A LAND SURFACE TEMPERATURE PRODUCT

John R. Schott, Ph.D.
Frederick and Anna B. Wiedman Professor
Digital Imaging and Remote Sensing Laboratory
Chester F. Carlson Center for Imaging Science
Rochester Institute of Technology
54 Lomb Memorial Drive
Rochester, New York 14623
Phone: 585-475-5170
Email: schott@cis.rit.edu
A Land Surface Temperature Product

Goals – Develop a methodology applicable to entire Archive (L4, L5 & L7) (L3?)

– Deliver methodology, software as appropriate and validation results/test sites to USGS for implementation.
A Land Surface Temperature Product

Approach – Focus initial efforts on north America to take advantage of available data
  - NAALSED (N.A. Emissivity maps)
  - NARR (N.A. Met data)
  – Use North America to clarify how to do Globe
    - Same approach with more interpolation of atmospheres & lower resolution emissivities
    - Identify/develop better global reanalysis
    - Build higher resolution global emissivity maps
A Land Surface Temperature Product

Implement Approach

Calibrate data base: Goddard, JPL, RIT
- L4, L5, L7 Updated trusted calibrations available – final error assessment ongoing

Atmospheric Compensation: RIT with JPL, USGS & Goddard

Emissivity values: JPL with RIT, USGS & Goddard
### Table 1: Residual Uncertainties in the data from the USGS Landsat Archive expressed in apparent temperature [K]. Values in parenthesis are the number of points included in the analysis.

<table>
<thead>
<tr>
<th>Uncertainty in Predicted Radiance $S^\text{p}$</th>
<th>Instrument Noise $S^\text{i}$</th>
<th>Modeled Uncertainty in Sensed Radiance $S^\text{L}$</th>
<th>Observed Variability About Best Fit Calibration Line $S^\text{RMS}$</th>
<th>Observed Variability Unaccounted Uncertainty $S^\text{w}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial (A) (0.31)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Temperature (RIT) (0.34)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Surface Radiometers &amp; Thermistors (JPL) (0.35)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Subsurface Temperatures (NOAA Buoys) (0.41)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat 7 (composite) (324)</td>
<td>0.21$^1$</td>
<td>0.41</td>
<td>0.48$^2$</td>
<td>0.25</td>
</tr>
<tr>
<td>RIT (51)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JPL (234)</td>
<td>0.40</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOAA Buoys (39)</td>
<td>0.46</td>
<td>0.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat 5</td>
<td>0.17-0.3</td>
<td></td>
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<tr>
<td>1984-1998 NOAA Buoy (102)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1997-2010 Composite (285)</td>
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<tr>
<td>RIT (29)</td>
<td>0.38-0.45</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JPL (149)</td>
<td>0.39-0.46</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOAA Buoys (107)</td>
<td>0.44-0.51</td>
<td>0.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat 4</td>
<td>0.22-0.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1982-2983 NOAA Buoy (9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1987-1992 NOAA Buoy (19)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

$^1$ NEΔT for the low gain is (0.26K)

$^2$ These are the best values to use for the expected uncertainty in the radiance values.
ATMOSPHERE
North America Regional Reanalysis (NARR) program

- 32 km. grid
- 3 hr temporal samples
- 29 atmospheric layers
- Spans entire Landsat time period
For each node we can estimate the atmospheric parameters ($\tau$, $L_u$, $L_d$) associated with altitudes $H_i$ from Modtran.
• Generate MODTRAN runs vs. Elevation(H) (H from USGS DEM)
  
  – Crop lower layers
  – Maintain CWV
  – Alternative logic?

Run Modtran for each altitude.

Output:

\[ \tau(H), L_u(H), L_d(H) \]
Height Interpolation - Sensitivity Study

- Compute parameters ($\tau, L_u, L_d$) at finely spaced intervals throughout range
- Compute parameters at 9 samples throughout range and linearly interpolate to any desired height
  - Samples regularly spaced
- Compute error in apparent temperature between temperature computed with finely sampled parameters and interpolated parameters
Height Interpolation - Sensitivity Study

2 August 2007
Height Interpolation - Sensitivity Study

2 August 2007
Height Interpolation - Sensitivity Study

Summer - Irregularly Spaced Samples

Error in Temp vs Ground Altitude

Error in Apparent Temperature [K]

Ground Altitude [km]

-0.4
-0.2
0.0
0.2
310 K
295 K
273 K
Temporal Interpolation

• NARR atmospheric profile before and after acquisition time
• Linearly interpolate to build atmospheric profile for desired time
• Build profile using daily radiosonde corrected to surface weather at desired time (i.e., Approach used in cal-val)
• Compute temperature at range of heights

