MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

First In-flight Radiometric Calibration of the CBERS-4 MUX and WFI

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Joint Agency Commercial Imagery Evaluation (JACIE)
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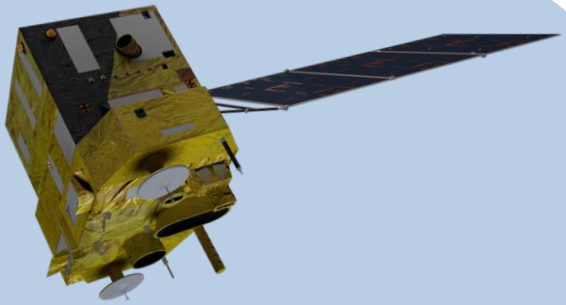
Fort Worth Convention Center
Fort Worth, Texas

South Dakota State University
Image Processing Lab

SDSU

Topics

- CBERS Program;
- Reflectance-based approach;
- Cross-calibration method (Landsat-8/OLI);
- Combination of techniques;
- Validation (Landsat-7/ETM+);
- Next Steps;



China Brazil Earth Resources Satellite - CBERS

- CBERS-1 → 1999-2003
- CBERS-2 → 2003-2009
- CBERS-2B → 2007-2010
- CBERS-3 → 2013 (failed launch)
- **CBERS-4 → On December 7 th, 2014**

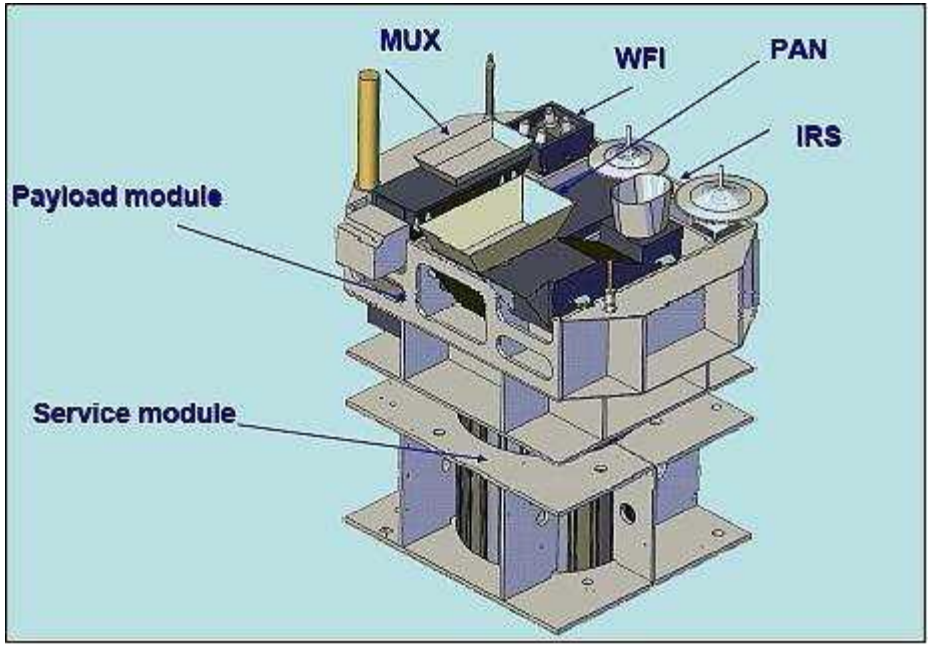
Brazil and China have a long-term remote sensing program called CBERS

China-Brazil Earth Resources Satellite
CBERS

China Brazil Earth Resources Satellite: CBERS-4

CBERS-4 carries four cameras:

- Panchromatic and Multispectral Camera (PAN);
- Multispectral Camera (MUX);
- Infrared System (IRS);
- Wide-Field Imager (WFI).

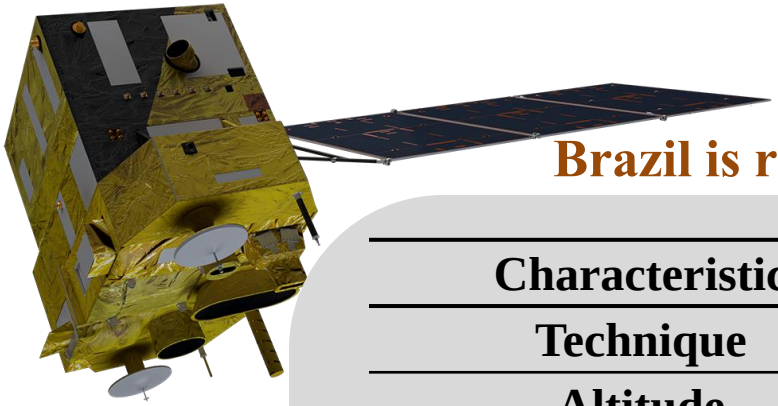


✓ Work Share: 50% China and 50% Brazil;

✓ The satellite CBERS-4 has a sun-synchronous orbit;

✓ The local solar time at the equator crossing is always 10:30a.m.

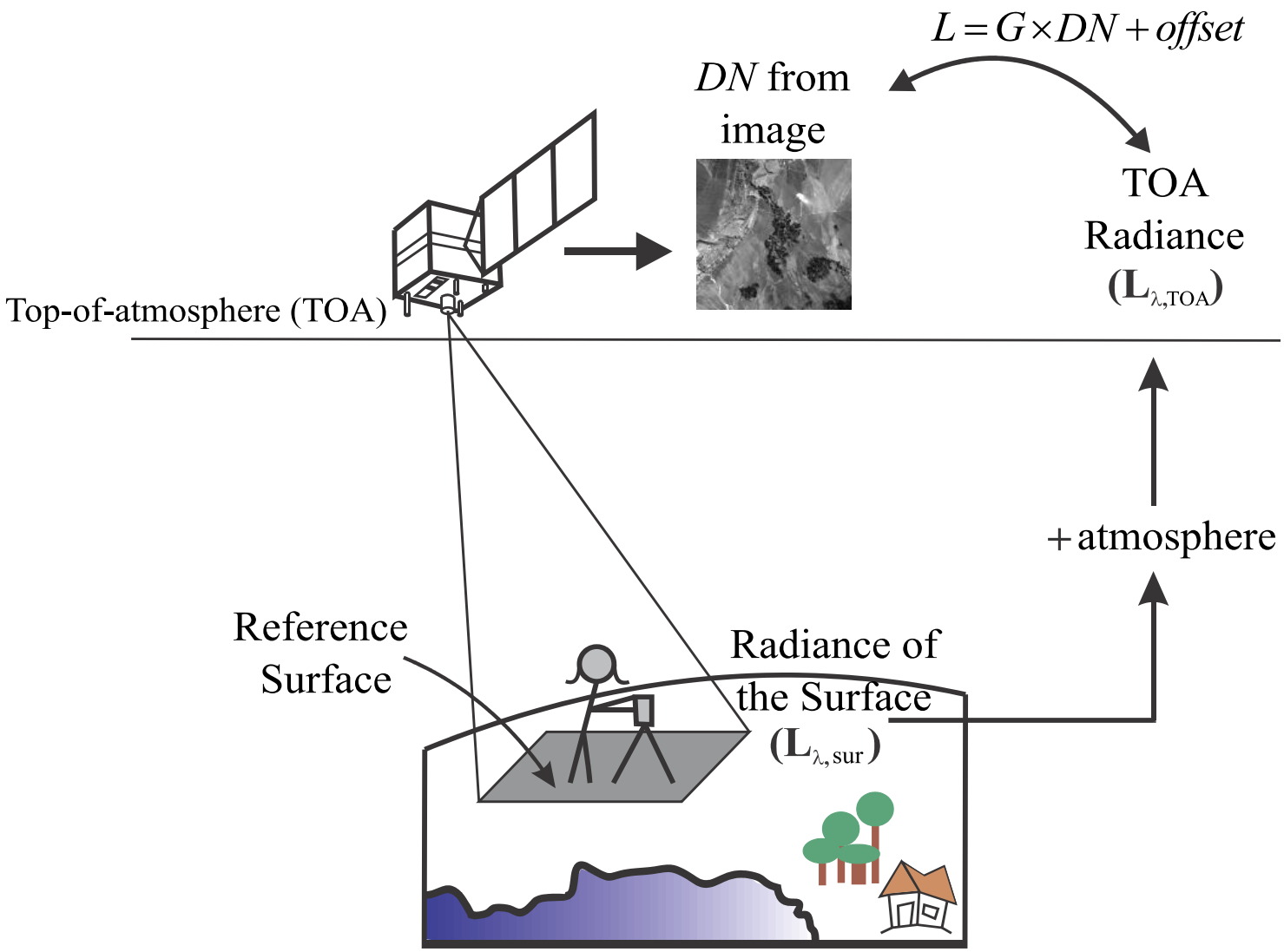
China Brazil Earth Resources Satellite: CBERS-4



Brazil is responsible for MUX and WFI:

Characteristic	MUX	WFI
Technique	Pushbroom	Pushbroom
Altitude	778 km	778 km
Swath Width	120 km	866 km
Field of View (FOV)	± 4º	± 28.63 º
Equator Crossing Time	10:30 am	10:30 am
Spectral Bands (nm)	Blue: 450 - 520 Green: 520 - 590 Red: 630 - 690 NIR: 770 - 890	Blue: 450 - 520 Green: 520 - 590 Red: 630 - 690 NIR: 770 - 890
Spatial Resolution	20 m	64 m (nadir)
Radiometric Resolution	8 bits	10 bits
Temporal Resolution	26 days	5 days

