Applications of Spectral Band Adjustment Factors (SBAF) for Cross-calibration

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

Outline

- Introduction
- Cross-calibration based on TOA Reflectance
- Cross-calibration Spectral Issues
- Summary

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Doelling (NASA LRC)

Sensors Used in the Study
L7 ETM+
Terra MODIS
EO-1 Hyperion
ENVISAT SCIAMACHY

Ensuring Data Quality is Paramount

- The ability to detect and quantify changes in the Earth's environment depends on sensors that can provide accurate, calibrated, consistent measurements of the Earth's surface over time

- In order to use remotely sensed data and ensure high science-quality observations, scientists need to know:
  - What part of the EM spectrum they are looking at **(Spectral)**
  - How much energy the instrument is receiving **(Radiometric)**
  - Where the energy is coming from
    - Center of pixel location **(Geometric)**
    - Bounds of the area from which the energy is coming **(Spatial)**

Need for Cross-calibration

- Tie similar (TM/ETM+) & differing (ETM+/MODIS) sensors onto a common radiometric scale
- Provide mission continuity, interoperability, & data fusion
- Essential where on-board references are not available or where vicarious calibration is not feasible
- Critical to coordinate observations from different sensors, exploiting their individual spatial resolutions, temporal sampling, and information content to monitor surface processes over broad scales in both time and space

Key Specifications (ETM+ & MODIS)

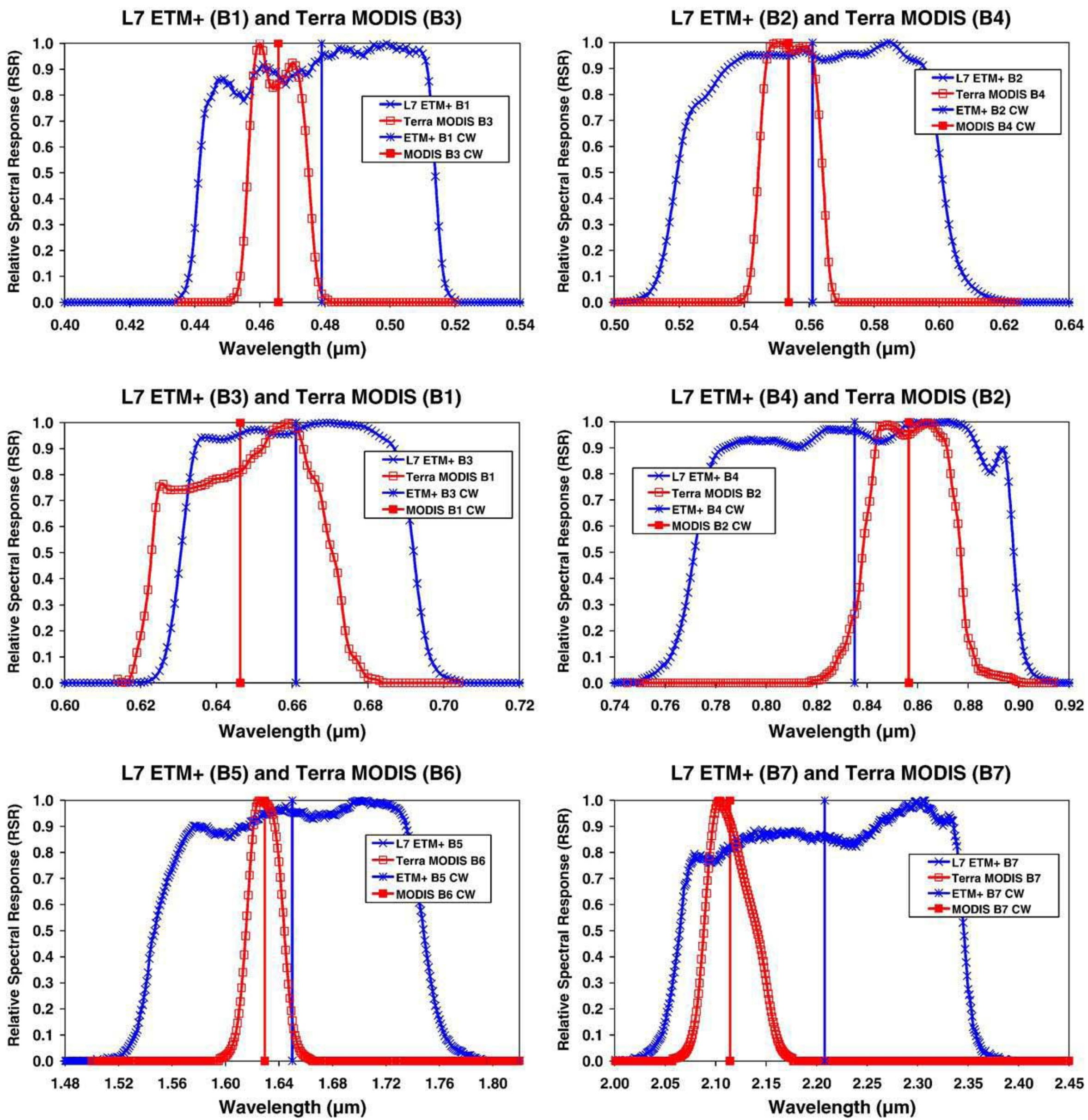
Platform	Terra	Landsat 7
Sensor	MODIS	ETM+
Number of bands	36	8
Spatial resolution	250 m, 500 m, 1 km	15 m, 30 m, 60 m
Swath	2330 km	183 km
Spectral coverage	0.4~14 μm	0.4~12.5 μm
Pixel quantization	12 bit	8 bit
Launch date	18-Dec-99	15-Apr-99
Orbit type	Sun synchronous	Sun synchronous
Equatorial Crossing Time	10:30 AM	10:00 AM
Altitude	705 km	705 km

