A LAND SURFACE TEMPERATURE PRODUCT

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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

Calibrate Archive

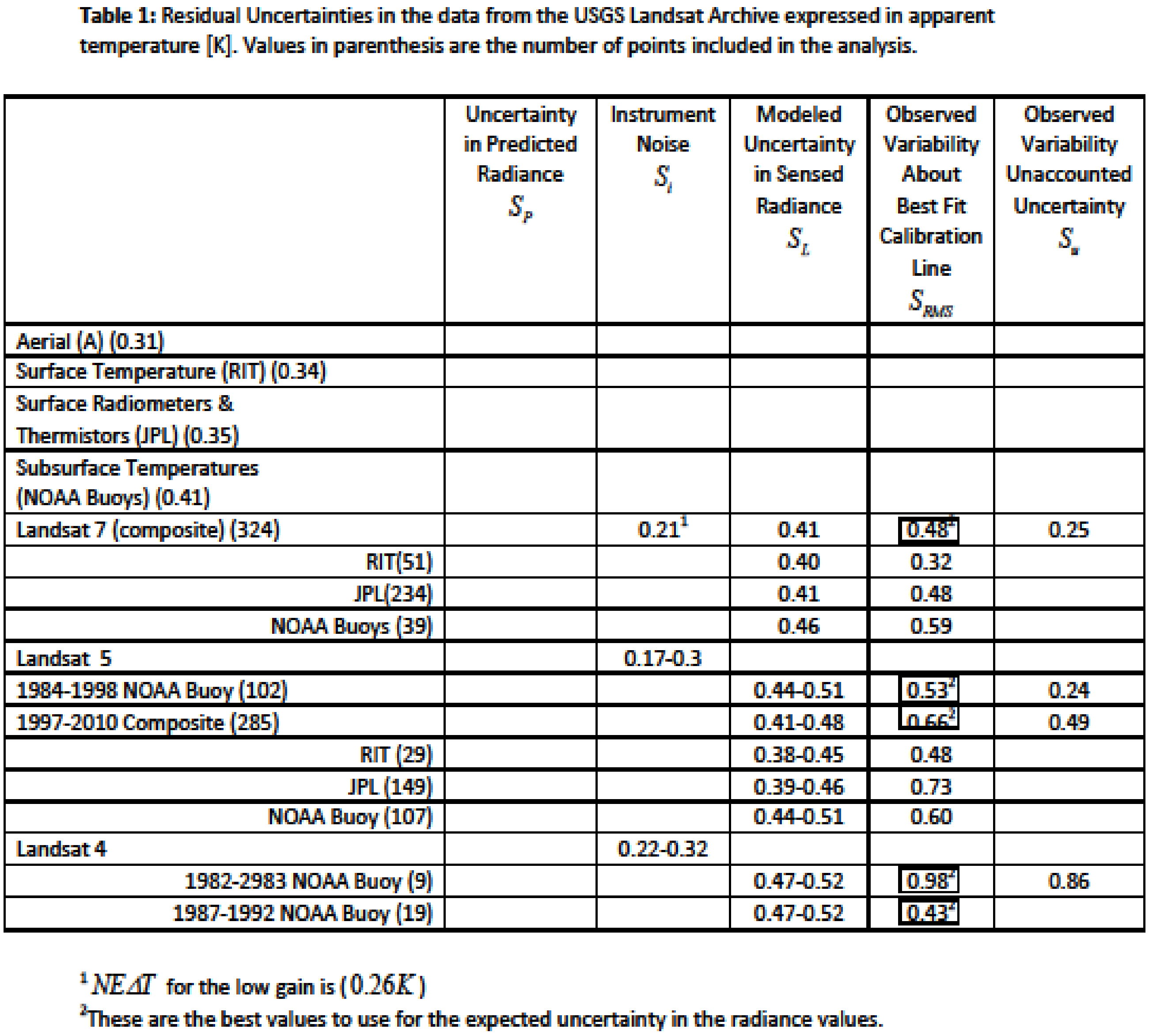


Table 1: Residual Uncertainties in the data from the USGS Landsat Archive expressed in apparent temperature [K]. Values in parenthesis are the number of points included in the analysis.

	Uncertainty in Predicted Radiance S_P	Instrument Noise S_i	Modeled Uncertainty in Sensed Radiance S_L	Observed Variability About Best Fit Calibration Line S_{RMS}	Observed Variability Unaccounted Uncertainty S_u
Aerial (A) (0.31)					
Surface Temperature (RIT) (0.34)					
Surface Radiometers & Thermistors (JPL) (0.35)					
Subsurface Temperatures (NOAA Buoys) (0.41)					
Landsat 7 (composite) (324)		0.21[1]	0.41	$\boxed{0.48}$[2]	0.25
RIT(51)			0.40	0.32	
JPL(234)			0.41	0.48	
NOAA Buoys (39)			0.46	0.59	
Landsat 5		0.17-0.3			
1984-1998 NOAA Buoy (102)			0.44-0.51	$\boxed{0.53}$[2]	0.24
1997-2010 Composite (285)			0.41-0.48	$\boxed{0.66}$[2]	0.49
RIT (29)			0.38-0.45	0.48	
JPL (149)			0.39-0.46	0.73	
NOAA Buoy (107)			0.44-0.51	0.60	
Landsat 4		0.22-0.32			
1982-2983 NOAA Buoy (9)			0.47-0.52	$\boxed{0.98}$[2]	0.86
1987-1992 NOAA Buoy (19)			0.47-0.52	$\boxed{0.43}$[2]	

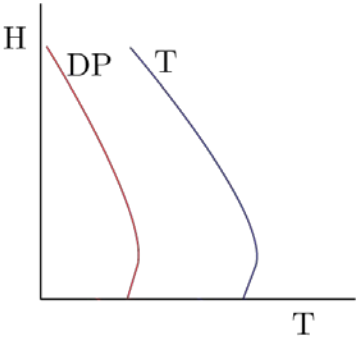
[1] $NE\Delta T$ for the low gain is $(0.26K)$

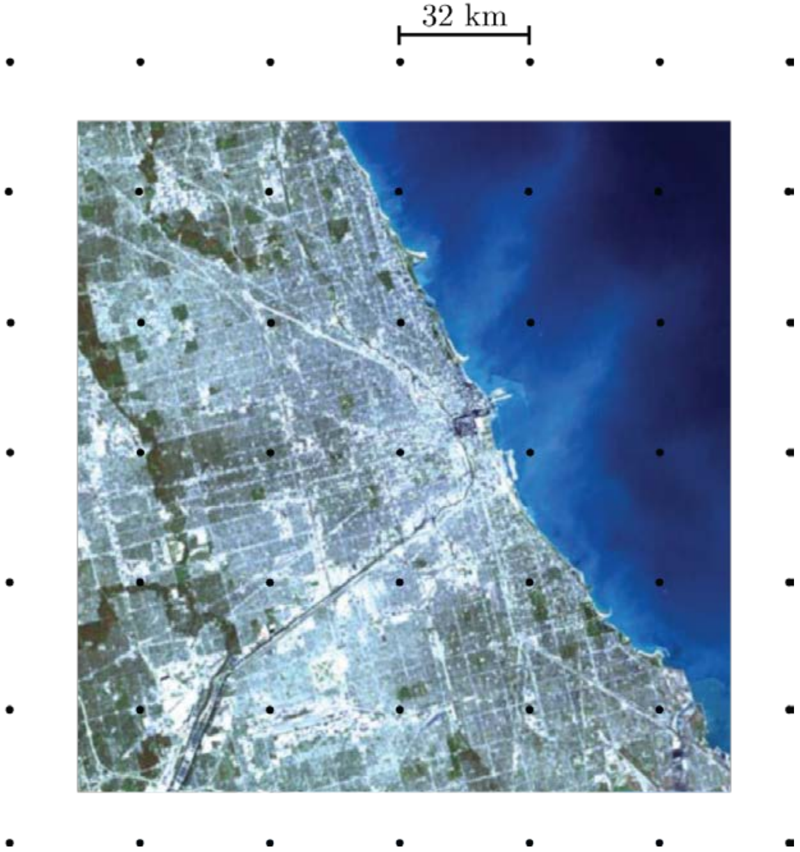
[2] These are the best values to use for the expected uncertainty in the radiance values.

ATMOSPHERE

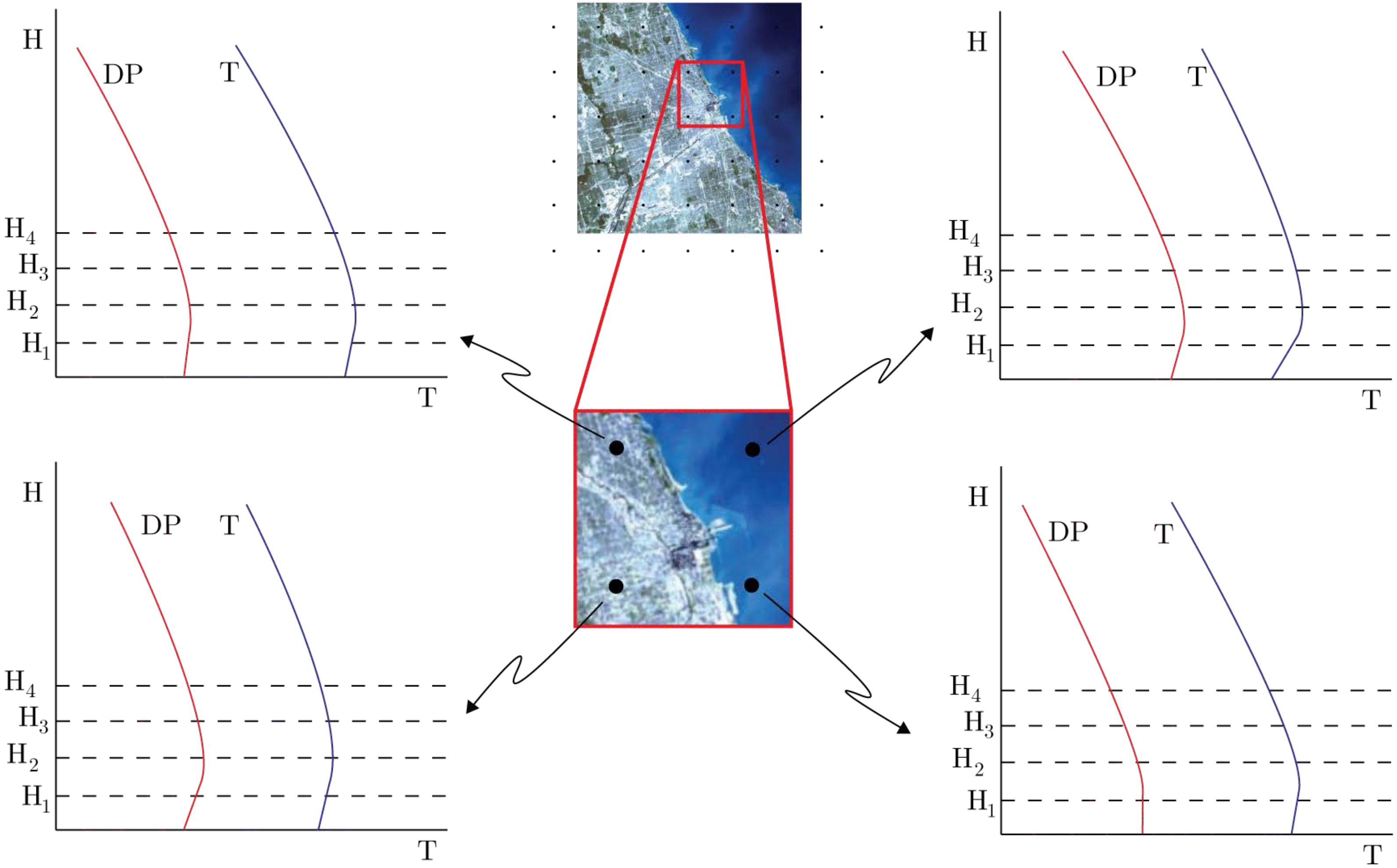
North America Regional Reanalysis (NARR) program

- 32 km. grid
- 3 hr temporal samples
- 29 atmospheric layers
- Spans entire Landsat time period

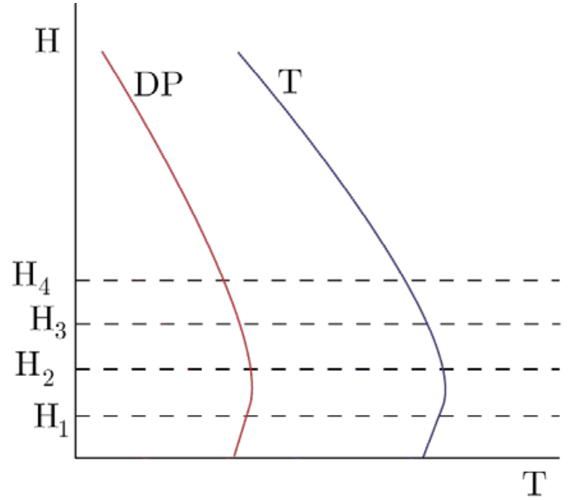




For each node we can estimate the atmospheric parameters (τ, L_u, L_d) associated with altitudes H_i from Modtran



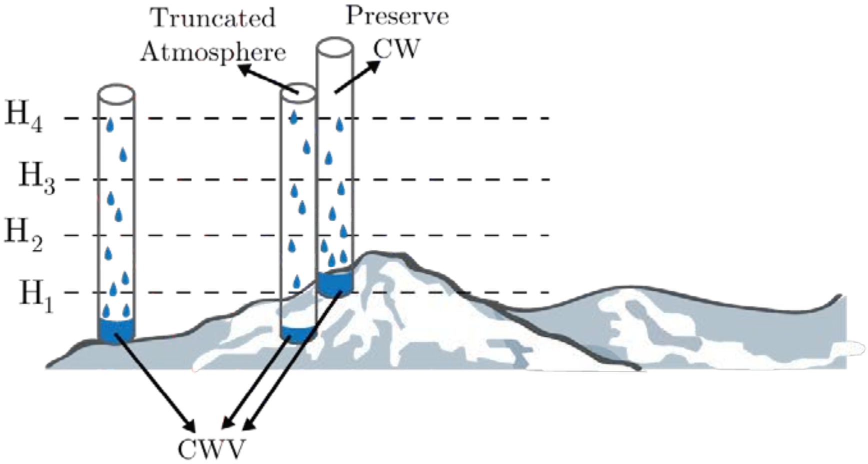
- Generate MODTRAN runs vs. Elevation(H) (H from USGS DEM)
    - Crop lower layers
    - Maintain CWV
    - Alternative logic?



Run Modtran for each altitude.

Output:

$\tau(\mathrm{H})$, $\mathrm{L_u(H)}$, $\mathrm{L_d(H)}$



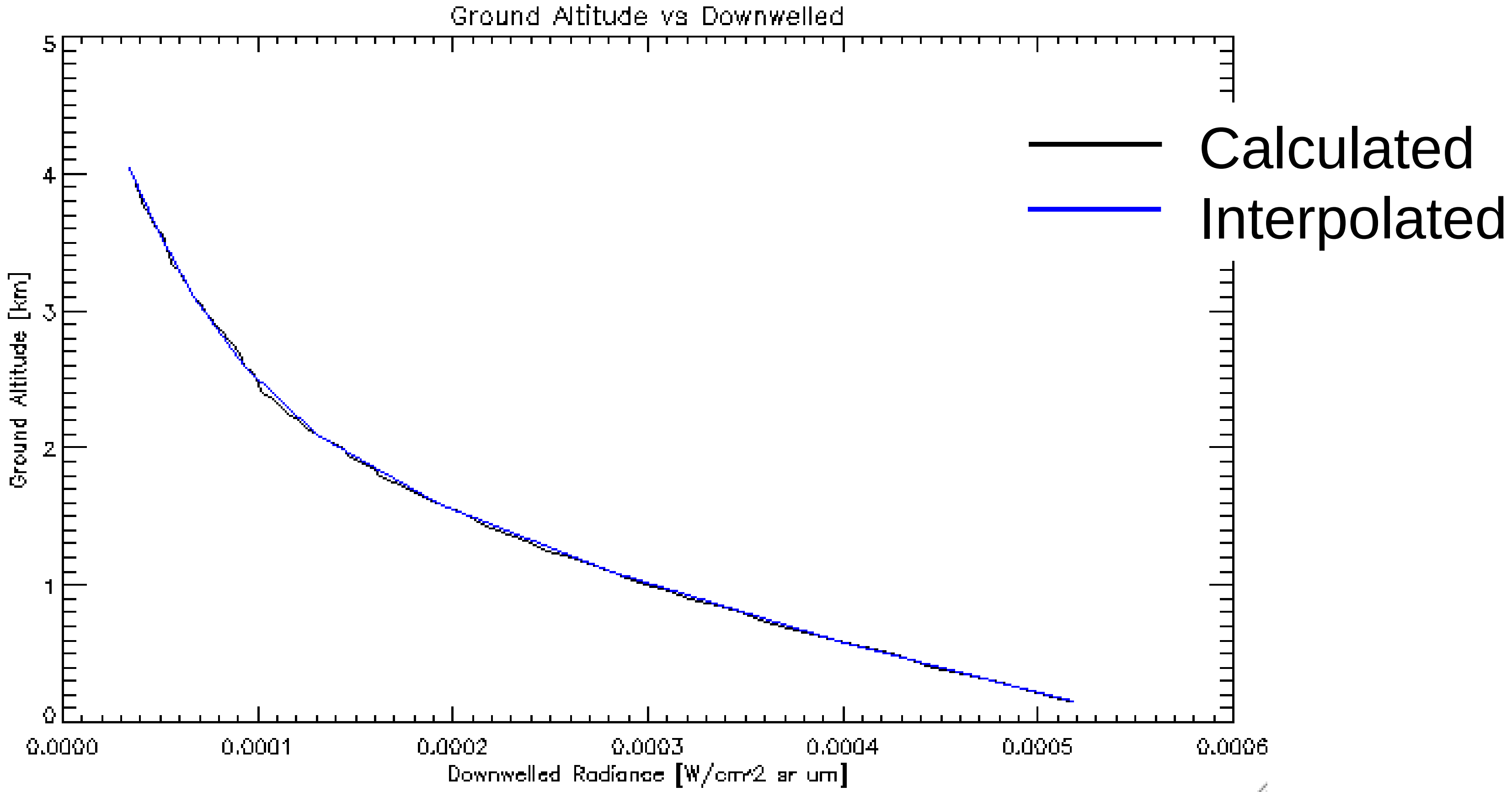
Height Interpolation - Sensitivity Study

- Compute parameters (τ, 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

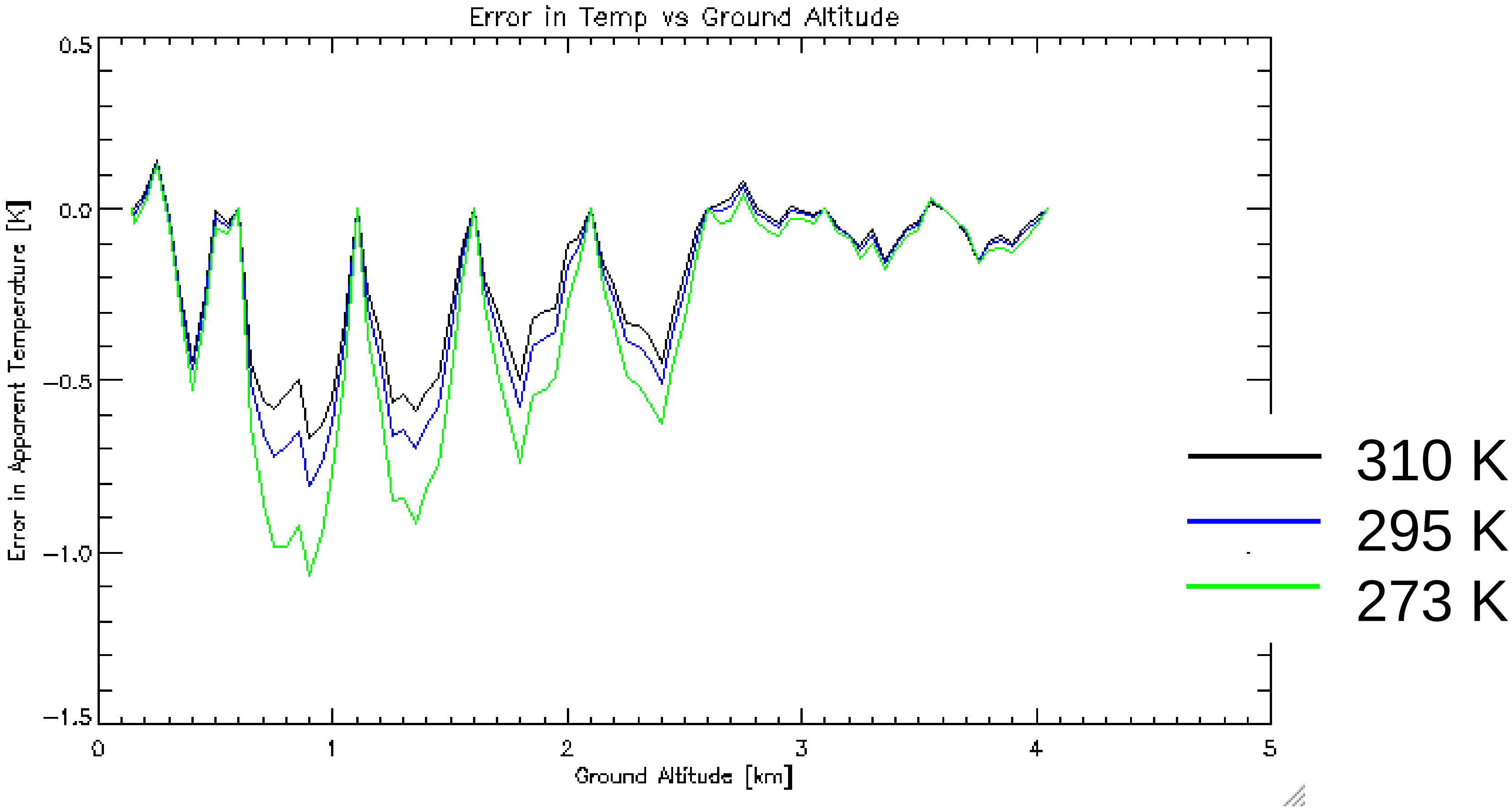
Height Interpolation - Sensitivity Study

