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)
<table>
<thead>
<tr>
<th>Data Products</th>
<th>Description</th>
<th>Information Required</th>
<th>Plans for Validation/Reprocessing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level-0</td>
<td>Reconstructed, unprocessed instrument data at full resolution; any communication artifacts removed.</td>
<td>Raw science data packets</td>
<td>Automated process, no reprocessing needed.</td>
</tr>
<tr>
<td>Level-1A</td>
<td>Reconstructed unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients.</td>
<td>Level-0 raw data</td>
<td>Automated process, minimal reprocessing.</td>
</tr>
<tr>
<td>Level-1B</td>
<td>Level 1a data that have been processed to sensor units by applying the coefficients for radiometric calibration and geometric resampling</td>
<td>Level-1A &amp; radiometric and geometric coefficients</td>
<td>Automated process, with full reprocessing as needed. Validation of at-sensor radiance using data from autonomous Lake Tahoe and Salton Sea cal/val sites.</td>
</tr>
<tr>
<td>Level-2</td>
<td>LST and spectral emissivity</td>
<td>Level-1B data, cloud mask, NWP atmospheric profiles, ASTER digital elevation data.</td>
<td>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.</td>
</tr>
<tr>
<td>Level-3</td>
<td>Evapotranspiration (ET),</td>
<td>Level-2 products, VNIR data from Landsat, met. data from NCEP.</td>
<td>Reprocessing as needed based on Level 2 reproprocessing. Validation with eddy covariance data from FLUXNET sites (global).</td>
</tr>
<tr>
<td>Level-4</td>
<td>Water Use Efficiency (WUE), Evaporative Stress Index (ESI)</td>
<td>Level-3 products, GPP</td>
<td>Reprocessing as needed based on Level 2 and 3 reproprocessing. Validation with eddy covariance data from FLUXNET sites (global).</td>
</tr>
</tbody>
</table>
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:
- \( B_\lambda \) = blackbody spectral radiance
- \( \lambda \) = 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:

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

$$L_{\lambda} = \text{Spectral Radiance}$$
HyspIRI/ECOSTRESS Spectral Response Functions
Thermal Infrared Radiative Transfer

\[ L_i(\theta) = \tau_i(\theta) \cdot e_i \cdot B_i(T_S) + \tau_i(\theta) \cdot (1 - e_i) \cdot \bar{L}_i + \int B_i(T(P)) d\tau_i \]

- **Emissivity**
- **Land Surface Temperature (LST)**
- **Surface Radiance**
- **Sky irradiance**
- **Transmissivity**
- **Path radiance**

**Sensor Radiance**
- **Surface Emission**
- **Surface Reflection**
- **Atmospheric Emission**

**Path radiance**

**Skin Temperature & Surface Emissivity**
Atmospheric Correction

Surface Radiance:

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

- **Atmospheric Parameters:** \( \tau_i(\theta), L_i(\theta), L_i^\uparrow(\theta) \)
  - 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
   - Requires 2 bands
   - Prescribed spectral emissivity
   - Regression coefficients should represent all configurations (atmospheric water content, view angle, surface $T_{air}$, …)

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

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

← ECOSTRESS
MODIS MOD21 Land Surface Temperature and Emissivity Algorithm Theoretical Basis Document

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

G. Hulley
S. Hook
Jet Propulsion Laboratory

August 2012

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

May 2011

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
• MASTER Land Surface Temperature/Emissivity Retrieval Scheme
• Prototype algorithm for HyspIRI
• See ATBDs at: http://hyspiri.jpl.nasa.gov/documents

START

Atmospheric Correction
MODTRAN 5.2

τ - Transmissivity
L↑ - Path radiance
L↓ - Sky irradiance

1. WVS coefficients
2. Water vapor estimate
3. NDVI
4. Water mask

NEW

Water Vapor Scaling (WVS) Model

Surface Radiance

Temperature/Emissivity Separation (TES) Algorithm

LST and spectral emissivity (bands 43, 44, 47-49)

1. NCEP (GDAS) atmospheric profiles
6 hourly, 1° resolution
2. ASTER Digital Elevation Model
NCEP currently used AVIRIS testing underway
Effect of Water Vapor Scaling (WVS) Model

*Tonooka, 2005*

![Graph showing the effect of water vapor scaling on emissivity and wavelength. The graph compares MODIS and ASTER WVS models with standard versions.]
ECOSTRESS Measurement Requirement (baseline) and Capability

Which LST&E algorithm will meet these requirements?

