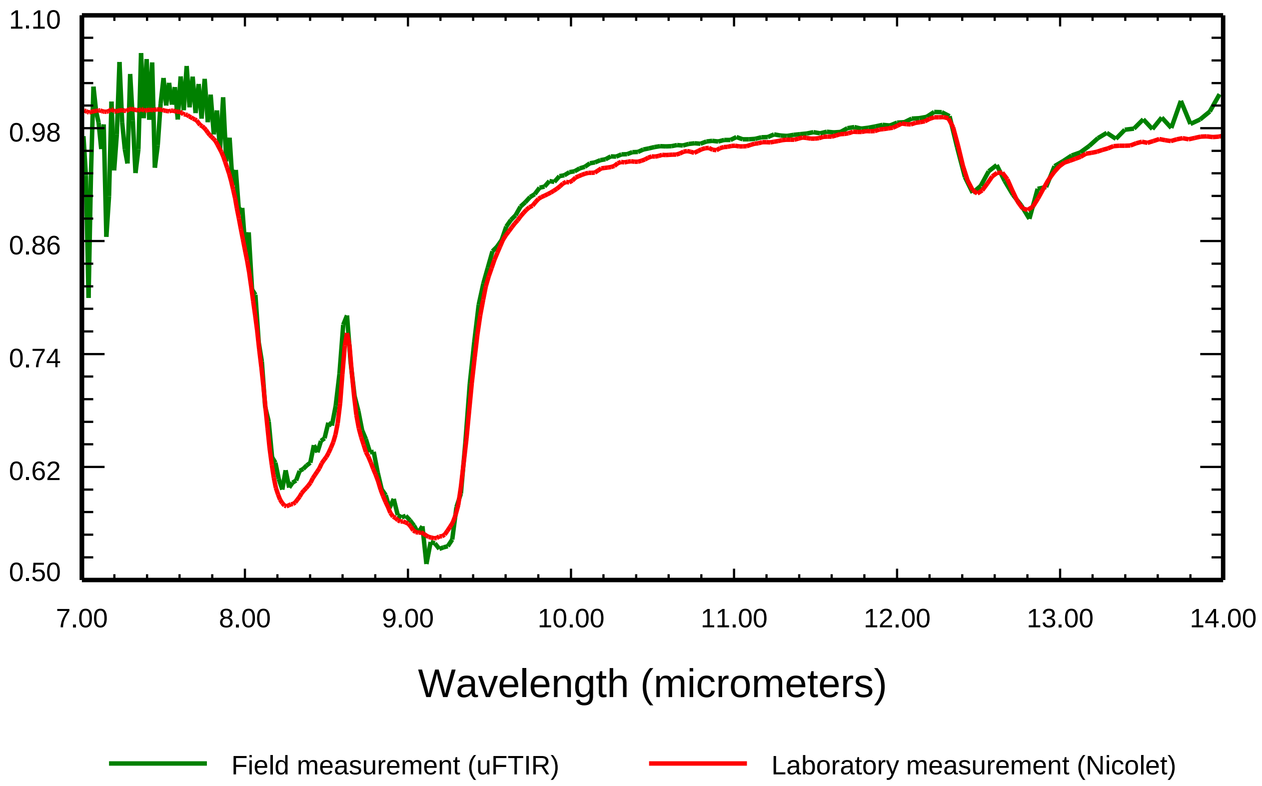


# Apparent Emissivity




Notice the atmospheric water lines superimposed on the spectrum and quart doublets around 8.5 and 13 μm

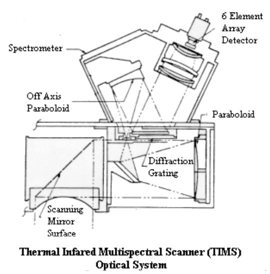
# Field vs Lab.

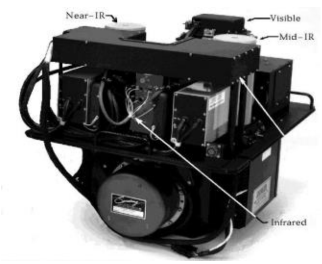


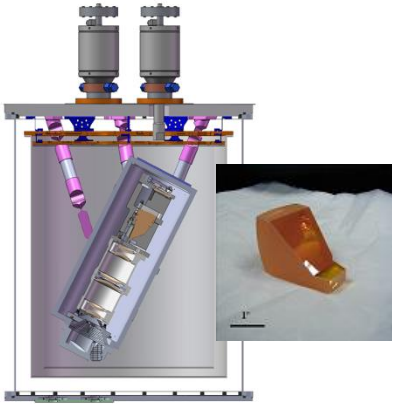

No more water lines!

# Airborne Measurements

Airborne Instruments



| Airborne Name | **TIMS** | **MASTER** | **QWEST** | **HyTES** |
|---|---|---|---|---|
| First Year of Operation | 1980 | 1998 | 2008 | 2012 |
| Number of TIR Bands | 6 | 10 | 56 | 256 |

TIME ->

HYPERSPECTRAL THERMAL EMISSION SPECTROMETER

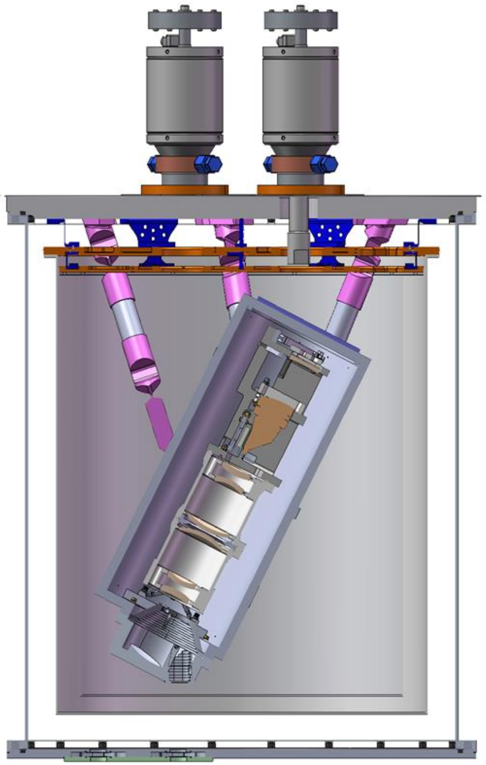
# HyTES

NASA • JET PROPULSION LABORATORY

# Hyperspectral Thermal Emission Spectrometer (HyTES)


## First Science Flights in April 2013

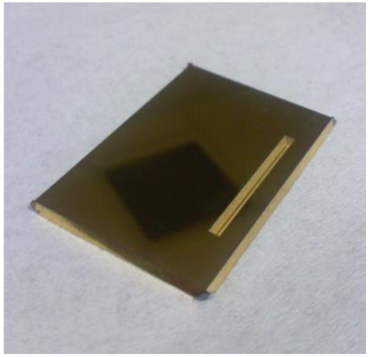
| Instrument Characteristic | HyTES |
|---|---|
| Mass (Scanhead)[1] | 12kg |
| Power | 400W |
| Volume | 1m x 0.5m (Cylinder) |
| Number of pixels x track | 512 |
| Number of bands | 256 |
| Spectral Range | 7.5-12 μm |
| Frame speed | 35 or 22 fps |
| Integration time (1 scanline) | 28 or 45 ms |
| Total Field of View | 50 degrees |
| Calibration (preflight) | Full aperture blackbody |
| Detector Temperature | 40K |
| Spectrometer Temperature | 100K |
| Slit Length and Width | 20 mm x 39 μm |
| IFOV | 1.7066 |
| Pixel Size/Swath at 2000 m flight altitude[2] | 3.41m/1868.33m |
| Pixel Size/Swath at 20,000 m flight altitude[2] | 34.13m/18683.31m |

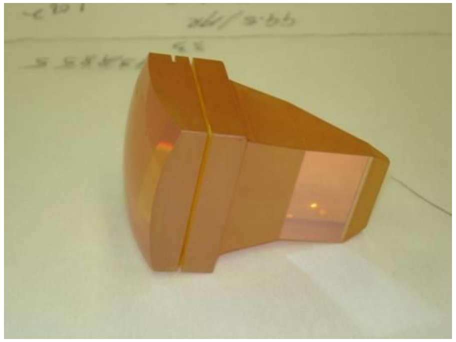
1. Does not include 1 rack of electronics to operate instruments; 2. Includes ~27 calibration pixels

# Key JPL developed technologies

- Current instruments provide high spectral and low spatial OR high spatial and low spectral resolution in thermal infrared. HyTES provides BOTH high spectral and spatial resolution. New design can be made very compact.