2 August 2007



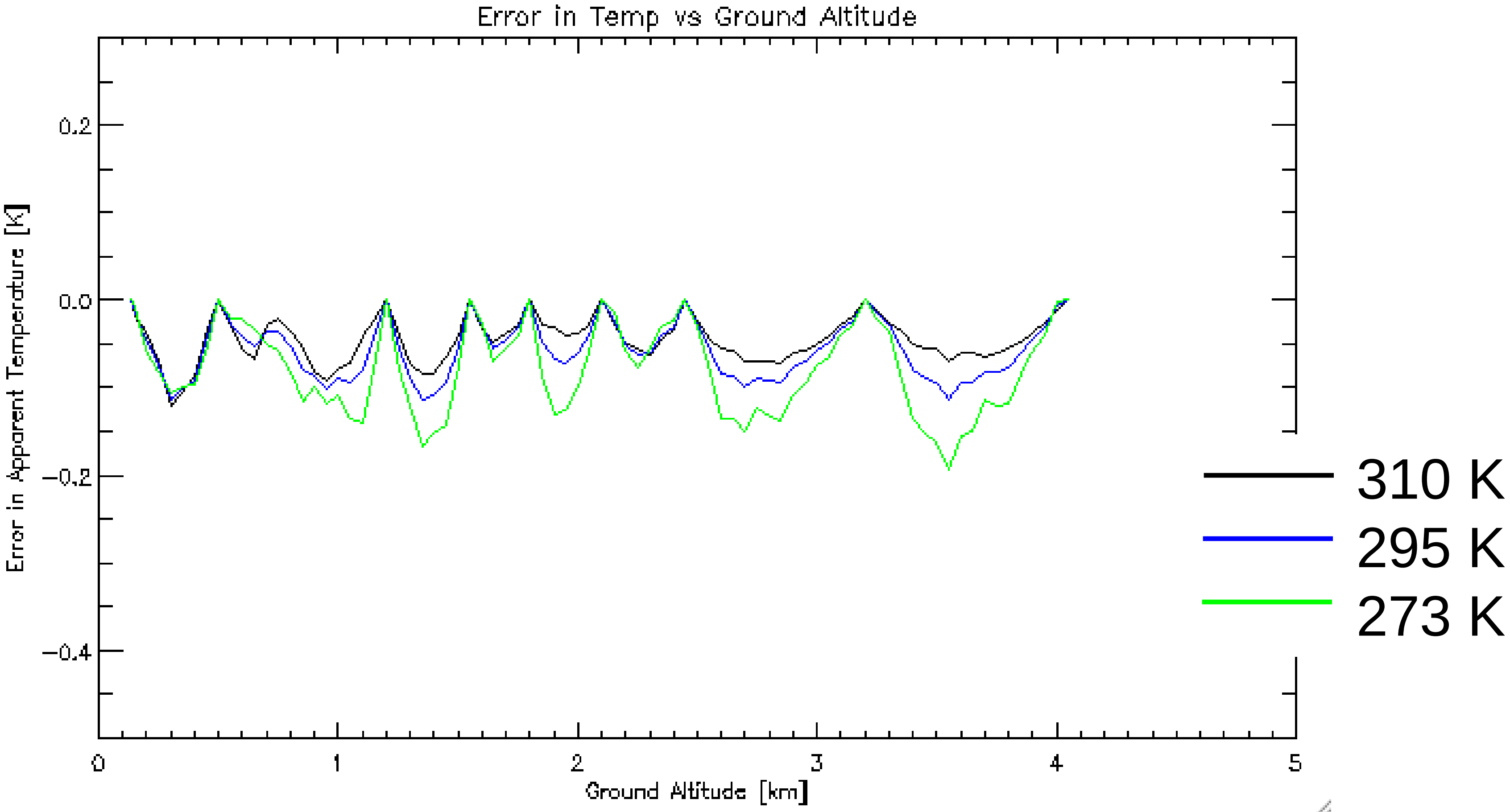
Height Interpolation - Sensitivity Study

2 August 2007



Height Interpolation - Sensitivity Study

Summer - Irregularly Spaced Samples



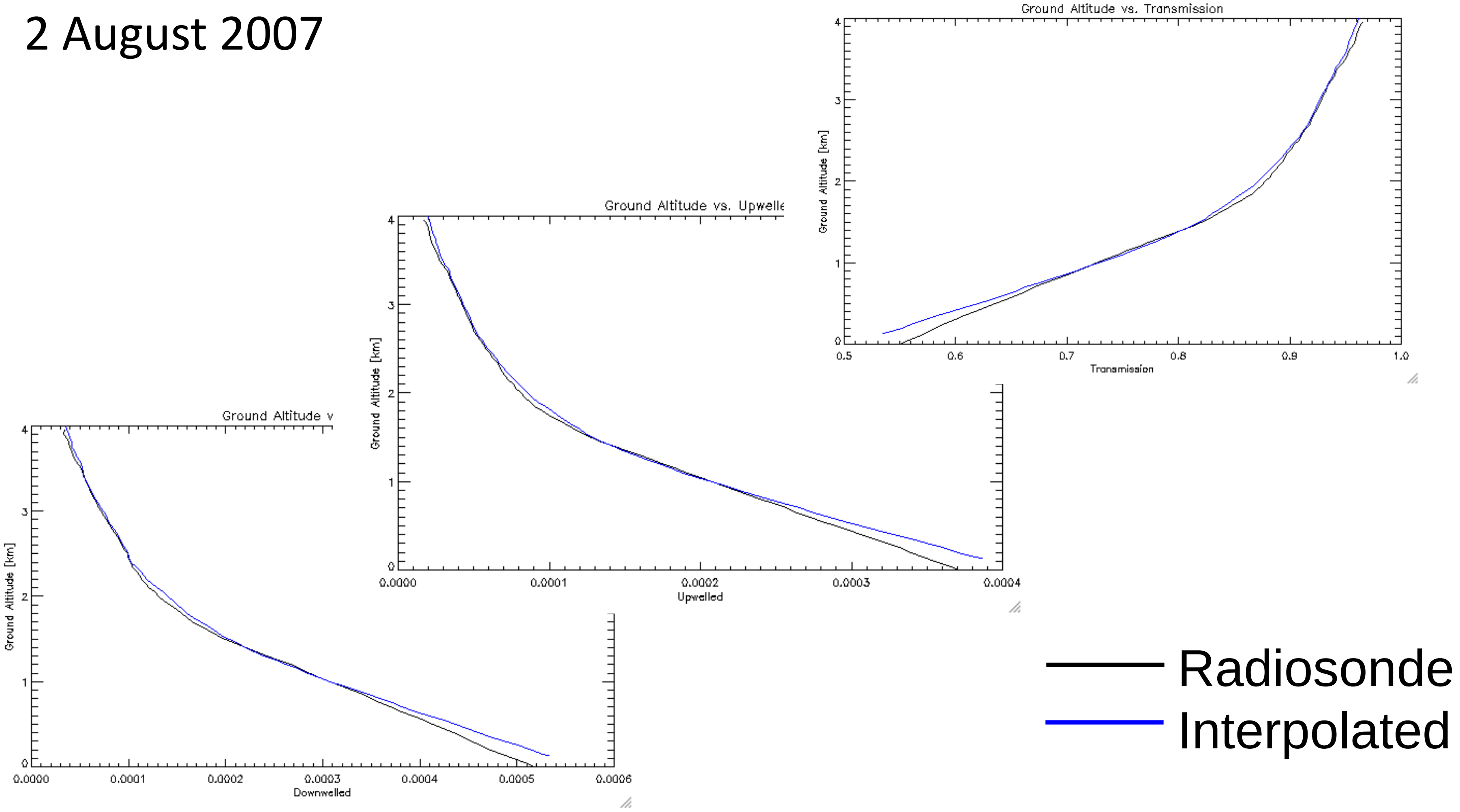
Temporal Interpolation

- 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 ie Approach used in cal-val)
- Compute temperature at range of heights

- Compute error in apparent temperature

Temporal Interpolation - Sensitivity Study

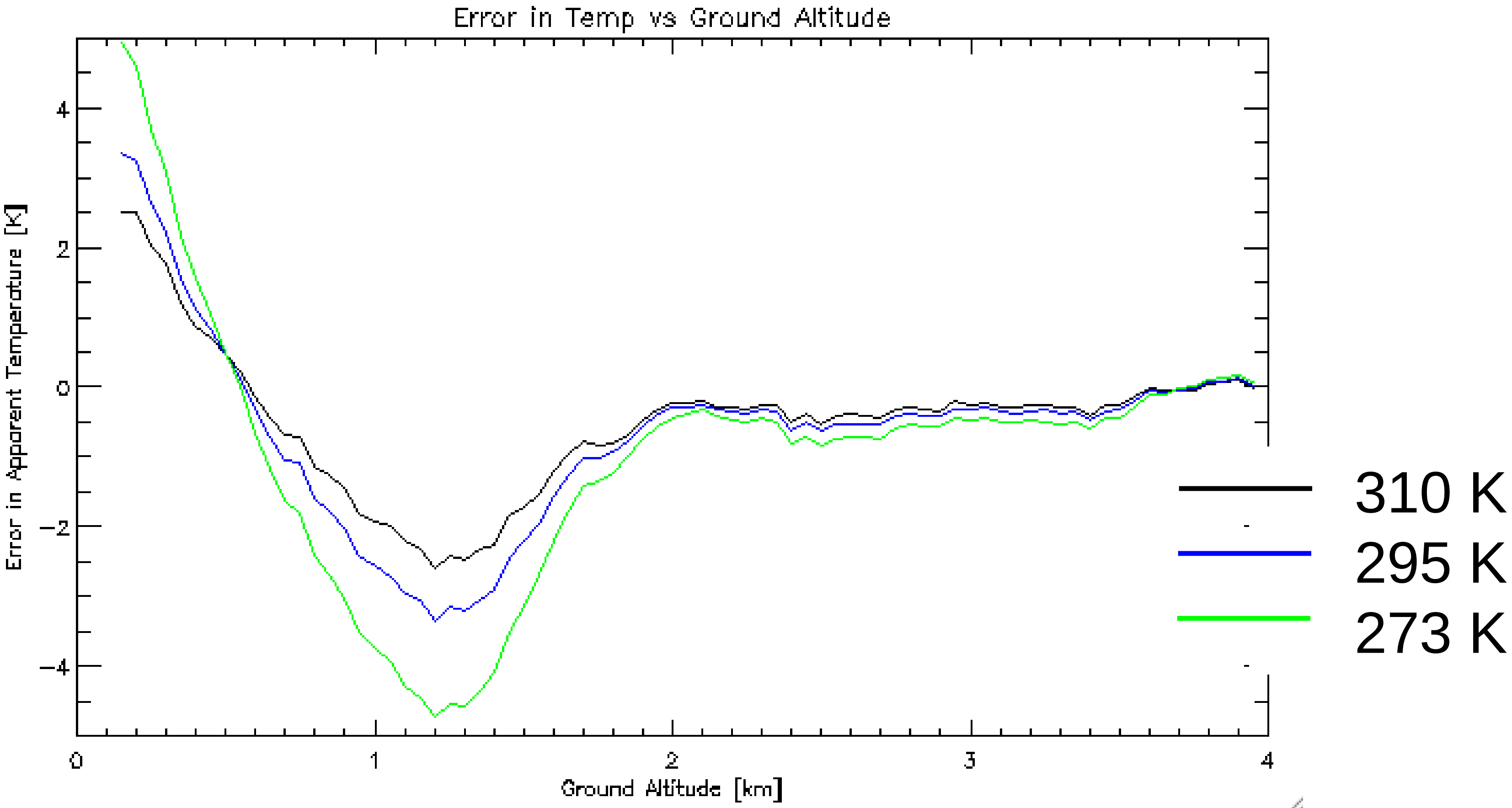
2 August 2007



Temporal Interpolation - Sensitivity Study

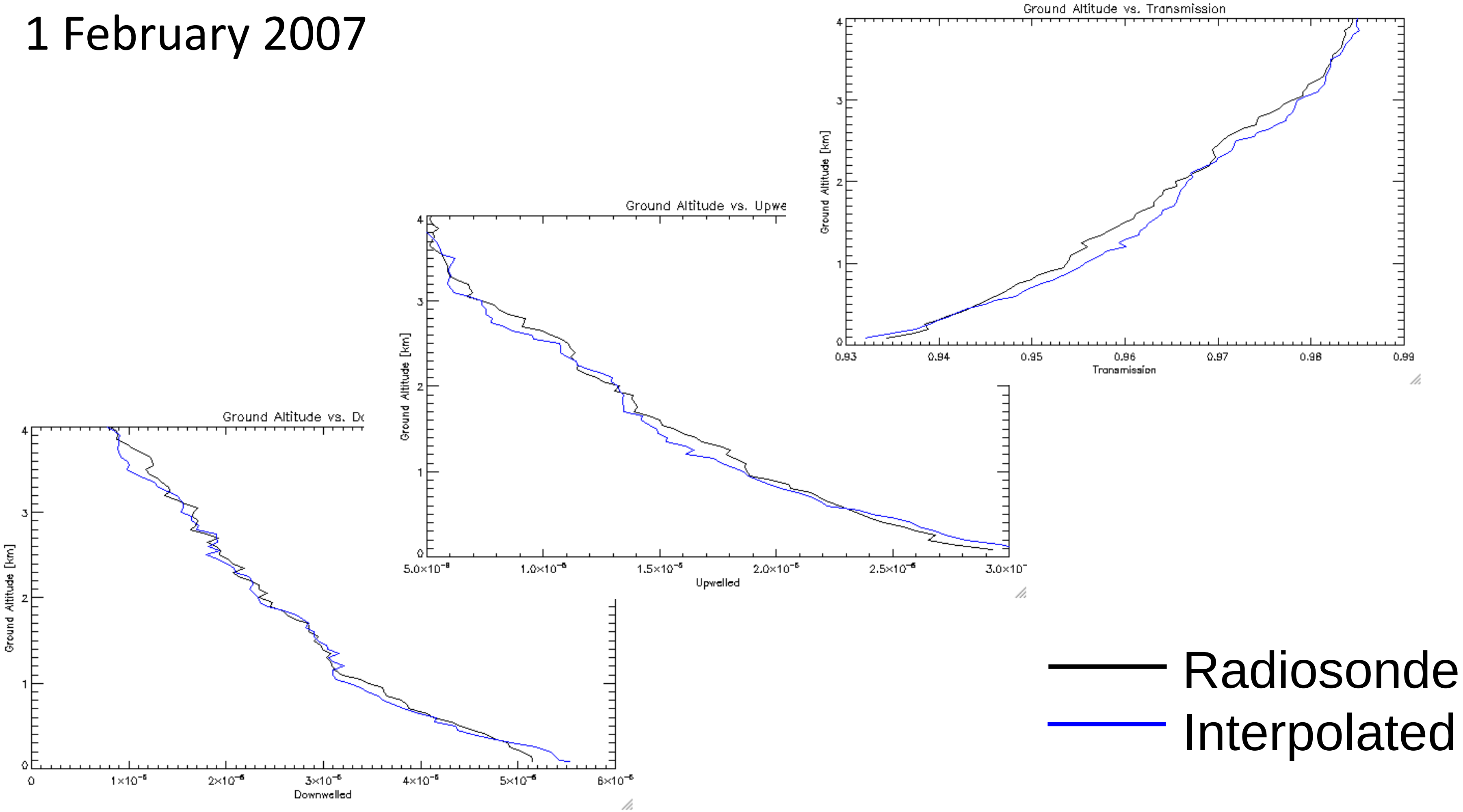
2 August 2007

Error in Temp vs Ground Altitude



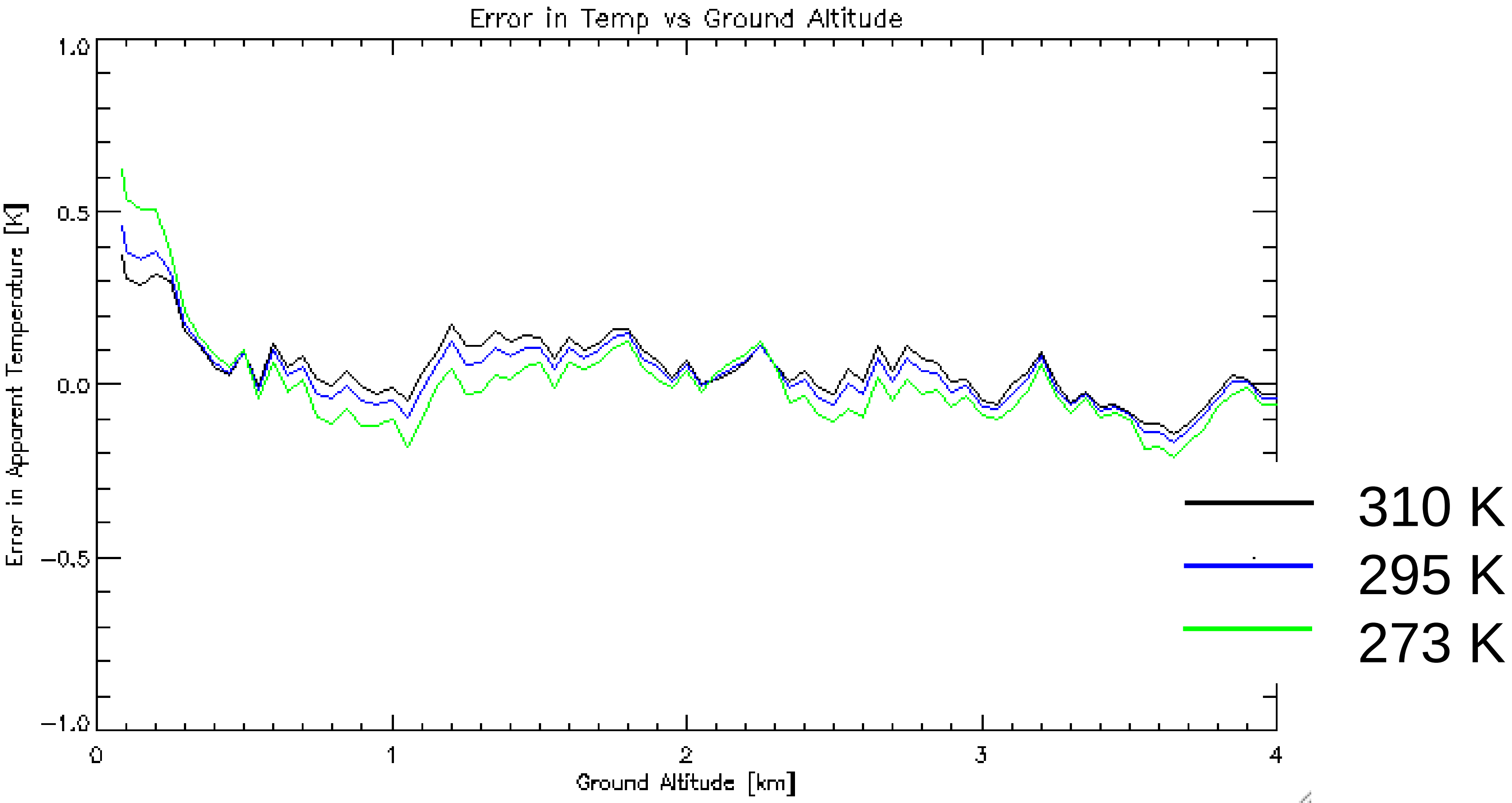
Temporal Interpolation - Sensitivity Study

1 February 2007



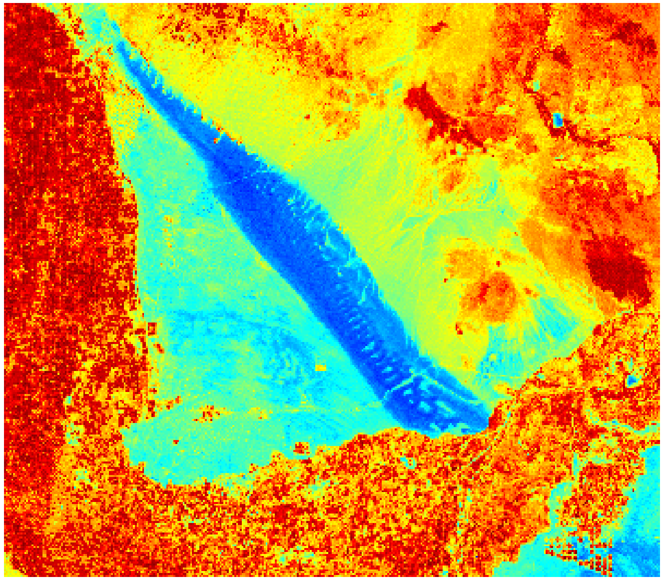
Temporal Interpolation - Sensitivity Study

