Vicarious Calibration—Current Capabilities and Future Possibilities

9 September 2019

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Co-authors:

- Jeff Czapla-Myers, University of Arizona
- Cibele Pinto, Morakot Kaewmanee, South Dakota State University
- Aaron Gerace, Nina Raqueno, Rochester Institute of Technology

U.S. Department of the Interior
U.S. Geological Survey

Outline

- **Definition**
- **Traditional Desert Sites**
  - Jeff Czapla-Myers, University of Arizona
- **Vegetative Sites**
  - Larry Leigh, Cibele Pinto, South Dakota State University
- **Pseudo Invariant Calibration Sites (PICS)**
  - Morakot Kaewmanee, South Dakota State University
- **Thermal Vicarious Calibration**
  - Aaron Gerace, Nina Raqueno, Rochester Institute of Technology
- **Summary/Conclusions**

Vicarious Calibration – A definition

- **For purposes of this presentation, Vicarious Calibration of spaceborne EO sensors are methods that rely on sources of information primarily external to, and not controlled by, the EO sensor.**
- **Primary divisions include:**
  - Methods that make direct measurements of the calibration target, including both manual and automated methodologies
    - Examples include traditional direct surface reflectance/temperature measurements, and automated methods such as RadCalNet
  - Methods that depend primarily on the inherent stability of the target to detect changes in sensor calibration and also be extended to absolute calibration
    - Often referred to as Pseudo Invariant Calibration Sites (PICS)
  - This talk focuses on Earth-based methods; Lunar methods are a separate session
- **Emphasis is on uncertainties inherent in the process, fundamental limitations, and thoughts on future improvements**

Vicarious Calibration—Status & Future

Traditional Desert Sites

Jeff Czapla-Myers

University of Arizona

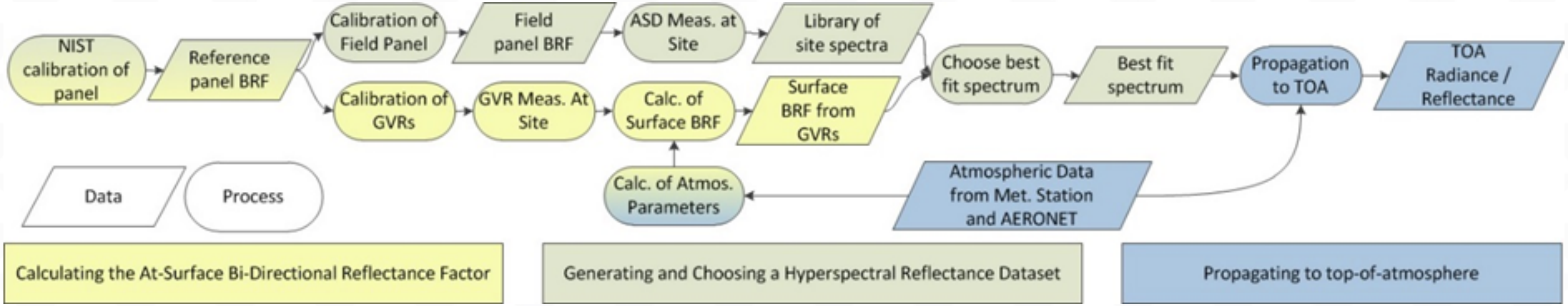
Uncertainty Statement for RadCaTS

Tracy Scanlon[1], Jeffrey Czapla-Myers[2], Andrew C. Banks[1], Nikolaus Anderson[2], Claire Greenwell[1], Emma Woolliams[1] and Kurt Thome[3]

1. NPL
2. University of Arizona
3. NASA GSFC

RadCalNet Working Group Meeting
ESA ESTEC, Noordwijk, Netherlands
26 Mar 2018

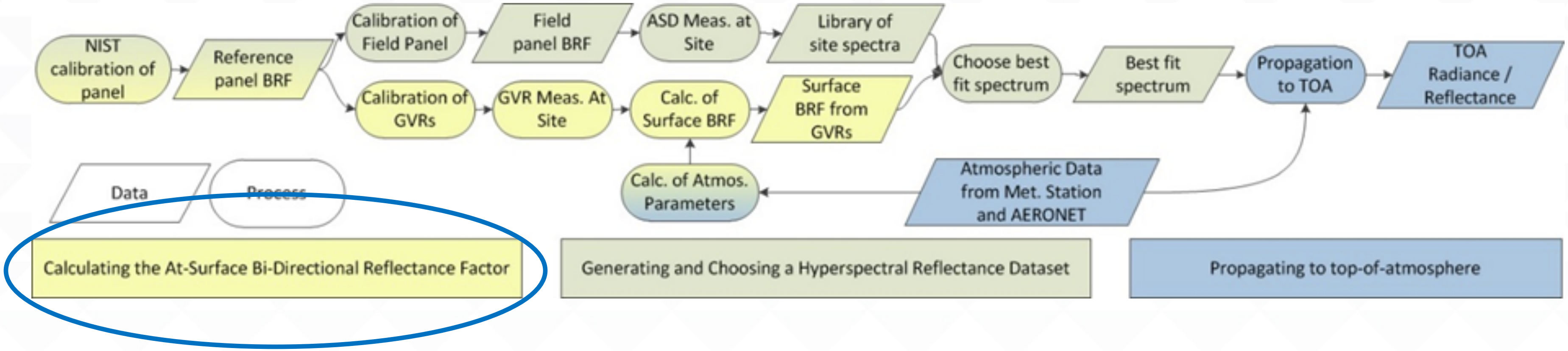
Traceability Chain for RadCaTS



$$u_2^c = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x} \right)^2 u^2 (x_i) + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u (x_i x_j)$$

- **Three stages for uncertainty analysis**
  - **A. BOA reflectance**
  - **B. Hyperspectral reference data set determination**
  - **C. Propagation to TOA reflectance**

Traceability Chain for RadCaTS



A. Surface BRF

1. **Calibration of ground-viewing radiometers (GVRs)**
   - **Radiometric calibration (UA lab measurements)**
2. **GVR output voltage**
   - **SNR (UA lab measurements)**
   - **Temperature effects (UA lab measurements)**
   - **Permanent degradation (monitor with CaTSSITTR)**
   - **Temporary degradation (dirt on glass)**
   - **Stray light (UA lab measurements)**
3. **Eo**
   - **Thuillier (literature)**
4. **Earth-sun distance**
   - **Negligible**
5. **Atmospheric parameters (transmittance and diffuse irradiance) determined using MODTRAN**
   - **Monte Carlo analysis (NPL supercomputer)**
6. **Solar zenith angle**
   - **Literature**
7. **Spatial representation**
   - **Spatial uniformity (Set to 2% at this point. Represents ‘good’ day)**

