

Spectral Band Difference Effects for Cross-Calibration in the Solar-Reflective Spectral Domain



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Introduction



- **For quantitative Earth observation applications to make full use of the ever-increasing number of Earth observation satellite systems, data from the various sensors involved must be on a consistent radiometric calibration scale.**
- **However, different applications and technology developments in Earth observation typically require different spectral coverage.**
- **The result is that relative spectral response functions differ significantly between sensors, even for spectral bands designed to look at the same region of the electromagnetic spectrum.**





Study Premise

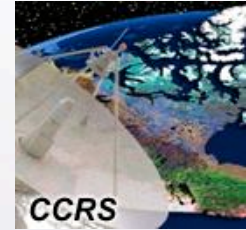


- **What is the impact of spectral band differences between satellite sensors on cross-calibration (Xcal) based on near-simultaneous imaging of common ground look targets in analogous spectral bands?**
- **Given that Landsat-7 ETM+ is well calibrated radiometrically, cross-calibration between the ETM+ and several other sensors was the starting point for the study .**
- **With spectral band difference effects (SBDEs) on cross-calibration between ETM+ and other sensors in hand, all other Xcal combinations between sensors can be readily examined (in the Landsat-centric spectral domain).**





Previous Studies

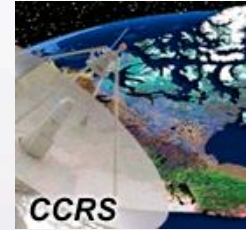


- **Teillet et al. (2001):**
 - **In 6 solar reflective bands for Landsat-7 ETM+ versus Landsat- 5 TM.**
- **Trishchenko (Trichtchenko) et al. (2002):**
 - **In red, near-infrared, and NDVI for NOAA-9 AVHRR versus other NOAA AVHRRs, Terra MODIS, SPOT-4 VGT, and ADEOS-2 GLI.**
- **Steven et al. (2003):**
 - **NDVI for 15 satellite sensors.**
- **Rao et al. (2003):**
 - **ATSR-2 versus MODIS, allowing for SBDEs.**





Assumptions

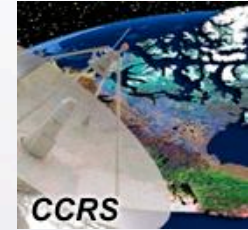


- **Temporal:**
 - Images acquired under clear sky conditions on the same day.
- **Spectral:**
 - Spectral bands with analogs to the six solar-reflective Landsat-7 ETM+ bands.
 - Spectral bands well characterized prior to launch and unchanged post-launch.
 - Out-of-band response not taken into consideration.
- **Radiometric:**
 - Nominal calibration coefficients are being checked.
 - Linear radiometric response over the range of relevant radiances.
 - Differences in radiometric resolution not taken into consideration.
 - Bidirectional reflectance effects not taken into account.
 - Terrain flat and horizontal.





Simulation Methodology



- Simulate spectral band adjustment factors for **R**eference and **eX**perimental sensors:
 - Start with calibration test site ground spectrum.
 - Use atmospheric radiative transfer code (CAM5S) to compute $\rho * iR$.
 - Use atmospheric radiative transfer code (CAM5S) to compute $\rho * iX$.
 - In analogous solar-reflective spectral bands.
 - Calculate band difference factor, $B_i = \rho * iR / \rho * iX$.
 - For all pair combinations of ETM+; ALI; MODIS; ASTER; MISR.
- Error in cross-calibration directly proportional to B_i .
- Simulate spectral band adjustment factors for NDVI:
 - $NDVI = (\rho * NIR - \rho * red) / (\rho * NIR + \rho * red)$. (8)
 - $B_N = (NDVIR / NDVIX)$. (9)
- Error in NDVI comparisons directly proportional to B_N .