1 February 2007



EMISSIVITY

A Land Surface Temperature (LST) Product for Landsat



Glynn Hulley, Simon Hook

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

Landsat CalVal Meeting, Sioux Falls, May 10, 2011

The North American ASTER Land Surface Emissivity Database (NAALSED)

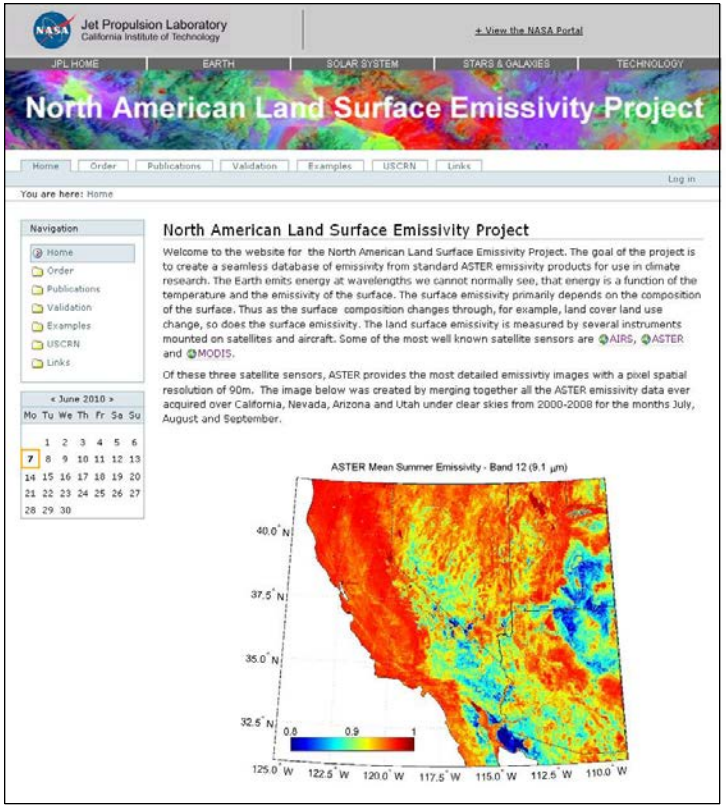
- Mean, seasonal emissivity product at 100m using all clear-sky ASTER scenes acquired since launch (2000-2010)

- <u>Summer product</u>: (Jul-Aug-Sep)
- <u>Winter product</u>: (Jan-Feb-Mar)

- Cloud detection methodology adapted from Landsat ACCA

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

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



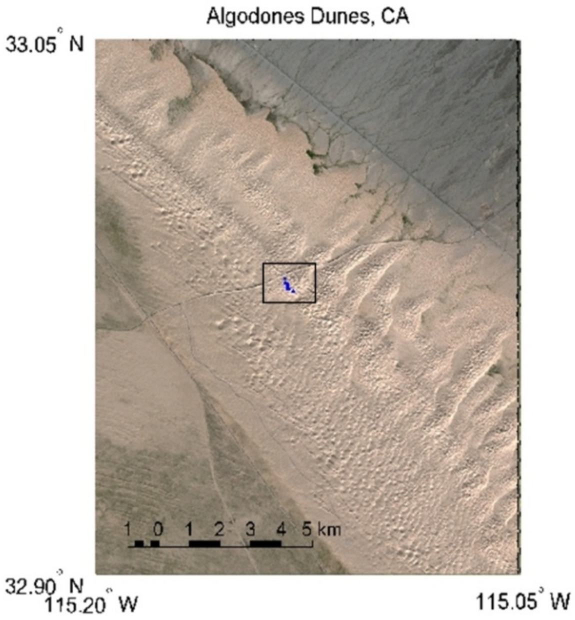
North American Land Surface Emissivity Project

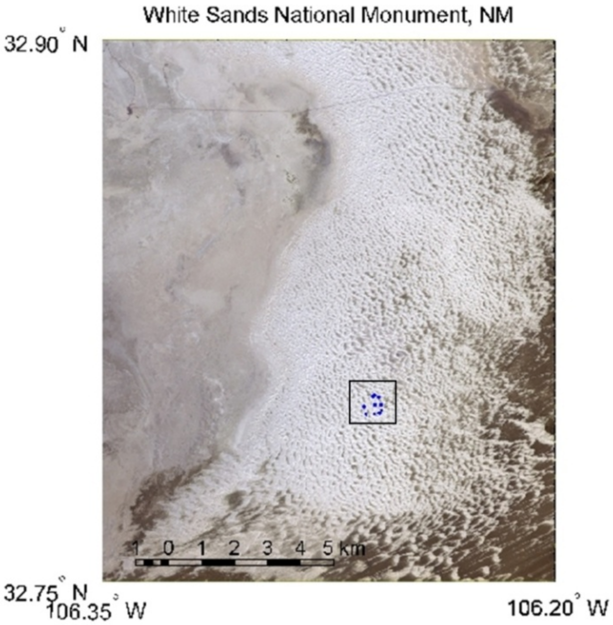
Welcome to the website for the North American Land Surface Emissivity Project. The goal of the project is to create a seamless database of emissivity from standard ASTER emissivity products for use in climate research. The Earth emits energy at wavelengths we cannot normally see, that energy is a function of the temperature and the emissivity of the surface. The surface emissivity primarily depends on the composition of the surface. Thus as the surface composition changes through, for example, land cover land use change, so does the surface emissivity. The land surface emissivity is measured by several instruments mounted on satellites and aircraft. Some of the most well known satellite sensors are AIRS, ASTER and MODIS.

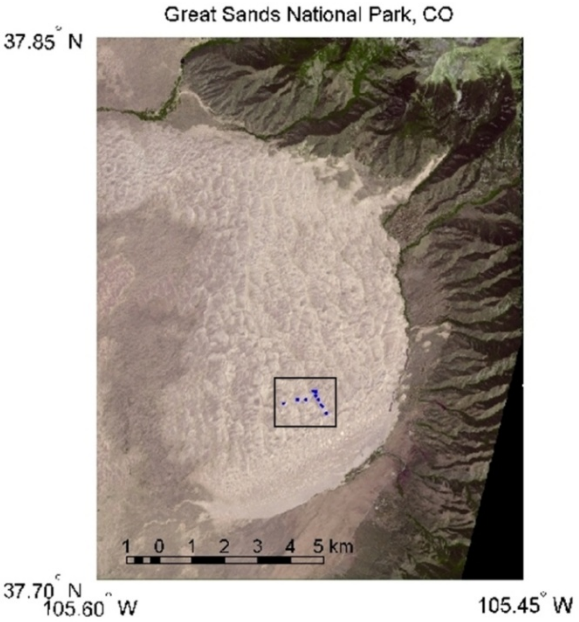
Of these three satellite sensors, ASTER provides the most detailed emissivtiy images with a pixel spatial resolution of 90m. The image below was created by merging together all the ASTER emissivity data ever acquired over California, Nevada, Arizona and Utah under clear skies from 2000-2008 for the months July, August and September.

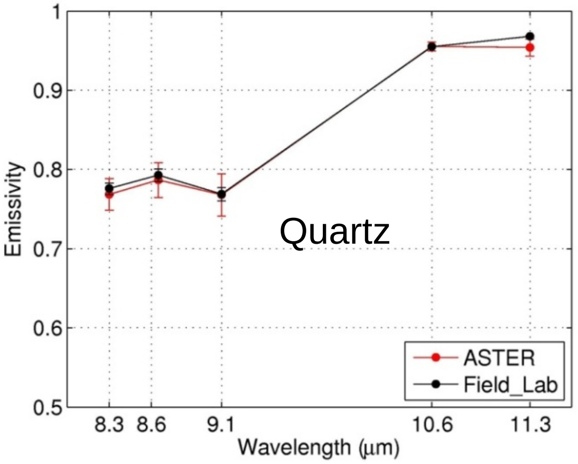
http://emissivity.jpl.nasa.gov

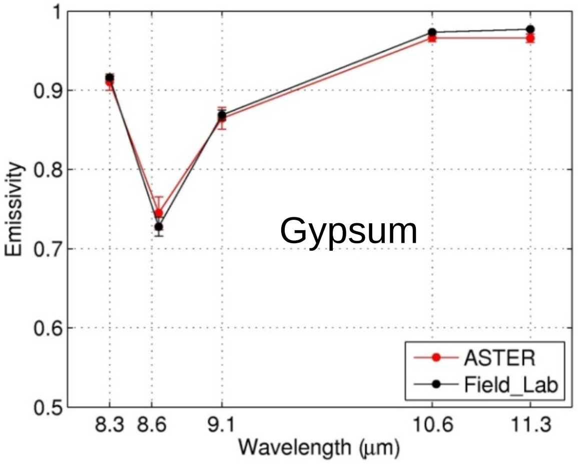
NAALSED validation at pseudo-invariant sand dune sites

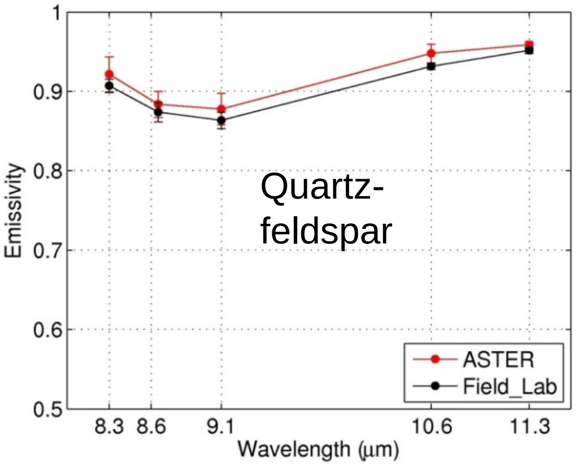




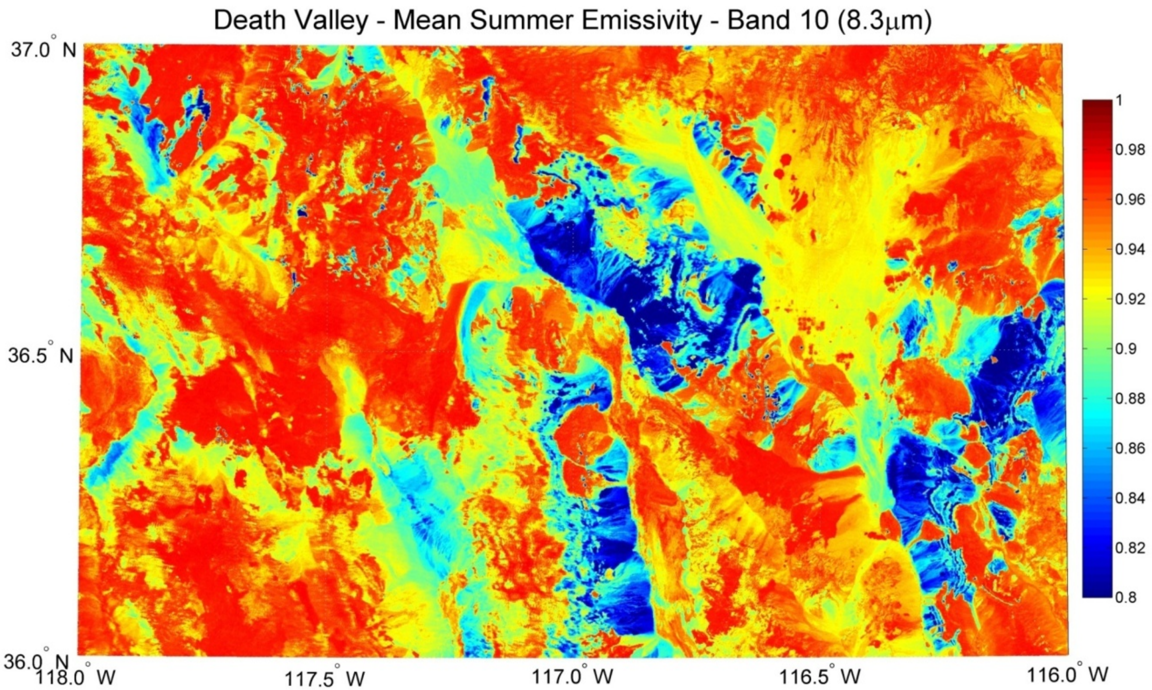








Hulley, G. C., Hook, S. J., and A.M. Baldridge, Validation of the North American ASTER Land Surface Emissivity Database (NAALSED) Version 2.0, *Remote Sensing of Environment* (2009)

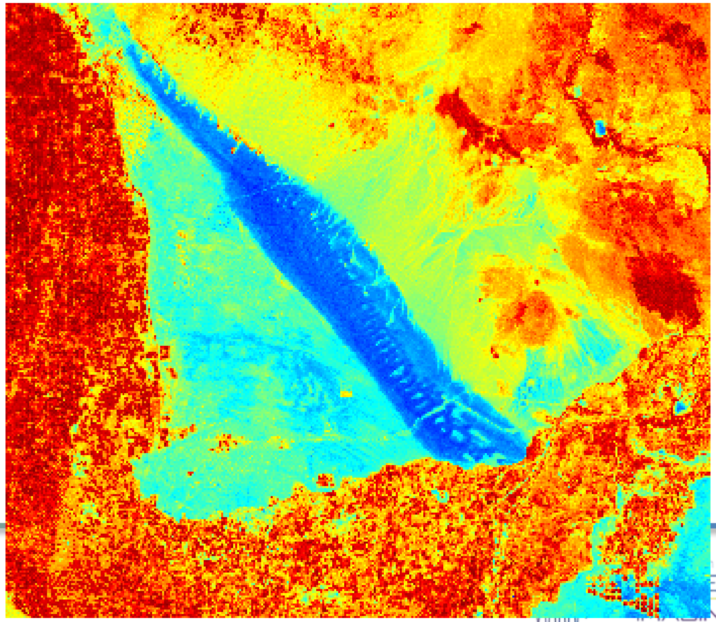


Death Valley

(Classification would assign at most two emissivity classes to most of this region)

Algodones Dunes

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



Landsat emissivity from Land Classification

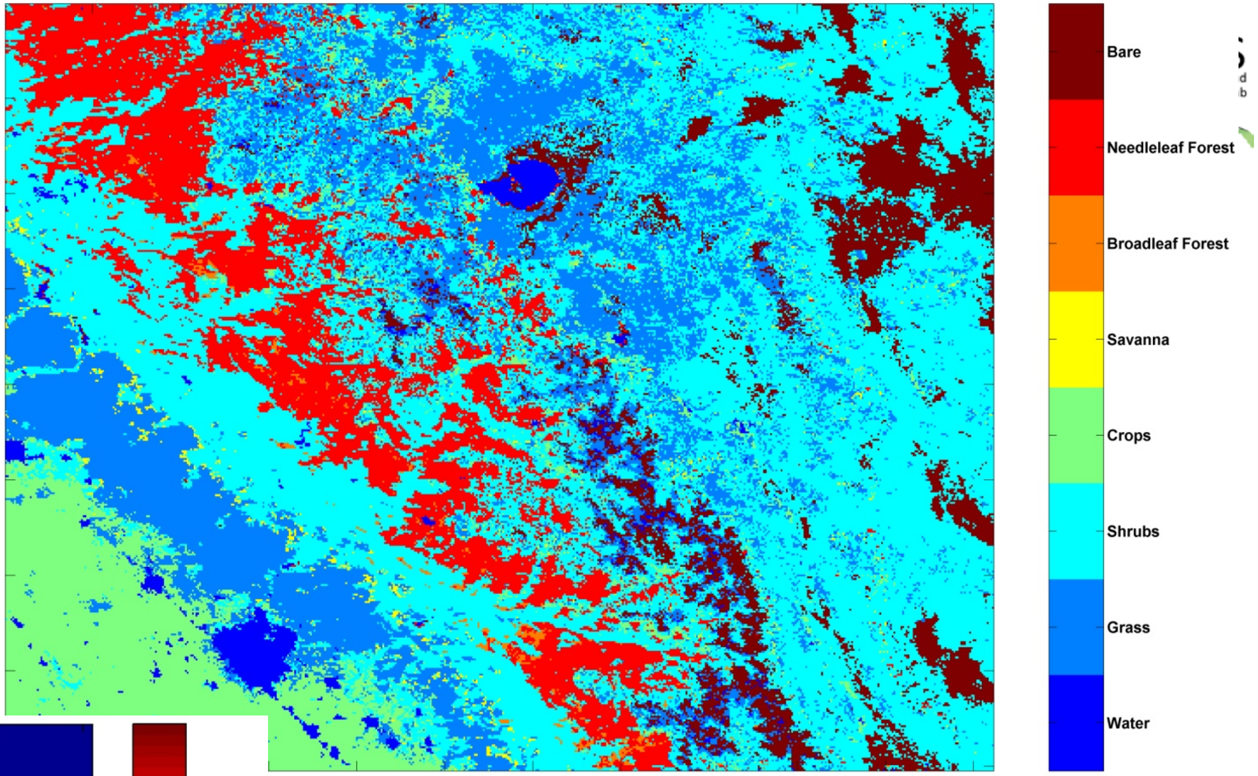
IGBP Class Type	Veg	Bare
Grasslands	0.953	0.971
Shrublands	0.972	0.958
Crops	0.983	0.971
Woody Savannas	0.982	0.971
Broadleaf Forest	0.981	0.971
Needleleaf Forest	0.989	0.971
Wetlands	0.992	0.971
Urban	0.990	0.950
Bare	0.970	0.958

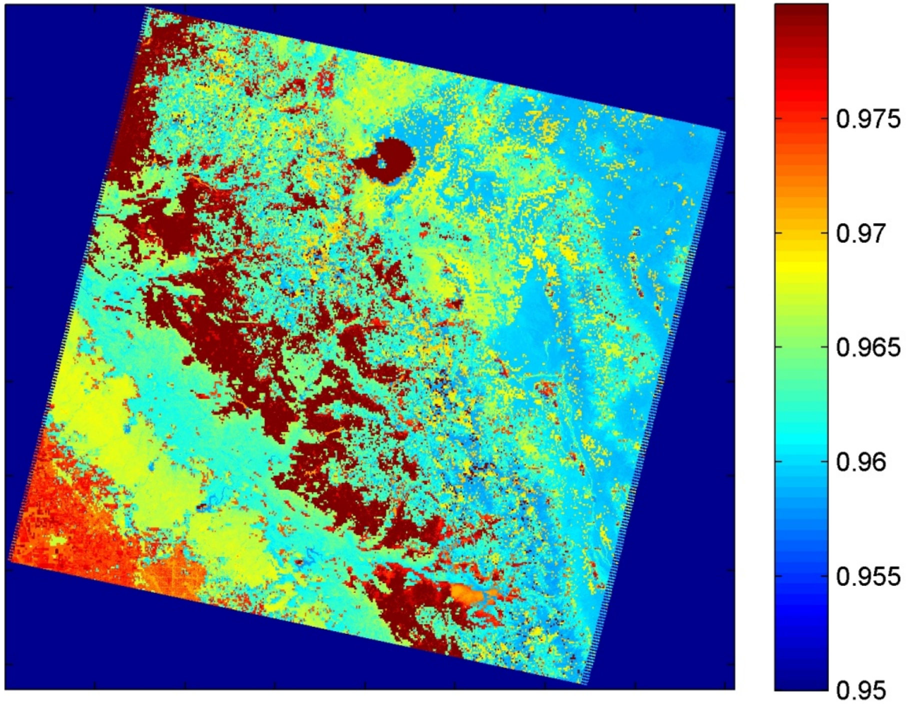
** 0.971 = typical soil emissivity for Landsat Band 6
0.958 = typical rock/sand emissivity for Landsat Band 6

** 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.

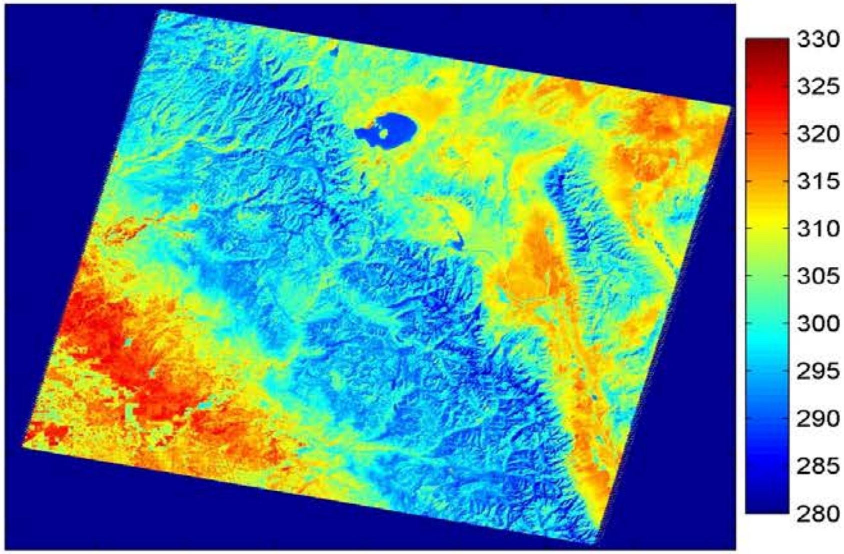
IGBP Land Cover Classification (MOD12 Product)