- Calibration Requirement
  - The calibration uncertainties of ETM+ at-sensor spectral radiances are ±5%
  - The calibration uncertainties of the MODIS Top-of-Atmosphere (TOA) reflectance products are ±2%, whereas a ±5% uncertainty requirement is specified for the at-sensor spectral radiance calibration

ETM+ & MODIS Relative Spectral Response (RSR)

Center Wavelengths are represented by the vertical straight line

- The ETM+ spectral coverage is wider than the MODIS bands
- ETM+ B3 and MODIS B1 have the most agreement in terms of the shape of the RSR profile
- MODIS B2 avoids water absorption feature at 0.836 µm
- Overall, better spectral agreement is in the VNIR bands compared to the SWIR bands
- The RSRs differ significantly, which gave the opportunity to explore, understand, quantify, and compensate for the differences in measurements as obtained from these two sensors



Catalog of Worldwide Test Sites for Sensor Characterization

http://calval.cr.usgs.gov/sites_catalog_map.php

Gyanesh Chander, GEO Task: DA-09-01a_2 Lead
SGT Inc., contractor to the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD. Work performed under USGS contract 08HQCN0005.

Scope of Test Sites

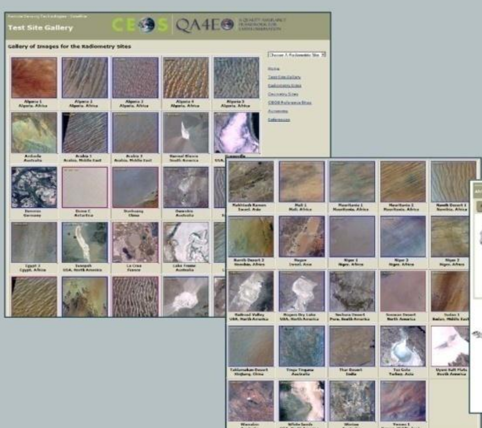
- Test sites are central to any future Quality Assurance/Quality Control (QA/QC) strategy
- Test sites provide a convenient means of obtaining information to verify sensor performance
- Test sites are the only practical means of deriving knowledge of biases between sensors
- Test sites allow, at some level, a means of bridging anticipated data gaps caused by lack of measurement continuity, due to lack of co-existent in-flight sensors