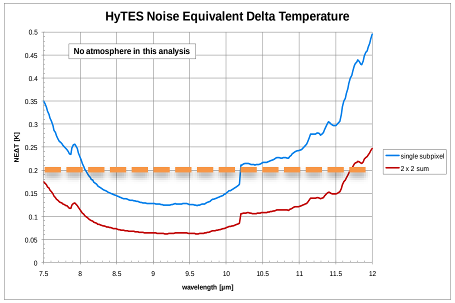
Long, straight slits: Victor White

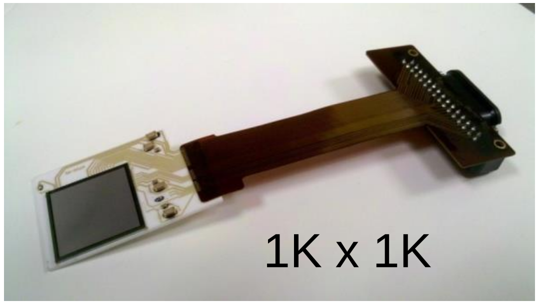


Compact Dyson Spectrometer: Zakos Mouroulis

Concave E-beam diffraction Grating: Dan Wilson

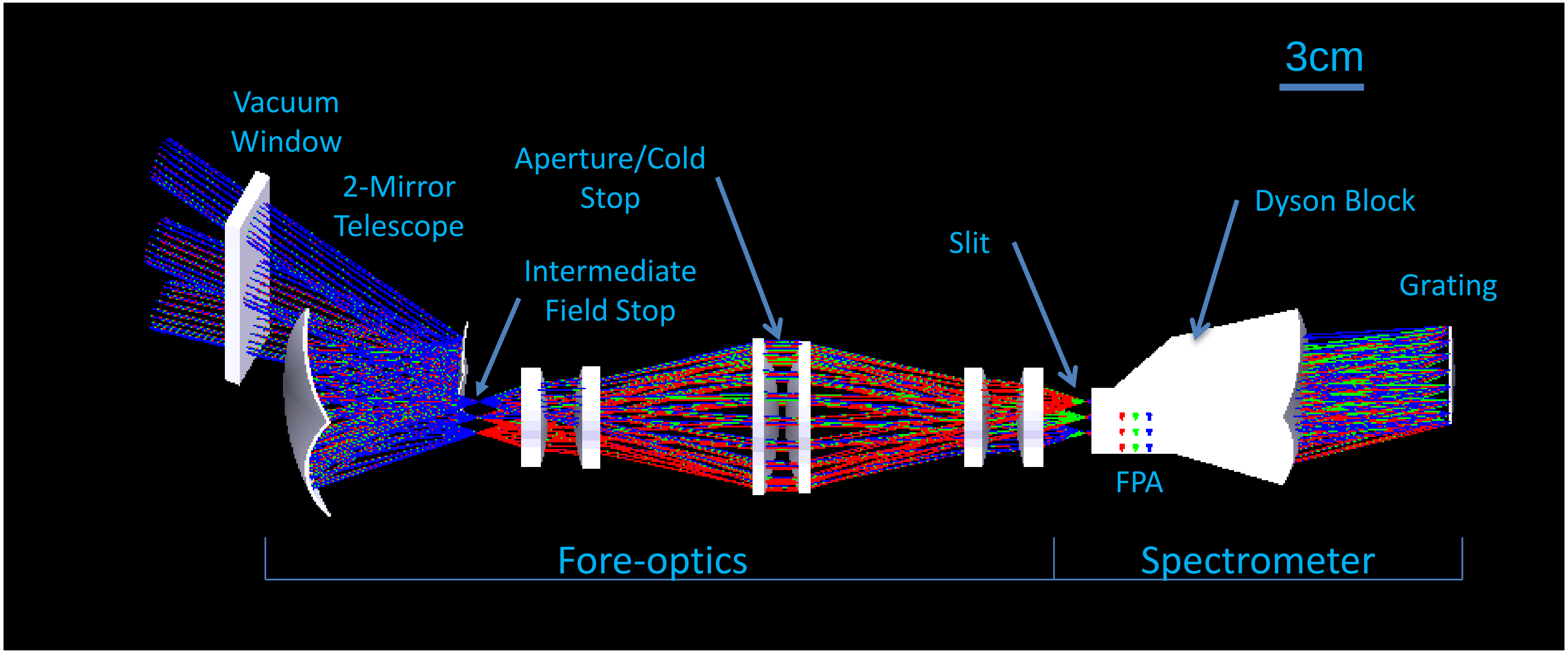
Advanced Designs: William Johnson



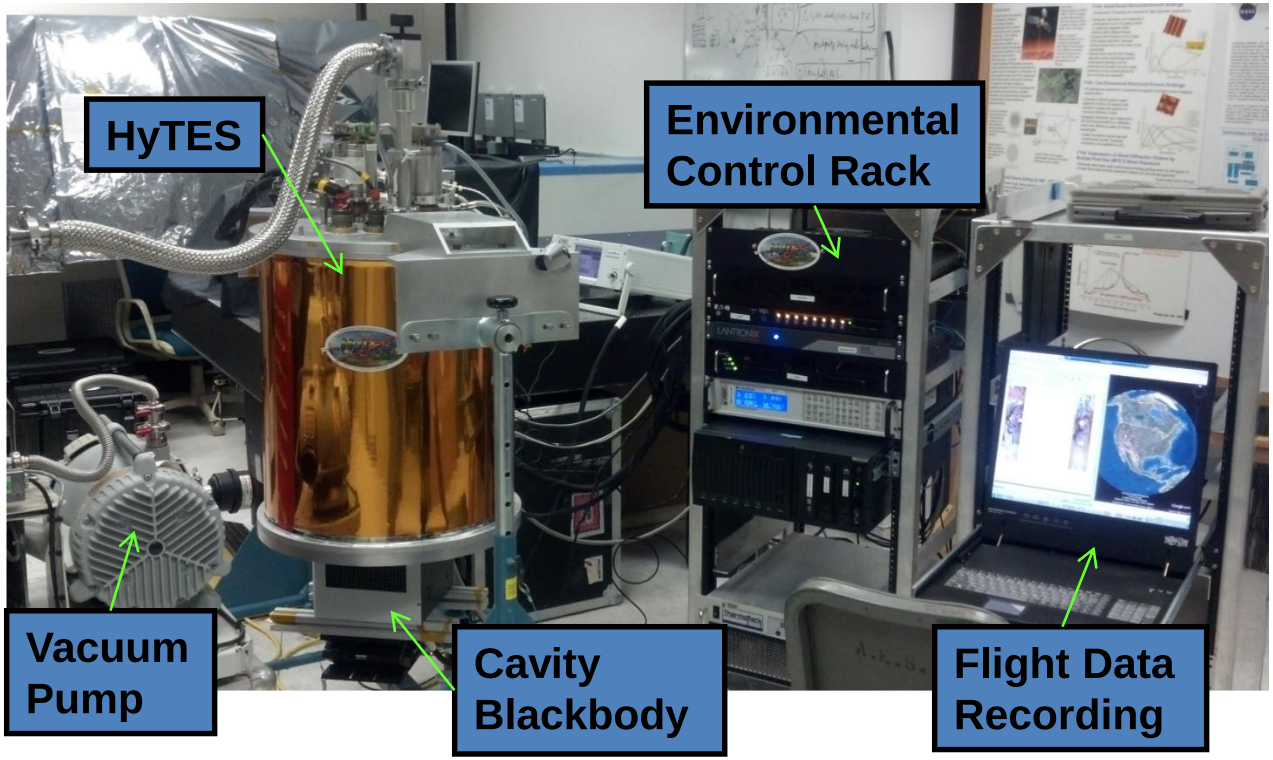

Multi-stack large format QWIP arrays: Sarath Gunapala

# HyTES Optics




HyTES Optical Layout
(The entire system is cold, so there's no real "cold stop" in the traditional fashion)

# HyTES Laboratory Setup

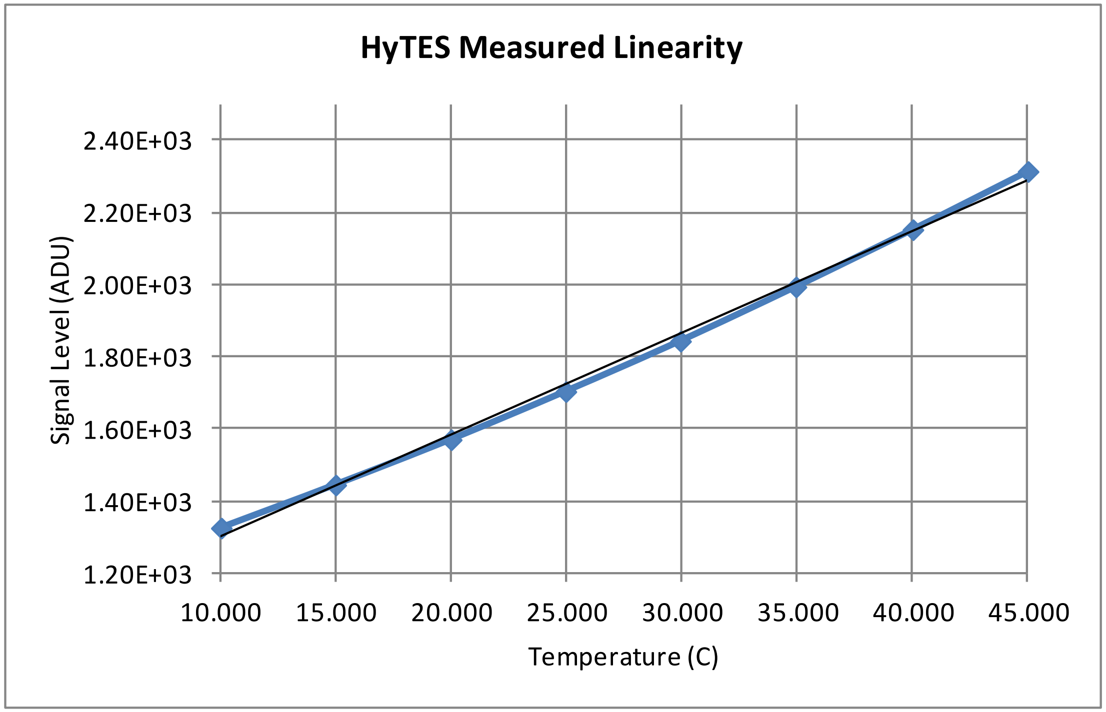



**Lab Test Procedure**

- **Cycle Blackbody Through Temperatures of 5, 10, 15, 20, 25, 30, 35, 40 and 45 ° C**
- **Blackbody DN's at 5 and 45 ° C used to Calculate 2-Point Calibration Coefficients**
- **Calculate Radiance and Brightness Temperature for Blackbody at 25 ° C.**

HyTES shown with high accuracy cavity blackbody. This is the set-up used for measuring system linearity, brightness temperature and NEDT.