• Compute error in apparent temperature
Temporal Interpolation - Sensitivity Study

2 August 2007

Ground Altitude vs. Upwell

Ground Altitude vs. Transmission

- Radiosonde
- Interpolated
Temporal Interpolation - Sensitivity Study

2 August 2007

Error in Temp vs Ground Altitude

- 310 K
- 295 K
- 273 K
Temporal Interpolation - Sensitivity Study

1 February 2007
Temporal Interpolation - Sensitivity Study

1 February 2007

Error in Temp vs Ground Altitude

Error in Apparent Temperature [K]

Ground Altitude [km]

310 K
295 K
273 K
EMISSIVITY
A Land Surface Temperature (LST) Product for Landsat

Glynn Hulley, Simon Hook

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

(c) 2011 California Institute of Technology. Government sponsorship acknowledged.
The North American ASTER Land Surface Emissivity Database (NAALSED)

- Mean, seasonal emissivity product at 100m using all clear-sky ASTER scenes acquired since launch (2000-2010)

- Summer product: (Jul-Aug-Sep)
- Winter product: (Jan-Feb-Mar)

- Cloud detection methodology adapted from Landsat ACCA

- USA (22-49° N)
  - Total Scenes: 29,653
  - Usable Scenes: 21,860 (74%)

- Canada (49-71° N)
  - Total Scenes: 34,496
  - Usable Scenes: 17,988 (52%)

http://emissivity.jpl.nasa.gov
NAALSED validation at pseudo-invariant sand dune sites

Algodones Dunes
(Classification does not distinguish bare dunes from surrounding desert shrubs)

Death Valley
(Classification would assign at most two emissivity classes to most of this region)
### Landsat emissivity from Land Classification

<table>
<thead>
<tr>
<th>IGBP Class Type</th>
<th>Veg</th>
<th>Bare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grasslands</td>
<td>0.953</td>
<td>0.971</td>
</tr>
<tr>
<td>Shrublands</td>
<td>0.972</td>
<td>0.958</td>
</tr>
<tr>
<td>Crops</td>
<td>0.983</td>
<td>0.971</td>
</tr>
<tr>
<td>Woody Savannas</td>
<td>0.982</td>
<td>0.971</td>
</tr>
<tr>
<td>Broadleaf Forest</td>
<td>0.981</td>
<td>0.971</td>
</tr>
<tr>
<td>Needleleaf Forest</td>
<td>0.989</td>
<td>0.971</td>
</tr>
<tr>
<td>Wetlands</td>
<td>0.992</td>
<td>0.971</td>
</tr>
<tr>
<td>Urban</td>
<td>0.990</td>
<td>0.950</td>
</tr>
<tr>
<td>Bare</td>
<td>0.970</td>
<td>0.958</td>
</tr>
</tbody>
</table>

**0.971 = typical soil emissivity for Landsat Band 6**
**0.958 = typical rock/sand emissivity for Landsat Band 6**

**All estimates derived from MODIS and SEVIRI land classifications at 11 micron (may need to be refined for Landsat)**
Sierra Nevadas, Mono Lake region, CA.

IGBP Land Cover Classification (MOD12 Product)

Classification Emissivities using Fractional Vegetation Cover Approach
Sierra Nevada, Mono Lake, CA.

Mean = 0.24 ± 0.51 K
Land Classification
Emissivities could have large errors over particular geologic surfaces!

e.g. Mafic rocks (basalt)
Summary

- Landsat LST algorithm developed for Landsat5 and Landsat7
  - Classification-based emissivities
  - NAALSED-based emissivities
- Scenes over California/Nevada downloaded for initial assessment of two algorithms
- Results show mean LST differences over diverse region (Sierra Nevadas) of $0.24 \pm 0.51$ K with max differences of $\sim 2$ K
- Shrublands and bare classifications tend to have largest errors $> 1$ K with LST too high (emissivity too low)
- Analysis over mafic surfaces (e.g. Basalt) show classification errors could be as large as 12 K!!
Questions? Help!
• Extract Bare Earth Emissivity from the North American Aster Land Surface Emissivity Database (NAALSED)
  
  – Emissivities ($\varepsilon_{13}, \varepsilon_{14}$) and regression coefficients (JPL)
    
    $$\varepsilon_{\text{landsat}} = C_{13} \varepsilon_{13} + C_{14} \varepsilon_{14} + C$$
LANDSAT 5 derived emissivity from NAALSED bands 13 & 14 over the Salton Sea and Imperial Valley, CA.(JPL)
Lake Tahoe
5 Class Classification Map

