Jet Propulsion Laboratory
California Institute of Technology

HyspIRI Thermal Infrared L1/L2: Algorithm Maturity and Cal-Val

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Theoretical Basis: Planck's law and Temperature

$$B_\lambda = \frac{c_1}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T_s}\right)-1\right]}$$

$$T_s = B_\lambda^{-1}\left(\frac{L_\lambda(\theta)-\rho_\lambda L^{\downarrow}}{\varepsilon_\lambda}\right)$$

where :

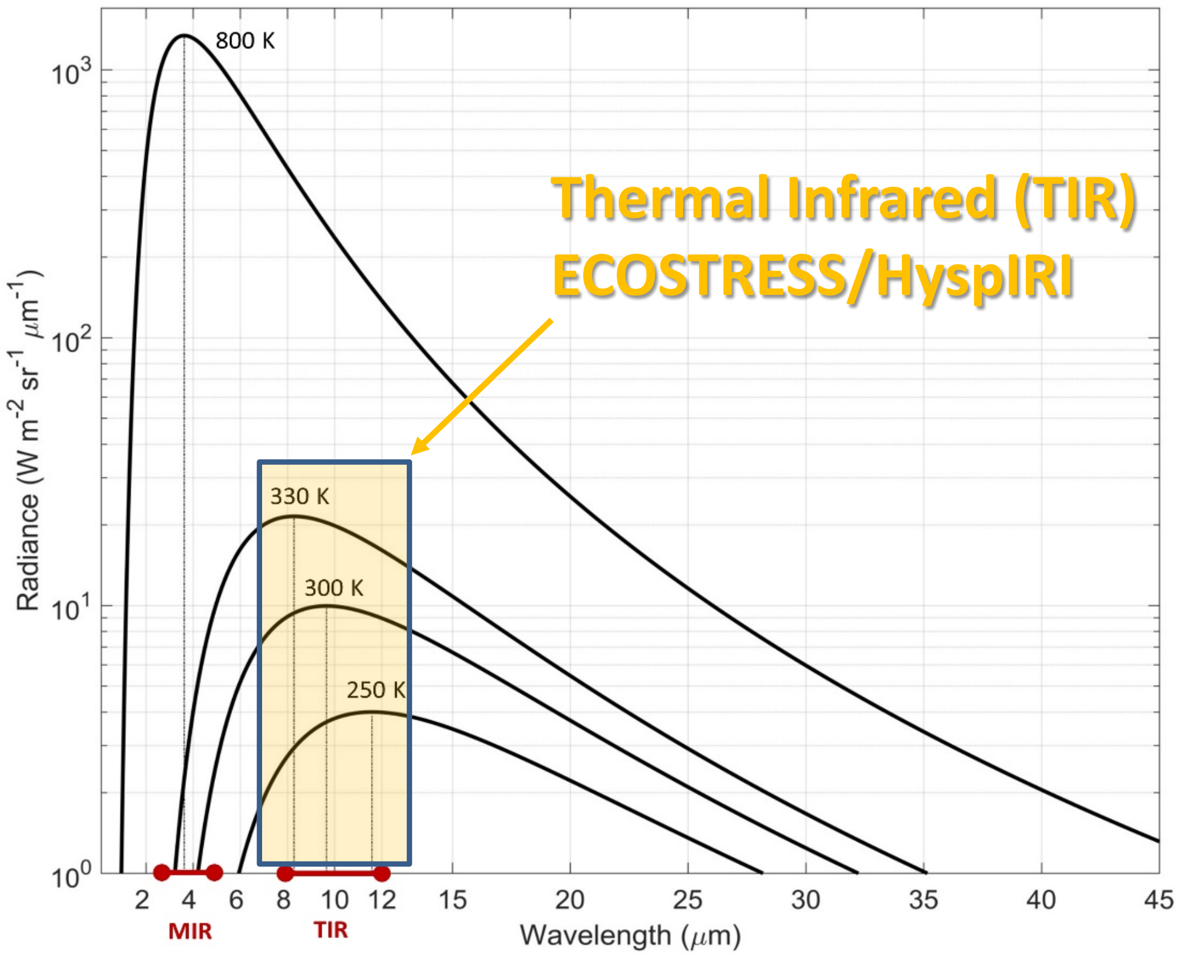
B_λ = blackbody spectral radiance

λ = wavelength

T_s = Surface Temperature

c_1 = first radiation constant

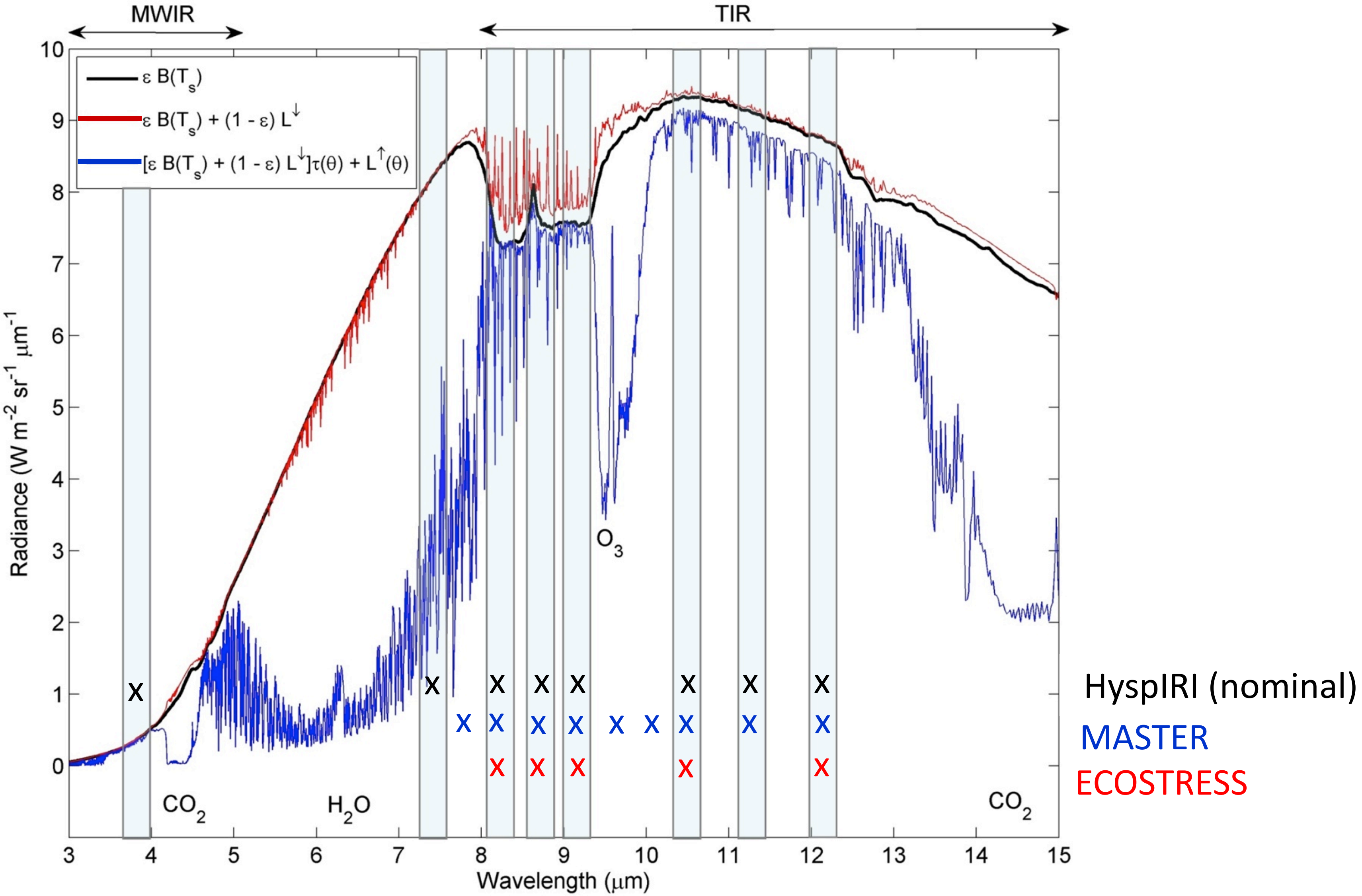
c_2 = second radiation constant



As the temperature increases the peak in the Planck function shifts to shorter and shorter wavelengths

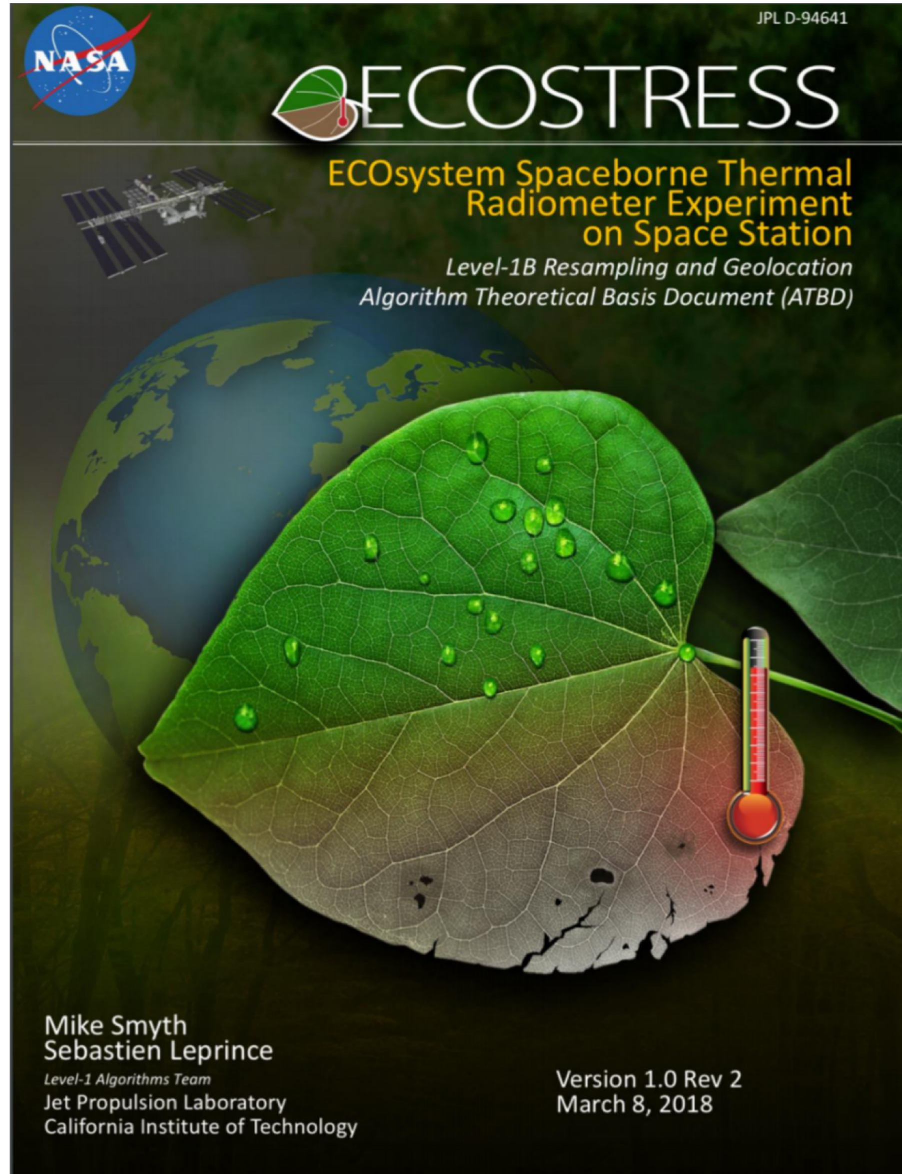
Thermal Infrared Radiative Transfer

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



L1A ATBD

L1B ATBD



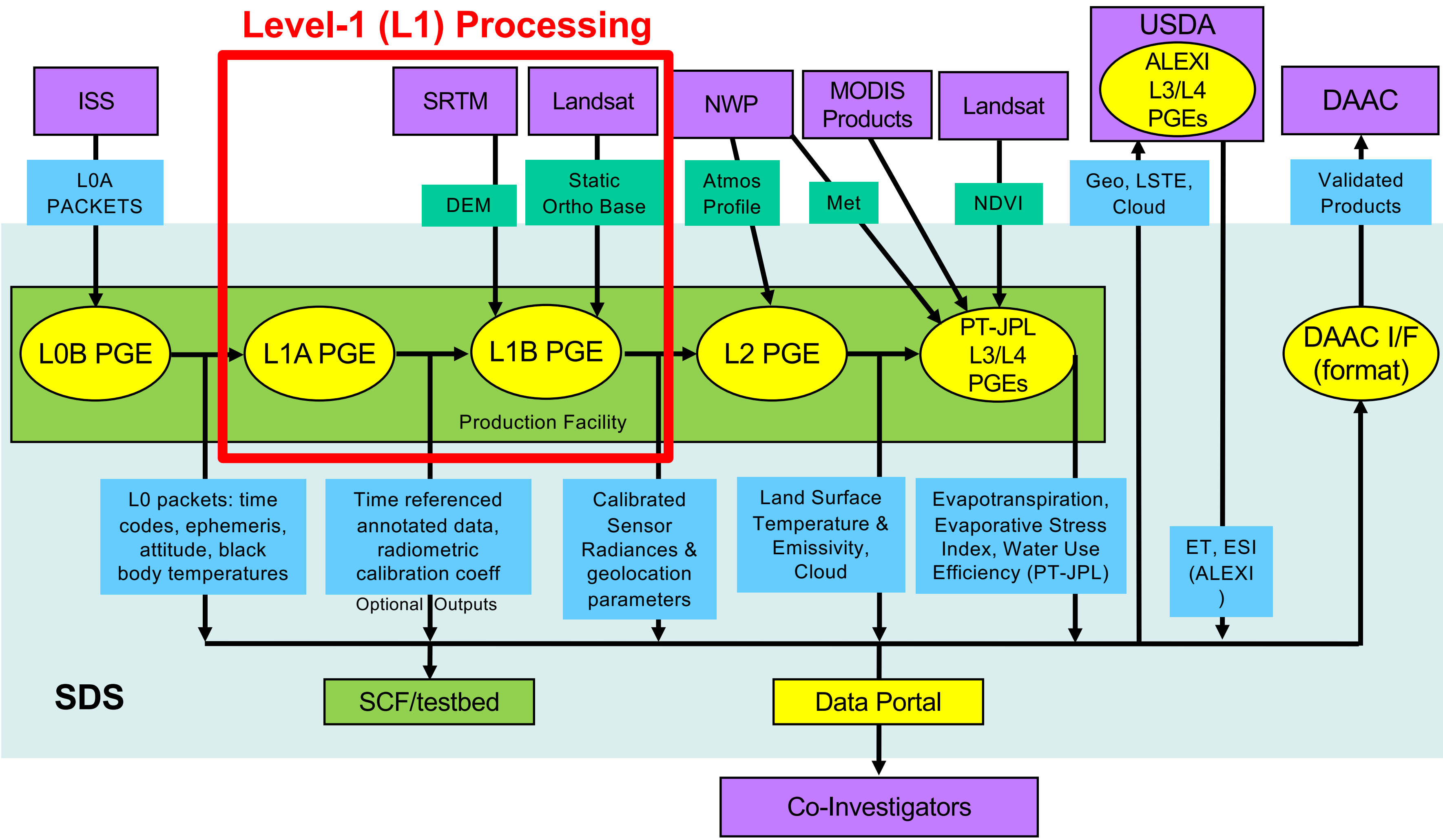
https://ecostress.jpl.nasa.gov/products/atbds-summary-table

L1 TIR Algorithm Overview

- L1 Processing consists of four PGEs (Product Generation Executable)
  - L1A
    - Raw Data Processing
      - Reformat incoming data packets, metadata, and ancillary data
    - Radiometric Calibration
      - Convert Image Pixel DNs to Radiance Coefficients
  - L1B
    - Resampling and Remapping
      - Merge Focal Plane overlap and average pixels (lines) to improve signal.
    - Geolocation
      - Initial Map Projection from ISS Ephemeris and Pointing data
      - Geolocation Matching (using Landsat orthobase) to correct for Positional Errors

L1 Overview - ECOSTRESS

L1 in the SDS Processing Flow

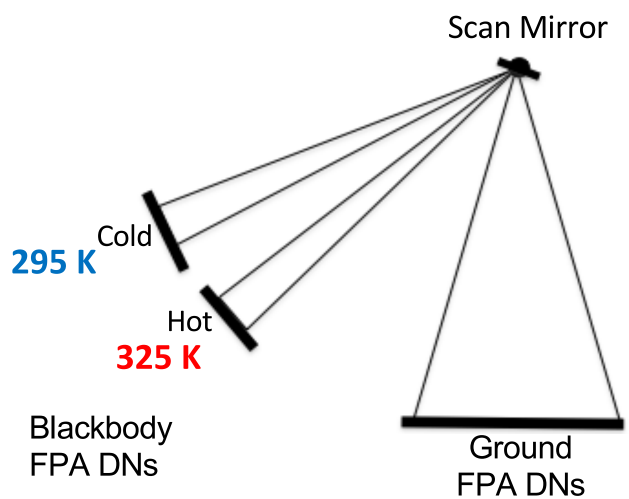


L1A Radiometric Calibration PGE

L1A Radiometric Two-Point Calibration*

Approach

- Read BB Temperatures.
- Create synthetic FPA 256x1 BB Temperature Images.
- Convert FPA BB Images to Radiances
- Collect FPA BB and Ground DNs.
- Apply 2pt Algorithm →



$$R_\lambda = a + bD_\lambda$$

$$a = \frac{R_h D_c - R_c D_h}{D_c - D_h} \qquad b = \frac{R_c - R_h}{D_c - D_h}$$

Where:

R = *Calculated Radiance of an input Digital Number (DN)*

a = *Offset Term*

b = *Gain Term*

D = *Input Earth Digital Number (DN)*

R_c = *Radiance of the Cold Blackbody (Section 3.3.2)*

R_h = *Radiance of the Hot Blackbody (Section 3.3.2)*

D_c = *Digital Number (DN) from the Cold Blackbody Calibration File (Section 3.3.3)*

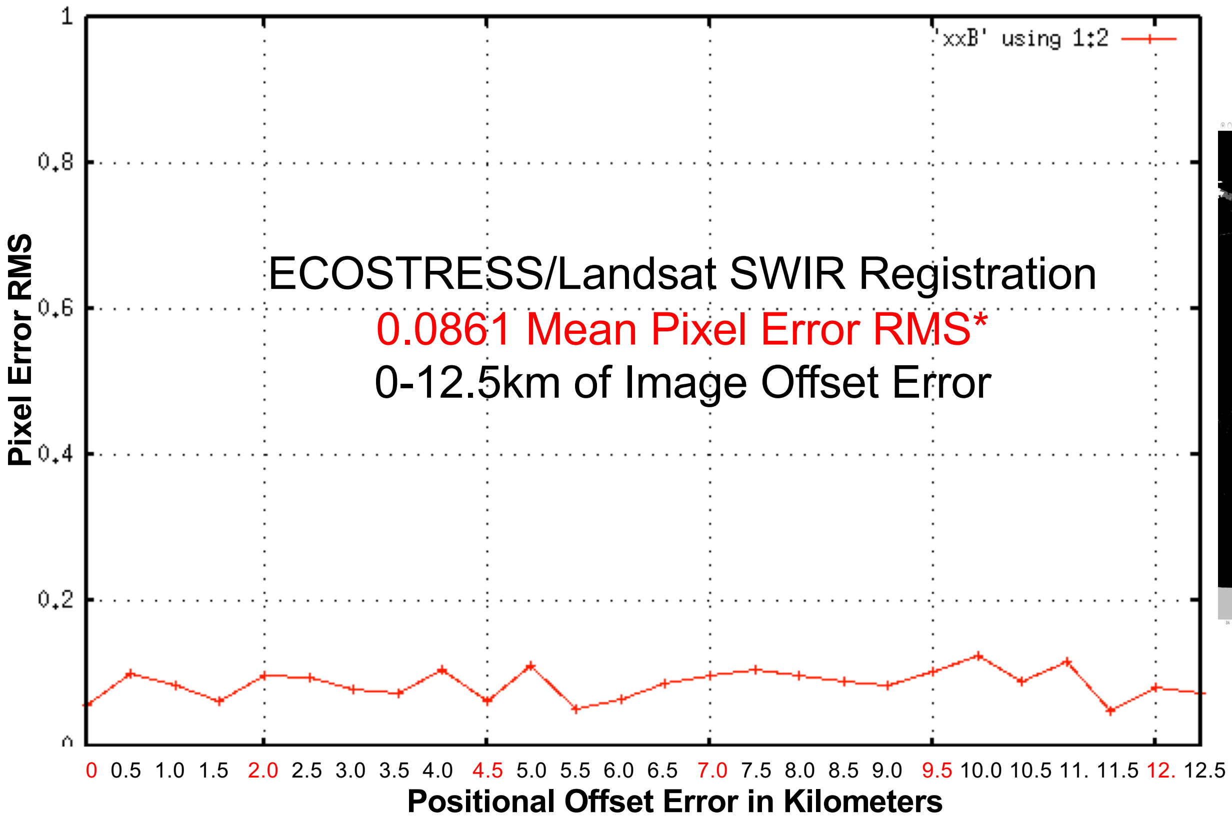
D_h = *Digital Number (DN) from the Hot Blackbody Calibration File (Section 3.3.3)*

Demonstrated accuracy at <0.5 K

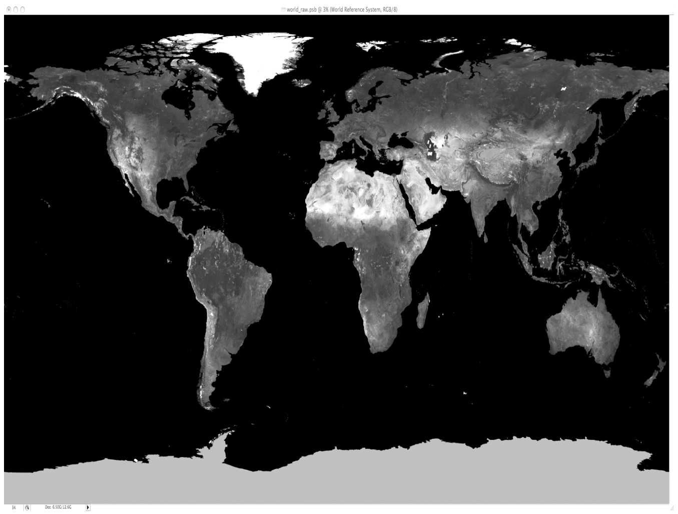
*Documented in: "Level-1 Focal Plane Array and Radiometric Calibration Algorithm Theoretical Basis Document (ATBD)," JPL D-94803.