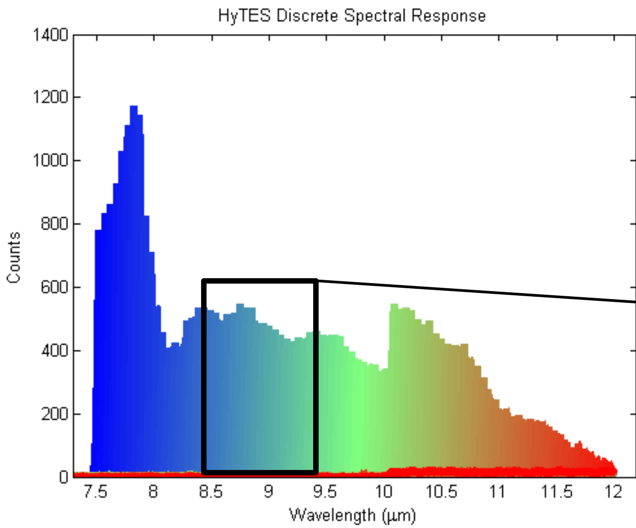
# HyTES Temperature Linearity



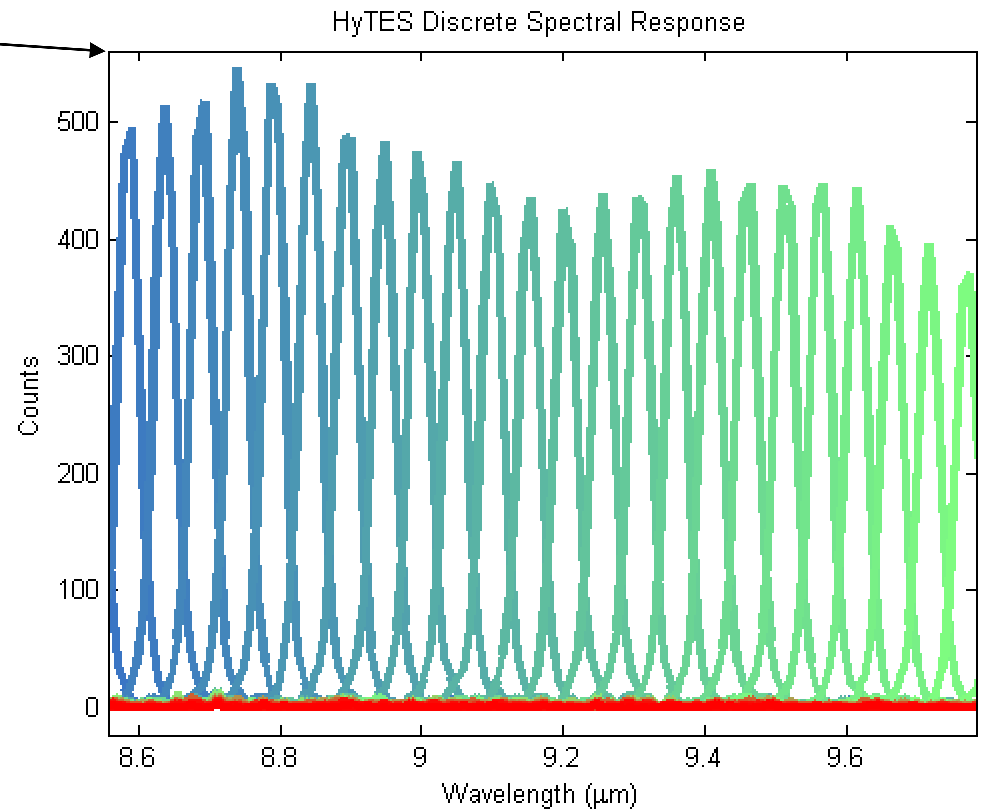

| Actual Temp (C) | Measured Temp (C) | ΔT (C) |
|---|---|---|
| 45 | 45.00 | 0 |
| 40 | 40.01 | 0.0054 |
| 35 | 34.94 | -0.0594 |
| 30 | 29.92 | -0.0769 |
| 25 | 24.95 | -0.05225 |
| 20 | 19.97 | -0.02695 |
| 15 | 14.96 | -0.03695 |
| 10 | 10.00 | 0 |

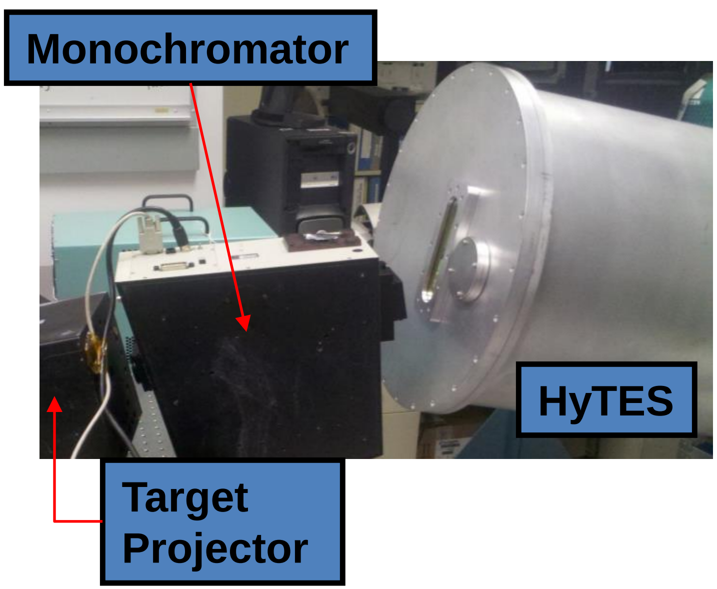
Excellent linearity measured (<+/- 0.1C)

# HyTES Spectral Response



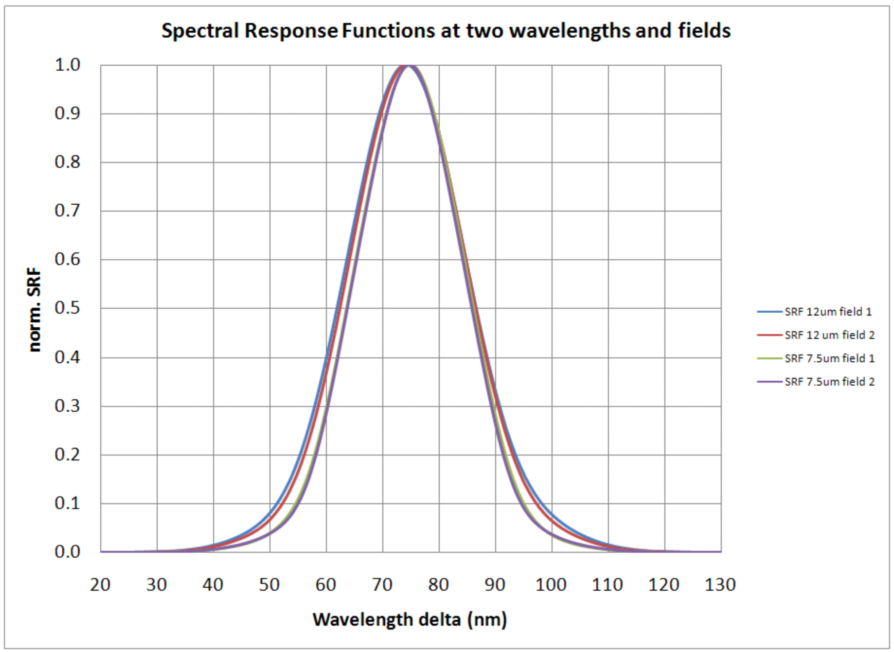

HyTES measured spectral response. A monochromator was cycled through each spectral band while positioned at the entrance aperture.