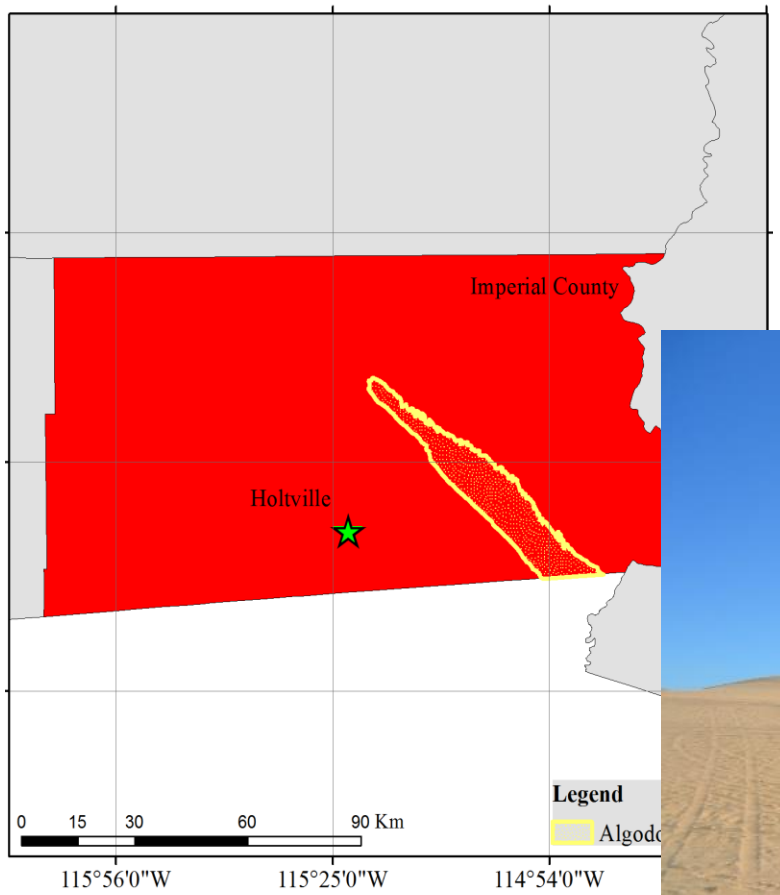
Radiometric Calibration: Reflectance-based approach

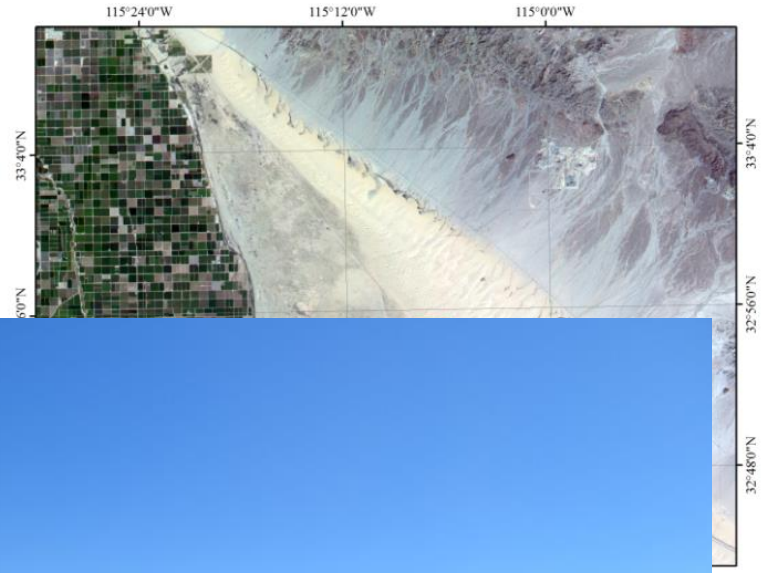


Reflectance-based approach: Algodones Dunes

Campaign: from 9th to 13rd March 2015

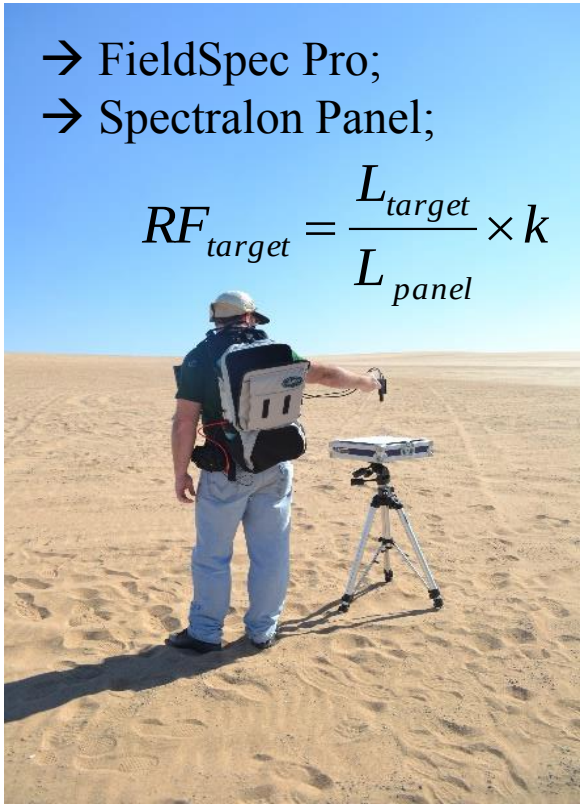
MUX/CBERS-4 image

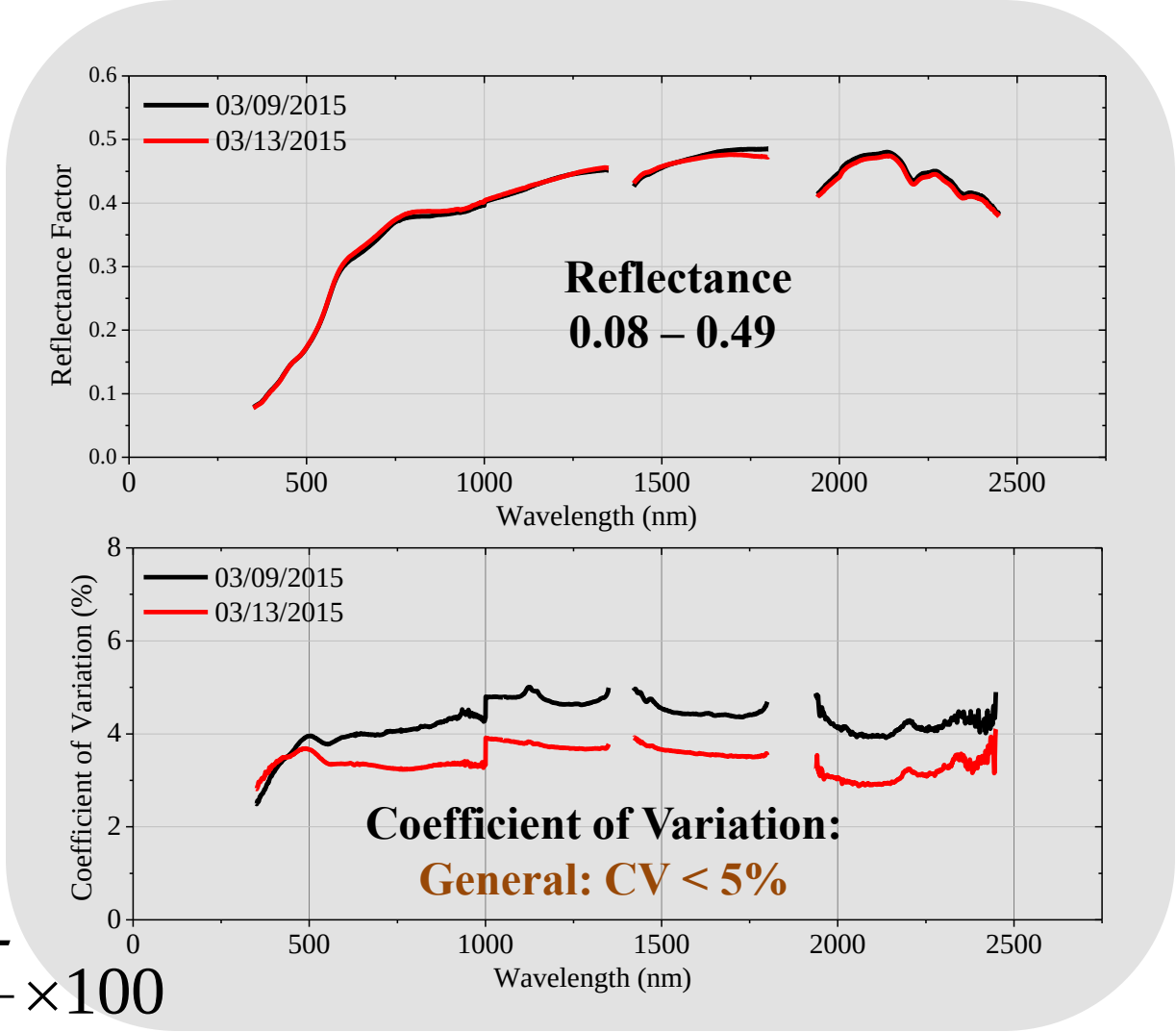




Reflectance-based approach:

Algodones Dunes → Reflectance



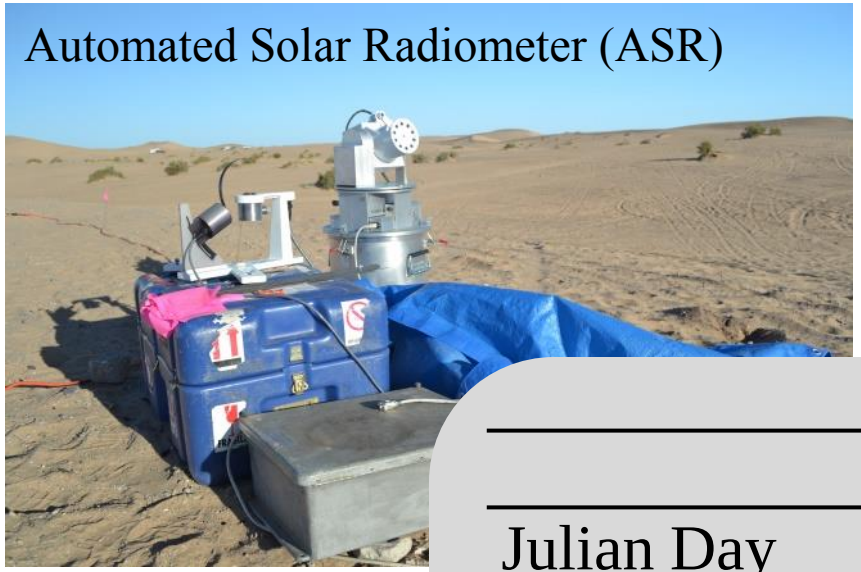


$$CV\% = \frac{\sigma}{\mu} \times 100$$

*Except:
→ Water absorption
→ Very noisy >2.4 μm

Reflectance-based approach:

Algodones Dunes → Atmosphere



03/09/2015	
Julian Day	68
Local Time	9h00 - 12h30
AOD at 550 nm [dimensionless]	0.066 ± 0.017
Water vapor [g/cm^2]	1.055 ± 0.014
VIS [km]	40.4 ± 2.3
Temperature [°C]	23 ± 4
Pressure [hPa]	999.64 ± 0.13

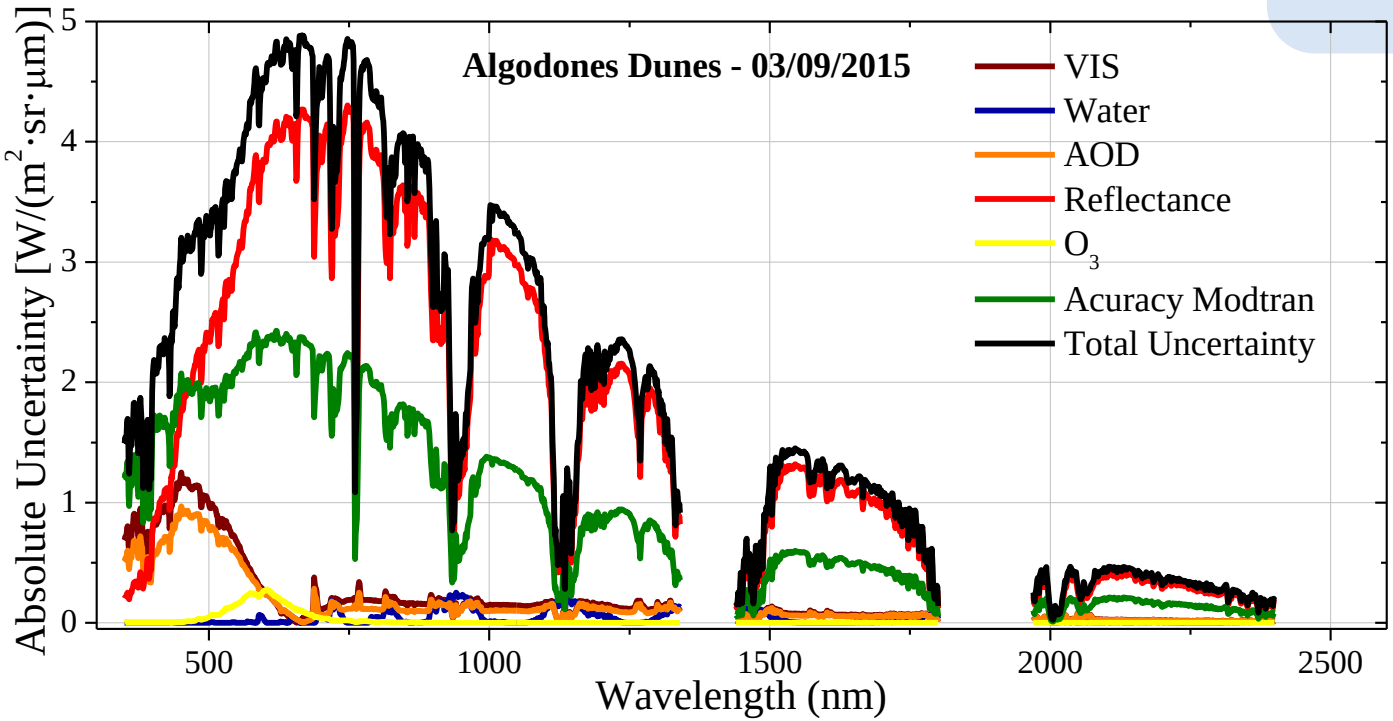
Reflectance-based approach:

Radiative Transfer Code

Impacts of the Input Uncertainties:

The data from the ground measurements (the atmospheric and surface reflectance data) are used as input to a radiative transfer code to predict the TOA radiance/reflectance.

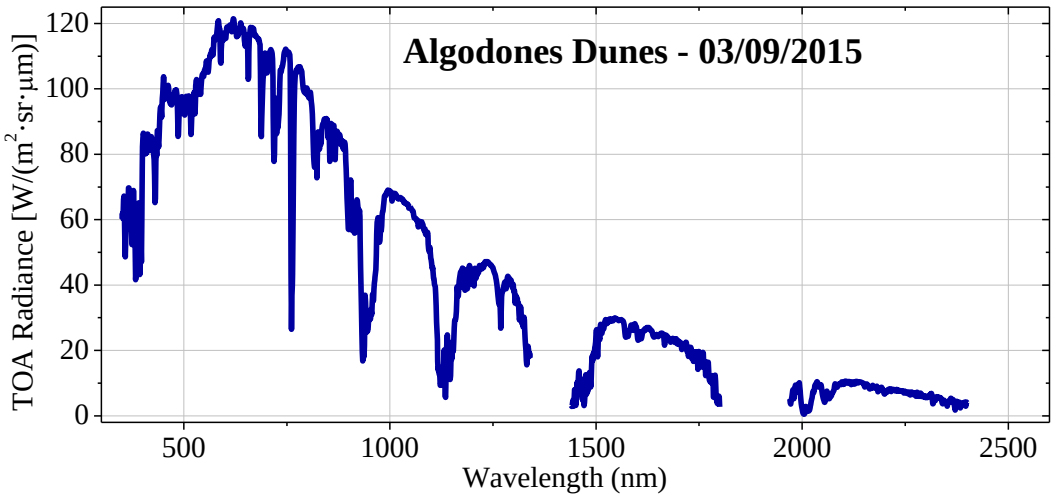
An estimate of the TOA radiance is incomplete unless accompanied with an uncertainty



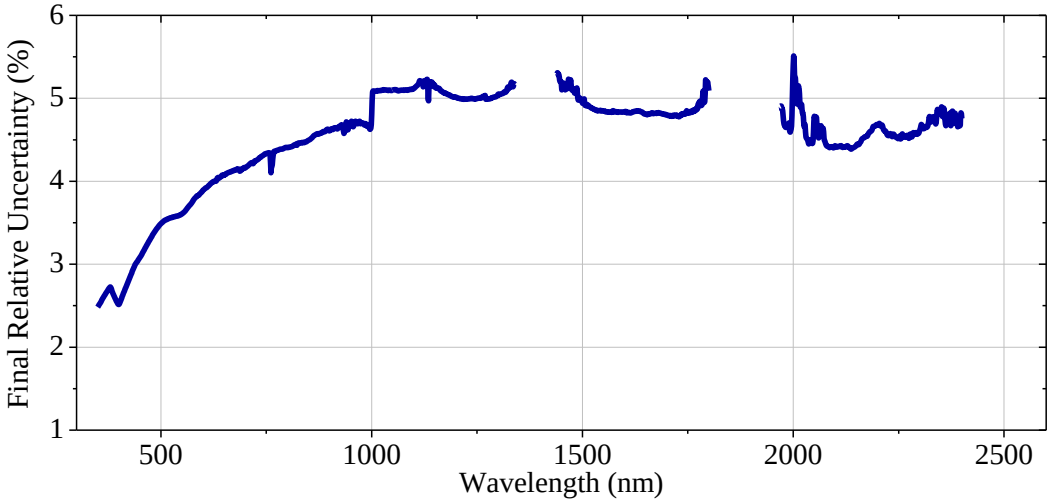
Reflectance-based approach:

Radiative Transfer Code

TOA Radiance predicted by MODTRAN:



2.5 – 5.5%



Reflectance-based approach:

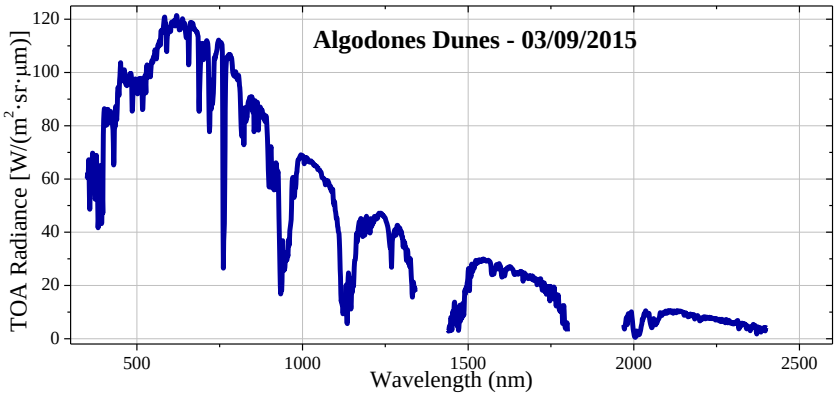
Band averaged at-sensor radiance

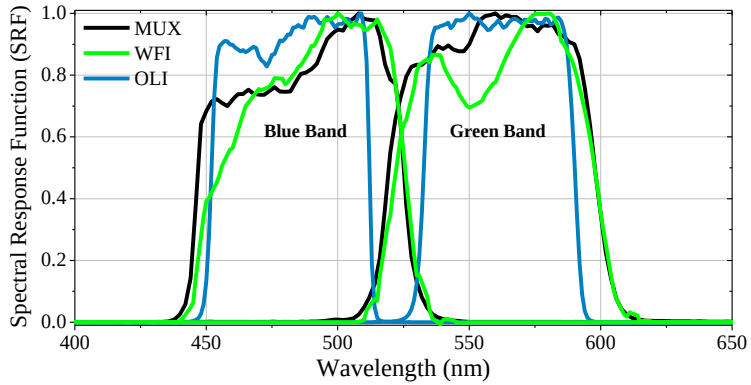
The output from MODTRAN (hyperspectral TOA radiance) are averaged with the Spectral Response Function (SRF) of the sensor of interest to find the band averaged at-sensor radiance values at each spectral band.