This portion of the talk will focus on the surface measurement…

Uncertainties for GVR Measurements at RVUS

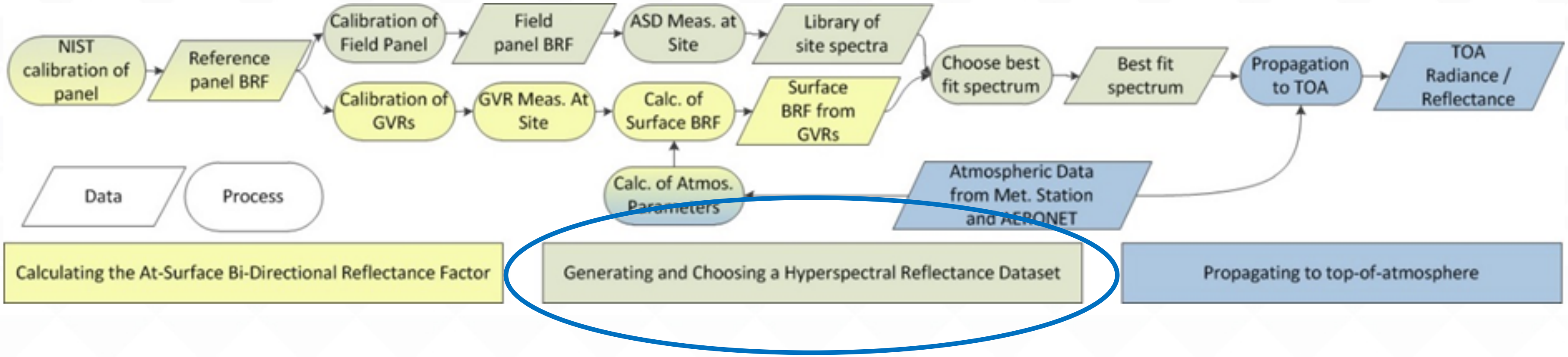
Channel Wavelength (nm)	C1 400	C2 450	C3 500	C4 550	C5 650	C6 850	C7 1000	C8 1550
Laboratory Calibration	2%	2%	2%	2%	2%	2%	2%	2%
Noise in field	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Stray light	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Instrument degradation	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Combined uncertainty	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%

Uncertainties for BRF Calculation

$$\rho_i = \frac{\pi C_{\mathrm{GVR},i} V_{\mathrm{GVR,fld},i}}{E_{\mathrm{sun},i} + E_{\mathrm{sky},i}}$$

Channel Wavelength (nm)	C1 400	C2 450	C3 500	C4 550	C5 650	C6 850	C7 1000	C8 1550
Radiance in field	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%	2.1%
MODTRAN uncertainty	2%	2%	2%	2%	2%	2%	2%	2%
Solar irradiance uncertainty	1.7%	1.5%	1.4%	1.3%	0.9%	1.1%	1%	1%
MODTRAN input uncertainty effect	1%	1%	1%	1%	1%	1%	1%	1%
Combined uncertainty associated with BOA reflectance	3.5%	3.4%	3.4%	3.3%	3.2%	3.3%	3.2%	3.2%

Traceability Chain for RadCaTS



Added Uncertainty with Hyperspectral Selection

Channel Wavelength (nm)	C1 400	C2 450	C3 500	C4 550	C5 650	C6 850	C7 1000	C8 1550
Combined uncertainty associated with BOA reflectance from GVR	3.5%	3.4%	3.4%	3.3%	3.2%	3.3%	3.2%	3.2%
Uncertainty associated with picking the spectrum	4.0%	3.1%	2.6%	2.2%	2.0%	1.8%	1.8%	1.7%
Combined uncertainty associated with BOA RadCalNet product	5.3%	4.6%	4.3%	4.0%	3.8%	3.8%	3.7%	3.6%

Areas for Improvement

- Using a solar irradiance model with smaller uncertainty (we need it to determine surface BRF)
- Better spatial sampling (linear motion of radiometer heads ($), or more radiometers ($$$))
- Improvements in diffuse sky irradiance modelling for wavelengths < 500 nm (e.g. blue region)

Vicarious Calibration—Status & Future

Vegetative Sites

Cibele Pinto, Larry Leigh

South Dakota State University

USGS

eccoe EROS CalVal Center of Excellence

Vicarious Calibration SDSU Vegetative Site

South Dakota State University (SDSU)
Image Processing Laboratory (IPLAB)

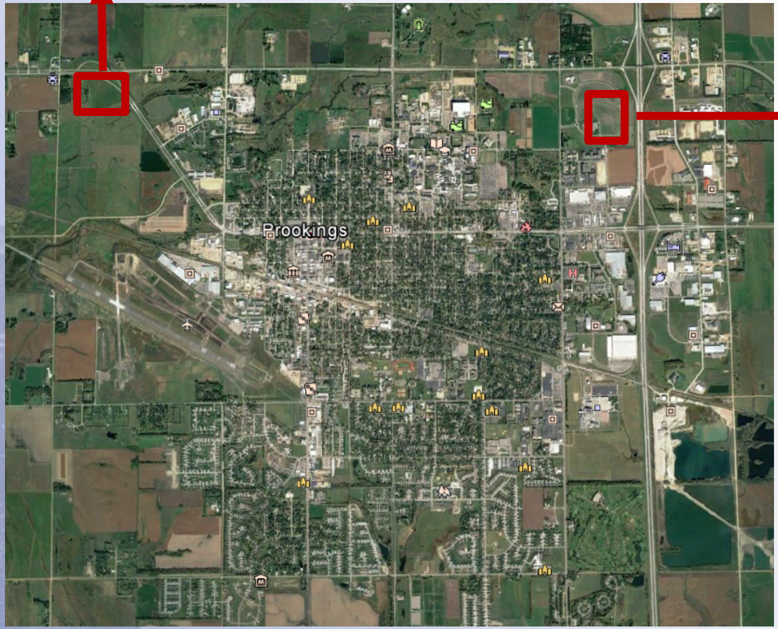
Cibele Teixeira Pinto, Ph.D.
Imaging Engineer - Research Associate
Cibele.TeixeiraPinto@sdstate.edu

South Dakota State University
Image Processing Lab

SDSU Vicarious Calibration Sites

SDSU Vegetative Site

North Airport Site (SDSU is the owner)

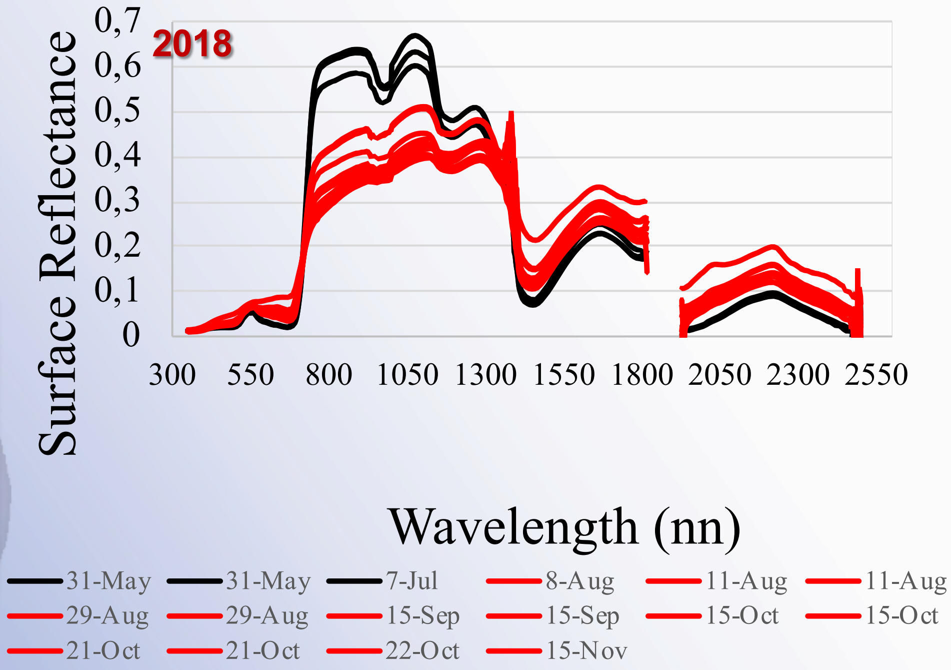


Research Park Site
(our backup)
(SDSU is the owner)