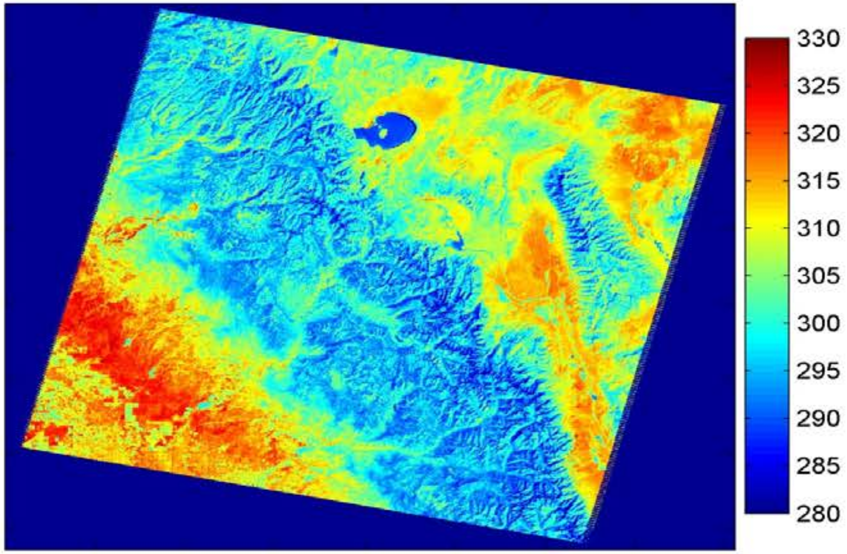


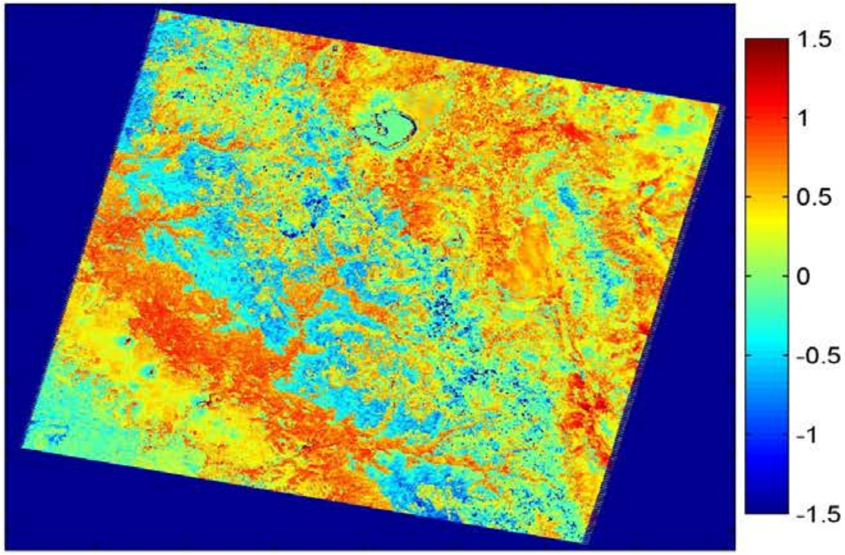


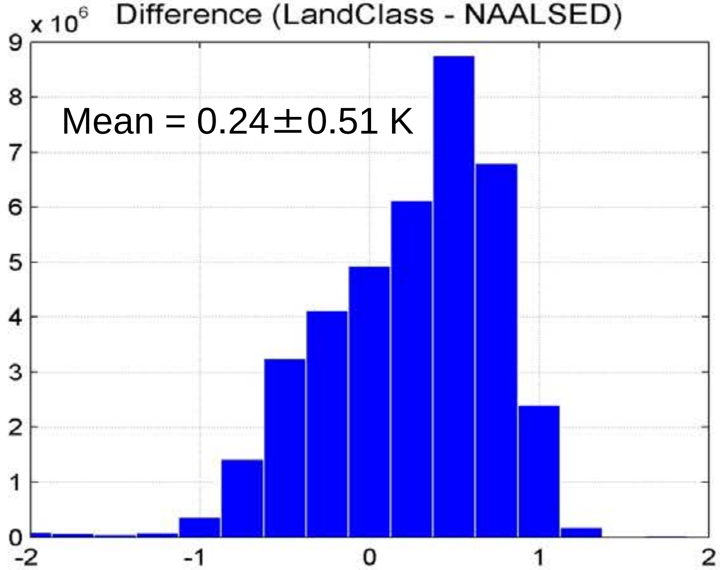
Classification Emissivities using Fractional Vegetation Cover Approach

Sierra Nevada, Mono Lake, CA.


Landsat5 LST (NAALSED)

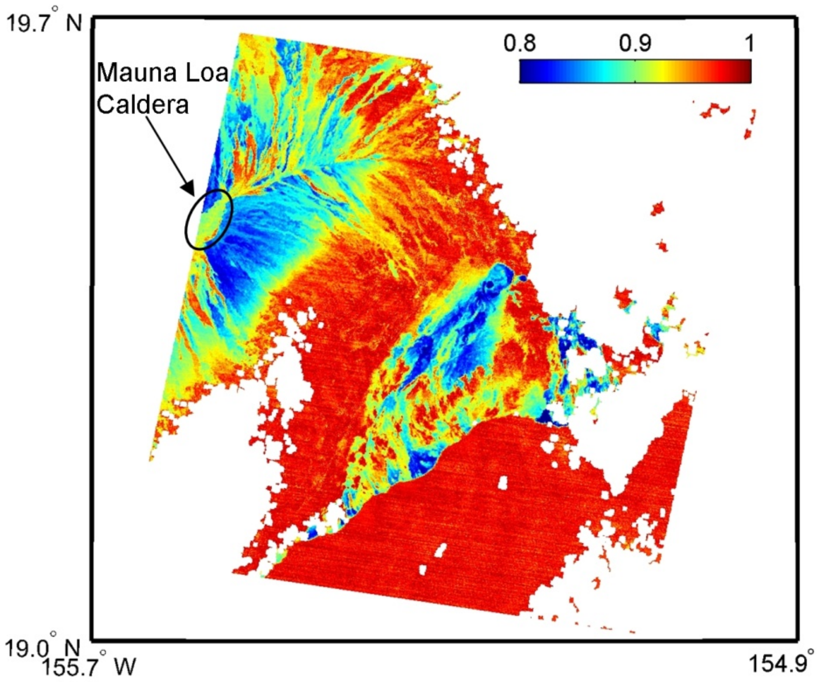

Landsat5 LST (LandClass)

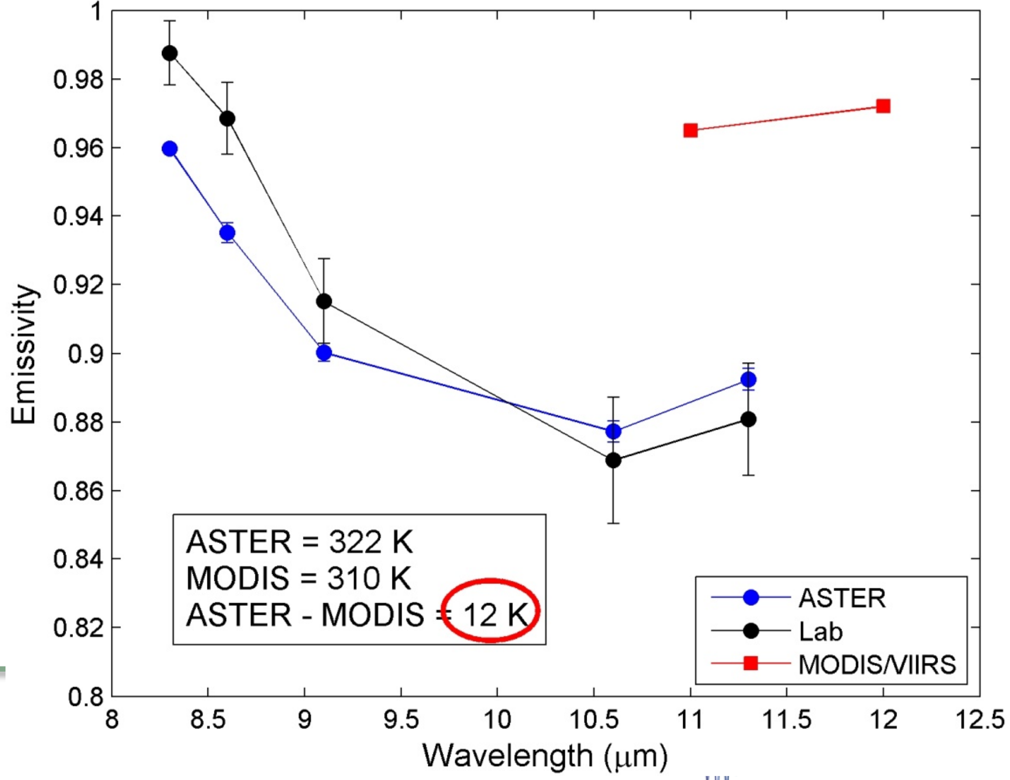

Difference (LandClass - NAALSED)


Difference (LandClass - NAALSED)

Land Classification Emissivities could have large errors over particular geologic surfaces!

e.g. Mafic rocks (basalt)




ASTER = 322 K
MODIS = 310 K
ASTER - MODIS = 12 K

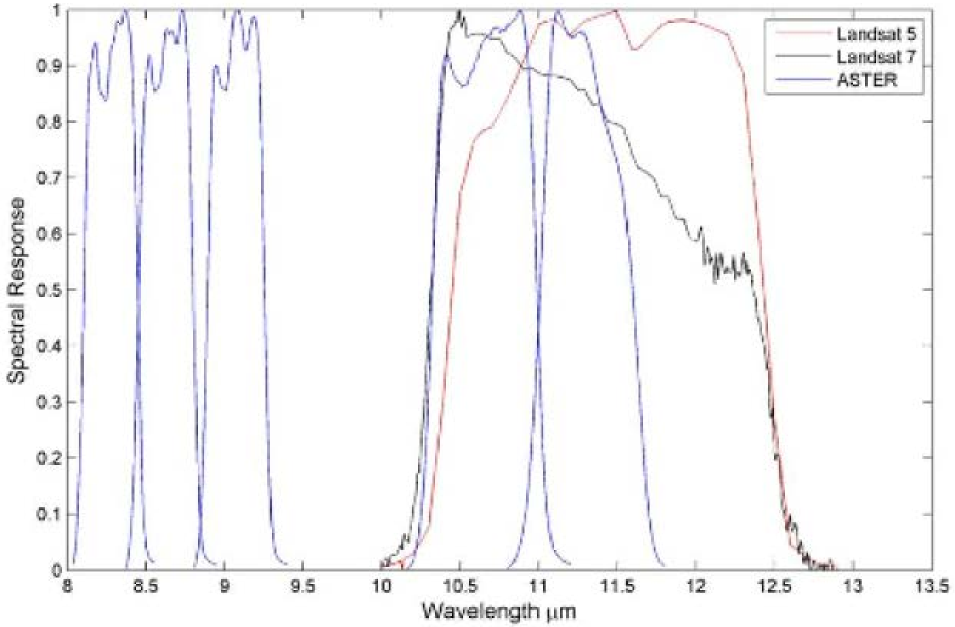
Summary

- 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 ± 0.51 K with max differences of ~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!!

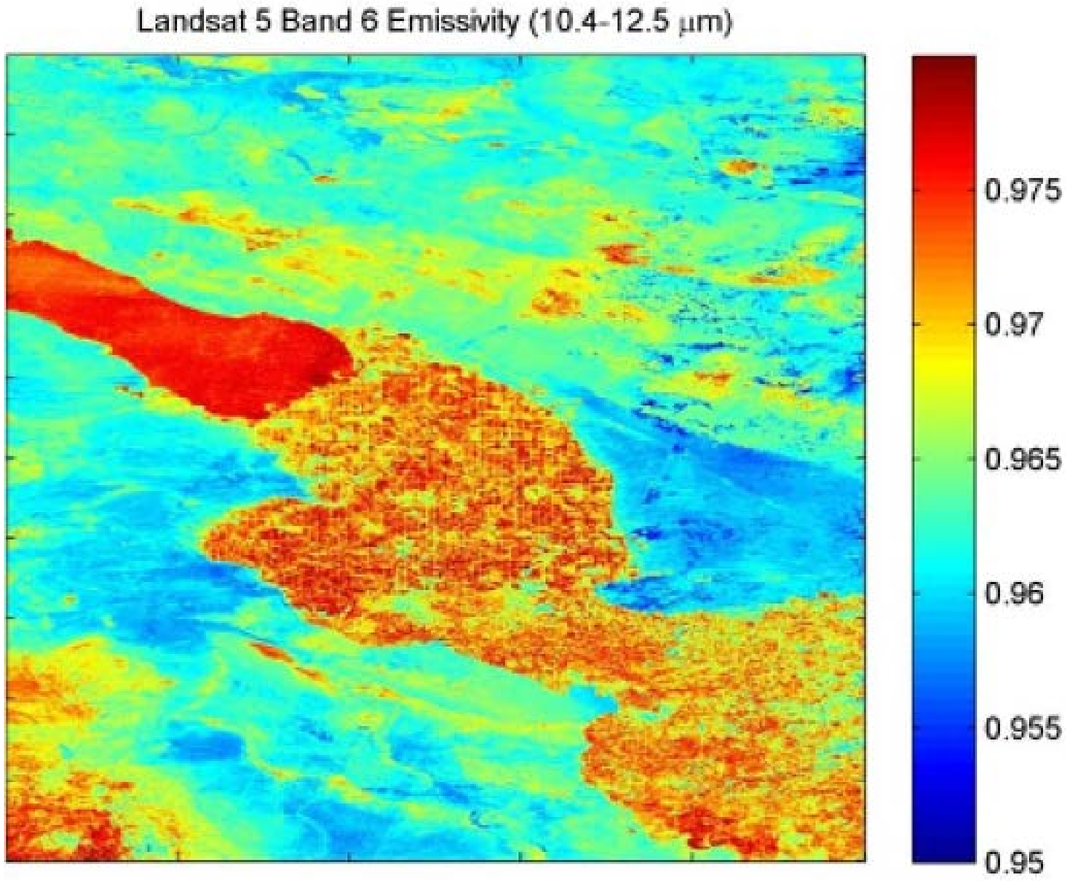
Questions? Help!

- Extract Bare Earth Emissivity from the North American Aster Land Surface Emissivity Database (NAALSED)
  - Emissivities ($\varepsilon_{13}, \varepsilon_{14}$) and regression coefficients (JPL)

$$\varepsilon_{landsat} = C_{13}\,\varepsilon_{13} + C_{14}\,\varepsilon_{14} + C$$

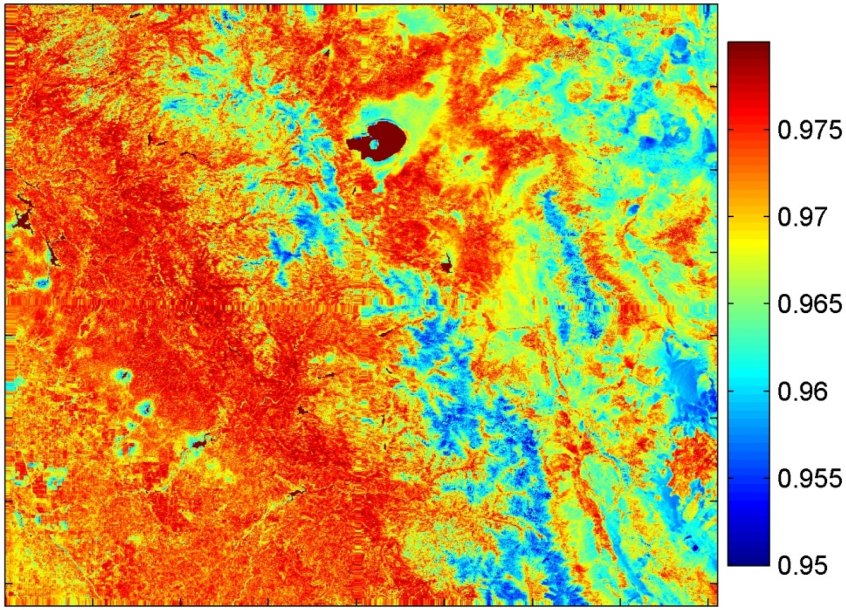


LANDSAT 5 derived emissivity from NAALSED bands 13 & 14 over the Salton Sea and Imperial Valley, CA.(JPL)

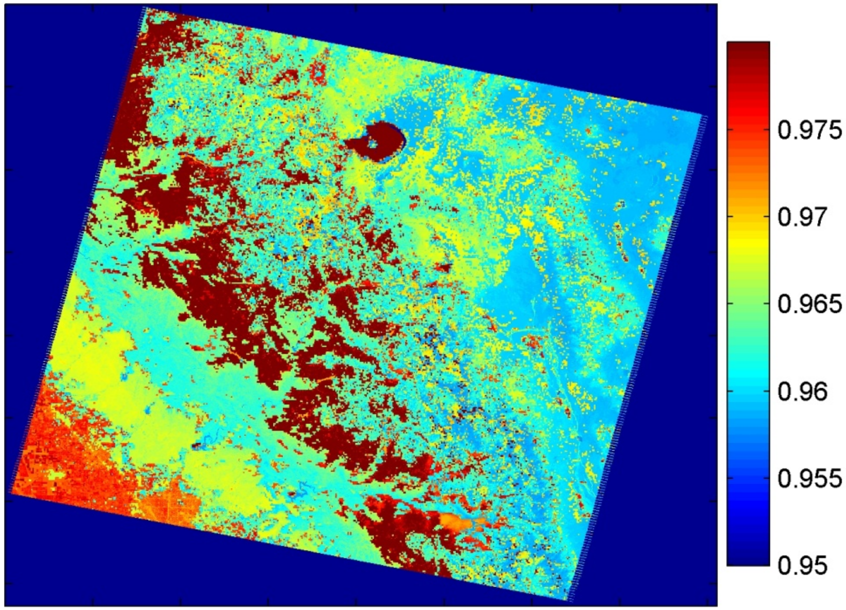


Sierra Nevada, Mono Lake, CA.

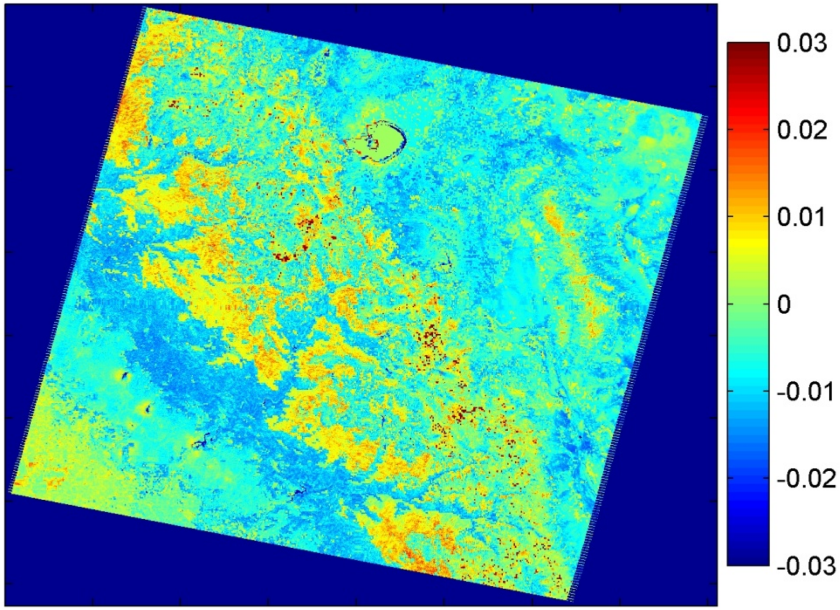
Landsat5 Band6 Emissivity (NAALSED)



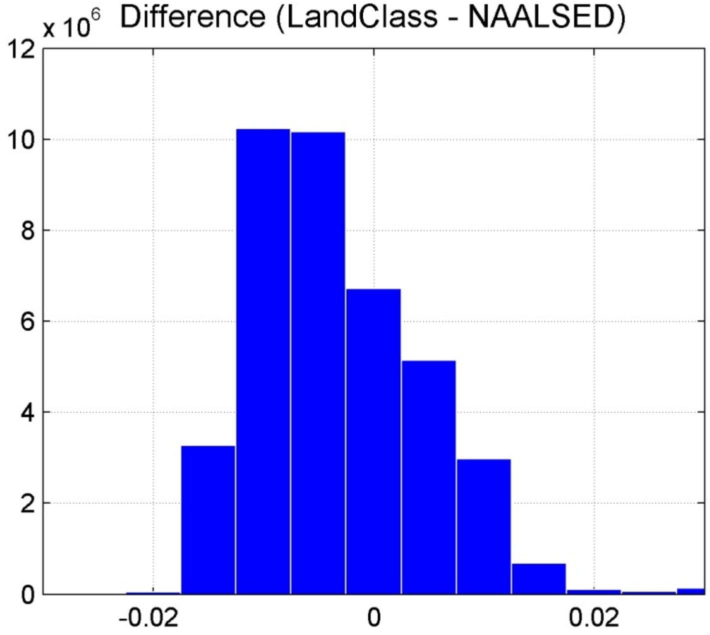
Landsat5 Band6 Emissivity (LandClass)



