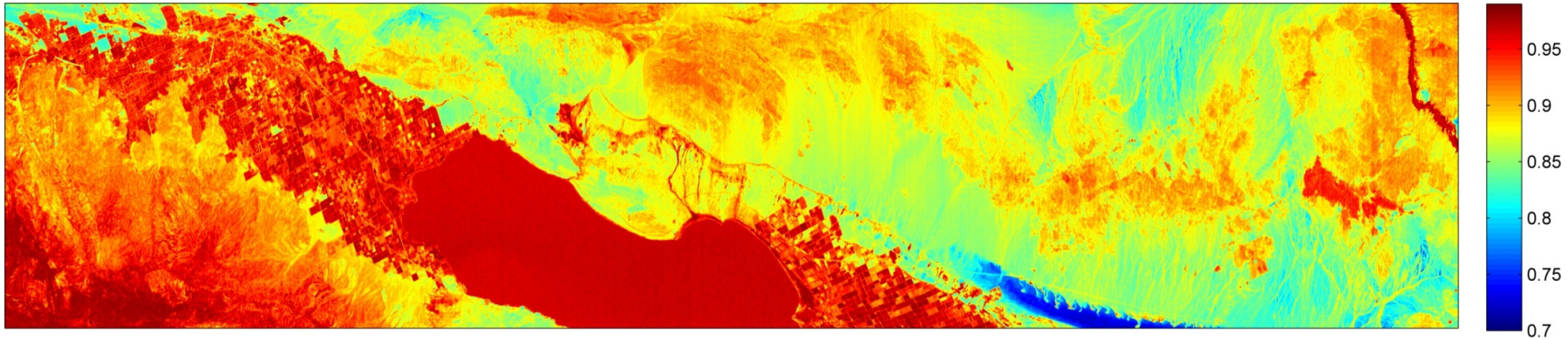
HysplRI-MASTER-HyTES Land Surface Temperature and Emissivity Products and Enhancements



Glynn Hulley, Pierre Guillevic, Nick Vance, Gerardo Rivera, Simon Hook, Robert Radocinski, Shane Grigsby[2], Dar Roberts[2], The HyTES Team

1. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
2. University of California Santa Barbara, CA

(c) 2014 California Institute of Technology. Government sponsorship acknowledged.

Outline

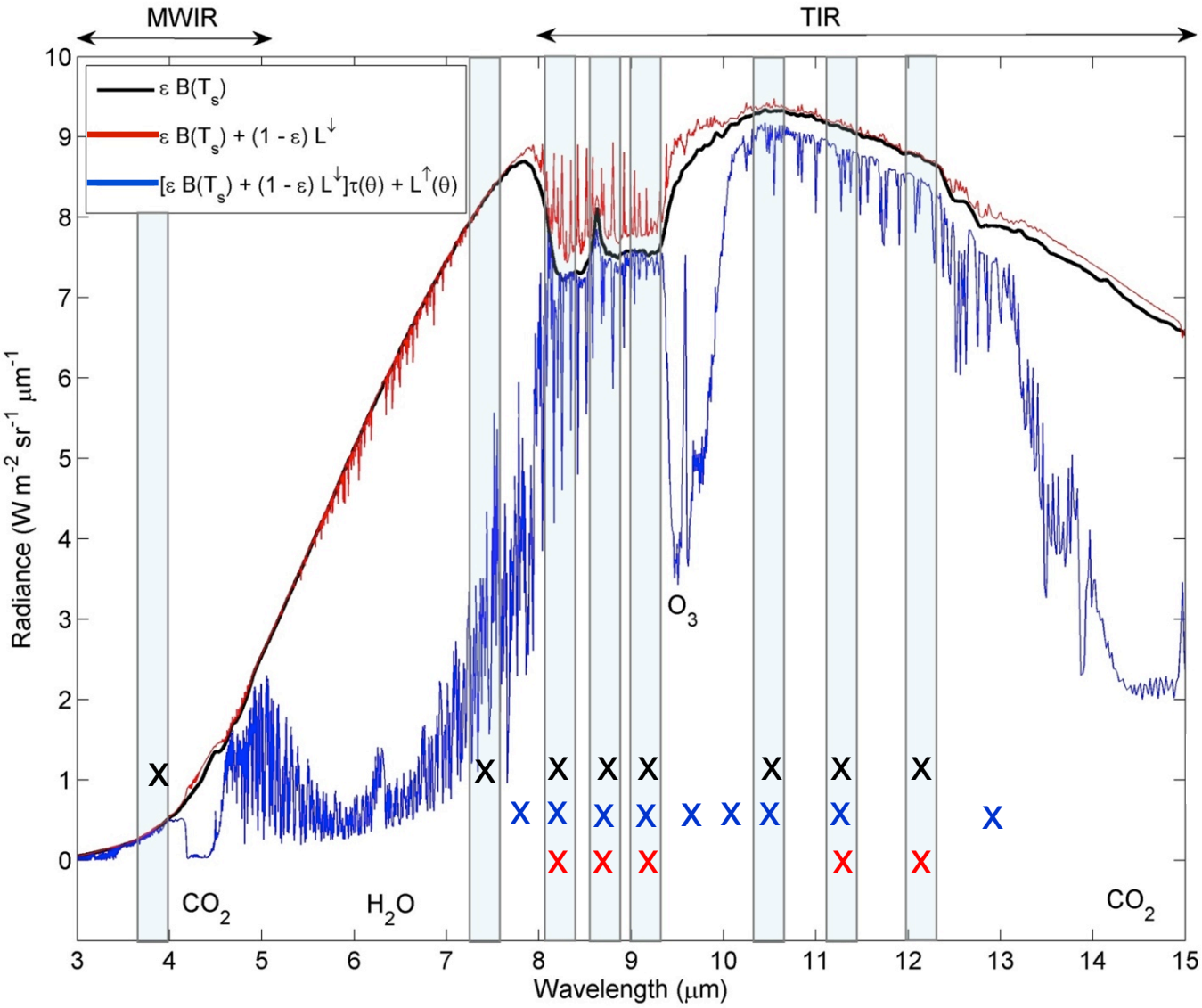
- **HyspIRI** L2 Algorithm and Thermal Infrared (TIR) Physics

- **MASTER** L2 TIR Products
  - Online order/browse tool
  - Examples
  - CalVal
  - AVIRIS synergy

- **HyTES** L2 TIR Products
  - Introduction, goals, objectives
  - Atmospheric Correction Techniques
  - L2 Temperature/Emissivity retrievals

Thermal Infrared Physics

$$L_{sat,\lambda} = \left[\varepsilon_\lambda B_\lambda(LST) + (1 - \varepsilon_\lambda) L^{\downarrow}_{sky,\lambda}\right] \tau_\lambda + L^{\uparrow}_{sky,\lambda}$$

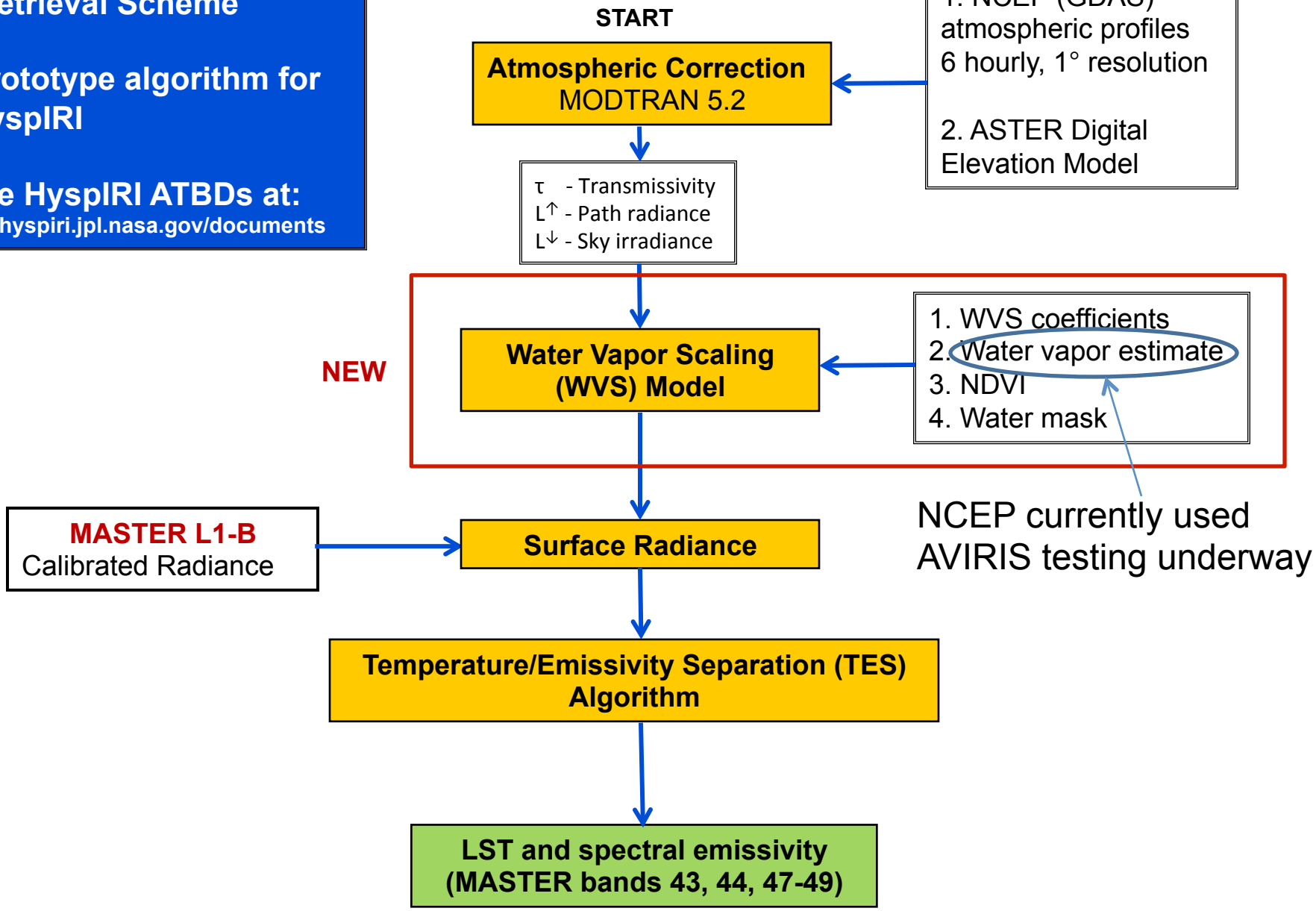


HyspIRI (nominal)

MASTER

ECOSTRESS

- **MASTER Land Surface Temperature/Emissivity Retrieval Scheme**
- **Prototype algorithm for HysplRI**
- **See HysplRI ATBDs at:** http://hyspiri.jpl.nasa.gov/documents

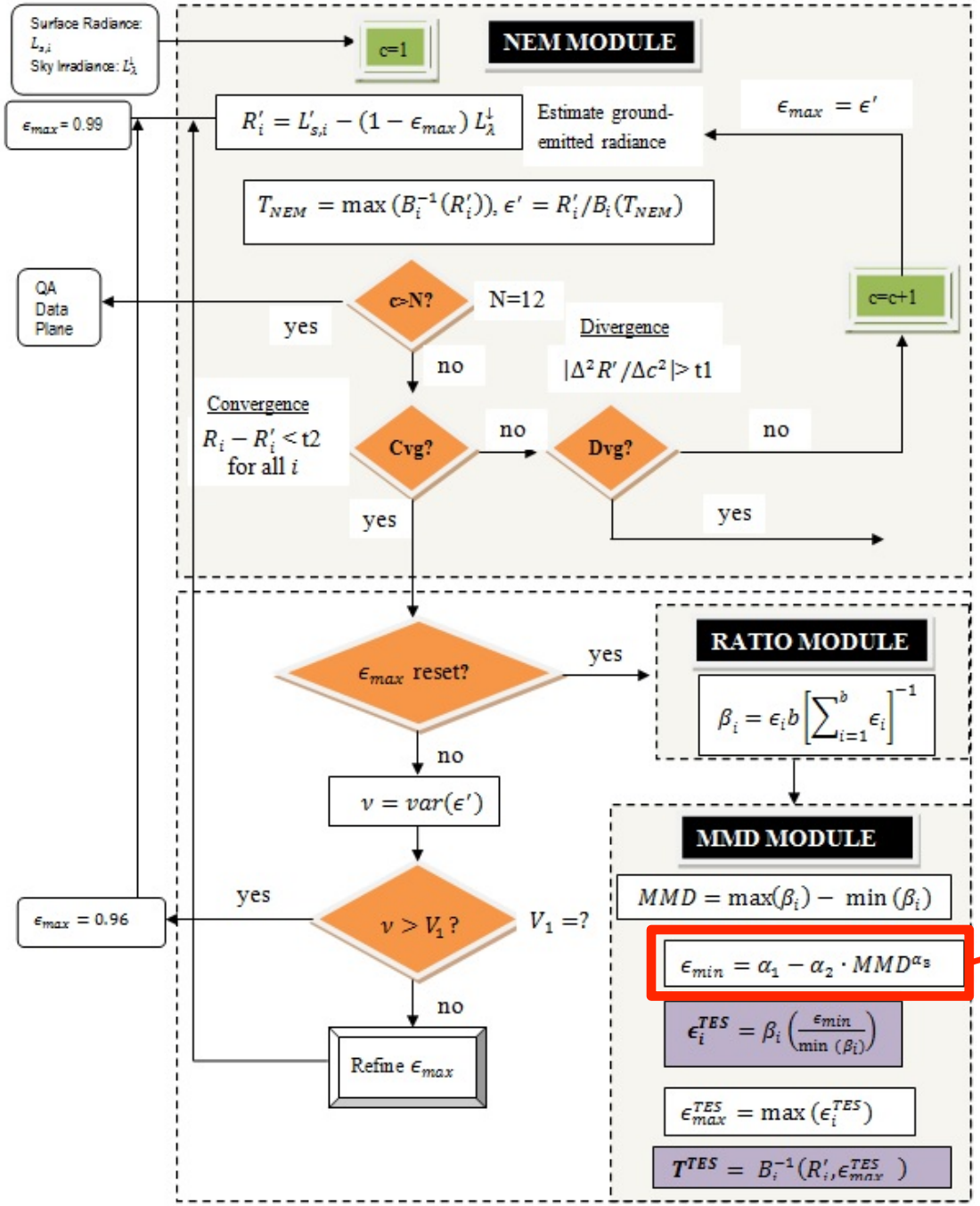


TES Algorithm

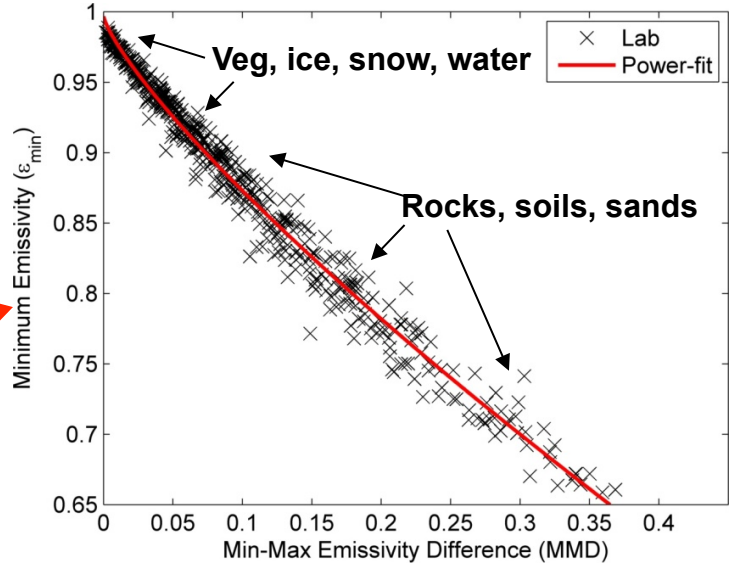
(Gillepsie et al. 1998)

LST&E Products using TES:

- ASTER 05/08
- MOD21 C6
- ASTER GED
- MASTER
- HyTES
- ECOSTRESS* (planned)
- VIIRS* (planned)