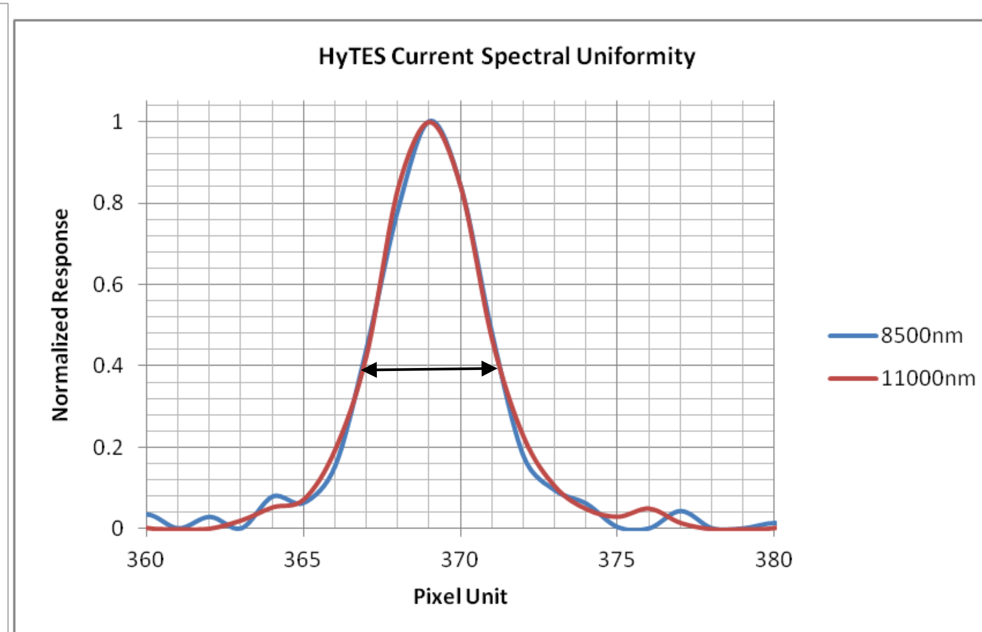



# HyTES Spectral Response

Predicted spectral response




Measured spectral response

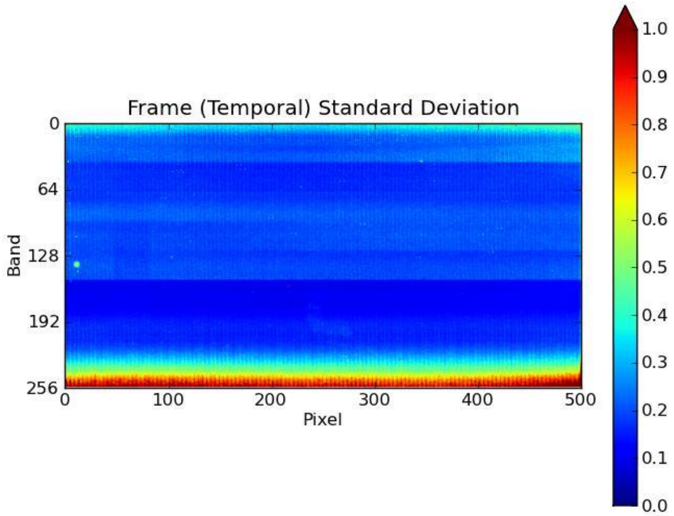


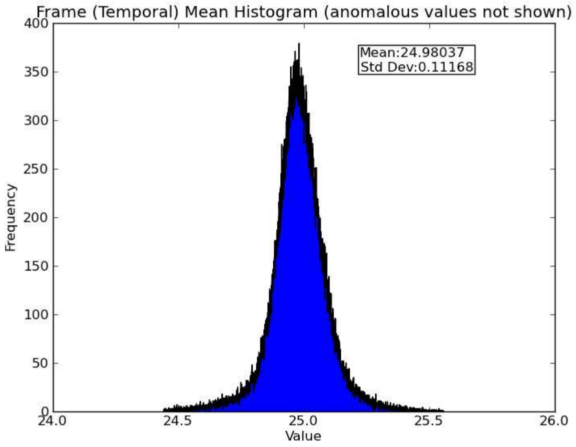

Arrow on measured response shows a FWHM of about 4 pixels (or 2 effective pixels) which is 35.2nm.

# HyTES NEDT

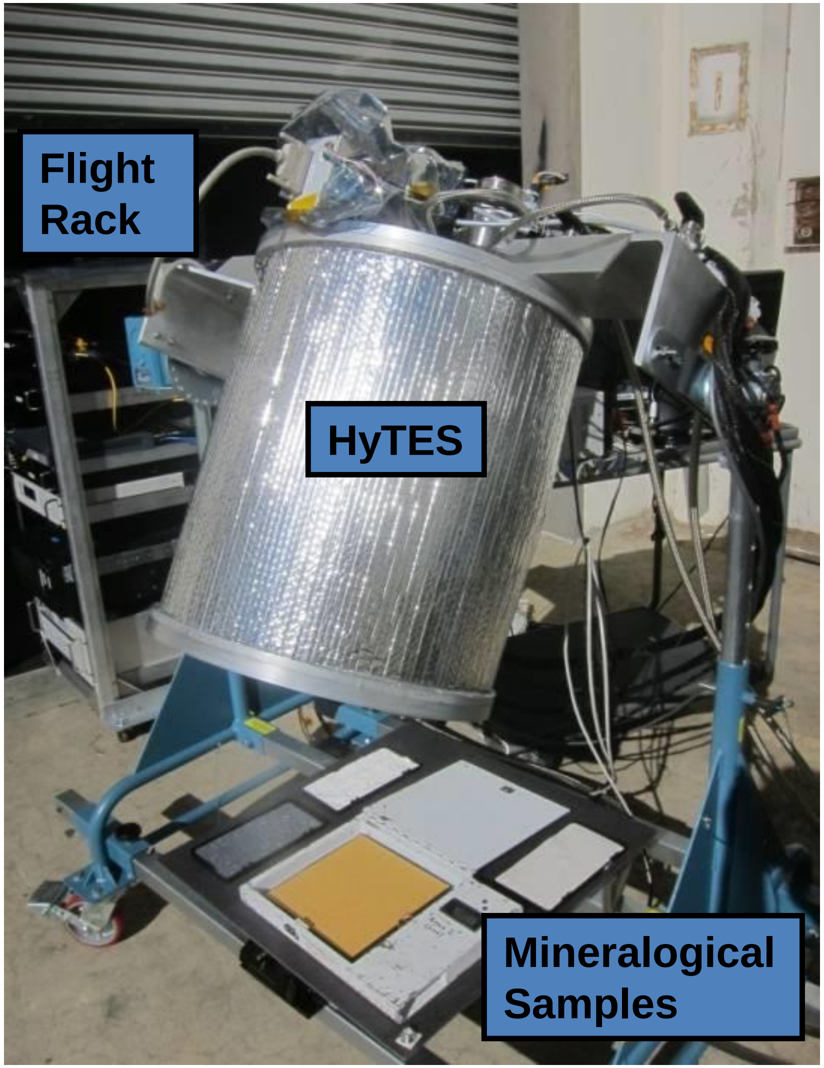
## Alignment 6

- **Brightness Temperature Within 0.5 ° C of 25 ° C (Black-body Set Point)**
- **Sensitivity (NEDT, Modeled as Standard Deviation) Better than 0.2 ° C Between 8.5 – 11.5 µm**
- **Two-Layer QWIP Detector Array**



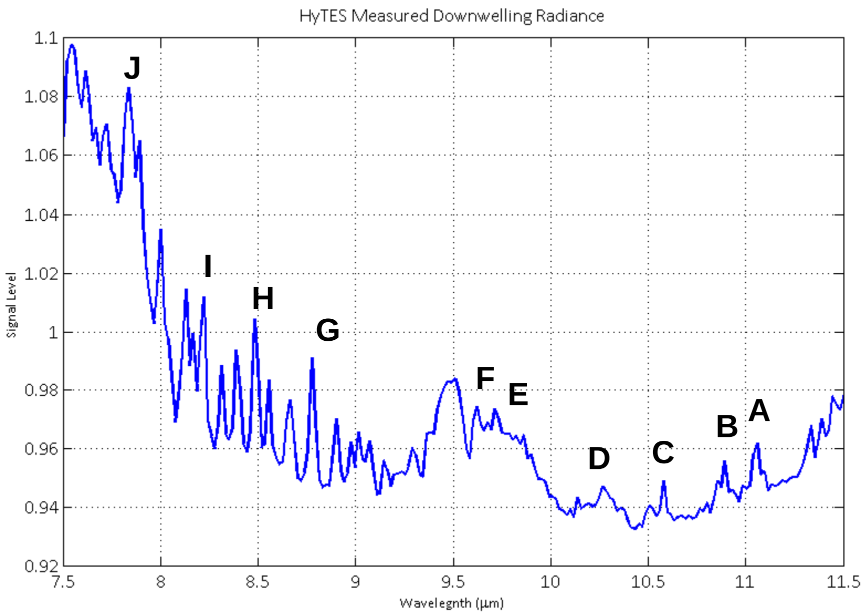
# HyTES Outside Setup

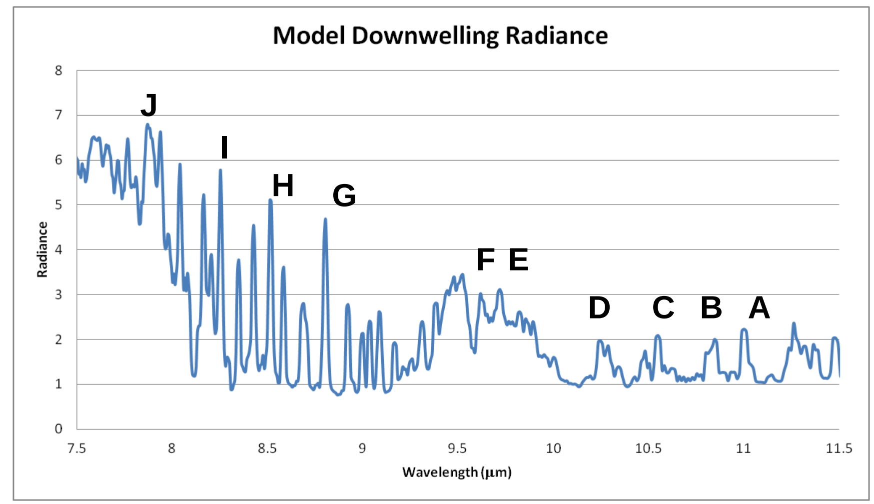



**<u>Test Procedure in Direct Sunlight</u>**

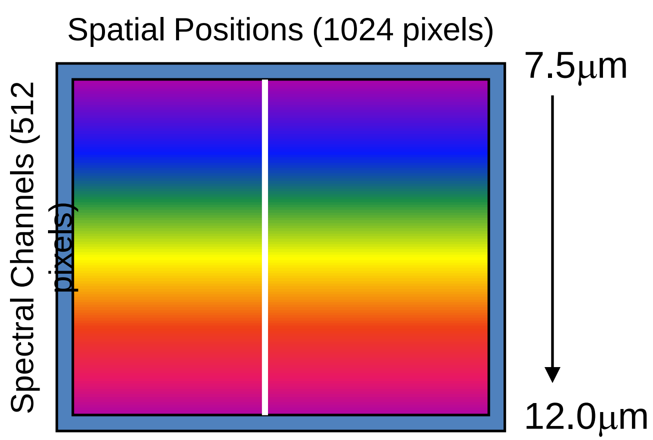
- **Obtain spectral calibration from downwelling radiance using diffuse gold.**
- **Observe mineralogical species: Quartz, Silicon Carbide**