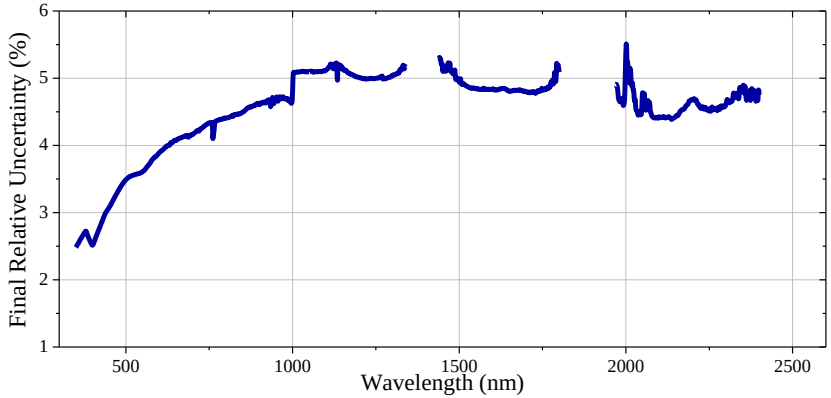
Mathematical Model:

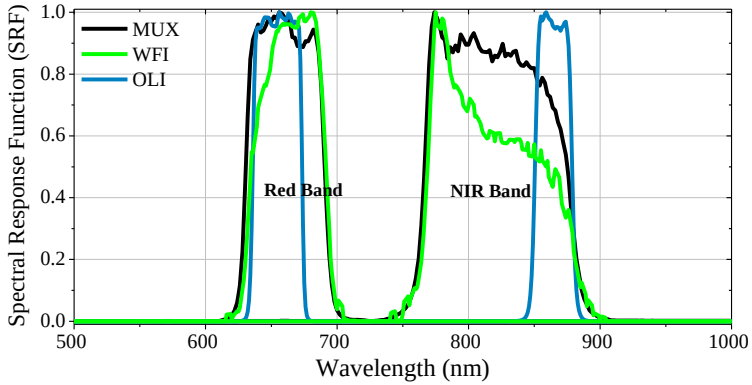
$$L_{band} = \frac{\int_0^\infty L_\lambda \times SRF_\lambda d\lambda}{\int_0^\infty SRF_\lambda d\lambda}$$

Uncertainty?









Propagation of Uncertainty

Methods for evaluating uncertainties :

Conventional Method:
ISO-GUM

Alternative Method:
Monte Carlo simulation

By classical method of uncertainties propagation described in the Guide to the Expression of Uncertainty in Measurement (GUM) (JCGM, 2008a):

Secondary quantity:

$$g = f(a, b, c, \ldots)$$

$$\sigma_g^{\ 2} = \left(\frac{\partial g}{\partial a}\right)^2 \times \sigma_a^{\ 2} + \left(\frac{\partial g}{\partial b}\right)^2 \times \sigma_b^{\ 2} + \left(\frac{\partial g}{\partial c}\right)^2 \times \sigma_c^{\ 2} + \ldots + COV$$

$$COV = 2 \times \left(\frac{\partial g}{\partial a}\right) \times \left(\frac{\partial g}{\partial b}\right) \sigma^2_{ab} + 2 \times \left(\frac{\partial g}{\partial a}\right) \times \left(\frac{\partial g}{\partial c}\right) \sigma^2_{ac} + 2 \times \left(\frac{\partial g}{\partial b}\right) \times \left(\frac{\partial g}{\partial c}\right) \sigma^2_{bc} + \ldots$$

Reflectance-based approach:
Band averaged at-sensor radiance

The output from MODTRAN (hyperspectral TOA radiance) are averaged with the Spectral Response Function (SRF) of the sensor of interest to find the band averaged at-sensor radiance values at each spectral band.

Mathematical Model:

$$L_{band} = \frac{\int_0^\infty L_\lambda \times SRF_\lambda d\lambda}{\int_0^\infty SRF_\lambda d\lambda}$$

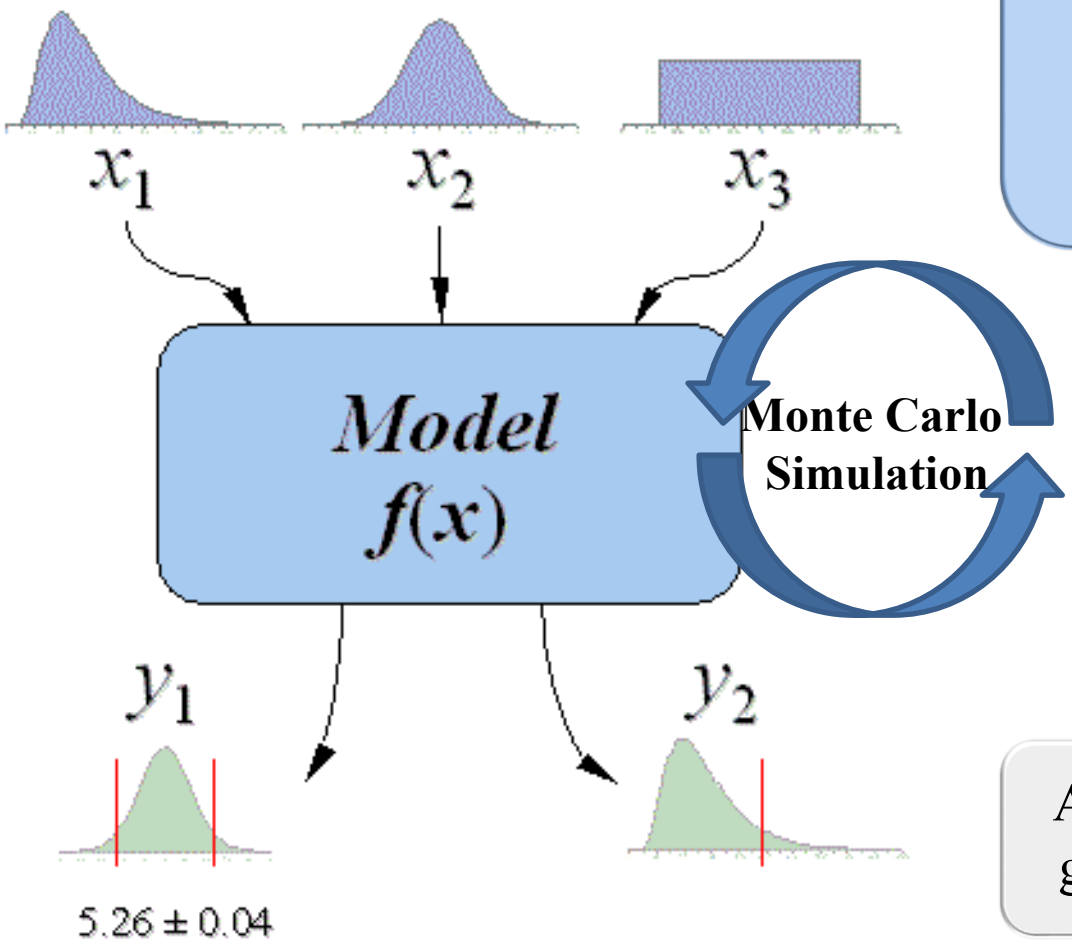
$$\sigma_g{}^2 = \left(\frac{\partial g}{\partial a}\right)^2 \times \sigma_a{}^2 + \left(\frac{\partial g}{\partial b}\right)^2 \times \sigma_b{}^2 + \left(\frac{\partial g}{\partial c}\right)^2 \times \sigma_c{}^2 + \ldots + COV$$

$$COV = 2 \times \left(\frac{\partial g}{\partial a}\right) \times \left(\frac{\partial g}{\partial b}\right) \sigma^2{}_{ab} + 2 \times \left(\frac{\partial g}{\partial a}\right) \times \left(\frac{\partial g}{\partial c}\right) \sigma^2{}_{ac} + 2 \times \left(\frac{\partial g}{\partial b}\right) \times \left(\frac{\partial g}{\partial c}\right) \sigma^2{}_{bc} + \ldots$$

<u>Alternative</u>: Monte Carlo Simulation (JCGM, 2008b)

Propagation of Uncertainty: Monte Carlo Simulation

Distribution for each input quantity (uniform, normal, triangular…)



The Monte Carlo method is a computational algorithm that depends on random and repeated sampling to obtain approximate results

These distributions are propagated M times (where M is iteration number) by a mathematical model of measurement

A new distribution is generated as a result

Reflectance-based approach:

Algodones Dunes → Results

Band MUX	Digital Number	TOA Radiance MODTRAN (Watts/(m2*srad*µm))
B1	56.4 ± 1.1	96 ± 3
B2	66.8 ± 1.6	108 ± 4
B3	74.2 ± 1.9	114 ± 5
B4	66.7 ± 1.6	91 ± 4

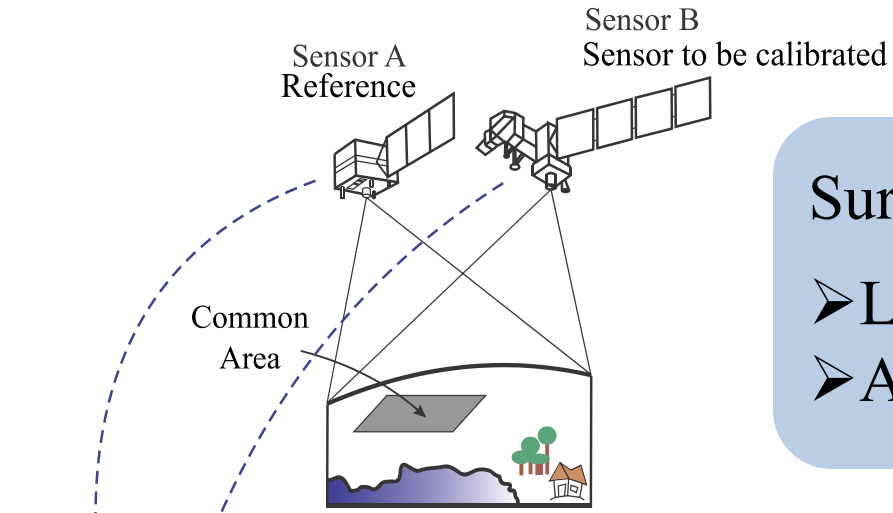
Band WFI	Digital Number	TOA Radiance MODTRAN (Watts/(m2*srad*µm))
B1	258.8 ± 2.7	96 ± 3
B2	212.7 ± 2.9	108 ± 4
B3	320 ± 5	114 ± 5
B4	260 ± 3	92 ± 4