$$\varepsilon_{\min} = 0.994 - 0.687 \cdot MMD^{0.737}$$

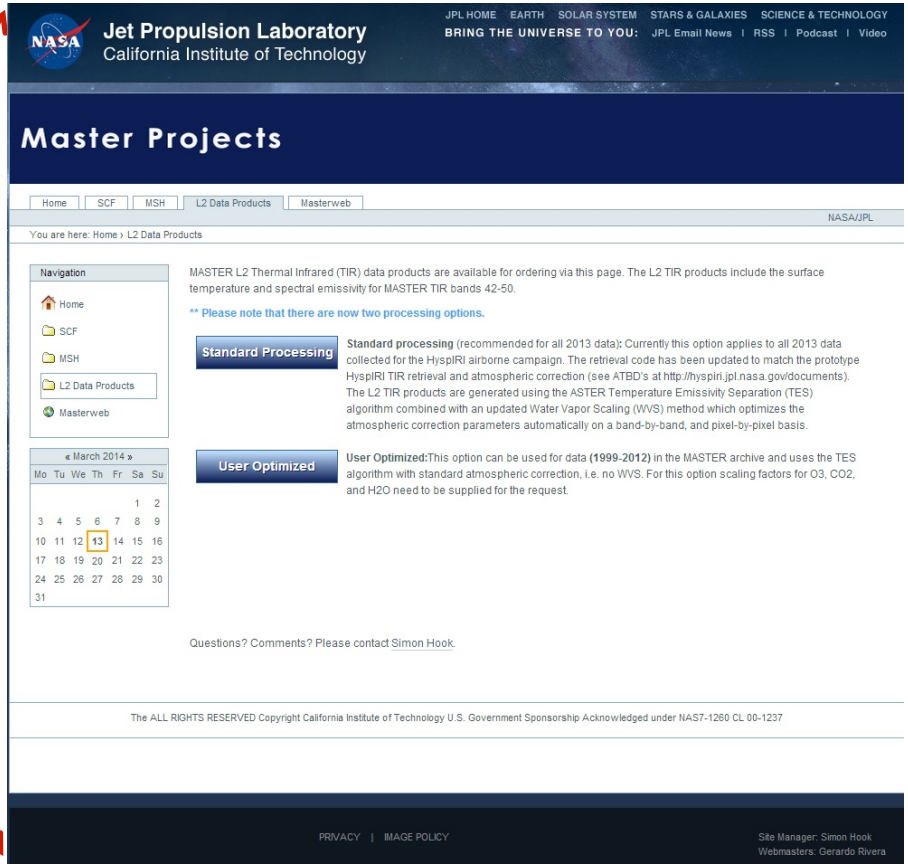


MASTER L2 Data Online Ordering

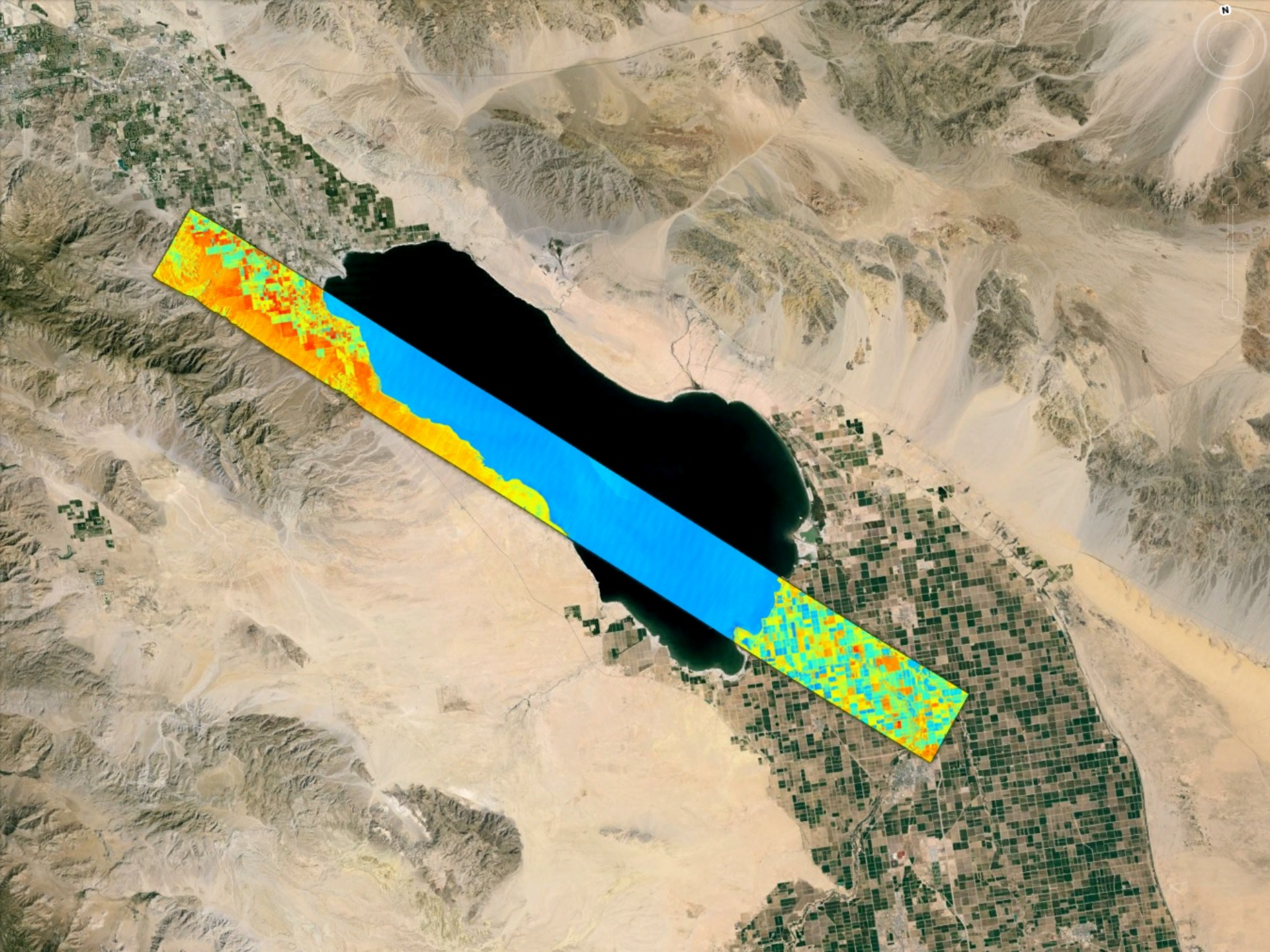
http://master.jpl.nasa.gov



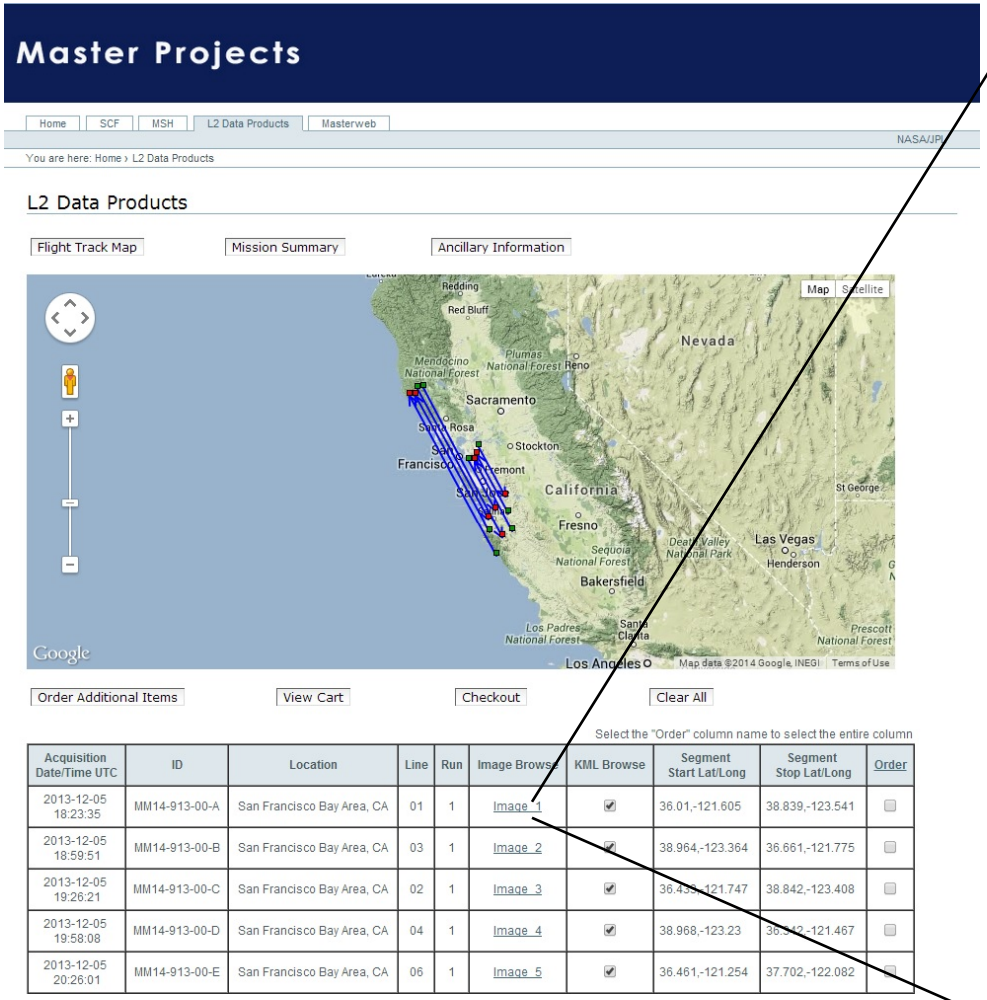
http://masterprojects.jpl.nasa.gov/L2_Products



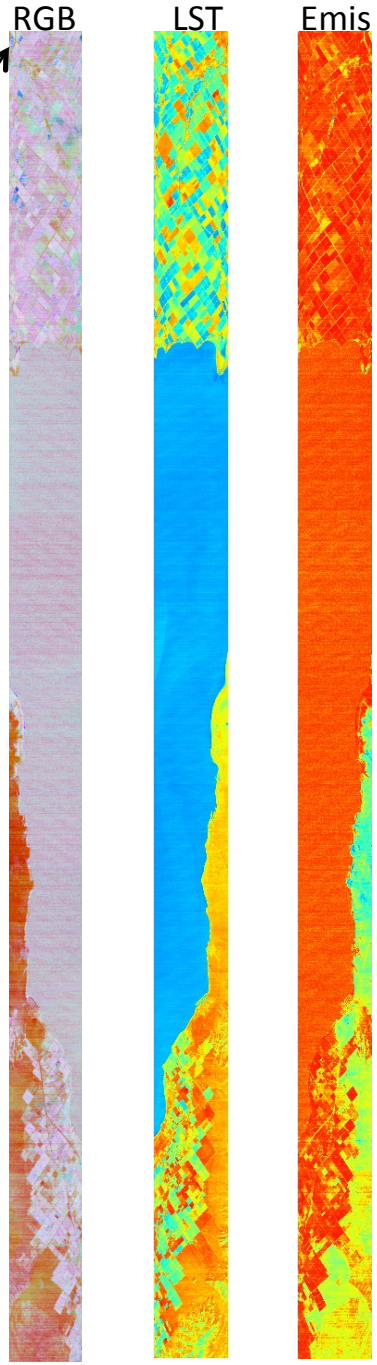
1. Standard (HysplRI): Post-2013 MASTER L2 data retrieved with TES+WVS code
2. User Optimized: Pre-2013 data using TES – optimization necessary (H2O, O3)



MASTER L2 Browse Images



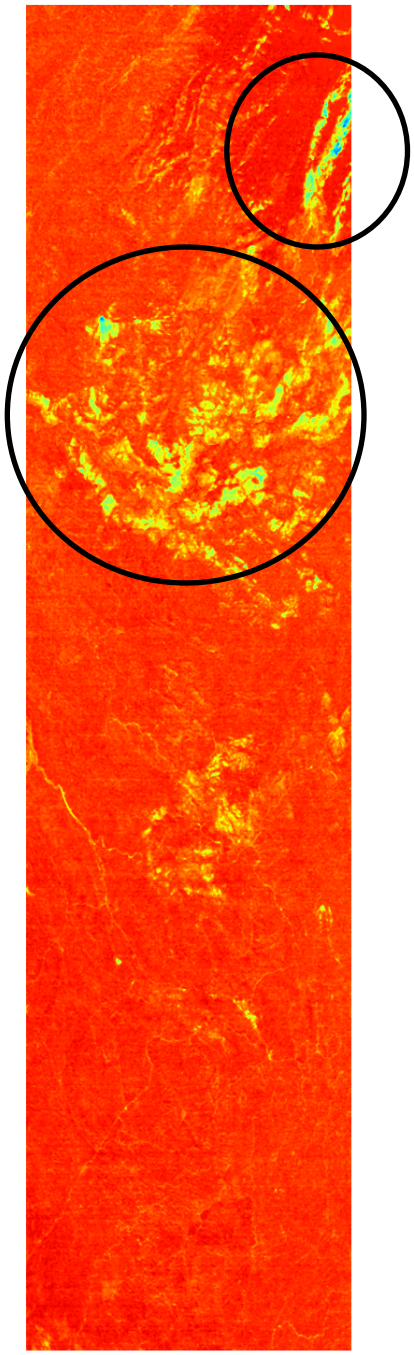
Acquisition Date/Time UTC	ID	Location	Line	Run	Image Browse	KML Browse	Segment Start Lat/Long	Segment Stop Lat/Long	Order
2013-12-05 18:23:35	MM14-913-00-A	San Francisco Bay Area, CA	01	1	Image_1	☑	36.01,-121.605	38.839,-123.541	☐
2013-12-05 18:59:51	MM14-913-00-B	San Francisco Bay Area, CA	03	1	Image_2	☑	38.964,-123.364	36.661,-121.775	☐
2013-12-05 19:26:21	MM14-913-00-C	San Francisco Bay Area, CA	02	1	Image_3	☑	36.453,-121.747	38.842,-123.408	☐
2013-12-05 19:58:08	MM14-913-00-D	San Francisco Bay Area, CA	04	1	Image_4	☑	38.968,-123.23	36.542,-121.467	☐
2013-12-05 20:26:01	MM14-913-00-E	San Francisco Bay Area, CA	06	1	Image_5	☑	36.461,-121.254	37.702,-122.082	☐

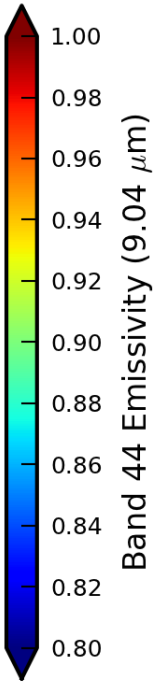


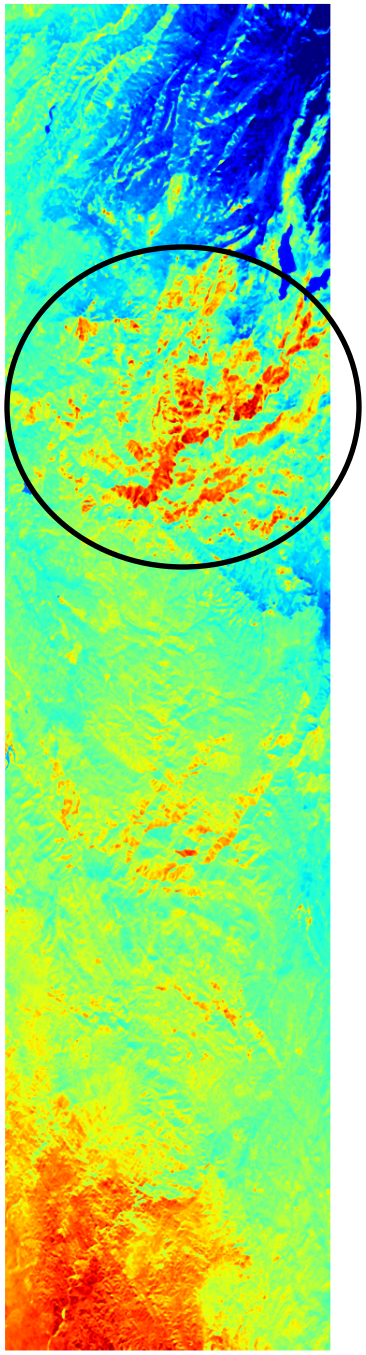


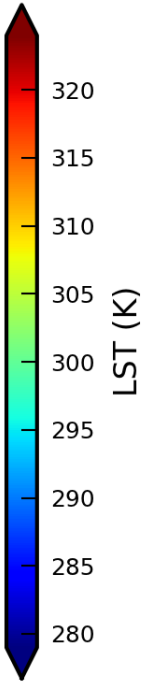
GiffingTool.com

Rim Fire Burn Scar/Yosemite
2014/04/07

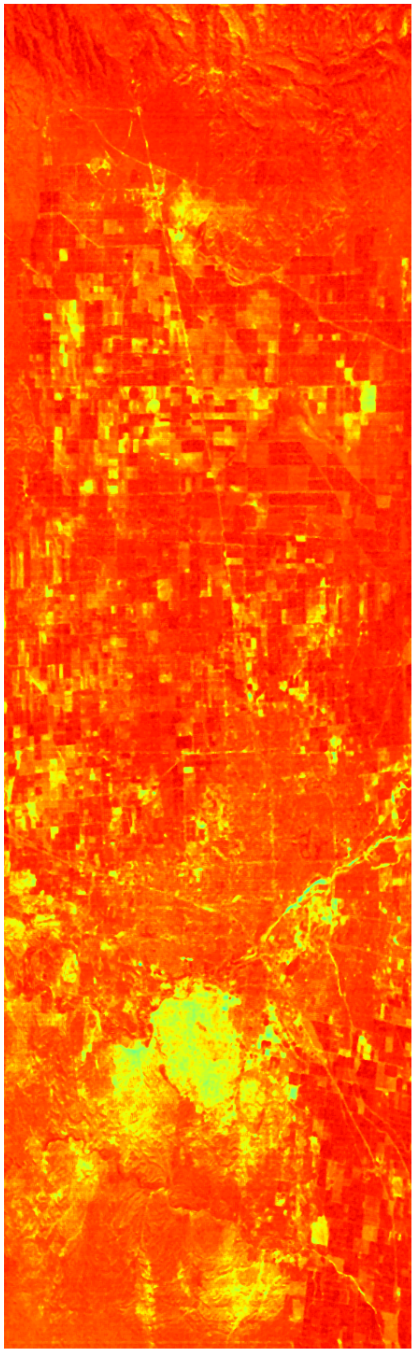


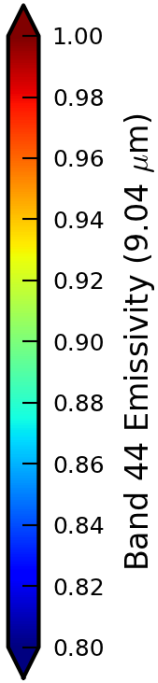


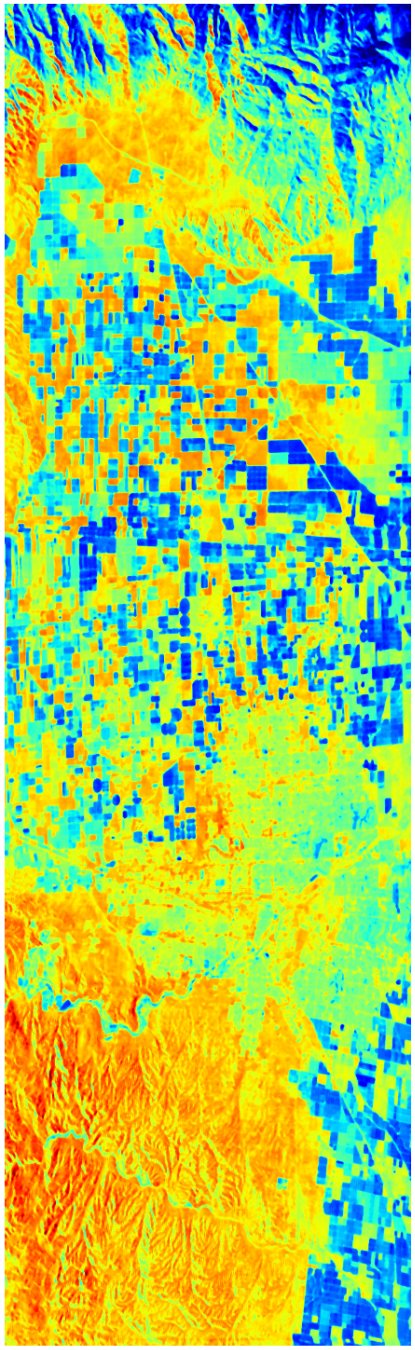


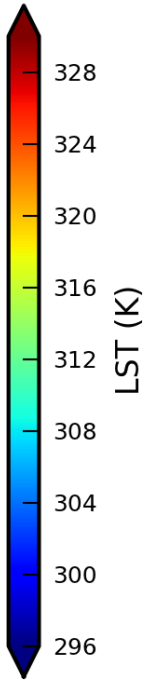


Central Valley 2014/08/26



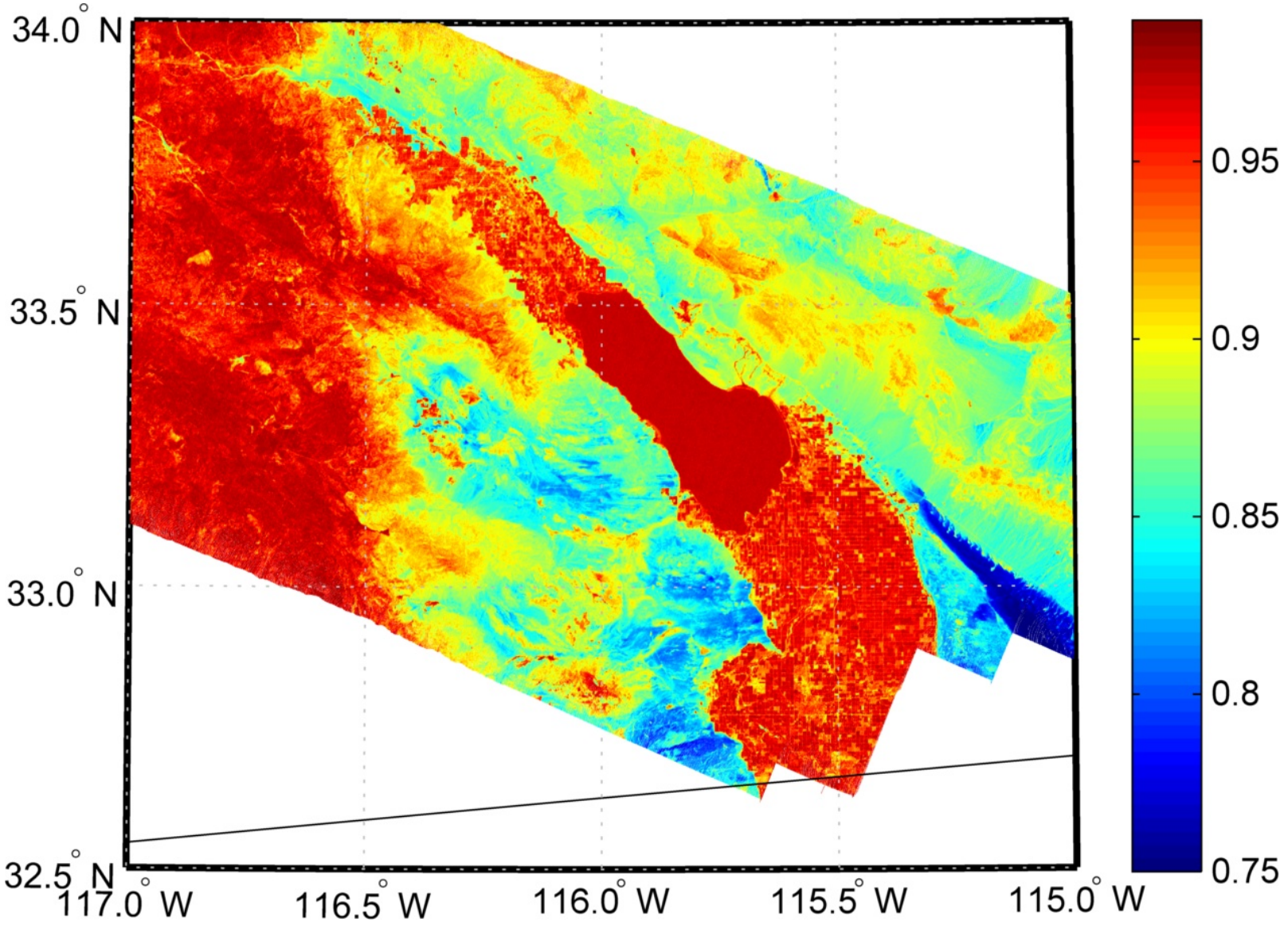






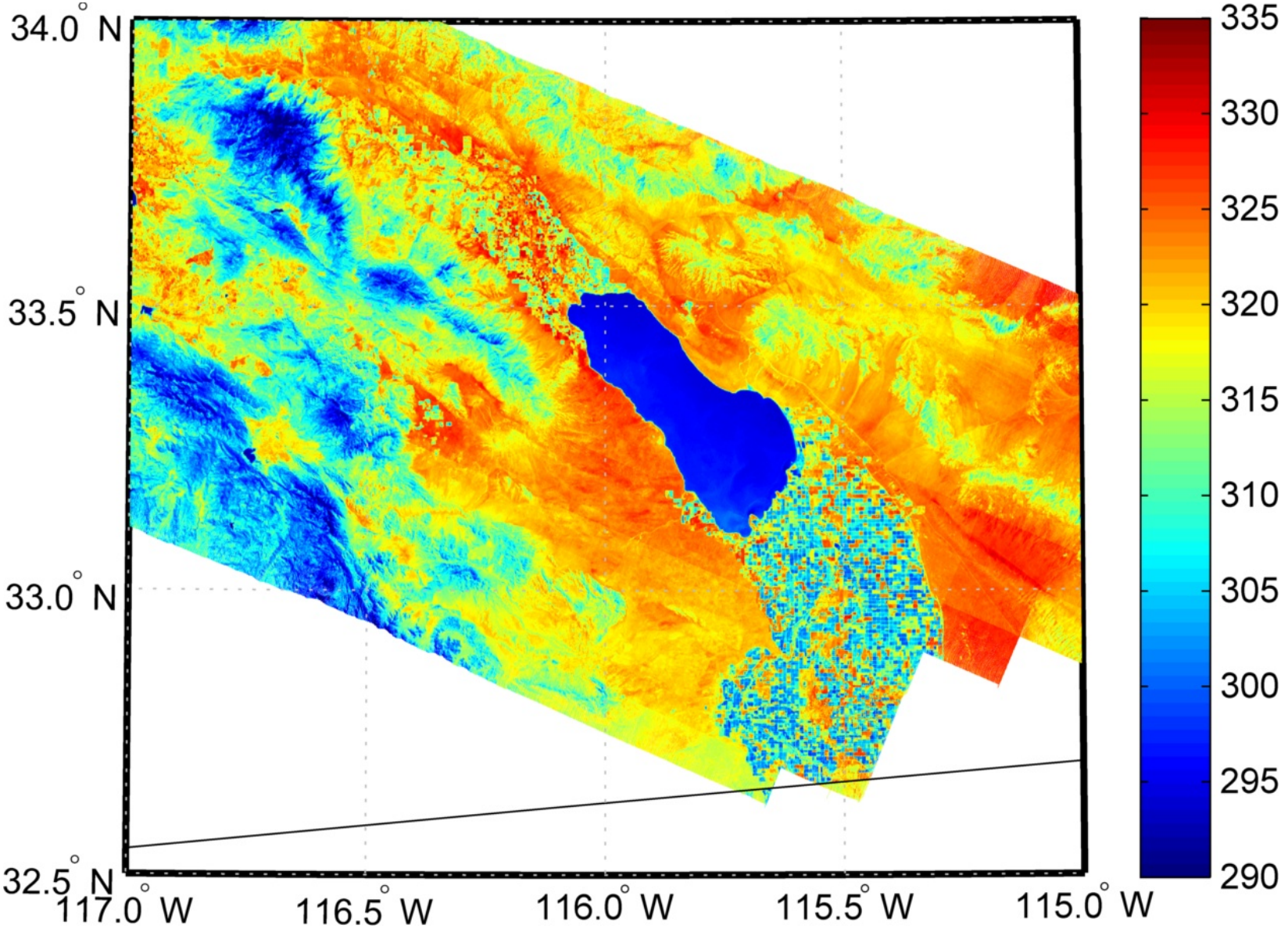
MASTER Emissivity Mosaic at ~60 m (HyspIRI)