# HyTES Spectral Accuracy



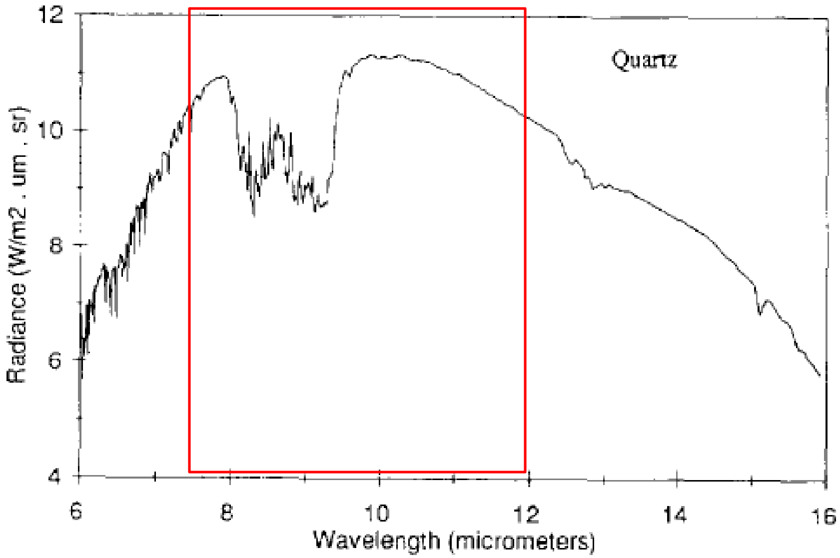



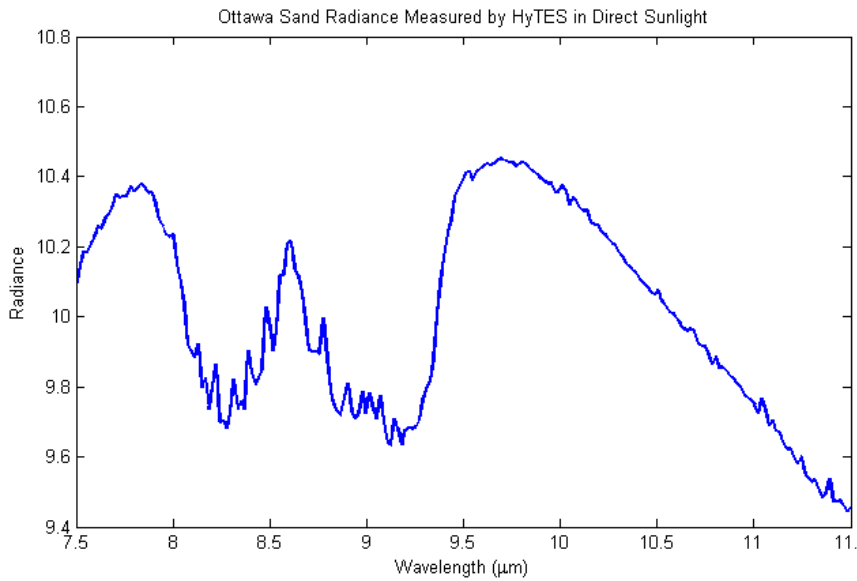

| | Model | HyTES | Δλ |
|---|---|---|---|
| A | 11.0010 | 11.01 | -0.009 |
| B | 10.8460 | 10.853 | -0.007 |
| C | 10.5485 | 10.5404 | 0.0081 |
| D | 10.2459 | 10.237 | 0.0089 |
| E | 9.7180 | 9.7246 | -0.0066 |
| F | 9.6150 | 9.6125 | 0.0025 |
| G | 8.8028 | 8.8051 | -0.0023 |
| H | 8.5106 | 8.5105 | 0.0001 |
| I | 8.2508 | 8.2524 | -0.0016 |
| J | 7.8740 | 7.875 | -0.001 |




HyTES spectral calibration is very good. Wavelength determination for each features is well within one bandwidth.

# HyTES Measured Spectra



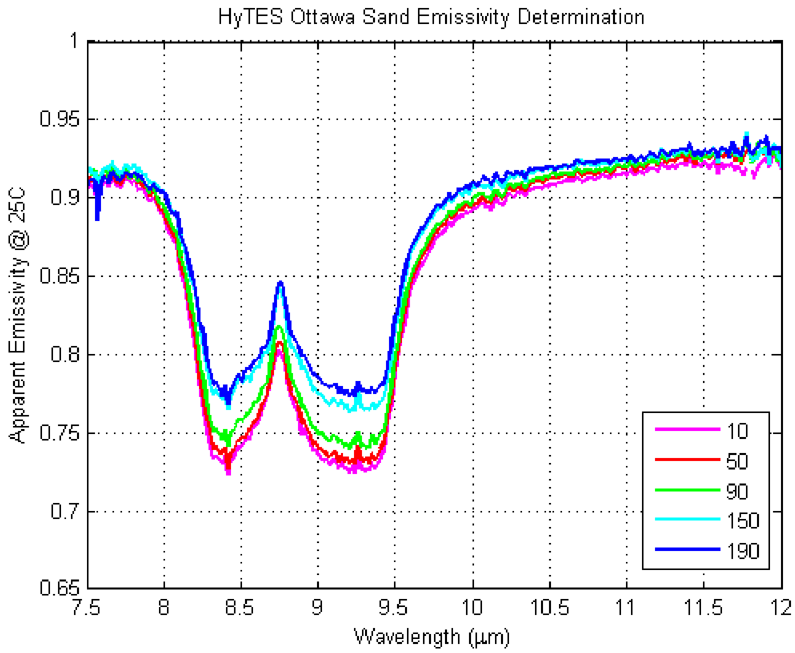



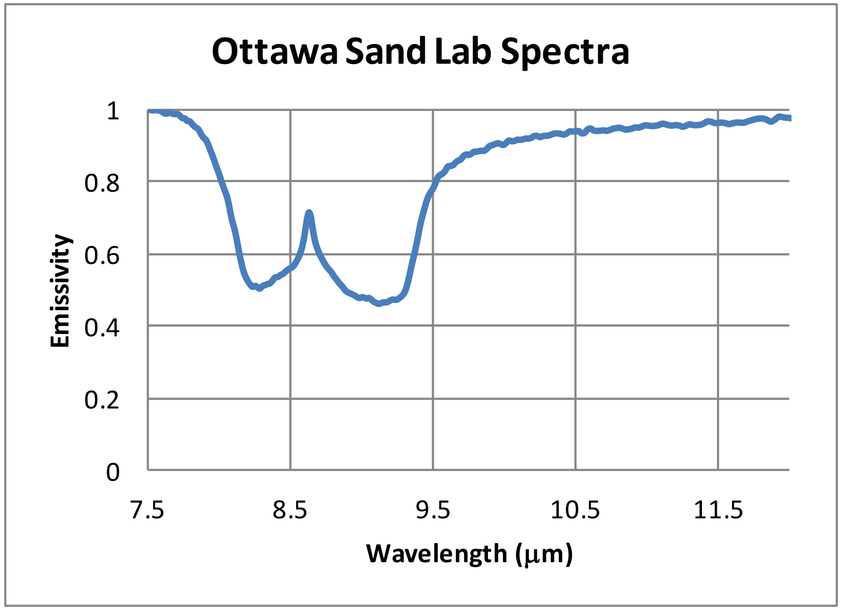

Previously measured field radiance of Quartz (micro-FTIR)

HyTES radiance measurement of Ottawa sand in direct sunlight.

# HyTES Measured Spectra

Similar mineralogical species shown at different spatial locations (same temperature assumed for all spatial samples).

