ECOSTRESS

L1/L2 Algorithms and Product Development

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Outline

1. ECOSTRESS Science Data Products
2. Thermal Infrared Theoretical Basis
3. Land Surface Temperature (LST) and Emissivity Algorithms
4. Uncertainty Analysis
5. Simulated ECOSTRESS L2 products (MASTER)

ECOSTRESS Data Products (L0->L4)

Data Products	Description	Information Required	Plans for Validation/Reprocessing
Level-0	Reconstructed, unprocessed instrument data at full resolution; any communication artifacts removed.	Raw science data packets	Automated process, no reprocessing needed.
Level-1A	Reconstructed unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients.	Level-0 raw data	Automated process, minimal reprocessing.
Level-1B	Level 1a data that have been processed to sensor units by applying the coefficients for radiometric calibration and geometric resampling	Level-1A & radiometric and geometric coefficients	Automated process, with full reprocessing as needed. Validation of at-sensor radiance using data from autonomous Lake Tahoe and Salton Sea cal/val sites.
Level-2	LST and spectral emissivity	Level-1B data, cloud mask, NWP atmospheric profiles, ASTER digital elevation data.	Automatic process, with full reprocessing as necessary (e.g. algorithm changes). Validation (T-based and R-based) using a global set of sites including water, vegetation, sand dunes, grasslands, and soil land cover types.
Level-3	Evapotranspiration (ET),	Level-2 products, VNIR data from Landsat, met. data from NCEP.	Reprocessing as needed based on Level 2 reprocessing. Validation with eddy covariance data from FLUXNET sites (global).
Level-4	Water Use Efficiency (WUE), Evaporative Stress Index (ESI)	Level-3 products, GPP	Reprocessing as needed based on Level 2 and 3 reprocessing. Validation with eddy covariance data from FLUXNET sites (global).

Theoretical Basis: Planck Function

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

$$T_s = B_\lambda^{-1}$$

where :

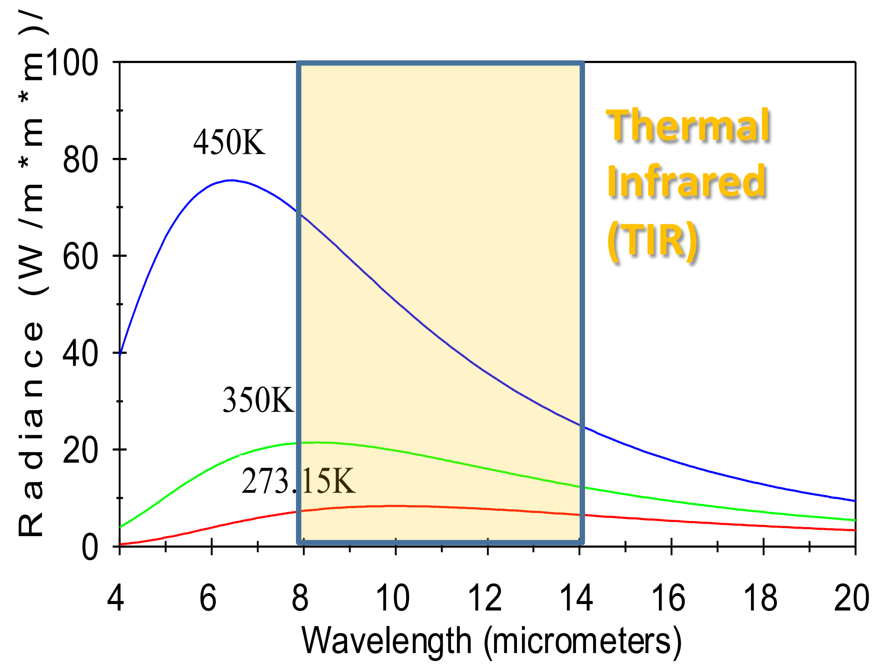
B_λ = blackbody spectral radiance

λ = wavelength

T_s = Surface Temperature

c_1 = first radiation constant

c_2 = second radiation constant



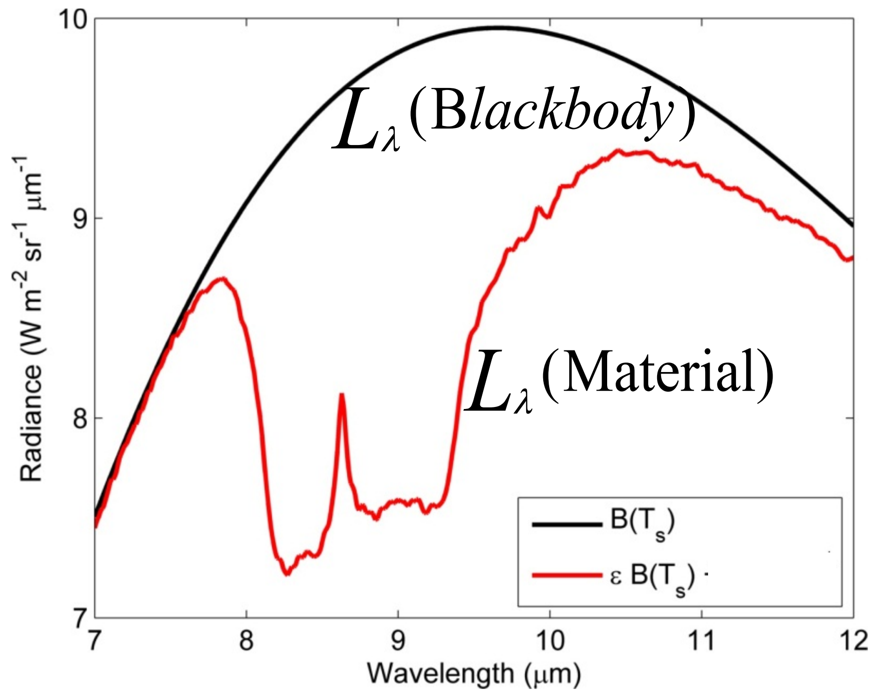
As the temperature increases the peak in the Planck function shifts to shorter and shorter wavelengths

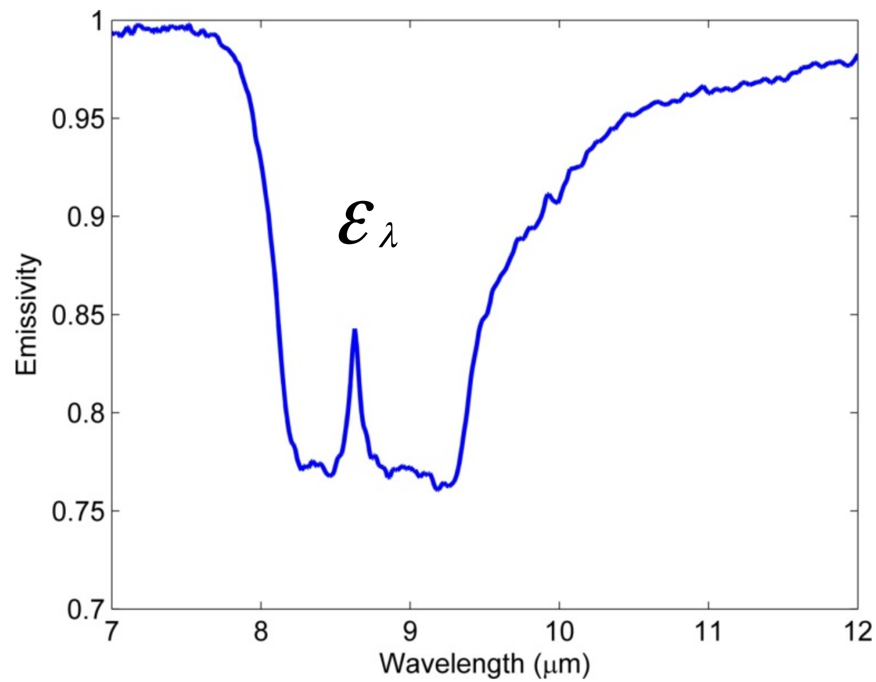
Spectral Emissivity

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

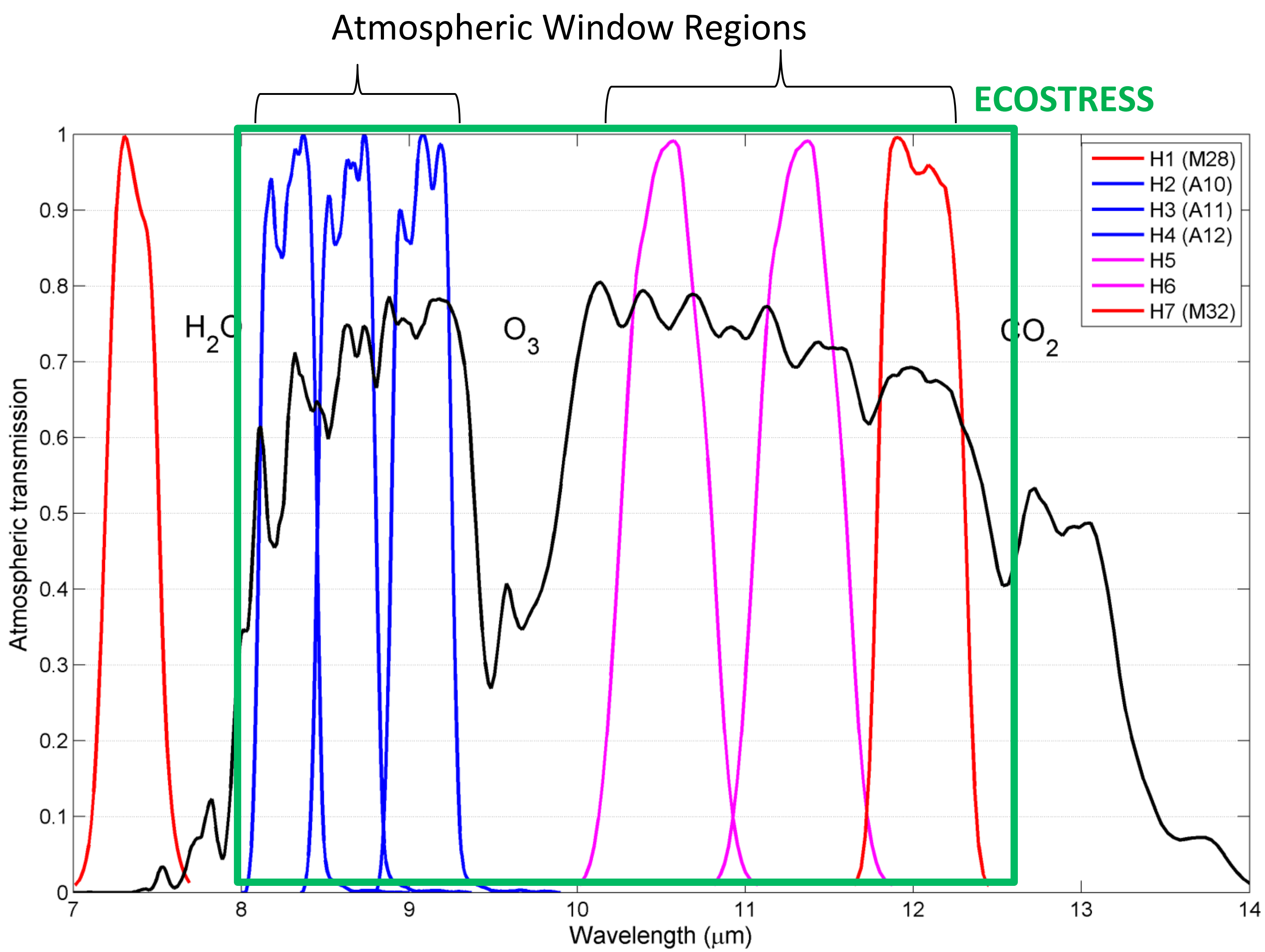
$$\varepsilon_\lambda = \frac{L_\lambda(\text{Material})}{L_\lambda(\text{Blackbody})}$$