L1B Geolocation Testbed

SWIR 1.6um Co-Registration Test Results (0-12.5km Offset)

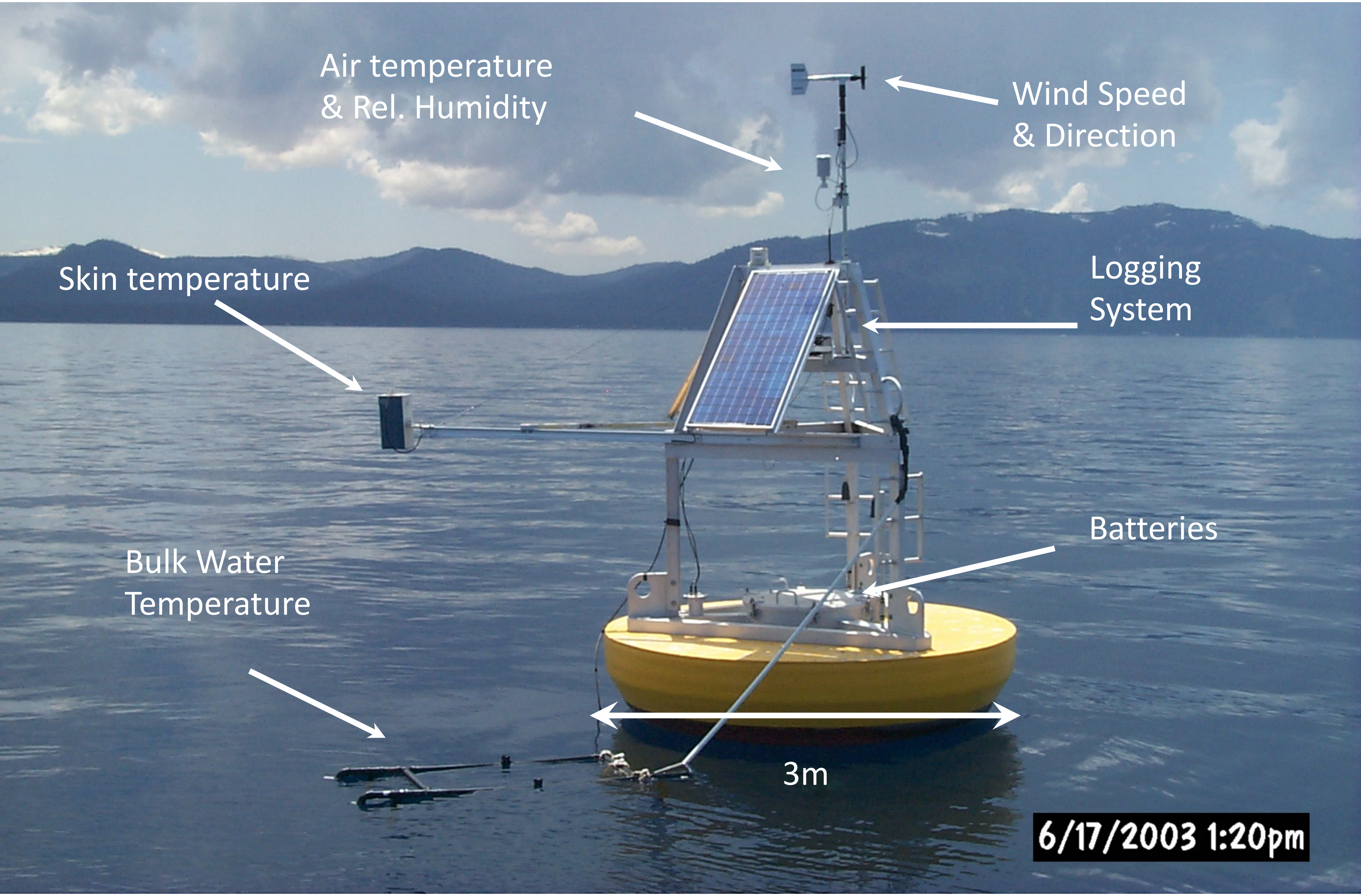


Landsat 7 Global Ortho-Base SWIR/TIR



*Using Pre-Launch AFIDS beta code

Lake Tahoe Cal/Val

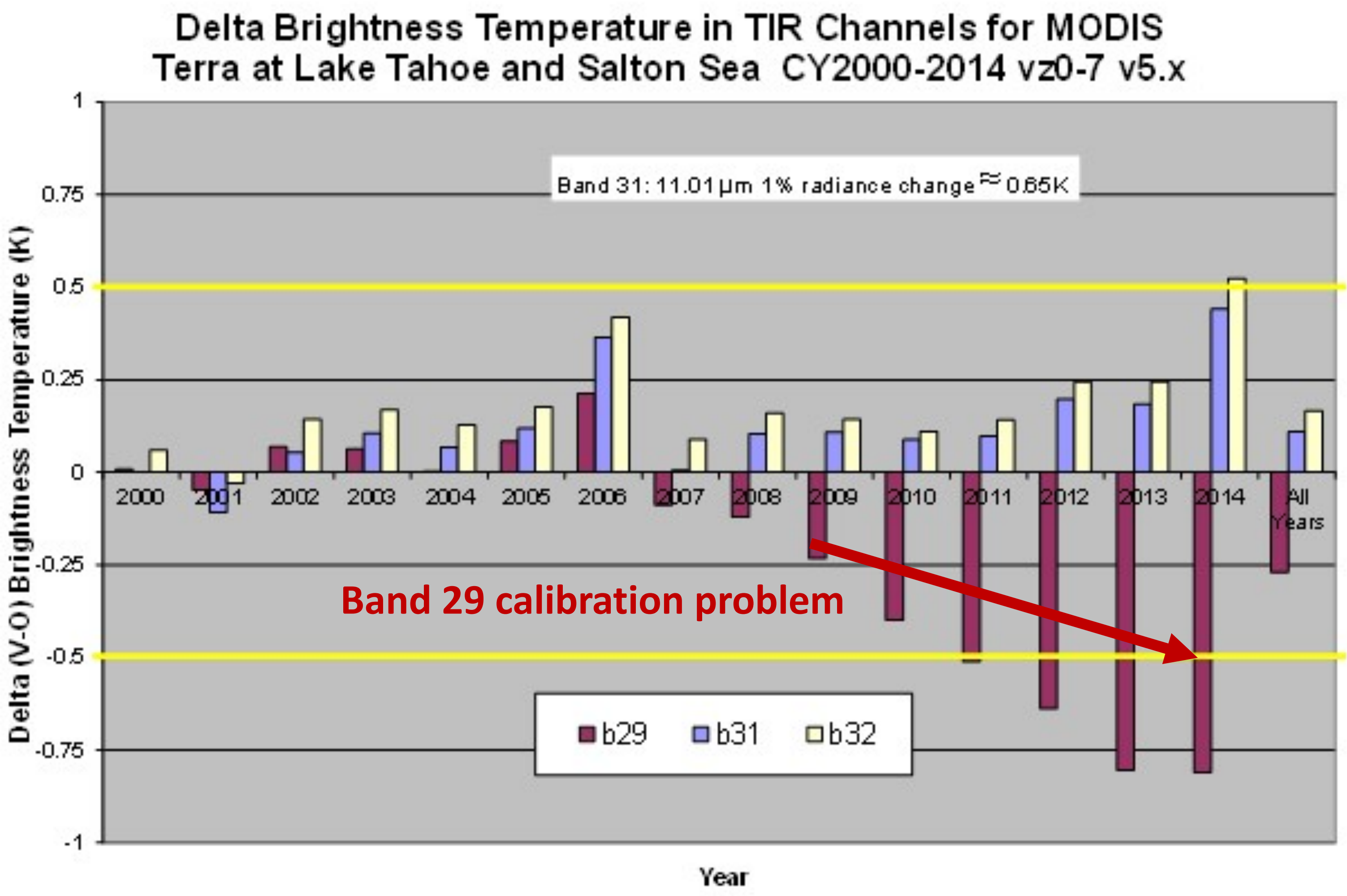


Radiometer Calibration - JPL

Bill Johnson

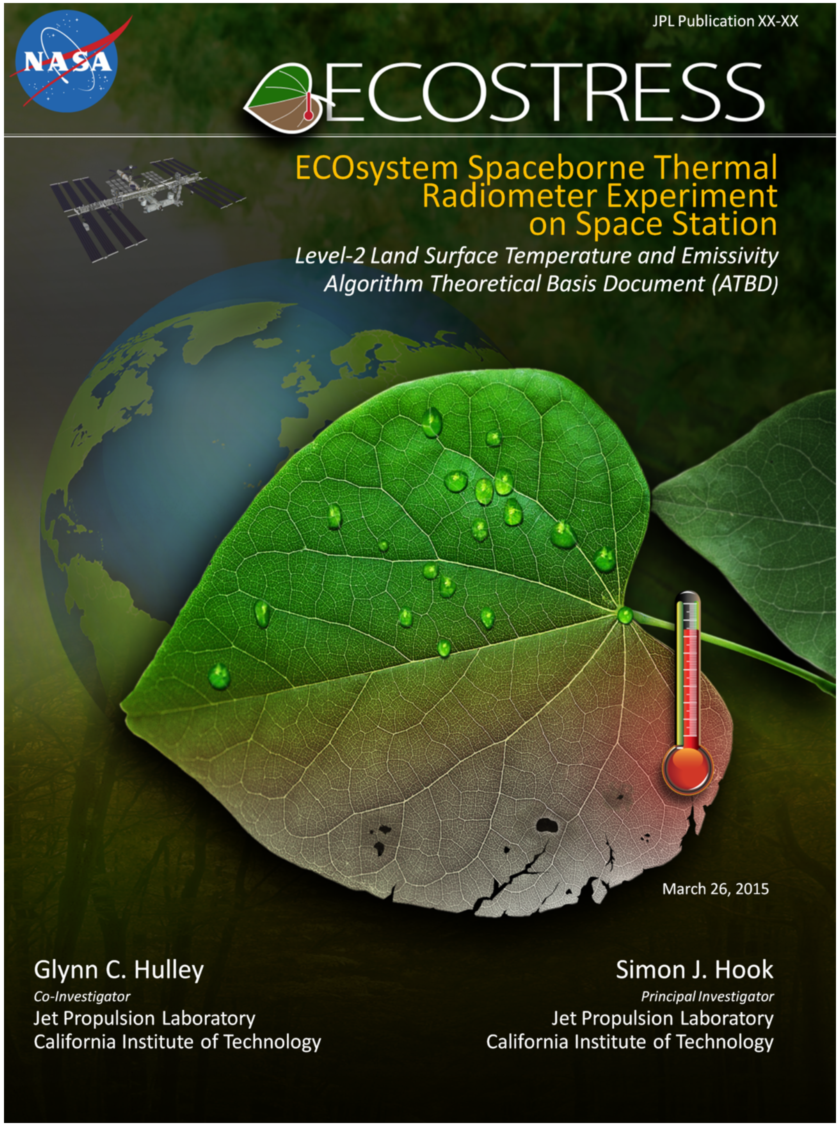
Brightness Temperature at Sensor : On-orbit Validation

Example results from MODIS



ECOSTRESS L2 ATBD

https://ecostress.jpl.nasa.gov/products/


JPL Publication XX-XX

ECOSTRESS

ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station

Level-2 Land Surface Temperature and Emissivity Algorithm Theoretical Basis Document (ATBD)

March 26, 2015

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HyspIRI L2 ATBD

https://hyspiri.jpl.nasa.gov/documents


JPL Publication 11-5

HyspIRI Level-2 Thermal Infrared (TIR) Land Surface Temperature and Emissivity Algorithm Theoretical Basis Document

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National Aeronautics and Space Administration

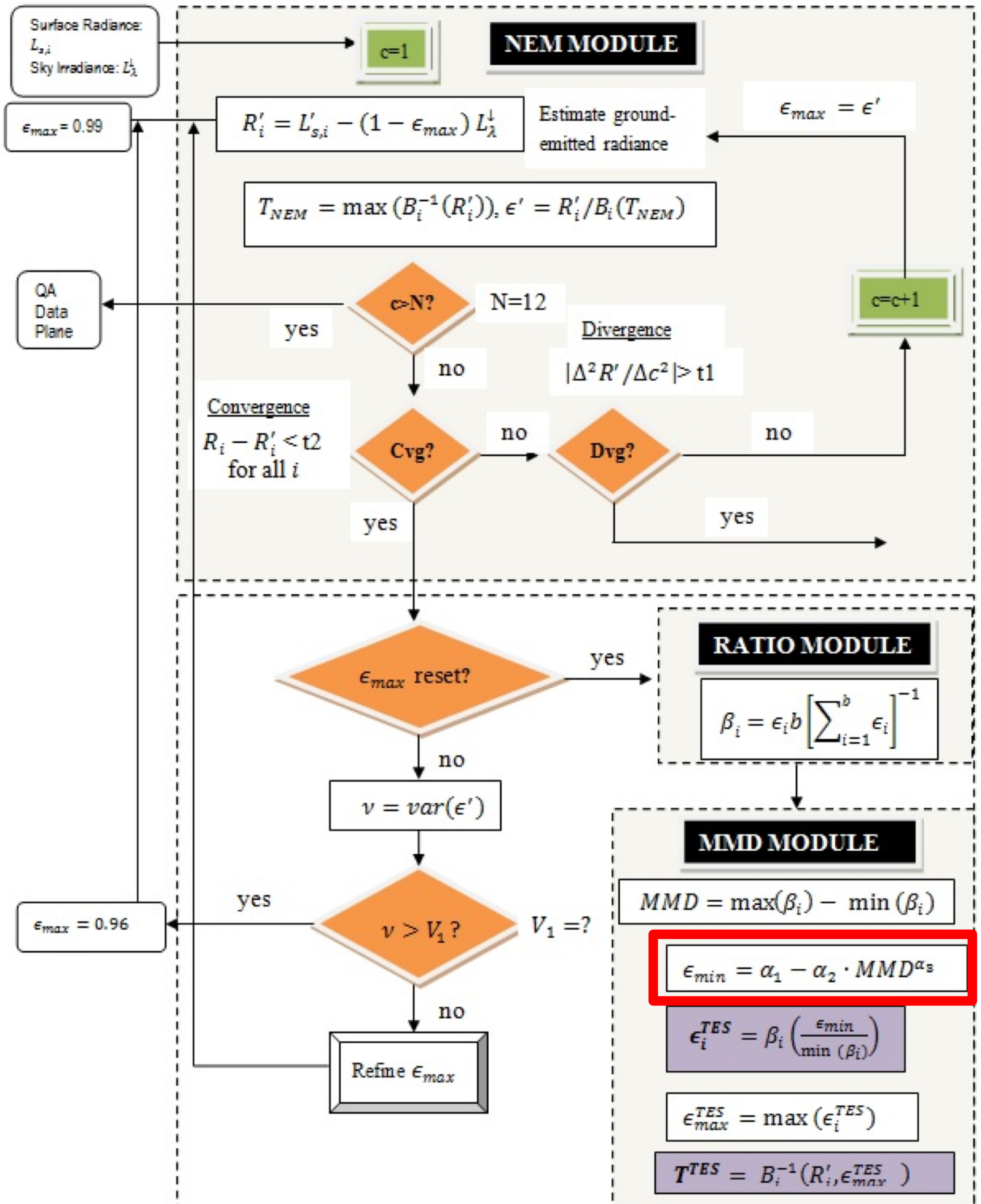
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

May 2011

L2 Temperature Emissivity Separation (TES) Heritage

LST&E Product Characteristics	ASTER *Terra - 2000*	MODIS *Terra – 2000* *Aqua - 2002*	VIIRS *NPP - 2011*	ECOSTRESS *ISS - 2018*
Core Algorithm	**TES***	**TES***	**TES***	**TES***
Product	AST05/08 - 2000	MOD21	VNP21	LSTE - 2018
Bands used	10 (8.3 µm) 11 (8.6 µm) 12 (9.1 µm) 13 (10.6 µm) 14 (11.3 µm)	29 (8.55 µm) 31 (11 µm) 32 (12 µm)	14 (8.55 µm) 15 (10.76 µm) 16 (12 µm)	1 (8.3 µm) 2 (8.6 µm) 3 (9.1 µm) 4 (11.2 µm) 5 (12 µm)
Radiative Transfer Model	MODTRAN	RTTOV	RTTOV	RTTOV
Atmospheric Profiles	NCEP/MOD07	MERRA-2 WVS model	MERRA-2 WVS model	GEOS5 WVS model
Spatial and Temporal Resolution	90 m 16-day	1-km Twice daily (am/pm)	750 m Twice daily (am/pm)	70 m Variable (CONUS – 5 day)
Science Data Products	- LST - Emissivity (bands 10-14)	- LST - Emissivity (bands 29, 31, 32)	- LST - Emissivity (bands 14, 15, 16)	- LST - Emissivity (bands 1-5)

***TES = Temperature Emissivity Separation Algorithm (Gillespie 1998, Hulley et al. 2012)**



TES Algorithm

LST&E Products using TES:

- ASTER 05/08
- MOD21 C6
- ASTER GED
- MASTER
- HyTES
- ECOSTRESS LSTE
- VIIRS VNP21

Temperature Emissivity Separation (TES) Algorithm

T-E separation is under-determined (ill-posed):

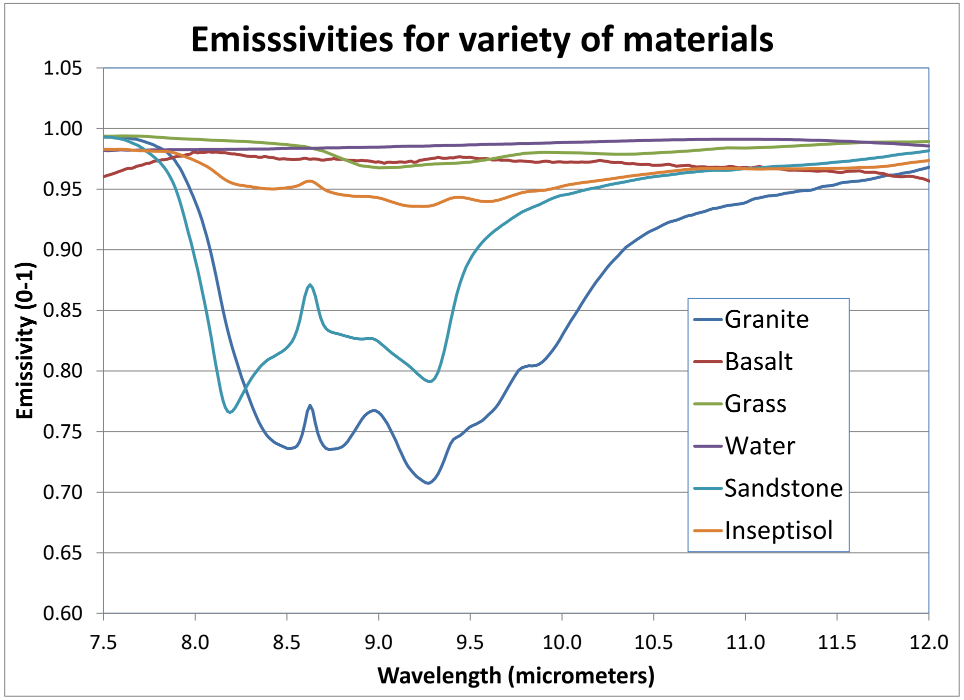
If have *N* measurements, always have *N+1* unknowns:

Radiance Band 1 = T + emissivity_1

Radiance Band 2 = T + emissivity_2

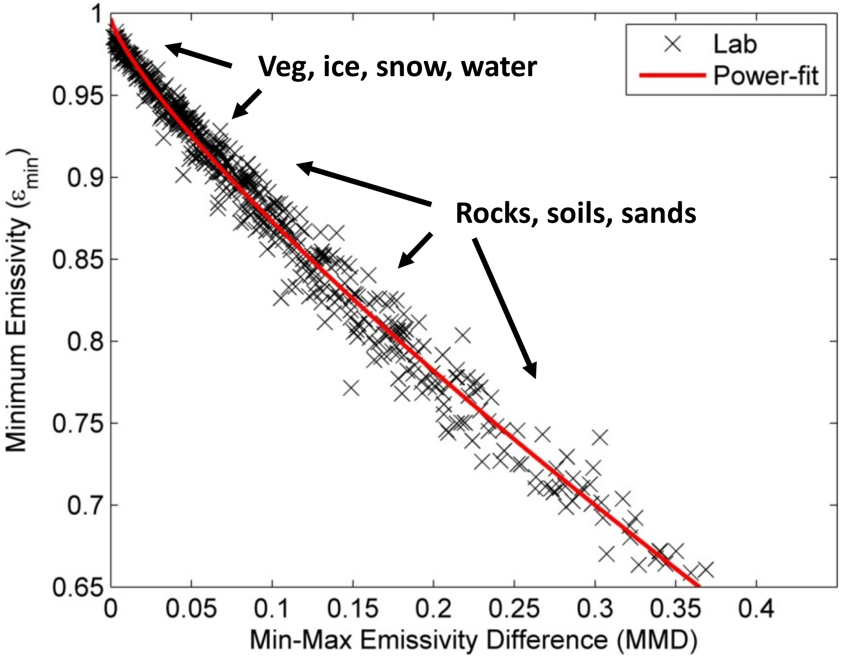
Radiance Band 3 = T + emissivity_3

…………………………. ……………………….