Cibele Teixeira Pinto, Ph.D.
South Dakota State University

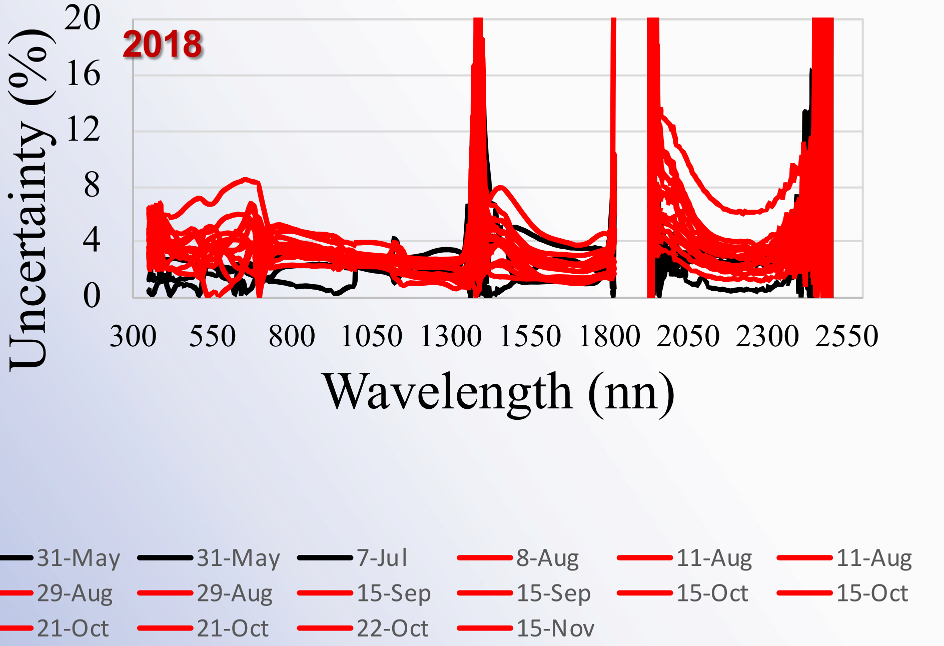
SDSU Vicarious Calibration Sites

Surface Reflectance Vegetative SDSU Sites



SDSU Vicarious Calibration Sites

Surface Reflectance Vegetative SDSU Sites



North Airport Site Uniformity ~ better that 4%

Cibele Teixeira Pinto, Ph.D.
South Dakota State University

Uncertainty

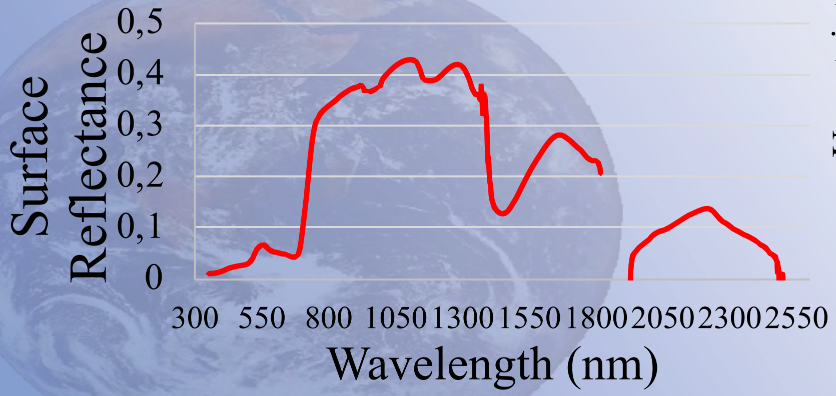
MODTRAN

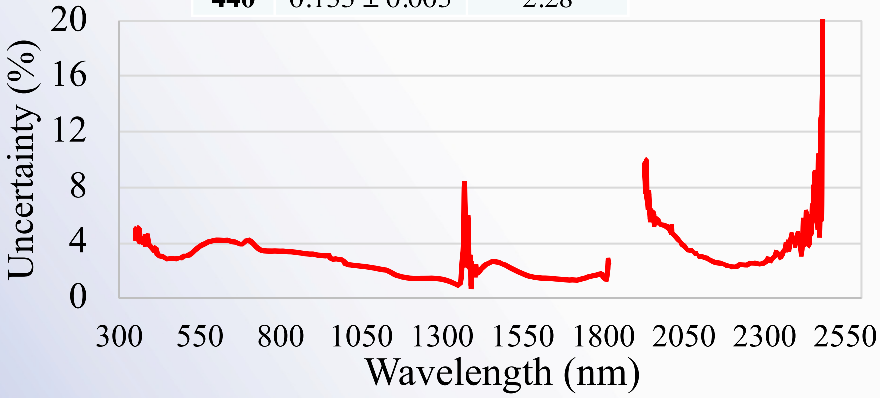
W (g/cm²)	σrelative (%)
0.429 ± 0.020	4.62

Inputs to MODTRAN:
- ✓ Ground Reflectance
- ✓ Column Water Vapor
- ✓ VIS (Visibility)
- ✓ AOD (Aerosol Optical Depth)
- ✓ O3 (Ozone)

VIS (km)
31.3 ± 0.8

Band nm	τAerosol	σRelative(%)
8/19/2014		
1020	0.0789 ± 0.0023	2.87
870	0.074 ± 0.004	4.82
670	0.099 ± 0.003	3.23
440	0.133 ± 0.003	2.28