L_λ = Spectral Radiance

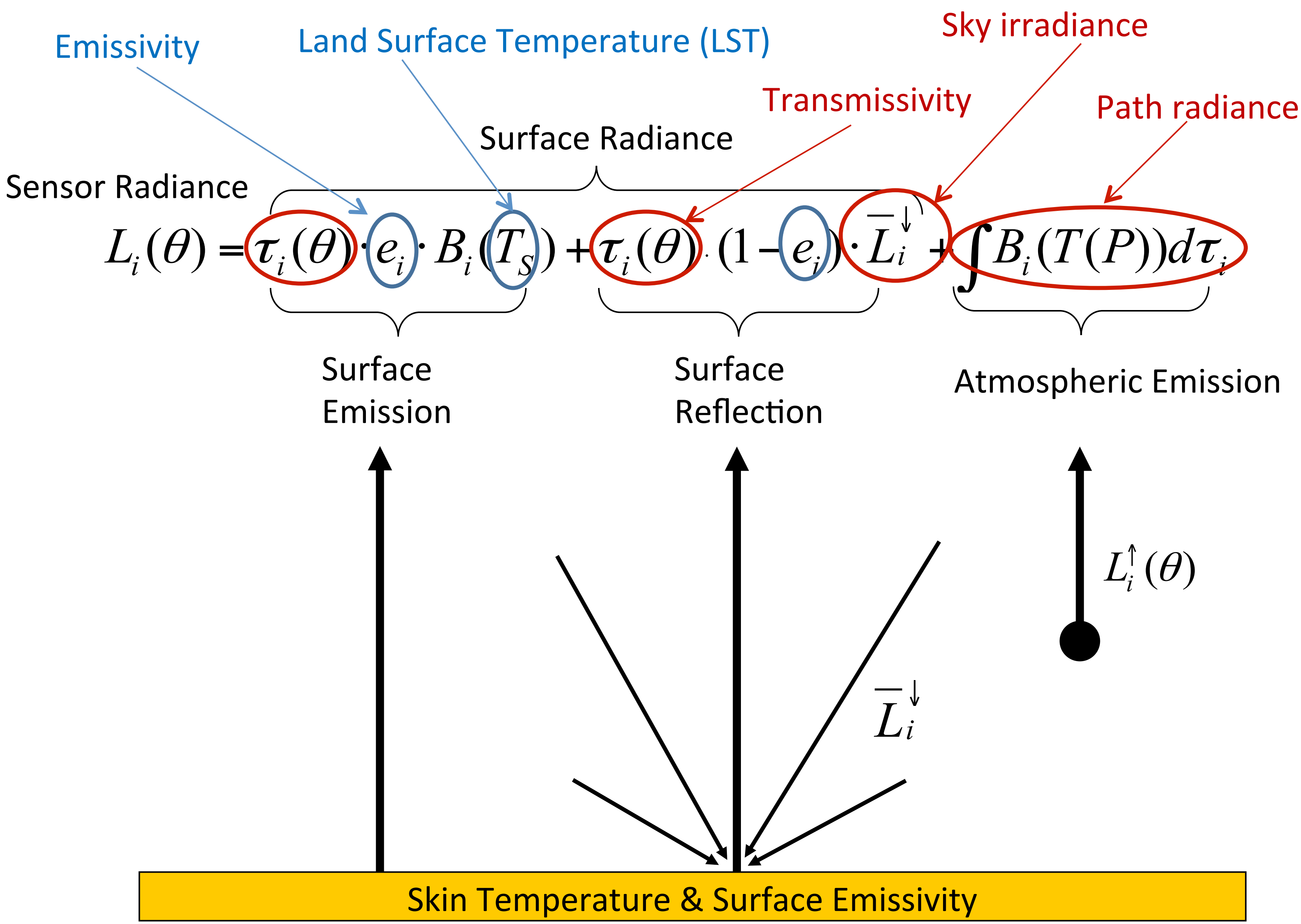




HyspIRI/ECOSTRESS Spectral Response Functions



Thermal Infrared Radiative Transfer



Atmospheric Correction

Surface Radiance: **Observed 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 model (MODTRAN)
- Atmospheric Profiles (coincident with observation)
- Elevation data

➢ **Water Vapor Scaling Method (Tonooka, 2005)**

- Used to improve accuracy on pixel-by-pixel basis

Temperature/Emissivity retrieval algorithms

To solve the under-determined temperature-emissivity problem:

N spectral measurements (N radiances) with N + 1 unknowns (N emissivity, 1 Temperature)

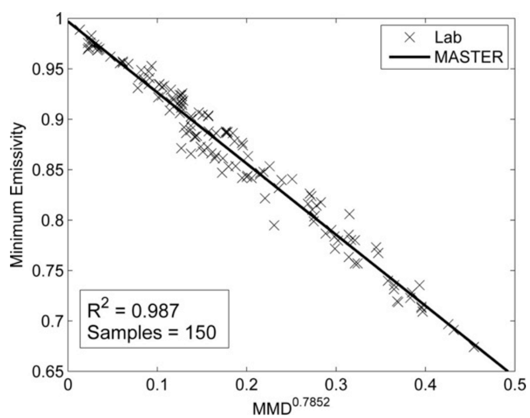
1. Split window approach

$$LST = a_0 + a_1 T_{11\mu m} + a_2 (T_{11\mu m} - T_{12\mu m})$$

   - Requires 2 bands
   - Prescribed spectral emissivity
   - Regression coefficients should represent all configurations (atmospheric water content, view angle, surface T_{air}, …)

2. Temperature-Emissivity Separation (TES) ← **ECOSTRESS**

   - Multispectral (minimum 3 bands)
   - Requires atmospheric profiles for full atmospheric correction with MODTRAN
   - Based on Emissivity model (Calibration Curve)



JPL Publication 12-17

MODIS MOD21 Land Surface Temperature and Emissivity Algorithm Theoretical Basis Document

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August 2012

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

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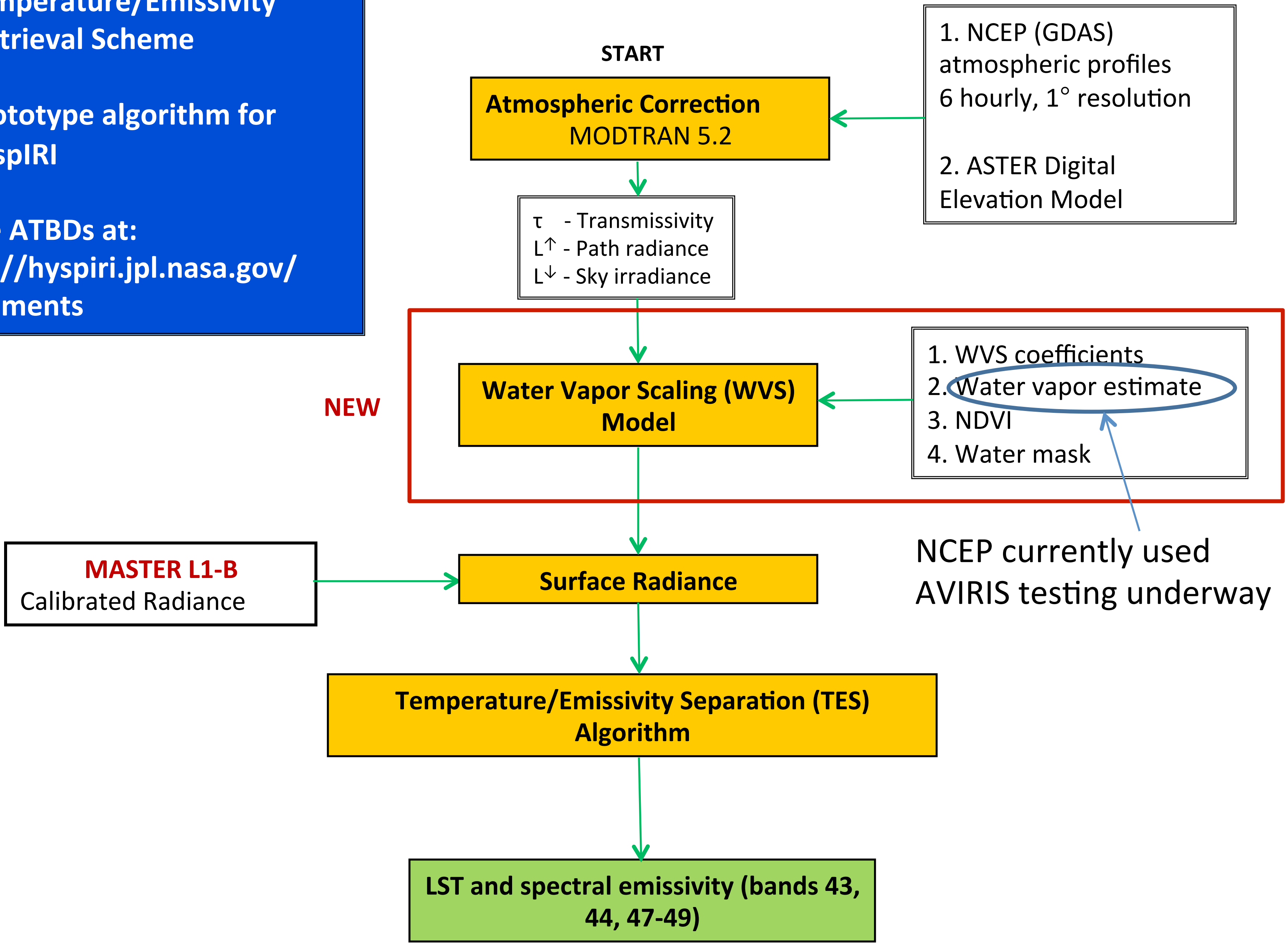
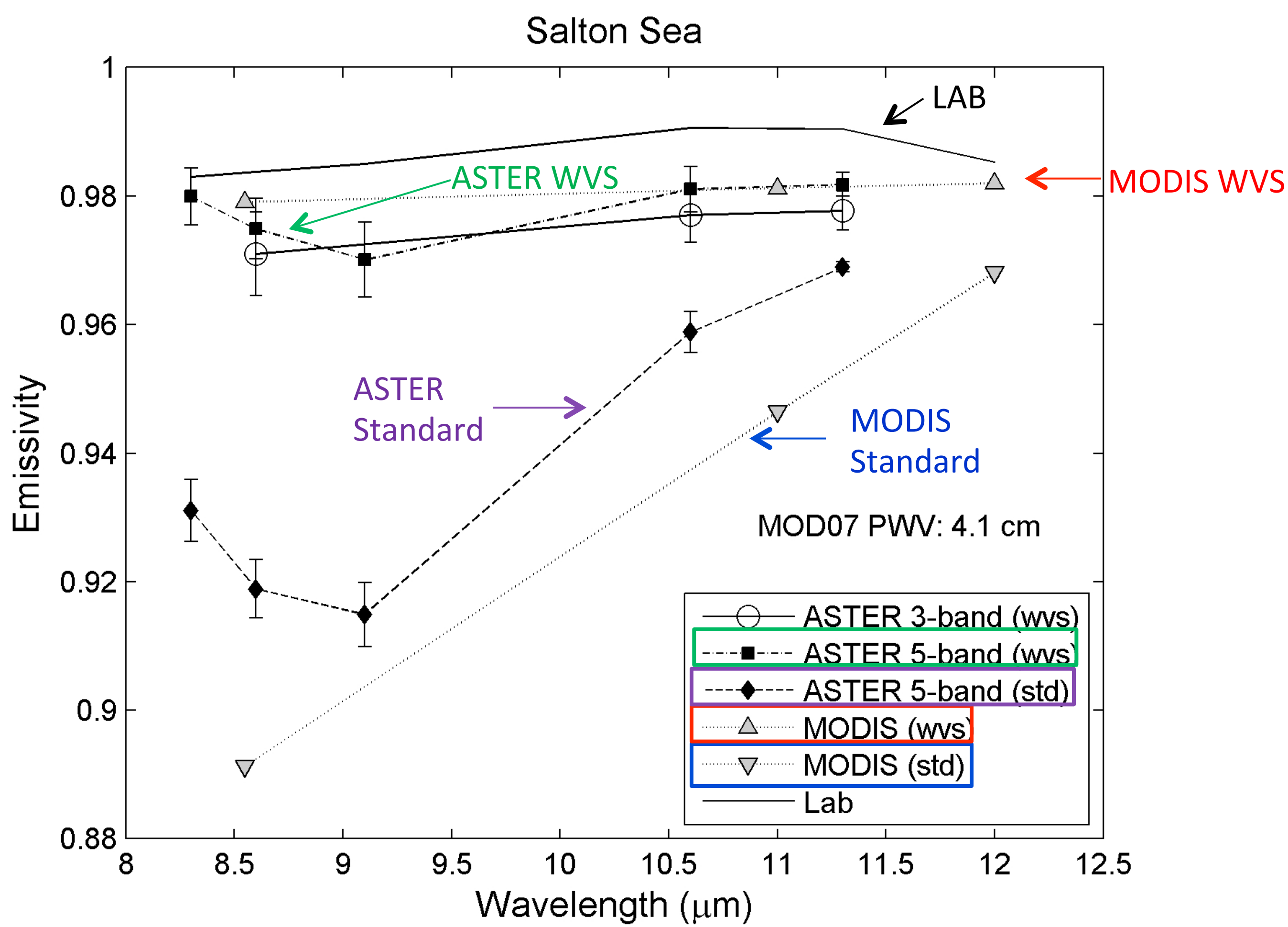
May 2011