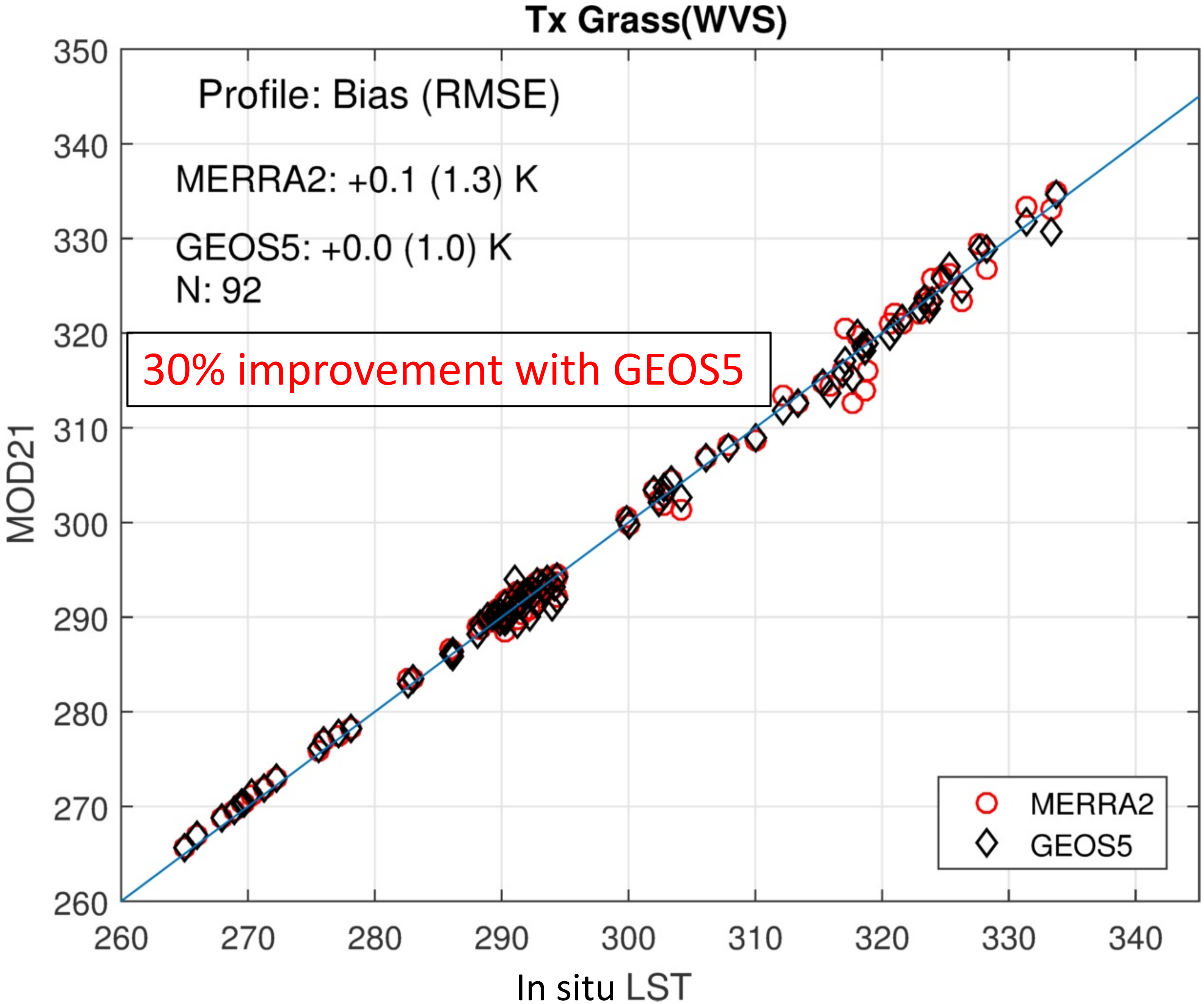
Emissivity Calibration Curve

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



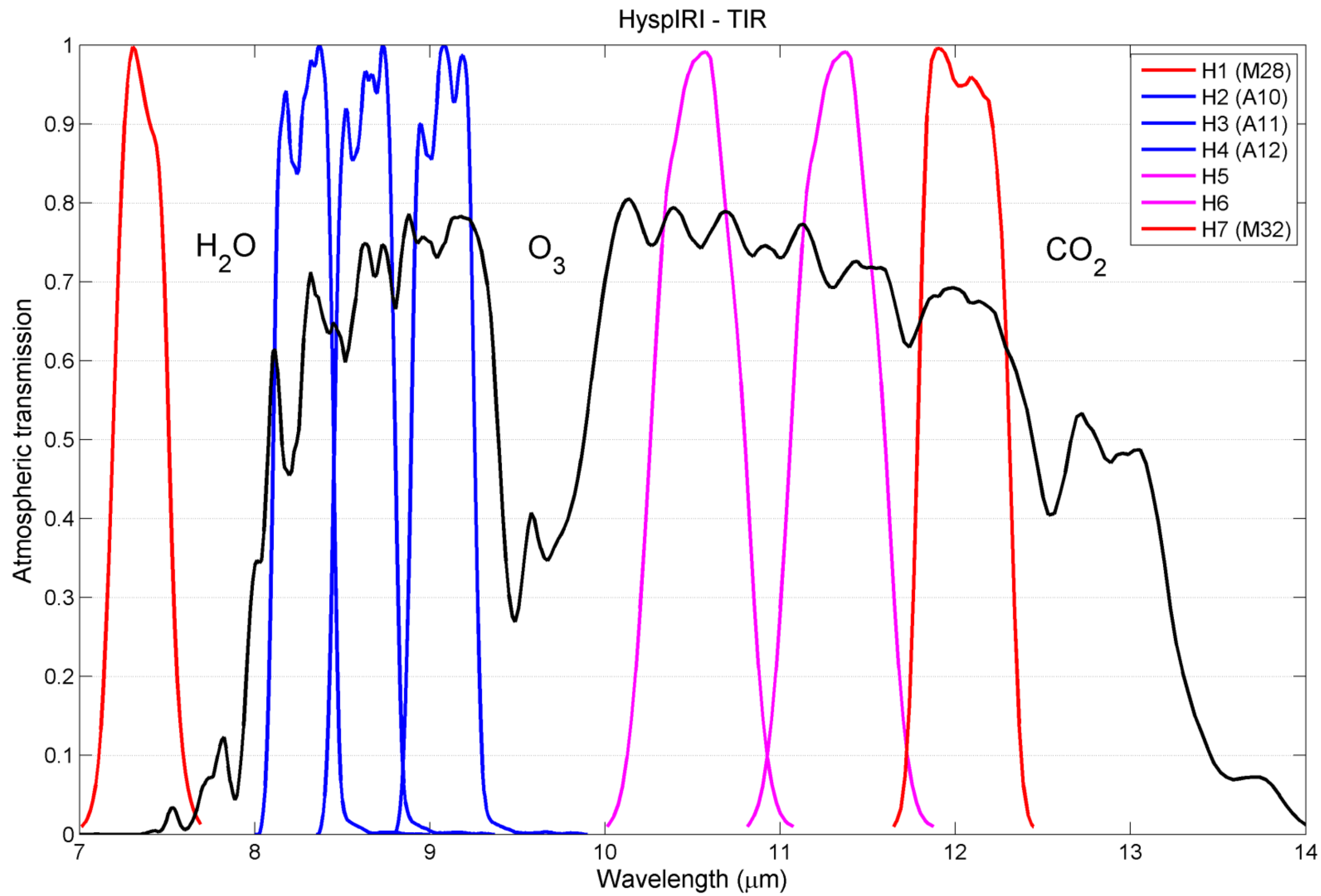
Atmospheric correction: NASA NWP models

NASA GMAO	MERRA-2	GEOS-5 FP
Description	Reanalysis from 1979-present	Analyses and forecasts in near real-time using recent GEOS-5 model
Spatial Resolution	0.5 degree (~50 km)	0.25 degree (~25 km)
Temporal Resolution	6 hourly	3 hourly
Vertical Resolution	42 pressure levels	42 pressure levels
Geophysical Data	Temperature, humidity, pressure	Temperature, humidity, pressure
Latency	Monthly	Daily



Tx Grass(WVS)
Profile: Bias (RMSE)
MERRA2: +0.1 (1.3) K
GEOS5: +0.0 (1.0) K
N: 92
30% improvement with GEOS5
MERRA2
GEOS5
MOD21
In situ LST
350
340
330
320
310
300
290
280
270
260
260
270
280
290
300
310
320
330
340

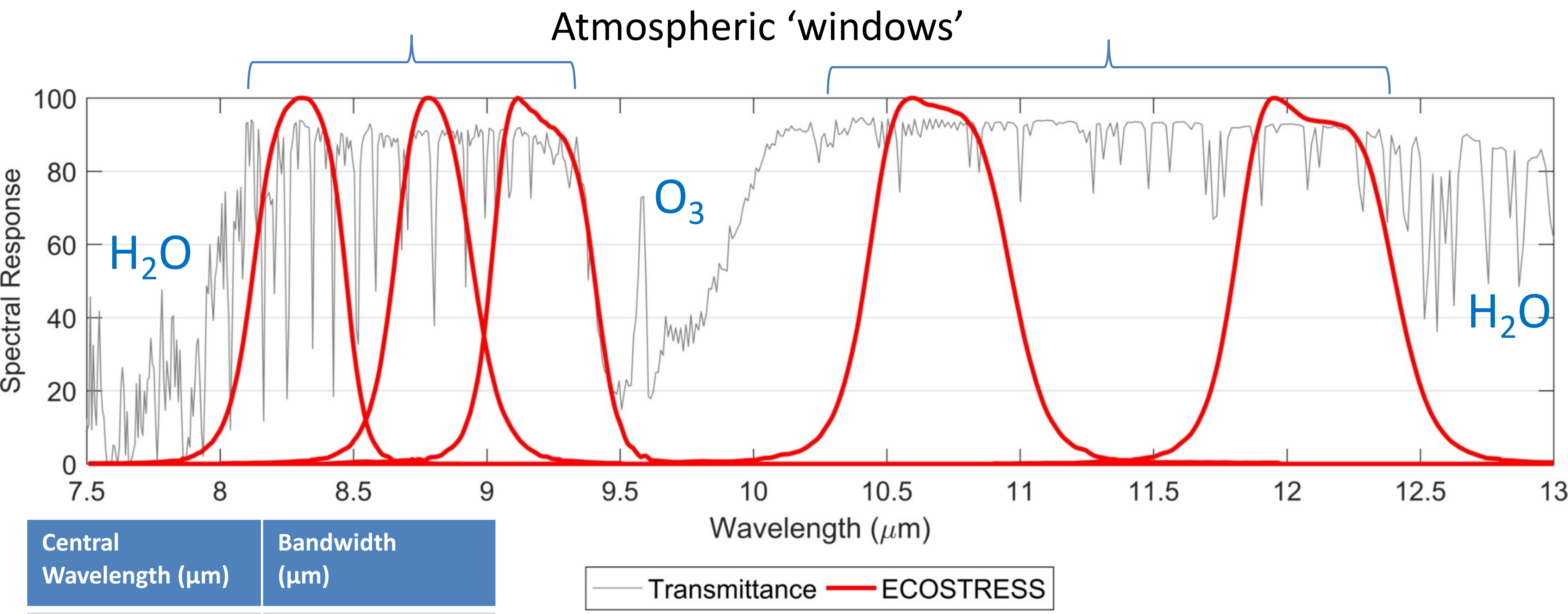
HyspIRI TIR Response Functions (Nominal)



HyspIRI TIR band study report – Ramsey, Realmuto, Hulley

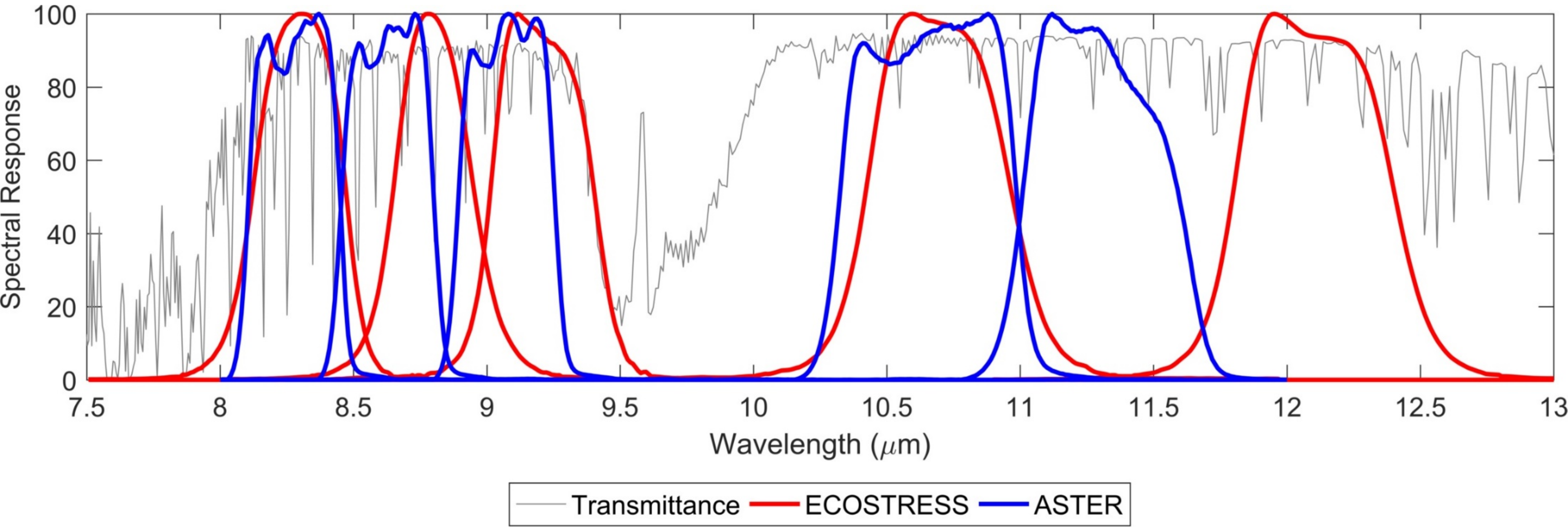
https://hyspiri.jpl.nasa.gov/downloads/reports_whitepapers/

ECOSTRESS

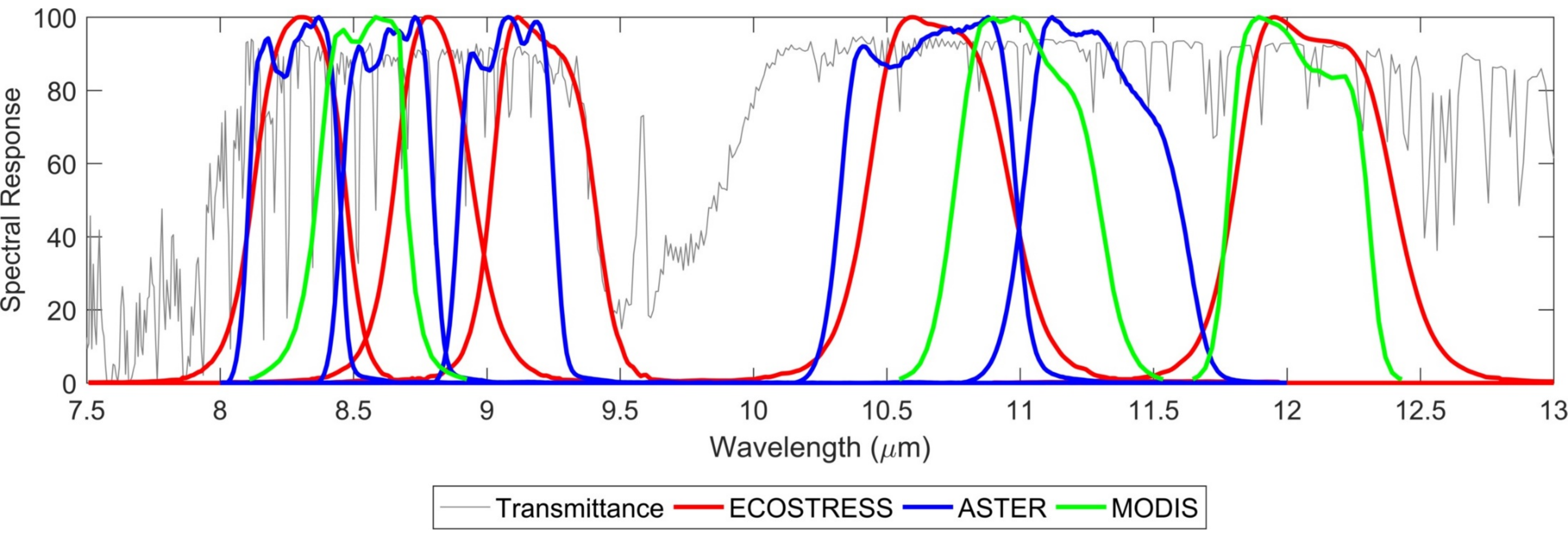


Central Wavelength (μm)	Bandwidth (μm)
8.29	0.355
8.80	0.309
9.20	0.395
10.6	0.553
12.09	0.610

Spectral Response Functions



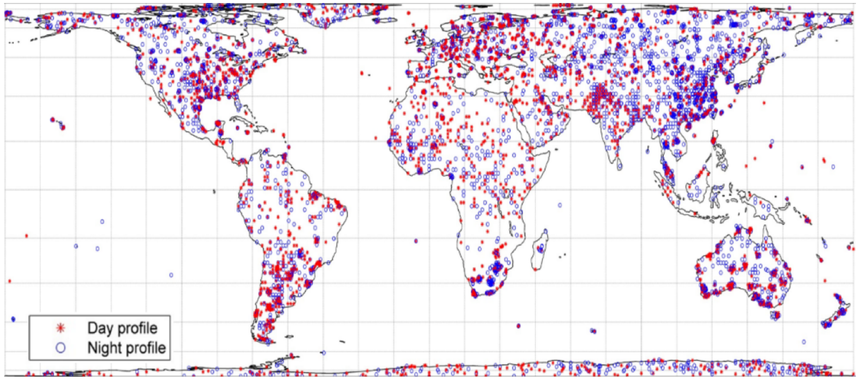
Spectral Response Functions



LST Uncertainty Analysis – number of bands

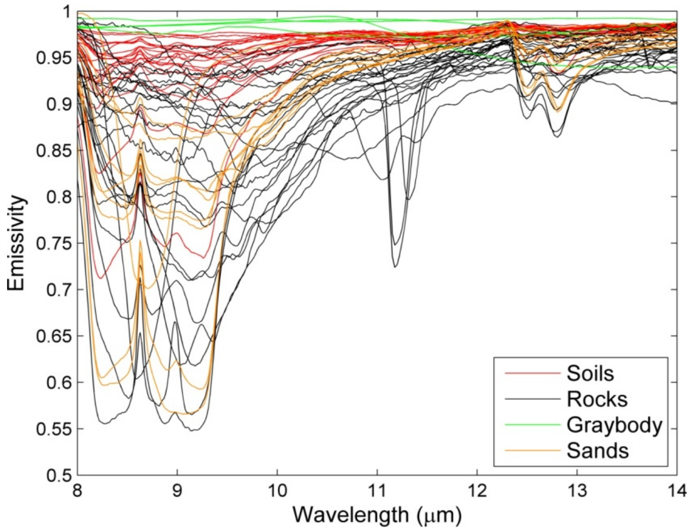
Hulley et al. 2012 (Uncertainty Analysis Study)			**LST Uncertainty (K)**			
Surface types	**Samples**	**MODTRAN Simulations**	**2 Bands Split-Window** **Landsat 8, MODIS, VIIRS**	**3 bands TES** **MODIS, VIIRS**	**5 bands TES** **ASTER, ECOSTRESS**	**6/7 bands TES** **HyspIRI/SBG**
Water, vegetation soils, rocks, sands	**111**	**9,158,832**	**2.66 K**	**1.49 K**	**1.13 K**	**1.05 K**