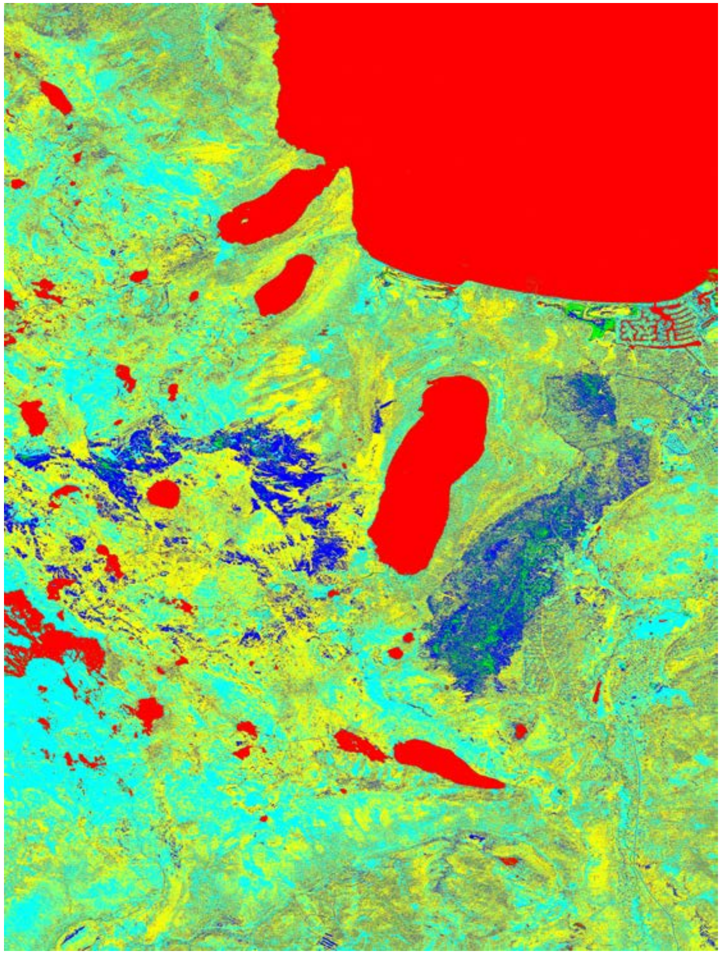
Difference (LandClass - NAALSED)



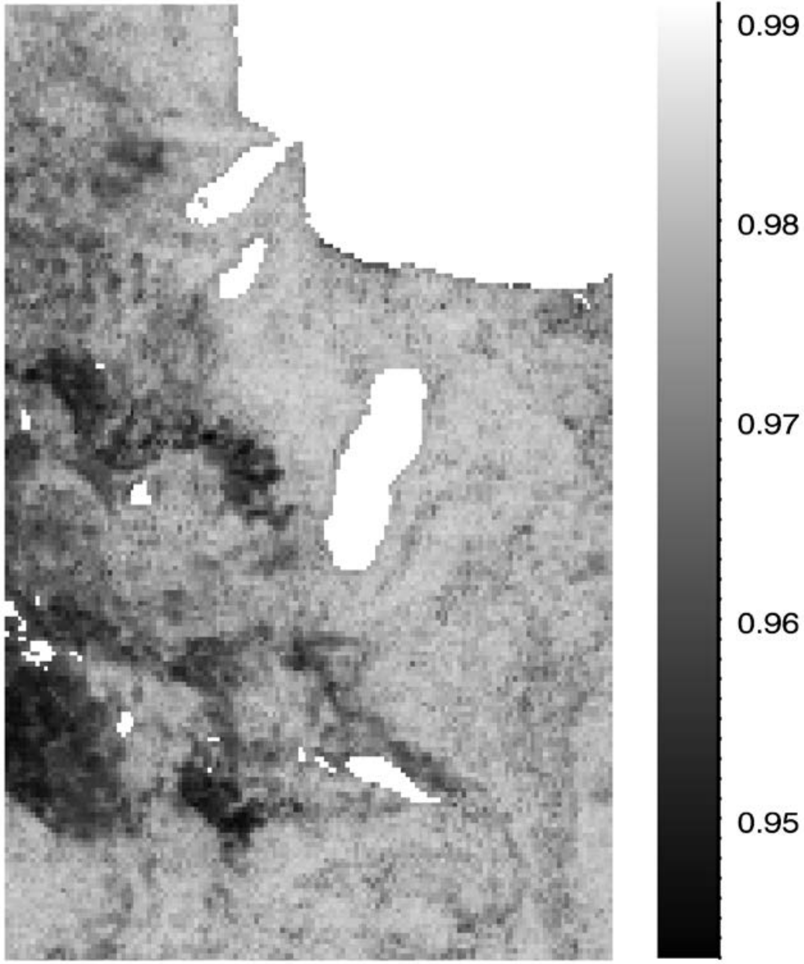
Difference (LandClass - NAALSED)



Lake Tahoe
5 Class Classification Map



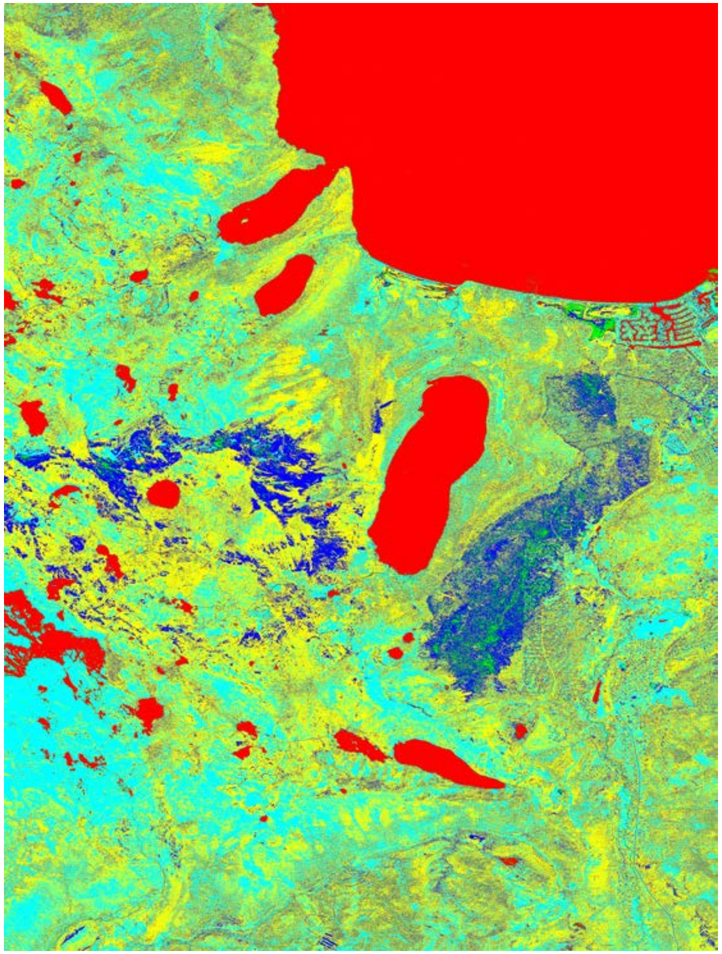
Aster Band 13
Lake Tahoe Emissivity Data



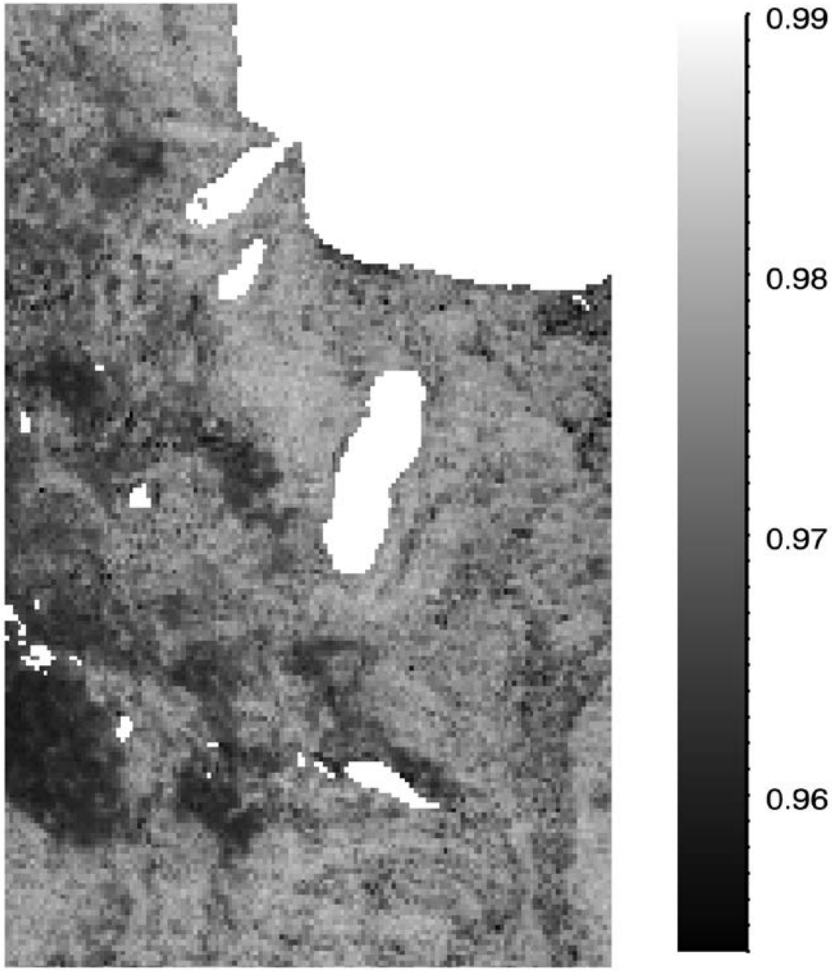
Class 1 Average Emissivity 0.988 SD 0.00736

Class 2 Average Emissivity 0.976 SD 0.00698

Lake Tahoe
5 Class Classification Map



Aster Band 14
Lake Tahoe Emissivity Data



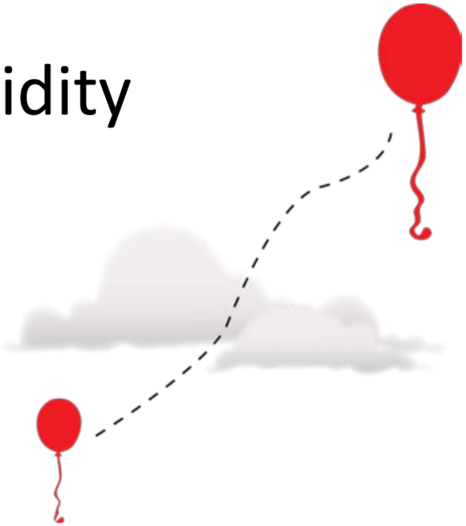
Class 1 Average Emissivity 0.988 SD 0.00644

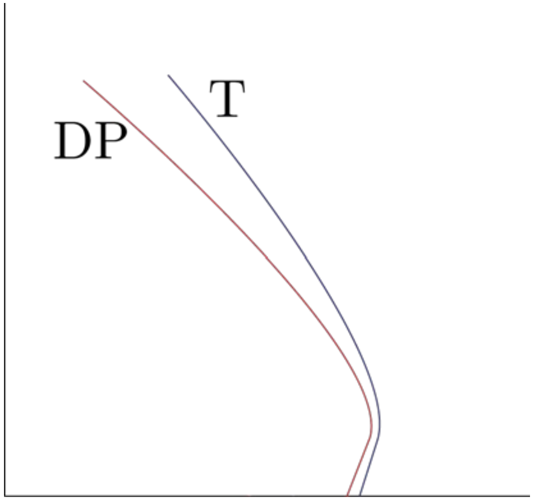
Class 2 Average Emissivity 0.974 SD 0.00476

Filters

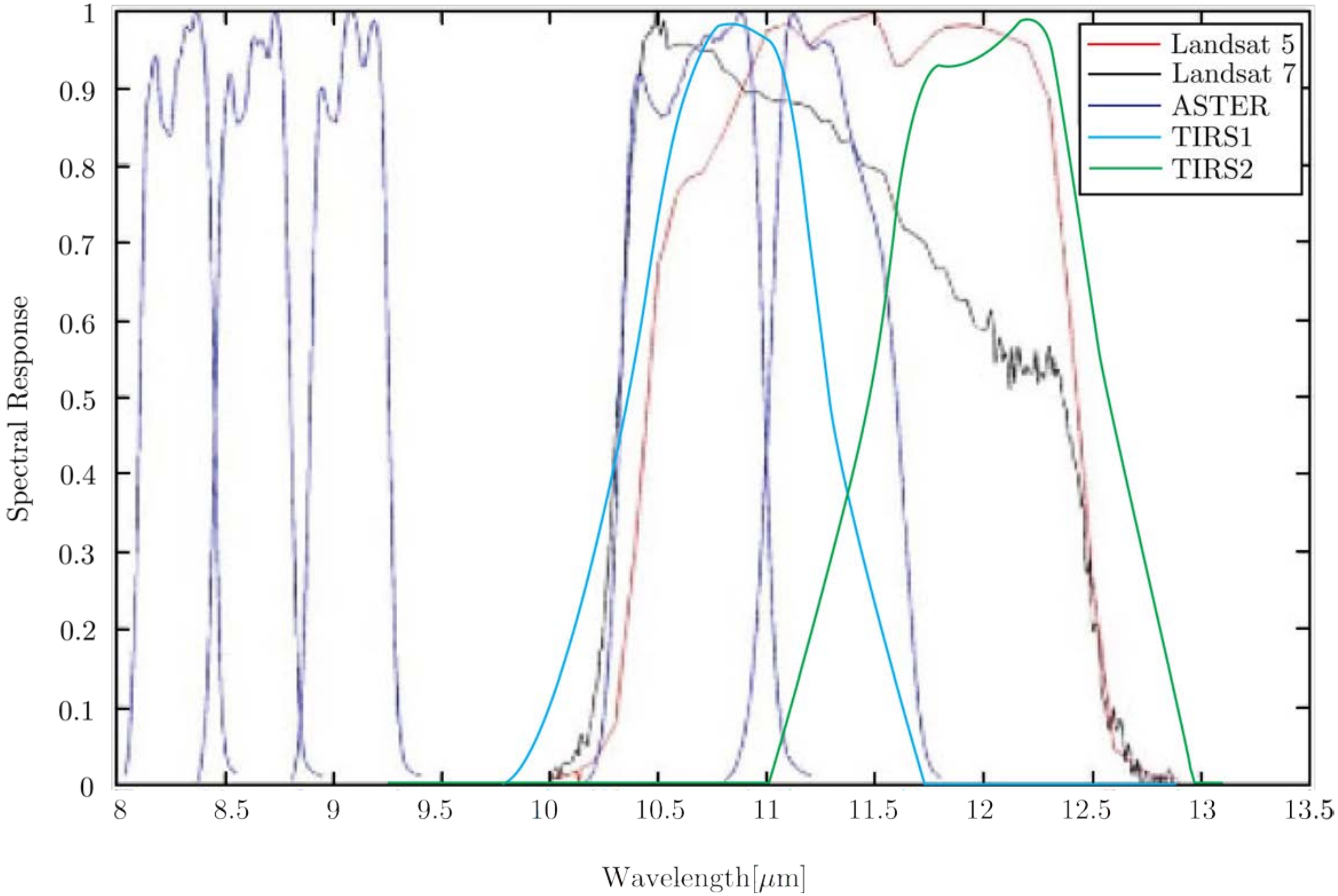
- Clouds
- Bad data
- High humidity

H	T
	⋮
	27
	25
	9999
	9999
2000	⋮
1000	
0	





Spectral Response Functions TIRS and the Future



A Land Surface Temperature Product

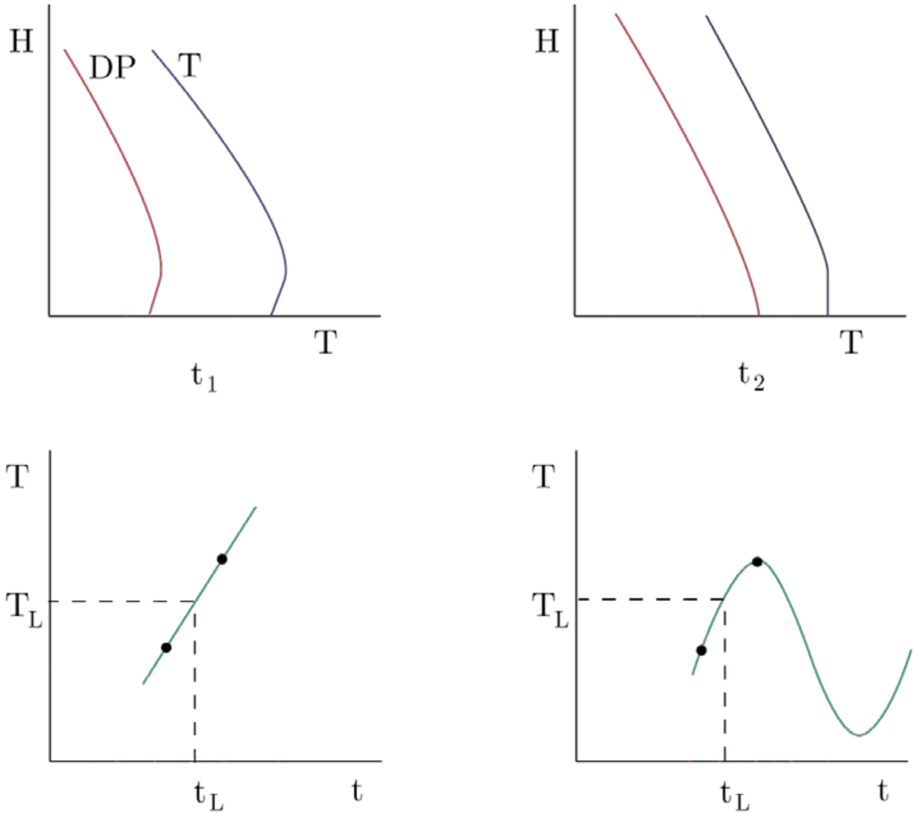
Validation

- 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



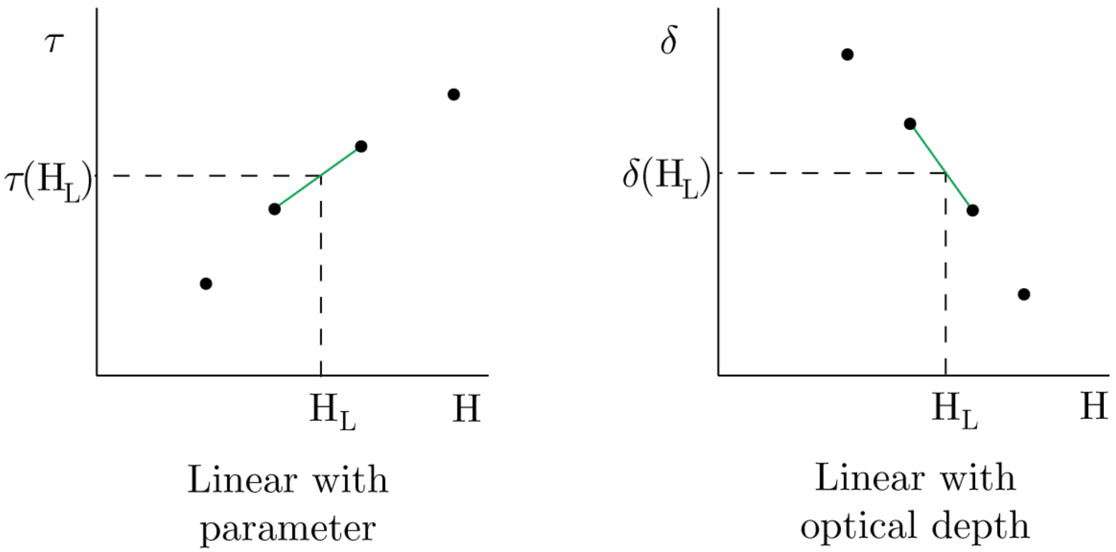
Profile samples at time 1 (t_1) and time 2 (t_2) for one sample location

Linear Interpolation for T at each altitude

Diurnal Interpolation for T at each altitude

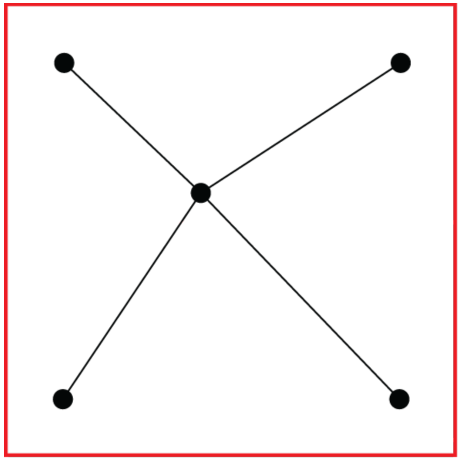
- Interpolate in parameter space (τ, L_u, L_d) on H for each profile site around the pixel of interest
  - Linear with H?
  - Linear in optical depth with H?

Interpolate to pixel height H_L

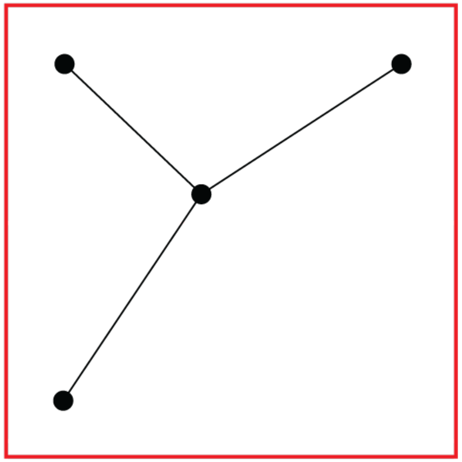


Output: $\tau(H_L,t_L)$, $L_u(H_L,t_L)$, $L_d(H_L,t_L)$

- Interpolate spatially in parameter space for fixed time and elevation at Nodes (profile sites)
  - Nearest neighbor?
  - Inverse distance (3 node, 4 node)?
  - Inverse exponential?