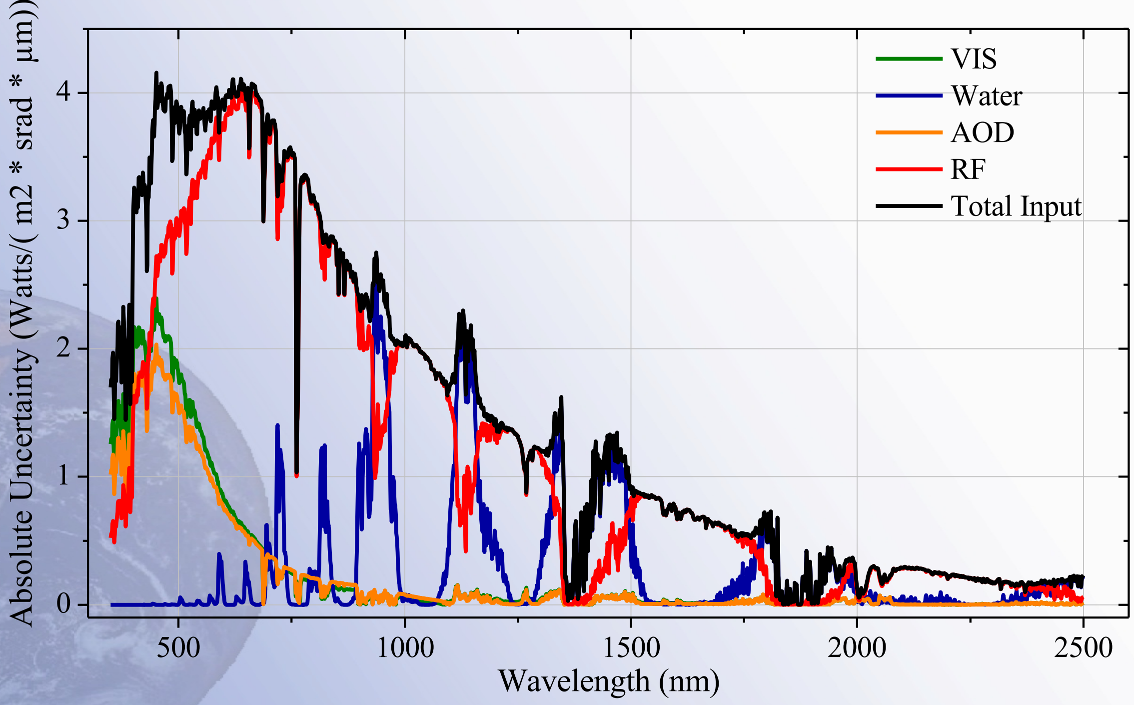




Uncertainty

Reflectance Factor (RF) → Ground Reflectance

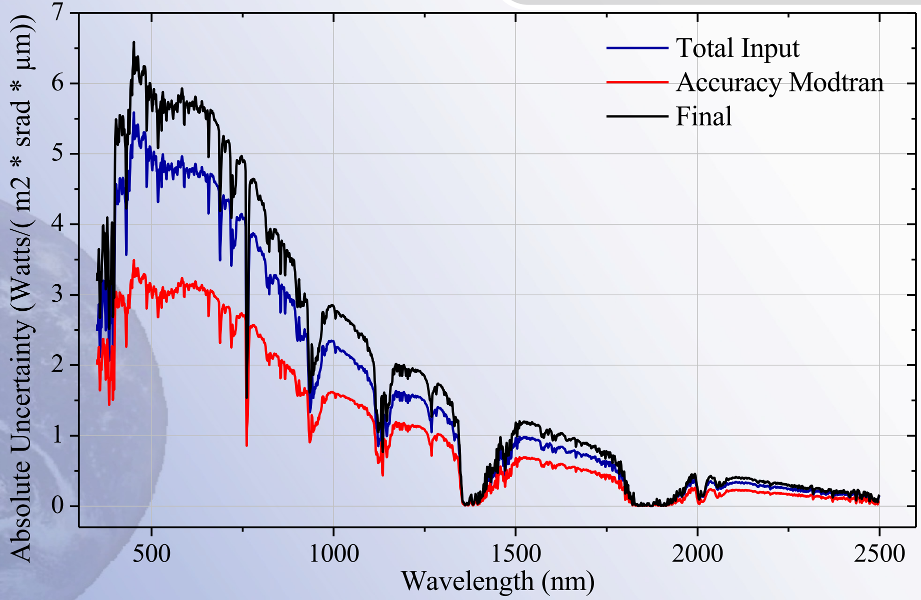
MODTRAN



Uncertainty

$$\sigma_{Final} = \sqrt{(\sigma_{Total\_Input})^2 + (\sigma_{Accuracy\_Modtran})^2}$$

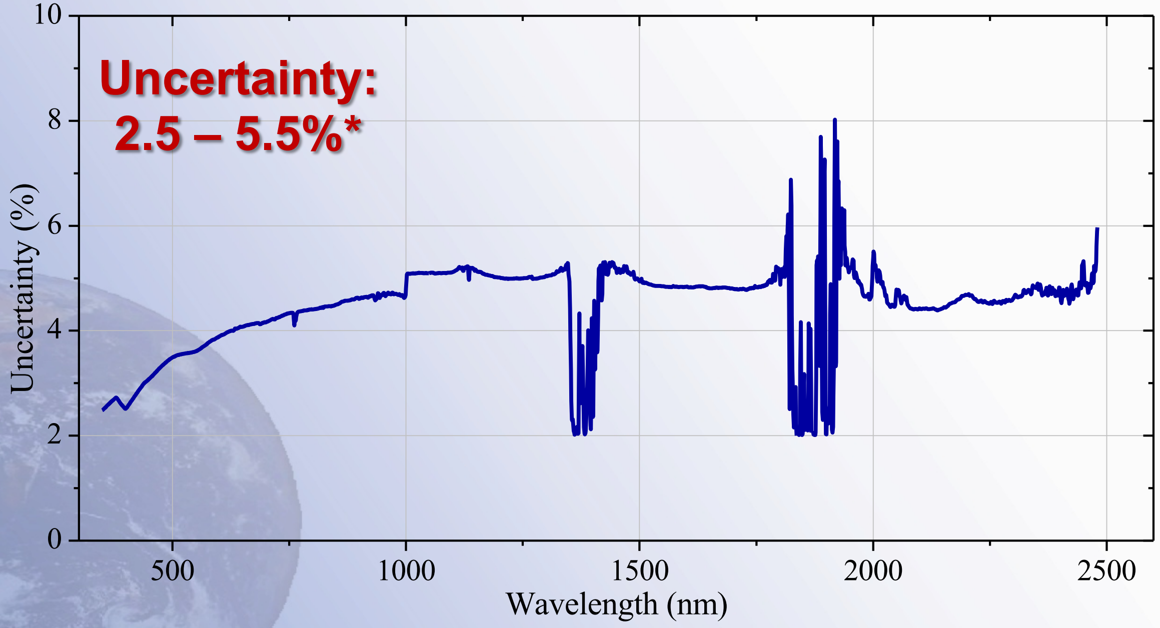
- ✓ Accuracy of MODTRAN → ± 3% (BERK et al.,1998)
- ✓ Impacts of the Input Uncertainties
- ✓ Final Uncertainty



Cibele Teixeira Pinto, Ph.D.
South Dakota State University

Uncertainty

Final Uncertainty



*Except: Water absorption (around 1.4 mm and 1.9 mm) & Very noisy >2.4 mm

Uncertainty

Reflectance-based approach sources of uncertainty

Source of uncertainty	*Source*	*TOA spectral radiance*
Ground reflectance measurement	—	2.1%
Reference panel calibration (BRF)	1.8%	—
Site measurement errors	1.0%	—
Optical depth measurements	—	$<0.1\%$
Extinction optical depth	0.5%	—
Absorption computations	—	—
Ozone Monitoring Instrument (OMI)	3.0%	—
Column water vapor	5.0%	—
Choice of aerosol complex index	100%	0.5%
Choice of aerosol size distribution	—	0.3%
Ångström's exponent	0.3%	—
Non-Lambertian surface	10%	—
Others	—	—
Nonpolarization vs. polarization	—	0.1%
Inherent accuracy of MODTRAN 5	—	2.0%
Uncertainty in SZA	—	0.2%
Total Uncertainty RSS	—	**3.0%**

***3% → Optimal day!**

(i) cloudless day;
(ii) stable atmosphere;
(iii) uniform site.

Source: D. Helder; D. Schott; J., Stone; T.; Pinto, C. T. (2018). Vicarious Calibration and Validation. In S. Liang (Ed.), Comprehensive Remote Sensing, vol. 1, pp. 475–518. Oxford: Elsevier. ISBN: 9780128032206. Chapter Title: Vicarious calibration and validation.

Opportunities for Improvement

- Improved surface reflectance measurement
- Improved atmospheric model
- Improved aerosol measurement
- Reasonable goal: 3% every day!

Vicarious Calibration—Status & Future

Pseudo Invariant Calibration Sites (PICS)

Morakot Kaewmanee

South Dakota State University

SDSU Absolute Calibration Model- State of the Art

Traditional PICS, Extended PICS (Cluster13)

By

Morakot Kaewmanee

Bipin Raut

Image Processing Lab,

South Dakota State University

SDSU PICS Absolute Calibration : State of the art

- **Absolute Calibration model with traditional PICS**
  - Libya4, Libya1, Niger1, Niger2, Sudan1, Egypt1
  - MODIS as the reference radiometer, Hyperion as the spectral profile, and BRDF model for SZA and VZA (spherical angles).
  - Accuracy of Model vs Measure is ~3% for all sites except Niger1 and Niger2 (~2-8%)
  - Total Uncertainty Analysis : 5-9%.