SeeBor Global Radiosonde database
(15,704 profiles)



\+

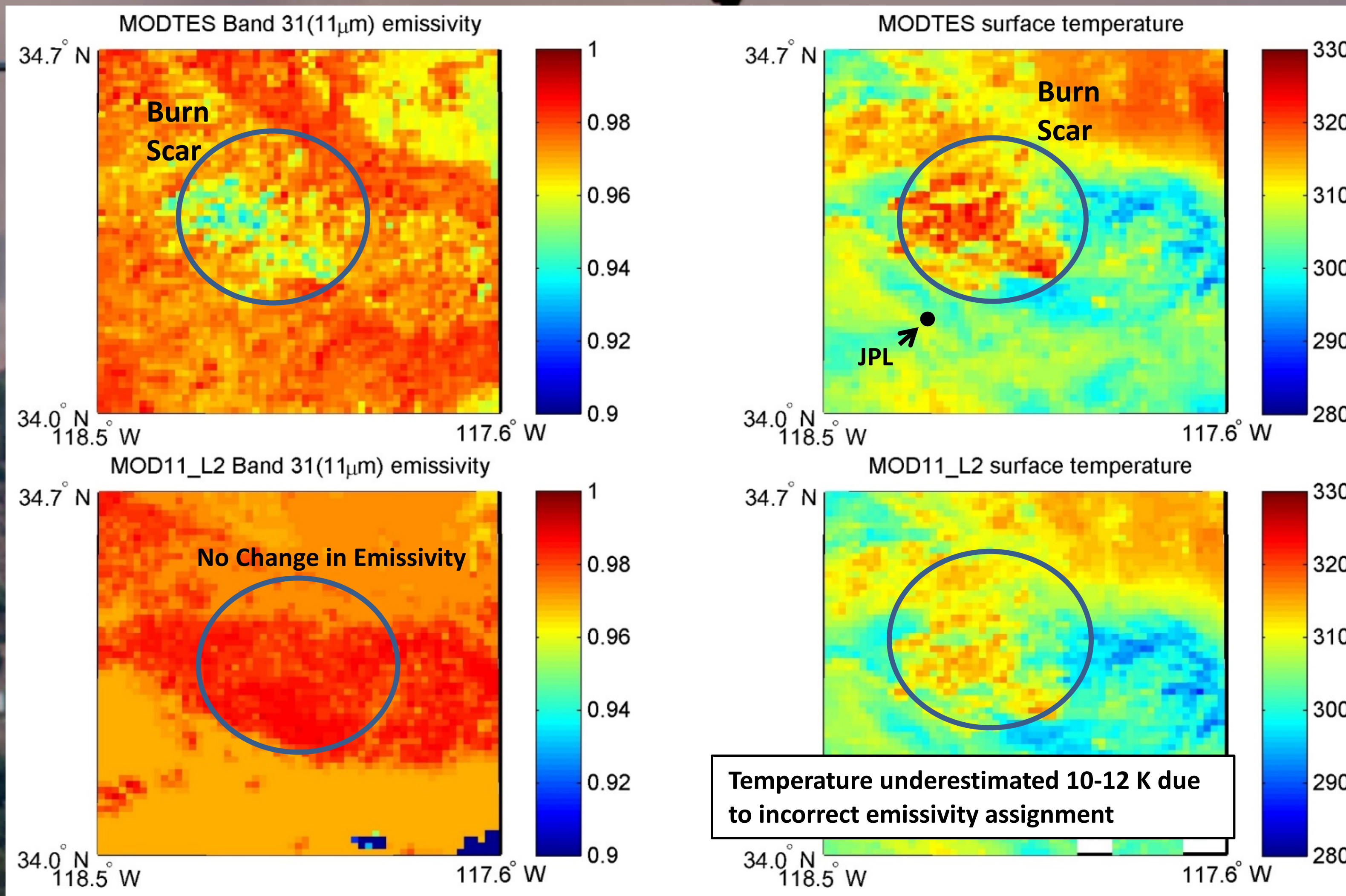
150 Surface types (ASTER speclib)



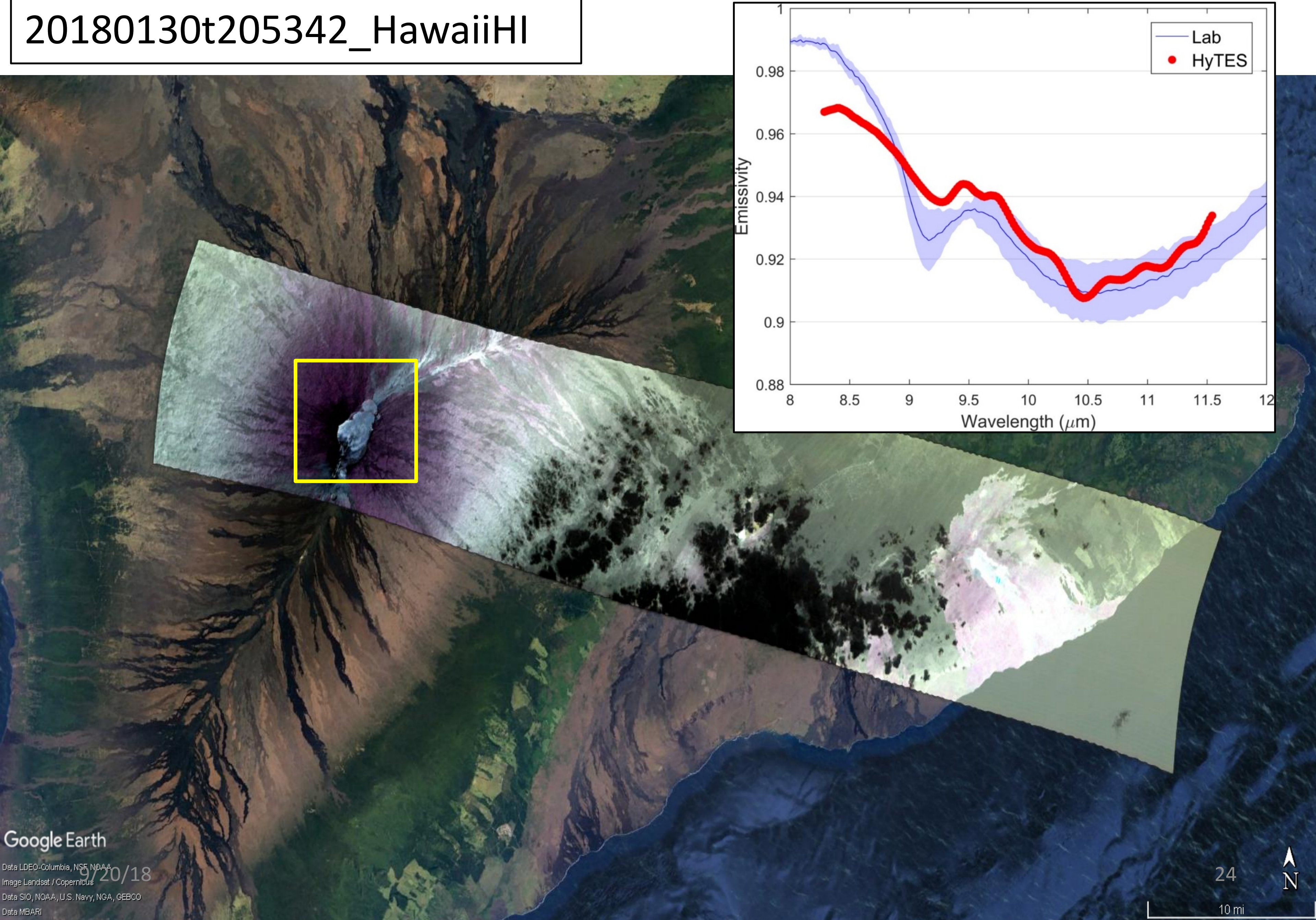
Station Fire: Multispectral capability

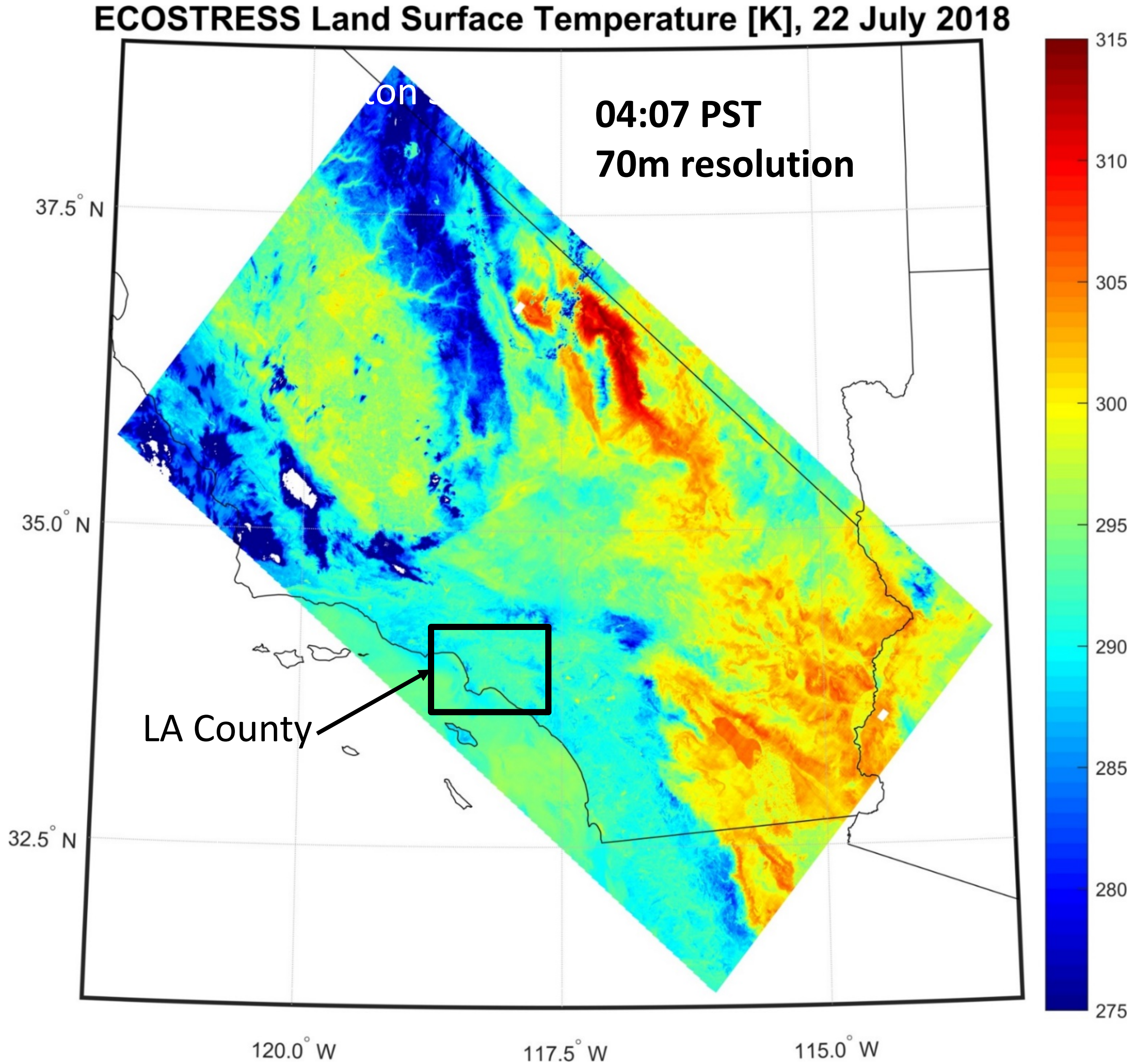
MOD21 (TES) →

MOD11 (2-band) →

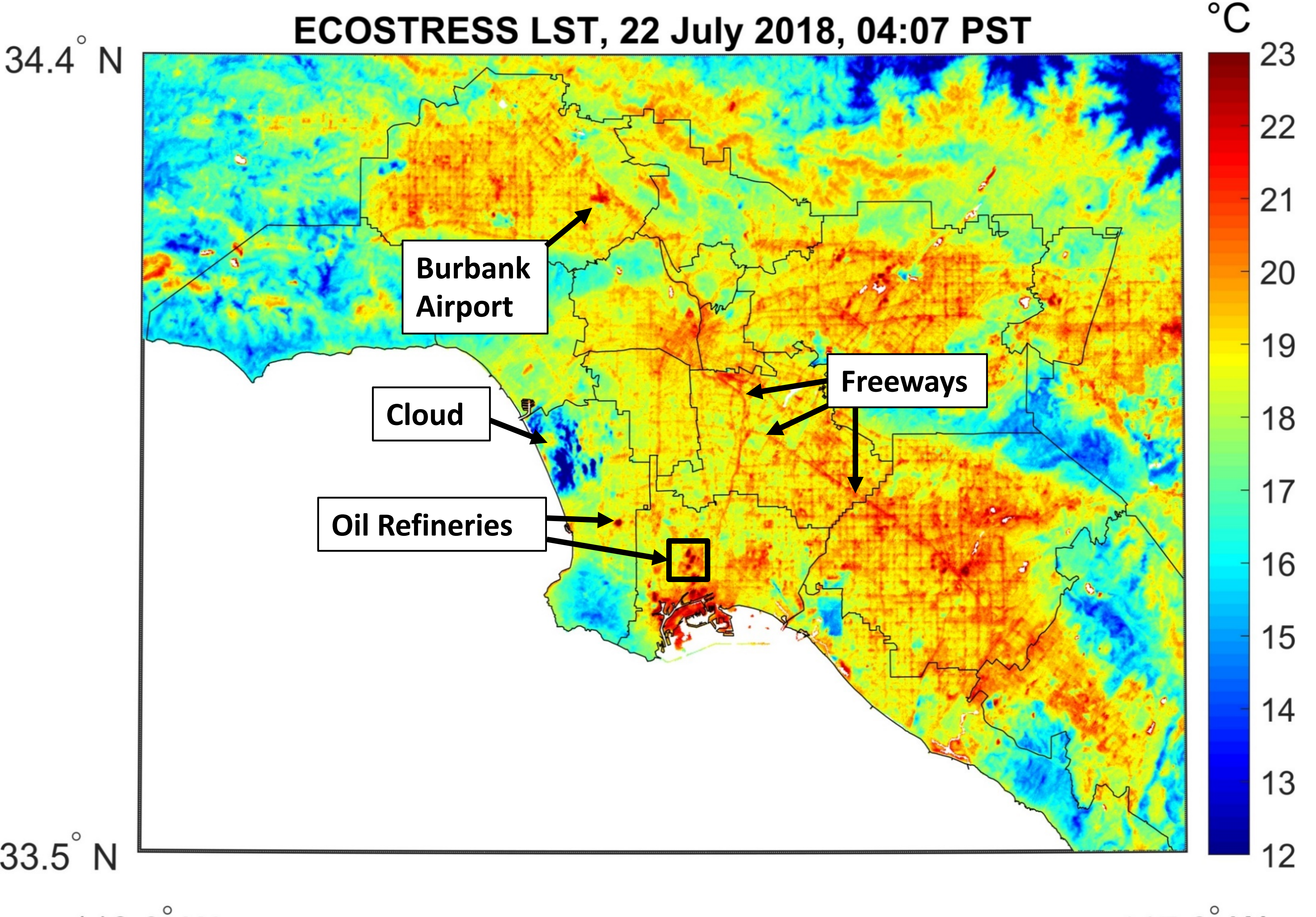


HyTES
20180130t205342_HawaiiHI

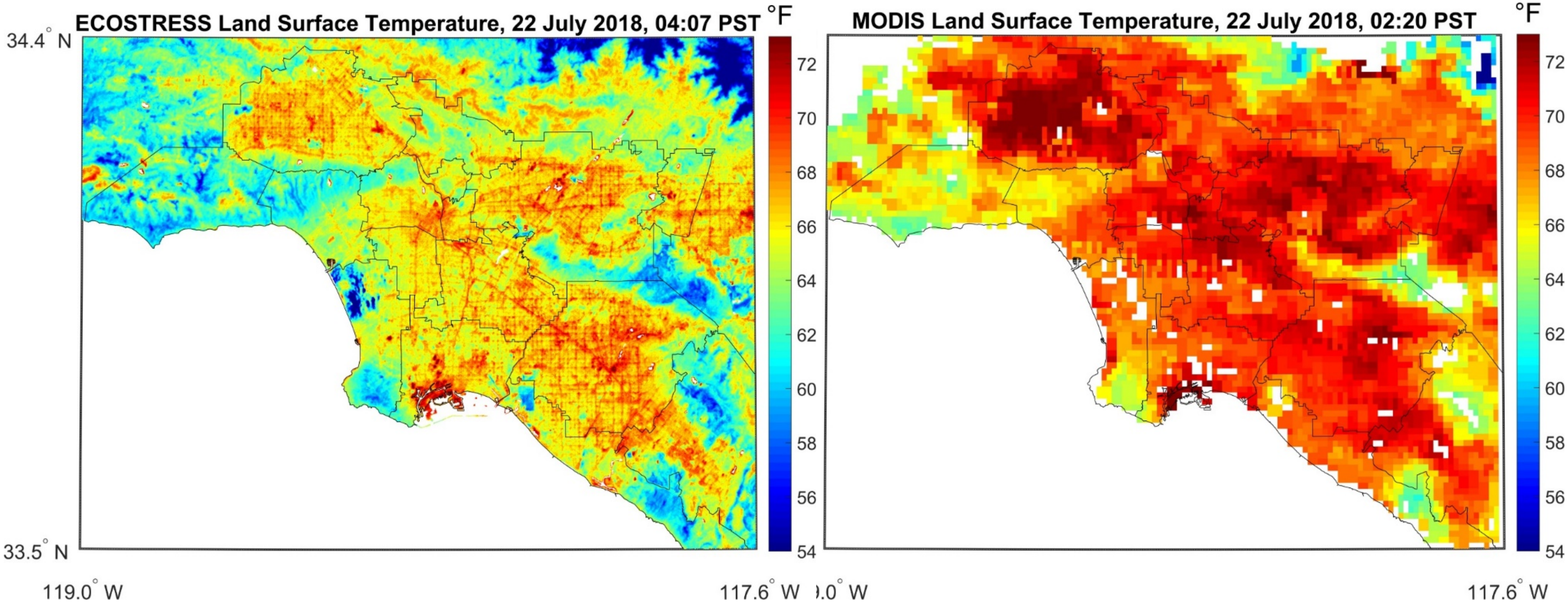




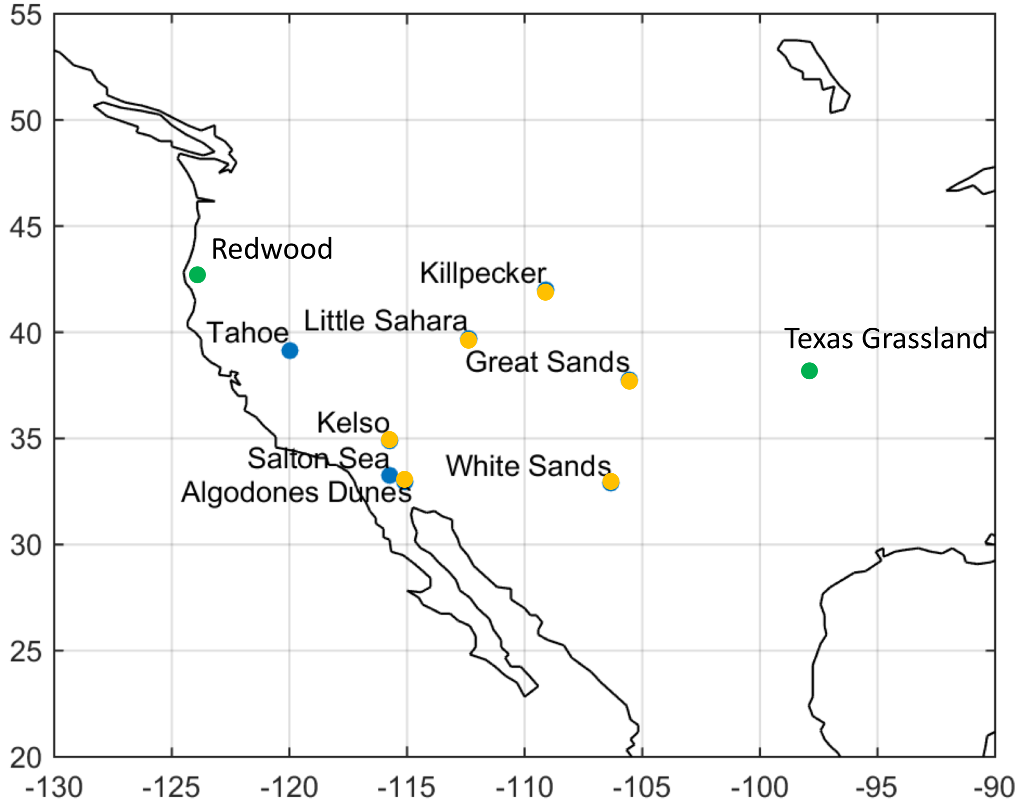
ECOSTRESS Land Surface Temperature [K], 22 July 2018
04:07 PST
70m resolution
LA County
37.5° N
35.0° N
32.5° N
120.0° W
117.5° W
115.0° W
315
310
305
300
295
290
285
280
275