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



Effect of Water Vapor Scaling (WVS) Model

Tonooka, 2005



ECOSTRESS Measurement Requirement (baseline) and Capability

Table F.1-3. ECOSTRESS measurement requirement and capability. Capability exceeds requirement in all cases.

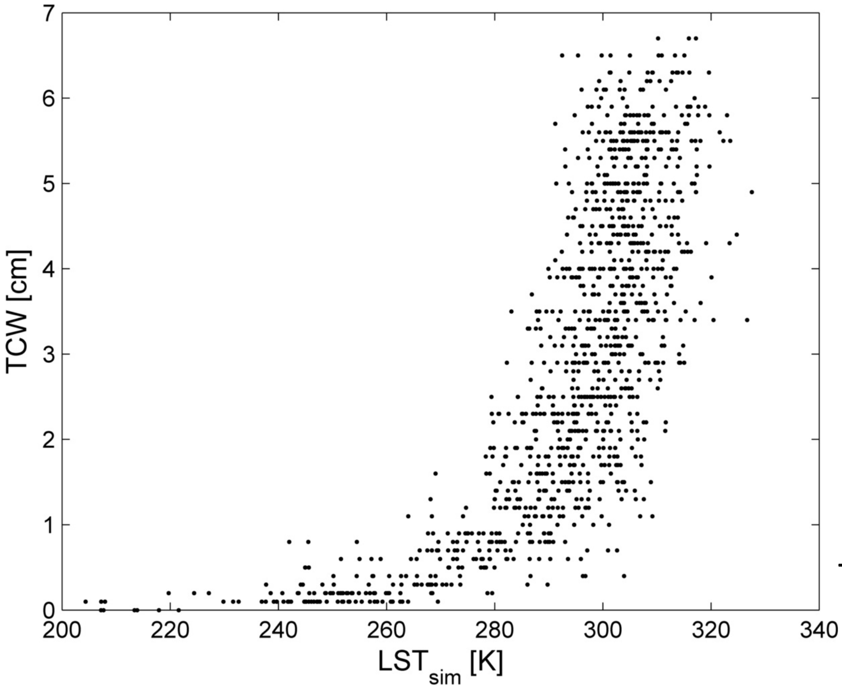
	Evapotranspiration			Land Surface Temperature (K)			BT at Sensor at 300 Kelvin (K)		
	Accuracy	Precision	Uncertainty	Accuracy	Precision	Uncertainty	Accuracy	Precision	Uncertainty
Requirement	15%	5%	16%	2	0.3	2.0	1.0	0.3	1.0
Capability	10%	1%	10%	1	0.2	1.0	0.5	0.1	0.5

Which LST&E algorithm will meet these requirements?

LST&E Uncertainty Analysis
(ROSES 2010 – Uncertainty Analysis Program)

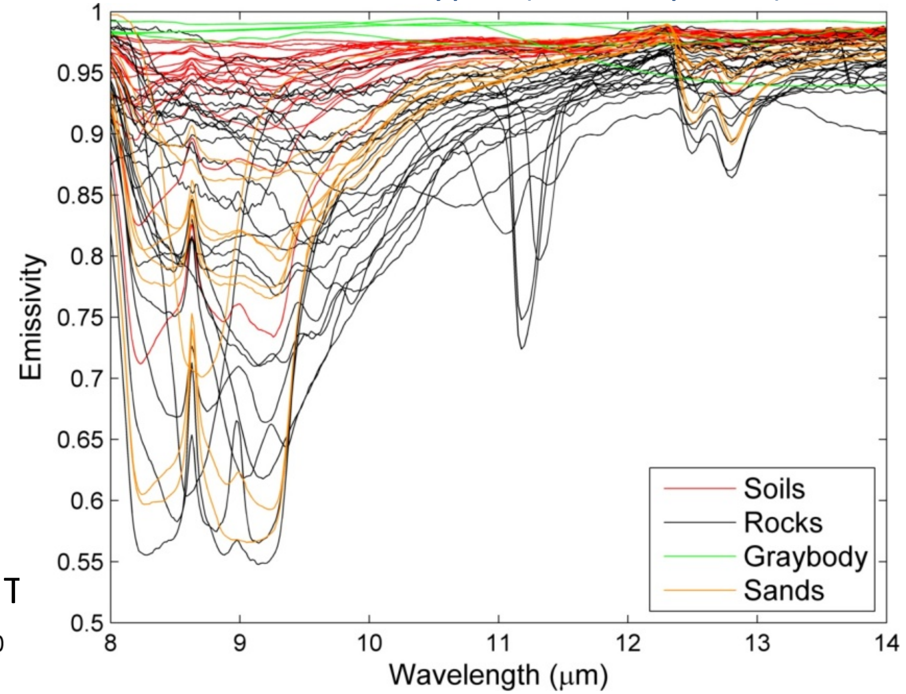
- Temperature/Emissivity Uncertainty Simulator (TEUSim) developed at JPL

382 Global Radiosondes (atmospheric data)



T

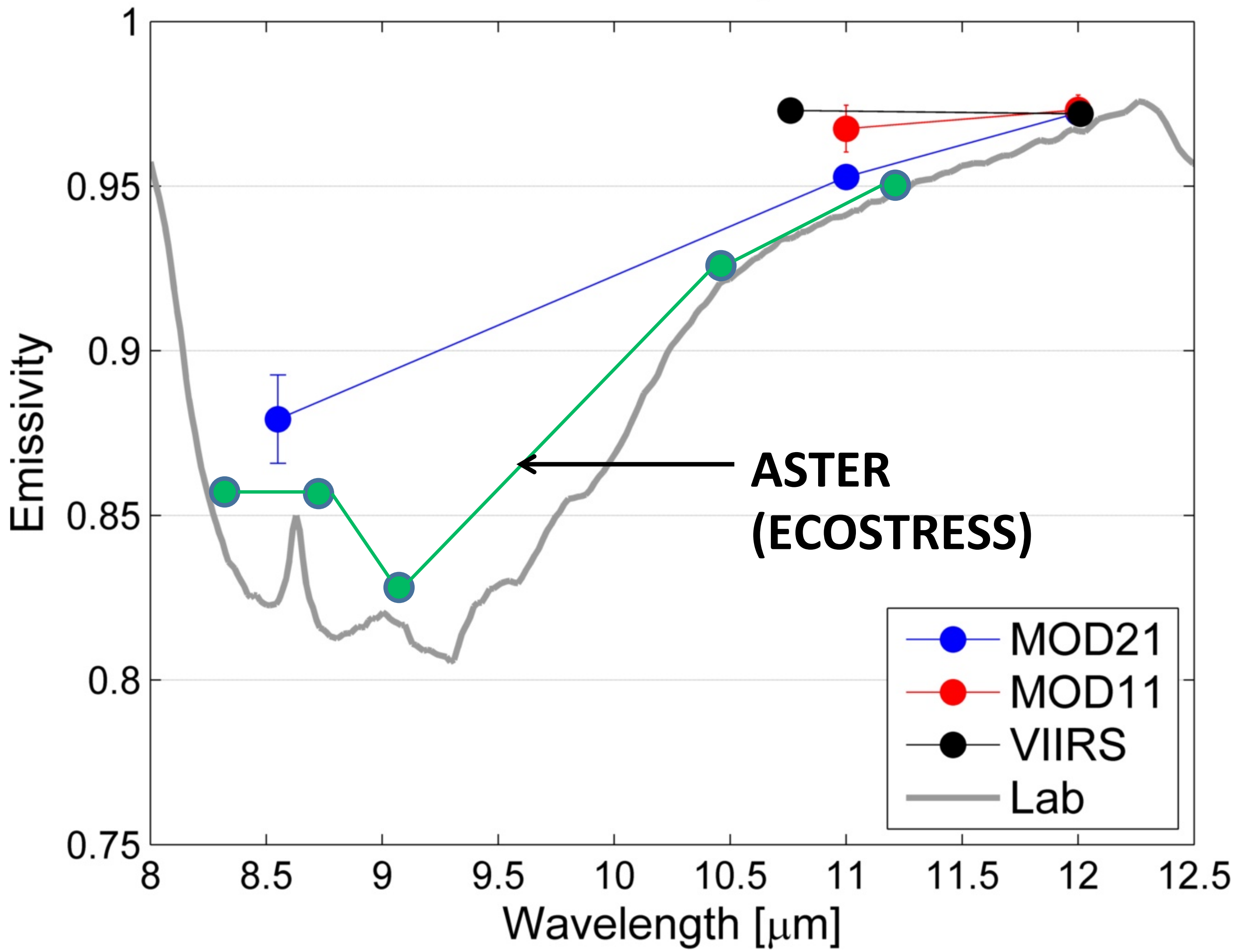
150 Surface types (ASTER speclib)