Sensors, Spectral Bands and Ground Targets



Satellite Sensors and Analogous Spectral Band Numbers (NIR = near infrared; SWIR = shortwave-infrared)

Satellite	Sensor	Blue Band	Green Band	Red Band	NIR Band	SWIR Band I	SWIR Band II
Landsat-7	ETM+	1	2	3	4	5	7
Earth Observing 1	ALI	1	2	3	4p	5	7
Terra	MODIS	3	4	1	2	6	7
Terra	MODIS	10	12	13	16	-	-
Terra	ASTER	-	1	2	3	4	6
Terra	MISR	1	2	3	4	-	-

Ground Target Spectra

(Analytical Spectral Devices (ASD) Spectrometer Data)

- Railroad Valley Playa, Nevada ([RVPN](#))
- Niobrara Grassland, Nebraska ([NIOB](#))



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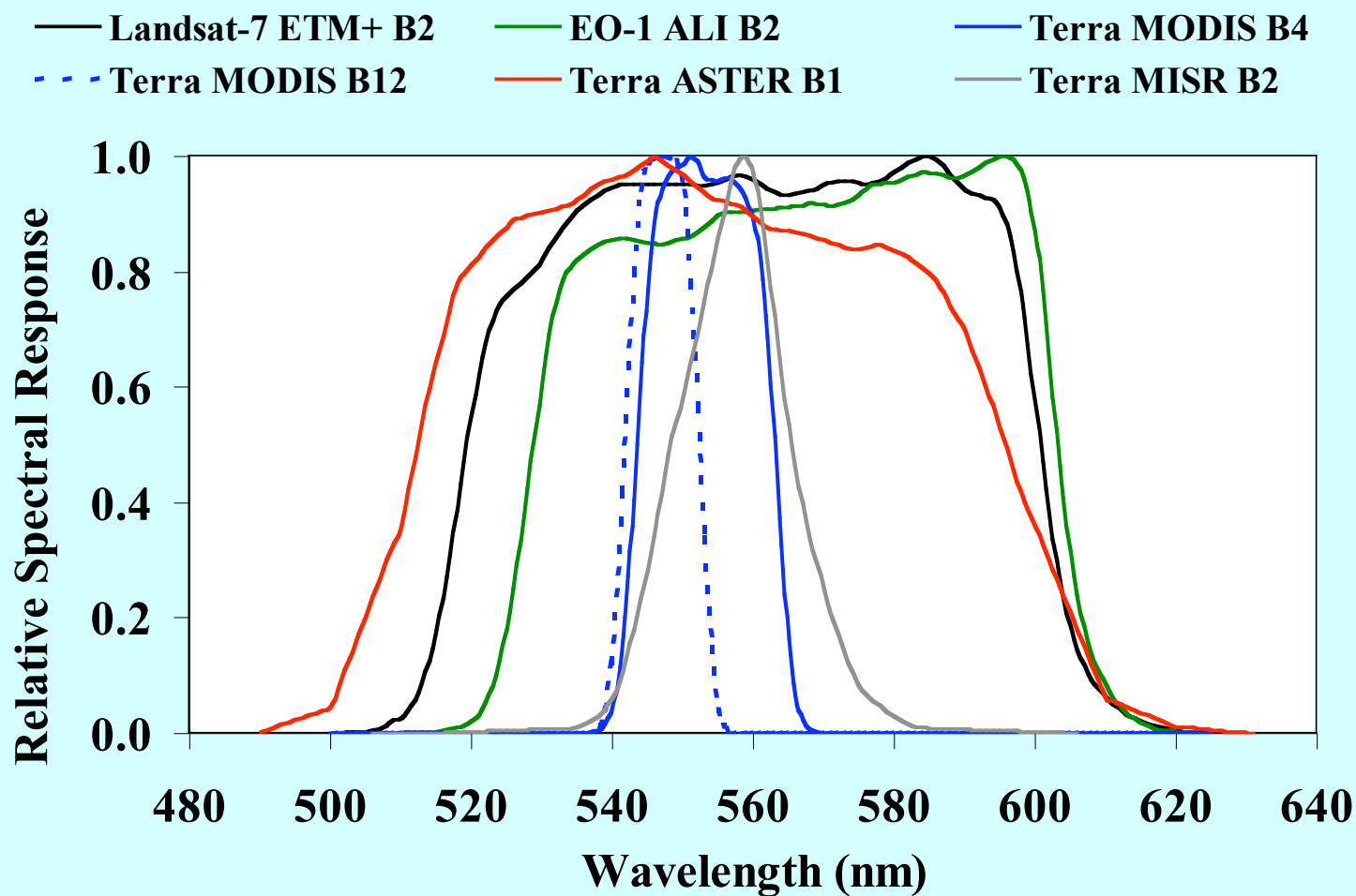
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ETM+ Band 2 Analogs