(Available on request)



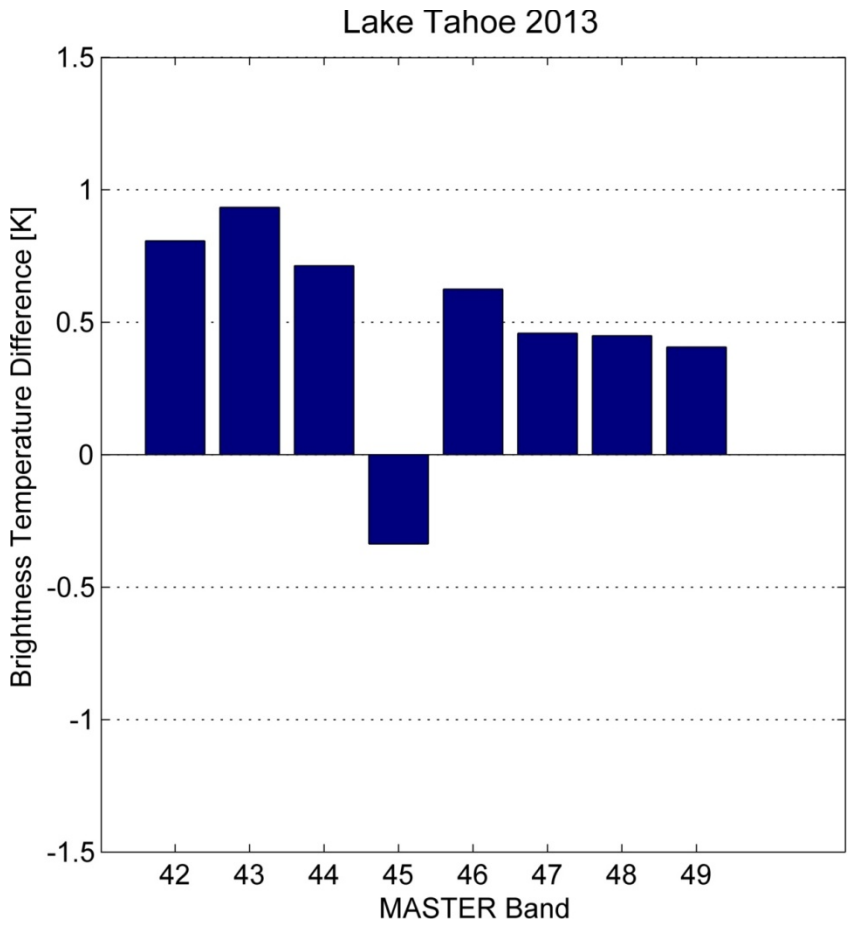
MASTER LST Mosaic at ~60 m (HyspIRI)

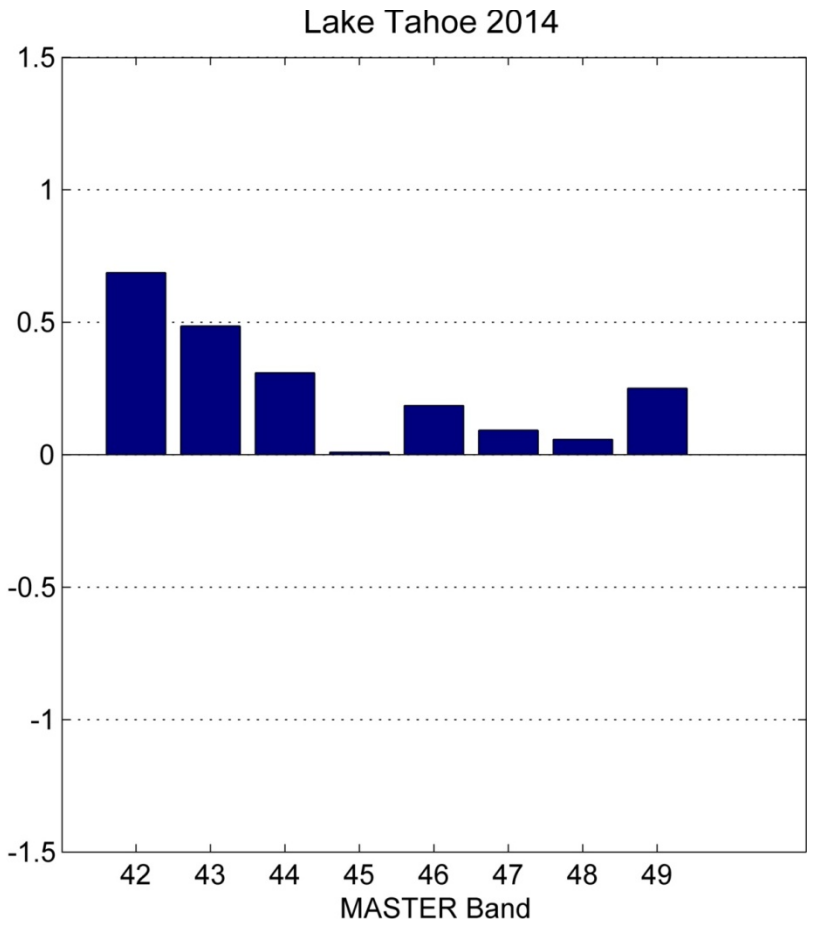
(Available on request)





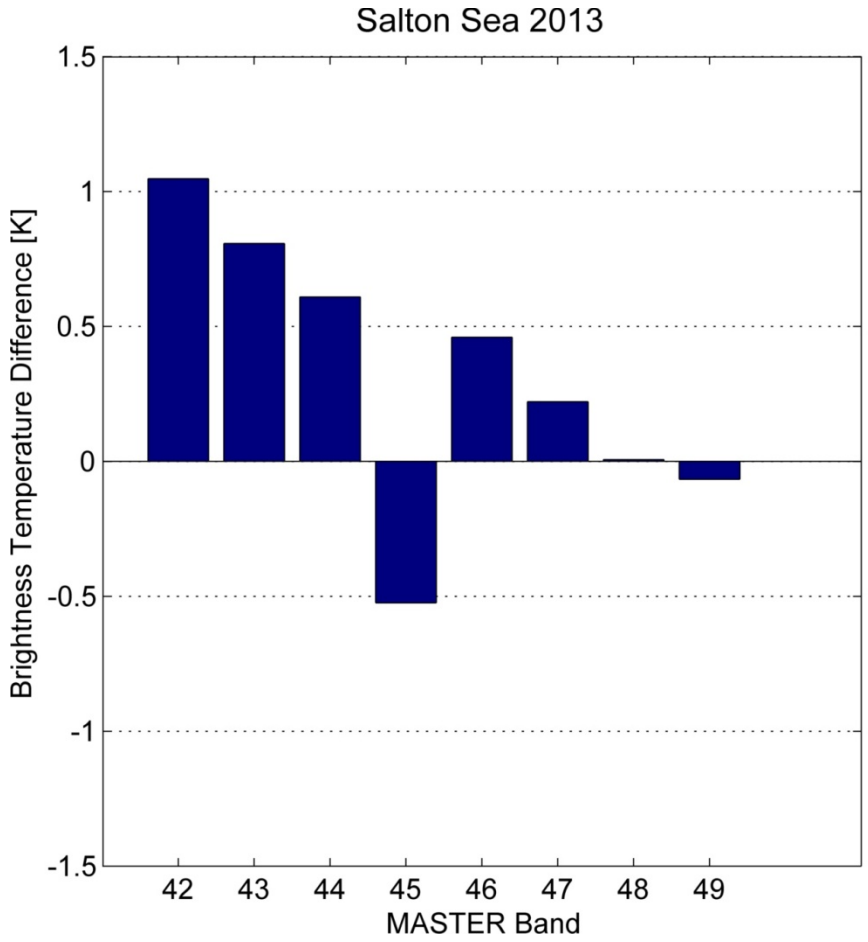
Lake Tahoe Calibration

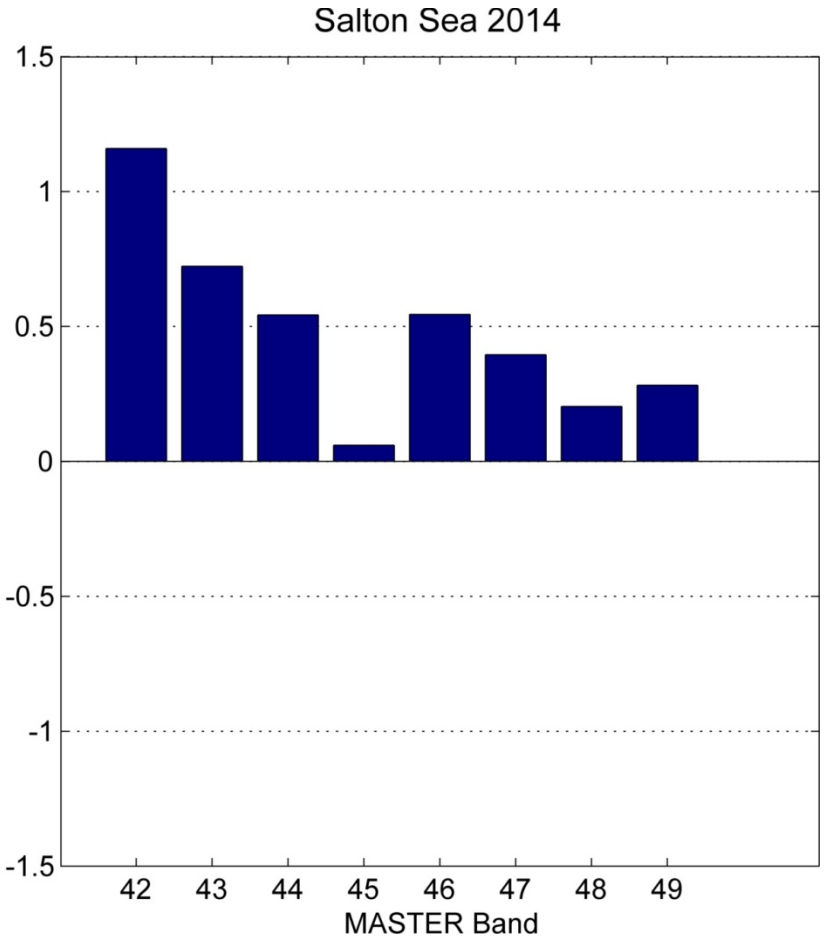




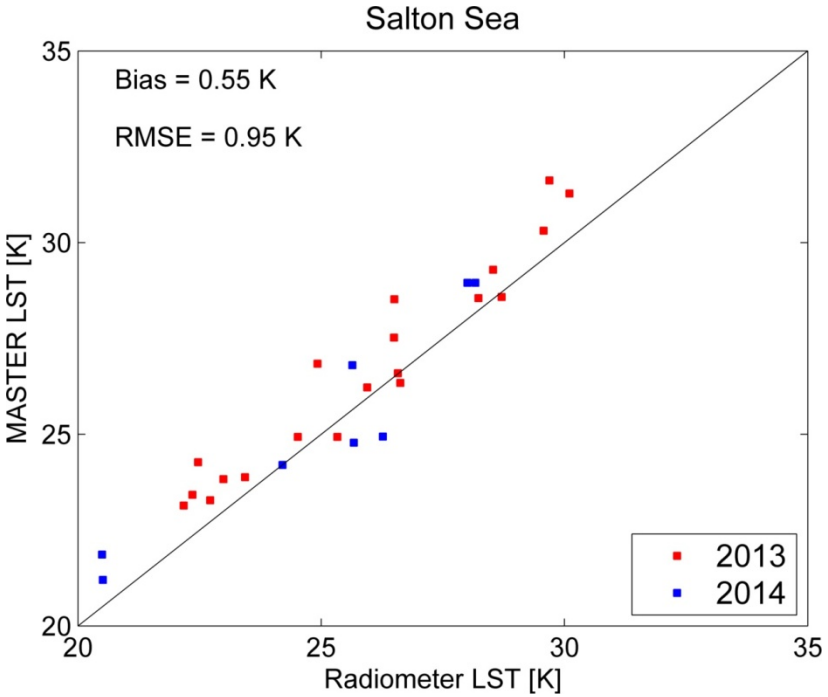


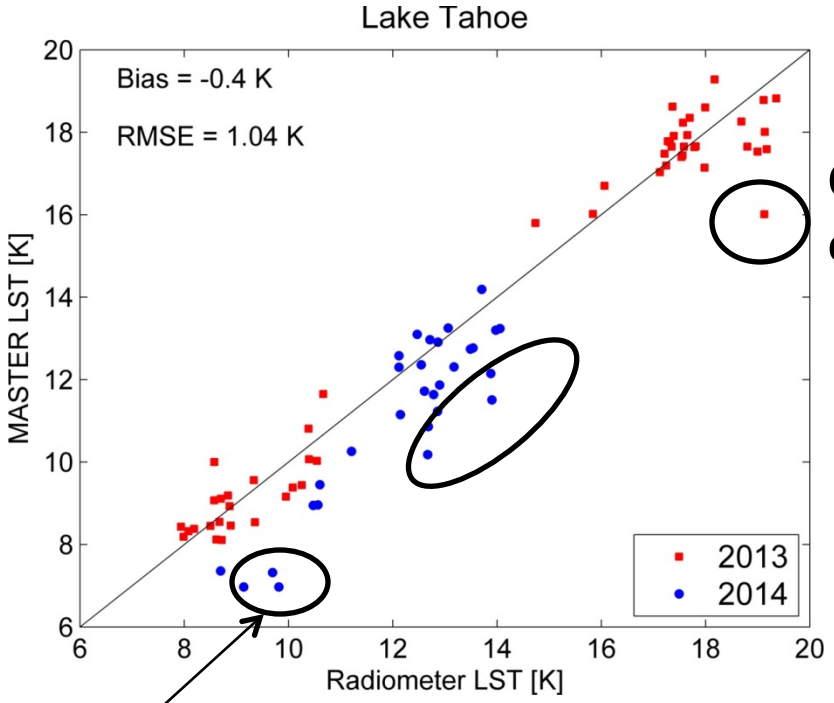
Salton Sea Calibration





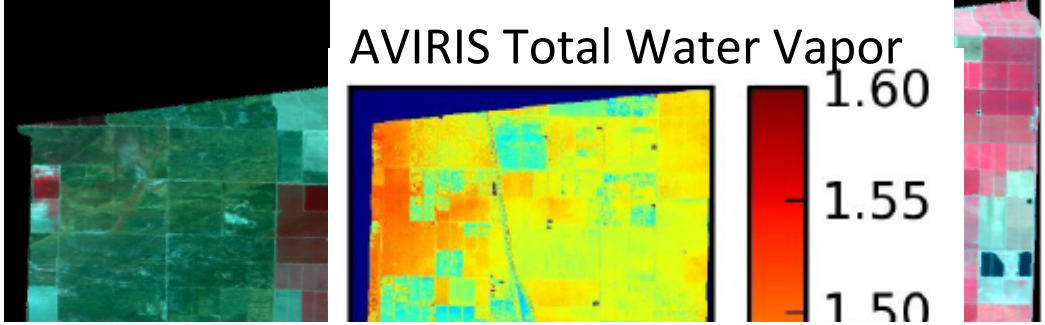
LST Validation





Cloud edge

Sensor view angle>30°
(WVS model optimized from 0-30°)



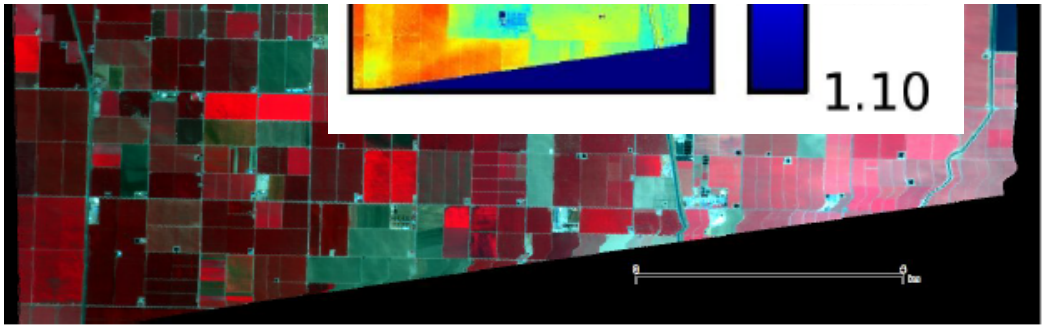
MASTER/AVIRIS Synergy Study

Delano Vinevards. CA

Improved surface temperature estimates with MASTER / AVIRIS sensor fusion

Shane P. Grigsby[a,*], Glynn C. Hulley[b], Dar A. Roberts[a], Christopher Scheele[c], Susan L. Ustin[d], Maria Mar Alsina[d]

[a] *Department of Geography, University of California Santa Barbara, CA, 93106*
[b] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109*
[c] *Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, WI, 53706*
[d] *Dept. of Land, Air and Water Resources, University of California Davis, CA, 95616*



MASTER LST validation with ground measurements (LiCor)

Grigsby et al. 2014 (RSE submission)

JPL (HyspIRI standard)

JPL (HyspIRI Planned)

Vine	Obs	LST Error [K]		
		TES (NCEP)	TES + WVS (NCEP)	TES + WVS (AVIRIS)
48	3	-3.24	-1.14	-0.51
21	2	-1.67	-0.24	-0.07
25	2	-1.56	0.29	0.45
13	1	-1.20	0.19	0.41
16	1	-3.19	-1.47	-1.40
10	2	-2.86	-0.41	-0.16
8	2	-2.14	-0.19	-0.07
1	1	-1.54	-0.05	0.07
RMSE		2.41 K	0.70 K	0.49 K ☆

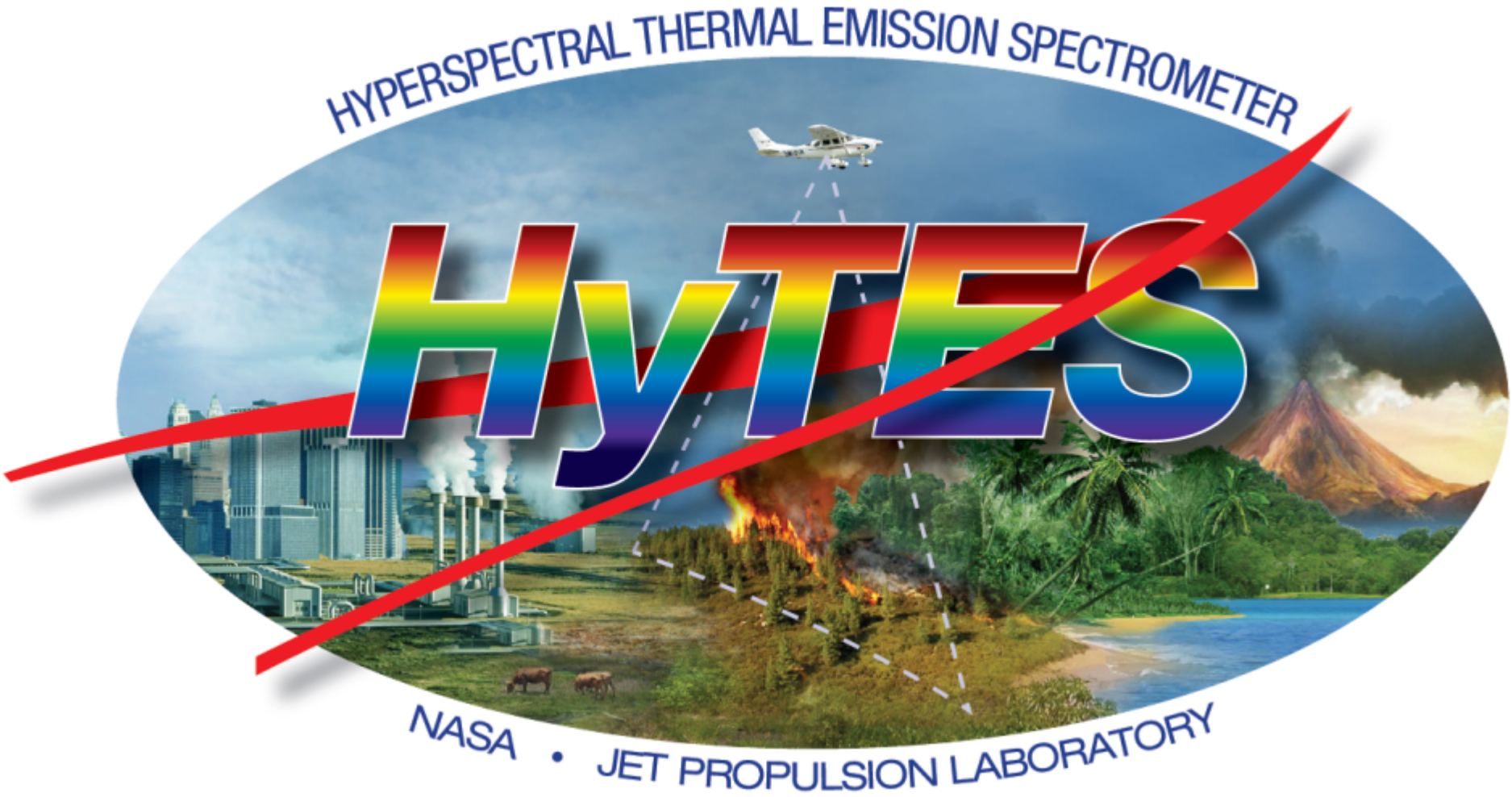
WVS = Water Vapor Scaling Model

TES = Temperature Emissivity Separation Algorithm

MASTER L2 TIR Summary

- Online ordering tool upgraded including overall layout, multiple scene orders, kml and jpeg browse images
- Calibration of MASTER TIR bands ~0.5 K
- Accuracy of LST/E improved with AVIRIS water vapor