Aster Band 13
Lake Tahoe Emissivity Data

Class 1  Average Emissivity  0.988  SD  0.00736
Class 2  Average Emissivity  0.976  SD  0.00698
Lake Tahoe
5 Class Classification Map

Aster Band 14
Lake Tahoe Emissivity Data

Class 1  Average Emissivity  0.988  SD  0.00644
Class 2  Average Emissivity  0.974  SD  0.00476
Filters

<table>
<thead>
<tr>
<th>H</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Clouds
- Bad data
- High humidity
Spectral Response Functions
TIRS and the Future
A Land Surface Temperature Product

Validation

– Use calibration sites – Atm. Compensation
  – Salton Sea (below sea level and hot)
  – East & West Coast (sea level – wide range of atmosphere)
  – Great Lakes (≈ 0.2 km)
  – Lake Tahoe (≈ 1.4 km)
• Covers all dates, all instruments
• Only tests atmospheric compensation since all targets are water

– Cross calibrate with other instruments
  – ASTER-MODIS
    » Need to account for time difference and any errors in alternate emissivity retrieval
  – Field sites?
    » Historical?
    » New???
Status_(RIT)

• Reading NARR GRIB files
• Converting NARR data to MODTRAN input files
• Generating Landsat passband atmospheric parameters from Modtran
• Evaluating height interpolators
• Learning about filtering issues
• Learning that atmosphere may be harder and emissivity easier than we thought
• Interpolate in time
  – Linear
  – Diurnal

Profile samples at time 1 \((t_1)\) and time 2 \((t_2)\) for one sample location

Linear Interpolation for \(T\) at each altitude

Diurnal Interpolation for \(T\) at each altitude
• Interpolate in parameter space \((\tau, L_u, L_d)\) on \(H\) for each profile site around the pixel of interest
  - Linear with \(H\)?
  - Linear in optical depth with \(H\)?

Interpolate to pixel height \(H_L\)

\[
\begin{align*}
\tau(H_L) & \quad \text{Linear with parameter} \\
\delta(H_L) & \quad \text{Linear with optical depth}
\end{align*}
\]

Output: \(\tau(H_L, t_L), L_u(H_L, t_L), L_d(H_L, t_L)\)
• Interpolate spatially in parameter space for fixed time and elevation at Nodes (profile sites)
  – Nearest neighbor?
  – Inverse distance (3 node, 4 node)?
  – Inverse exponential?

Output of Spatial Interpolation

\[ L_{surf} = \frac{L_s - L_u}{\tau} = \varepsilon L_T + (1 - \varepsilon)L_d \]
Height Interpolation - Sensitivity Study

2 August 2007

[Graphs showing interpolated vs. calculated data, with lines labeled "Calculated" and "Interpolated"]
• Compute $\tau$, $L_u$, $L_d$, $L_{surf} = (L_s - L_u) / \tau = \varepsilon L_T + (1 - \varepsilon) L_d$

Know:
- $\tau_A (H_L), L_{u_A} (H_L), L_{d_A} (H_L)$
- $\tau_B (H_L), L_{u_B} (H_L), L_{d_B} (H_L)$
- ...
- $\tau_L, L_{u_L}, L_{d_L}$

Interpolate

- Nearest neighbor
  $$\tau_L = \tau_A, L_{u_L} = L_{d_L} \ldots$$

- Linear in $1/d$
  $$\tau_L = \frac{\tau_A}{d_A} + \frac{\tau_B}{d_B} + \frac{\tau_C}{d_C} + \frac{\tau_D}{d_D} + \frac{1}{\sum_i d_i}$$

- Linear in $e^d$
  $$\tau_L = \frac{\tau_A e^{d_A} + \tau_B e^{d_B} + \tau_C e^{d_C} + \tau_D e^{d_D}}{\sum_i e^{d_i}}$$

Output:
- $\tau (H_L, t_L, L)$, $L_{u} (H_L, t_L, L)$, $L_{d} (H_L, t_L, L)$

$$L = \begin{bmatrix} x \\ y \\ H_L \end{bmatrix}$$
Temporal Interpolation - Sensitivity Study

• Average 11 am and 2 pm NARR profiles
  – Compute temperature at range of heights
• Build profile using daily radiosonde corrected to surface weather at desired time
• Compute temperature at range of heights
• Compute error in apparent temperature
Correct Emissivity for High NDVI conditions

Note: an error in emissivity of 0.01 corresponds to 0.7K error in temperature in these bands.