LST Algorithm Uncertainty Analysis

Hulley et al. 2012 (ESDR Uncertainty Analysis)			**LST Accuracy (K)**		
Surface types	**Samples**	**MODTRAN Simulations**	**Split-Window (MOD11)**	**3-band TES (MOD21)**	**5-band TES (ASTER)**
Dense vegetation, Water, Ice, Snow	8	660,096	1.59	2.19	1.63
Rocks	48	3,960,576	4.31	1.44	1.45
Soils	45	3,713,040	1.27	0.89	0.91
Sands	10	825,120	2.38	1.12	0.99
Total	**111**	**9,158,832**	**2.66**	**1.49**	**1.13**

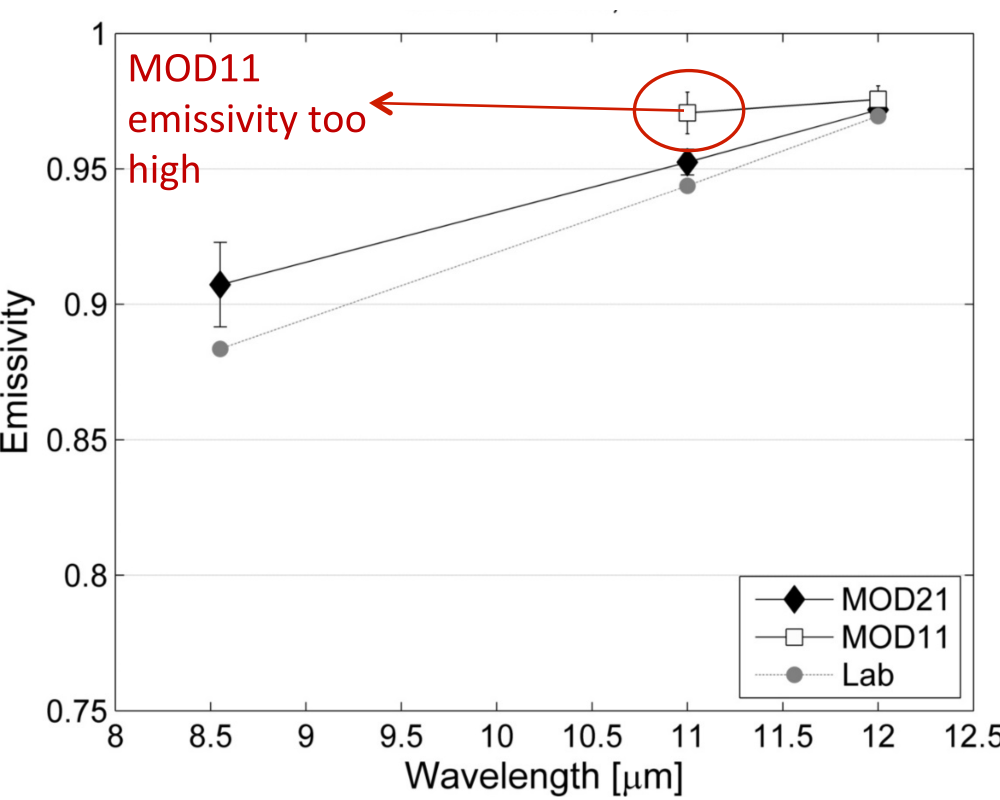
TES 5-band approach meets ~1 K accuracy capability for **ECOSTRESS**

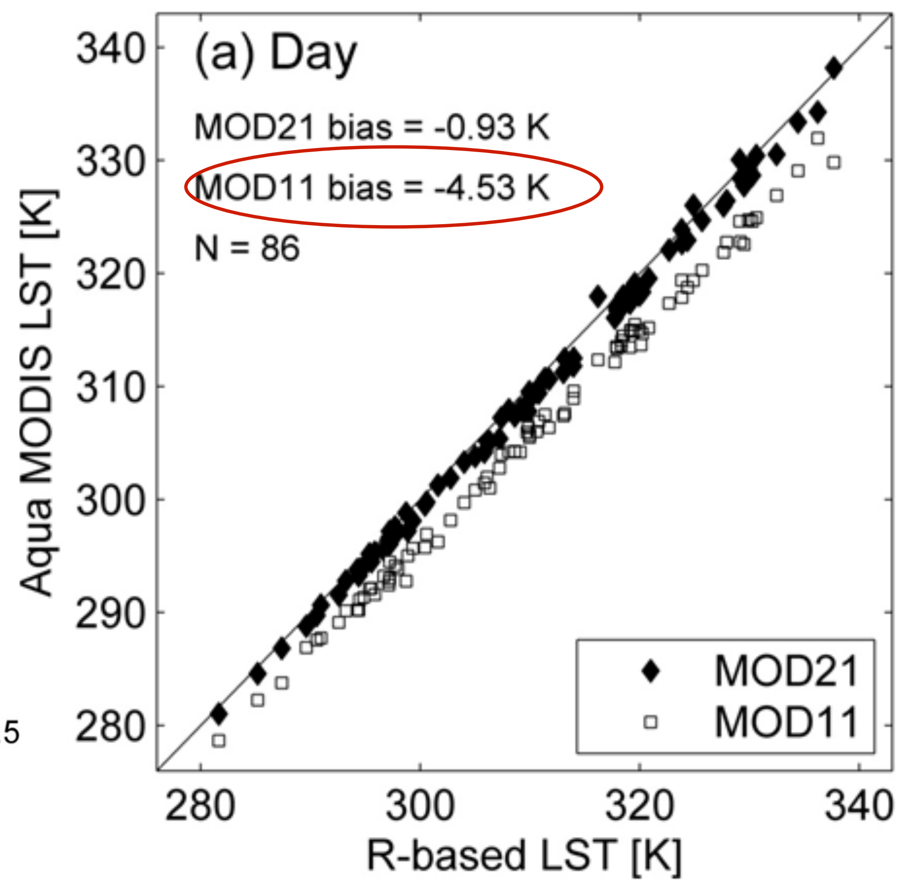


Emissivity
Wavelength [μm]
1
0.95
0.9
0.85
0.8
0.75
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
ASTER
(ECOSTRESS)
MOD21
MOD11
VIIRS
Lab

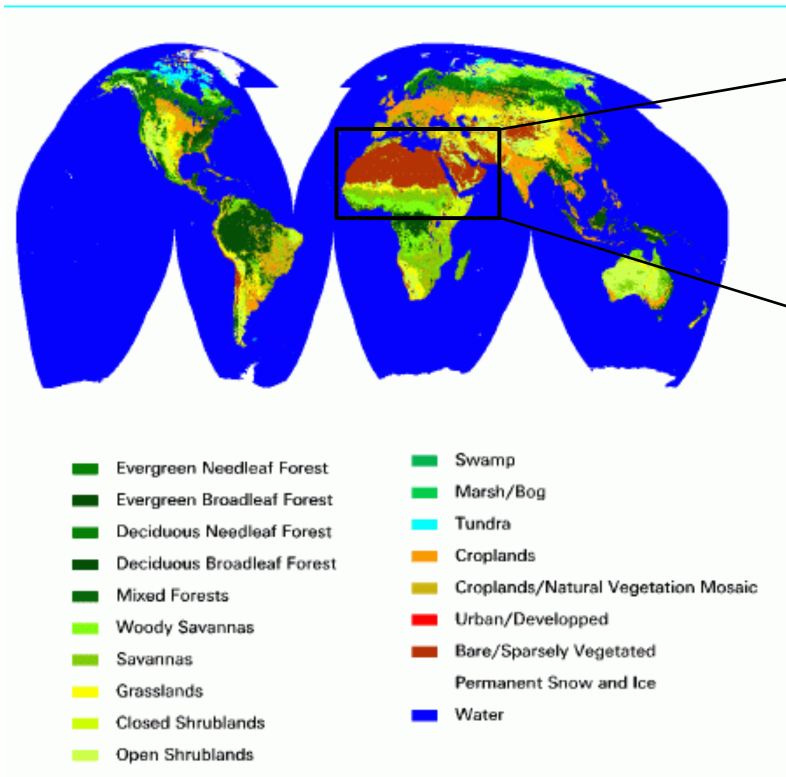
Emissivity error vs LST error

2.5% Emissivity error = ~4.5 K LST error (2-band Split-window, e.g. MOD11)
2.5% Emissivity error = ~1.5 K LST error (3-band TES e.g. MOD21)