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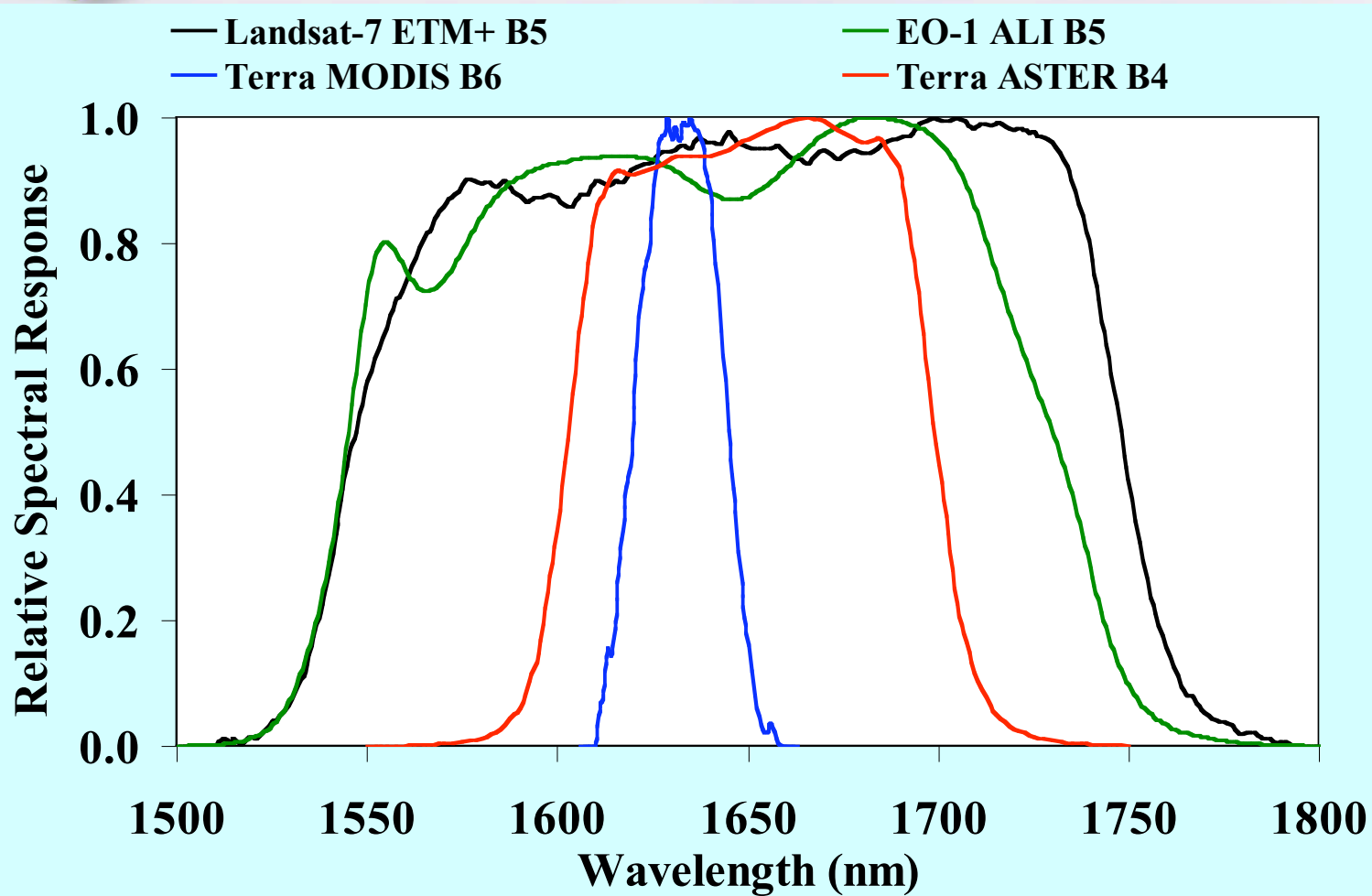