Publications:

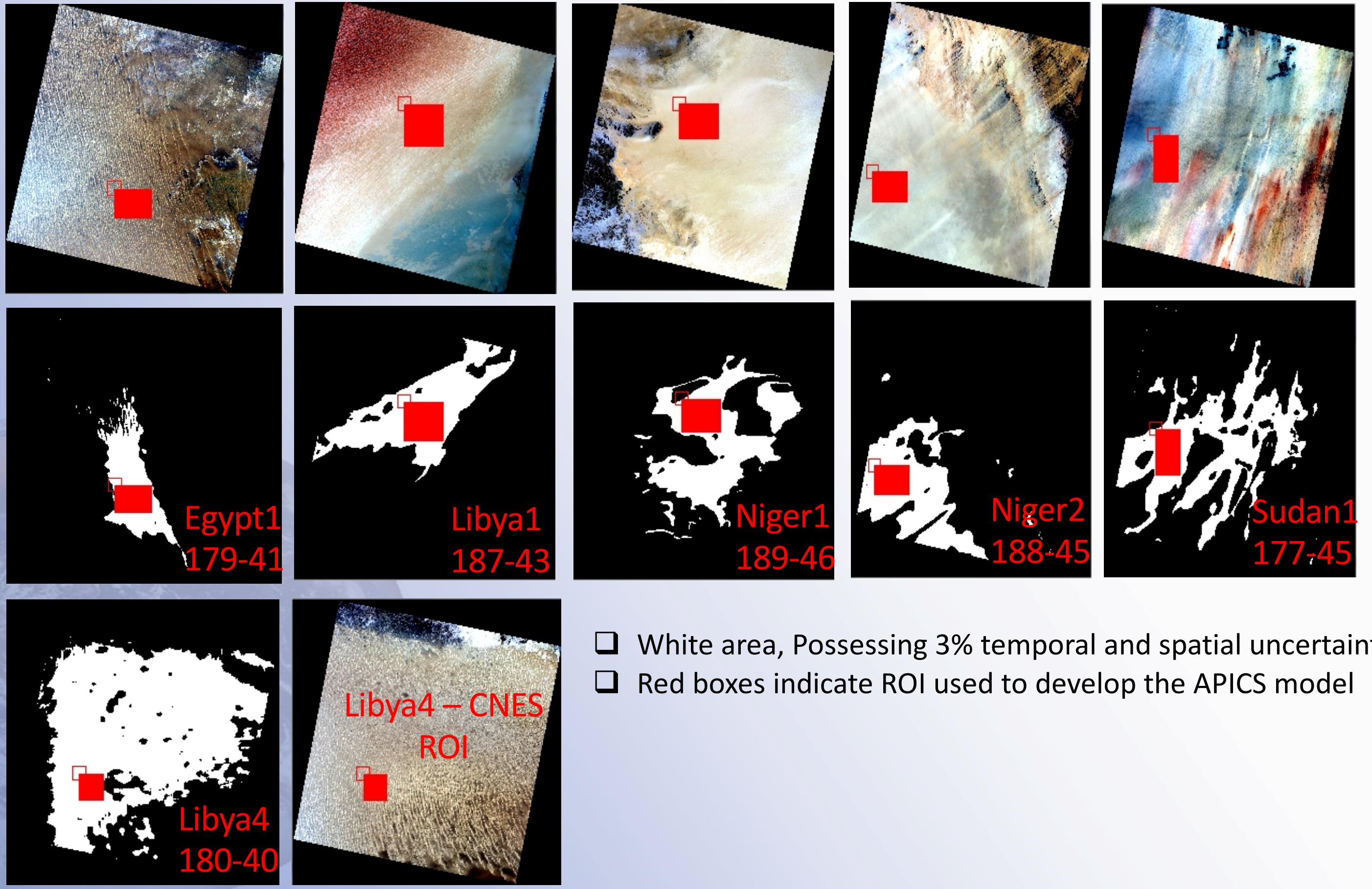
2014, Nischal Mishra, Dennis Helder, Amit Angal, Jason Choi, Xiaoxiong Xiong, **Absolute Calibration of Optical Satellite Sensors Using Libya 4 Pseudo Invariant Calibration Site** , Remote Sensing, ISSN 2072-4292,2014)

2017, Kaewmanee,M., Helder, D, **Refined Absolute PICS Calibration Model over Libya-4 using Sentinel 2A, 2B and Landsat 7,8 Collection-1 data for Validation**, PECORA 20, Sioux Falls, November 2017.

2018, Barsi, J.A.; Alhammoud, B.; Czapla-Myers, J.; Gascon, F.; Haque, M.O.; Kaewmanee, M.; Leigh, L.; Markham, B.L. **Sentinel-2A MSI and Landsat-8 OLI radiometric cross comparison over desert sites**. *European Journal of Remote Sensing* **2018**, *51*, 822-837

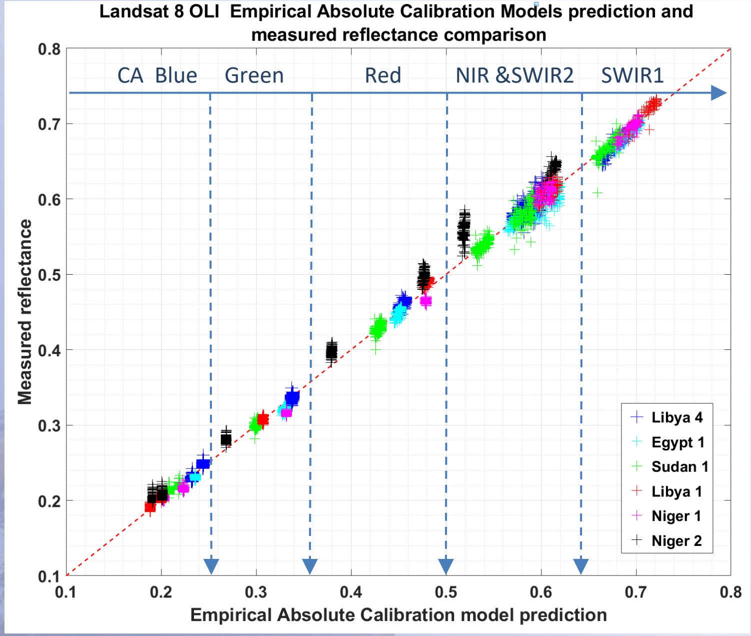
2019, Raut, B.; Kaewmanee, M.; Angal, A.; Xiong, X.; Helder, D. **Empirical Absolute Calibration Model for Multiple Pseudo-Invariant Calibration Sites**. *Remote Sens.* **2019**, *11*, 1105.)