ECOSTRESS LST, 22 July 2018, 04:07 PST
°C
23
22
21
20
19
18
17
16
15
14
13
12
34.4° N
33.5° N
119.0° W
117.6° W
Burbank Airport
Freeways
Cloud
Oil Refineries

ECOSTRESS (left) compared to MODIS (right) highlight ~200x improved spatial detail of temperature



LST&E Validation Sites (Stage 1)

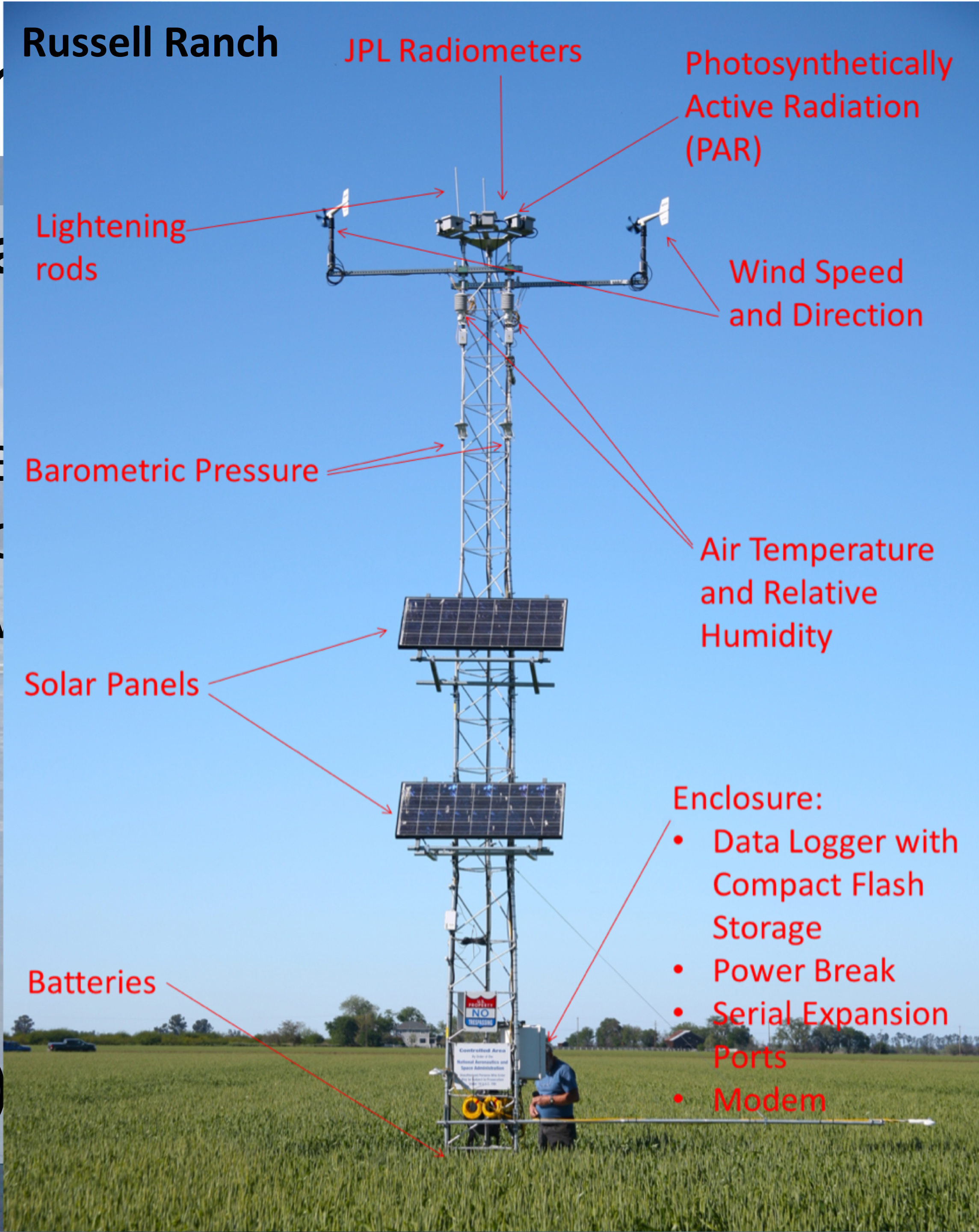


Temperature-based and Radiance-based validation methods

(Wan et al. 2008, Guillevic et al. 2012, Schneider et al. 2013, Hulley et al. 2012, Hook et al. 2007)

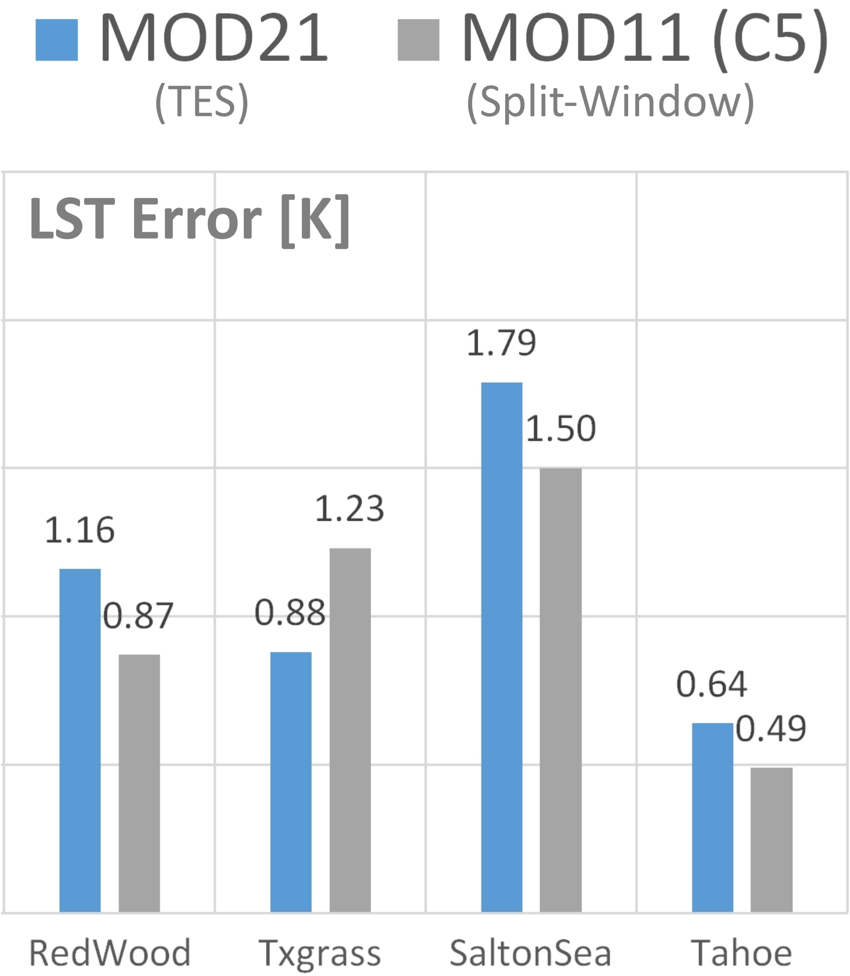
Temper

- **Method 1: Tempera**
- Measure the tempe the overpass and co temperature retriev
- Core Tval sites:
  - Lake Tahoe
  - Salton Sea
  - Russell Ranch
  - Gobabeb (Namibia)



Validation: Graybody Sites

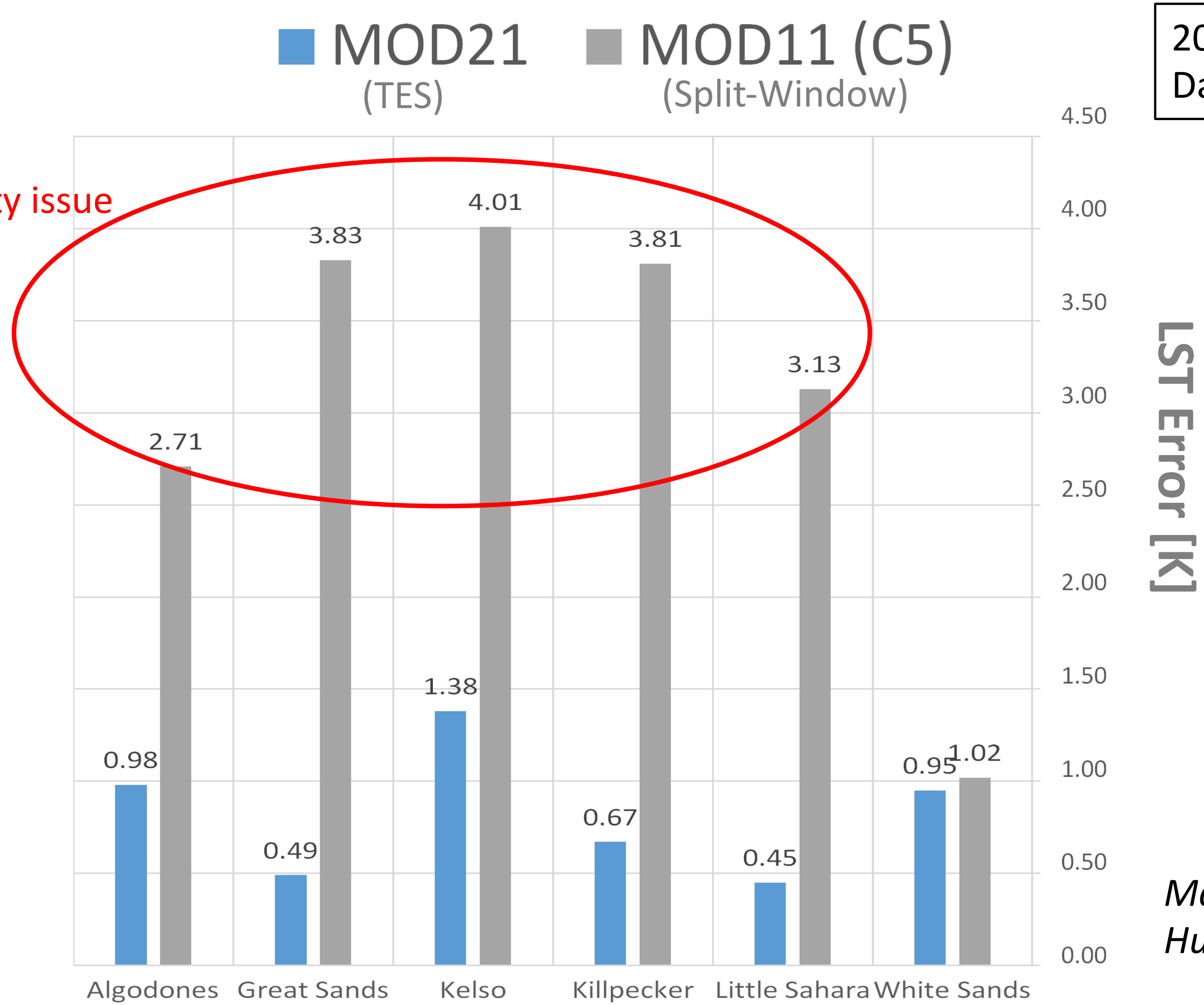
2003-2005
Day and Night



Malakar and Hulley, 2014

2003-2005
Day and Night

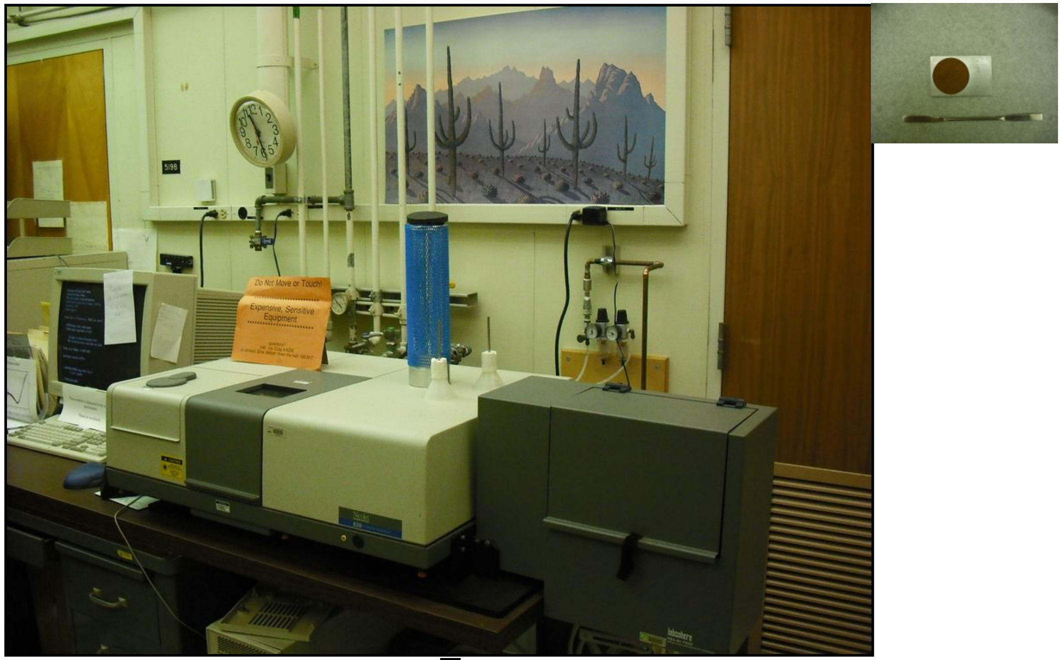
MOD11
Emissivity issue



Malakar and Hulley, 2014

Samples collected in field

Reflectance measured using Nicolet 520 FTIR spectrometer



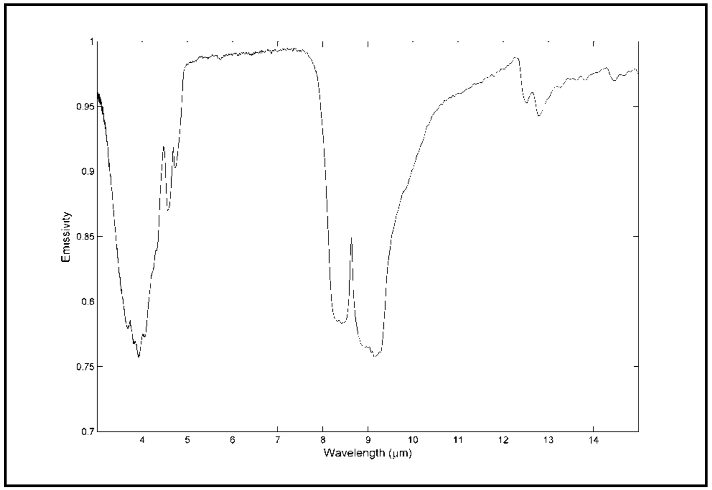
Emissivity Validation

$\varepsilon = 1 - r$

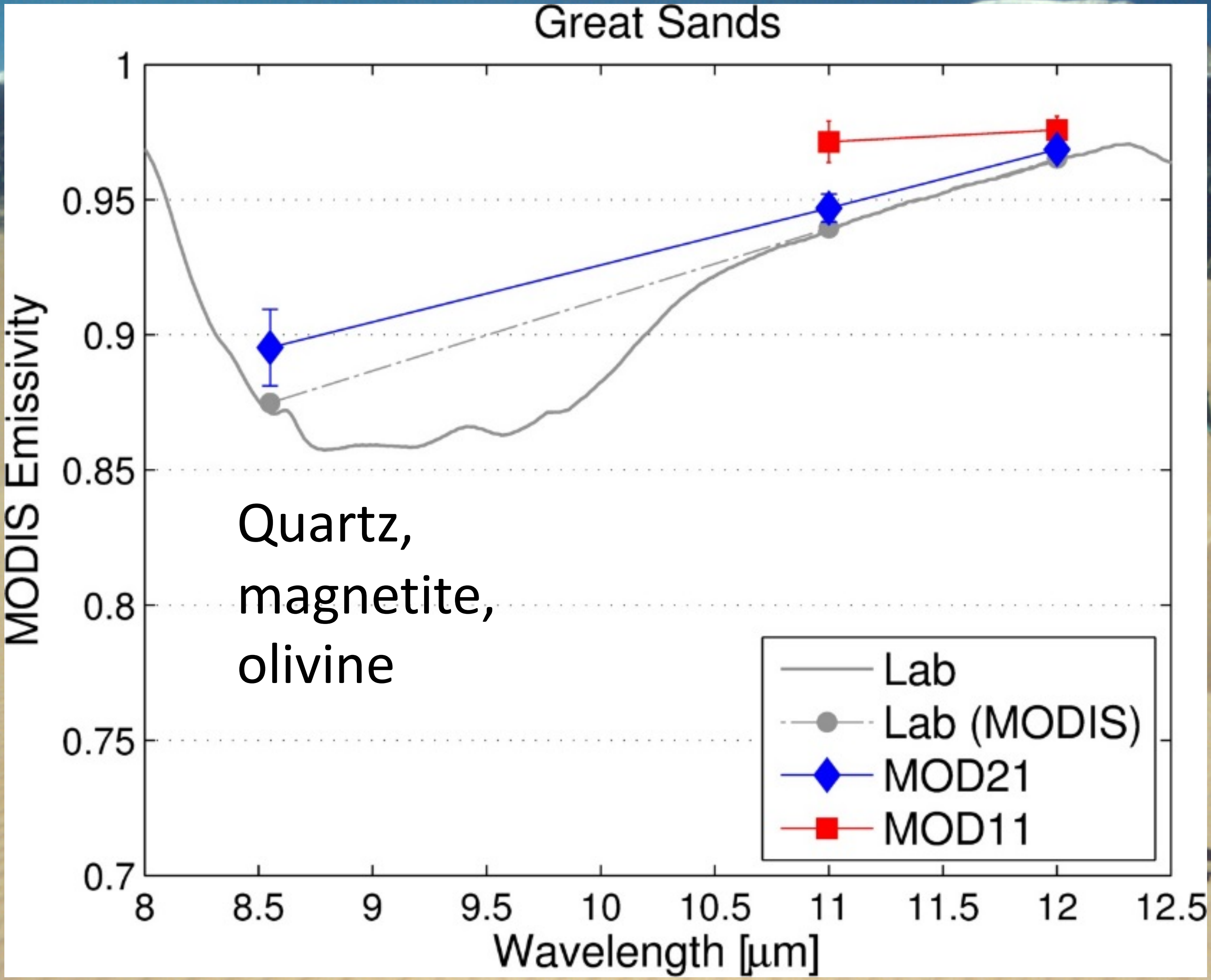
spectral range: 2.5 – 15 μm

spectral resolution: 4 cm^{-1}

1000 scans in 10 minutes



Great Sands, CO (2003-2005)



Quartz, magnetite, olivine

New TIR Field Instruments (arriving soon)

1. Nulling field portable thermal infrared imager (FLIR camera)

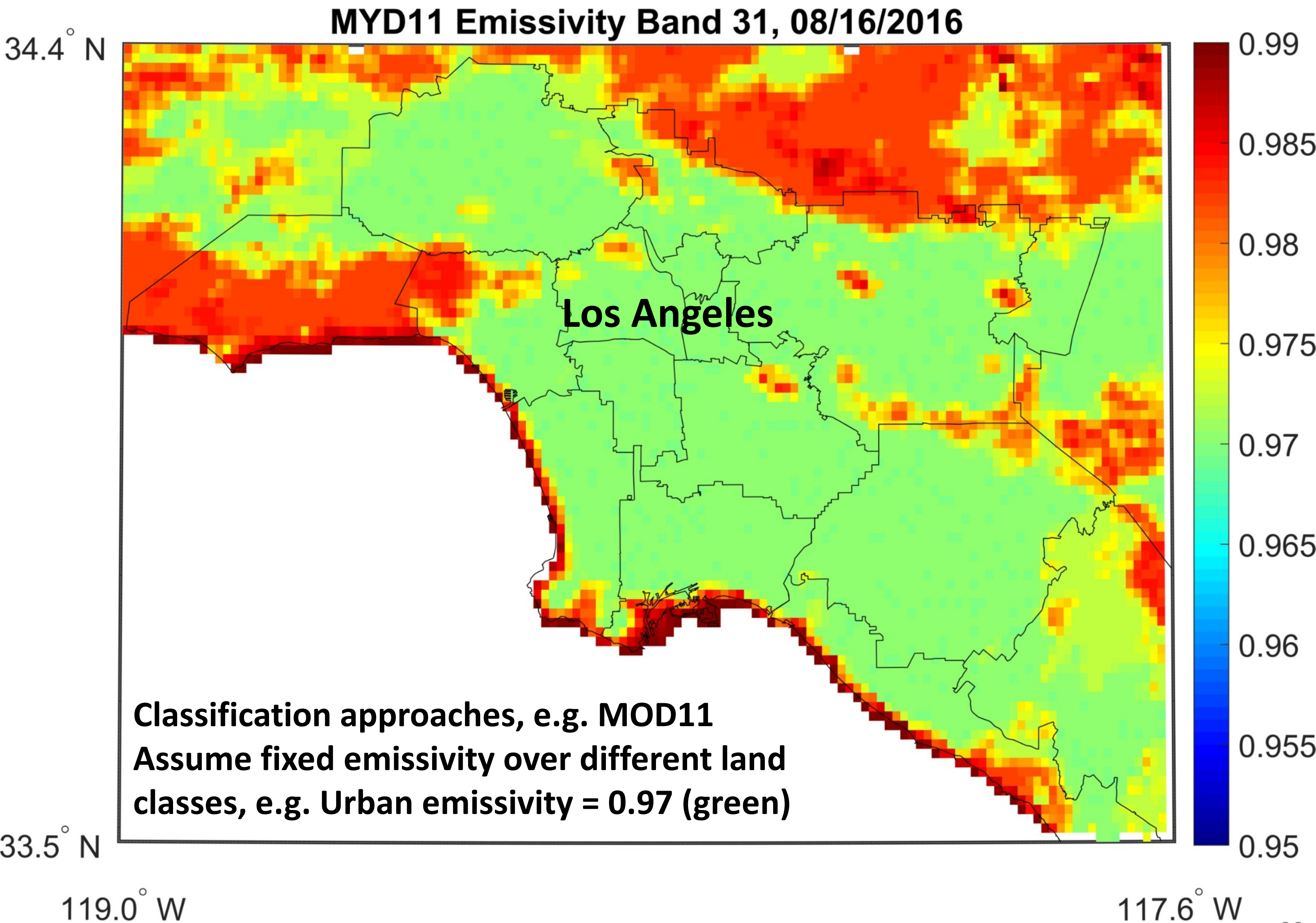
2. Field FT-IR spectrometer (shown at right).