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

<table>
<thead>
<tr>
<th></th>
<th>Evapotranspiration</th>
<th>Land Surface Temperature (K)</th>
<th>BT at Sensor at 300 Kelvin (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>Precision</td>
<td>Uncertainty</td>
</tr>
<tr>
<td>Requirement</td>
<td>15%</td>
<td>5%</td>
<td>16%</td>
</tr>
<tr>
<td>Capability</td>
<td>10%</td>
<td>1%</td>
<td>10%</td>
</tr>
</tbody>
</table>
LST&E Uncertainty Analysis
(ROSES 2010 – Uncertainty Analysis Program)

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

382 Global Radiosondes (atmospheric data)  
150 Surface types (ASTER speclib)
### LST Algorithm Uncertainty Analysis

<table>
<thead>
<tr>
<th>Surface types</th>
<th>Samples</th>
<th>MODTRAN Simulations</th>
<th>Split-Window (MOD11)</th>
<th>3-band TES (MOD21)</th>
<th>5-band TES (ASTER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense vegetation, Water, Ice, Snow</td>
<td>8</td>
<td>660,096</td>
<td>1.59</td>
<td>2.19</td>
<td>1.63</td>
</tr>
<tr>
<td>Rocks</td>
<td>48</td>
<td>3,960,576</td>
<td>4.31</td>
<td>1.44</td>
<td>1.45</td>
</tr>
<tr>
<td>Soils</td>
<td>45</td>
<td>3,713,040</td>
<td>1.27</td>
<td>0.89</td>
<td>0.91</td>
</tr>
<tr>
<td>Sands</td>
<td>10</td>
<td>825,120</td>
<td>2.38</td>
<td>1.12</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>111</strong></td>
<td><strong>9,158,832</strong></td>
<td><strong>2.66</strong></td>
<td><strong>1.49</strong></td>
<td><strong>1.13</strong></td>
</tr>
</tbody>
</table>

TES 5-band approach meets ~1 K accuracy capability for **ECOSTRESS**
Emissivity error vs LST error

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

MOD11 emissivity too high
Emissivity: Split-Window versus TES retrieval

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

\[ L_{\text{sat},\lambda} = \left[ \varepsilon_{\lambda} B_{\lambda}(LST) + (1 - \varepsilon_{\lambda}) L_{\text{sky},\lambda}^\downarrow \right] \tau_{\lambda} + L_{\text{sky},\lambda}^\uparrow \]
Uncertainty Parameterization
How do we make the uncertainties useful?

\[ \delta LST_{MODIS} = a_0 + a_1 TCW + a_2 SVA + a_3 TCW \cdot SVA + a_4 TCW^2 + a_5 SVA^2 \]  

(10)

- \( a_i \) = 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

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

MOD11 mean cold bias of ~3 K over arid, semi-arid sites
Lake Tahoe/Salton Sea
LST Validation

<table>
<thead>
<tr>
<th></th>
<th>MOD11 (Split-Window)</th>
<th>MOD21 (TES 3-band)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lake Tahoe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMSE [K]</td>
<td>0.49</td>
</tr>
<tr>
<td><strong>Salton Sea</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2008-2010)</td>
<td>Bias [K]</td>
<td>-0.47</td>
</tr>
<tr>
<td></td>
<td>RMSE [K]</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Split-Window Approach:
Use Land Classes (IGBP) to assign emissivities based on lab measurements

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

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

Emisssivities for variety of materials

Calibration Curve

R^2 = 0.987
Samples = 150
Sensor to Surface Products (two approaches)

- System response functions
  - Radiances
- Coefficients
  - Emissivity
  - Cloud Masks
- Atmospheric Profiles
  - Water vapor scaling
- Cloud Masks
  - NDVI
- T-E Separation (TES)
- Temperature and Spectral Emissivity
- Temperature
THIRSTY presents a significant improvement in spatial resolution, temporal coverage, and accuracy (from spectral coverage) over most other TIR instruments

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

### Atmospheric Profiles:
- 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

### Atmospheric profile uncertainties:
- Tair 2 K
- RH 10 (20) %

<table>
<thead>
<tr>
<th>TES</th>
<th>LST RMSE (K) – Vegetation</th>
<th>LST RMSE (K) – Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NEDT 0.1 K</td>
<td>NEDT 0.3 K</td>
</tr>
<tr>
<td>3-band</td>
<td>1.57 (2.33)</td>
<td>1.60 (2.34)</td>
</tr>
<tr>
<td>5-band</td>
<td>1.55 (2.15)</td>
<td>1.57 (2.18)</td>
</tr>
<tr>
<td>8-band</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>NEDT 0.1 K</td>
<td>NEDT 0.3 K</td>
</tr>
<tr>
<td>3-band</td>
<td>1.54</td>
<td>1.59</td>
</tr>
<tr>
<td>5-band</td>
<td>1.44</td>
<td>1.47</td>
</tr>
<tr>
<td>8-band</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>