Characteristics of Sensors which can Benefit from Test Sites

- Gain
- Stability
- Modulation Transfer Function (MTF)
- Uniformity
- Stray light
- Polarization
- Spectral
- Signal-to-Noise Ratio (SNR)
- Geolocation
- Camera model
- Band-to-band
- Internal Geometry

Well-Established Site Selection Criteria for Radiometry Test Sites

- High spatial uniformity over a large area (within 3%)
- Surface reflectance [0, 1] greater than 0.3
- Flat spectral reflectance
- Temporally invariant surface properties (within 2%)
- Horizontal surface with nearly lambertian reflectance
- At high altitude, far from ocean, urban, and industrial areas
- In arid regions with low probability of cloud cover



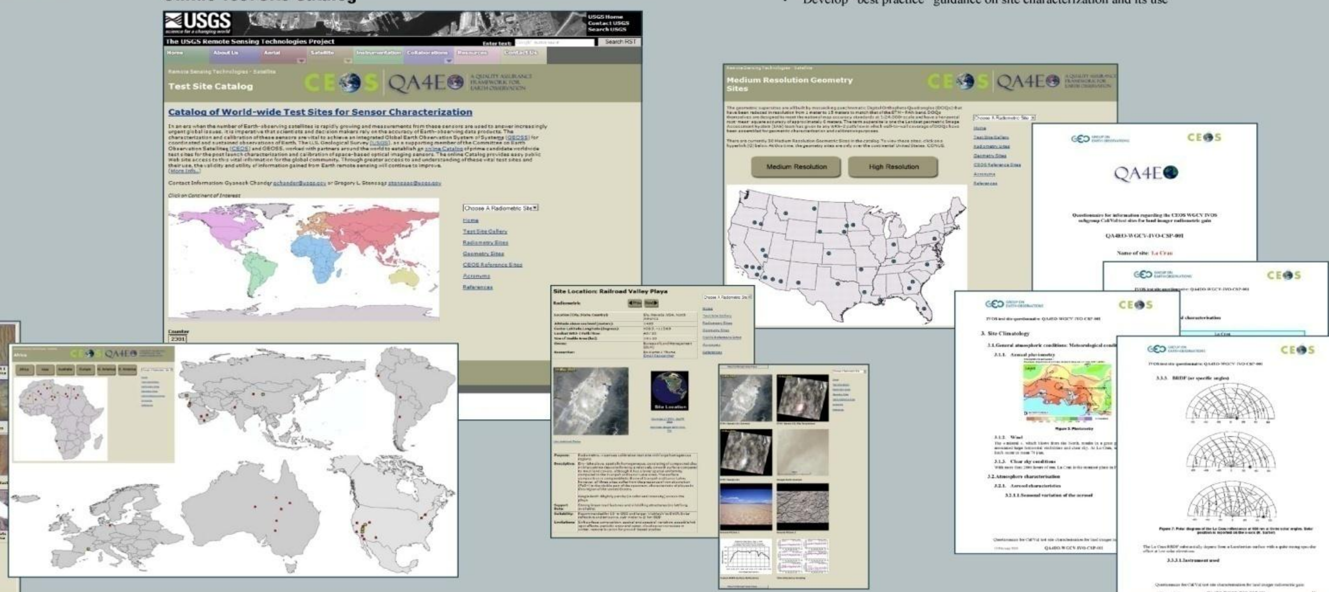
CEOS Reference Standard Test Sites

- The instrumented sites are primarily used for field campaigns to obtain radiometric gain. These sites can serve as a focus for international efforts, facilitating traceability and cross-comparison to evaluate biases of in-flight sensors in a harmonized manner
- The pseudo-invariant desert sites have high reflectance with low aerosol loading and practically no vegetation. Consequently, these sites can be used to evaluate the long-term stability of a sensor and facilitate cross-comparison of multiple sensors