- <u>Next STEPS:</u>
  - Expand Water Vapor Scaling (WVS) model to 45° view angle
  - Produce cloud mask product for entire campaign
  - Further testing of AVIRIS water vapor in more humid regions
  - Implement AVIRIS-derived water vapor maps
  - Re-process entire campaign L2 data with changes above



PI – Simon J. Hook

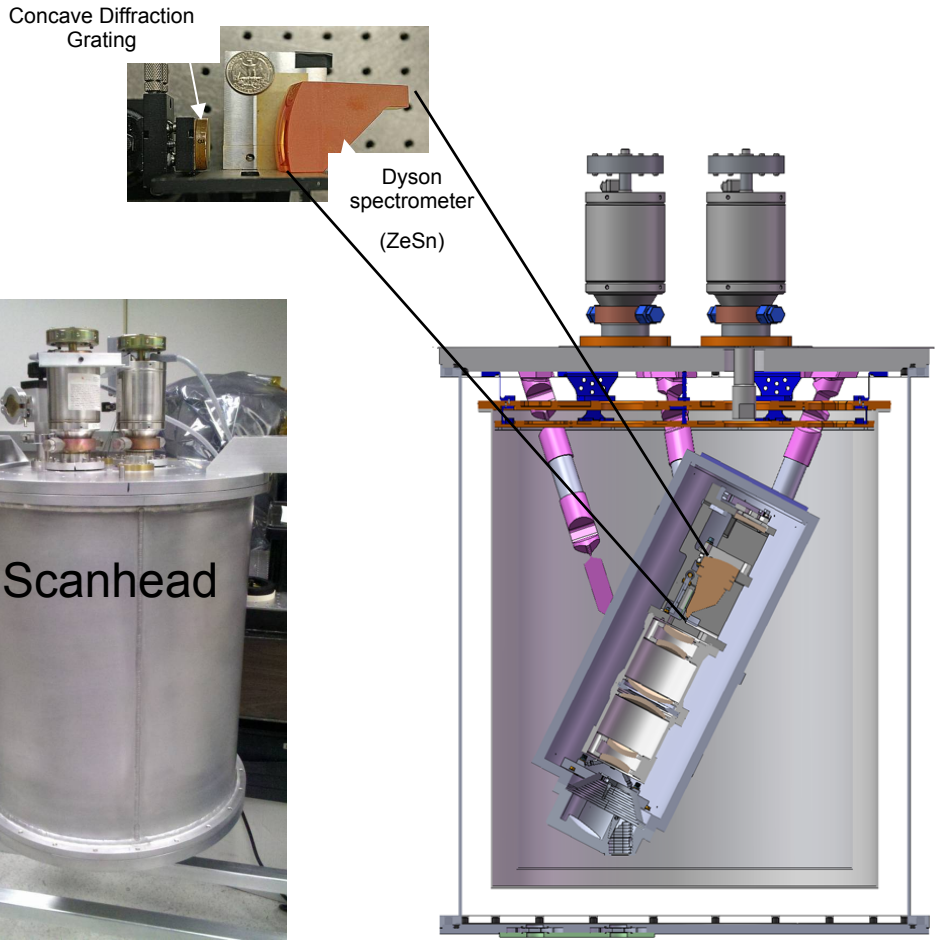
Science campaign (July 2nd to July 12th 2014)

© 2014 California Institute of Technology. Government sponsorship acknowledged.

HyTES Instrument Characteristics



Twin Otter Flights:
2012 (Engineering)
2013, 2014 (Science)



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 um
Detector	Multi-stack QWIP
Total Field of View	50 degrees
Calibration (preflight)	Full aperture blackbody
Swath Width	1.8 – 3.6 km
Pixel size at 2000 m flight altitude	3.64m
Pixel size at 20,000 m flight altitude	36.4m

Advanced Instrument Designs:
William Johnson

HyspIRI Risk Reduction Plan
ESTO - IIP

HyTES Key Science Results for 2014 (More details on Thursday afternoon talk)

1) Detection of anthropogenic methane over challenging areas, e.g. cities where thermal in-scene clutter makes detection difficult. This includes detection of natural (seeps) and managed systems (e.g. feedlots, pipelines, oil fields, landfills, storage facilities)

2) Detection of additional gases. Can now detect:
   a) Salton Sea (NH3 and H2S)
   b) La Brea Tar Pits (CH4)
   c) Kern River Oil Field (CH4)
   d) Ace Cogeneration Plant (SO2, NO2)
   e) Granada Hills (CH4)
   f) South and North Bakersfield Pipeline (CH4)

3) Acquisition of data over selected HyspIRI sites e.g. Teakettle, Soaproot Saddle, Tonzi Ranch for evaluation with HyspIRI campaign data

4) Acquisition of data over ecological, agricultural and geological sites for performance evaluation

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California Institute of Technology

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HyTES
Hyperspectral Thermal Emission Spectrometer

Home | Science | Instrument | Specifications | Platform | Order | Snapshots

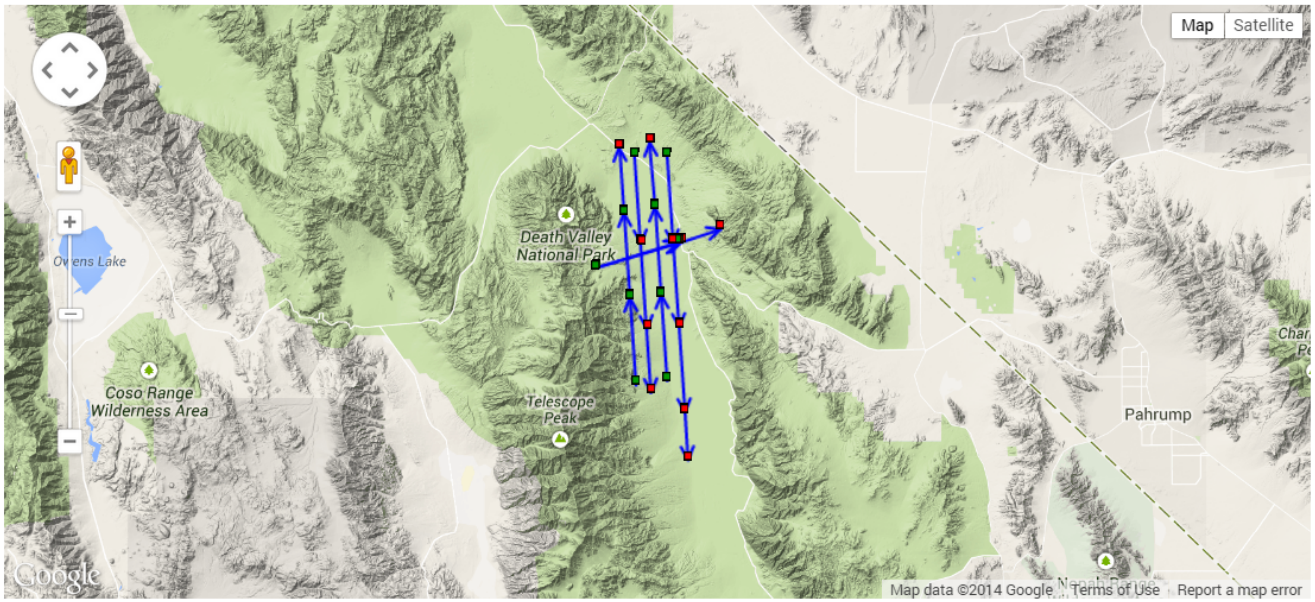
NASA/JPL

You are here: Home › Order

Order

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

Flight Line Summary | Spectral Response Function Data | Wave Matrix Data



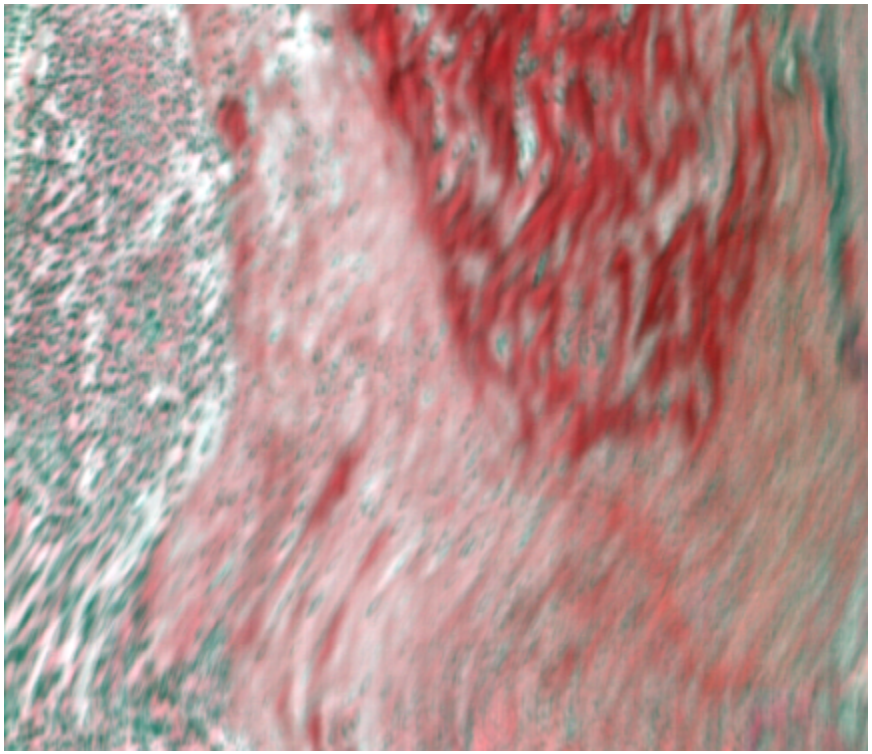
Order Additional Items | View Cart | Checkout | Clear All

Select the "Order" column name to select the entire column

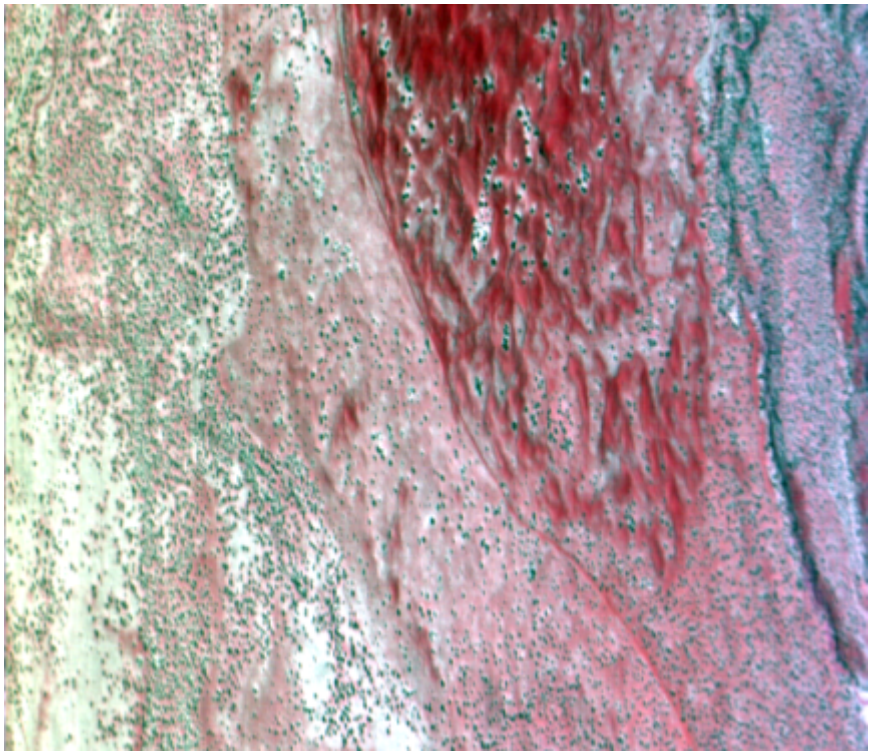
Acquisition Date/Time UTC	ID	Location	Line	Run	Segment	Image Browse or Download	KML Overlay Browse		Segment Start Lat/Long	Segment Stop Lat/Long	Order
							Line	Image/Download			
2014-07-12 222539	222539	Death Valley, CA	5	3	1	or	☑	☐ or	36.4248, -117.024	36.4626, -116.872	☐
2014-07-12 222539	222539	Death Valley, CA	5	3	2	or	☑	☐ or	36.4621, -116.874	36.4833, -116.793	☐

HyTES imagery from campaigns

Coral Pink, UT



2013



2014

L1A: 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 imagery from campaigns

Jet Propulsion Laboratory



2013



2014

L1A: 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 Atmospheric Correction

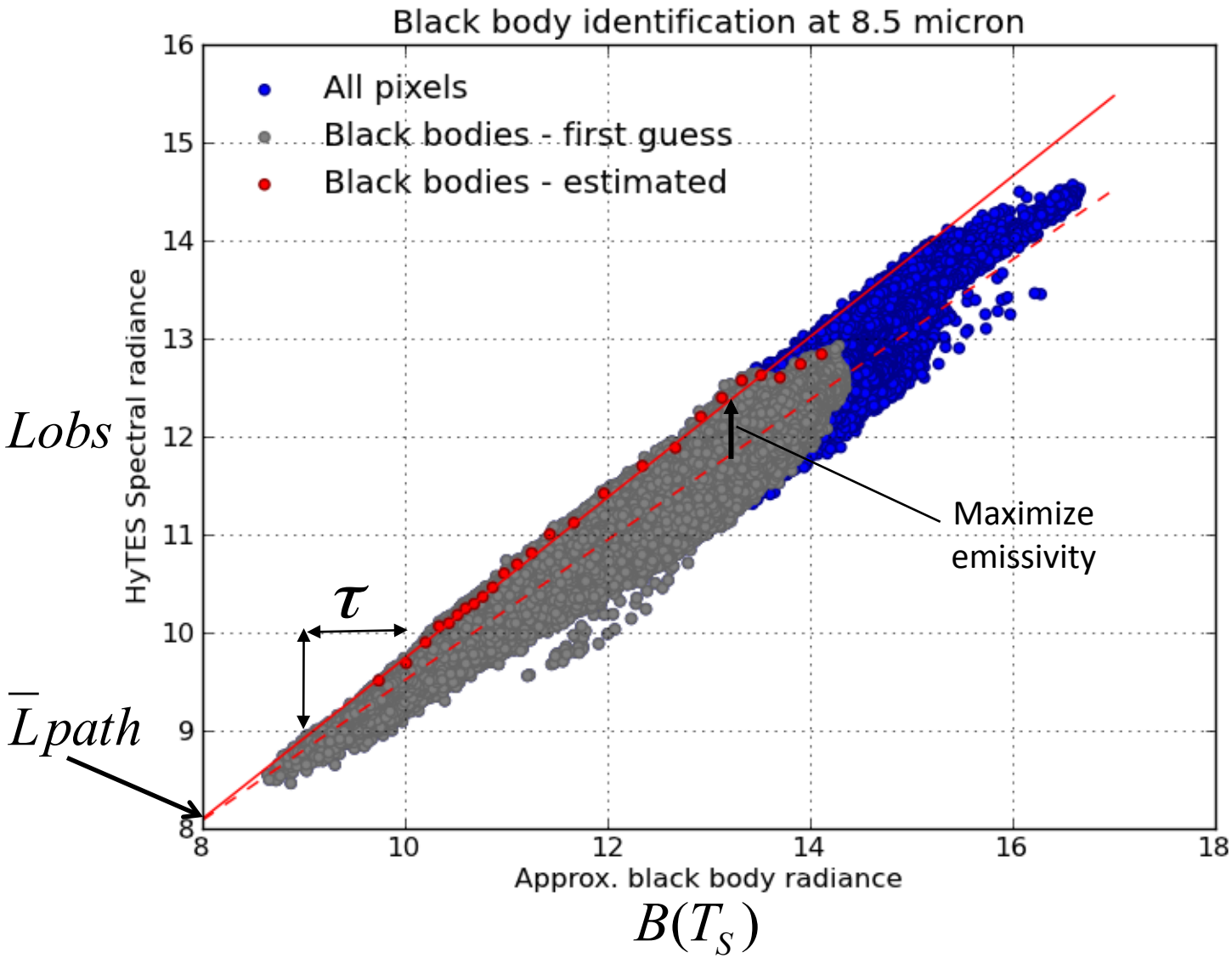
- MODTRAN 5.2
  - PROS: Fast, accurate if atmospheric profile known and data well calibrated
  - CONS: Errors from band misregistration, profile interpolation errors, calibration error

- In-Scene Atmospheric Correction (ISAC)
  - PROS: Uses spectral information from sensor
  - CONS: Slow, relies on blackbody pixels with broad temperature distribution, assumes atmosphere does not vary over scene

ISAC 'Graybody' mode

$$Lobs = \tau[\cancel{\varepsilon} \cdot B(T_S) + \cancel{(1-\varepsilon)\bar{L}sky}] + \bar{L}path$$