DN from Image (MUX and WFI)

Values predicted by Modtran

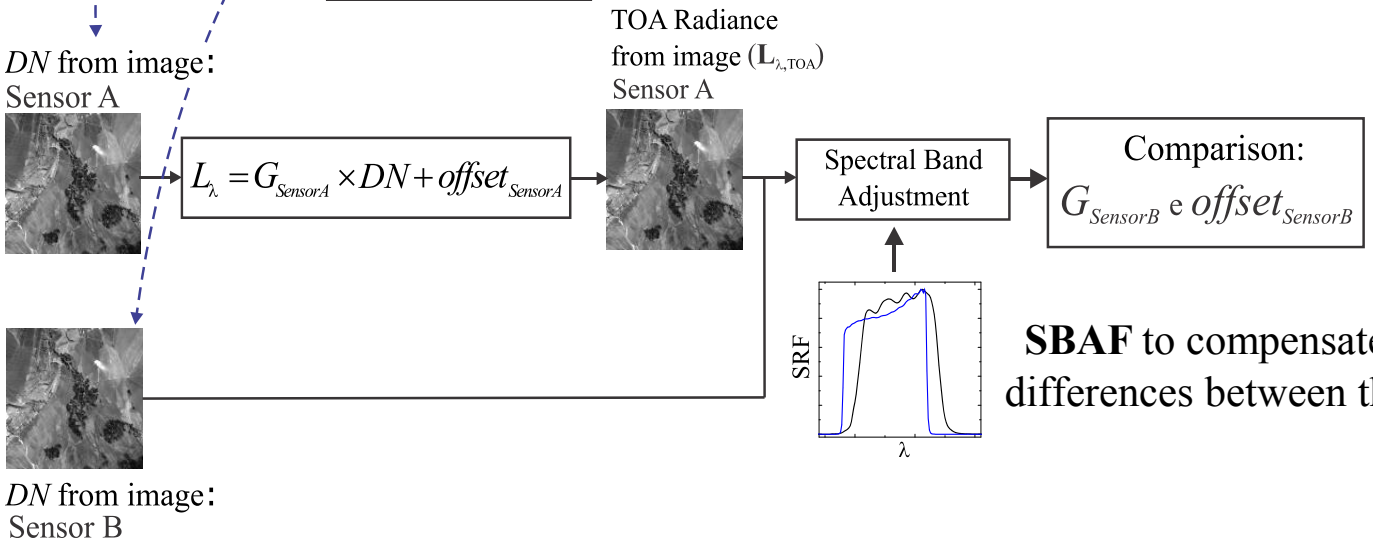
Uncertainty Algodones Dunes: 3.4-4.4%

Cross-calibration Method



Surfaces:

- Libya-4 (Pseudo Invariant Calibration Site);
- Atacama Desert (Chile);

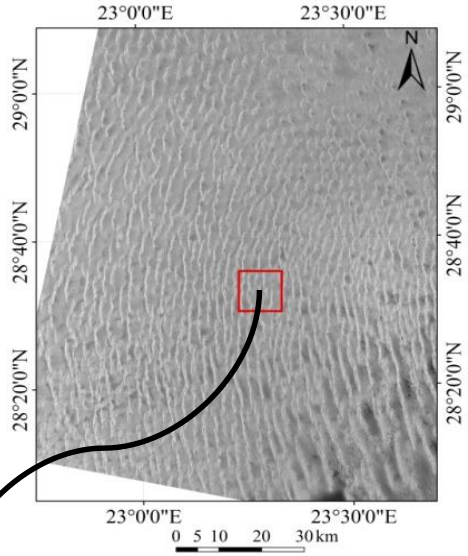


SBAF to compensate the SRF differences between the sensors.

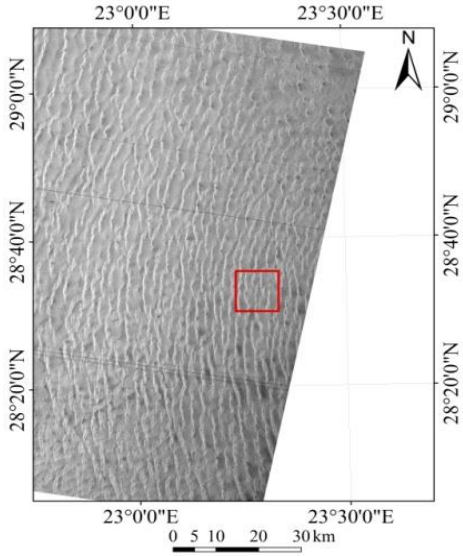
Cross-calibration Method: Libya-4

July, 2015

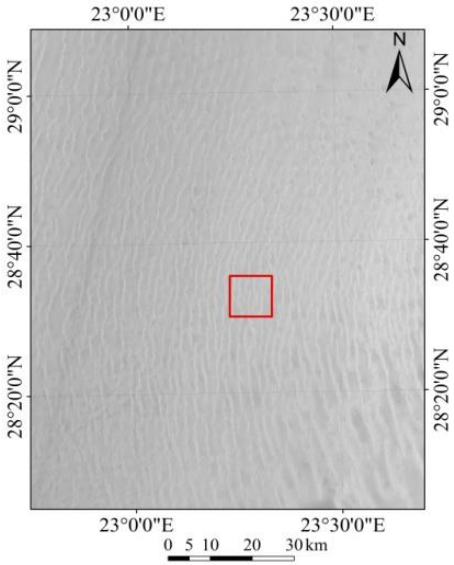
Landsat-8/OLI

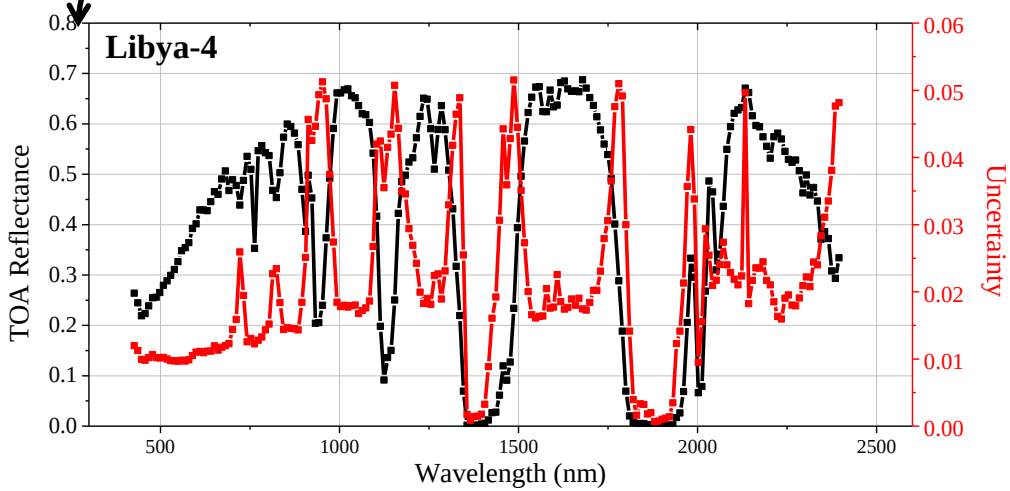


CBERS-4/MUX



CBERS-4/WFI





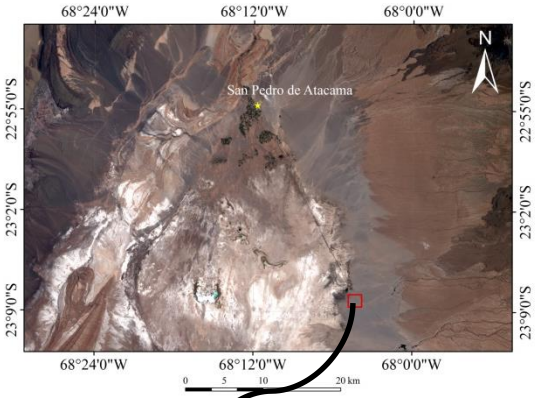
Average TOA reflectance profile of 224 EO-1 Hyperion images over Libya-4 from 2004 to 2014.

The TOA Reflectance profile was used to derive SBAF

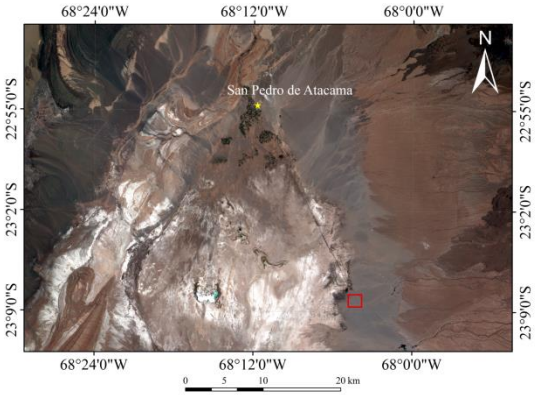
Cross-calibration Method:

Atacama Desert (Chile)