Technical Equipment, Facilities and Infrastructure Management (**TEFIM**)

SPECIFICATIONS				
Item	**Parameter**	**Value**	**Units**	**Comments**
1	Spectral Range	2 - 16	micrometers	Standard IR
2	Spectral Resolution (FWHH)	4	wavenumbers	Standard, 1 sec. scan
3	Size (WxDxH)	36x20x23	centimeters	(14"x8"x9")
4	Weight	< 7	kilograms	(< 15 pounds)

Summary

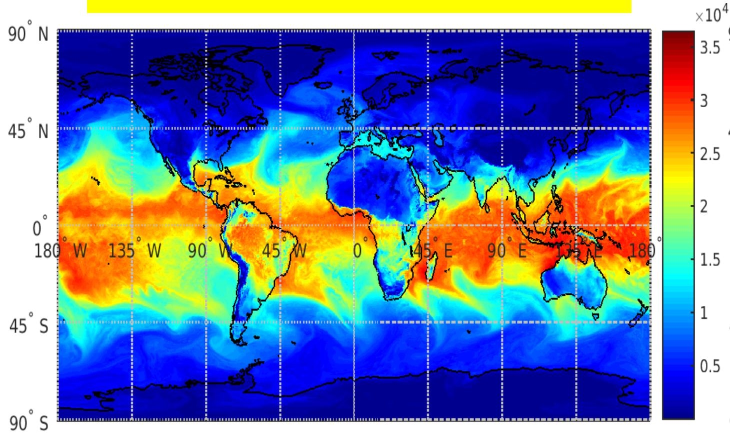
- HyspIRI L1 instrument and algorithm maturity from ECOSTRESS/PHyTIR ‘pathfinder’
- HyspIRI L2 Products:
  - Land Surface Temperature (LST)
  - Spectral Emissivity (6 bands)
  - Cloud Mask
  - Error estimates and Quality Control
- Well defined and strong L2 TES algorithm heritage (ASTER, MODIS, VIIRS, HyTES, MASTER)
- L1/L2 ATBD and other documentation complete
- CalVal sites established


MYD11 Emissivity Band 31, 08/16/2016
34.4° N
33.5° N
119.0° W
117.6° W
Los Angeles
0.99
0.985
0.98
0.975
0.97
0.965
0.96
0.955
0.95
Classification approaches, e.g. MOD11
Assume fixed emissivity over different land classes, e.g. Urban emissivity = 0.97 (green)

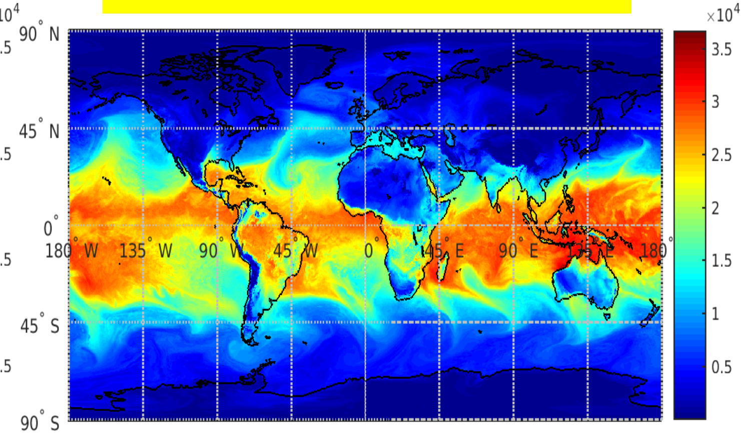
MERRA Global Water Vapor Field (level 1)

(Water vapor at 2m, ppmv)

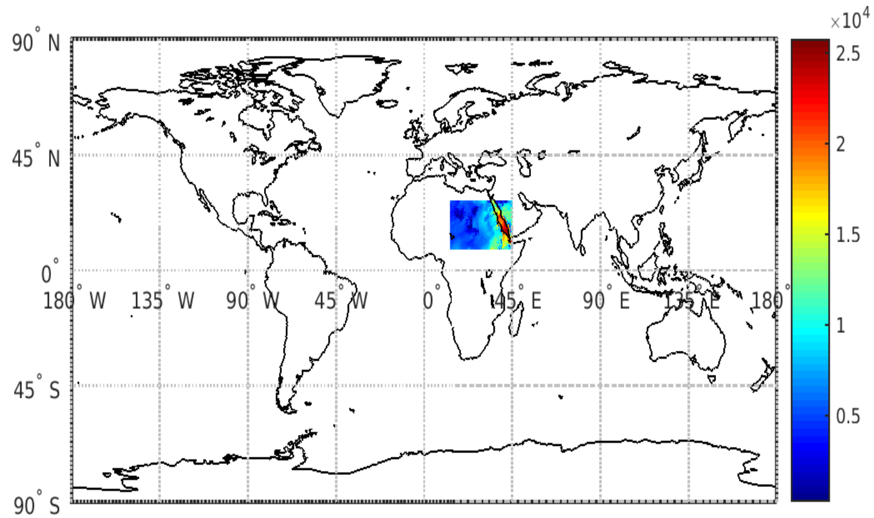
Native Grid 1 – 06hr UTC



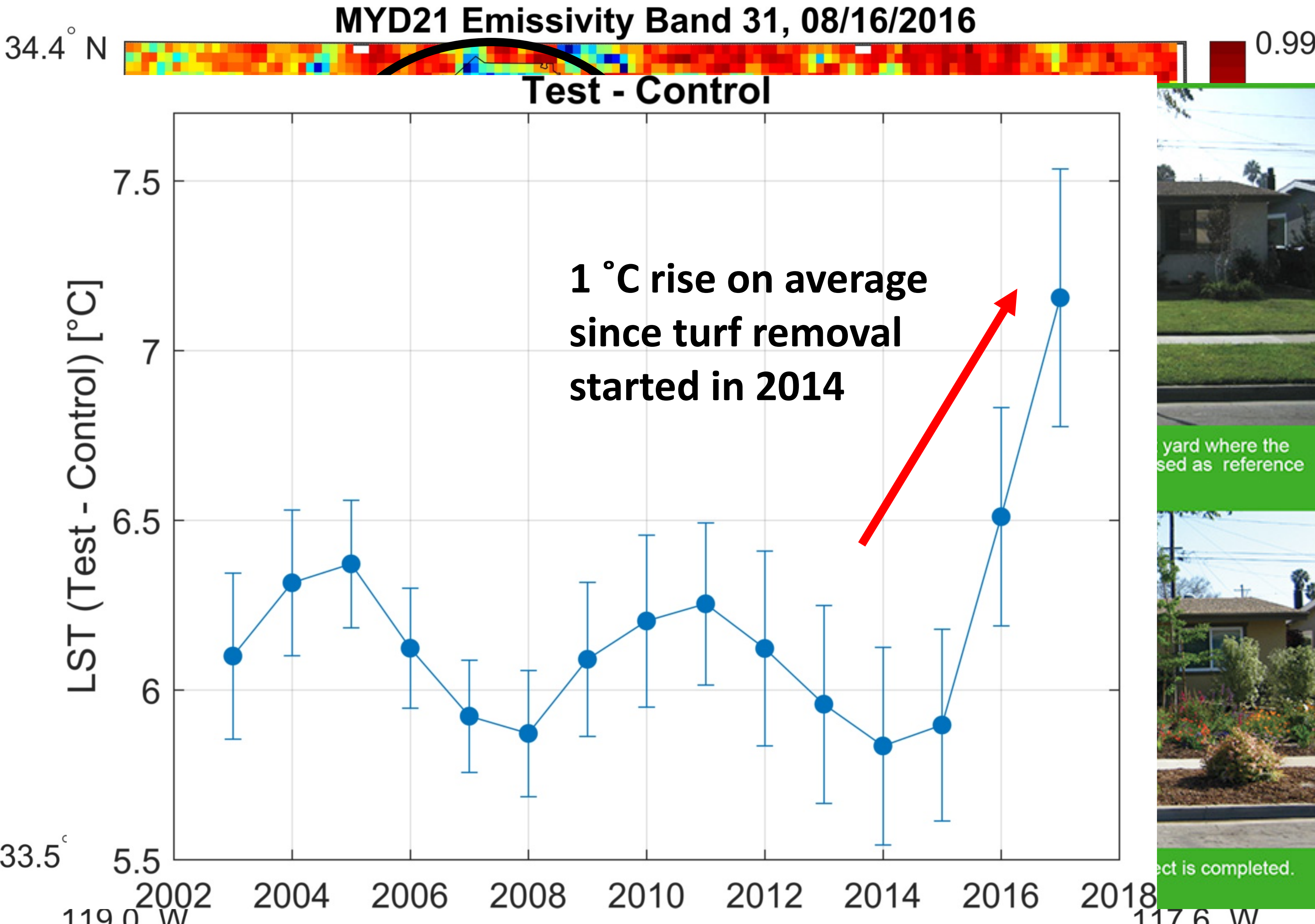
Native Grid 2 – 12hr UTC

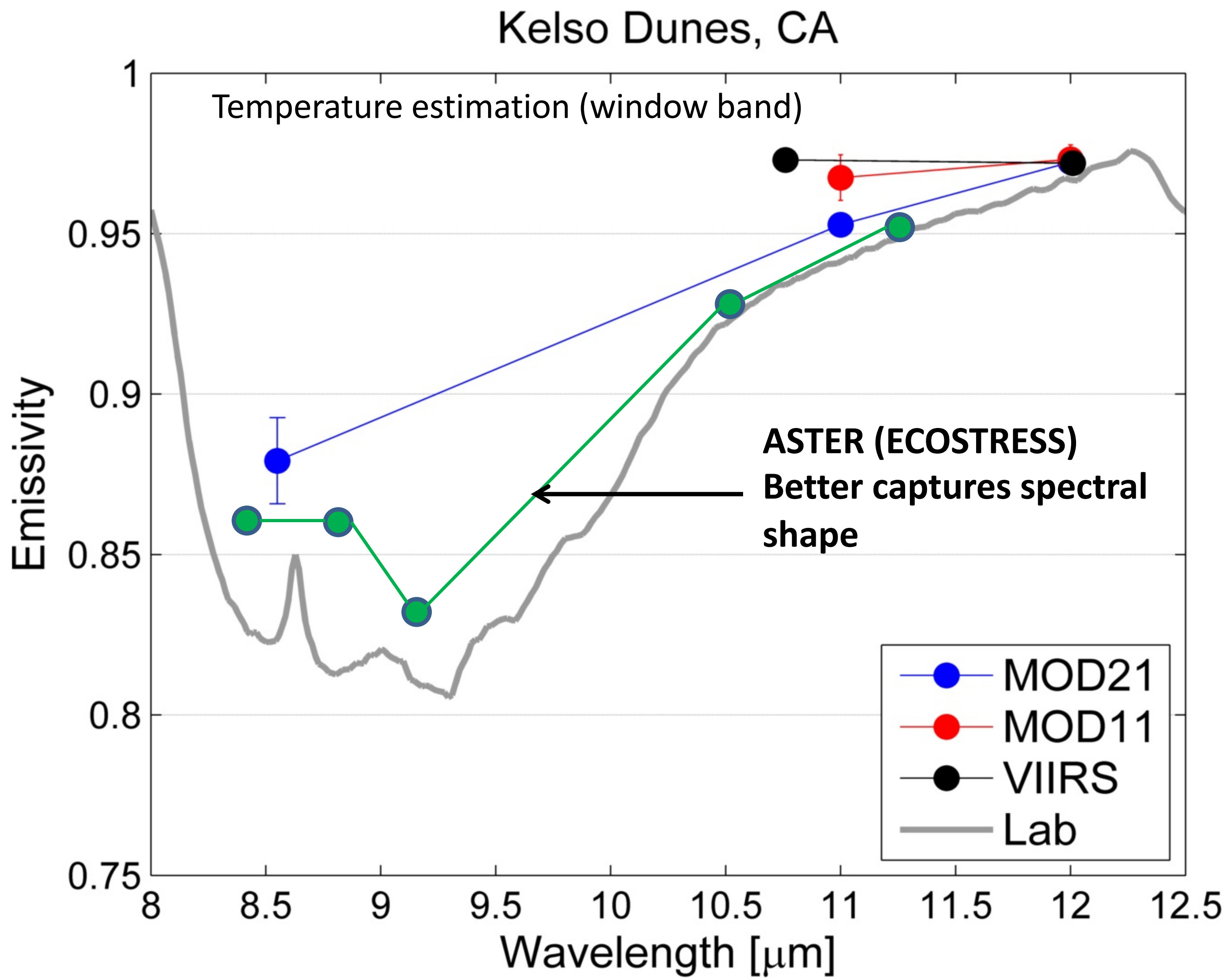


Native Grid 3 – Clipped and time-interpolated to 'ECOSTRESS' swath at 11hr UTC



***Profiles and other ancillary data can be saved to hdf, netcdf or other format at this point for use in L3/L4*


MYD21 Emissivity Band 31, 08/16/2016
34.4° N
0.99
33.5°
119.0 W
117.6 W
Test - Control
LST (Test - Control) [°C]
7.5
7
6.5
6
5.5
2002
2004
2006
2008
2010
2012
2014
2016
2018
1 ˚C rise on average since turf removal started in 2014
yard where the
sed as reference
ect is completed.



Kelso Dunes, CA
Temperature estimation (window band)
ASTER (ECOSTRESS)
Better captures spectral shape
Emissivity
Wavelength [μm]
1
0.95
0.9
0.85
0.8
0.75
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
MOD21
MOD11
VIIRS
Lab


TESLARATI
@_tom.cross_

Theoretical Basis: Surface Temperature

Radiometric ('Brightness') Temperature

$$T_\lambda(\theta) = B_\lambda^{-1}\left(L_\lambda(\theta)\right)$$

Land Surface ('Skin') Temperature (LST)

$$T_s = B_\lambda^{-1}\left(\frac{L_\lambda(\theta) - \rho_\lambda L^\downarrow}{\varepsilon_\lambda}\right)$$

where :

B_λ = blackbody spectral radiance

λ = wavelength

T_s = Surface Temperature

$T_\lambda(\theta)$ = Surface Brightness Temperature

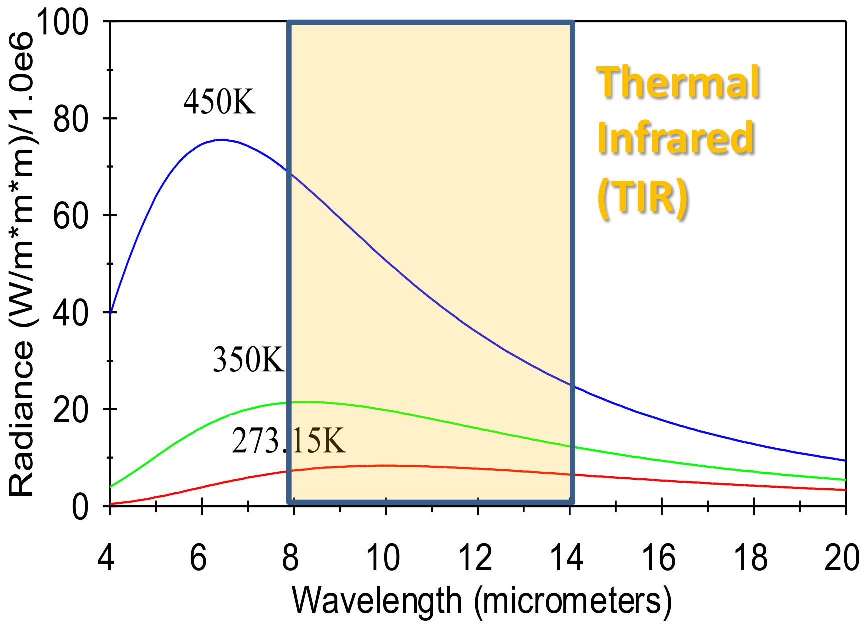
ρ_λ = Surface Reflection

$L^\downarrow$ = Downwelling Sky Irradiance

ε_λ = Emissivity

Planck Function

$$B_\lambda = \frac{c_1}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T_s}\right) - 1\right]}$$



in the Planck function shifts to shorter and shorter wavelengths

Theoretical Basis: Land Surface Temperature (LST)

1. Radiometric ('Brightness') Temperature

$$T_\lambda(\theta) = B_\lambda^{-1}\left(L_\lambda(\theta)\right)$$

2. Land Surface ('Skin') Temperature (LST)

$$T_s = B_\lambda^{-1}\left(\frac{L_\lambda(\theta) - \rho_\lambda L^{\downarrow}}{\varepsilon_\lambda}\right)$$

where:

B_λ = blackbody spectral radiance

λ = wavelength

T_s = Surface Temperature

$T_\lambda(\theta)$ = Surface Brightness Temperature

ρ_λ = Surface Reflection

$L^{\downarrow}$ = Downwelling Sky Irradiance

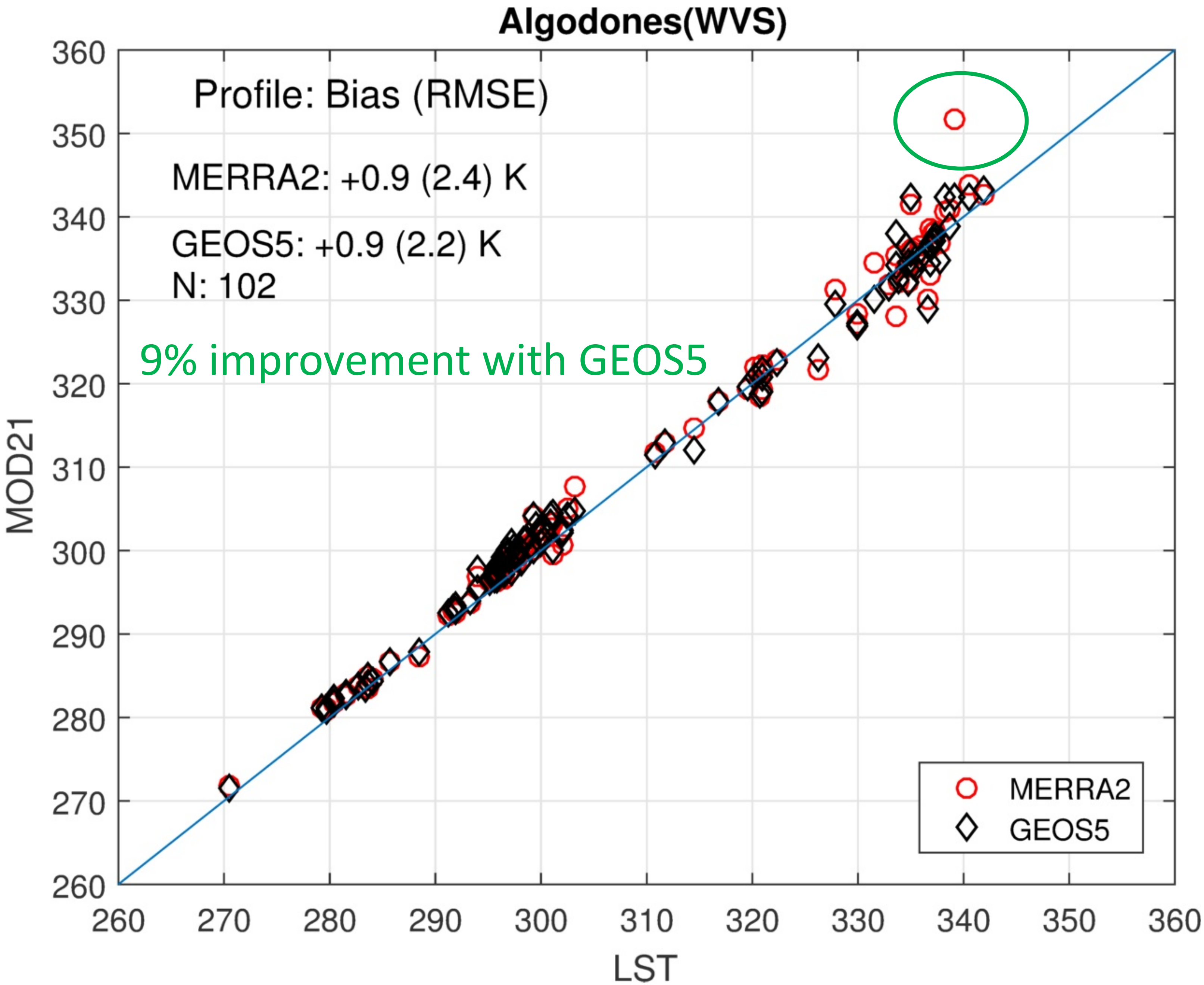
ε_λ = Emissivity

Temperature Validation

- **Method 2: Radiance-based (Rval)**

  Measure the emissivity and use an independent atmospheric profile (e.g. radiosonde). Forward calculate the ground temperature needed to match the at-sensor radiance and compare to retrieved temperature (Radiative Closure Simulation).