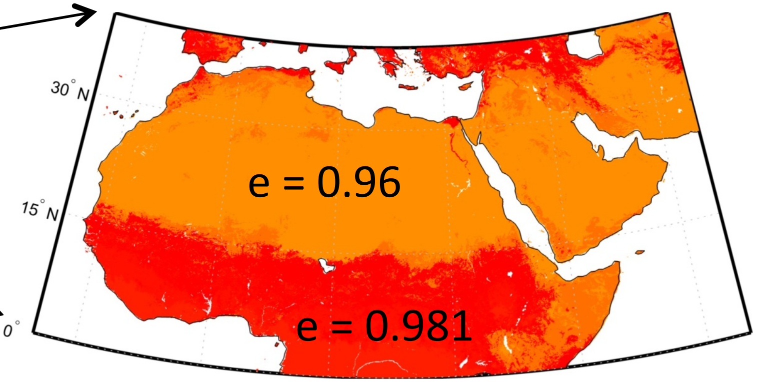




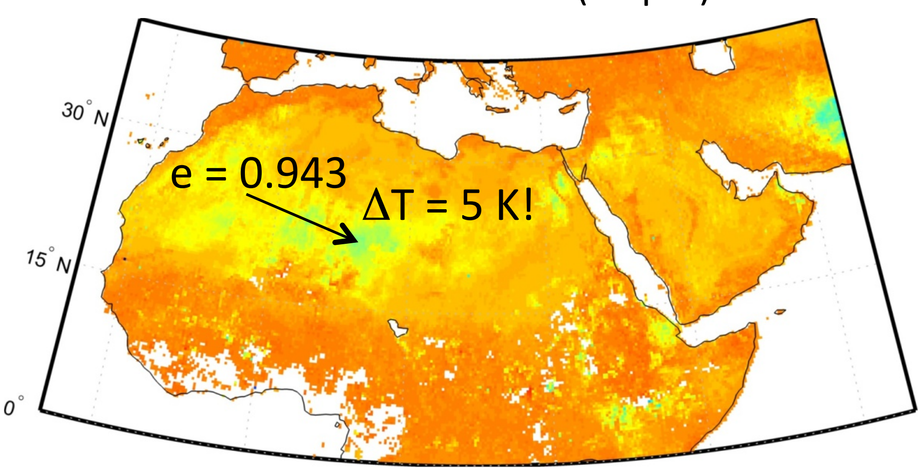
Emissivity: Split-Window versus TES retrieval



Split-window:
MOD11 band 31 (11 µm)

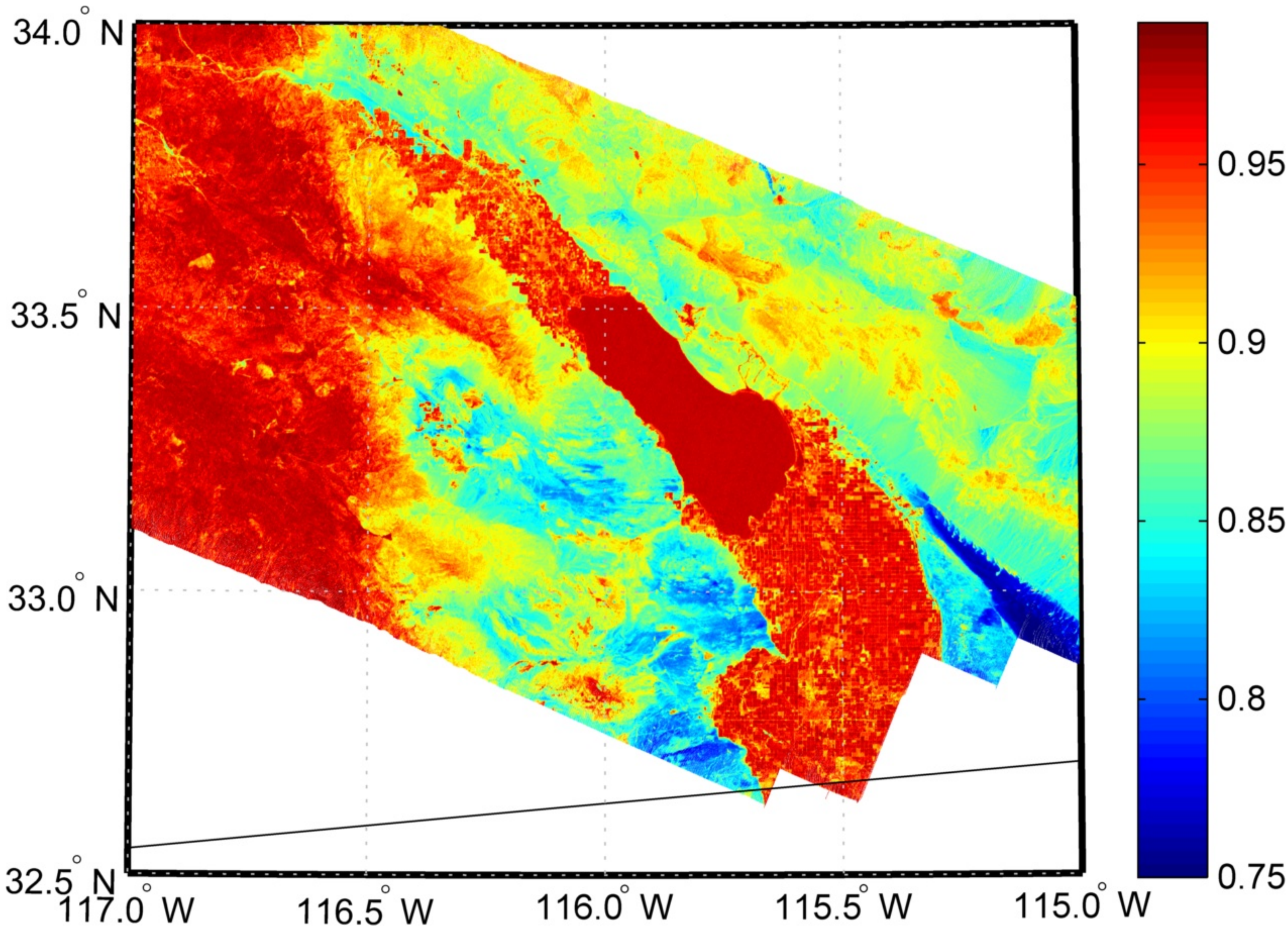


TES Retrieval:
MOD21 band 31 (11 µm)

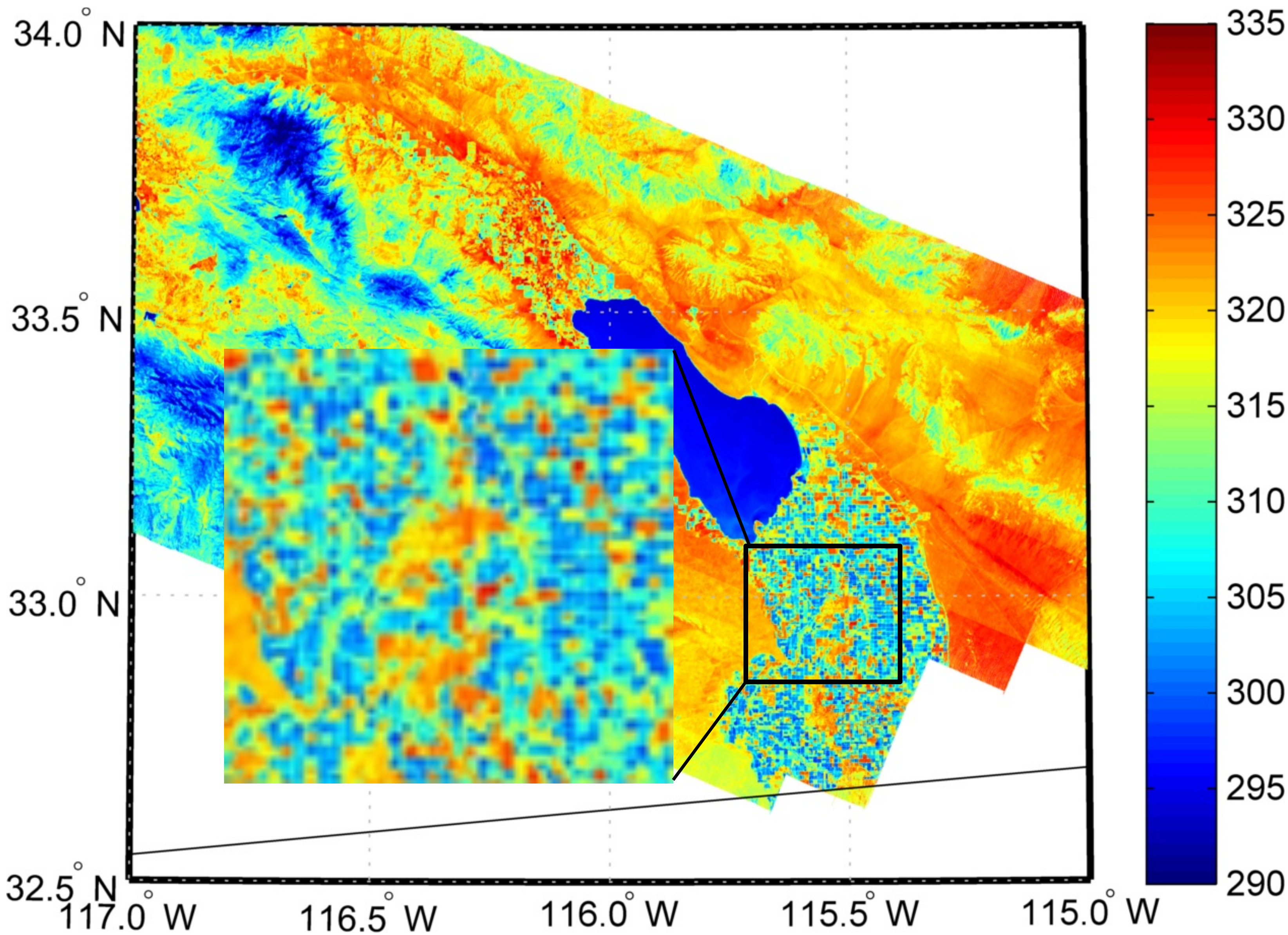


MOD11 classified as bare and assigned single emissivity but a wide range in emissivity as seen with MOD21 (TES)

MASTER Emissivity Mosaic at ~60 m (ECOSTRESS)



MASTER LST Mosaic at ~60 m (ECOSTRESS)

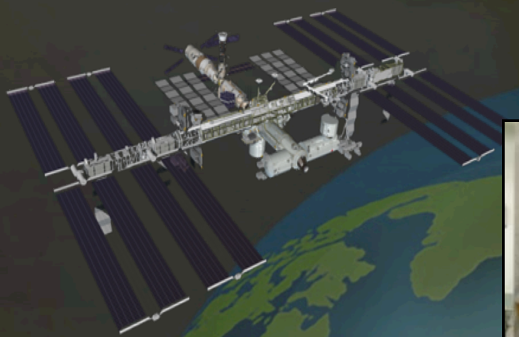


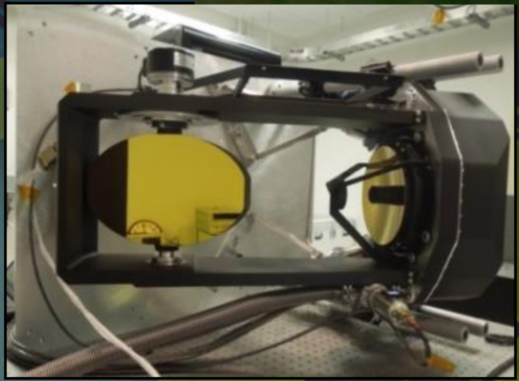
Summary

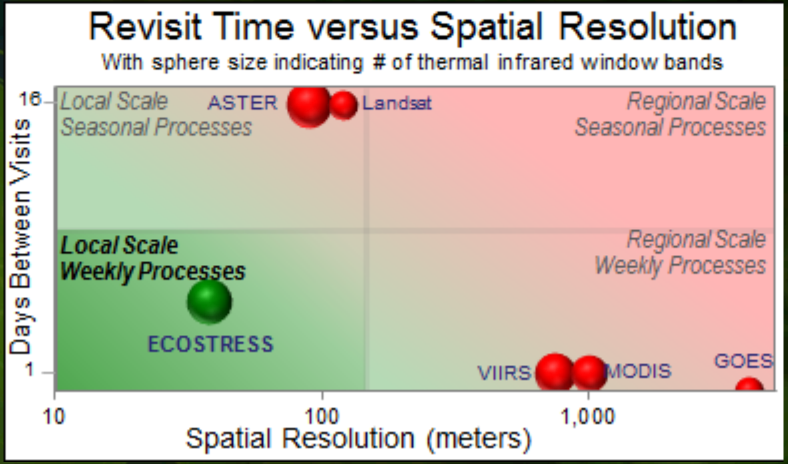
- ECOSTRESS L2 LST&E Algorithms well characterized with full uncertainty statistics
- 5-band TES algorithm will meet ECOSTRESS capability of 1 K (LST) and 10% (Evapotranspiration) accuracy
- Physically retrieving emissivity with TES algorithm is critical for retrieving accurate LST
- A 5-band instrument will improve cloud detection capabilities and allow for surface compositional studies