Fig. 3. Average emissivity spectra for different soil samples included in the ASTER spectral library (http://speclib.jpl.nasa.gov). ‘Inceptisol’ refers to the mean value for all the soil samples included in the ASTER library and classified as Inceptisol (7 samples). These values have been chosen a soil emissivities in the NDVI method. ‘All soils’ refers to the mean value for all the soil samples included in the ASTERlib (49 samples). Error bars refer to the standard deviation of the mean values. The emissivity spectrum obtained from field measurements (Field) and the one measured in the JPL are also given for comparison.[Munoz et al. (2006) RSofE V.103,#4, pp. 474-487].
Profile samples at time 1 ($t_1$) and time 2 ($t_2$) for one sample location

Linear Interpolation for $T$ at each altitude

Diurnal Interpolation for $T$ at each altitude
Run Modtran for each altitude.

Output:

\[ \tau(H), L_u(H), L_d(H) \]
Interpolate to pixel height $H_L$

Output: $\tau(H_L, t_L), L_u(H_L, t_L), L_d(H_L, t_L)$
Know:
\( \tau_A(H_L), L_u(H_L), L_d(H_L) \)
\( \tau_B(H_L), L_u(H_L), L_d(H_L) \)
\[
\vdots
\]
\( ?: \)
\( \tau_L, L_u(L), L_d(L) \)

Interpolate

**Nearest neighbor**
\[ \tau_L = \frac{\tau_A}{d_A} + \frac{\tau_B}{d_B} + \frac{\tau_C}{d_C} + \frac{\tau_D}{d_D} + \sum_i \frac{1}{d_i} \]

**Linear in 1/d**
\[ \tau_L = \frac{\tau_A e^{-d_A} + \tau_B e^{-d_B} + \tau_C e^{-d_C} + \tau_D e^{-d_D}}{\sum_i e^{-d_i}} \]

Output:
\[ \tau(H_L, t_L, L), L_u(H_L, t_L, L), L_d(H_L, t_L, L) \]

\[ L = \begin{bmatrix} x \\ y \\ H_L \end{bmatrix} \]
Output of Spatial Interpolation

\[ L_{\text{surf}} = \frac{L_s - L_u}{\tau} = \varepsilon L_T + (1-\varepsilon)L_d \]
A Land Surface Temperature Product

Timeline: Year 1 Define Approach
- identify limitations
- identify filters
- perform sensitivity analysis
- identify QC issues

Implement & Test methodology

Year 2 Refine Algorithms and extend approach to Global database.
Evaluate initial products.
- compare to ASTER/MODIS
- compare to truth
- user evaluation

Year 3 Refine Global Algorithm based on Year 2 results
- validate at range of trusted sites
- deliver final tools to USGS
Height Interpolation - Sensitivity Study

1 February 2007

Error in Temp vs Ground Altitude

Ground Altitude [km]

Error in Apparent Temperature [K]

-0.4
-0.2
0.0
0.2
0.4

310 K
295 K
273 K
A Land Surface Temperature “trial” Product

Timeline: Year 1 Define Approach
- identify limitations
- identify filters
- perform sensitivity analysis
- identify QC issues
Implement & Test methodology

Caveats: North America only
No cloud filter (Default to NAALSED emissivity)
May have no correction for current vegetation condition
QC map may be limited or non existent
Limited Formal Validation of Implementation
Height Interpolation

- Begin with NARR atmospheric profile
- Truncate layers below desired altitude
- Linearly interpolate so lowest layer is at ground altitude
Height Interpolation

0.468

0.468 9.625e+02 2.971e+02 6.393e+0.1
Height Interpolation - Sensitivity Study

• Compute parameters $(\tau, L_u, L_d)$ at finely spaced intervals throughout range

• Compute parameters at 9 samples throughout range and linearly interpolate to any desired height
  – Samples regularly spaced

• Compute error in apparent temperature between temperature computed with finely sampled parameters and interpolated parameters
Height Interpolation - Sensitivity Study

2 August 2007
Height Interpolation - Sensitivity Study

2 August 2007
Height Interpolation - Sensitivity Study

2 August 2007
Height Interpolation - Sensitivity Study

1 February 2007

Error in Temp vs Ground Altitude

Error in Apparent Temperature [K]

Ground Altitude [km]

310 K
295 K
273 K
Spatial Interpolation

• Atmospheric parameters at each grid point interpolated to desired altitude
• Bilinearly interpolate in UTM coordinates to desired location
Spatial Interpolation - Sensitivity Study

- Larger grid and interpolate to known NARR point
- Use radiosonde data as atmospheric profile and interpolate to that location
Introduction