4 node



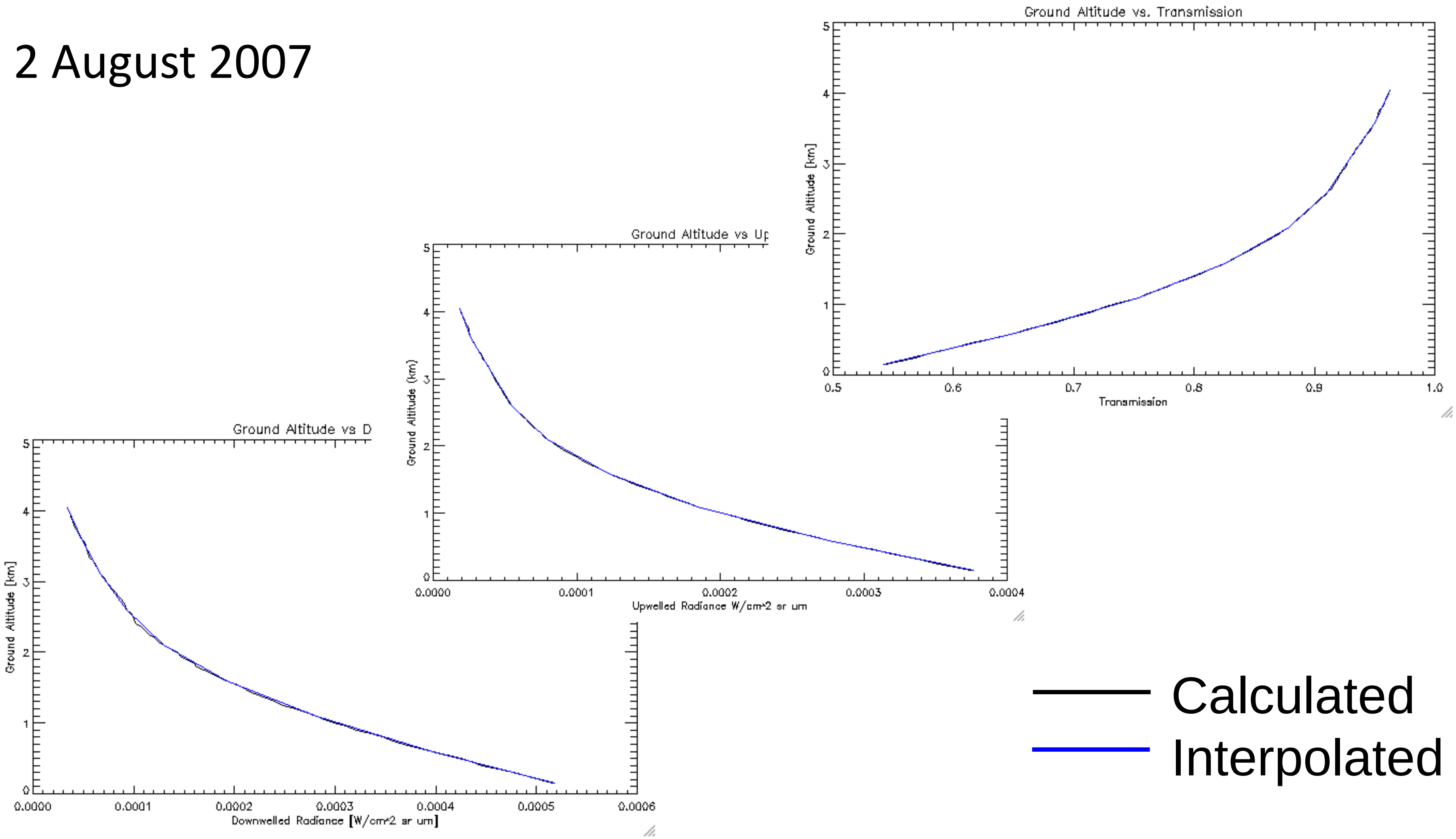
3 node

Output of Spatial Interpolation

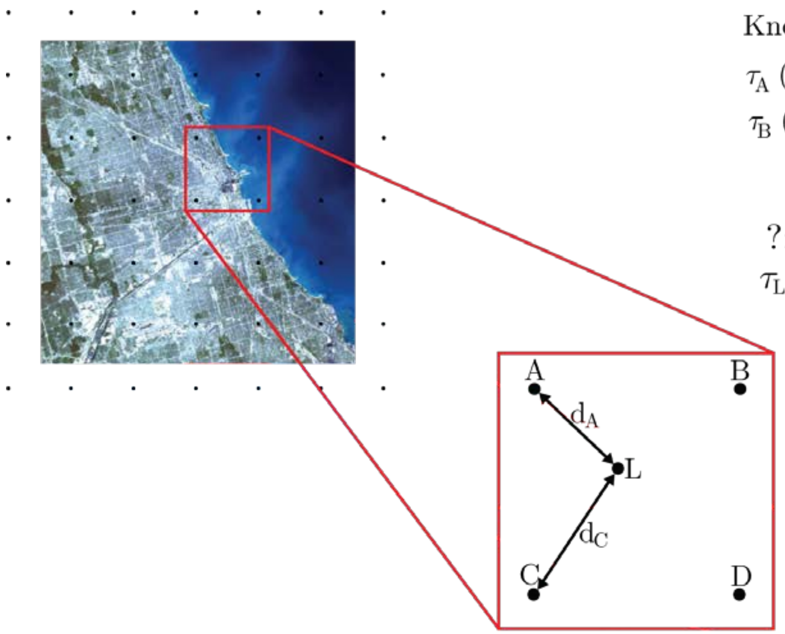
$$L_{surf} = \frac{L_s - L_u}{\tau} = \varepsilon L_T + (1-\varepsilon) L_d$$

Height Interpolation - Sensitivity Study

2 August 2007



- Compute τ, L_u, L_d, $L_{surf} = (L_s - L_u)/\tau = \varepsilon L_T + (1 - \varepsilon) L_d$



Know:

$\tau_A\ (H_L),\ L_{u_A}(H_L),\ L_{d_A}(H_L)$

$\tau_B\ (H_L),\ L_{u_B}(H_L),\ L_{d_B}(H_L)$

$\vdots$

?:

$\tau_L,\ L_{u_L},\ L_{d_L}$

Interpolate

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

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

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

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

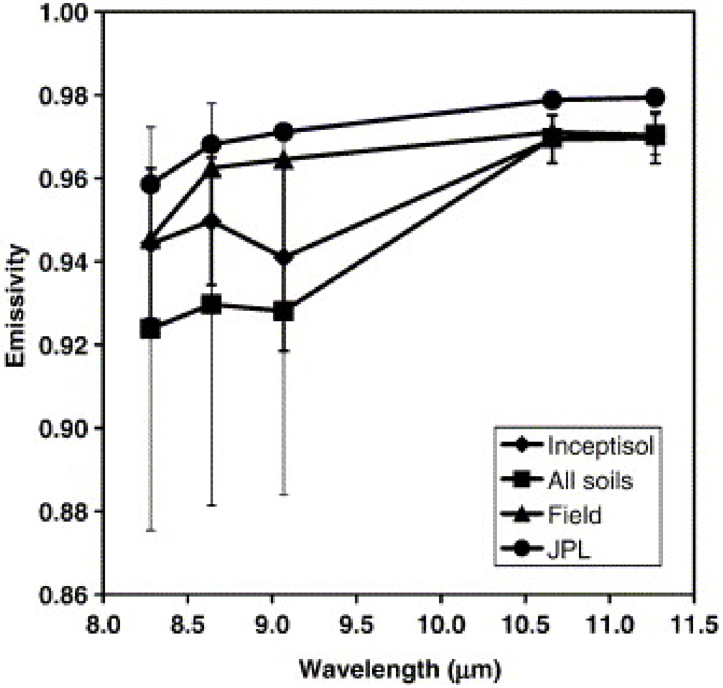
$$L = \begin{bmatrix} x \\ y \\ H_L \end{bmatrix}$$

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.

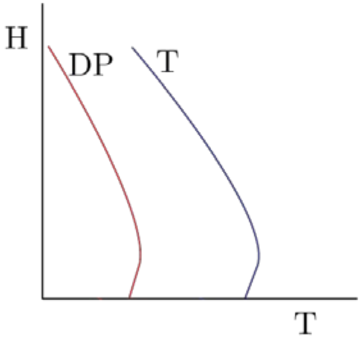


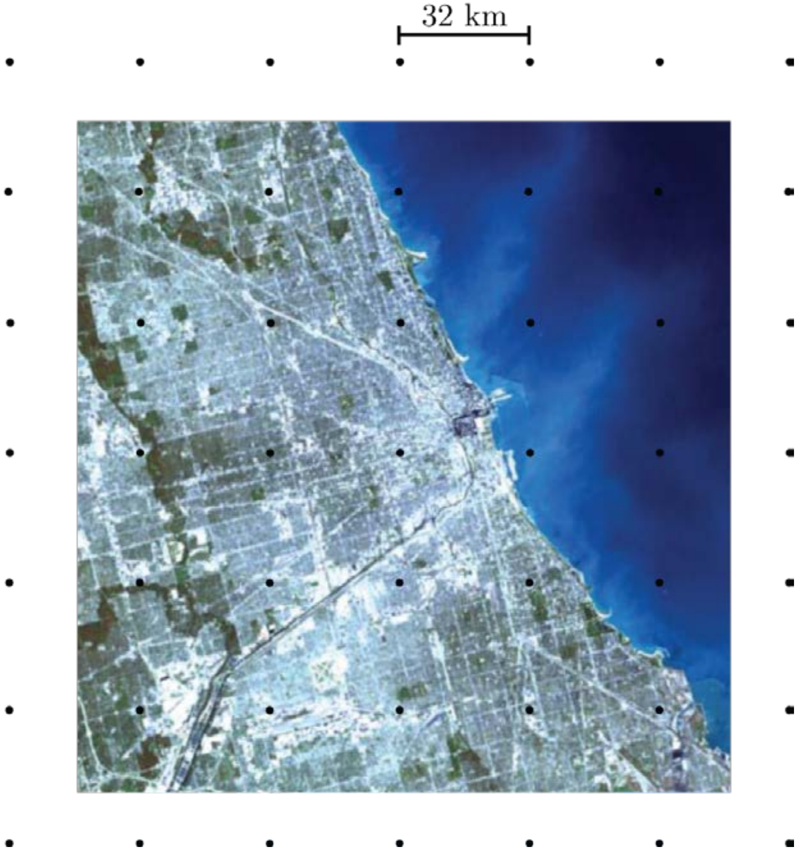
$$\varepsilon_{13} = 0.968 + 0.022\ P_{\mathrm{V}}$$

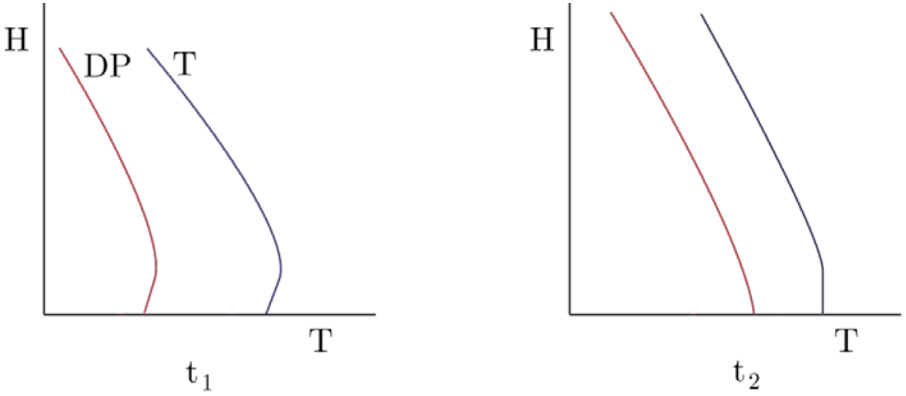
$$\varepsilon_{14} = 0.970 + 0.020\ P_{\mathrm{V}}$$

$$P_{\mathrm{V}} = \left(\frac{\mathrm{NDVI}-\mathrm{NDVI_s}}{\mathrm{NDVI_v}-\mathrm{NDVI_s}}\right)^2$$

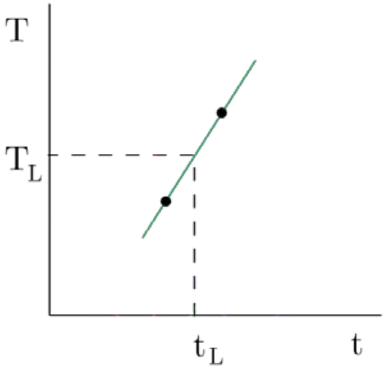
Fig. 3. Average emissivity spectra for different soil samples included in the ASTER spectral library (http://speclib.jpl.nasa.gov). ‘Inceptisol’ refers to the mean value for all the soil samples included in the ASTER library and classified as Inceptisol (7 samples). These values have been chosen a soil 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].


H
DP
T
T

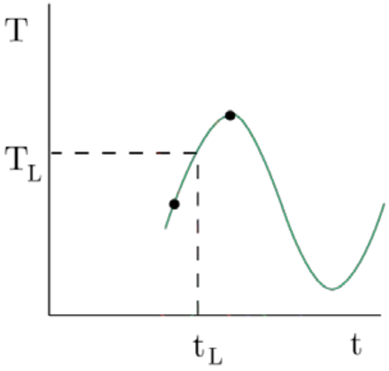

32 km



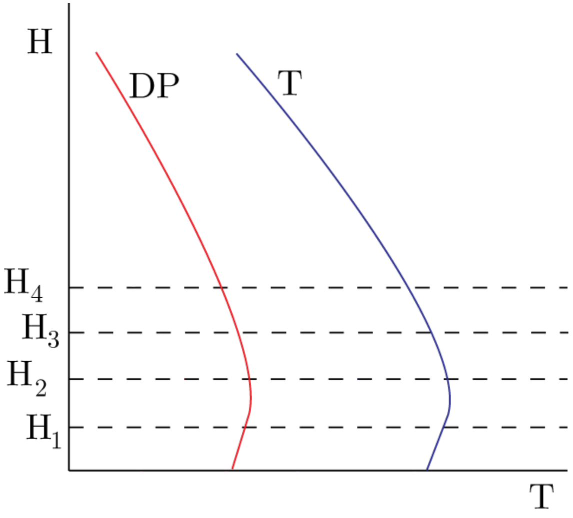
Profile samples at time 1 (t_1) and time 2 (t_2) for one sample location



Linear Interpolation
for T at each altitude



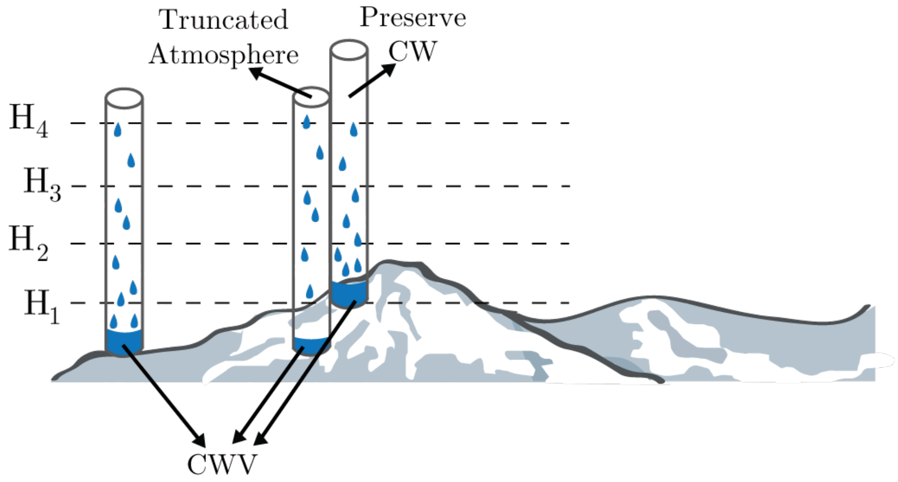
Diurnal Interpolation
for T at each altitude



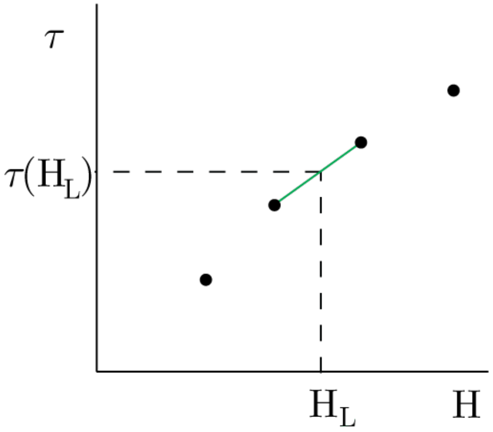
Run Modtran for each altitude.

Output:

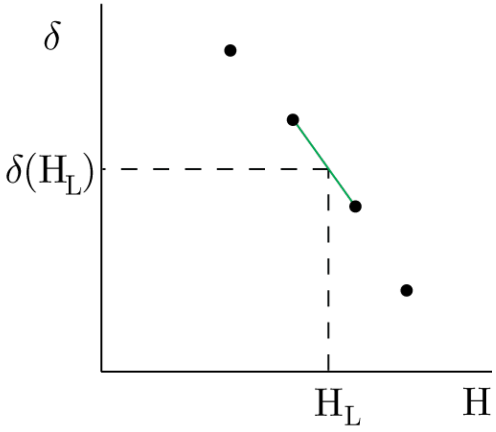
$\tau(H)$, $L_u(H)$, $L_d(H)$



Interpolate to pixel height H_L

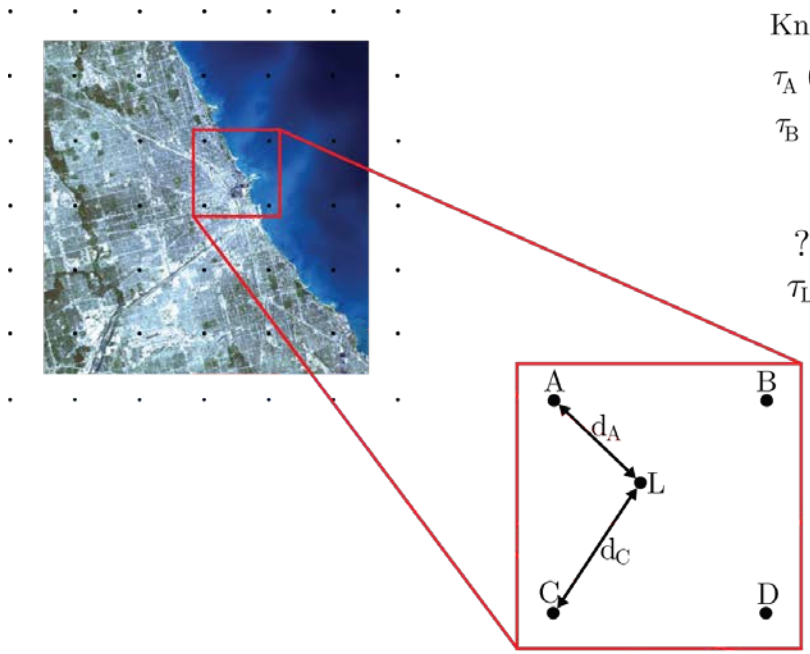


Linear with parameter



Linear with optical depth

Output: $\tau(H_L,t_L)$, $L_u(H_L,t_L)$, $L_d(H_L,t_L)$



Know:

$\tau_A\ (H_L),\ L_{u_A}(H_L),\ L_{d_A}(H_L)$

$\tau_B\ (H_L),\ L_{u_B}(H_L),\ L_{d_B}(H_L)$

⋮

?:

$\tau_L,\ L_{u_L},\ L_{d_L}$

Interpolate

Nearest neighbor → $\tau_L = \tau_A,\ L_{u_L} = L_{d_L}\ \dots$

Linear in 1/d →

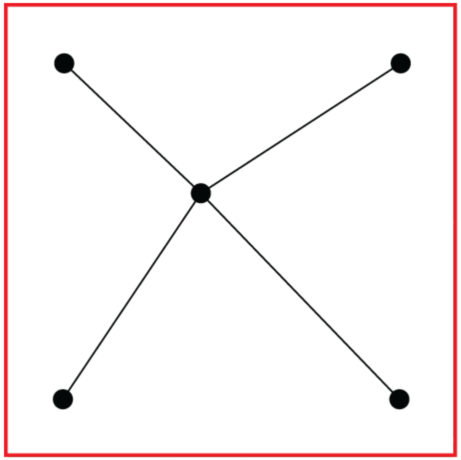
$$\tau_L = \frac{\frac{\tau_A}{d_A} + \frac{\tau_B}{d_B} + \frac{\tau_C}{d_C} + \frac{\tau_D}{d_D}}{\sum_i \frac{1}{d_i}},\ \dots$$

Linear in e^{-d} →

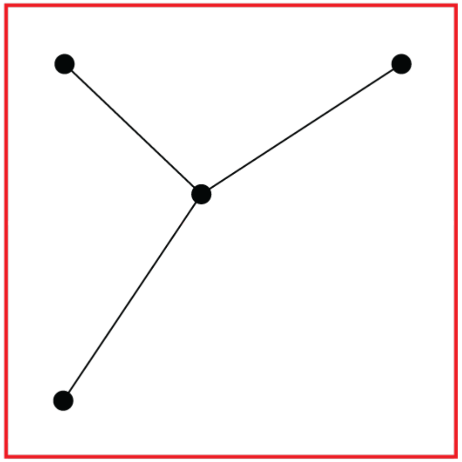
$$\tau_L = \frac{\tau_A e^{-d_A} + \tau_B e^{-d_B} + \tau_C e^{-d_C} + \tau_D e^{-d_D}}{\sum_i e^{-d_i}},\ \dots$$