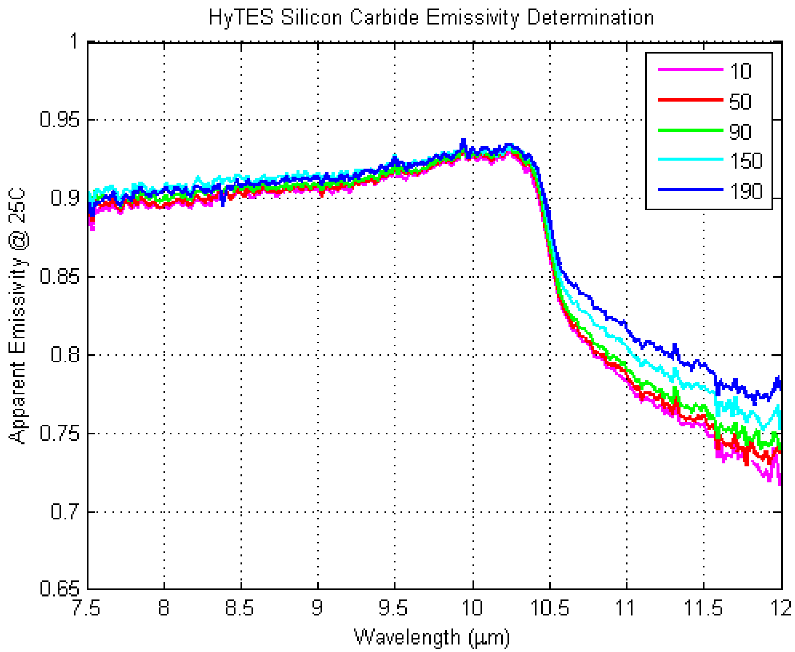


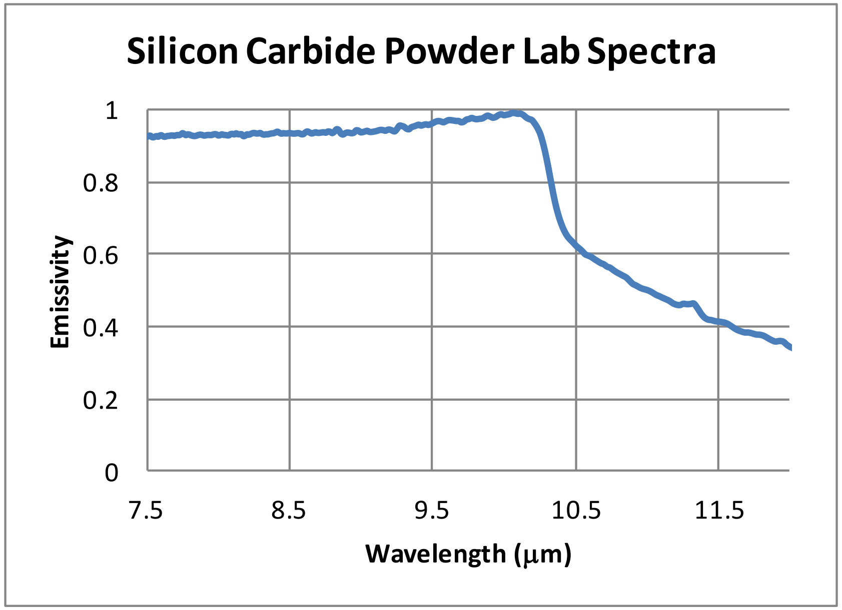




Excellent shape agreement.

# HyTES Measured Spectra

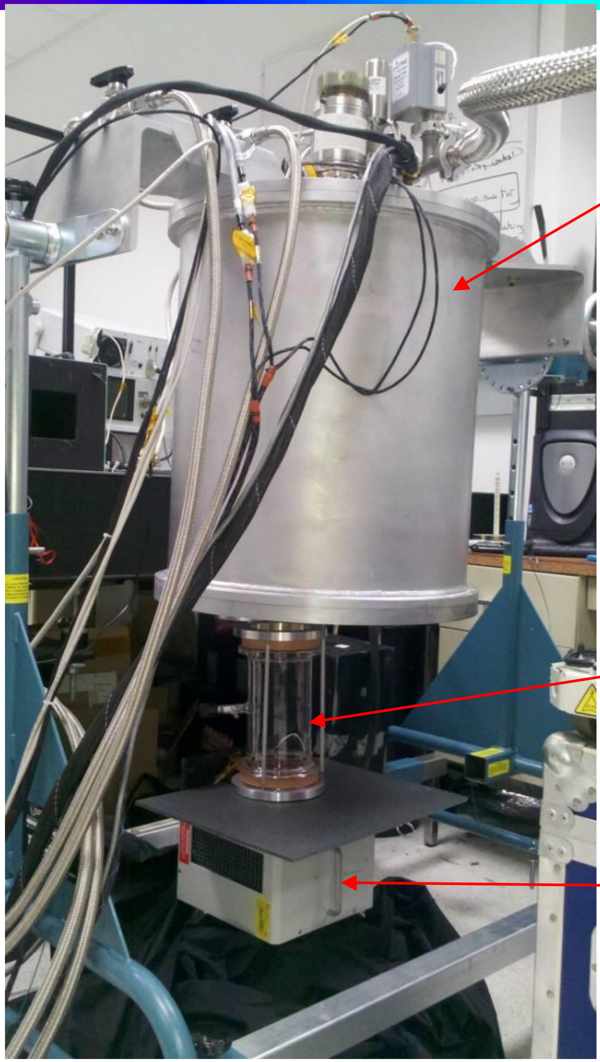
Similar mineralogical species shown at different spatial locations (same temperature assumed for all spatial samples).




Excellent shape agreement.

# HyTES Gas Measurement Set-up



HyTES Scan head

Gas cell housing

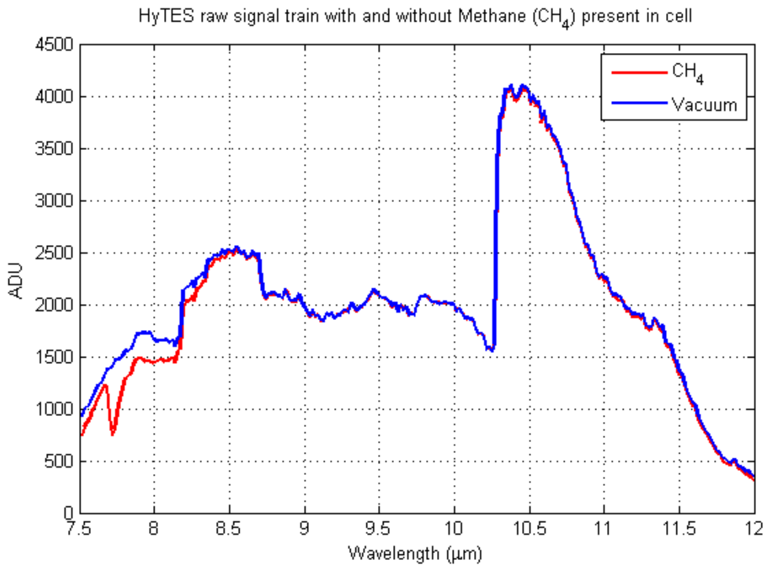
Blackbody transmission source

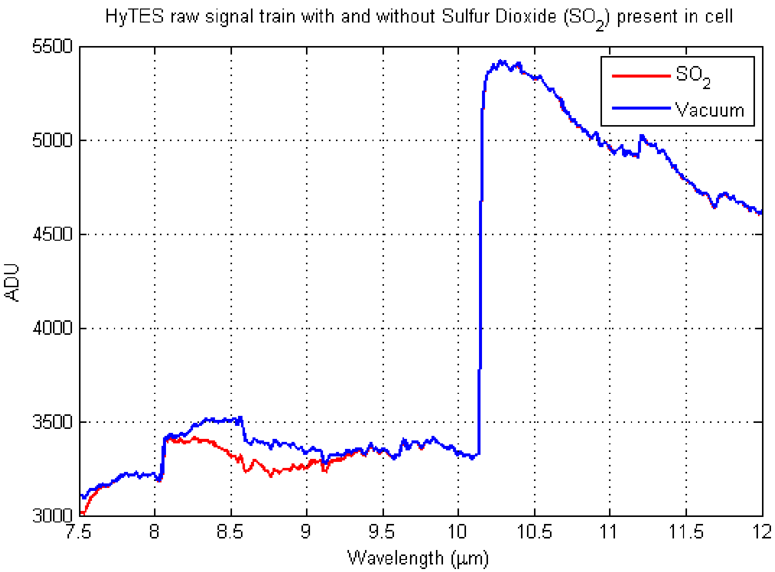
Custom cell housing

- **200mm cell length**
- **ZnSe transmission optics with anti-reflection coatings for maximum transmission.**
- **All gas species are held at 50torr pressure**

# HyTES Gas Measurement

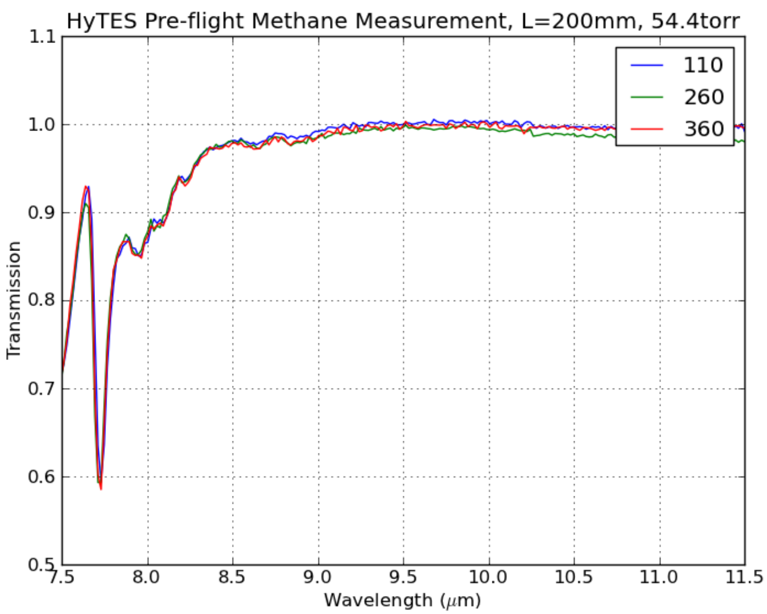
$CH_4$ and $SO_2$ raw signals measured in the field and in the lab before flight.