• Land Surface Temperature (LST) has been identified as an important Earth System Data Record (ESDR) by NASA
  – Long-term climate trend analysis
  – Water and drought monitoring tool for agricultural applications
  – Used in Ecological models, e.g. evapotranspiration, soil moisture

• Reflectance data derived from visible, shortwave bands:
  – Determine biophysical parameters (e.g. using vegetation indices)
  – Monitor land cover changes, and derive land cover classification maps

• LST data derived from thermal infrared data:
  – Provide information on land water use
  – Assist in land cover mapping

• Thermal data has been largely under-utilized due to problems with deriving the land surface emissivity (impossible with 1 band)

• **Goal:** Develop Landsat LST product for Landsat-7 and extending back to Landsat-4 (1982) using an ASTER gridded emissivity product (NAALSED).
Landsat LST Status

❖ Progress:
  ✓ Downloaded ~9500 TM scenes for California/Nevada (1984-2011) for initial algorithm testing
  ✓ Landsat LST algorithm developed for TM and ETM+ data:
    – Classification-based emissivities
    – NAALSED-based emissivities
  ✓ Comparisons between two methods completed for several scenes covering broad range of different land cover types

❖ Next Steps:
  ✓ Generate monthly and annual LST maps of California/Nevada using both approaches
  ✓ Make assessment of which approach is best, in terms of accuracy and computational speed
  ✓ Generate North American Landsat LST product
NAALSED v3 Summer Emissivity (Jul-Aug-Sep 2000-2010)
Band 12 (9.1 µm), 5km

Gaps to be filled during Jul-Sep 2011 acquisition period
Landsat band 6 emissivity from ASTER

Coefficient regressed from 150 lab spectra consisting of rocks, soils, vegetation, water and ice and convolved to appropriate spectral responses.

Landsat-5: \[ \epsilon_{10.4-12.5} = 0.305 \epsilon_3 + 0.468 \epsilon_4 + 0.223 \]

Landsat-7: \[ \epsilon_{10.4-12.5} = 0.44 \epsilon_3 + 0.4 \epsilon_4 + 0.156 \]
Landsat emissivity from Land Classification

Use an estimate of vegetation fraction ($f_v$) computed from NDVI to estimate effective emissivity from IGBP land cover classification maps.

$$ee = e_{veg} * f_v + e_{bare}(1 - f_v)$$

- $ee$ = effective emissivity
- $f_v$ = fractional vegetation cover
- $e_{veg}$ = vegetation emissivity (assigned from land cover map)
- $e_{bare}$ = soil/rock emissivity  (assigned according to vegetation type)

$$f_v = 1 - (\text{NDVI}_{\text{max}} - \text{NDVI})/(\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}})$$

- NDVI = Normalized Difference Vegetation Index
- NDVI$_{max}$ = 0.8
Landsat emissivity from NAALSED

- Max emissivity: ~0.98 (Salton Sea, Crops)
- Min emissivity: ~0.94 (Algodones dunes)

Worst case scenario: $\delta e = 0.04 \Rightarrow \delta T = 2.85 \text{ K}$ (for surface at 11 $\mu$m, 300 K)
Single-band Temperature Inversion

Surface Radiance:

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

Observed Radiance

\[ \tau_i(\theta), L_i^\uparrow(\theta), L_i^\downarrow(\theta) \]

Atmospheric Parameters:

Estimated using radiative transfer code such as MODTRAN with atmospheric profiles and elevation data.

Surface emitted radiance

\[ B_i(T_S) = \frac{1}{e_i} \left( \frac{L_i(\theta) - L_i^\uparrow(\theta)}{\tau_i(\theta)} + \overline{L_i} \right) \]

Invert Planck function to get LST

\[ T_S = B_i^{-1} \]
Atmospheric Correction

- NCEP atmospheric profiles (6 hourly, 1ºx1º)
  - Spatially interpolated to 10 km across scene
  - Temporally interpolated to Landsat observation time
- MODTRAN 5.2 Radiative Transfer Model
- GTOPO30 Elevation model (USGS)
- To minimize computation time, downwelling sky radiation was modeled from path radiance using regression with RT simulations.
  - CLAR radiosondes used for radiative transfer (380 global sondes)

\[ L_{sky} = a + bL_{path} + cL_{path}^2 \]

- \( L_{sky} \) = Downwelling sky irradiance
- \( L_{path} \) = Path radiance
- \( a = 0.0194 \)
- \( b = 0.5469 \)
- \( c = 0.0254 \)
The End

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California