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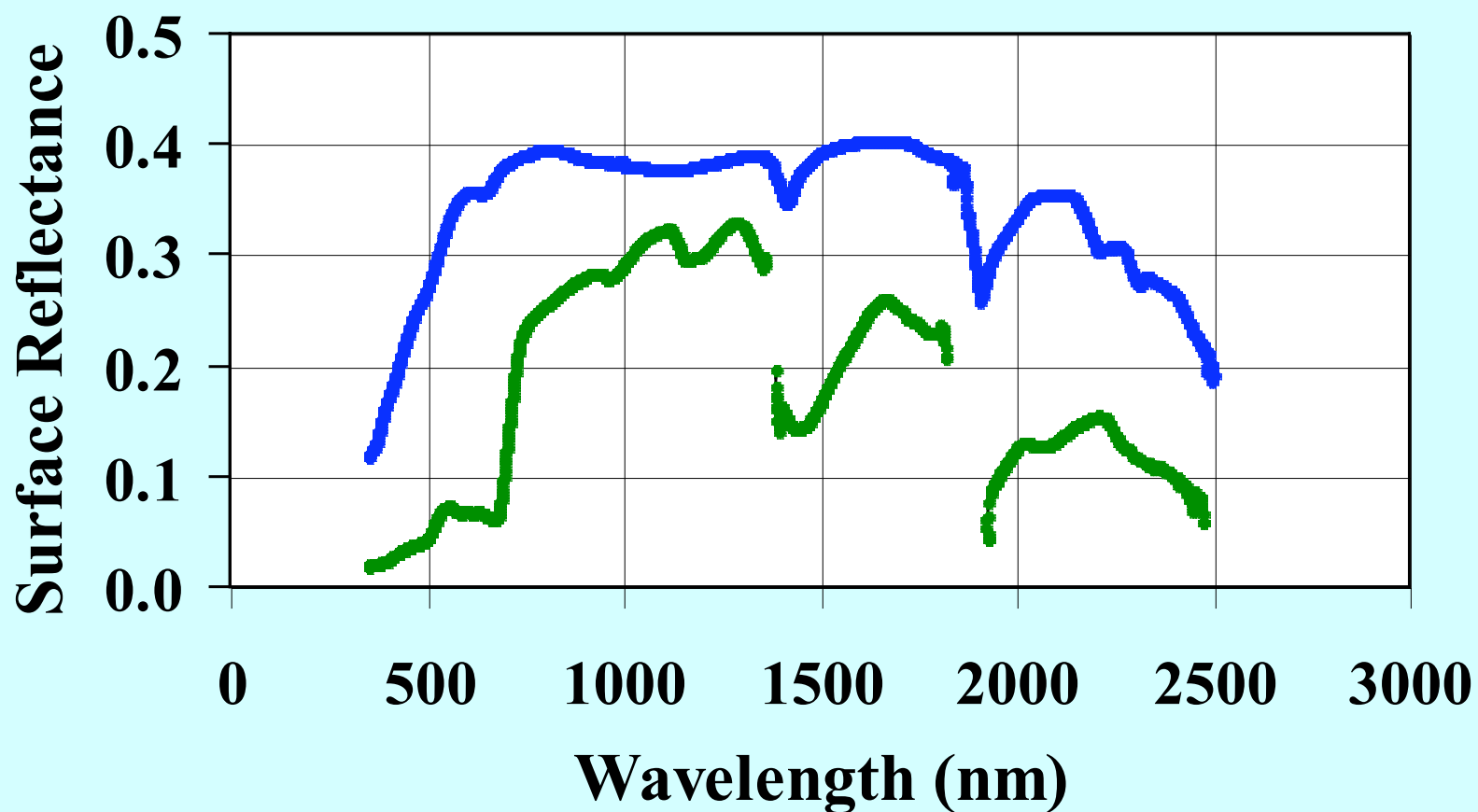