CEOS Reference Standard Test Sites

#	Site Name	Center Latitude	Center Longitude	Point Of Contact (POC)	Affiliation	Email
Instrumented Sites						
1	Railroad Valley Playa	38.50	-115.69	Kurtis J. Thome	NASA/GSFC	kurtis.thome@nasa.gov
2	Ivanpah Playa	35.57	-115.40	Kurtis J. Thome	NASA/GSFC	kurtis.thome@nasa.gov
3	Lspec Frenchman Flat	36.81	-115.93	Carol J. Bruegge	NASA/JPL	Carol.J.Bruegge@jpl.Nasa.Gov
4	La Crau	43.56	4.86	Patrice Henry	CNES	patrice.henry@cnes.fr
5	Dunhuang	40.13	94.34	Xiuqing Hu	NSMC/CMA	huxq@cma.gov.cn
6	Negev, Southern Israel	30.11	35.01	Arnon Karnieli	Ben Gurion University	karnieli@bgu.ac.il
7	Tuz Golu	38.83	33.33	Selime Gurol	TUBITAK UZAY	selime.gurol@uzay.tubitak.gov.tr
8	Dome C	-74.50	123.00	Stephen Warren	University of Washington	sgw@atmos.washington.edu
Pseudo-Invariant Test Sites						
1	Libya 4	28.55	23.39	Patrice Henry	CNES	patrice.henry@cnes.fr
2	Mauritania 1	19.40	-9.30	Patrice Henry	CNES	patrice.henry@cnes.fr
2	Mauritania 2	20.85	-8.78	Patrice Henry	CNES	patrice.henry@cnes.fr
3	Algeria 3	30.32	7.66	Patrice Henry	CNES	patrice.henry@cnes.fr
4	Libya 1	24.42	13.35	Patrice Henry	CNES	patrice.henry@cnes.fr
5	Algeria 5	31.02	2.23	Patrice Henry	CNES	patrice.henry@cnes.fr