Location of ROIs for the development of APICS Model: Traditional PICS



- White area, Possessing 3% temporal and spatial uncertainty
- Red boxes indicate ROI used to develop the APICS model

One-to-one plot of predicted and Measured TOA Reflectance APICS: Landsat 8 for all 6 Sites

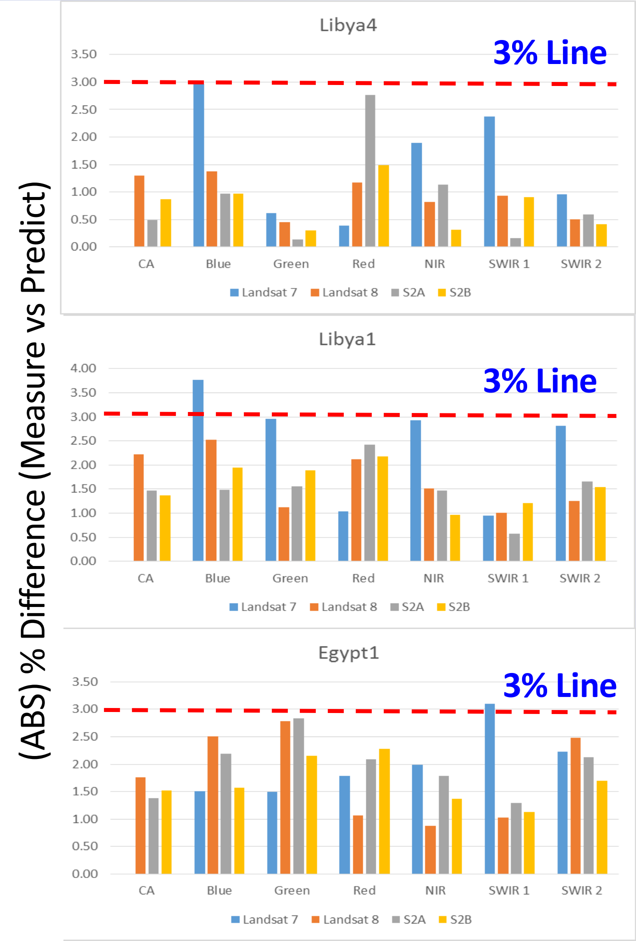


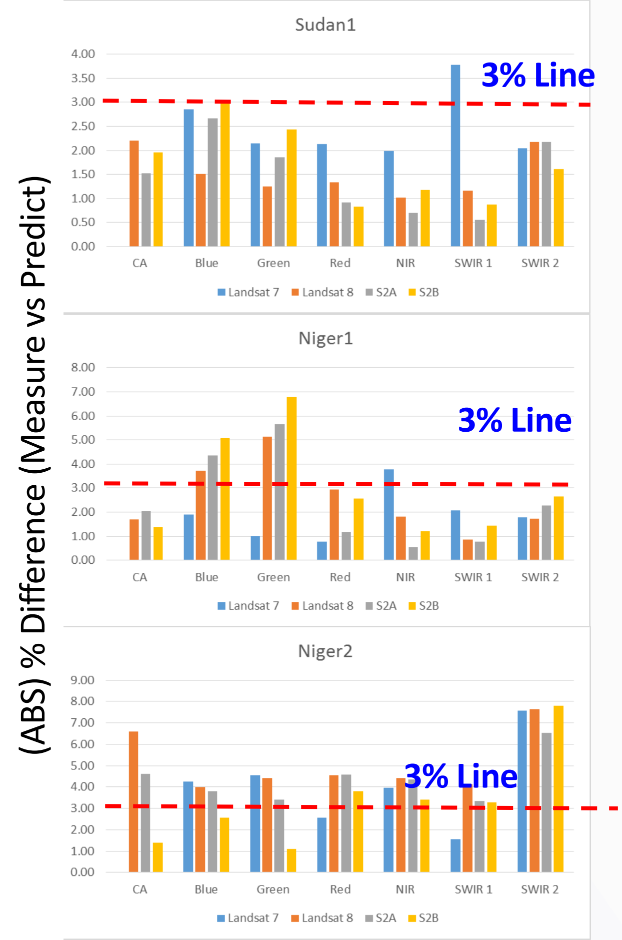
APICS Uncertainty Analysis

Uncertainty Sources	% Uncertainty	Remarks
K-scale Factor	0.1-8.7%	For all Bands & all Sites
Hyperion Spectra	1.3-4.8%	
SZA	0.1%	
VZA	0.5%	
Sites Variation	1-3%	
Satellite Calibration	3-5%	S2A, S2B, L7 = 5% L8 = 3%
Total Uncertainty	**1-9%**	For all Bands & all Sites

- Libya4, Libya1, Sudan1 and Egypt1 shows the APICS Model total uncertainty within 5-6% for all bands
- Niger 1 and Niger 2 have large uncertainty due to K-scale factor and Hyperion spectra (not many data are used in the model)
- 6 PICS provides an opportunity to have an absolute calibration every 4-5 days for Landsat style sensors

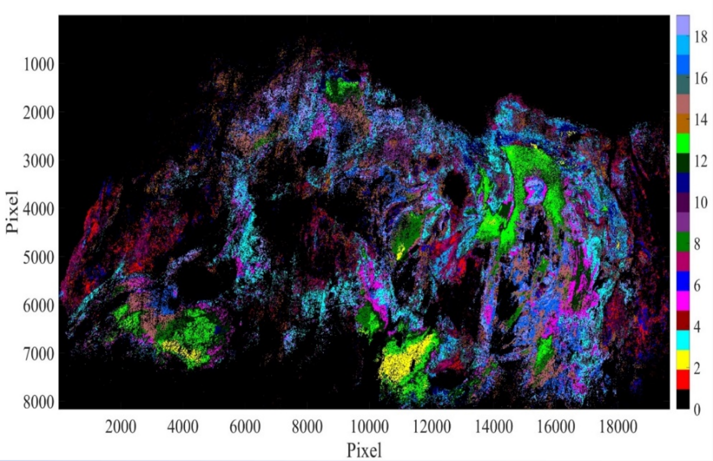
Summary of Traditional APICS Performance : Landsat 7,8 and Sentinel 2A, 2B





PICS Absolute Calibration : State of the art

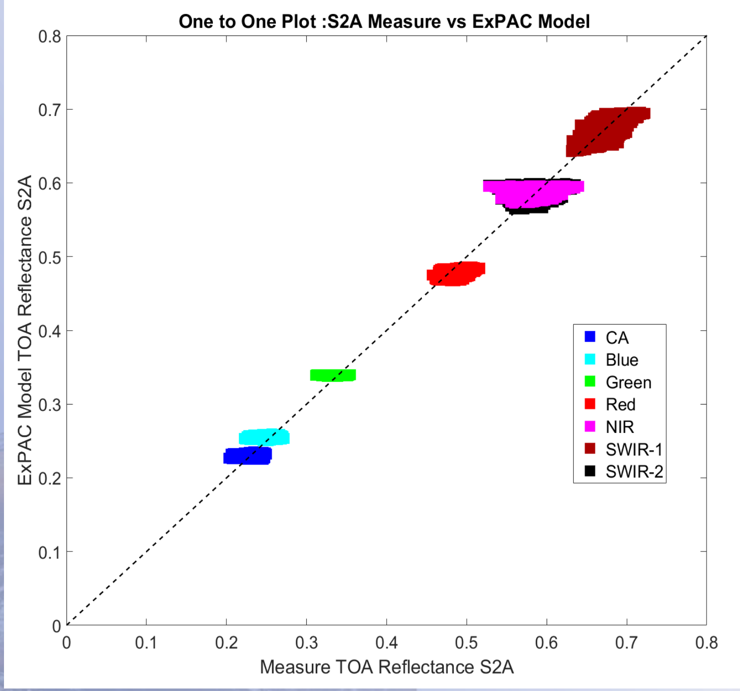
- **Absolute Calibration with Extended PICS (Cluster13)**
  - Based on the study Classification of North Africa for Use as an Extended Pseudo Invariant Calibration Sites (EPICS) for Radiometric Calibration and Stability Monitoring of Optical Satellite Sensors, M Shrestha, L Leigh, D Helder - Remote Sensing, 2019.
  - Identified areas possessing similar spectral profile as Libya4, across Northern African deserts. Largest area was classified as Cluster 13.
  - Initial study to develop absolute calibration model for Cluster 13 'Extended PICS Absolute Calibration Model' or ExPAC Model shows that the accuracy of prediction vs measure is within 3% for all bands, validated with Landsat 7, 8 and Sentinel 2A, 2B.
  - Landsat 8 OLI as reference radiometer.
  - EO-1 Hyperion as spectral profile.
  - BRDF model for SZA and SAA converted to Cartesian coordinates.