ETM+ Band 5 Analogs





RVPN and NIOB Ground Target Spectra (ASD Data from June 1999)



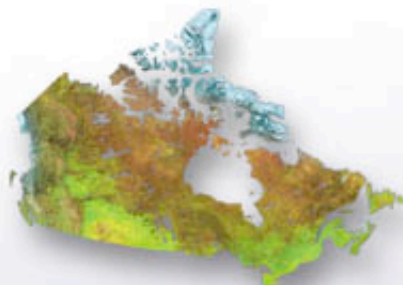
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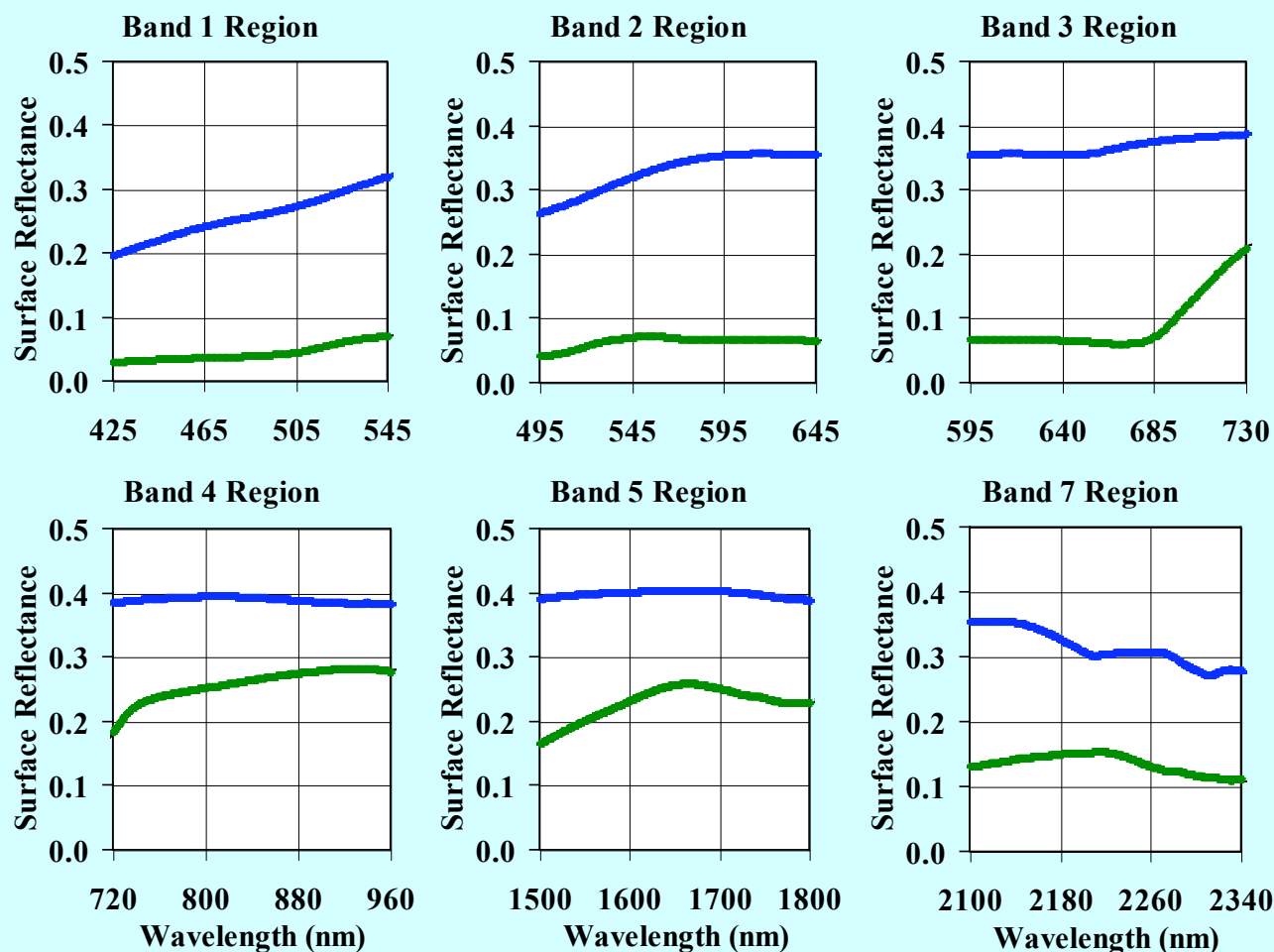
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RVPN and NIOB Ground Spectra in the Landsat Spectral Regions