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

$$L = \begin{bmatrix} x \\ y \\ H_L \end{bmatrix}$$



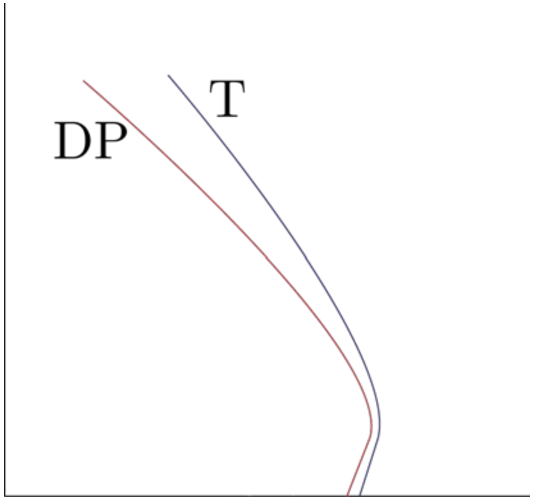
4 node

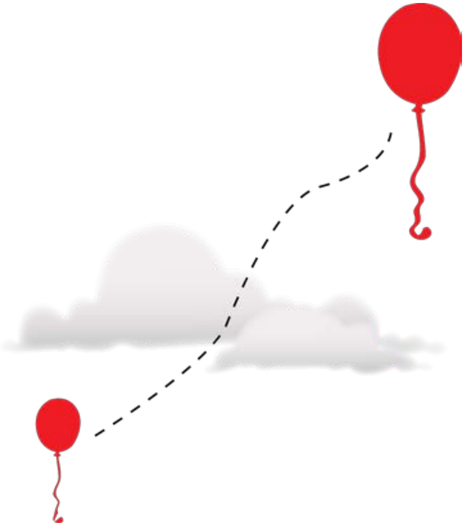


3 node

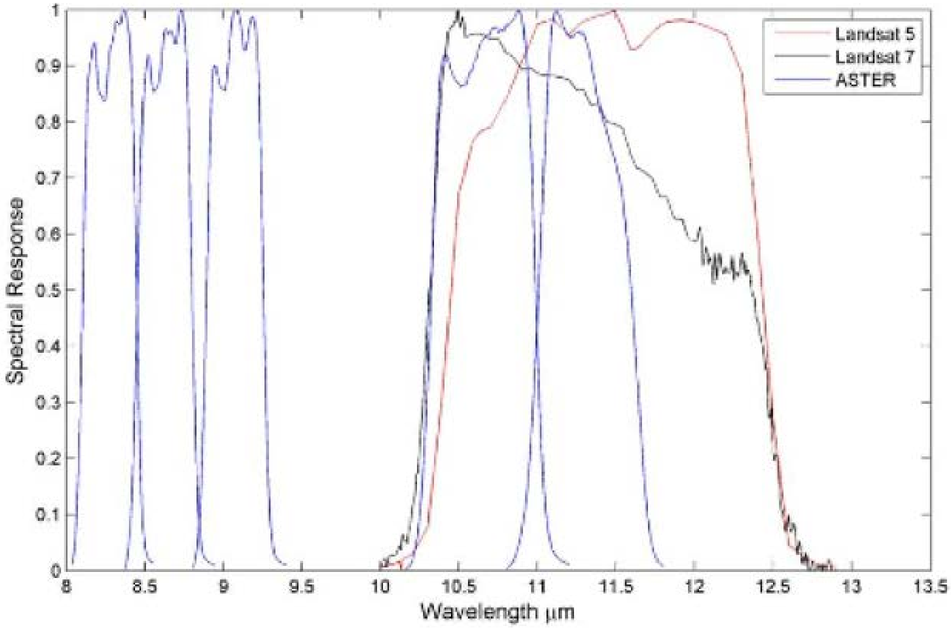
Output of Spatial Interpolation

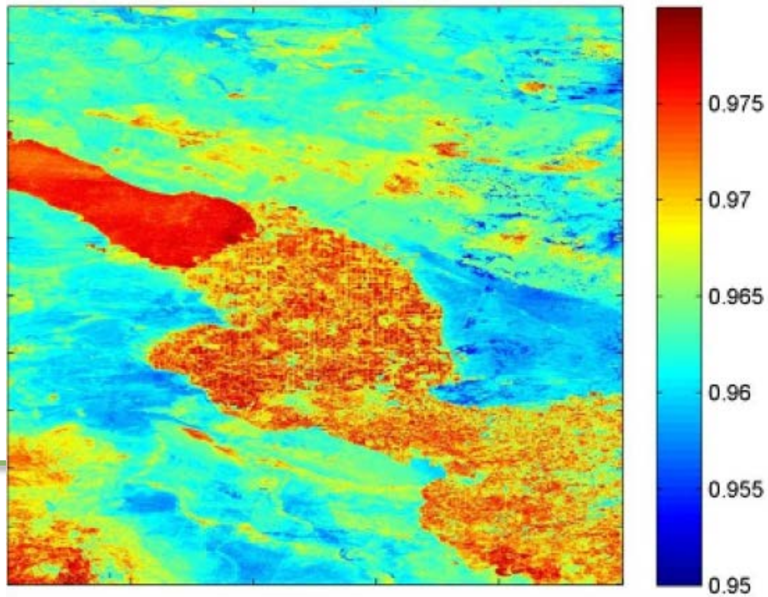
$$L_{\text{surf}} = \frac{L_s - L_u}{\tau} = \varepsilon L_T + (1-\varepsilon) L_d$$





H	T
	⋮
	27
	25
	9999
	9999
2000	⋮
1000	
0	




Landsat 5 Band 6 Emissivity (10.4-12.5 μm)

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.

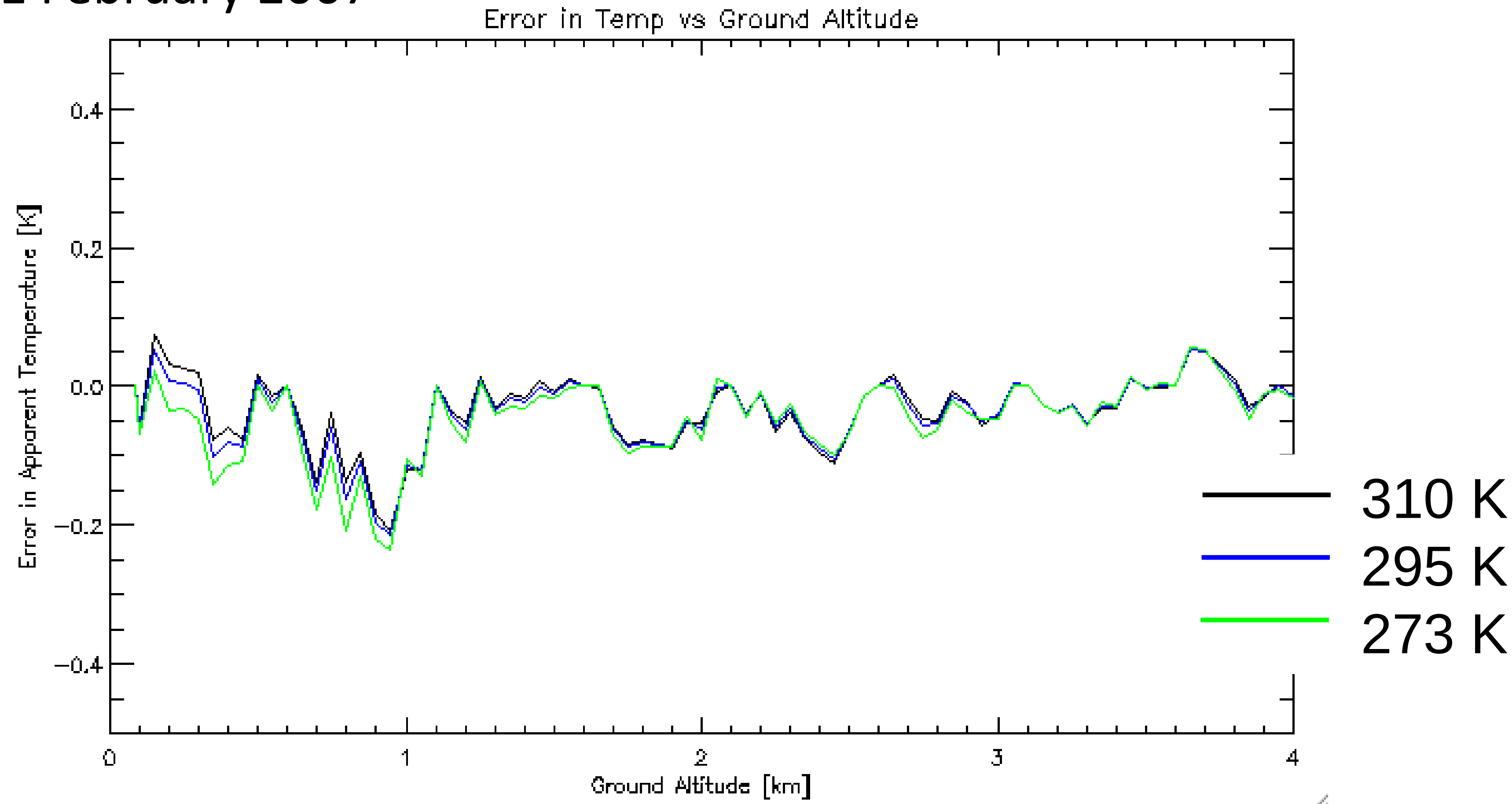
- compare to ASTER/MODIS
- compare to truth
- user evaluation

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



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

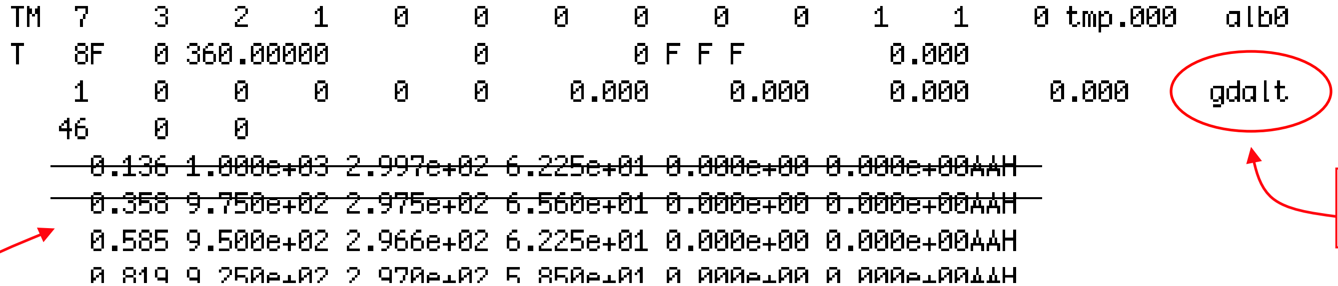
QC map may be limited or non existent

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



```
TM   7     3     2     1     0     0     0     0     0     0     1     1     0 tmp.000    alb0
T    8F    0 360.00000           0           0 F F F           0.000
     1     0     0     0     0     0      0.000      0.000      0.000      0.000     gdalt
    46     0     0
     ~~0.136 1.000e+03 2.997e+02 6.225e+01 0.000e+00 0.000e+00AAH~~
     ~~0.358 9.750e+02 2.975e+02 6.560e+01 0.000e+00 0.000e+00AAH~~
     0.585 9.500e+02 2.966e+02 6.225e+01 0.000e+00 0.000e+00AAH
     0.819 9.250e+02 2.970e+02 5.850e+01 0.000e+00 0.000e+00AAH
```

0.468

0.468 9.625e+02 2.971e+02 6.393e+0.1

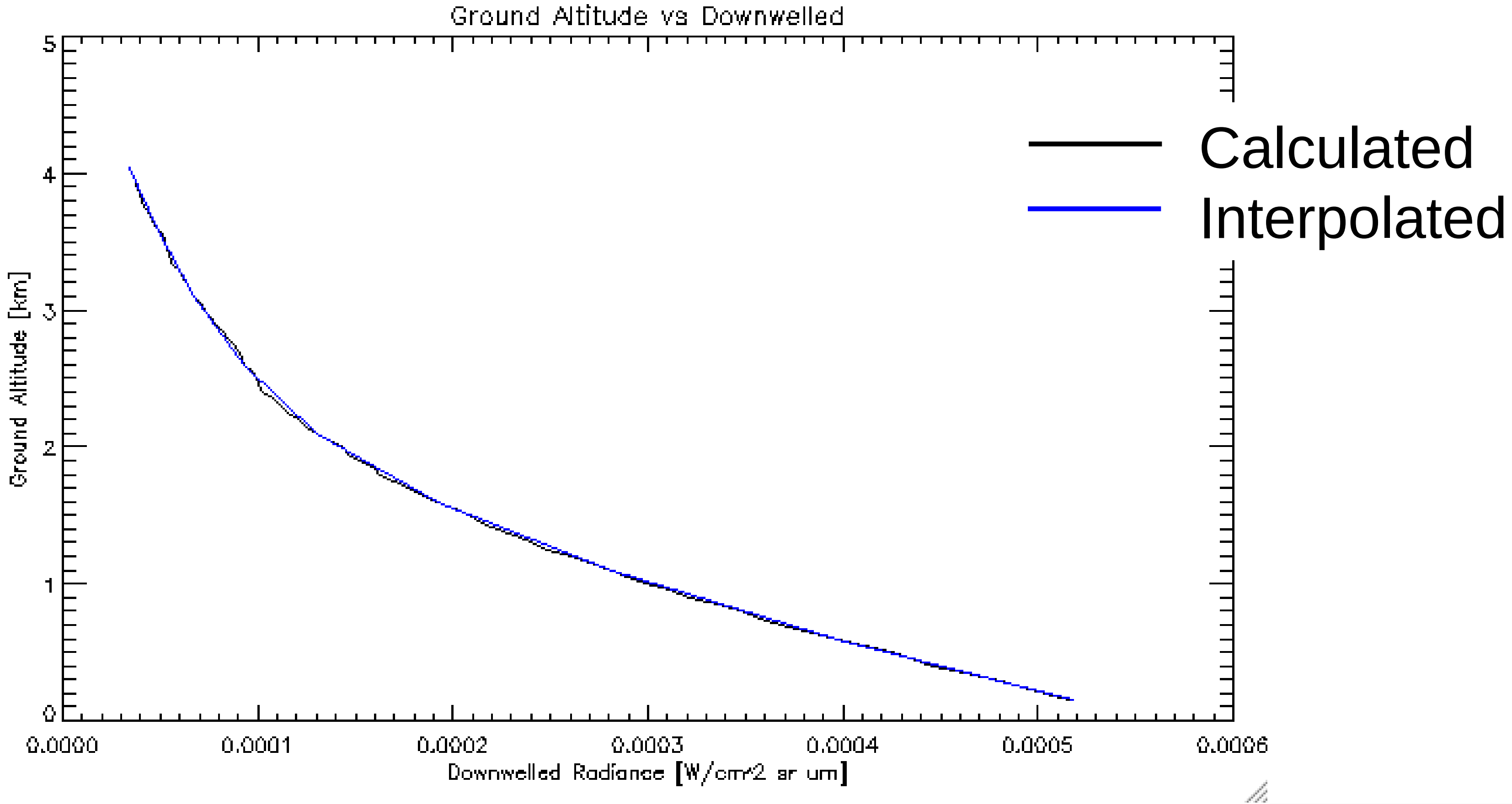
Height Interpolation - Sensitivity Study

- Compute parameters (τ, 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

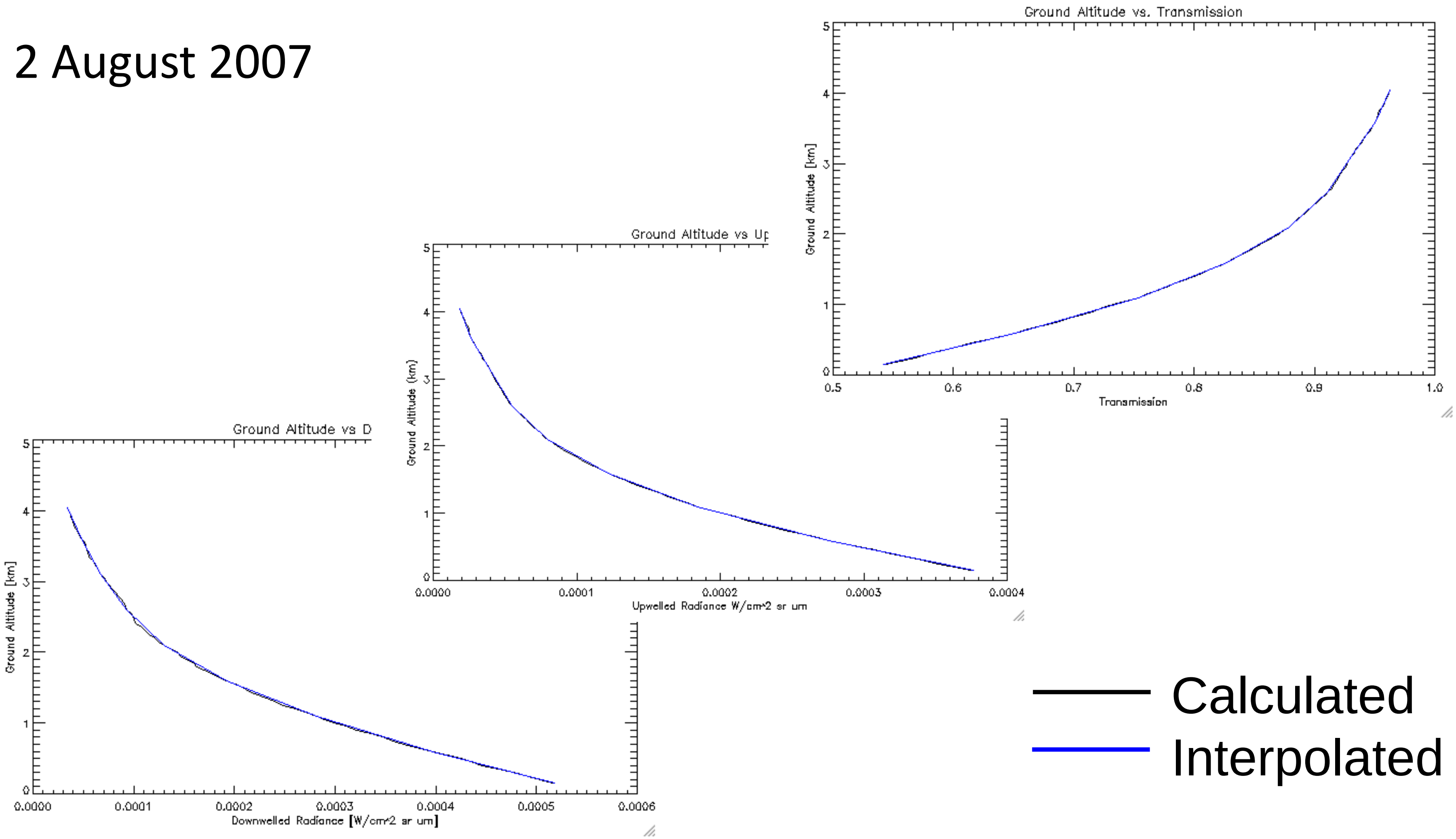
Height Interpolation - Sensitivity Study