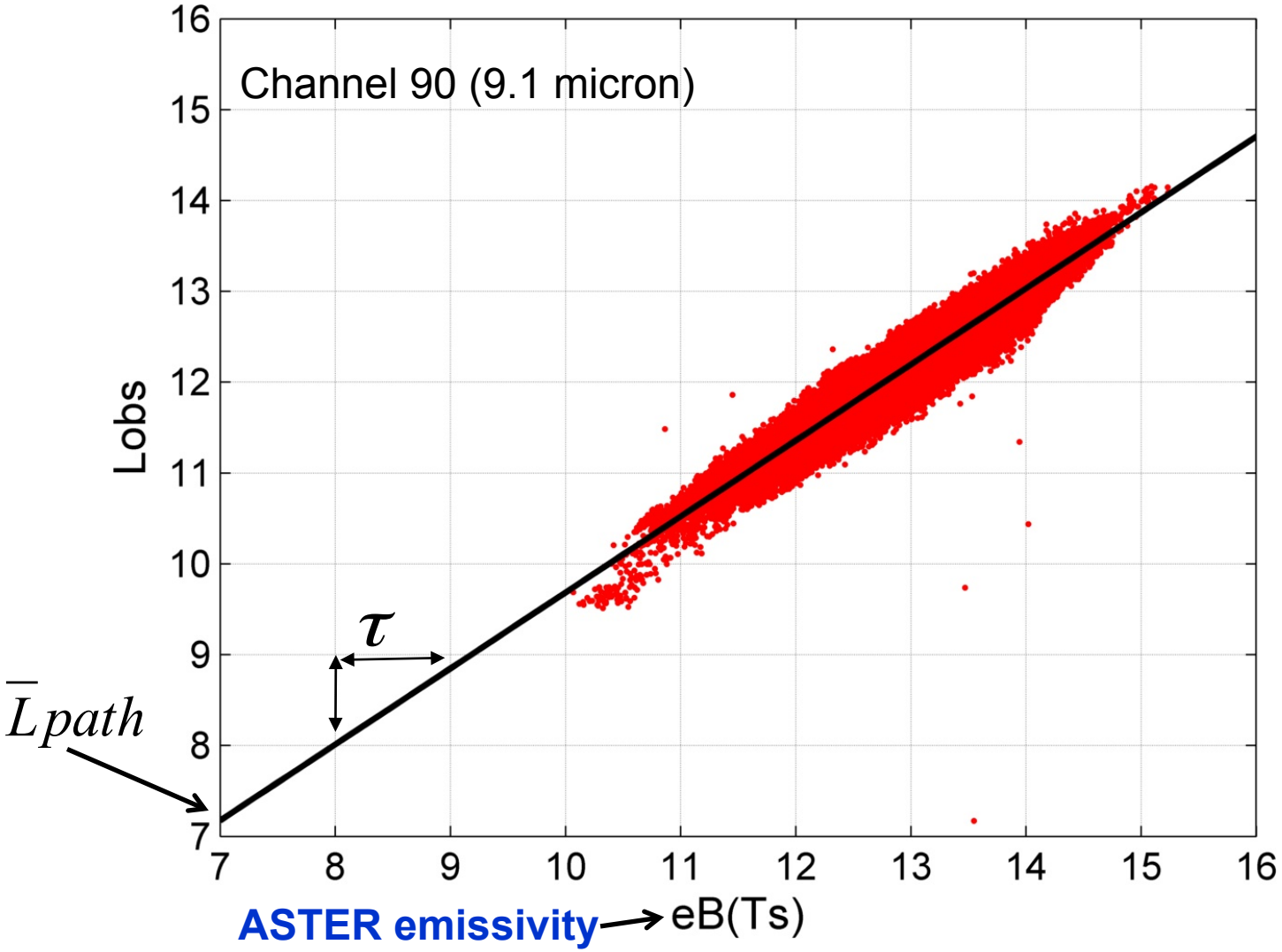
$$Lobs = \tau[B(T_S)] + \bar{L}path$$



ISAC 'Desert' mode

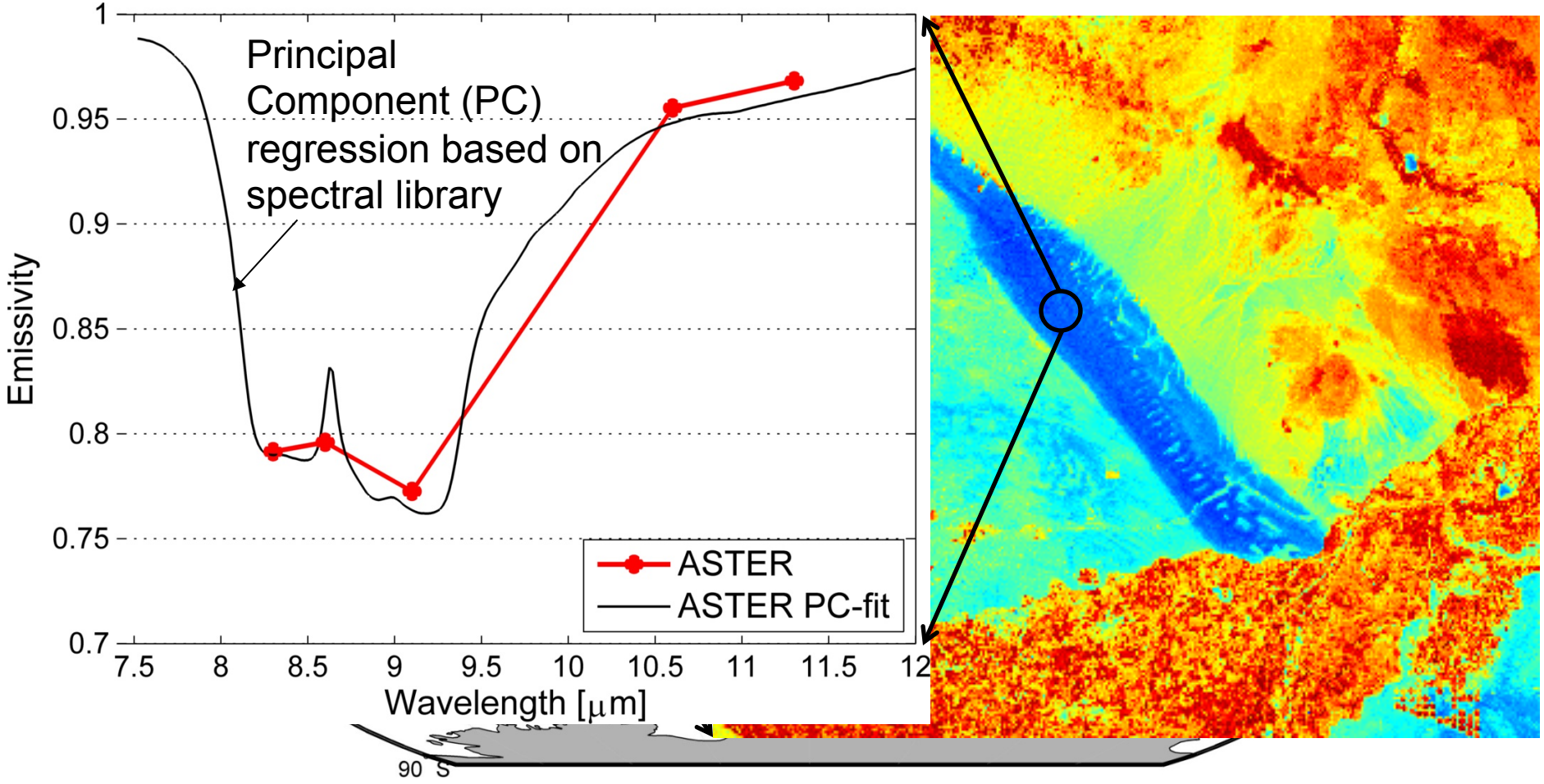
ASTER emissivity

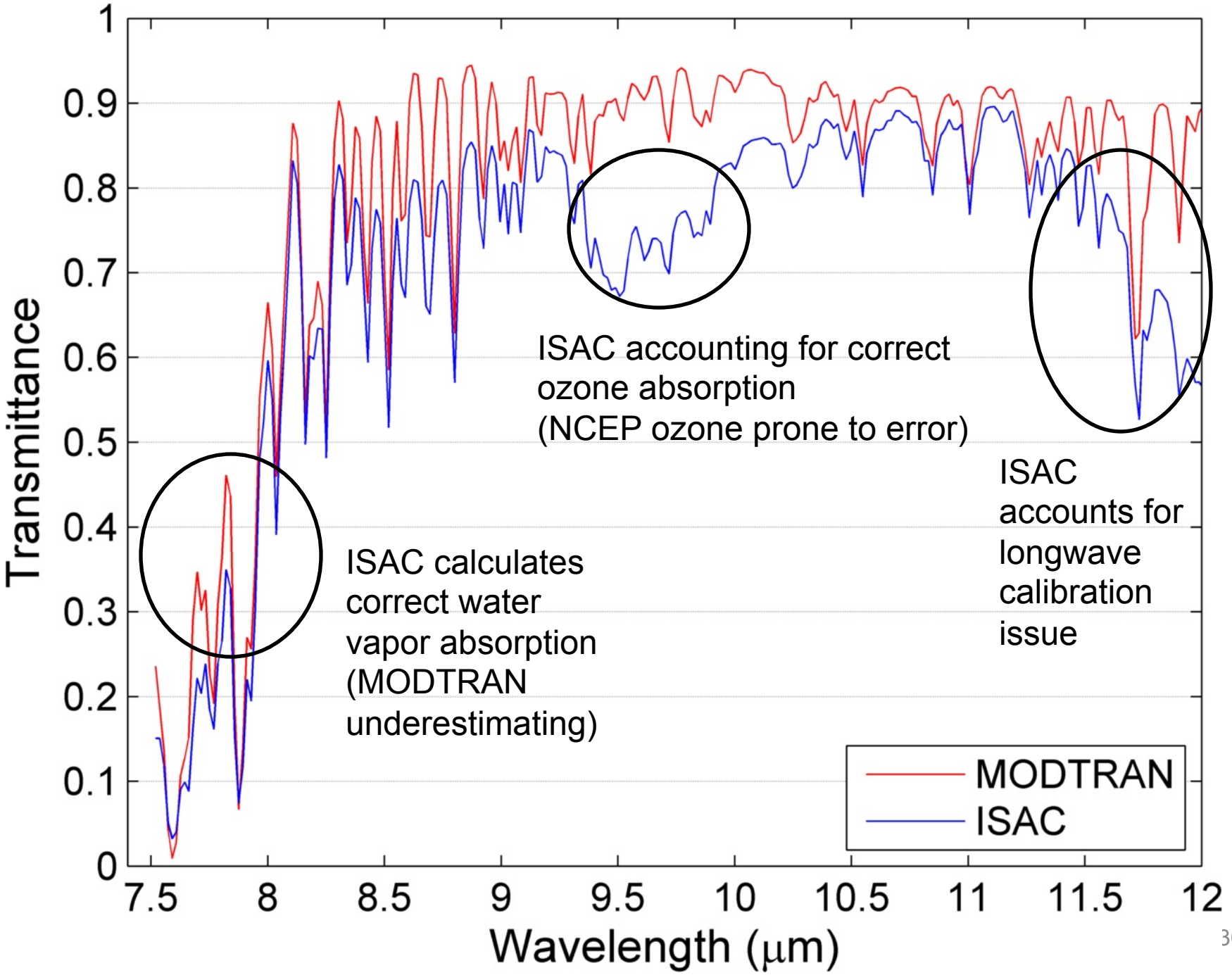
$$Lobs = \tau[\bar{e} \cdot B(T_S)] + \bar{L}path$$

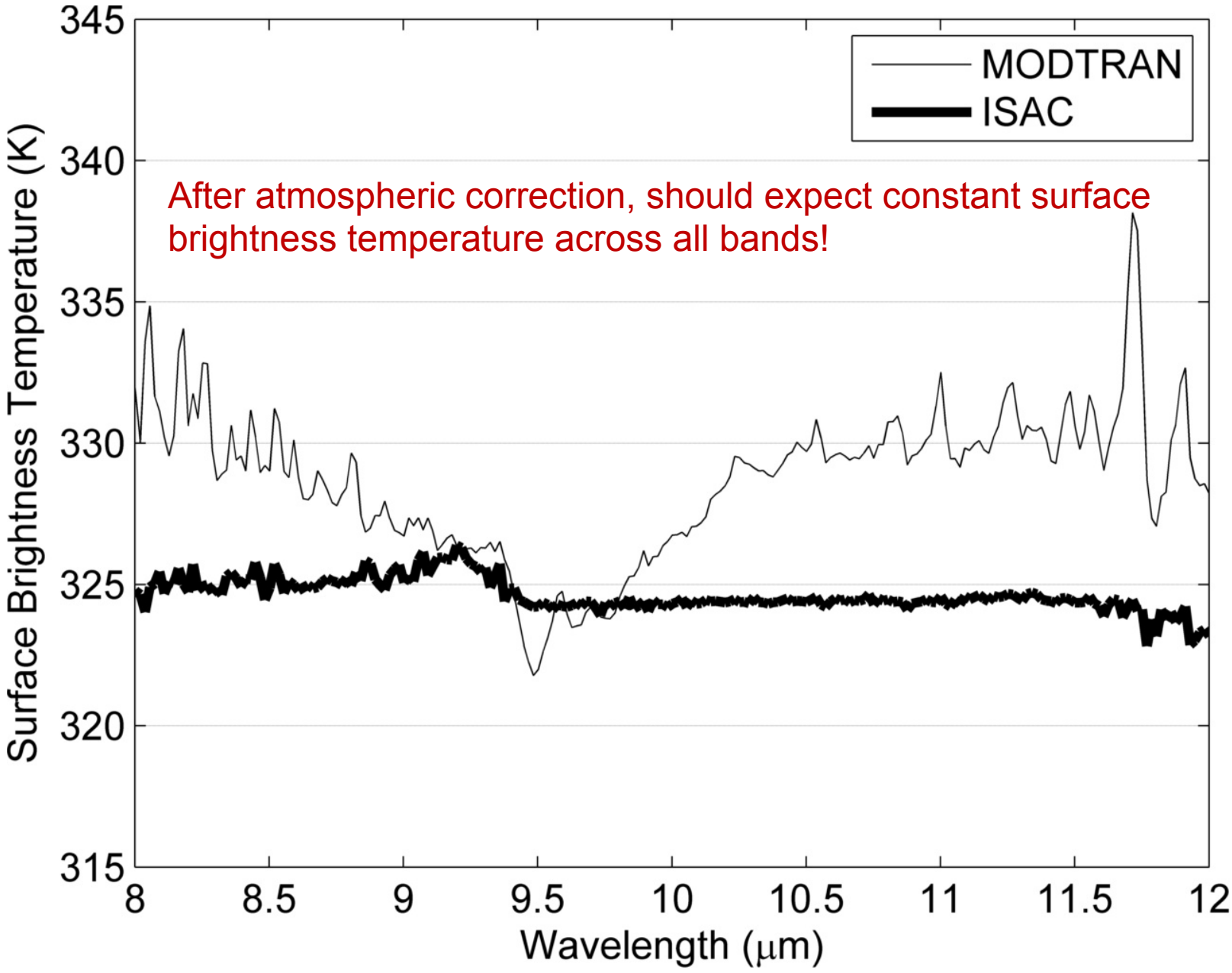


ASTER-Global Emissivity Database (GED)

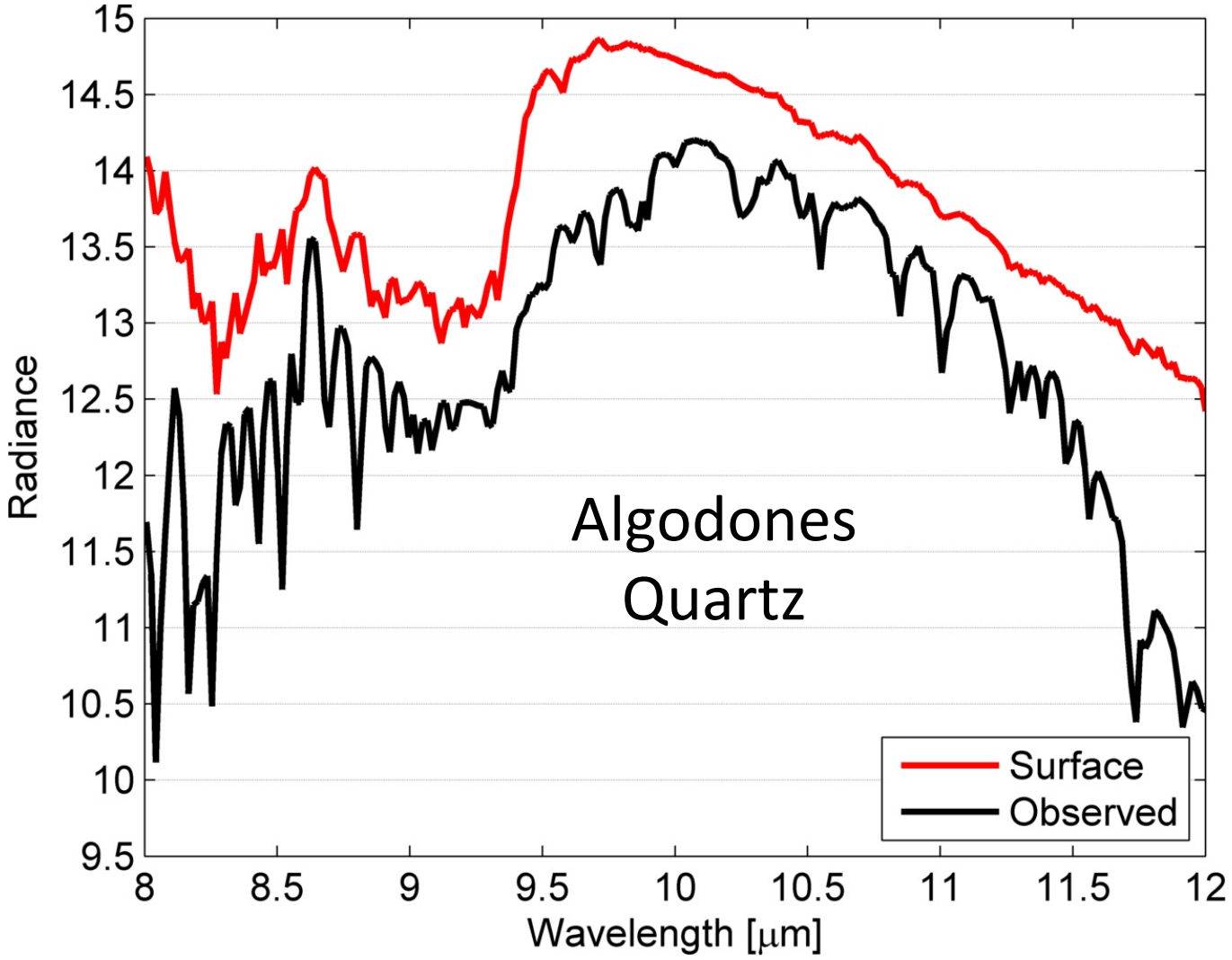
Spectral	Spatial	Temporal	Products	Emissivity Accuracy
5 Bands (8-12 µm)	~100 m	Mean Climatology (2000-2008)	Emissivity, NDVI, GDEM, Water mask, LST	<1.5% (nominal)

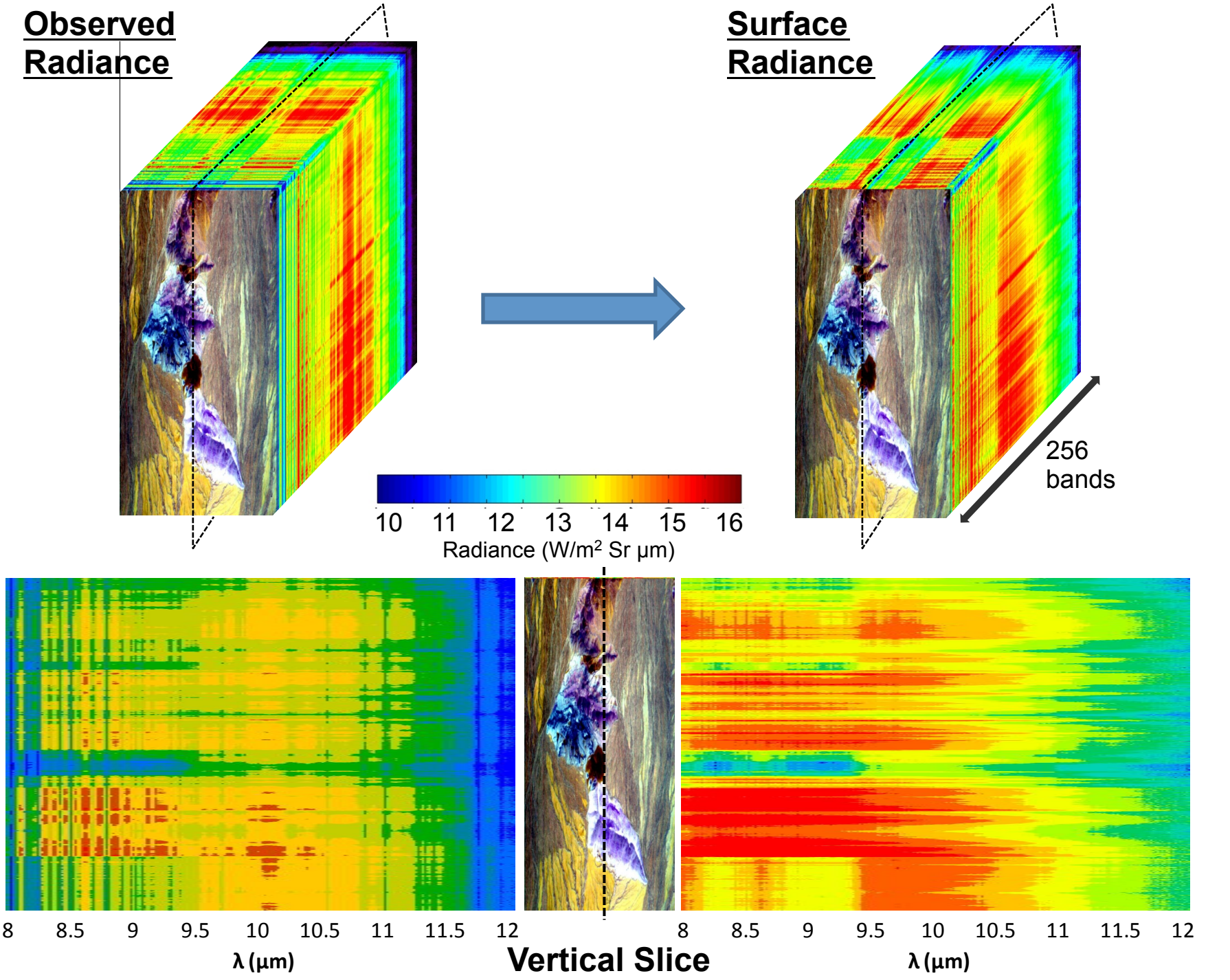



Transmittance
Wavelength (μm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
ISAC calculates correct water vapor absorption (MODTRAN underestimating)
ISAC accounting for correct ozone absorption (NCEP ozone prone to error)
ISAC accounts for longwave calibration issue
MODTRAN
ISAC


MODTRAN
ISAC
After atmospheric correction, should expect constant surface brightness temperature across all bands!
Surface Brightness Temperature (K)
345
340
335
330
325
320
315
8
8.5
9
9.5
10
10.5
11
11.5
12
Wavelength (μm)