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Other Parameters



- **Aerosol Optical Depth at 0.55 mm:** 0.05
- **Aerosol Model:** Continental
- **Atmospheric Model:** US62
- **Solar Zenith Angle:** 60 degrees
- **Viewing Geometry:** Nadir
- **Earth-Sun Distance:** 1 AU
- **Elevation (RVPN):** 1.425 km
- **Elevation (NIOB):** 0.76 km





Results Template for Spectral Band Difference Effects



Bi = Ratio TOA Reflectance (Y-axis Sensor) / Ratio TOA Reflectance (X-axis Sensor)												
Sensor Spectral Bands	RailroadValley Playa						Niobrara Grassland					
ETM+ Band 1 Analogs	A	B	C	D	E	F	A	B	C	D	E	F
A: Landsat-7 ETM+ B1	1						1					
B: EO-1 ALI B1		1						1				
C: Terra ASTER N/A			1						1			
D: Terra MODIS B3				1						1		
E: Terra MODIS B10					1						1	
F: Terra MISR B1						1						1
Difference 0-1 percent, i.e., ratio = {0.990 - 1.010} Difference 1-3 percent, i.e., ratio = {0.970 - 0.989999}, {1.010001 - 1.030} Difference 3-7 percent, i.e., ratio = {0.930 - 0.969999}, {1.030001 - 1.070} Difference > 7 percent, i.e., ratio = {0.929999 and below}, {1.070001 and above}												





Spectral Band Difference Factor Results for Band 1 and 2 Analogs



Sensor Spectral Bands	RailroadValley Playa						Niobrara Grassland					
ETM+ Band 1 Analogs	A	B	C	D	E	F	A	B	C	D	E	F
A: Landsat-7 ETM+ B1	1	0.995		1.005	0.990	1.025	1	1.032		0.967	1.076	0.844
B: EO-1 ALI B1		1		1.010	0.995	1.030		1		0.937	1.043	0.818
C: Terra ASTER N/A												
D: Terra MODIS B3				1	0.985	1.020				1	1.113	0.873
E: Terra MODIS B10					1	1.035					1	0.784
F: Terra MISR B1						1						1
ETM+ Band 2 Analogs	A	B	C	D	E	F	A	B	C	D	E	F
A: Landsat-7 ETM+ B2	1	0.996	1.005	0.990	0.988	0.989	1	1.018	0.982	0.956	1.005	0.966
B: EO-1 ALI B2		1	1.009	0.994	0.992	0.993		1	0.965	0.939	0.987	0.949
C: Terra ASTER B1			1	0.985	0.983	0.984			1	0.974	1.023	0.984
D: Terra MODIS B4				1	0.998	0.999				1	1.051	1.010
E: Terra MODIS B12					1	1.001					1	0.961
F: Terra MISR B2						1						1





Spectral Band Difference Factor Results for Band 3 and 4 Analogs



Sensor Spectral Bands	RailroadValley Playa						Niobrara Grassland					
ETM+ Band 3 Analogs	A	B	C	D	E	F	A	B	C	D	E	F
A: Landsat-7 ETM+ B3	1	0.998	1.001	0.997	1.016	0.950	1	1.004	0.962	0.983	1.017	1.015
B: EO-1 ALI B3		1	1.003	0.999	1.018	0.952		1	0.958	0.979	1.013	1.011
C: Terra ASTER B2			1	0.996	1.015	0.949			1	1.022	1.057	1.055
D: Terra MODIS B1				1	1.019	0.953				1	1.035	1.033
E: Terra MODIS B13					1	0.935					1	0.998
F: Terra MISR B3						1						1
ETM+ Band 4 Analogs	A	B	C	D	E	F	A	B	C	D	E	F
A: Landsat-7 ETM+ B4	1	0.947	1.037	0.961	0.942	0.948	1	0.911	1.069	0.926	0.906	0.911
B: EO-1 ALI B4p		1	1.095	1.015	0.995	1.001		1	1.173	1.016	0.995	1.000
C: Terra ASTER B3			1	0.927	0.908	0.914			1	0.866	0.848	0.852
D: Terra MODIS B2				1	0.980	0.986				1	0.978	0.984
E: Terra MODIS B16					1	1.006					1	1.006
F: Terra MISR B4						1						1