EXTRAS

ECOSTRESS

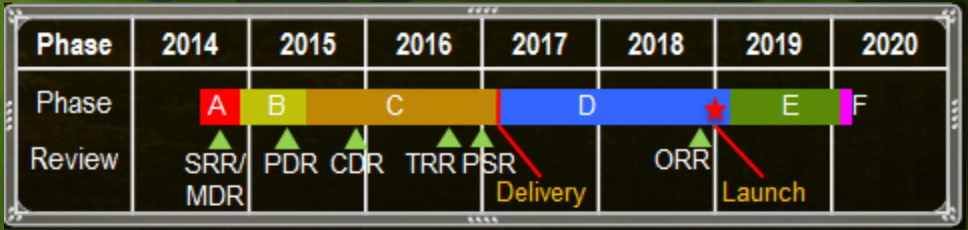


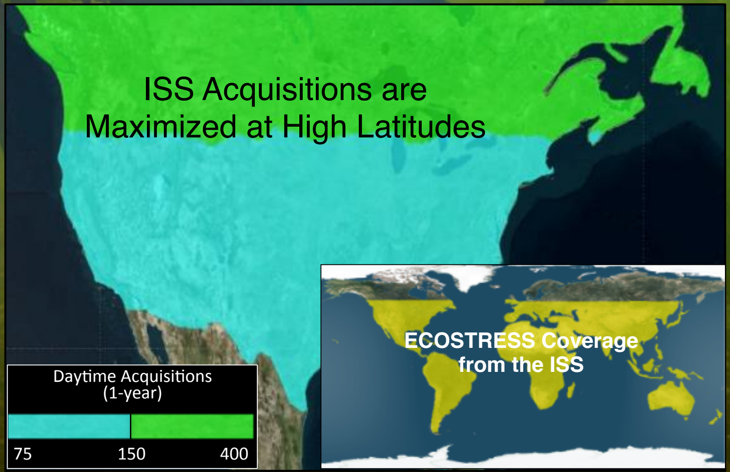




Mission

- Class D $30M cost cap
- 31-months from project start to delivery
- JPL implementation and management
- 69-month project duration (Phase A-F)
- On ISS-JEMS Module
- 12-month Science Operations (Phase E)

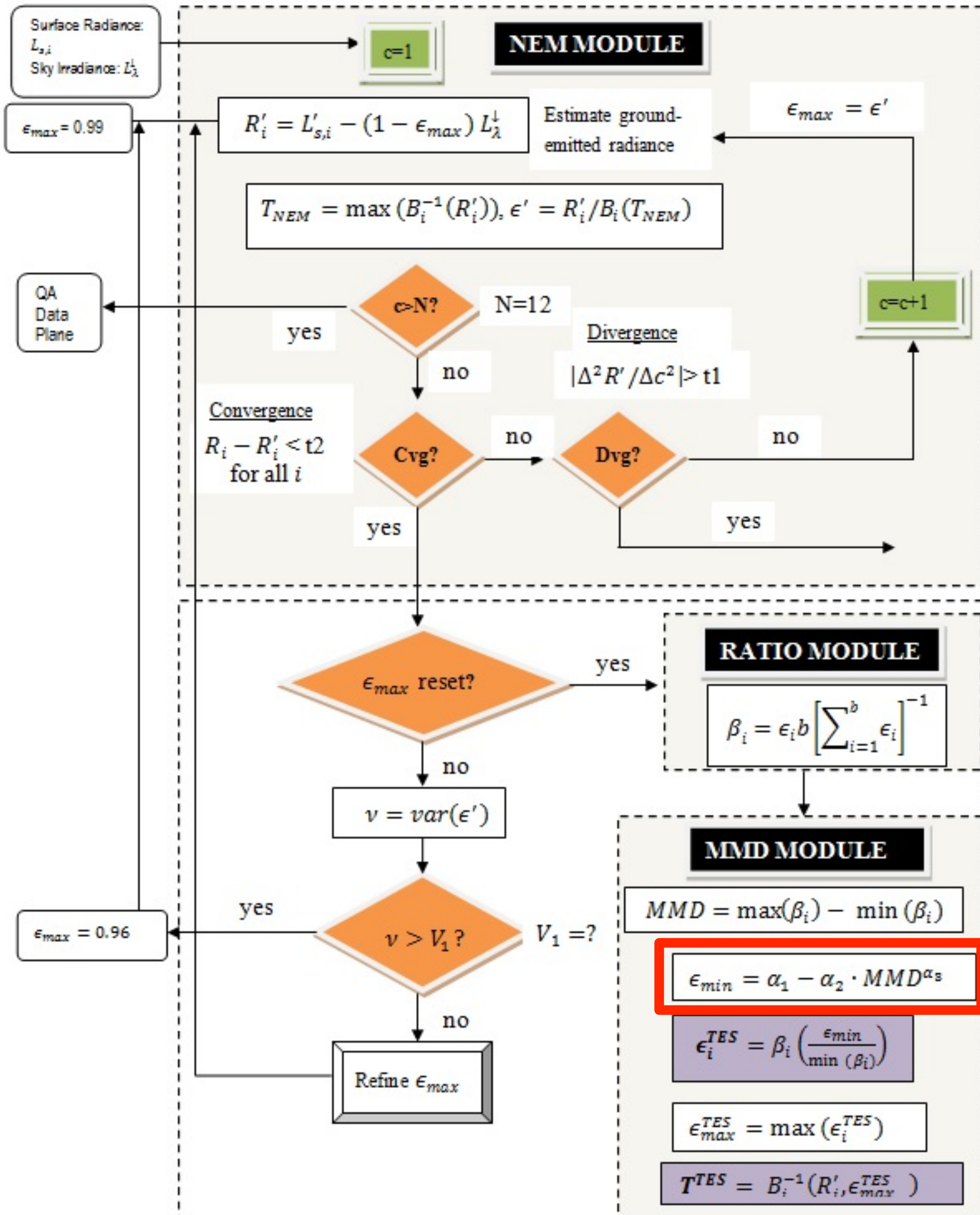




The inclined, precessing ISS orbit enables ECOSTRESS to sample the diurnal cycle in critical regions across the globe at spatiotemporal scales missed by current instruments in Sun-synchronous polar and high-altitude geostationary orbits.

Instrument

- Leverages functionally-tested PHyTIR space-ready hardware developed under the NASA Instrument Incubator Program:
  - Spectral resolution: 5 bands in the thermal infrared window (8-12.5 μm) part of the electromagnetic spectrum
  - Noise equivalent delta temperature: ≤ 0.1 K
  - Spatial resolution: 38 m x 57 m
  - Swath width: 384 km (51°)
- *Well understood measurement and algorithms based on prior missions, such as ASTER, MODIS, and Landsat*



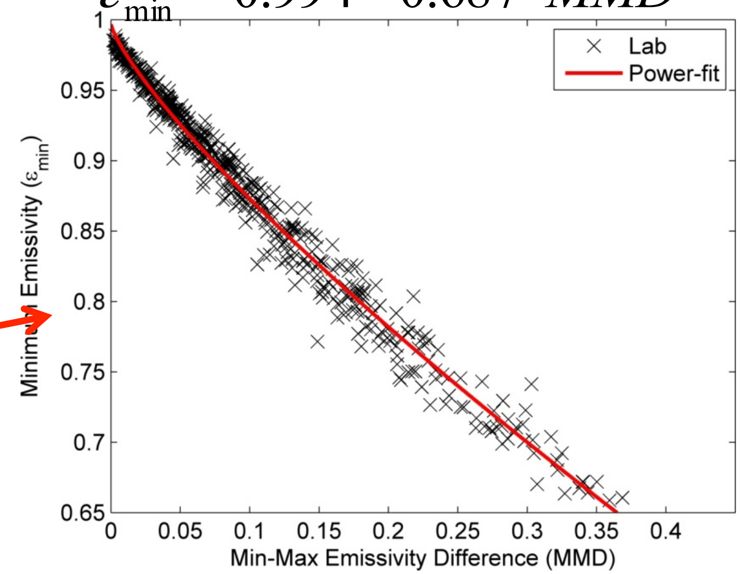
TES Algorithm

(Gillepsie et al. 1998)

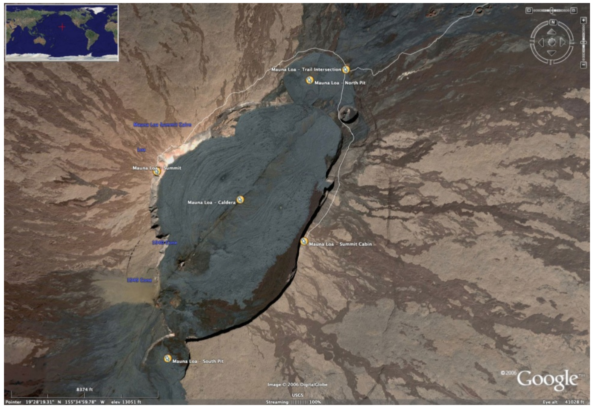
TES LST&E Products:

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

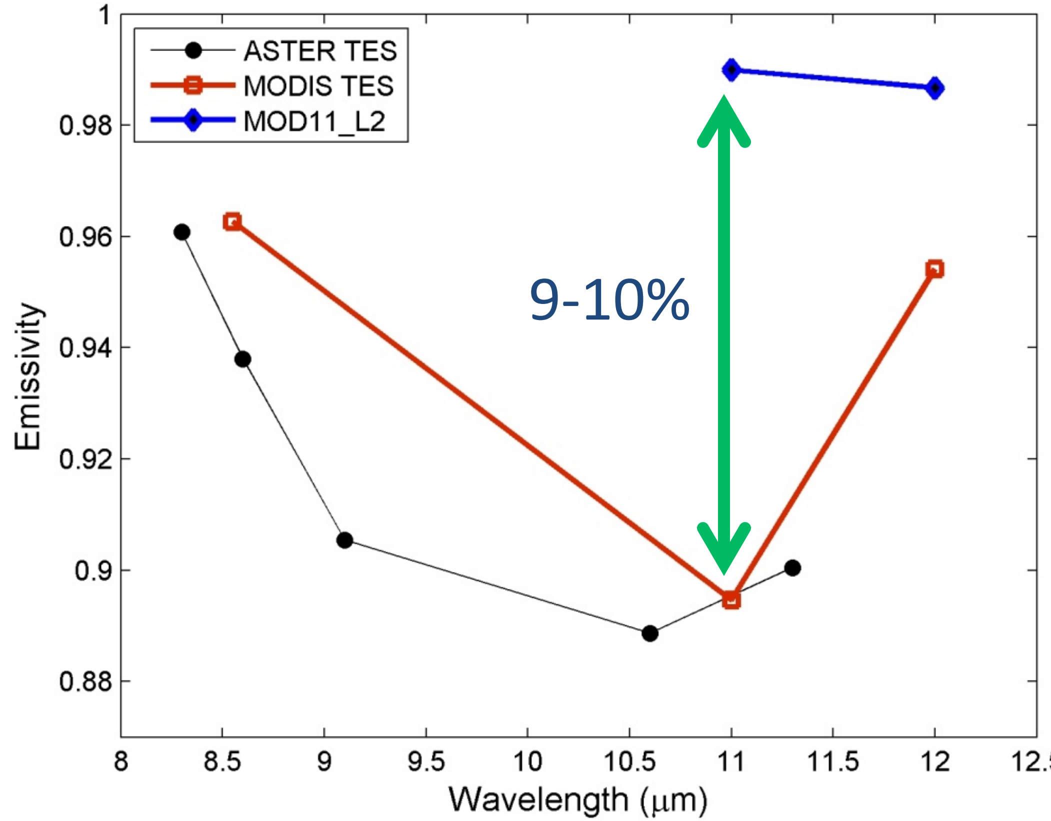
$$\varepsilon_{\min} = 0.994 - 0.687 \cdot MMD^{0.737}$$



Physical TES retrieval (MOD21) vs Classification (MOD11)



- Mauna Loa Caldera, Hawaii
- Mafic lava flow (basalt)

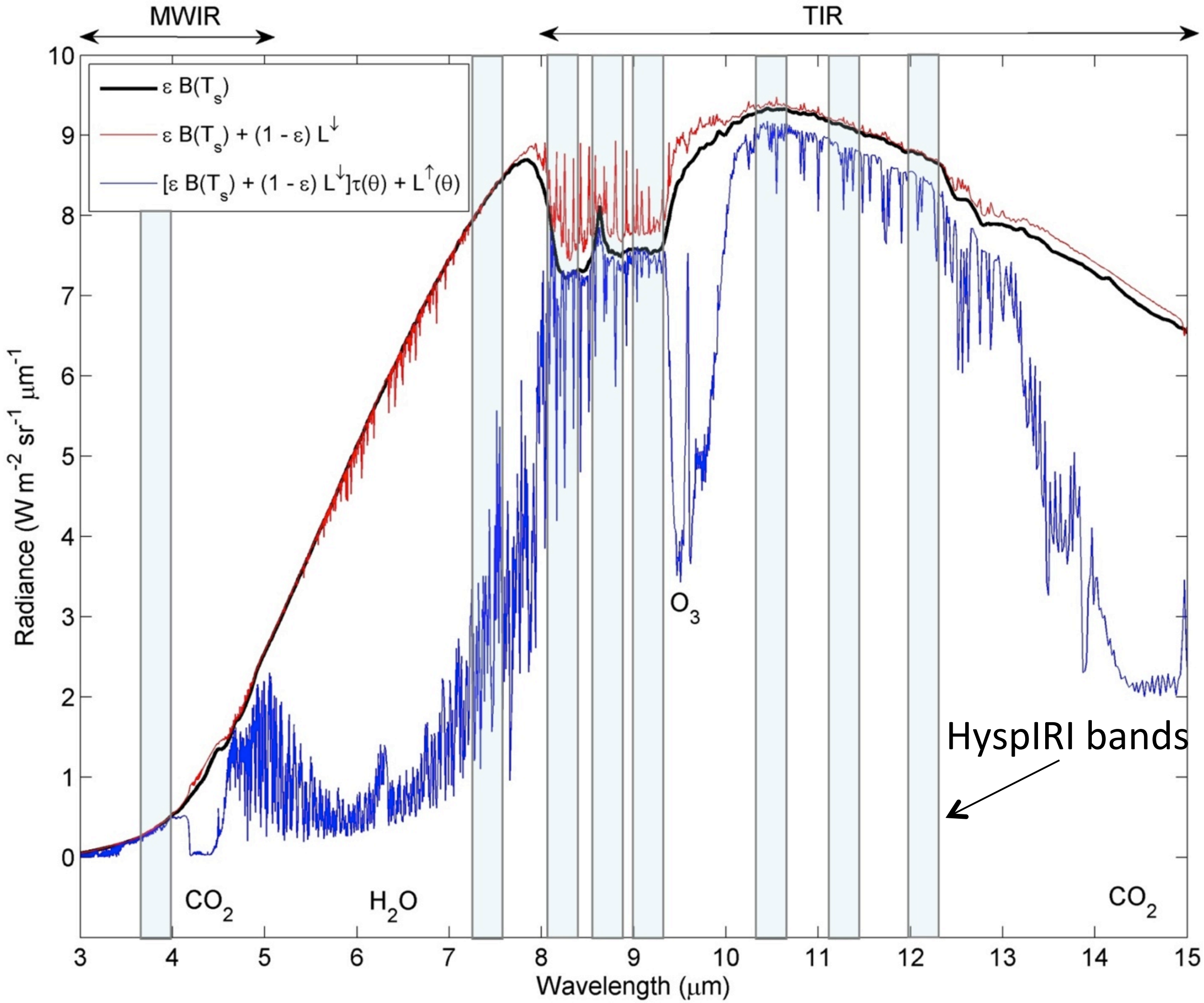


Average temperatures over Caldera

ASTER TES:	322 ±1 K
MOD21:	324 ±0.8 K
MOD11_L2:	310 ±0.5 K

Thermal Infrared Radiative Transfer

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

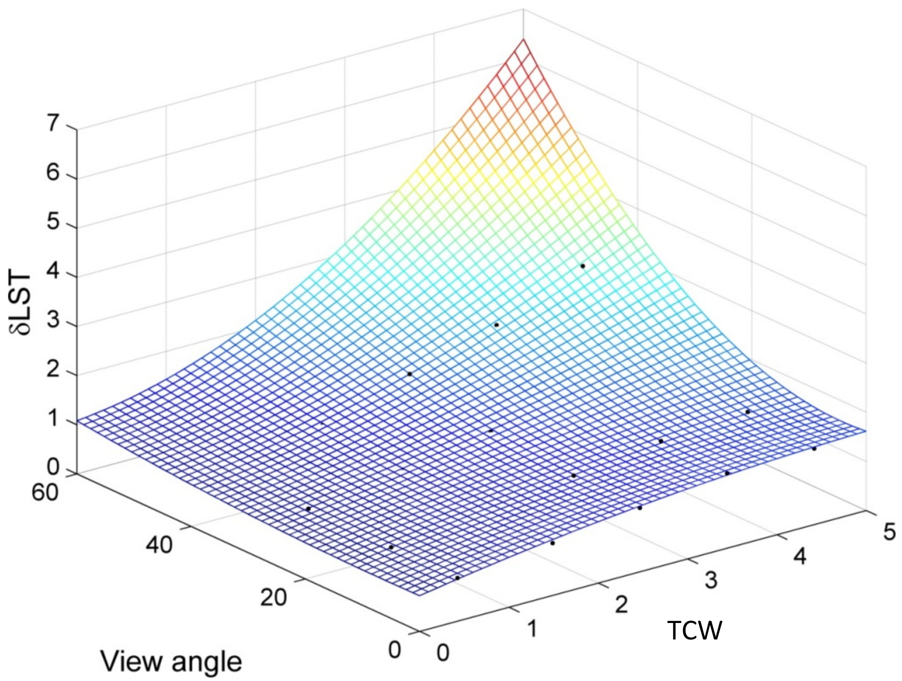


Uncertainty Parameterization

How do we make the uncertainties useful?

$$\delta LST_{MODIS} = a_o + a_1 TCW + a_2 \mathrm{SVA} + a_3 TCW \cdot SVA + a_4 TCW^2 + a_5 SVA^2 \qquad (10)$$

$\boldsymbol{a_i}$ = regression coefficients dependent on surface type (gray, bare, transition)
SVA = sensor view angle
TCW = total column water estimate (cm), e.g. from MOD07, NCEP



LST Validation over semi-arid sites

Sites	Obs (2003-2005)	MOD11 (split-window)	MOD21 (TES 3-band)
		Bias (K)	
Algodones	956	-1.84	1.39
Great Sands	546	-3.38	0.42
Kelso	759	-3.27	0.36
Killpecker	463	-3.29	0.12
Little Sahara	670	-2.73	0.78
White Sands	742	-0.08	1.15

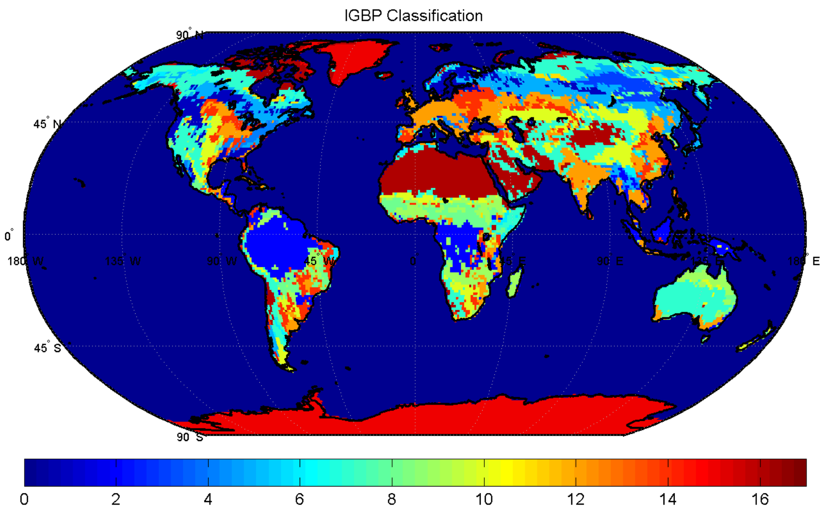
MOD11 mean cold bias of ~3 K over arid, semi-arid sites