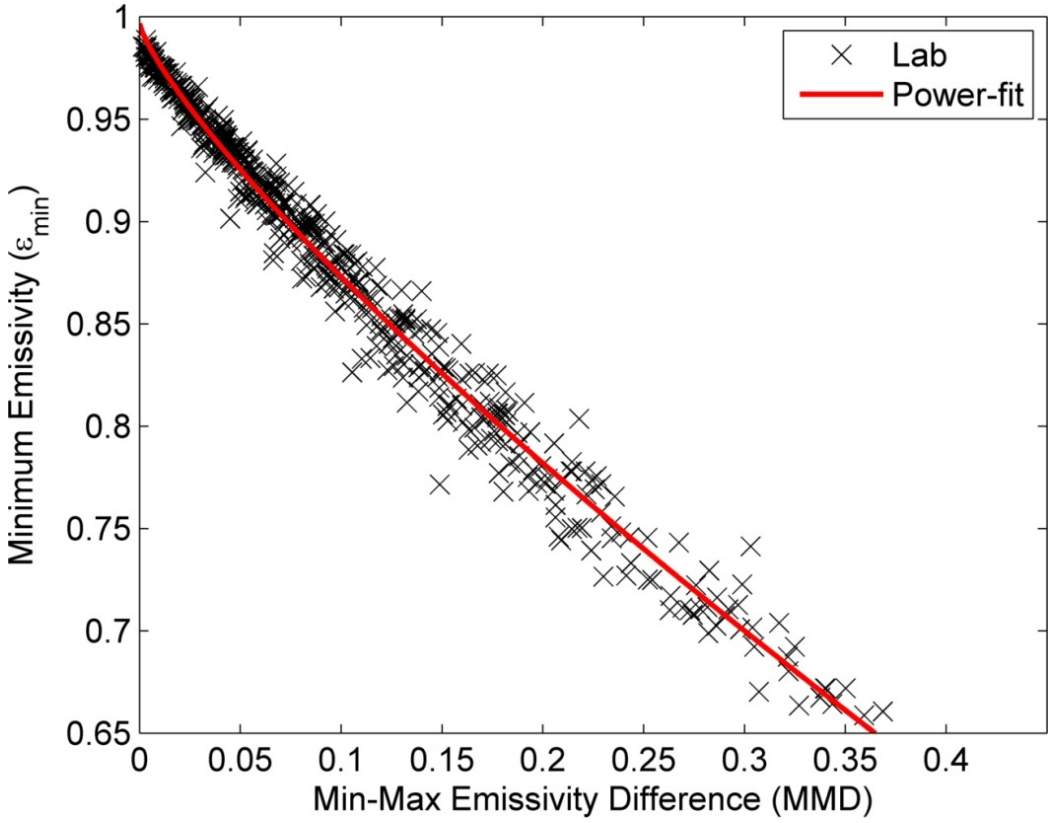
HyTES Atmospheric Correction

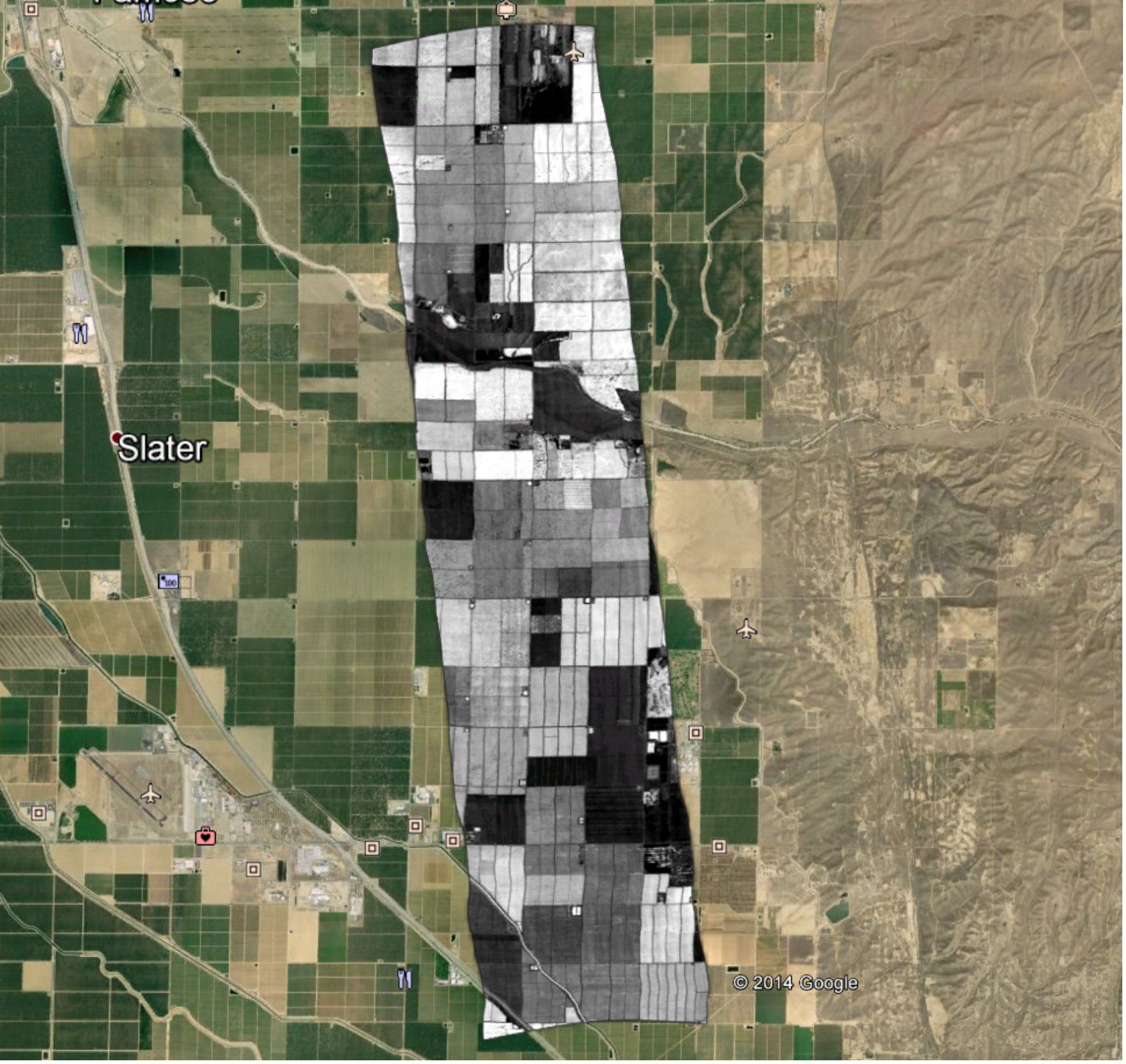



Observed Radiance
Surface Radiance
256 bands
10 11 12 13 14 15 16
Radiance (W/m2 Sr μm)
8 8.5 9 9.5 10 10.5 11 11.5 12
λ (μm)
Vertical Slice
8 8.5 9 9.5 10 10.5 11 11.5 12
λ (μm)

HyTES –TES Calibration Curve

$$\varepsilon_{\min} = 0.994 - 0.687 \cdot MMD^{0.737}$$





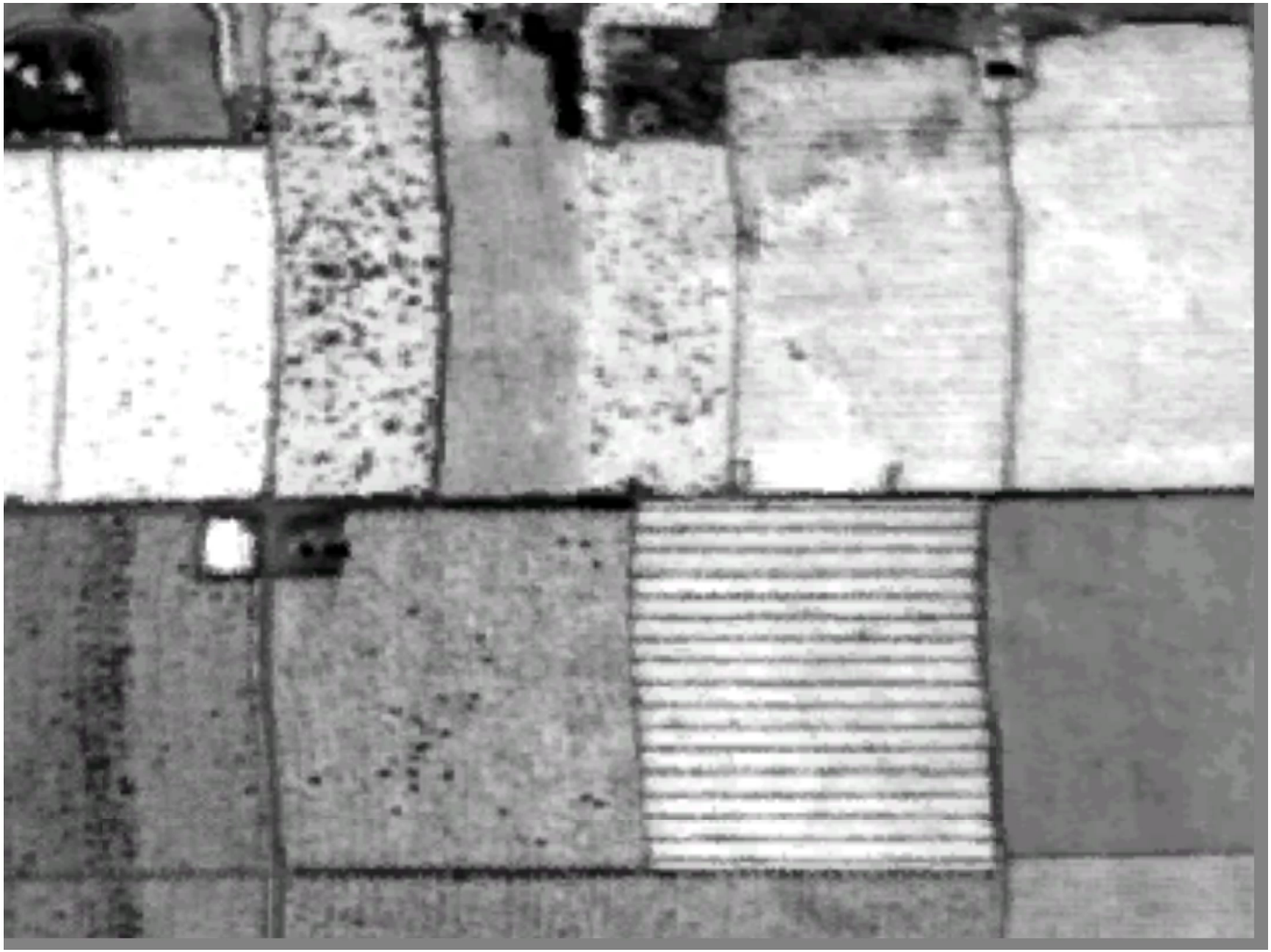
2014-07-08.184138.CitrusBakersfield.Line1-Run1

70° C

345
340
335
330
325
320
315
310
305

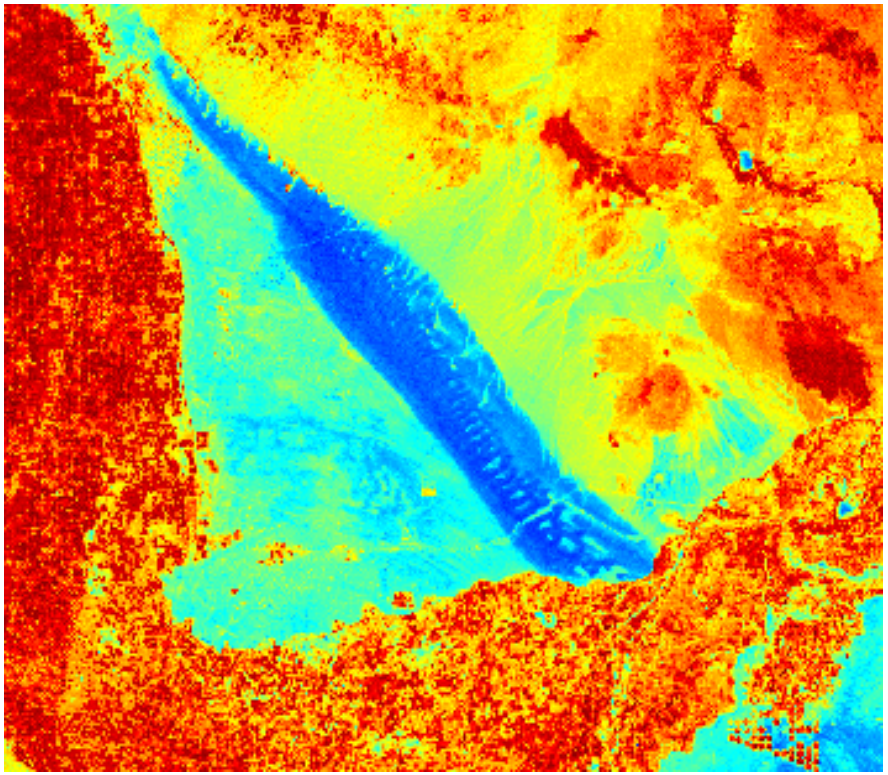
LST (K)

35 ° C

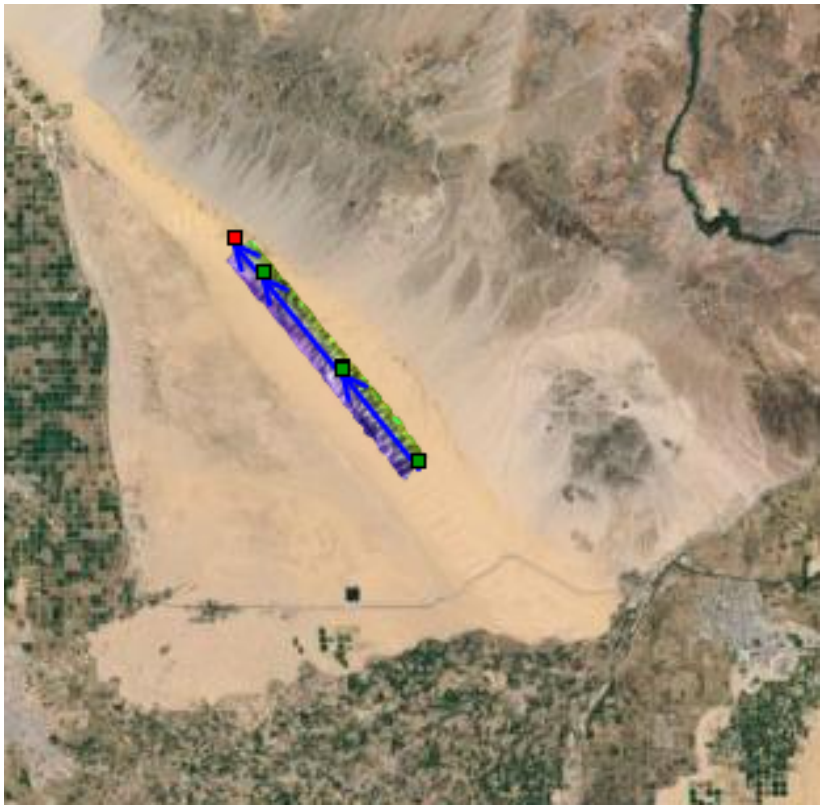


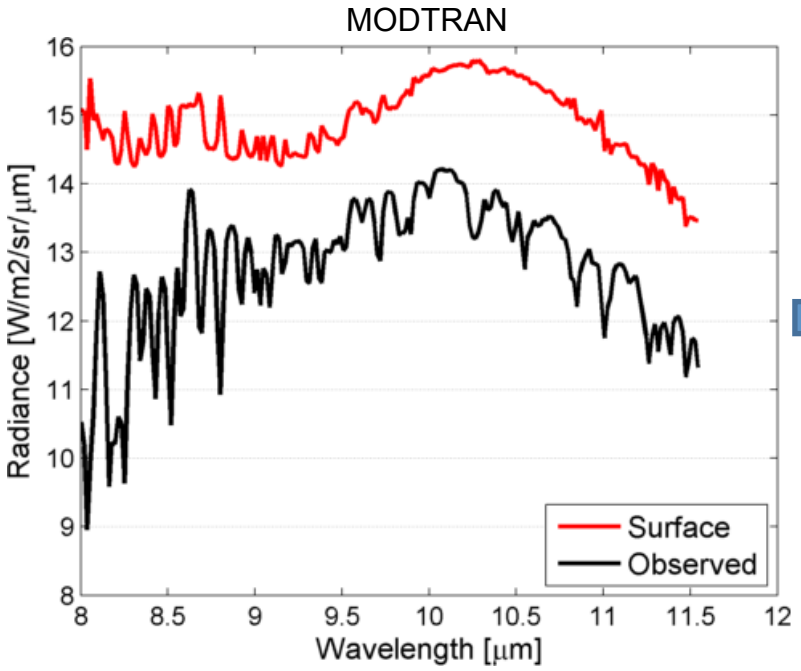
HyTES ISAC ‘Desert’ test: Algodones dunes

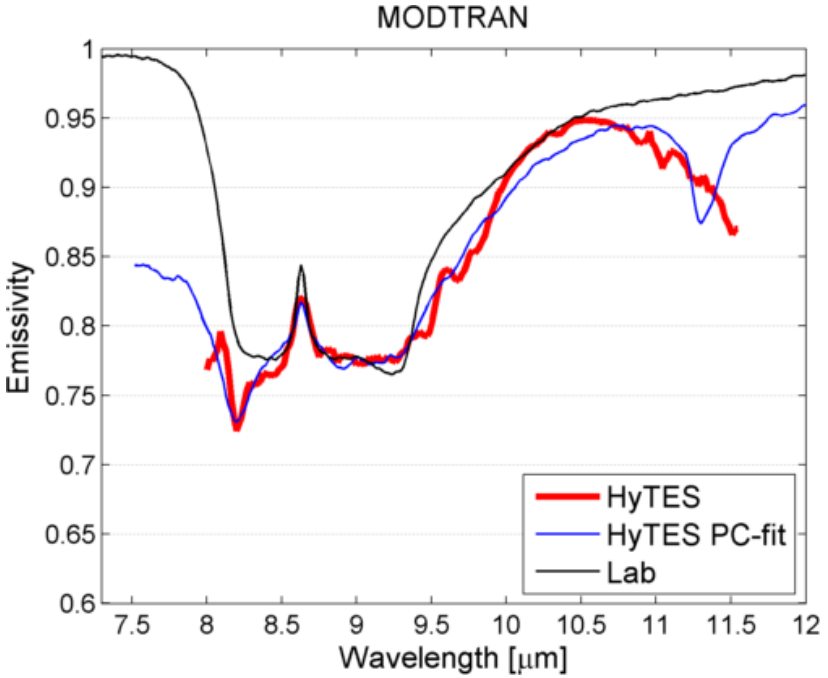
ASTER GED Emissivity (9.1 μm)