Spectral Band Difference Factor Results for Band 5 and 7 Analogs



Sensor Spectral Bands	RailroadValley Playa						Niobrara Grassland					
ETM+ Band 5 Analogs	A	B	C	D	E	F	A	B	C	D	E	F
A: Landsat-7 ETM+ B5	1	0.989	0.976	0.972			1	0.992	0.931	0.920		
B: EO-1 ALI B5		1	0.987	0.983				1	0.939	0.927		
C: Terra ASTER B4			1	0.996					1	0.988		
D: Terra MODIS B6				1						1		
E: Terra MODIS N/A												
F: Terra MISR N/A												
ETM+ Band 7 Analogs	A	B	C	D	E	F	A	B	C	D	E	F
A: Landsat-7 ETM+ B7	1	0.957	0.938	0.795			1	0.947	0.804	0.846		
B: EO-1 ALI B7		1	0.980	0.831				1	0.849	0.893		
C: Terra ASTER B6			1	0.848					1	1.052		
D: Terra MODIS B7				1						1		
E: Terra MODIS N/A												
F: Terra MISR N/A												





Spectral Band Difference Factor Results for NDVI Analogs



Sensor	Niobrara Grassland					
ETM+ NDVI Analogs	A	B	C	D	E	F
A: Landsat-7 ETM+	1	1.068	0.923	1.080	1.080	1.076
B: EO-1 ALI		1	0.864	1.011	1.011	1.007
C: Terra ASTER			1	1.170	1.170	1.166
D: Terra MODIS B1B2				1	1.000	0.996
E: Terra MODIS B13B16					1	0.996
F: Terra MISR						1





Results: SBDEs on Cross Calibration (Xcal): Test Site Comparison



- **Without corrections for spectral band difference effects:**
 - **The RVPN calibration site is less susceptible to SBDEs than the NIOB site in almost all sensor Xcal combinations examined.**
 - **For the NIOB site and for the sensors involved, with few exceptions, the spectral content of the scene must be known for accurate cross-calibration based on near-simultaneous imaging.**





Results

SBDEs on Cross Calibration (Xcal): Spectral Region Comparisons



- Without corrections for spectral band difference effects:
 - Green is the optimum spectral region for RVPN in that 2/3 of the Xcal combinations are “very good” and the other 1/3 are all “good”.
 - The “poorest” spectral region overall is the NIR for both test sites.
 - For the NIOB site, there are no spectral regions that can be considered “very good” and only the green and red spectral regions have more than a few “good” Xcal combinations.
 - For the RVPN site, the ETM+ band 7 analog spectral region is also to be avoided in the absence of SBDE corrections.





Results

SBDEs on Cross Calibration (Xcal): Sensor Combination Comparisons

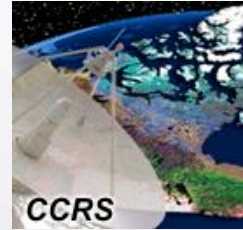


- Without corrections for spectral band difference effects:
 - Sensor Xcal combinations involving ETM+, ALI, ASTER and one MODIS band set (bands 3, 4, and 1) are “very good” in the blue, green and red spectral regions for RVPN (the one exception is the band 2 analog band combination of ASTER band 1 and MODIS band 4 where $B_i = 0.985$).
 - Sensor Xcal combinations involving MISR are the most susceptible to SBDEs, with generally “poor” results.
 - There are no sensor Xcal combinations for which the entire Landsat solar-reflective spectral domain yields “good” results in the absence of SBDE corrections.





Results SBDEs on: NDVI Comparisons



- **Without corrections for spectral band difference effects:**
 - **There are a few “very good” cases but, overall, NDVI is highly susceptible to SBDEs, with a percent root mean square difference in BN from unity of 9.4 % across the set of 15 comparisons.**





Concluding Remarks (1/2)



- It is clear from the results that, except for a limited number of cases, sound sensor cross-calibration using common ground targets requires that the spectral characteristics of the common ground look targets used be known.
- Low-cost Xcal methodologies that seek to complement the more accurate calibrations from costly field campaigns should somehow take SBDEs into account.