Online Test Site Catalog



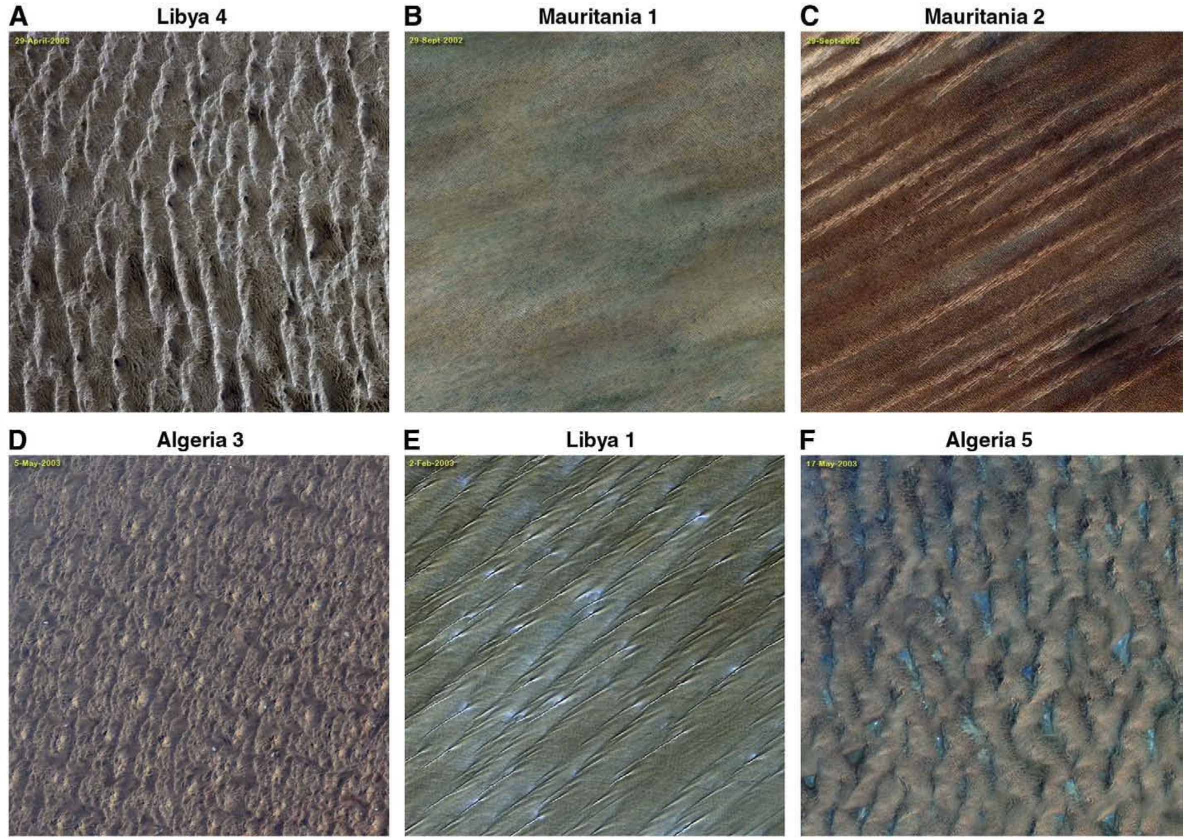
Summary

- The test site catalog provides a comprehensive list of prime candidate terrestrial targets for consideration as benchmark sites for the postlaunch calibration of space-based optical sensors
- The online test site catalog provides easy public Web site access to this vital information for the global community
- The incompleteness of available information on even these prime test sites is an indication that much more coordination and documentation are still needed to facilitate the wider use of calibration test sites in remote sensing

Proposed Future Plans

- Gather complete site characterization data & define core measurements (eg. Instruments)
- Create an operational network of land sites ("Landnet") & develop online data access infrastructure
- Encourage agencies to acquire, archive, and provide data over the CEOS sites
- Integrate the catalog into the CEOS Cal/Val portal
- Establish traceability chain for primary site data
- Develop "best practice" guidance on site characterization and its use

Test Sites Used for Cross-calibration

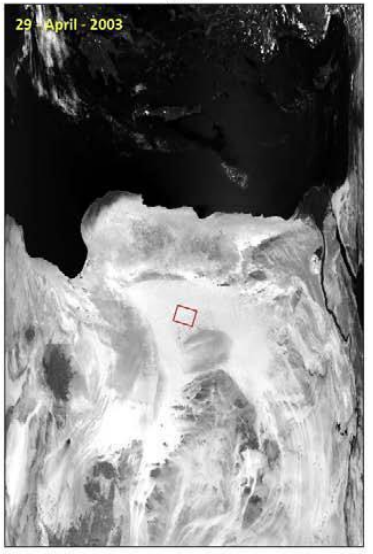


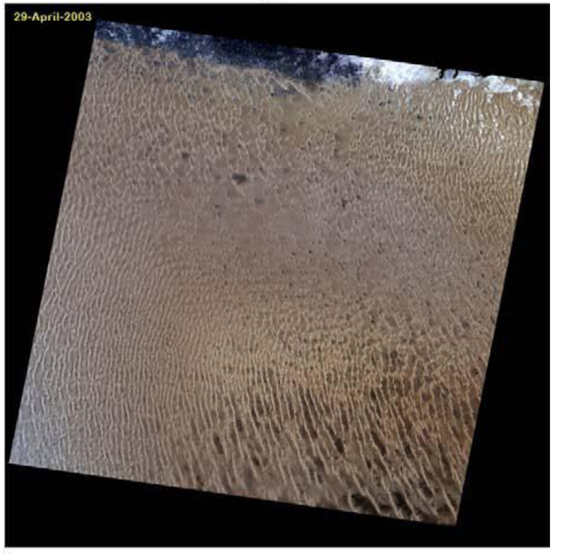
- The Pseudo-Invariant Calibration Sites (PICS) located in the Sahara Desert in Africa were used for the cross-cal study
- These site exhibits good spatial, temporal uniformity, with no vegetation, low aerosol loading, and has minimal cloud cover

Region of Interest (ROI)