  Works day/night and globally when accurate in situ emissivity information is available



Algodones(WVS)
Profile: Bias (RMSE)
MERRA2: +0.9 (2.4) K
GEOS5: +0.9 (2.2) K
N: 102
9% improvement with GEOS5
MOD21
LST
MERRA2
GEOS5
360
350
340
330
320
310
300
290
280
270
260

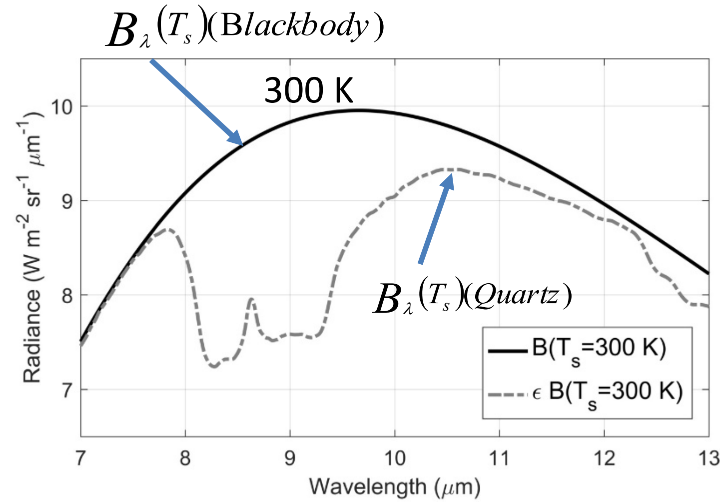
Theoretical Basis: Surface Emissivity

Blackbody Radiance

$$L_\lambda = B_\lambda(T_s)$$

Planck

L_λ

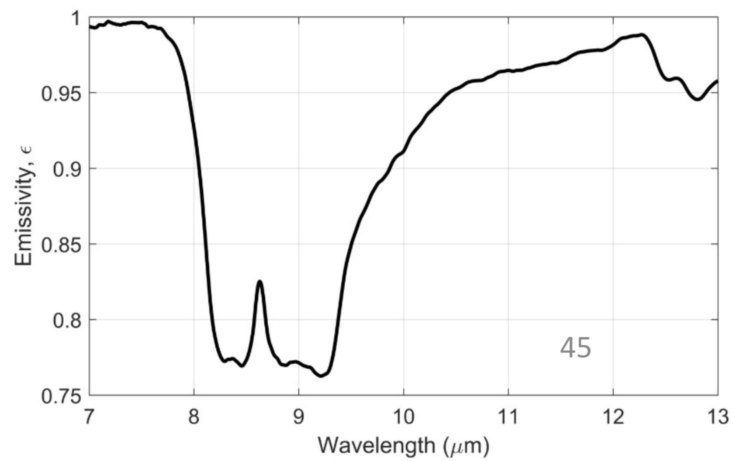


Spectral Emissivity:

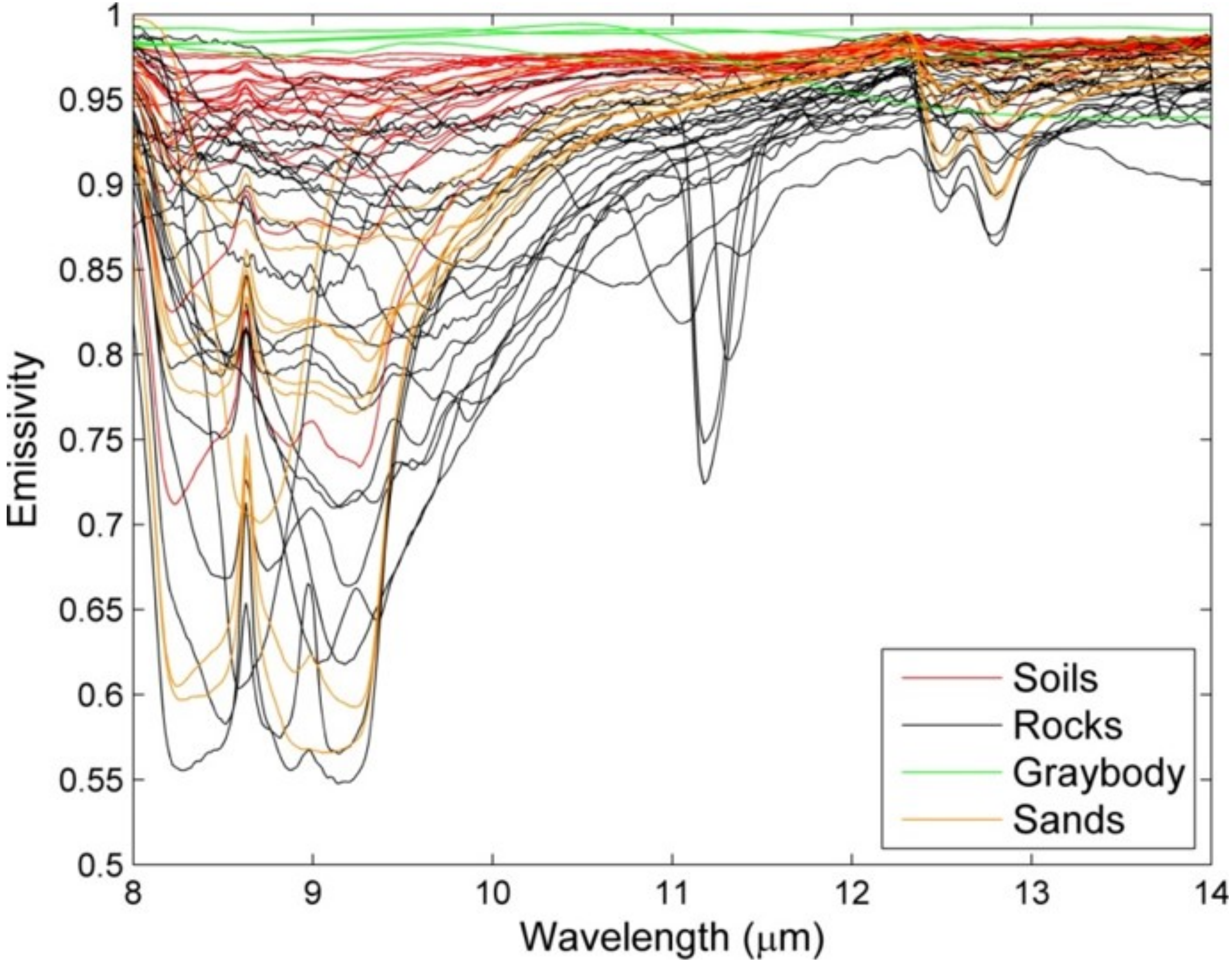
ratio of the spectral radiance of a material to that of a blackbody at the same temperature:

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

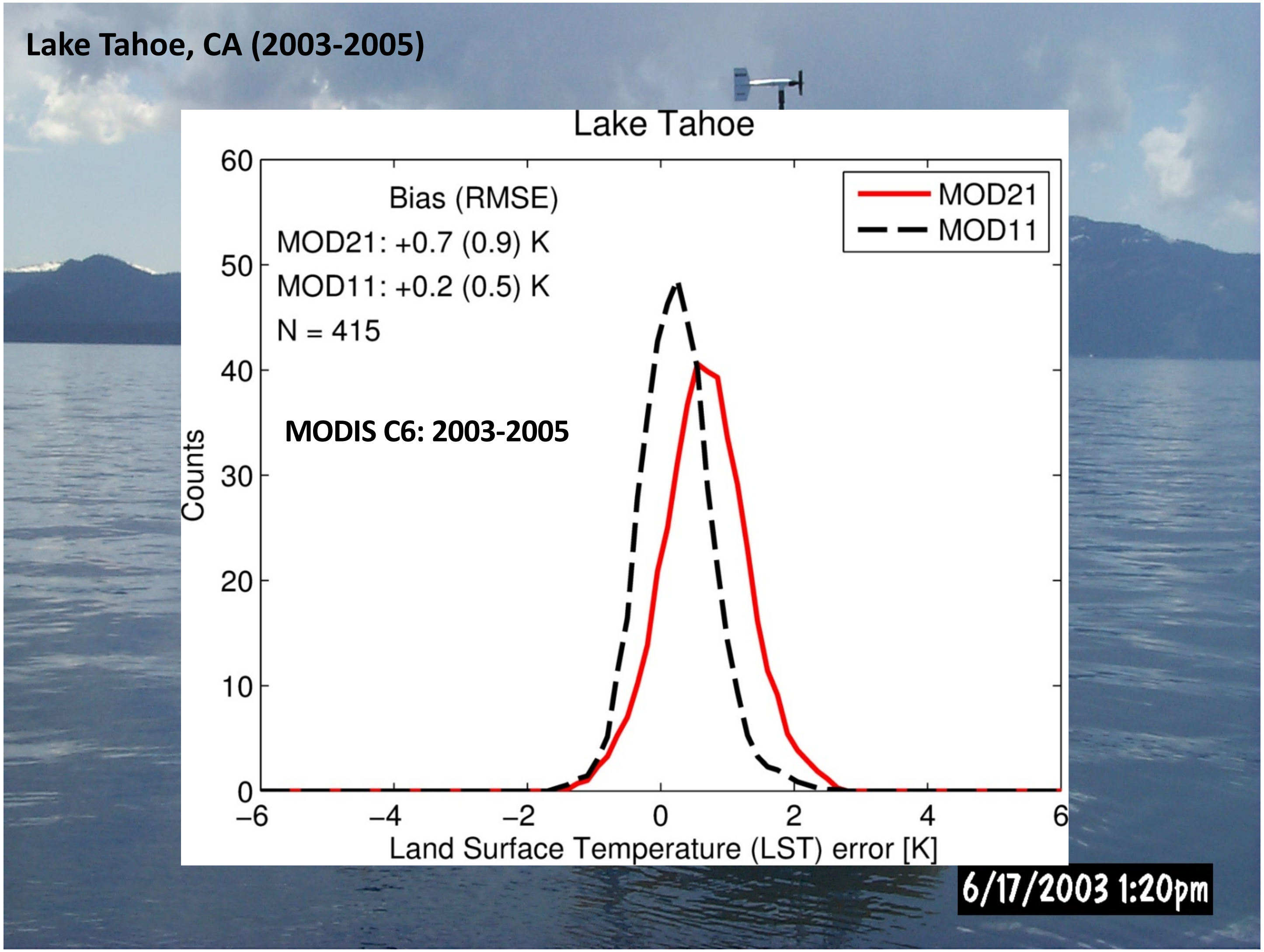
ε_λ



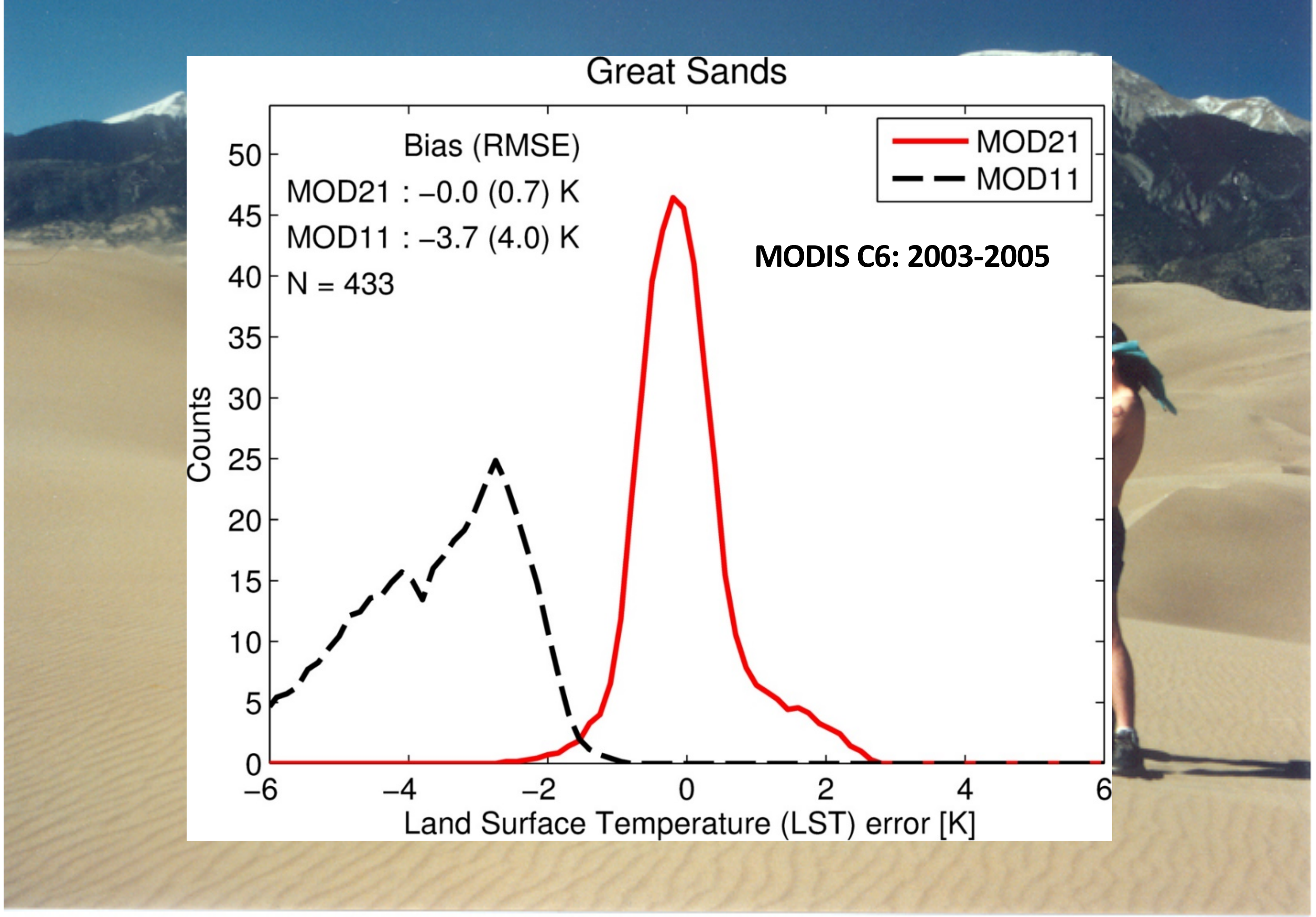
Emissivity



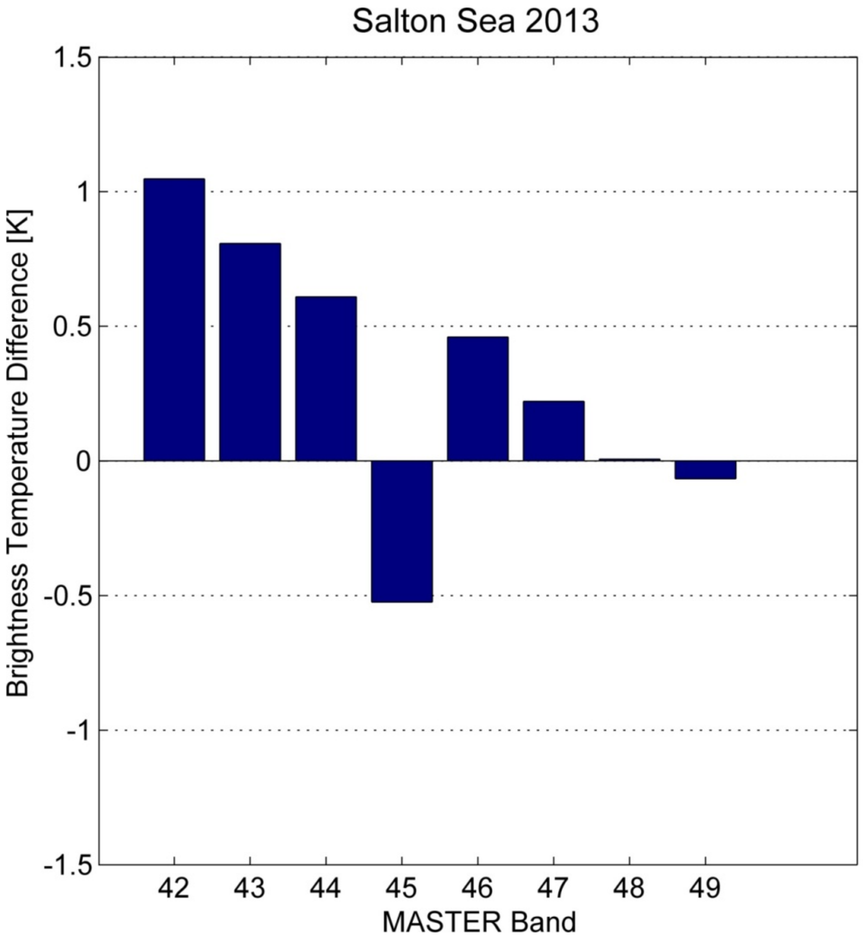
Emissivity
Wavelength (μm)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
8
9
10
11
12
13
14
Soils
Rocks
Graybody
Sands

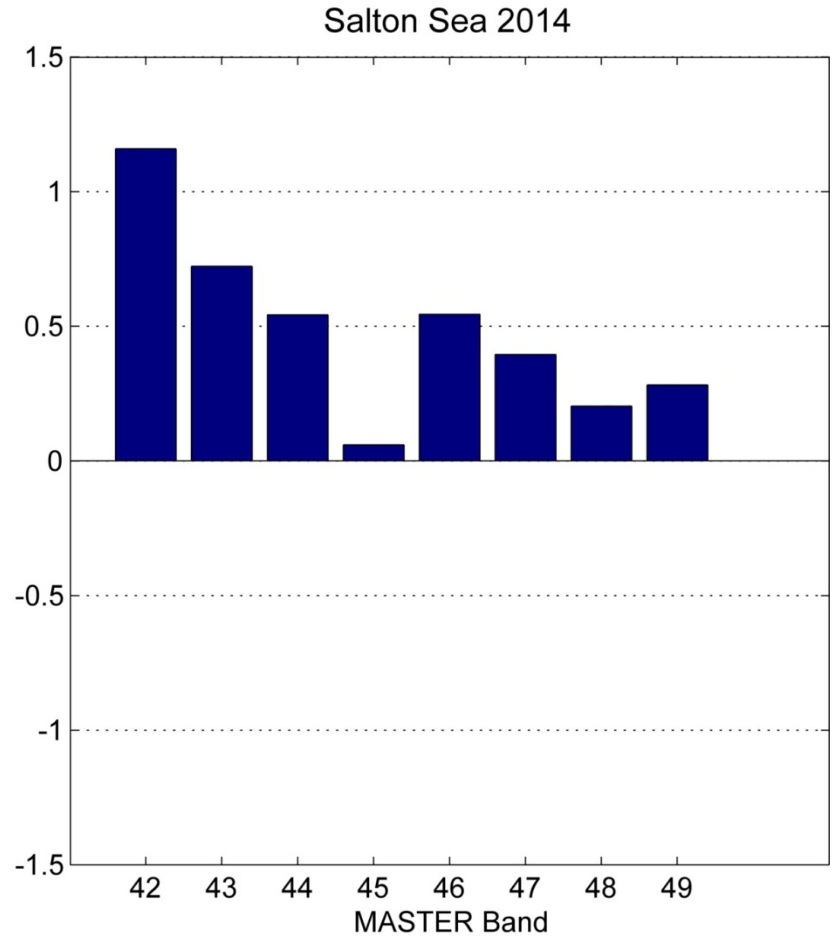

Lake Tahoe, CA (2003-2005)
Lake Tahoe
Bias (RMSE)
MOD21: +0.7 (0.9) K
MOD11: +0.2 (0.5) K
N = 415
MODIS C6: 2003-2005
MOD21
MOD11
Counts
Land Surface Temperature (LST) error [K]
60
50
40
30
20
10
0
−6
−4
−2
0
2
4
6
6/17/2003 1:20pm