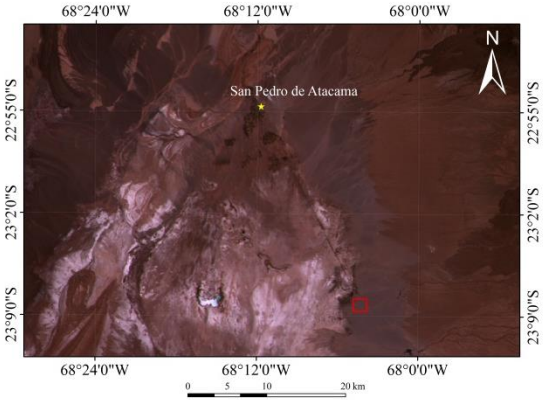
Landsat-8/OLI

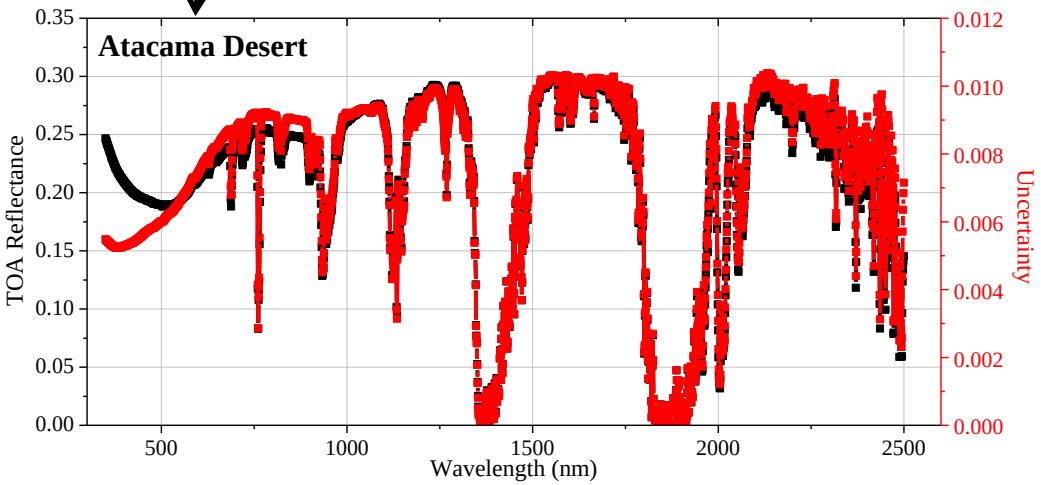


CBERS-4/MUX



CBERS-4/WFI





November, 2015

TOA reflectance over Atacama Desert profile from ground measurements.

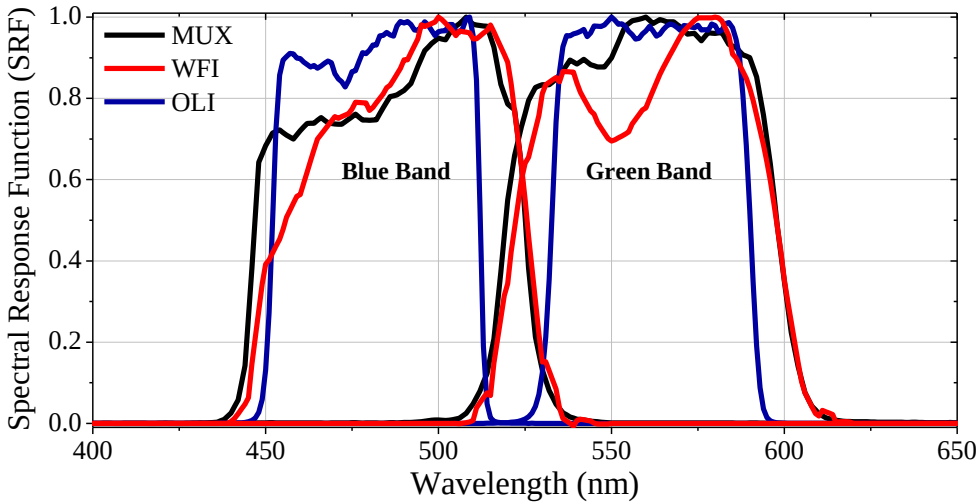
The TOA Reflectance profile was used to derive SBAF

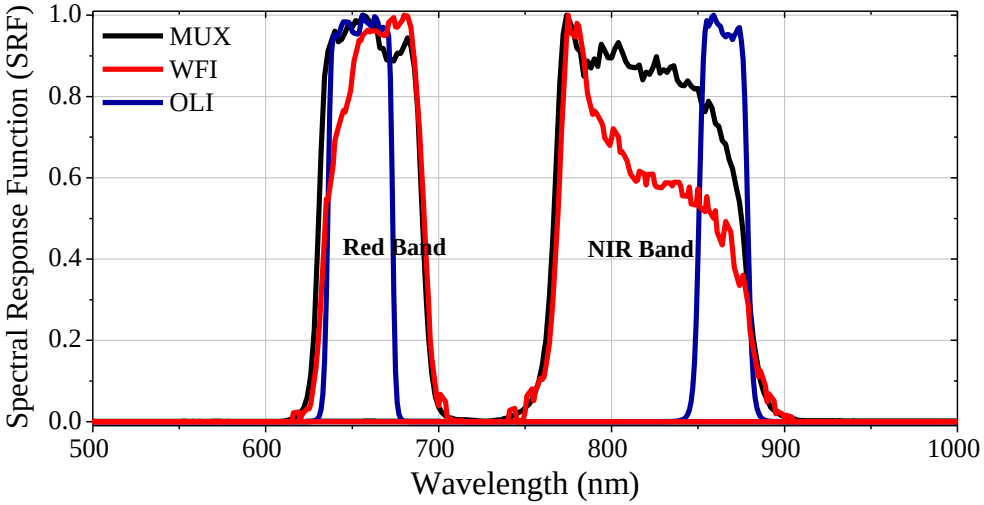
Cross-calibration Method:

Spectral Band Adjustment Factor (SBAF)

$$SBAF = \frac{\rho_{\lambda,A}}{\rho_{\lambda,B}} = \frac{\dfrac{\int_0^\infty \rho_\lambda \times SRF_{\lambda,A} d\lambda}{\int_0^\infty SRF_{\lambda,A} d\lambda}}{\dfrac{\int_0^\infty \rho_\lambda \times SRF_{\lambda,B} d\lambda}{\int_0^\infty SRF_{\lambda,B} d\lambda}}$$

SBAF to compensate the SRF differences between the sensors.





Cross-calibration Method:

Spectral Band Adjustment Factor (SBAF)

Mathematical Model:

$$SBAF = \frac{\rho_{\lambda,A}}{\rho_{\lambda,B}} = \frac{\dfrac{\int_0^\infty \rho_\lambda \times SRF_{\lambda,A} d\lambda}{\int_0^\infty SRF_{\lambda,A} d\lambda}}{\dfrac{\int_0^\infty \rho_\lambda \times SRF_{\lambda,B} d\lambda}{\int_0^\infty SRF_{\lambda,B} d\lambda}}$$

$$\sigma_g^{\ 2} = \left(\frac{\partial g}{\partial a}\right)^2 \times \sigma_a^{\ 2} + \left(\frac{\partial g}{\partial b}\right)^2 \times \sigma_b^{\ 2} + \left(\frac{\partial g}{\partial c}\right)^2 \times \sigma_c^{\ 2} + \ldots + COV$$

$$COV = 2 \times \left(\frac{\partial g}{\partial a}\right) \times \left(\frac{\partial g}{\partial b}\right) \sigma^2_{ab} + 2 \times \left(\frac{\partial g}{\partial a}\right) \times \left(\frac{\partial g}{\partial c}\right) \sigma^2_{ac} + 2 \times \left(\frac{\partial g}{\partial b}\right) \times \left(\frac{\partial g}{\partial c}\right) \sigma^2_{bc} + \ldots$$

<u>Alternative</u>: Monte Carlo Simulation (JCGM, 2008b)

Cross-calibration Method:

Spectral Band Adjustment Factor (SBAF)

SBAF and its uncertainty used to compensate the MUX/CBERS-4 TOA reflectance to match OLI/Landsat-8 TOA reflectance.

Libya-4		
Band	**SBAF**	**Uncertainty (%)**
Blue	0.982 ± 0.007	0.73
Red	1.008 ± 0.005	0.48
Green	0.992 ± 0.007	0.66
NIR	1.108 ± 0.015	1.37
Atacama Desert		
Band	**SBAF**	**Uncertainty (%)**
Blue	1.0007 ± 0.0018	0.18
Red	1.0011 ± 0.0018	0.18
Green	1.006 ± 0.003	0.32
NIR	1.012 ± 0.006	0.59

✓ **Libya-4: 0.48-1.38%**

SBAF and its uncertainty used to compensate the WFI/CBERS-4 TOA reflectance to match OLI/Landsat-8 TOA reflectance.

Libya-4		
Band	**SBAF**	**Uncertainty (%)**
Blue	0.972 ± 0.007	0.71
Red	1.015 ± 0.005	0.48
Green	0.986 ± 0.007	0.71
NIR	1.111 ± 0.015	1.38
Atacama Desert		
Band	**SBAF**	**Uncertainty (%)**
Blue	1.0020 ± 0.0018	0.18
Red	1.0034 ± 0.0018	0.18
Green	1.004 ± 0.003	0.33
NIR	1.017± 0.006	0.61

✓ **Atacama Desert: 0.18-0.61%**

Cross-calibration Method

Radiance in MUX and WFI sensors having as reference the OLI sensor:

TOA reflectance:

$$\rho_{\lambda,OLI} = \frac{\pi \cdot L_{\lambda,OLI} \cdot d_{OLI}^{2}}{[E_{SUN_\lambda} \cdot \cos\theta_z]_{OLI}}$$

$$\rho_{\lambda,MUX} = \frac{\pi \cdot L_{\lambda,MUX} \cdot d_{MUX}^{2}}{[E_{SUN_\lambda} \cdot \cos\theta_z]_{MUX}}$$

The combination of Equations:

$$L_{\lambda,MUX} = L_{\lambda,OLI} \cdot \frac{[E_{SUN_\lambda} \cdot \cos\theta_z]_{MUX}}{[E_{SUN_\lambda} \cdot \cos\theta_z]_{OLI}} \cdot \frac{\rho_{\lambda,MUX}}{\rho_{\lambda,OLI}} \cdot \frac{d_{OLI}^{2}}{d_{MUX}^{2}}$$

- ✓ **Earth-Sun distance**
- ✓ **Spectral Band Adjustment Factor (SBAF)**
- ✓ **θ is the solar zenith angle (illumination);**
- ✓ **Exoatmospheric solar irradiance;**

With this equation the radiance value of the sensor to be calibrated (MUX) is obtained from the reference sensor radiance (OLI)

Cross-calibration Method:

Results→ Libya-4

Band MUX	Digital Number	TOA Radiance from OLI [W/(m²·sr·µm)]
B1	90 ± 3	147 ± 5
B2	112 ± 4	183 ± 7
B3	131 ± 4	214 ± 7
B4	118 ± 3	171 ± 6