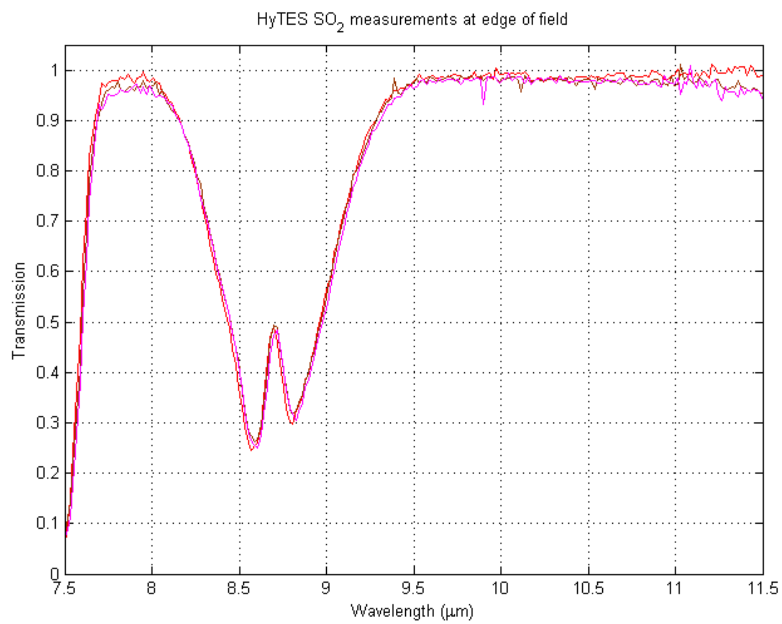


# HyTES Gas Measurement

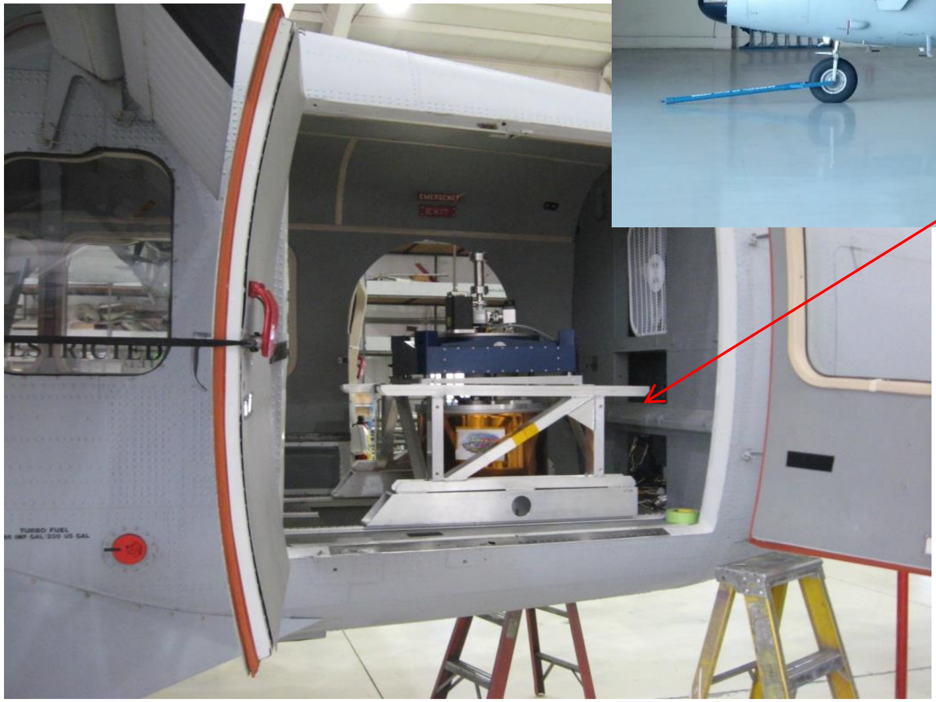
$CH_4$ and $SO_2$ raw signal converted to transmission spectra. Absorption spectra agree with spectra in NIST and PNNL databases



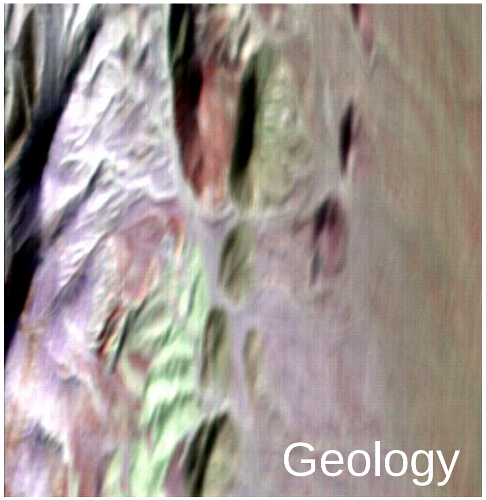
# Twin Otter 300 Series with NADIR View Port