Concluding Remarks (2/2)



- **Spectral data and tools recommended to facilitate cross-calibration between satellite sensors:**
 - **On-line central repository of:**
 - **Relative spectral response profiles for as many Earth observation sensors as possible.**
 - **Well-documented target spectra from surface measurements at key calibration test sites.**
 - **Tools for easy transformations between different wavelength grids to facilitate comparisons.**
- **Coordinate central repositories and activities with the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV).**





Work in Progress to Extend Study



- **Xcal combinations of 17 Earth observation satellites:**

ETM+

TM

AVNIR

ALI

ASTER

HRG

Ikonos

QuickBird

AVHRR

VGT

ATSR-2

MODIS

GLI

MISR

SeaWiFS

OCTS

MERIS

- **Scene spectral content: 11 ground targets:**

Unity reflectance

Snow (CAM5S)

Railroad Valley playa Nevada

Dry sand (CAM5S)

Newell County rangeland Alberta

Bright vegetation (CAM5S)

South Dakota "3M" grass site

Niobrara grassland site

Black spruce

Clear water (CAM5S)

Zero reflectance

- **Scene spectral content:
Examining role of:**

Different solar zenith angles

Atmospheric models

Aerosol optical depths

- **Landsat-centric spectral domain.**





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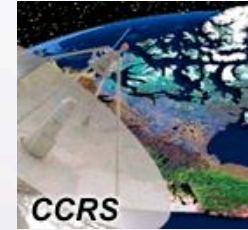
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Basic Equations for Raw Data in Solar Reflective Spectral Band i



The image quantized level Q_i (in counts) is related to TOA radiance L_i^* (in Watts/(m² sr μm)) in spectral band i by

$$Q_i = G_i L_i^* + Q_{oi} , \quad (1)$$

such that bias-corrected image values are given by

$$\Delta Q_i = Q_i - Q_{oi}$$

$$\Delta Q_i = G_i L_i^*$$

$$\Delta Q_i = G_i \rho_i^* E_{oi} \cos\theta / (\pi ds^2) . \quad (2)$$

where G_i = sensor responsivity (in counts per unit radiance),

ρ_i^* = TOA reflectance,

Q_{oi} = zero-radiance bias (in counts),

E_{oi} = exo-atmospheric solar irradiance (in W/(m² μm)),

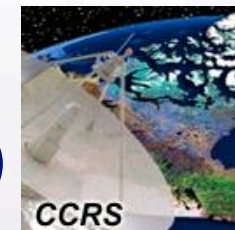
θ = solar zenith angle,

ds = the Earth-Sun distance in Astronomical Units.





Cross-Calibration and Spectral Band Difference Effect (SBDE)



The combination of equation (2) for image data from reference sensor (“R”) and another sensor (“X”) yields

$$\Delta Q_{iX} = (G_{iX} / G_{iR}) \Delta Q_{iR} = M_i \Delta Q_{iR} , \quad (3)$$

where

M_i is the slope that characterises ΔQ_{iX} as a function of ΔQ_{iR} .

$$\Delta Q_{iX} = A_i \Delta Q_{iR} . \quad (4)$$

$$A_i = B_i (E_{oi} \cos \theta)_R / (E_{oi} \cos \theta)_X , \quad (5)$$

$$B_i = \rho^*_{iR} / \rho^*_{iX} . \quad (6)$$

Know All
But B_i

G_{iX}
Assumed
Unknown
So Don't
Know ρ^*_{iX}

A_i adjusts other sensor image data for illumination and spectral band difference effects, where B_i is a spectral band difference adjustment factor.

The other sensor's updated responsivity G_{iX} is then given in spectral band i by

$$G_{iX} = M_i G_{iR} \quad \text{in counts/(Watts/(m}^2 \text{ sr } \mu\text{m))} . \quad (7)$$

Thus, near-simultaneous data pairs make it possible to use well-calibrated reference sensor image data to update the radiometric calibration of another sensor.