Band WFI	Digital Number	TOA Radiance from OLI [W/(m²·sr·µm)]
B1	379 ± 12	149 ± 5
B2	373 ± 12	182 ± 7
B3	590 ± 17	214 ± 7
B4	495 ± 13	173 ± 6

DN from Image (MUX and WFI)

TOA Radiance from OLI

Uncertainty Libya-4: 3.3-3.7%

Cross-calibration Method:

Results→ Atacama Desert

Band MUX	Digital Number	TOA Radiance from OLI [W/(m²·sr·µm)]
B1	74.0 ± 1.1	124 ± 3
B2	76.8 ± 1.2	122 ± 3
B3	78.0 ± 1.2	121.7 ± 2.4
B4	65.8 ± 1.0	92.5 ± 1.5

Band WFI	Digital Number	TOA Radiance from OLI [W/(m²·sr·µm)]
B1	332 ± 4	124 ± 3
B2	274 ± 4	122 ± 3
B3	351 ± 5	121.5 ± 2.4
B4	289 ± 4	93.1 ± 1.5

DN from Image (MUX and WFI)

TOA Radiance from OLI

Uncertainty Atacama Desert: 1.6-2.7%

Combination of techniques:

Reflectance-based approach and Cross-calibration method

✓ Uncertainty Algodones Dunes (Reflectance-based) → **3.4 – 4.4%**

✓ Uncertainty Libya-4 (Cross-calibration) → **3.3 – 3.7%**

✓ Uncertainty Atacama Desert (Cross-calibration) → **1.6 – 2.7%**

The results from Algodones Dunes, from Libya-4 and from Atacama Desert were used together to estimate the calibration gains for the MUX and WFI.

Combination of techniques:

Radiometric calibration of MUX /CBERS-4

MUX/CBERS-4

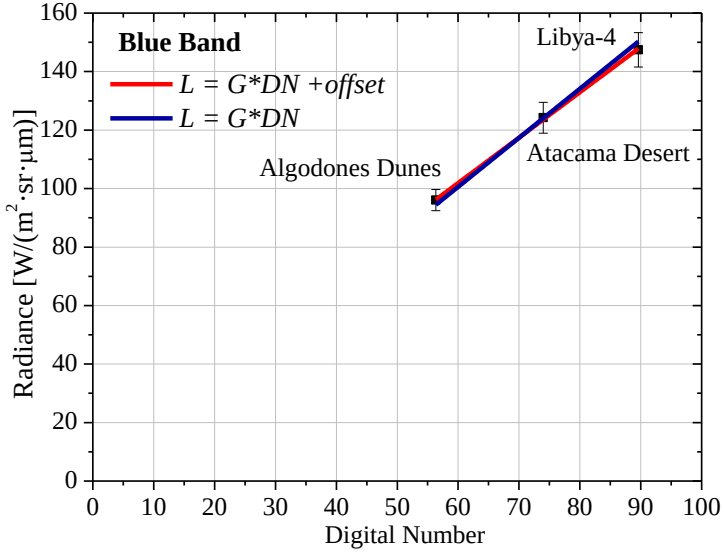
Linear regression

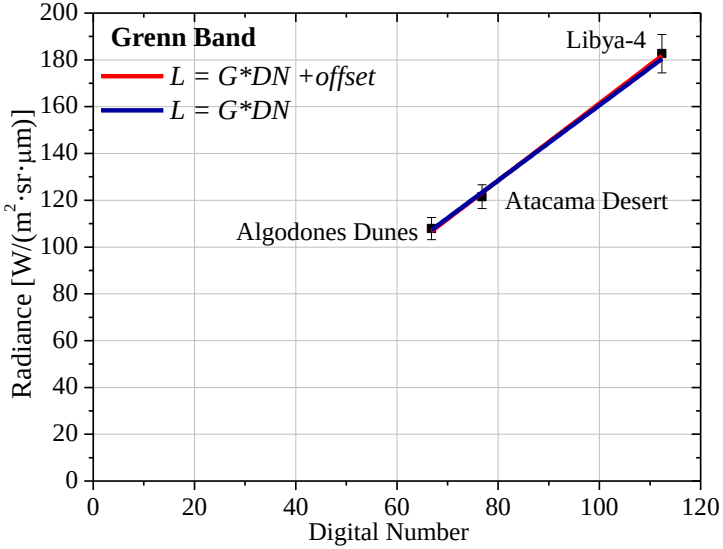
Fit Equation:

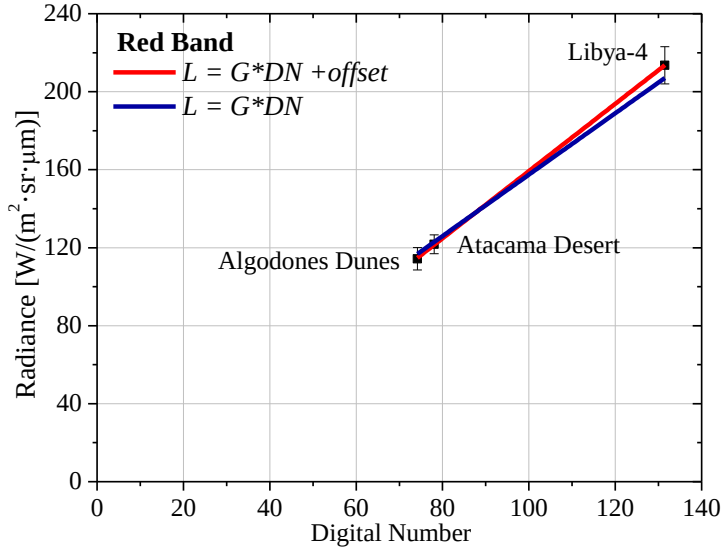
[free intercept]

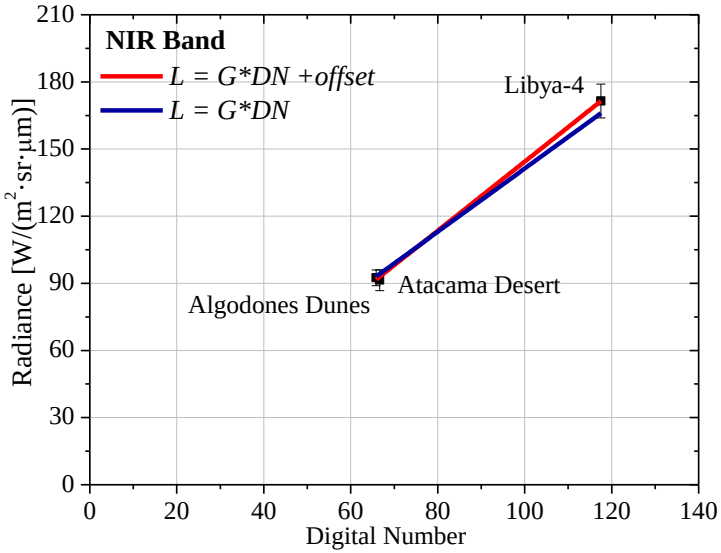
Fit Equation:

[forced zero intercept]









Combination of techniques:

Radiometric calibration of WFI /CBERS-4

WFI/CBERS-4

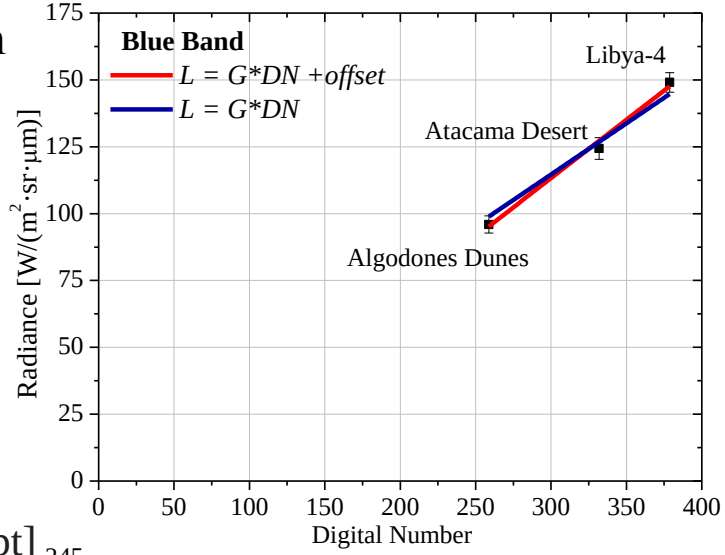
Linear regression

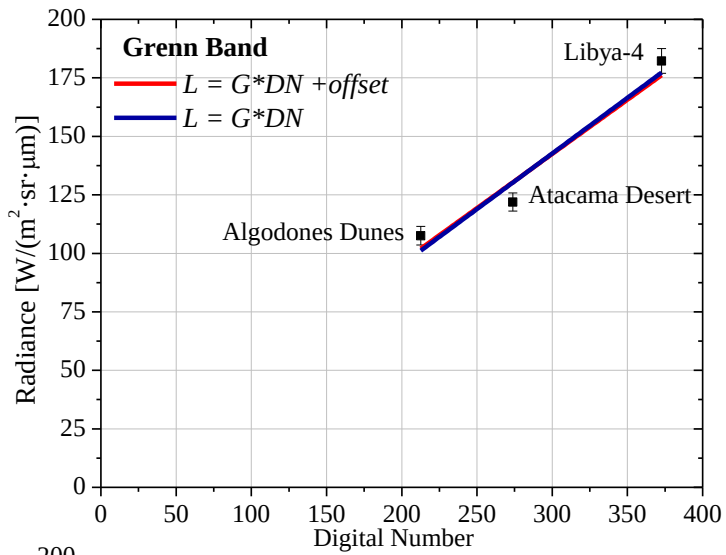
Fit Equation:

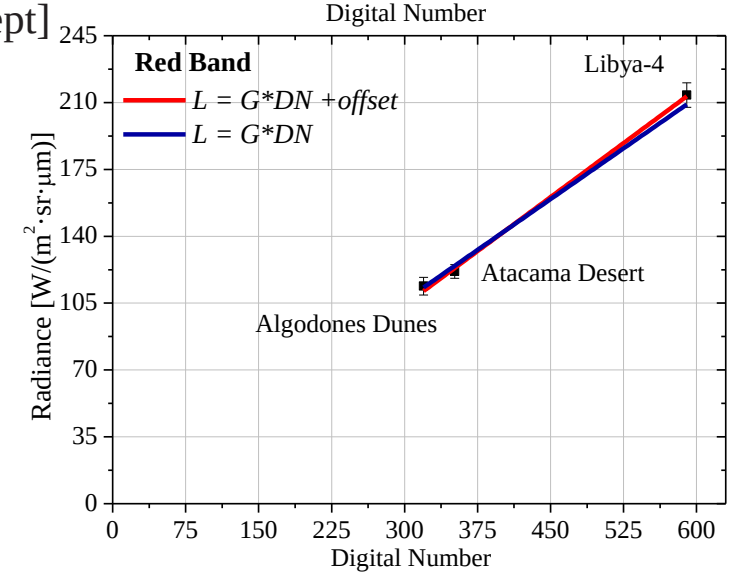
[free intercept]

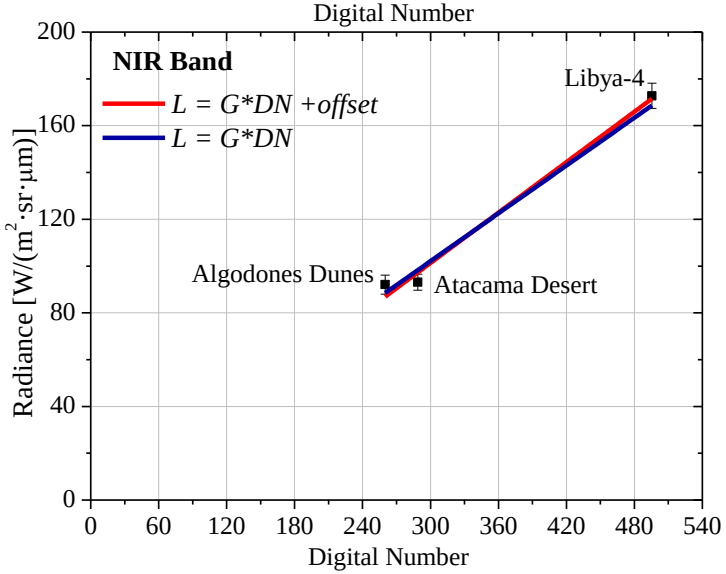
Fit Equation:

[forced zero intercept]









$L_i = G_i \times ND_i + offset_i$

Combination of techniques:

Reflectance-based approach and Cross-calibration method

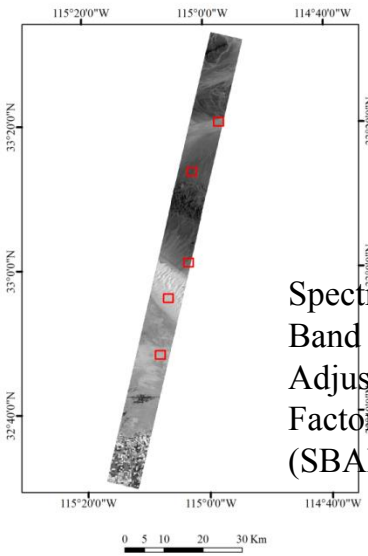
Band	Fit Equation: [free intercept] Slope (G_i) [W/(m2·sr·µm)]/DN	Intercept ($offset_i$) [W/(m²·sr·µm)]	Fit Equation: [forced zero intercept] Slope (G_i) [W/(m2·sr·µm)]/DN	
MUX				
Blue	1.56 ± 0.21	8 ± 15	1.68 ± 0.04	
Green	1.64 ± 0.23	-3 ± 18	1.60 ± 0.04	
Red	1.72 ± 0.19	-13 ± 16	1.57 ± 0.03	**1.9-2.1%**
		-9 ± 11	1.41 ± 0.03	
WFI				
		-12 ± 17	0.376 ± 0.008	
		16 ± 16	0.468 ± 0.010	
Red	0.38 ± 0.04	-9 ± 15	0.351 ± 0.007	
NIR	0.36 ± 0.03	-9 ± 10	0.331 ± 0.006	**1.8-2.2%**

There was no statistical evidence for using offsets other than zero

Validation:

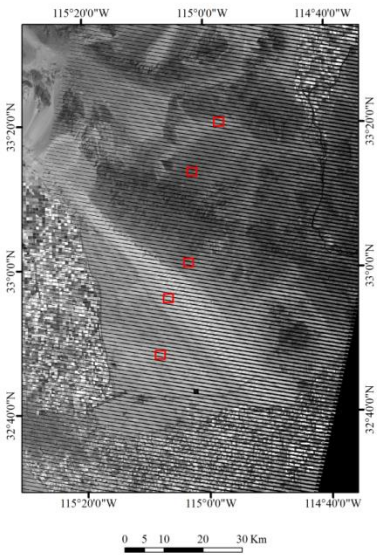
MUX, WFI, ETM+ and Hyperion metadata

Hyperion/EO-1

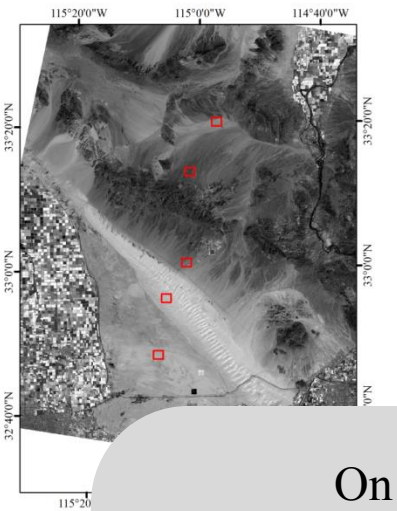


Spectral Band Adjustment Factor (SBAF)

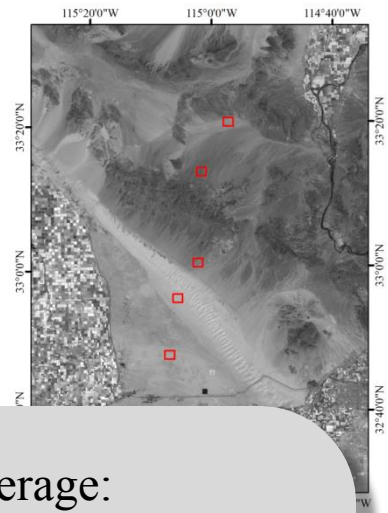
ETM+/Landsat-7



MUX/CBERS-4



WFI/CBERS-4



$$Difference\ (\%) = \left(\frac{\rho_{CBERS,\lambda} - \rho_{Landsat,\lambda}}{\rho_{Landsat,\lambda}} \right) \times 100$$

On average:

MUX and EMT+

2.7% → free intercept

1.9% → forced zero intercept

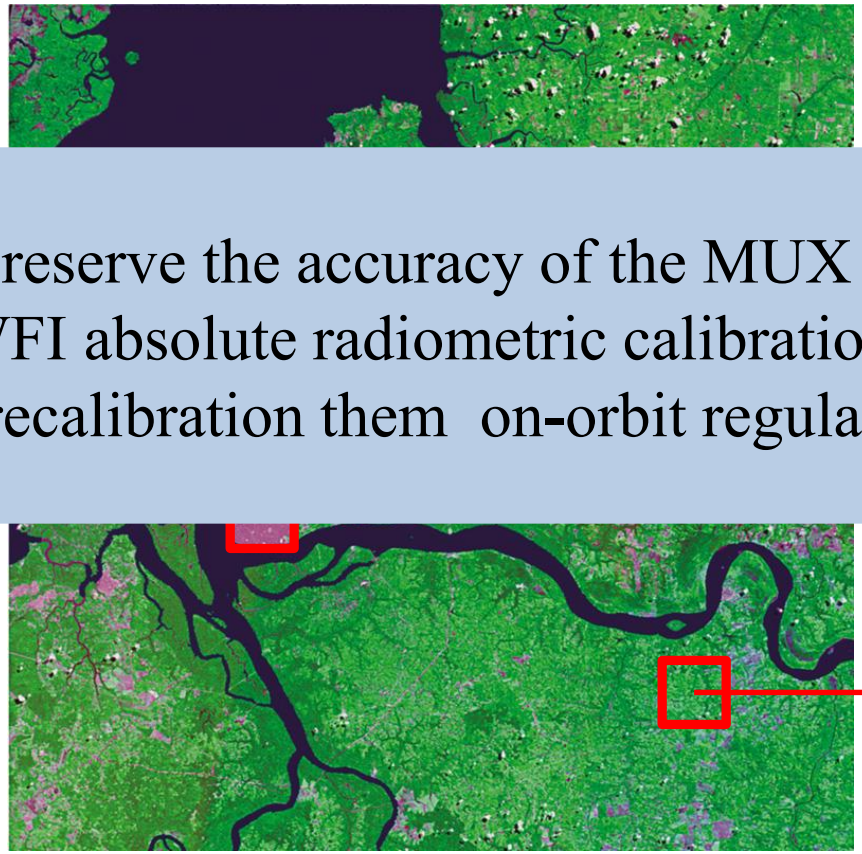
WFI and EMT+

4.8% → free intercept

4.2% → forced zero intercept

Next Steps

Check the radiometric coefficients using other targets on the earth's surface:



✓ Water

✓ Urban area

✓ Vegetation

Preserve the accuracy of the MUX and WFI absolute radiometric calibration by recalibration them on-orbit regularly.

Fit Equation: [forced zero intercept]	
Slope (G_i) [W/(m2·sr·µm)]/DN	
MUX	
1.68 ± 0.04	
1.60 ± 0.04	
1.57 ± 0.03	
1.41 ± 0.03	
WFI	
0.376 ± 0.008	
0.468 ± 0.010	
0.351 ± 0.007	
0.331 ± 0.006	

MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

First In-flight Radiometric Calibration of the CBERS-4 MUX and WFI

Thanks!

Cibele Teixeira Pinto
National Institute for Space Research

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Fort Worth, Texas

South Dakota State University
Image Processing Lab

SDSU