Great Sands, CO (2003-2005)



Salton Sea L1 Calibration

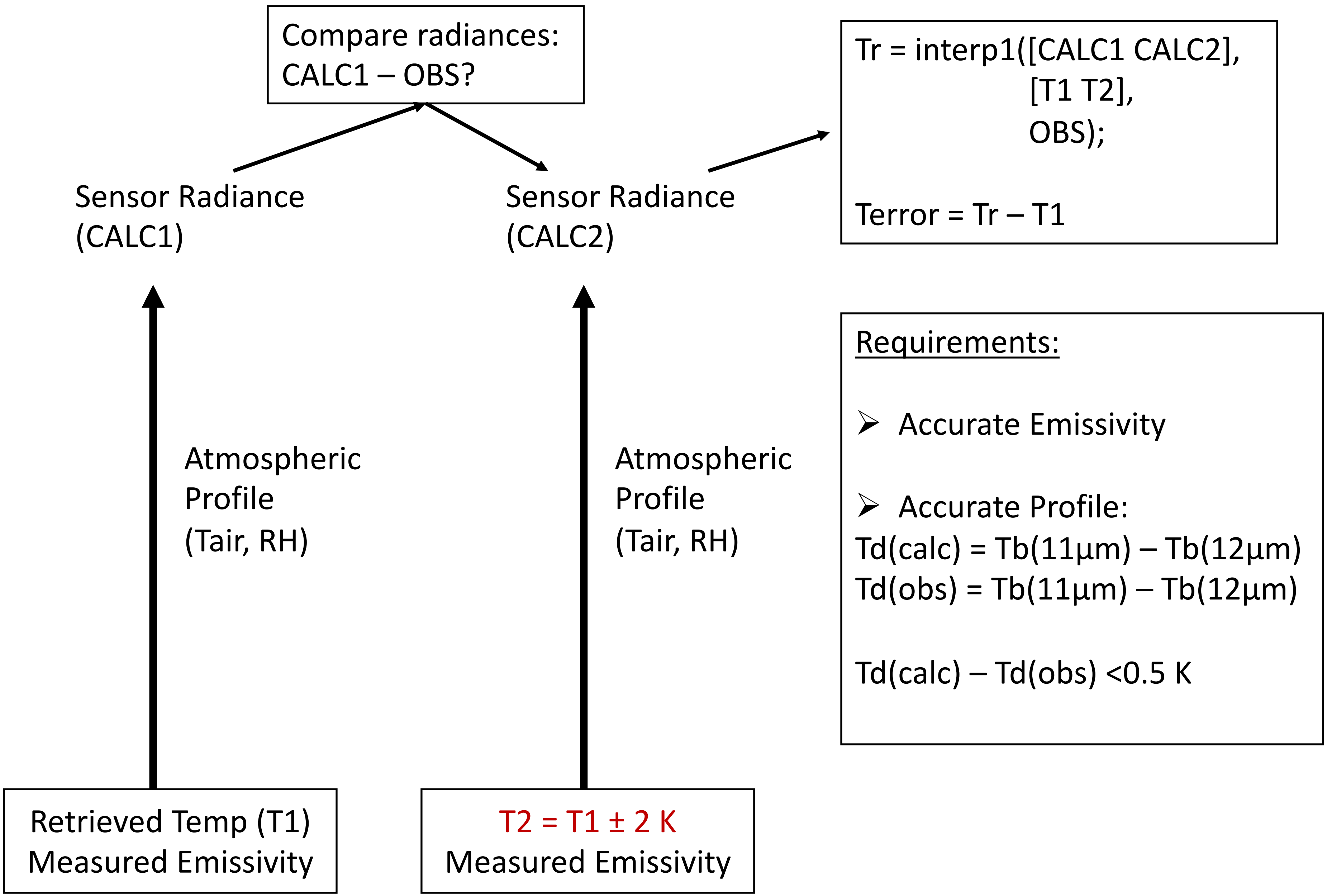




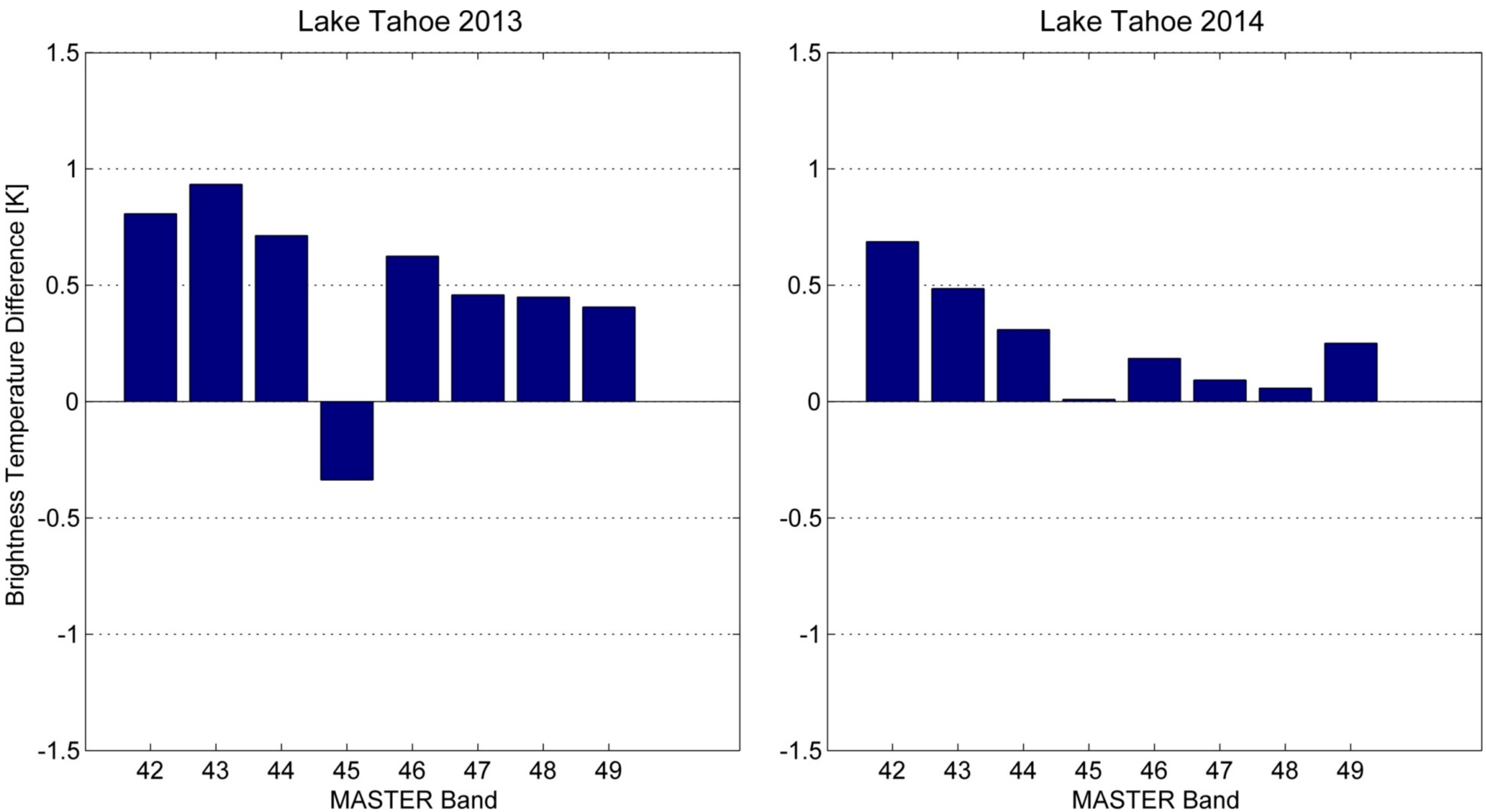
Baseline	Threshold (Mission Success)
VSWIR:380 to 2500 nm at ≤10 nm sampling at the specified signal-to-noise ratio and accuracy with >95% spectral/spatial uniformity at ≤30 m nadir spatial sampling with <16 day revisit to provide	VSWIR:380 to 2500 nm at ≤10 nm sampling at >80% of the specified signal-to-noise ratio and accuracy with >90% spectral/spatial uniformity at ≤30 m nadir spatial sampling with <16 day revisit to provide
VSWIR:>60% seasonal and >80% annual coverage of the terrestrial and shallow water regions of the Earth	VSWIR:> 50% seasonal and >70% annual coverage of the terrestrial and shallow water regions of the Earth
three years with a subset of measurements available near-real-time for designated science and applications.	two years.
TIR: 8 spectral bands from the 3-5 micron and 8-12 micron regions of the spectrum at the specified noise-equivalent-delta-temperature and accuracy at ≤60 m nadir spatial sampling with ≤5 day revisit	TIR: 8 spectral bands from the 3-5 micron and 8-12 micron regions of the spectrum at >80% the specified noise-equivalent-delta-temperature and accuracy at ≤60 m nadir spatial sampling with ≤5 day revisit
TIR: >60% Monthly, >70% seasonal and >85% annual coverage of the terrestrial and shallow water regions of the Earth	TIR: > 40% Monthly, > 60% seasonal and >70% annual coverage of the terrestrial and shallow water regions of the Earth

*30 m, 16 Day VSWIR

Radiance-Based Temperature Validation



MASTER TIR Calibration



L1A Radiometric Calibration PGE

L1A Radiometric Calibration Steps*

- **<u>Purpose: Convert Image TIR DNs to Radiance:</u>**
  - Procedure for each image:
    - Read temperatures from Sensor's Cold (~295K) and Hot (~325K) Blackbodies.
    - Create synthetic FPA temperature images of Cold and Hot Blackbodies and convert them to Radiance (Watt/m2/sr/um) using the center wavelength of each TIR band and the Planck function.
    - Collect push-whisk FPA Digital Number (DN) scans of the Cold and Hot Blackbodies And Ground for all wavelengths.
    - Using the FPA Radiance values and corresponding FPA DNs, use a two-point affine transformation (creating gain/offset coefficients) to convert each Ground pixel's DN to Radiance.

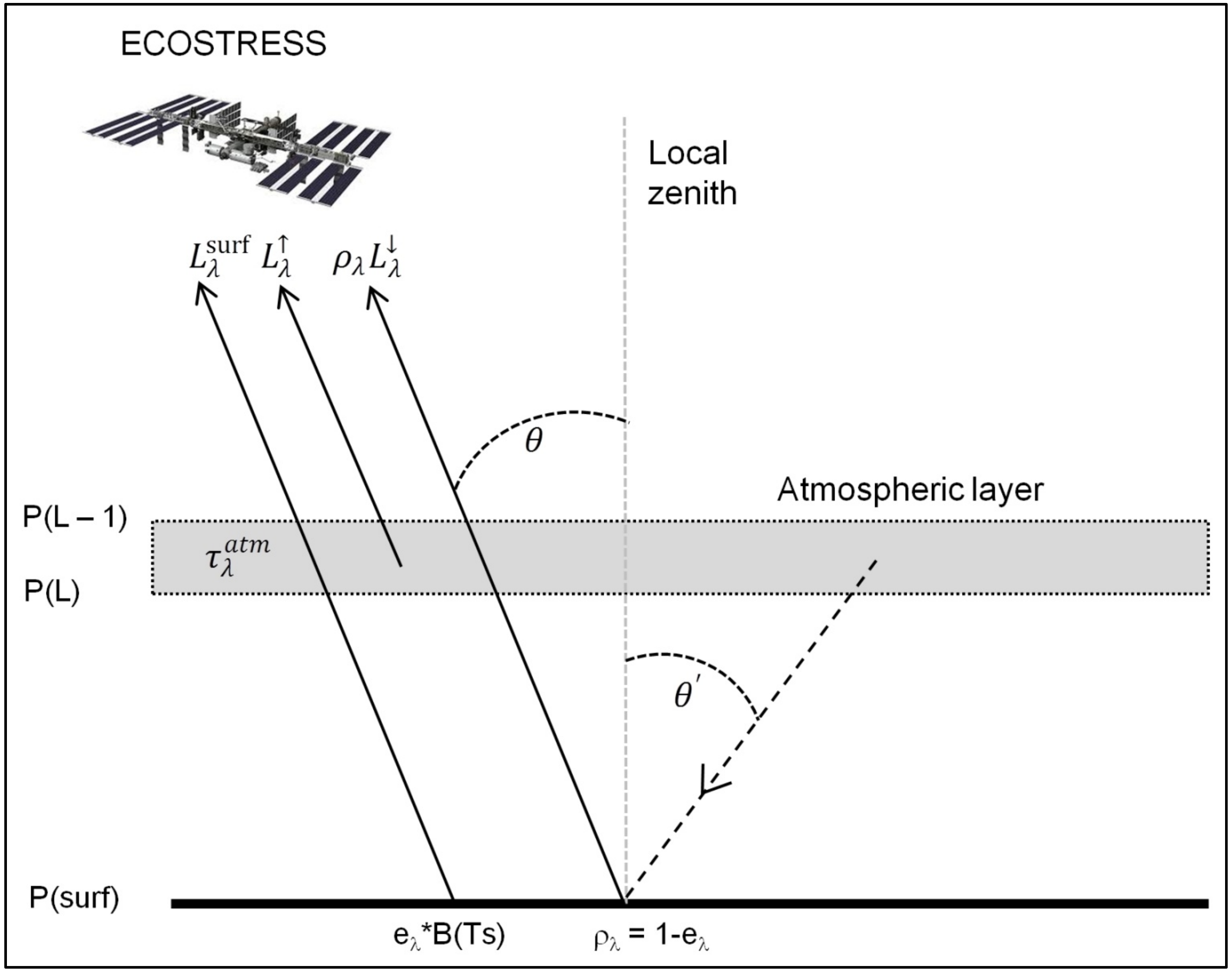
- Accuracy is expected to be better than the <u>1.0 Kelvin</u> requirement.

- Ground Radiance and Temperature images can be generated for Validation and Verification purposes as necessary (optional parameters).

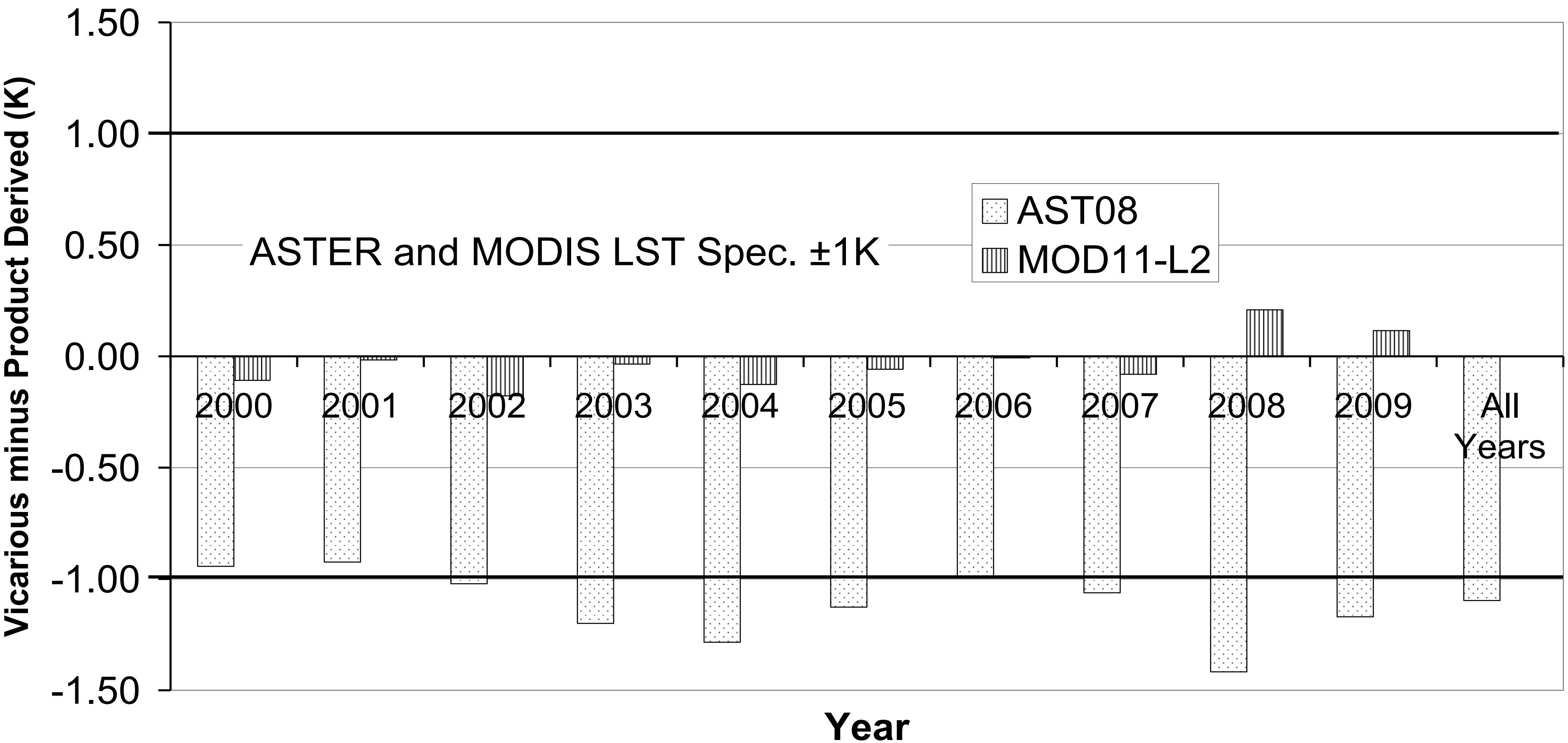
*Documented in: "Level-1 Focal Plane Array and Radiometric Calibration Algorithm Theoretical Basis Document (ATBD)," JPL D-94803.

Atmospheric correction + Temperature Emissivity Separation (TES)

$$L_\lambda(\theta) = \tau_\lambda(\theta)\left[L_\lambda^{surf} + (1-\varepsilon_\lambda)\overline{L}_\lambda^{\downarrow}\right] + L_\lambda^{\uparrow} \qquad L_\lambda^{surf} = \varepsilon_\lambda B(Ts)$$



Tahoe LST validation



The MODIS product is accurate to (± 0.2K), while the ASTER product has a bias of 1-2 K due to residual atmospheric correction effects

L1 TIR Overview

- Level-1 (L1) is part of the Science Data System (SDS), where the SDS:
  - Creates L0, L1, L2, L3, and L4 products, and
  - Delivers products to the Land Process DAAC (Sioux Falls, SD)
- Level-1 Inputs include:
  - L0 Data
    - Raw Image Data Packets
    - Spacecraft Orbital Metadata
  - Ancillary Data
    - Landsat Ortho-Rectified Image Base (geolocation)
    - Digital Terrain Models (pass-through)
      - Elevation
      - Land/Water Mask
- Level-1 Outputs include:
  - Calibrated Radiance images with
  - Geolocation (position) and
  - Associated metadata

Science Data Products	
L0	Raw data
L1	Radiometrically corrected Radiances
L2	Emissivity
L3	Evapotranspiration
L4	Water Use Efficiency, Evaporative Stress Index

Outline

1. L1 Algorithm Maturity
2. L1 Cal/Val
3. L2 Algorithm Maturity
4. L2 Cal/Val

TIR Instrument Characteristics

Spectral	
Bands (8) µm	3.98 µm, 7.35 µm, 8.28 µm, 8.63 µm, 9.07 µm, 10.53 µm, 11.33 µm, 12.05 µm
Bandwidth	0.084 µm, 0.32 µm, 0.34 µm, 0.35 µm, 0.36 µm, 0.54 µm, 0.54 µm, 0.52 µm
Accuracy	<0.01 µm
Radiometric	
Range	Bands 2–8 = 200 K – 500 K; Band 1 = 1200 K
Resolution	< 0.05 K, linear quantization to 14 bits
Accuracy	< 0.5 K 3-sigma at 250 K
Precision (NEdT)	< 0.2 K
Linearity	>99% characterized to 0.1 %
Spatial	
IFOV	60 m at nadir
MTF	>0.65 at FNy
Scan Type	Push-Whisk
Swath Width	600 km (±25.5° at 623-km altitude)
Cross Track Samples	9,300
Swath Length	15.4 km (± 0.7 degrees at 623 km altitude)
Down Track Samples	256
Band to Band Co-Registration	0.2 pixels (12 m)
Pointing Knowledge	10 arcsec (0.5 pixels) (approximate value, currently under evaluation)
Temporal	
Orbit Crossing	11 a.m. Sun synchronous descending
Global Land Repeat	5 days at Equator
On Orbit Calibration	
Lunar views	1 per month {radiometric}
Blackbody views	1 per scan {radiometric}
Deep Space views	1 per scan {radiometric}
Surface Cal Experiments	2 (day/night) every 5 days {radiometric}
Spectral Surface Cal Experiments	1 per year
Data Collection	
Time Coverage	Day and Night
Land Coverage	Land surface above sea level
Water Coverage	Coastal zone minus 50 m and shallower
Open Ocean	Averaged to 1-km spatial sampling
Compression	2:1 lossless