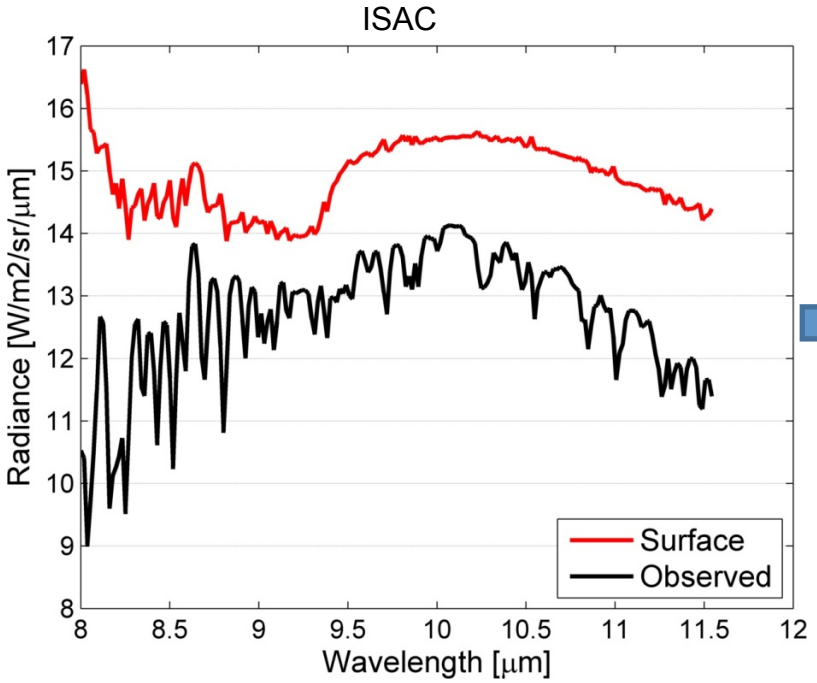


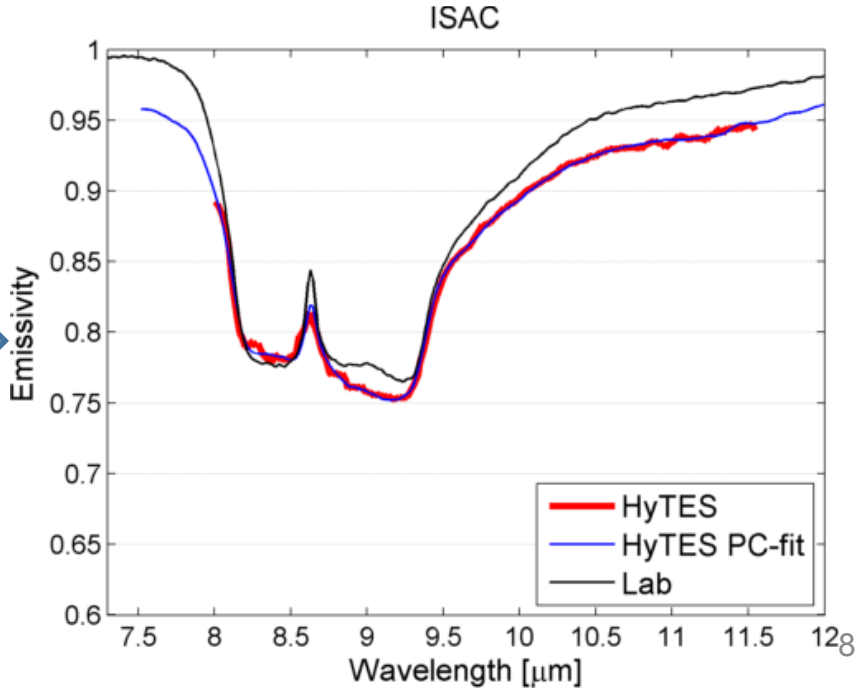
HyTES RGB

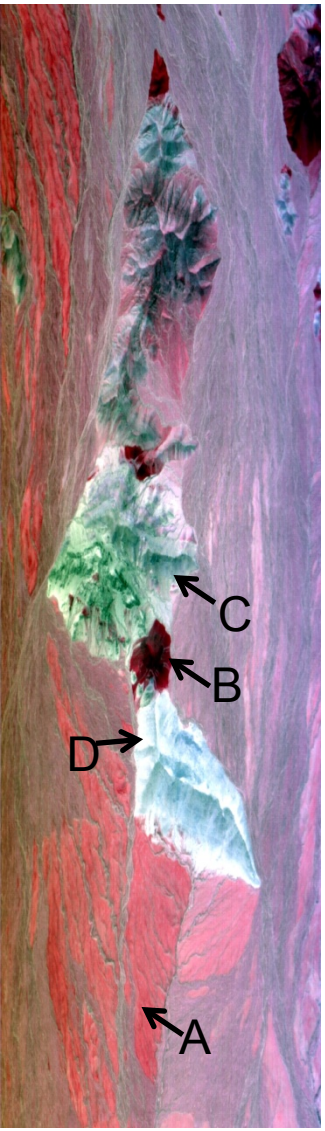


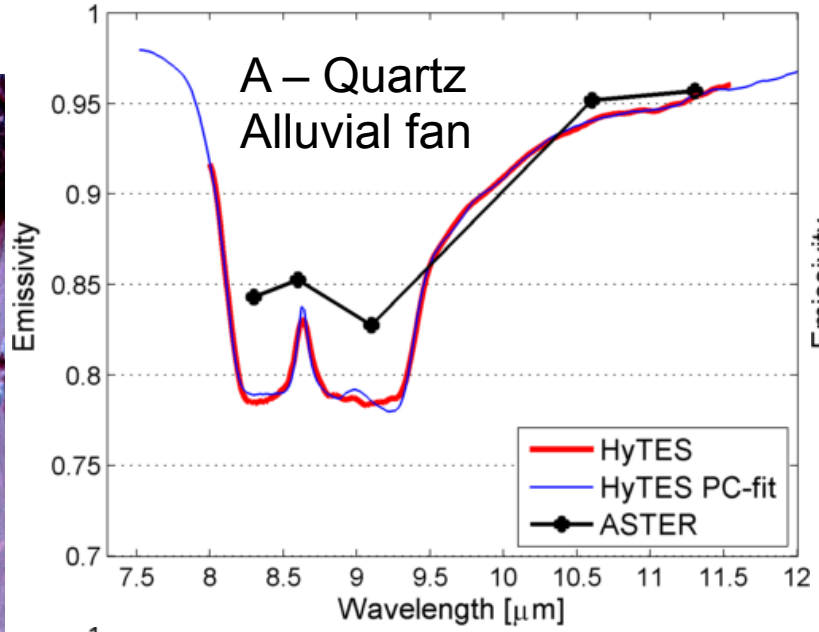

MODTRAN
Radiance [W/m2/sr/μm]
Wavelength [μm]
Surface
Observed

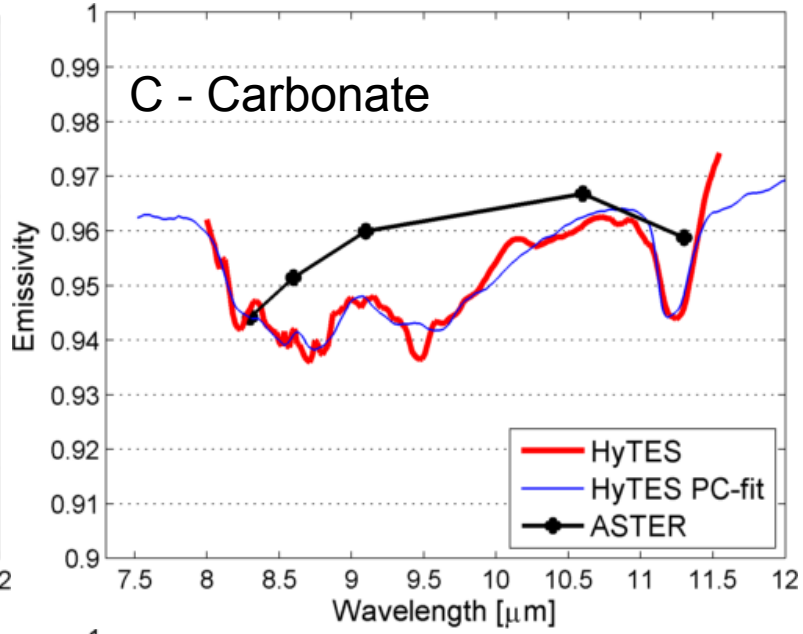

MODTRAN
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
Lab

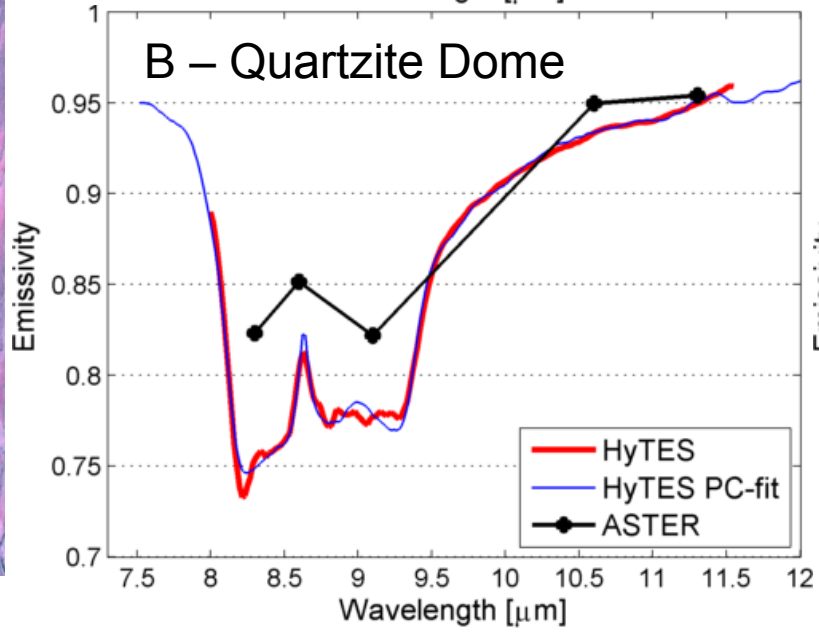

ISAC
Radiance [W/m2/sr/μm]
Wavelength [μm]
Surface
Observed

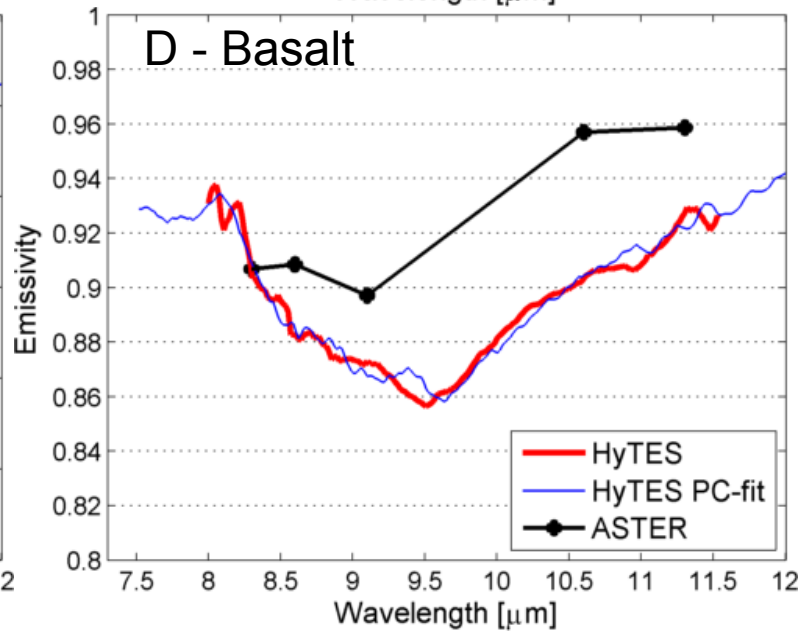

ISAC
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
Lab

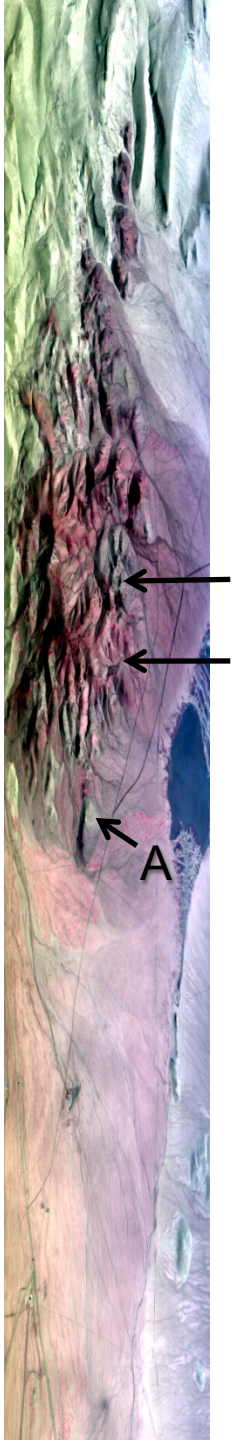

C
B
D
A

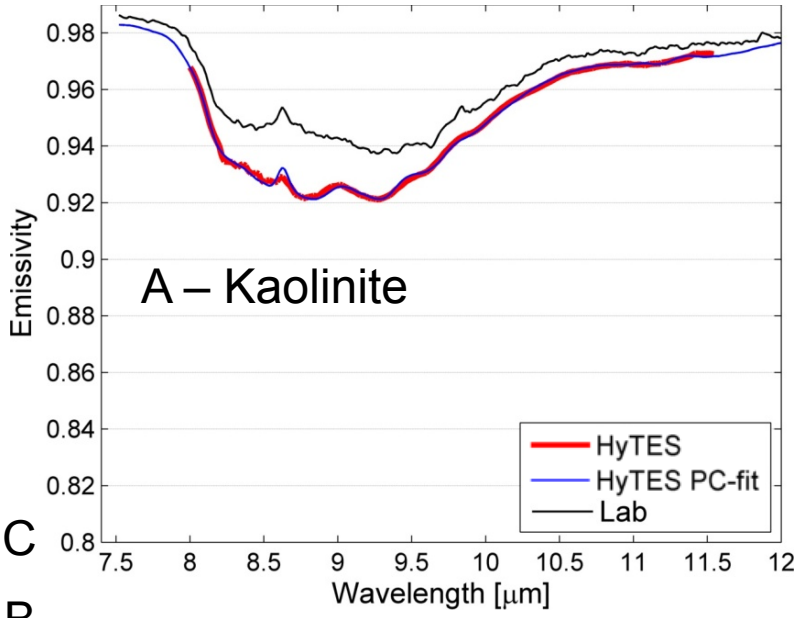

A – Quartz
Alluvial fan
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
ASTER

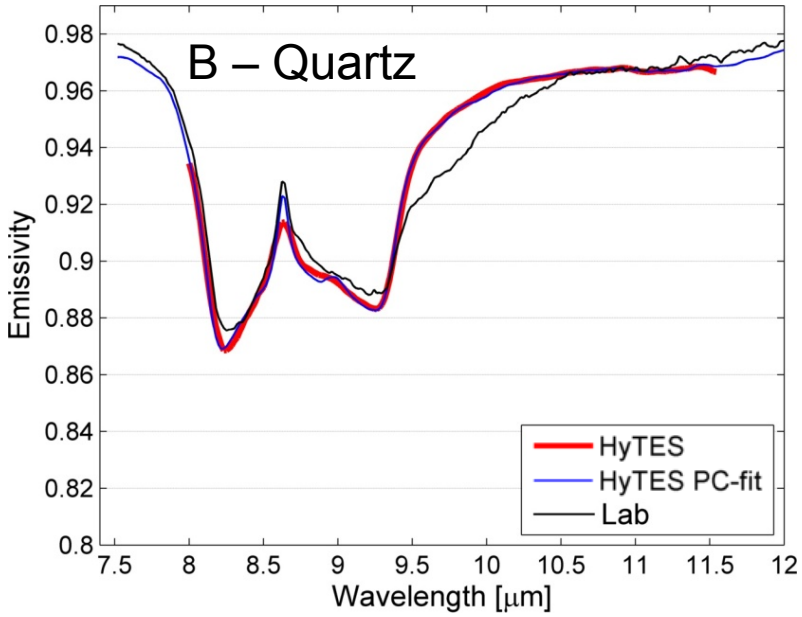

C - Carbonate
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
ASTER

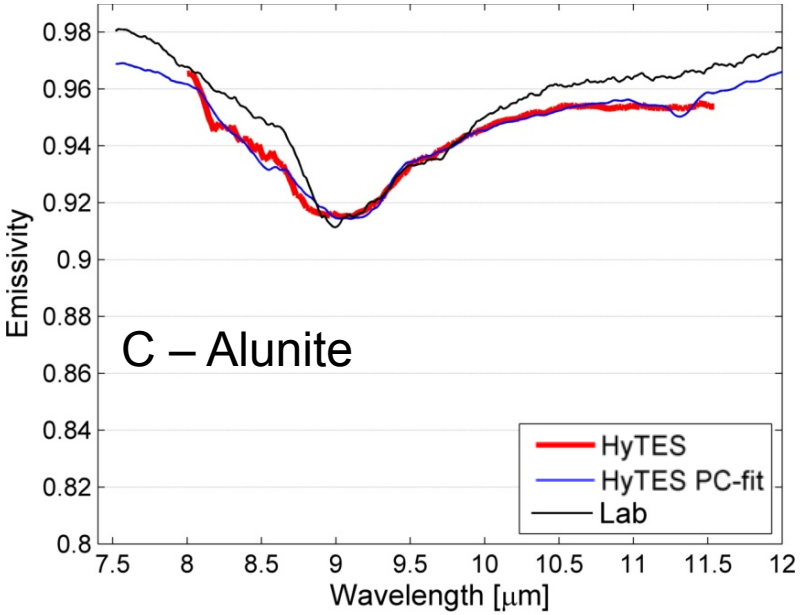

B – Quartzite Dome
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
ASTER


D - Basalt
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
ASTER


C
B
A


A – Kaolinite
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
Lab


B – Quartz
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
Lab


C – Alunite
Emissivity
Wavelength [μm]
HyTES
HyTES PC-fit
Lab

The End

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

JPL 400-1278 7/06

Relevance to HysplRI

- MASTER TIR online ordering and browse tool:
  - Support for HysplRI prep. airborne activities research (FY13-15)
  - Prototype for distribution of HyTES-TIR data

- MASTER improved atmospheric correction
  - TES + Water Vapor Scaling (WVS) method
  - Closer simulation of HysplRI-TIR L2 algorithms

(e.g. ATBDs at http://hyspiri.jpl.nasa.gov/documents)

Thermal Infrared Radiative Transfer

At-sensor Radiance

Surface Radiance

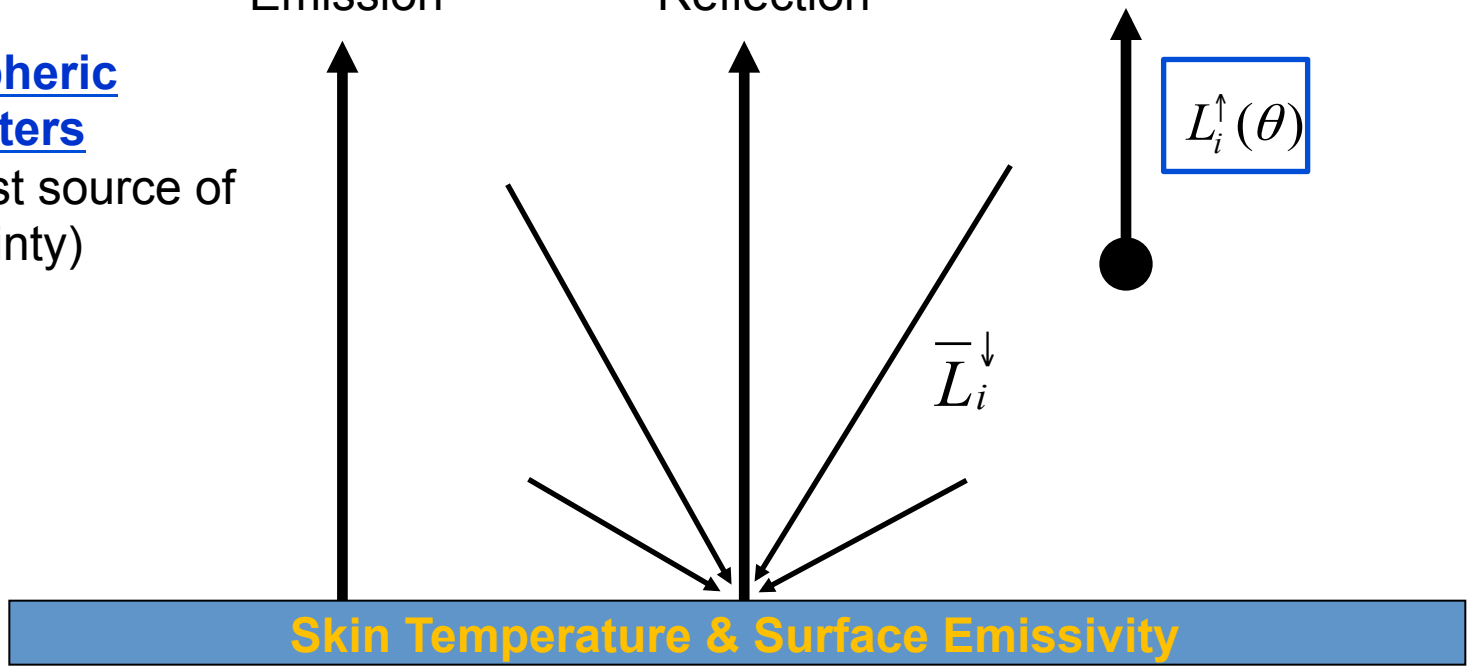
$$L_i = \tau_i \cdot e_i \cdot B_i(T_S) + \tau_i \cdot (1 - e_i) \cdot \overline{L}_i^{\downarrow} + \int B_i(T(P))d\tau_i$$

Surface Emission

Surface Reflection

Atmospheric Emission

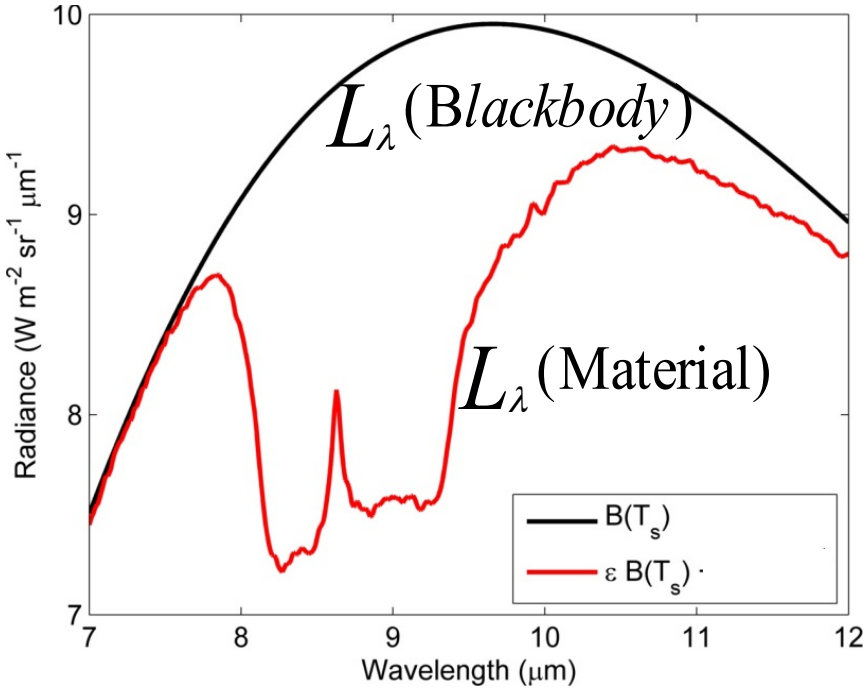
Atmospheric Parameters
(Greatest source of Uncertainty)

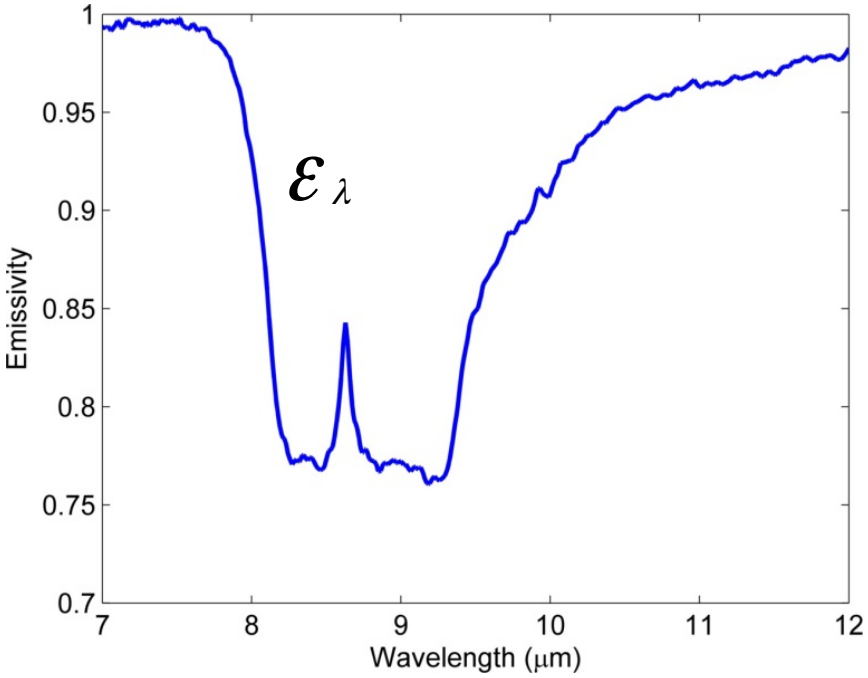


Spectral Emissivity

Emissivity: ratio of the spectral radiance of a material to that of a blackbody at the same temperature:

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





Water Vapor Scaling (WVS) method

Tonooka, H., (2005), Accurate Atmospheric Correction of ASTER Thermal Infrared Imagery Using the WVS Method, IEEE Trans. Geos. Remote Sens., 43 (12)

Surface brightness temperature

Observed brightness temperature

Total column water estimate

EMC/WVD equation

$$T_{g,i} = \alpha_{i,o} + \sum_{k=1}^{n} \alpha_{i,k} T_k$$

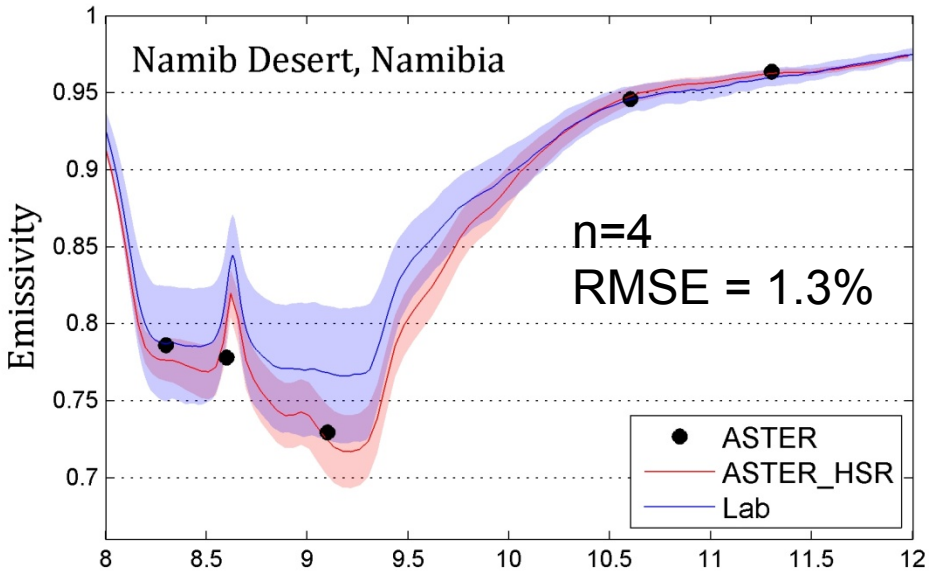
$$\alpha_{i,k} = p_{i,k} + q_{i,k} W + r_{i,k} W^2 \quad (k = 0,1,..,n)$$

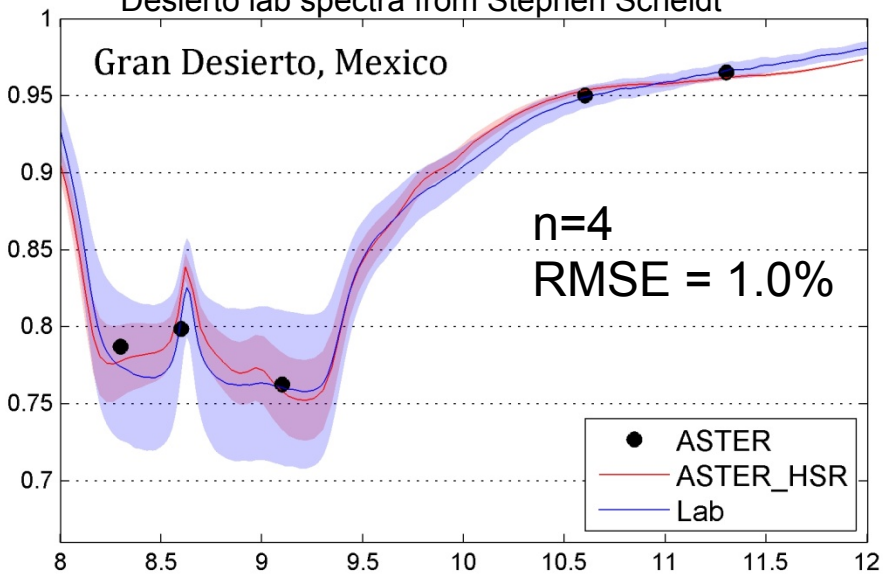
Scaling factor

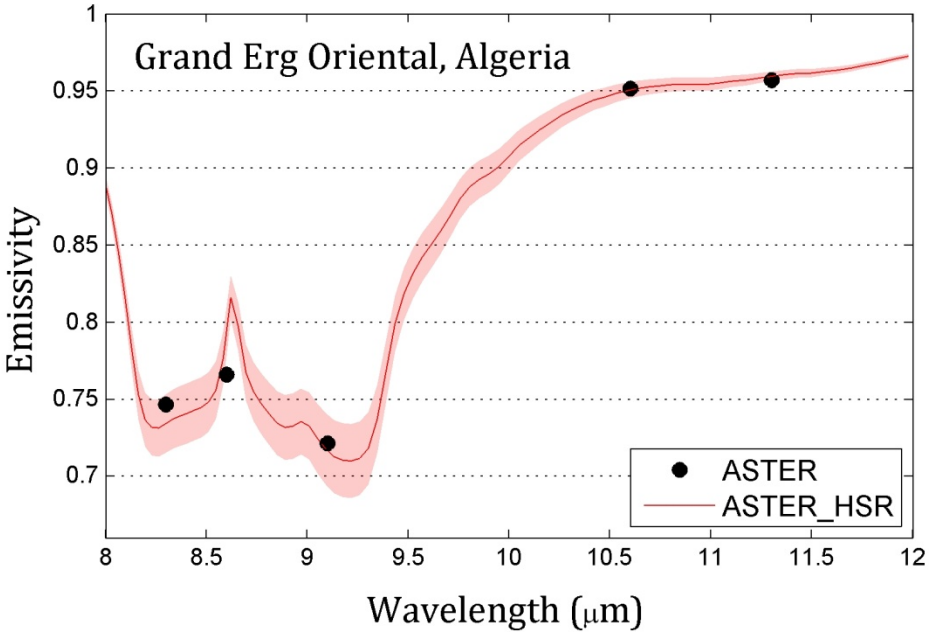
$$\gamma^{a_i} = \frac{\ln\left[\frac{\tau_i(\gamma_2)^{\gamma_1^{a_i}}}{\tau_i(\gamma_1)^{\gamma_2^{a_i}}} \cdot \left(\frac{B_i(T_{g,i}) - L_i^{\uparrow}(\gamma_1)/(1-\tau_i(\gamma_1))}{L_i - L_i^{\uparrow}(\gamma_1)/(1-\tau_i(\gamma_1))}\right)^{\gamma_1^{a_i} - \gamma_2^{a_i}}\right]}{\ln\left(\frac{\tau_i(\gamma_2)}{\tau_i(\gamma_1)}\right)}$$

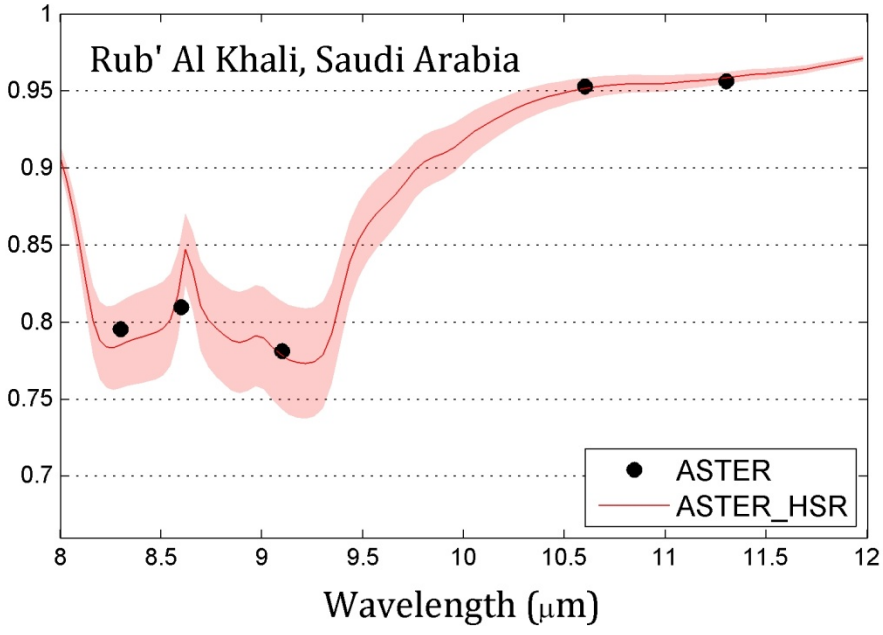
ASTER-GED High Spectral Resolution (HSR) Emissivity

*Desierto lab spectra from Stephen Scheidt









Death Valley ‘Bowtie’

Rock types difficult to distinguish in visible image from Google Earth





HyTES Thermal RGB

Emissivity Variations allow rock type to be separated:

Red = quartz-rich
Green = carbonate
Purple = quartz-poor
Maroon = quartzite

Atmospheric Correction

Observed Radiance

Surface Radiance:

$$L_{surf,i} = e_i \cdot B_i(T_S) + (1 - e_i) \cdot \overline{L_i}^{\downarrow} = \frac{L_i(\theta) - L_i^{\uparrow}(\theta)}{\tau_i(\theta)}$$

- **Atmospheric Parameters:** $\tau_i(\theta)$, $L_i^{\uparrow}(\theta)$, $L_i^{\downarrow}(\theta)$

Estimated using radiative transfer code such as MODTRAN with atmospheric profiles (NCEP) and elevation data (ASTER DEM)

NCEP data (6-hourly, 1º spatial resolution, 26 levels)

Method of UWiremis HSR algorithm

$$\vec{e} = \vec{c}U$$

$$\vec{c} = \vec{e} * U^T (UU^T)^{-1}$$

Reference:
Borbas and Ruston, 2010,
EUM -NWPSAF-MO-VS-042

$\vec{e}$ is the HSR emissivity spectra

$\vec{c}$ is the PCA coefficient vector

U is the matrix of the first PCs of the lab emissivity spectra

- Most Important Idea (Bill Smith)

  Represent high spectral resolution infrared emissivity as a linear combination of a limited number (e.g. 6) of eigenfunctions of a set of laboratory spectra that covers 3.7 to 14.3μm.

- Accuracy depends on
  - UWiremis BF emissivity DB and MODIS MYD11 data
  - Set of laboratory spectra (current version contains 123 selected lab spectra on 5 wavenumber [cm^{-1}] spectral resolution)

- Output: emissivity spectra with 416 spectral points between 3.7 and 14.3 μm

Principal Component Regression

1. Eigenvector assumption:

$$\varepsilon(\nu_{hsr}) = c \cdot U(\nu_{hsr}) \qquad (1)$$

ν_{hsr} High spectral resolution (hsr) wavenumbers (84 between 835-1250 cm-1)

$\varepsilon(\nu_{hsr})$ HSR Emissivity

$U(\nu_{hsr})$ First *n* eigenvectors of 142 lab measurements (142,84)

c Regression coefficient

2. Regression coefficients:

$$c = \varepsilon(\nu) \cdot A^T \left(AA^T\right)^{-1} \qquad (2)$$

$\varepsilon(\nu)$ Emissivity of 5 ASTER bands

$A = SRF \otimes U(\nu_{hsr})$ Convolve first *n* eigenvectors with ASTER SRFs

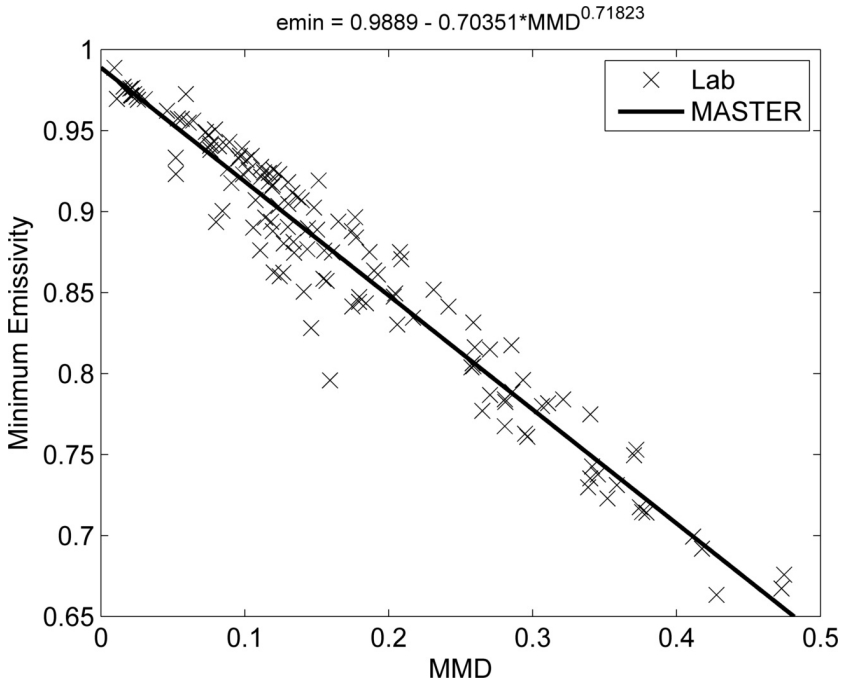
3. Apply c to equation (1)

Band-dependent TES Calibration curves

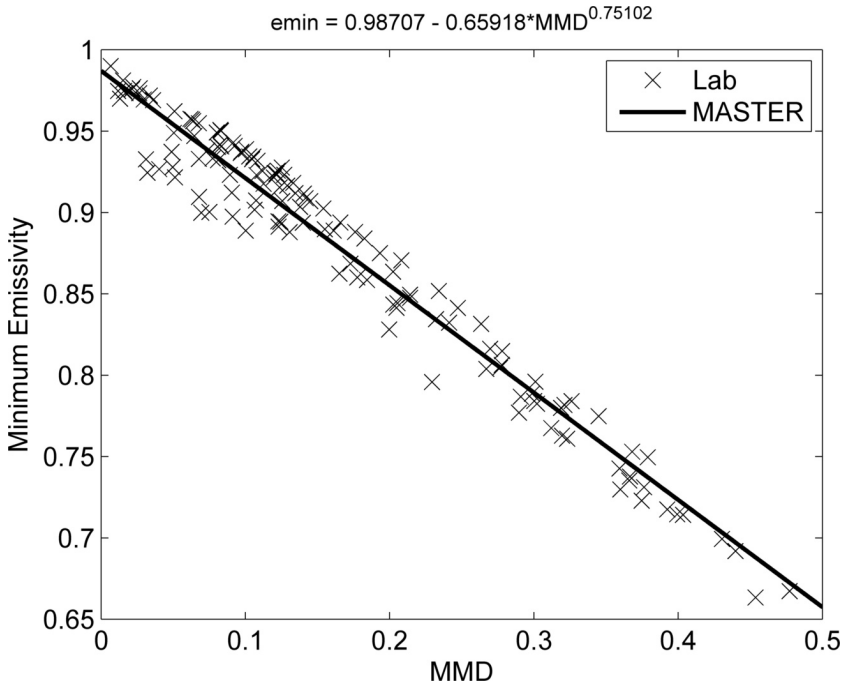
TES algorithm can be run for a combination of MASTER TIR bands:

- Minimum of 3 bands required
- At least one band between 11-12 µm (48 or 49)
- At least one band between 8 - 9.5 µm (43 or 44)

Bands 43, 44, 47, 48



Bands 43, 44, 49



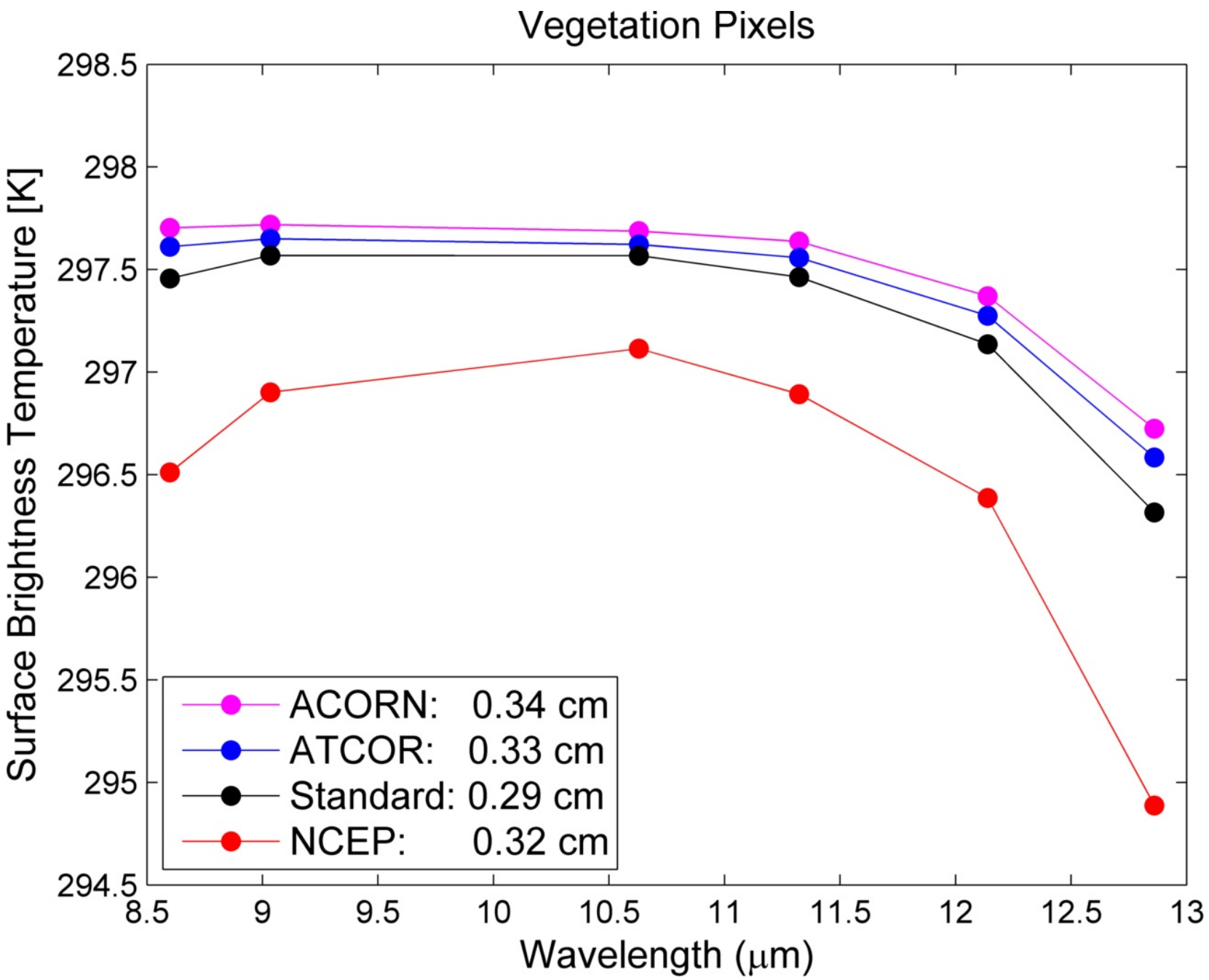
Water Vapor Scaling (WVS)

γ is used to modify and improve atmospheric correction terms:

Transmittance: $$\tau_i(\gamma) = \tau_i(\gamma_1)^{(\gamma^{a_i} - \gamma_2^{a_i} / \gamma_1^{a_i} - \gamma_2^{a_i})} \cdot \tau_i(\gamma_2)^{(\gamma_1^{a_i} - \gamma^{a_i} / \gamma_1^{a_i} - \gamma_2^{a_i})}$$

Path Radiance: $$L_i^{\uparrow}(\gamma) = L_i^{\uparrow}(\gamma_1) \cdot \frac{1 - \tau_i(\gamma)}{1 - \tau_i(\gamma_1)}$$

Sky Radiance: $$L_i^{\downarrow}(\gamma) = a_i + b_i \cdot L_i^{\uparrow}(\gamma) + c_i \cdot L_i^{\uparrow}(\gamma)^2$$


Vegetation Pixels
Surface Brightness Temperature [K]
298.5
298
297.5
297
296.5
296
295.5
295
294.5
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13
Wavelength (μm)
ACORN: 0.34 cm
ATCOR: 0.33 cm
Standard: 0.29 cm
NCEP: 0.32 cm

HyTES Overall Objective and Science Goal

- Objective: 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.

- Science Goal: Provide precursor high spectral and spatial resolution thermal infrared data for the NRC Recommended HyspIRI mission and for use in Earth Science Studies
  - Optimal band placement for HyspIRI TIR for surface compositional mapping and volcanic ash/gas detection (e.g. SO2)
  - Prelim Band Study report available at HyspIRI website (Ramsey, Realmuto, Hulley)

MASTER Band Placement (VSWIR/MWIR)