Lake Tahoe/Salton Sea LST Validation

		MOD11 (Split-Window)	**MOD21 (TES 3-band)**
Lake Tahoe (2003-2005)	Bias [K]	0.12	0.22
	RMSE [K]	0.49	0.54
Salton Sea (2008-2010)	Bias [K]	-0.47	1.01
	RMSE [K]	0.98	1.33

Split-Window Approach:

Use Land Classes (IGBP) to assign emissivities based on lab measurements



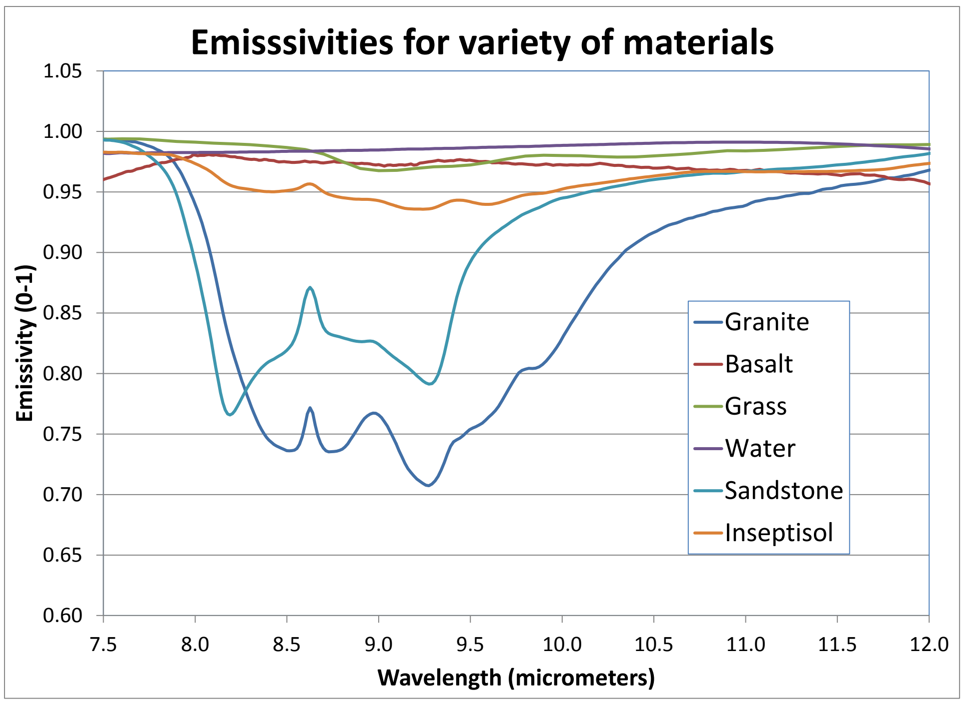
IGBP CLASS ID (i)	IGBP CLASS Description
0	Water Bodies
1	Evergreen Needleleaf Forest
2	Evergreen Broadleaf Forest
3	Deciduous Needleleaf Forest
4	Deciduous Broadleaf Forest
5	Mixed Forest
6	Closed Shrublands
7	Open Shrublands
8	Woody Savannas
9	Savannas
10	Grasslands
11	Permanent Wetlands
12	Croplands
13	Urban and Built-Up
14	Cropland/Natural Vegetation Mosaic
15	Snow and Ice
16	Barren or Sparsely Vegetated
17	Missing Data

VIIRS Algorithm:

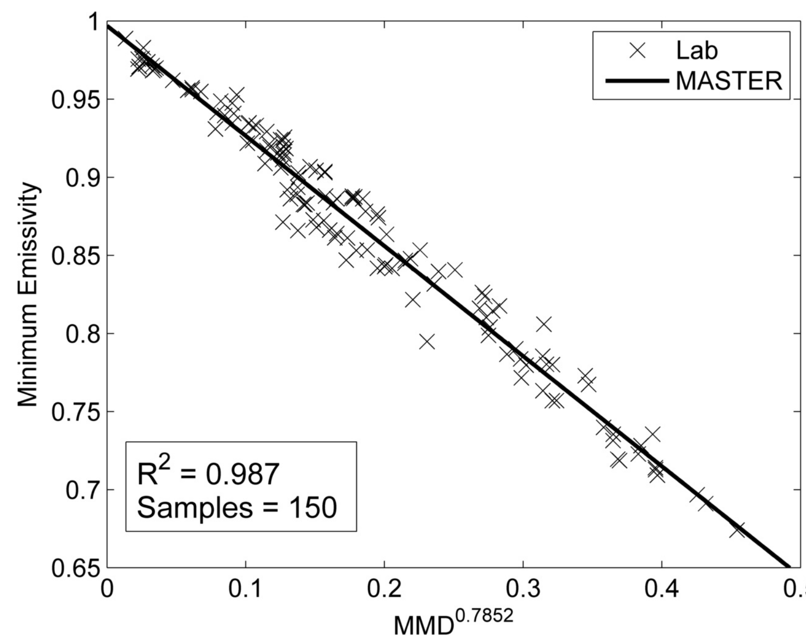
$$Ts = a_0(i) + a_1(i)\, T_{11} + a_2(i)\, (T_{11}-T_{12}) + a_3(i)\, (\sec\theta-1) + a_4(i)\, (T_{11}-T_{12})^2$$

Temperature/Emissivity Separation (TES)

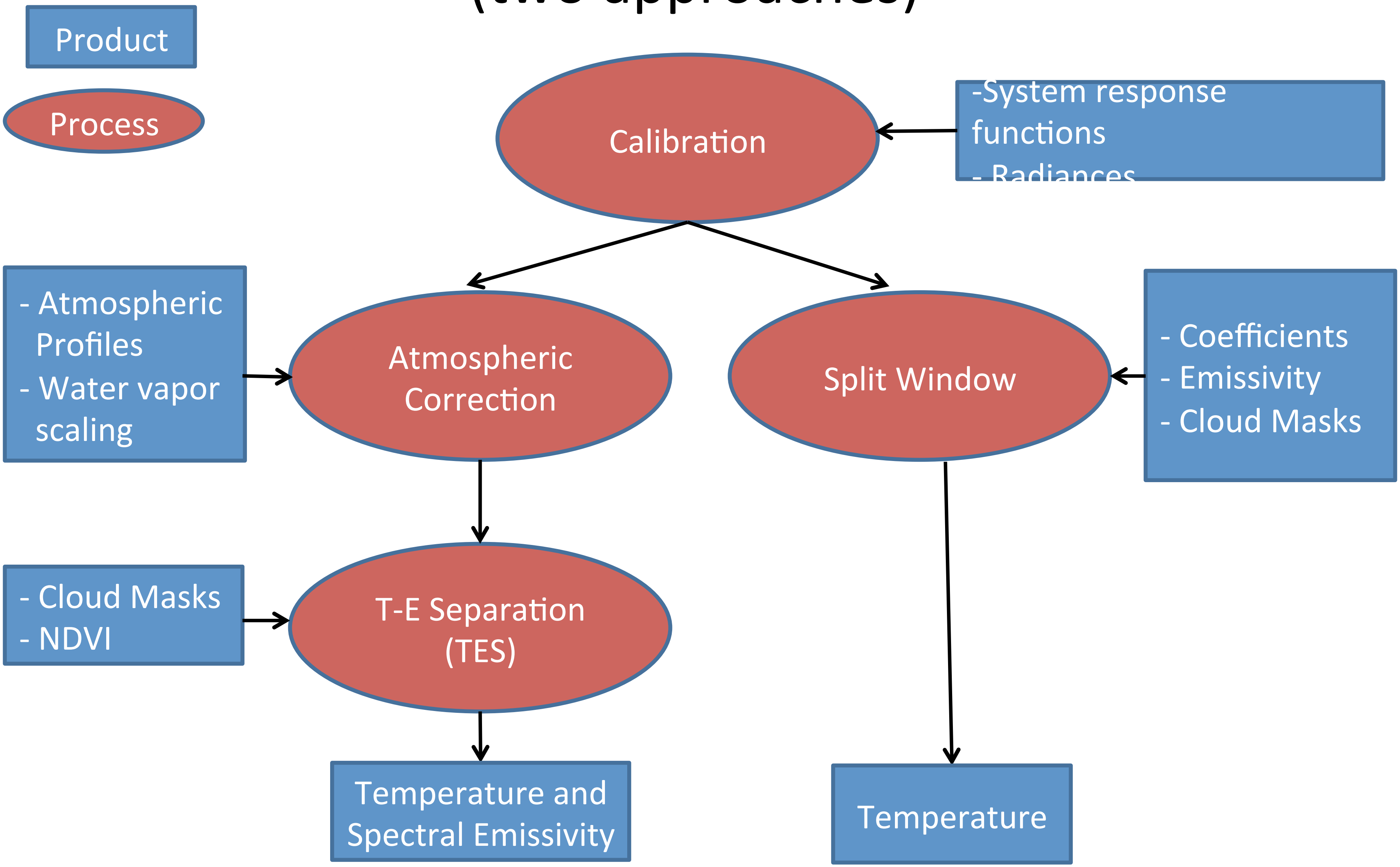
T-E separation is under-determined
If have N equations always have N+1 unknowns:
Radiance Band 1 = T + e_1
Radiance Band 2 = T + e_2
Radiance Band 3 = T + e_3



Calibration Curve



Sensor to Surface Products
(two approaches)



THIRSTY presents a significant improvement in spatial resolution, temporal coverage, and accuracy (from spectral coverage) over most other TIR instruments

Instrument	Platform	Resolution (m)	Launch year	Revisit (days)	Daytime overpass	TIR bands (8-12 μm)
ASTER	Terra	90	2000	16	10:30 am	5
TIRS	Landsat 8	120	2013	16	10:11 am	2
NIRST	Aquarius	350	2011	Daily	6:00 am/pm	2
VIIRS	S-NPP	750	2011	Daily	1:30 am/pm	4
MODIS	Terra/Aqua	1000	2000/2002	Daily	10:30/1:30 am/pm	4
GOES	Multiple	4000	2000	Daily	15 min	2

TES Accuracy Simulations

<u>Atmospheric Profiles:</u>

- 382 Global Radiosonde profiles (0-6 cm TCW)
- Each Tair varied by [-2 0 2] K
- Each RH varied by [0.8 1 1.2]
- Tsurf varied from [-5 0 5 10] K

<u>Atmospheric profile uncertainties:</u>

- Tair 2 K
- RH 10 (20) %

TES	LST RMSE (K) – Vegetation		
	NEDT 0.1 K	NEDT 0.3 K	NEDT 0.5 K
3-band	1.57 (2.33)	1.60 (2.34)	1.61 (2.41)
5-band	1.55 (2.15)	1.57 (2.18)	1.61 (2.25)
8-band	?	?	?

TES	LST RMSE (K) – Soils		
	NEDT 0.1 K	NEDT 0.3 K	NEDT 0.5 K
3-band	1.54	1.59	1.62
5-band	1.44	1.47	1.47
8-band	?	?	?