Arriving at Grand Junction

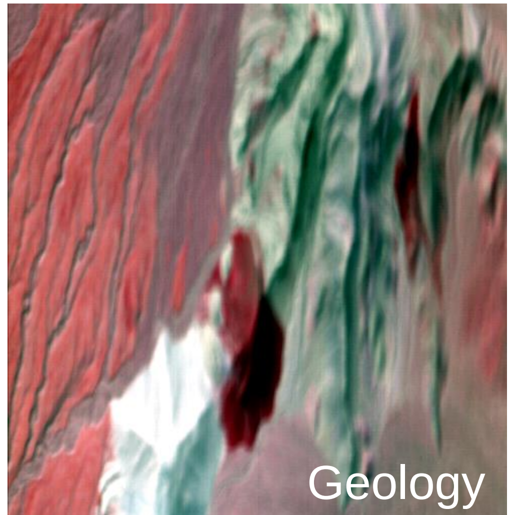



# April 2013 Campaign Snapshots

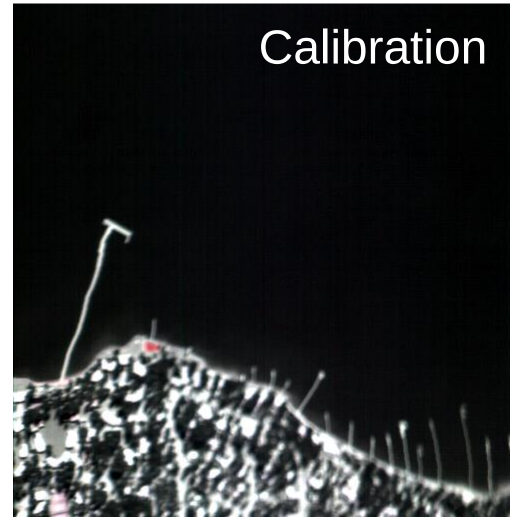
Cuprite, NV




Death Valley, CA

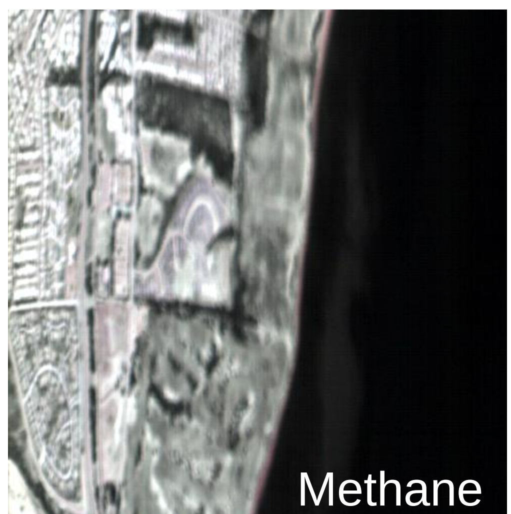



Lake Tahoe, CA/NV

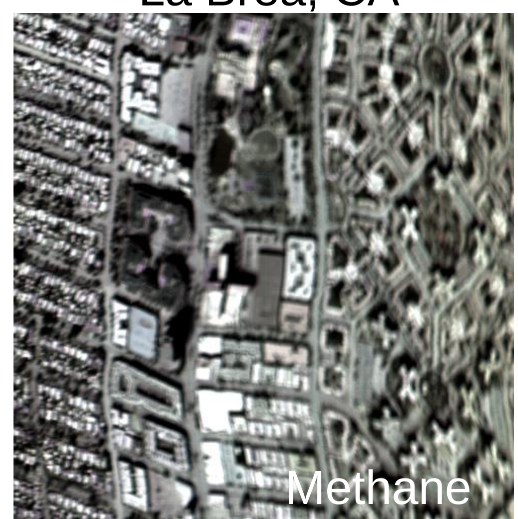



NASA/JPL, CA


Santa Barbara, CA



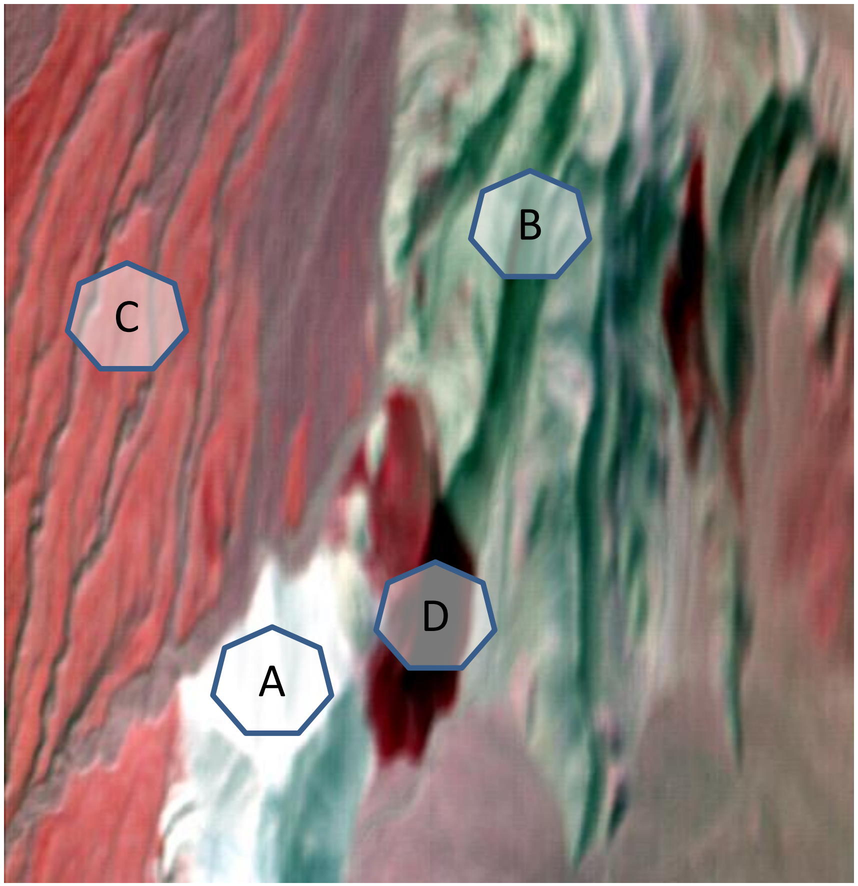

La Brea, CA

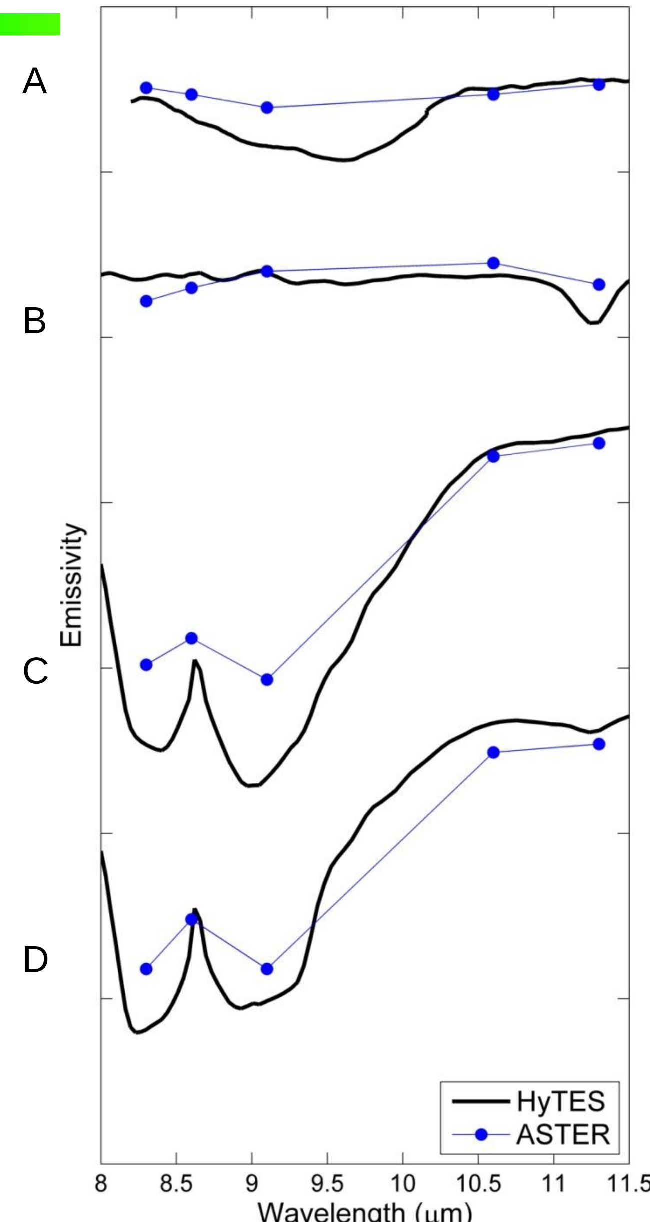



bands 150 (10.08 µm), 100 (9.17 µm), 58 (8.41 µm), 58 displayed at RGB each image is 485 x 512 pixels

# HyTES Spectra: Death Valley, CA

2013-04-24.190040.DeathValley.Line2-Run1-Segment22



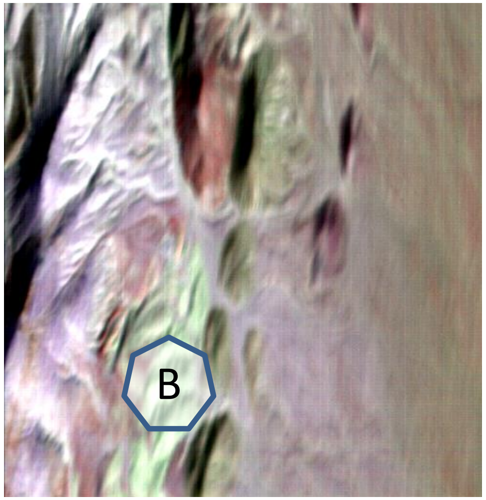




Key:
A – Volcanic (Basalt)
B – Carbonate
C – Quartz alluvial fan
D – Quartzite dome

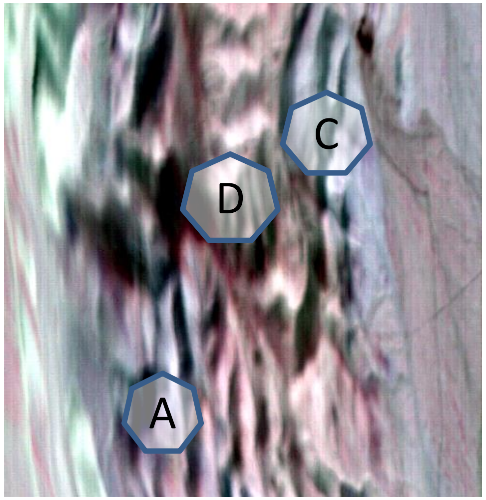
- Single-pixel retrievals
- Atmospheric correction – MODTRAN and NCEP profiles
- Retrieval - Online/Offline

# HyTES Spectra: Cuprite, NV

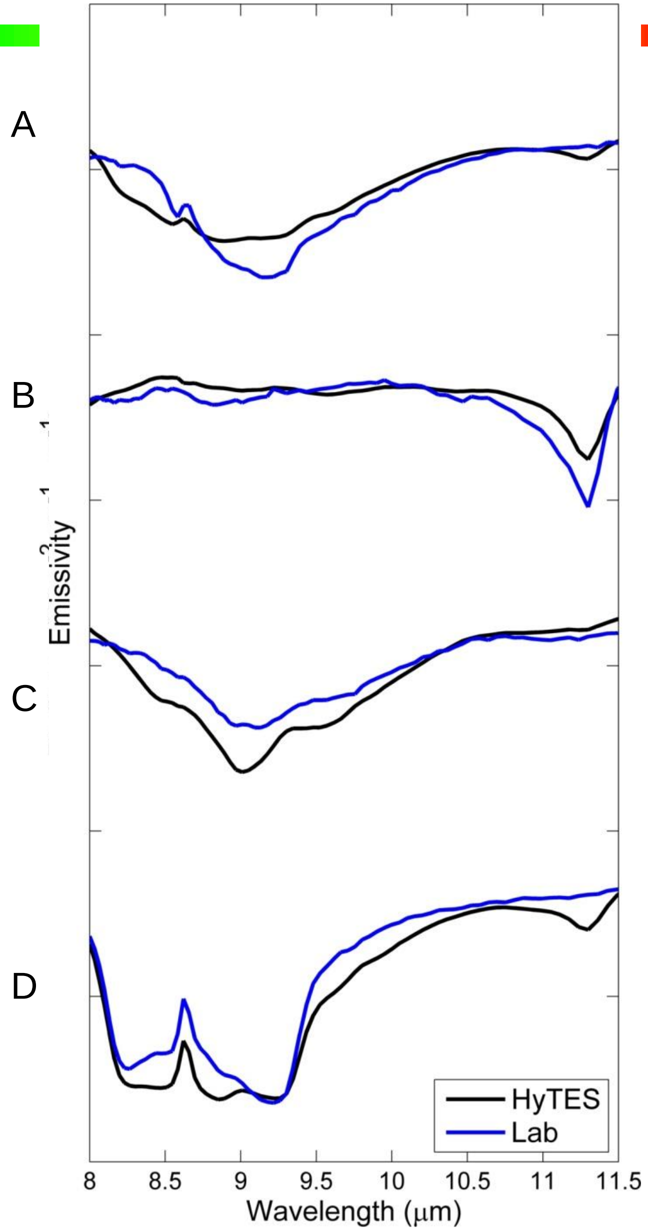
2013-04-24.173326.Cuprite.Line2-Run1




2013-04-24.172629.Cuprite.Line1-Run1




Key:
A – Kaolinite
B – Carbonate
C – Alunite
D – Quartz



# Wrap-Up

- What we talked:
  - Theory, Field Measurements, Airborne Measurements
- What we still need to talk about
  - Atmospheric correction, Temperature-Emissivity separation, Spaceborne measurements, On-orbit calibration and validation, higher level data products (slicia maps, gas maps (e.g. ammonia, methane, fire products, evaptranspiration etc)
- If this was helpful then perhaps I should do a part 2!

- Find out more at:
  - http://hyspiri.jpl.nasa.gov, http://master.jpl.nasa.gov
  - http://hytes.jpl.nasa.gov, http://ecostress.jpl.nasa.gov