2 August 2007



Height Interpolation - Sensitivity Study

2 August 2007

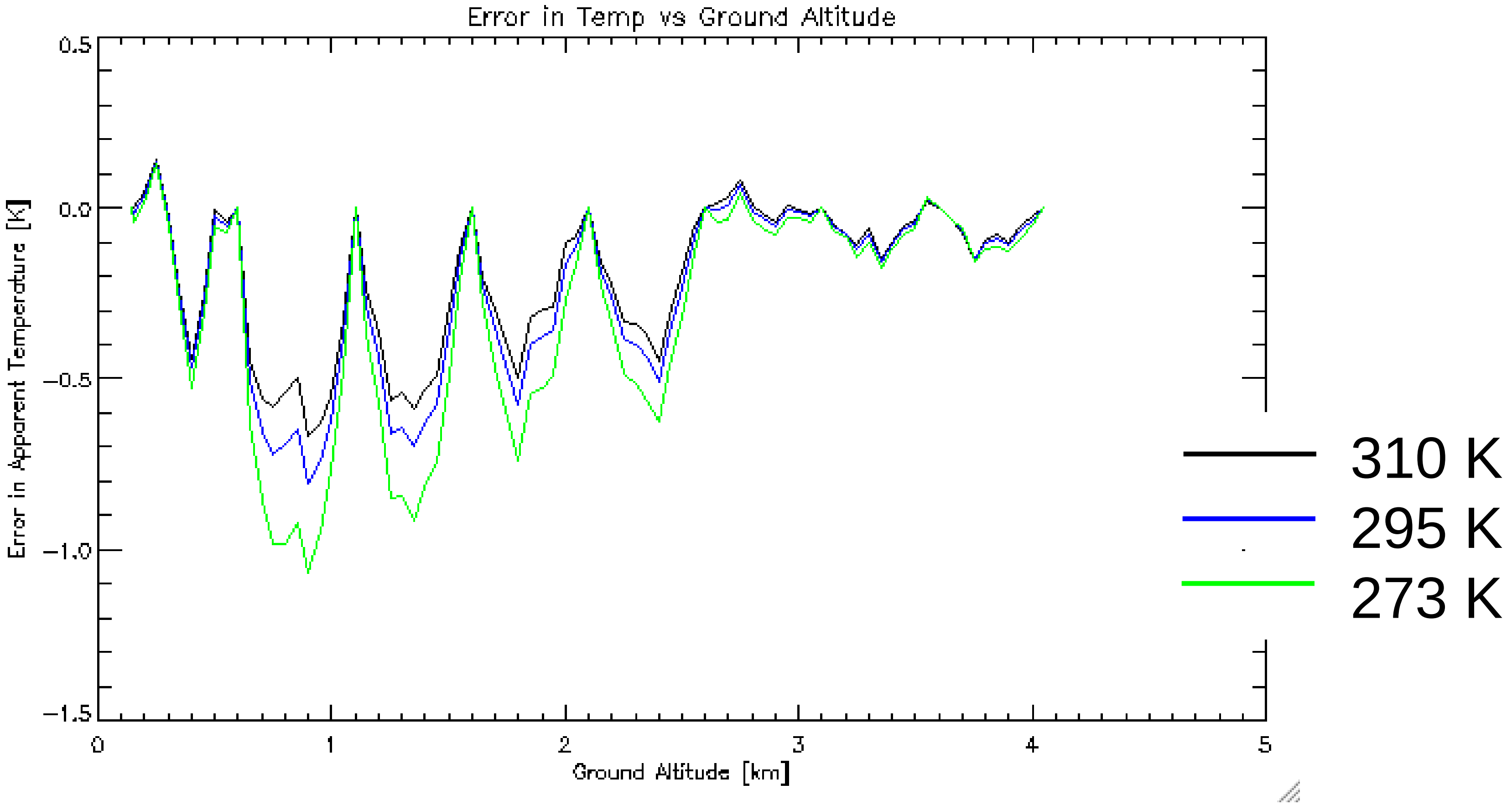


— Calculated

— Interpolated

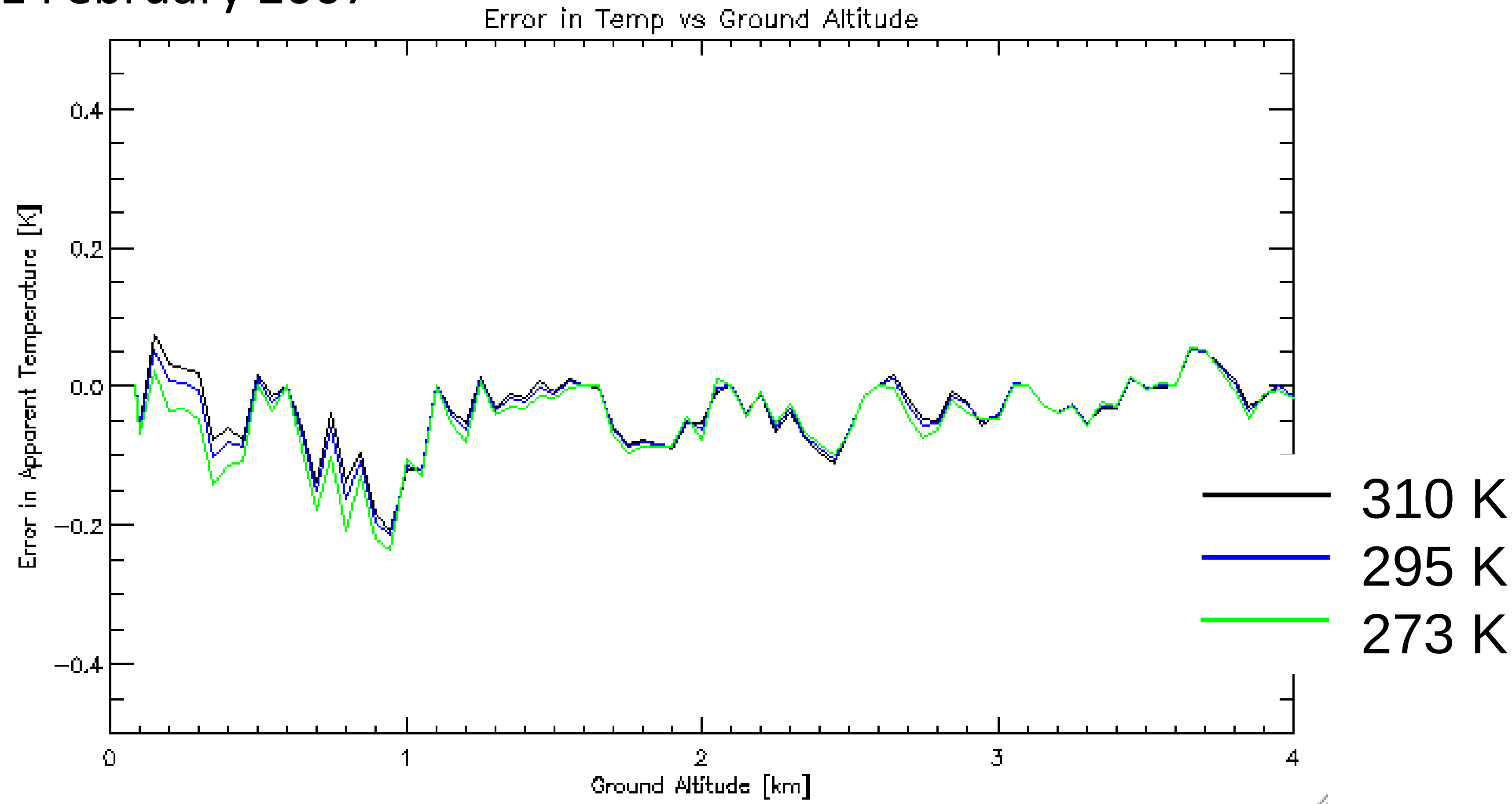
Height Interpolation - Sensitivity Study

2 August 2007



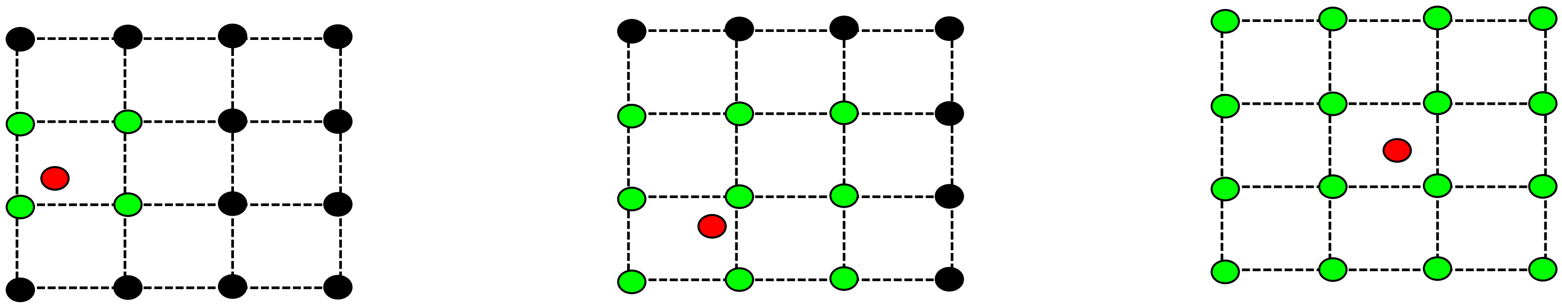
Height Interpolation - Sensitivity Study

1 February 2007



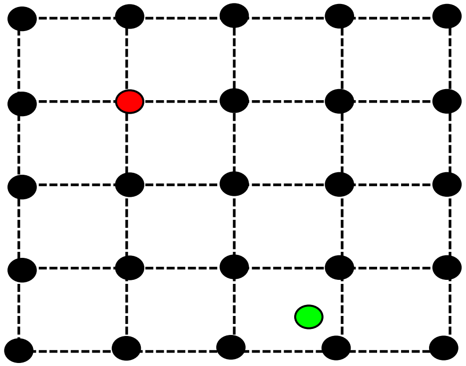
Spatial Interpolation

- 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

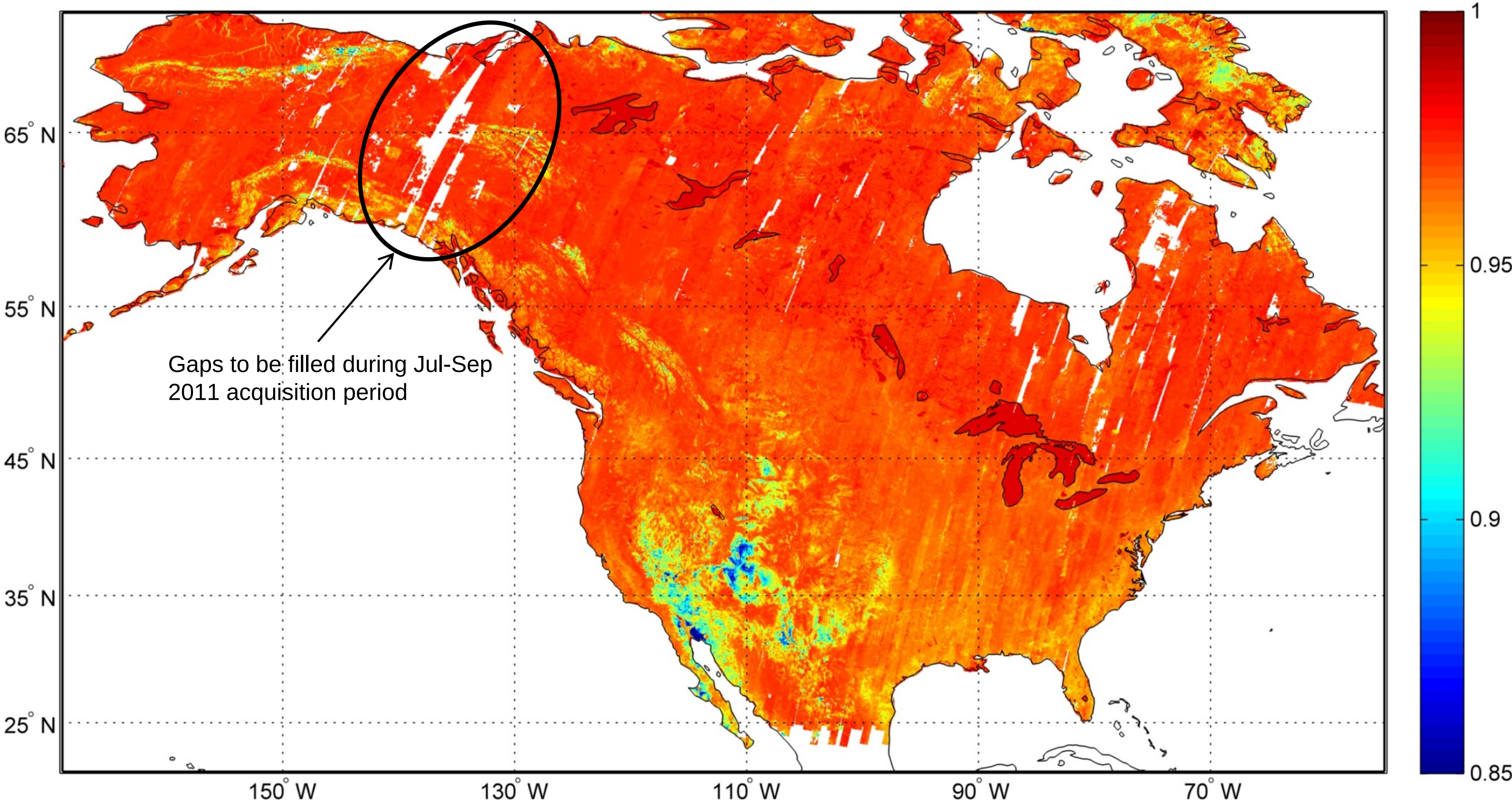
- Thermal data has been largely under-utilized due to problems with deriving the land surface emissivity (impossible with 1 band)

- ***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

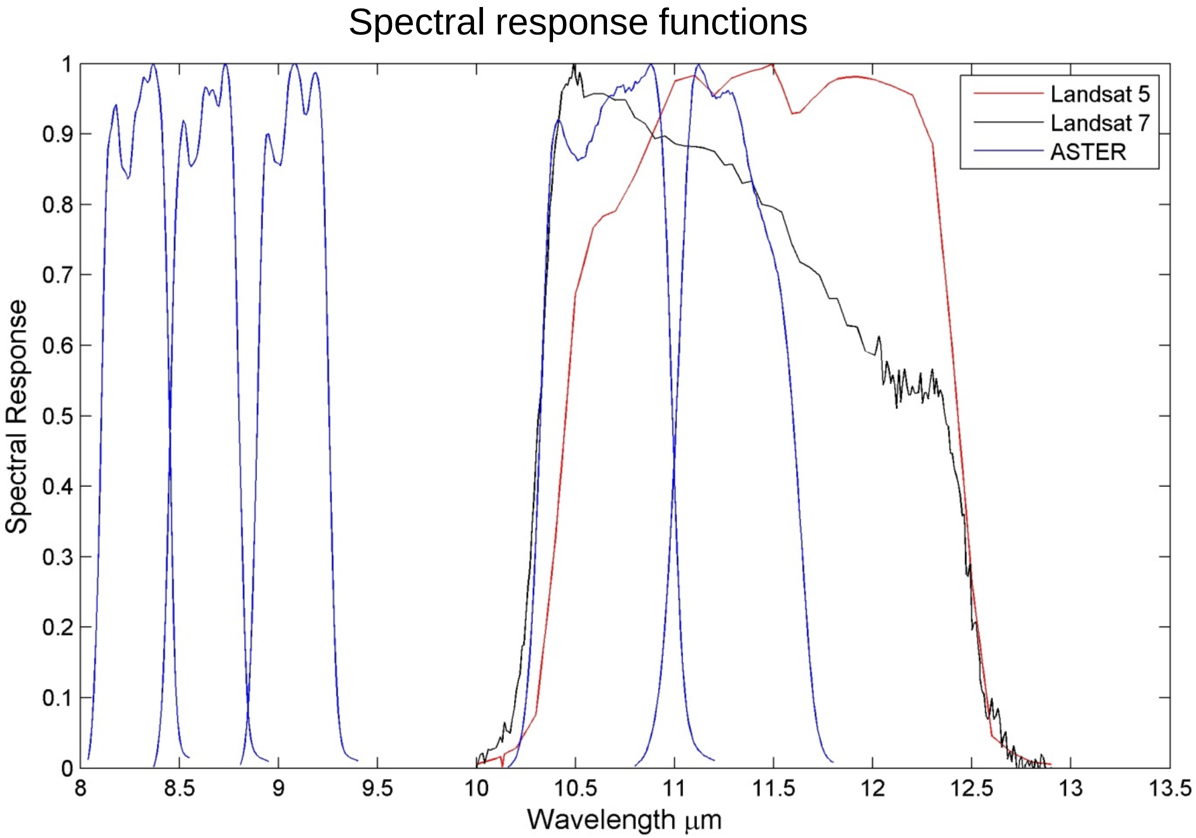
- ❖ Progress:
  - ✓ Downloaded ~9500 TM scenes for California/Nevada (1984-2011) for initial algorithm testing
  - ✓ Landsat LST algorithm developed for TM and ETM+ data:
    - Classification-based emissivities
    - NAALSED-based emissivities
  - ✓ Comparisons between two methods completed for several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



Landsat-5: $\epsilon_{10.4-12.5} = 0.305\,\epsilon_{13} + 0.468\,\epsilon_{14} + 0.223$

Landsat-7: $\epsilon_{10.4-12.5} = 0.44\,\epsilon_{13} + 0.4\,\epsilon_{14} + 0.156$

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

Landsat emissivity from Land Classification

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

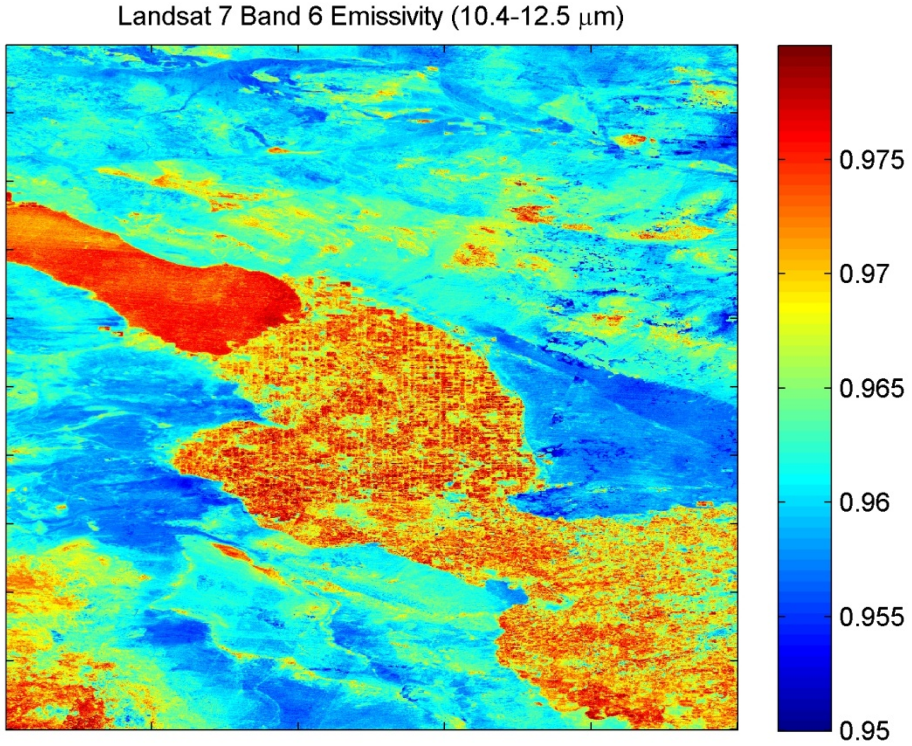
$$ee = e_{veg}*fv + e_{bare}(1 – fv)$$

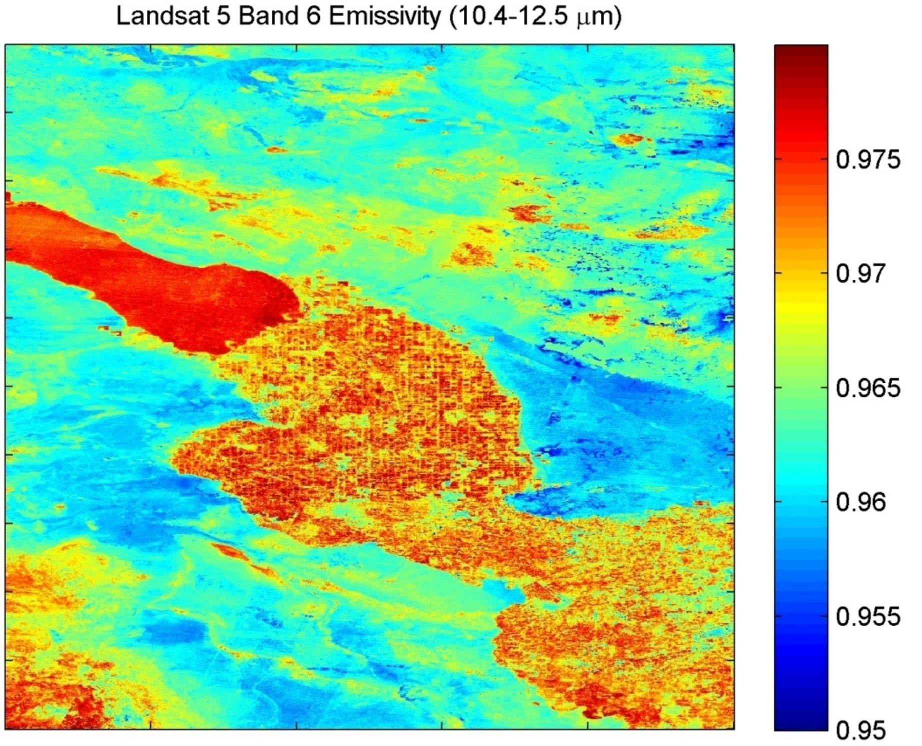
ee = effective emissivity
fv = fractional vegetation cover
e_{veg} = vegetation emissivity (assigned from land cover map)
e_{bare} = soil/rock emissivity (assigned according to vegetation type)

$$fv = 1 – (NDVI_{max} – NDVI)/(NDVI_{max} – NDVI_{min})$$

NDVI = Normalized Difference Vegetation Index

Landsat emissivity from NAALSED


Landsat 7 Band 6 Emissivity (10.4-12.5 µm)


Landsat 5 Band 6 Emissivity (10.4-12.5 µm)

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

Worst case scenario: $\delta e = 0.04 \Rightarrow \delta T = 2.85$ K (for surface at 11 µm, 300 K)

Single-band Temperature Inversion

Surface Radiance:

Observed Radiance

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

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

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

Surface emitted radiance

$$B_i(T_S) = \frac{1}{e_i}\left(\frac{L_i(\theta) - L_i^{\uparrow}(\theta)}{\tau_i(\theta)} - (1-e_i)\overline{L}_i^{\downarrow}\right)$$

Invert Planck function to get LST $\longrightarrow$

$$T_S = B_i^{-1}$$

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)

$$Lsky = a + b*Lpath + c*Lpath^2$$

Lsky = Downwelling sky irradiance

Lpath = 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

www.nasa.gov