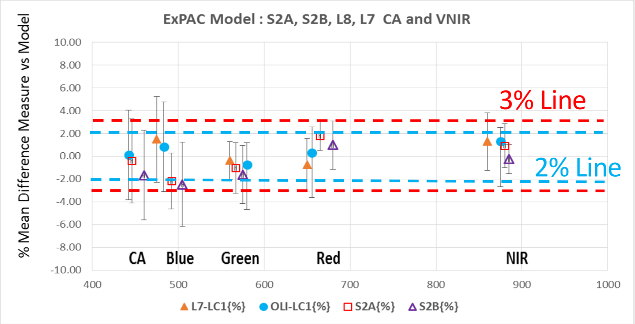


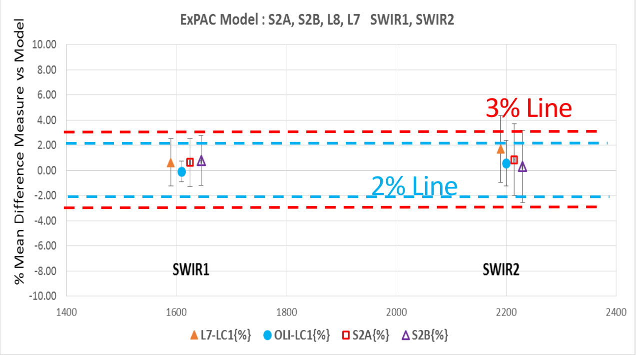
Green pixels = Cluster 13

Measure vs ExPAC Model –S2A

Summary of ExPAC vs S2A, 2B, L7, L8







- ExPAC Model can predict satellite measurement within 3% or better for all 4 satellites and all bands.
- Ability to have a daily calibration point using Cluster 13 as a target.
- Especially useful for short-lived satellites—can perform/assess the sensor’s calibration more frequent *(a daily basis).*

Limitations we are facing and way forward

- No current hyperspectral data over Northern African deserts.
- Need better resolution of hyperspectral data, 1nm resolution.
- Develop ExPAC model using dark target.
- Develop ExPAC model on API platform for broader usage.
- Uncertainty Analysis for ExPAC Model and Publication.

Reference radiometer is the fundamental limitation with this approach!

Vicarious Calibration—Status & Future

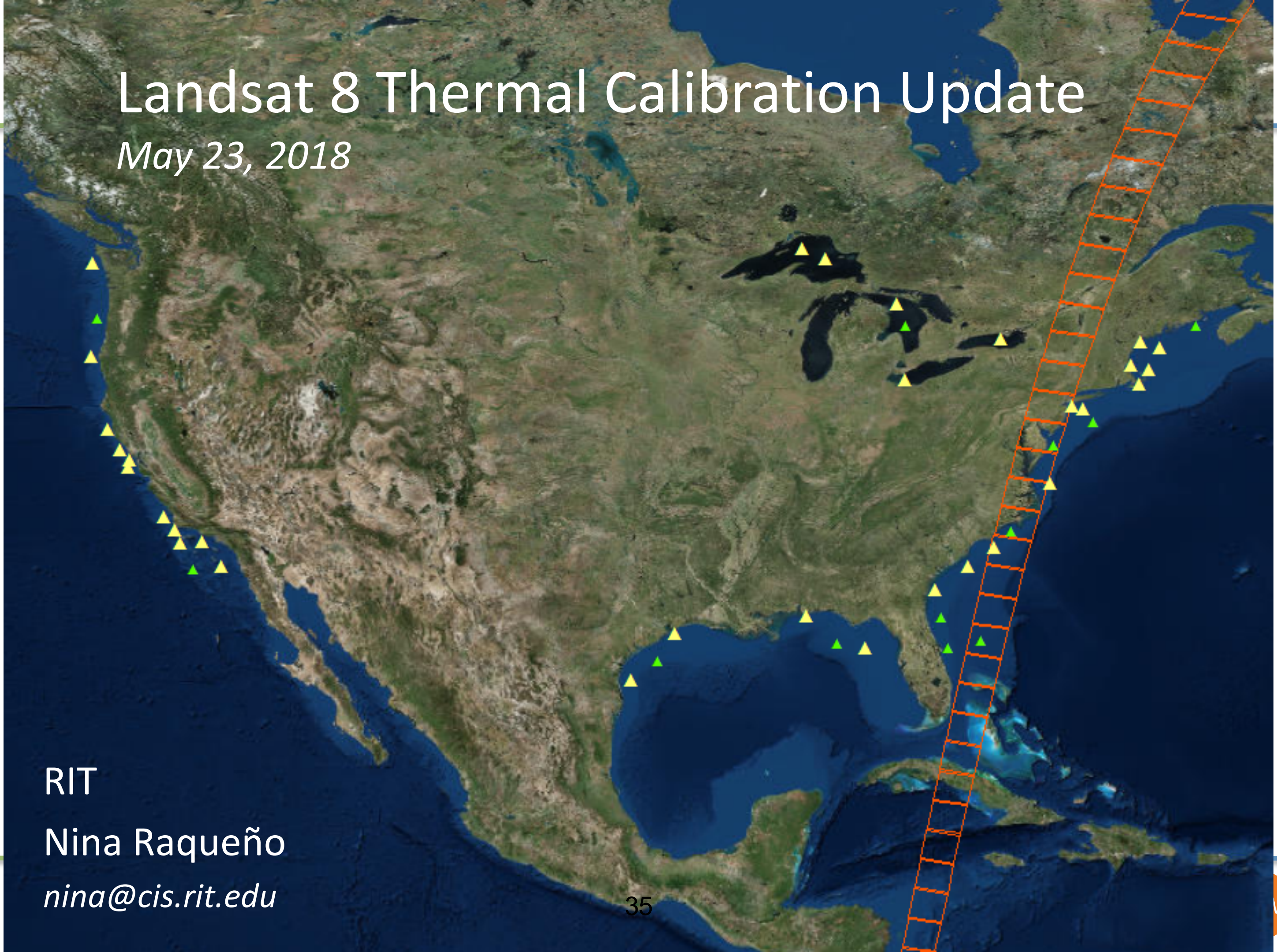
Thermal Vicarious Calibration

Nina Raqueno, Aaron Gerace

Rochester Institute of Technology

Landsat 8 Thermal Calibration Update

May 23, 2018



RIT

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DIRS Digital Imaging and Remote Sensing Lab

R·I·T

Chester F. Carlson CENTER for IMAGING SCIENCE

Approach

Site and Scene Selection

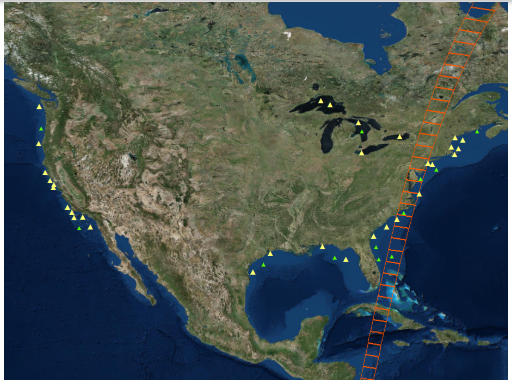
Computation of Bulk to Skin Temperature

Recreation of Atmospheric Column:
Surface Correction
Upper Air Interpolation and Processing

Obtaining Predicted At-Sensor Radiance

Compare to Image Derived Radiance

Landsat L8 Thermal Calibration



New Data:

Jan 2017 – Apr 2018

100s scenes processed

100+ results

cloud mask failures, marginal scenes

83 calibration points (28 different buoys)

Temp. Range 276-301 K (37-82 F)

Updated weather data access

Collection1

Updated Scene Download Tools

USGS/EROS Inventory Service JSON and Python

Filters

High RH at any altitude layer

BQA cloud mask

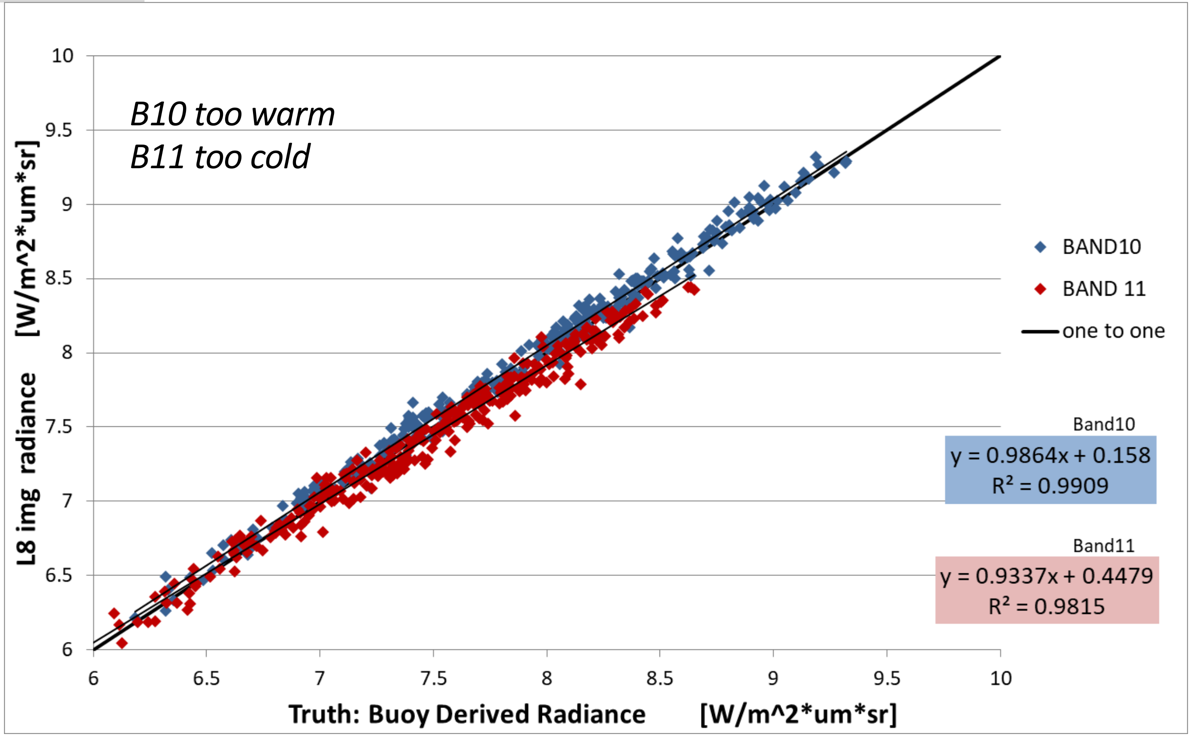
missing buoy, weather, or radiosonde

Additional visual cloud inspection

Live update to FTP site

L8 Thermal Vicarious Cal: RIT Buoys 2013-2017

Collection1



Summary

				JPL/RIT Combo		RIT A		RIT B	
	Archive	Archive	2016	V5	V5	Col1	Col1	Col1	Col1
RMSE	L4	L5	L7	L8 B10	L8 B11	L8 B10	L8 B11	L8 B10	L8 B11
Temp [K]	0.55	0.7	0.5	0.63	1.53	0.68	1.67	0.69	1.15

Treat Side A and Side B separately.
Apply correction based on combined JPL/RIT 100s of cal. points.

	Buoy - L8 Temperature [K]		
Side A		Band10	Band11
	Min	-2.05	-0.92
	Max	1.47	2.54
	Ave	-0.15	0.89
	StDev	0.54	0.62
	RMSE	0.68	1.67

	Buoy - L8 Temperature [K]		
Side B		Band10	Band11
	Min	-1.53	-1.65
	Max	1.19	3.14
	Ave	-0.51	0.20
	StDev	0.46	0.71
	RMSE	0.69	1.15

R·I·T

Total Process Error

Atm.	T	ϵ	τ	S_τ	L_u	S_{L_u}	L_d	S_{L_d}	$S_{L_{11}}$ [K]	$S_{Tat-sensor}$ [K]
26Jan02 (dry)	274	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	285								0.439	[illegible]
	300								0.494	0.533
28Apr03	274	0.986	0.9406	0.0006	0.4266	0.0040	0.7566	0.0094	0.405	0.436
	[illegible]								0.437	0.471
	[illegible]								0.492	0.530
27May90	274	0.986	0.8617	0.0009	0.9608	0.0068	1.6523	0.011	0.352	0.414
	[illegible]								[illegible]	0.445
	300								[illegible]	0.501
24Jun90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.426
	[illegible]								[illegible]	0.459
	[illegible]								[illegible]	0.517
24Oct98	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.427
	[illegible]								[illegible]	0.459
	[illegible]								0.464	0.519
16Aug85	274	0.986	0.7946	0.0029	2.056	0.0243	1.6611	0.045	0.313	0.400
	285								0.330	0.421
	300								0.368	[illegible]
06Jul99 (moist)	274	0.986	0.3846	0.0027	5.3754	0.0240	7.0086	0.028	0.149	0.391
	285								0.140	0.370
	300								0.142	0.374

- ✓ Due to the (negative signed) correlation term $\rho_{\tau,Lu}$
- ✓ Expected error of ±0.454 K
- ✓ Most dominant: target temperature term (LBB), where the emissivity term was found to most dominant at high target temperatures (i.e. 300 K) except for warm moist atmospheres
- ✓ Most sensitive: the emissivity term which was eventually overtaken by the transmission term τ in the presence of warm and highly moisture rich atmospheric profiles

Future Improvements?

Where buoys fit in
and areas that could be expanded…

- Incorporate reanalysis data to densify atmospheric characterization
- Supplement Buoys with UAS thermal imagery
- Additional Global Buoys
  - Switch to reanalysis NARR/MERRA
  - Validate Specific Buoys
  - Mechanics auto access to buoys from varied sources

Summary/Conclusions

With regard to earth-viewing vicarious calibration methods:

- **Need for more accurate input data**
  - Surface reflectance measurements (2%)
  - Solar irradiance models (2%)
  - Water (buoy) temperatures
- **Need for more accurate atmospheric models**
  - Modtran used in these examples (2-3%)
- **Need for more accurate reference radiometers**
  - PICS uses MODIS for absolute calibration model (3%)
  - PICS trending inherently limited by desert surface/atmosphere (~1%)
- **Outlook: steady progress still possible.**
  - Goal of 3% consistent overall uncertainty for now(?)
  - Improvements beyond that will be quite difficult
  - *Substantial value exists in the independent measurements vicarious calibration provides*