- The full swath MODIS B3 and ETM+ B321 image over the Libya 4 test site

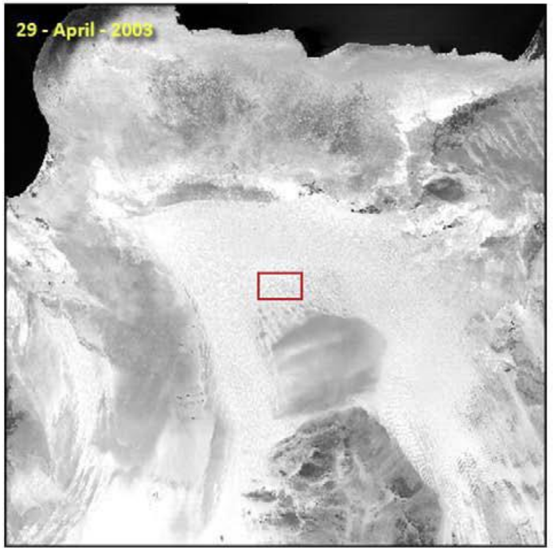
- The ETM+ area is marked as a rectangular box in the MODIS image

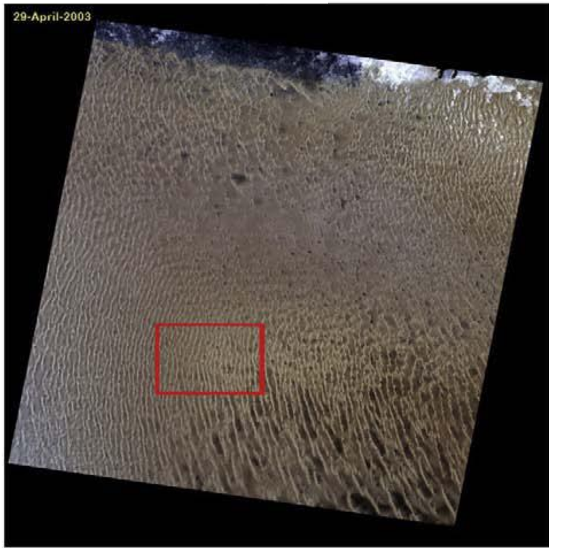




- The region inside the red rectangle ROI is used for calculating statistics

- ROIs within image were selected such that view was nadir

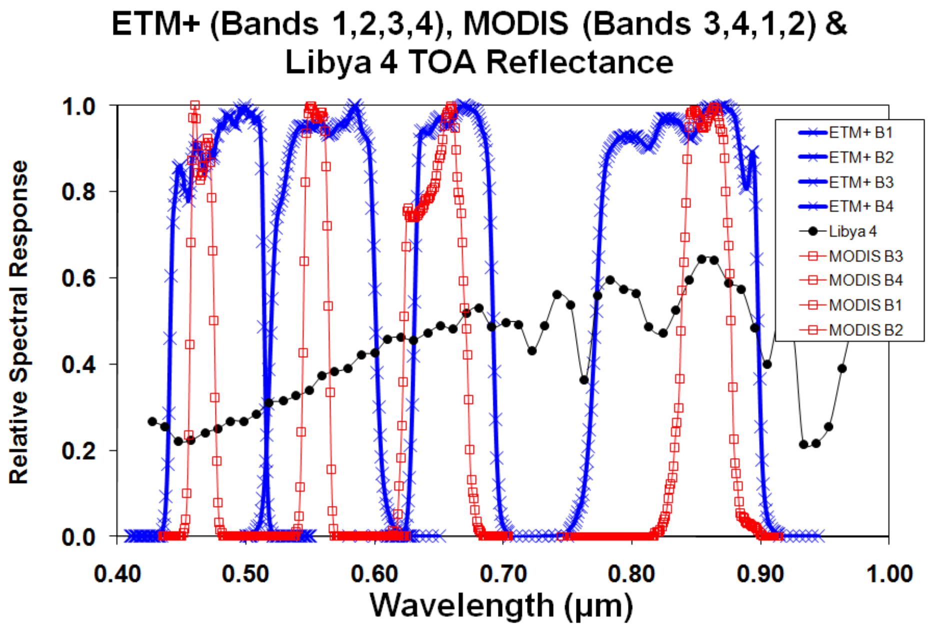


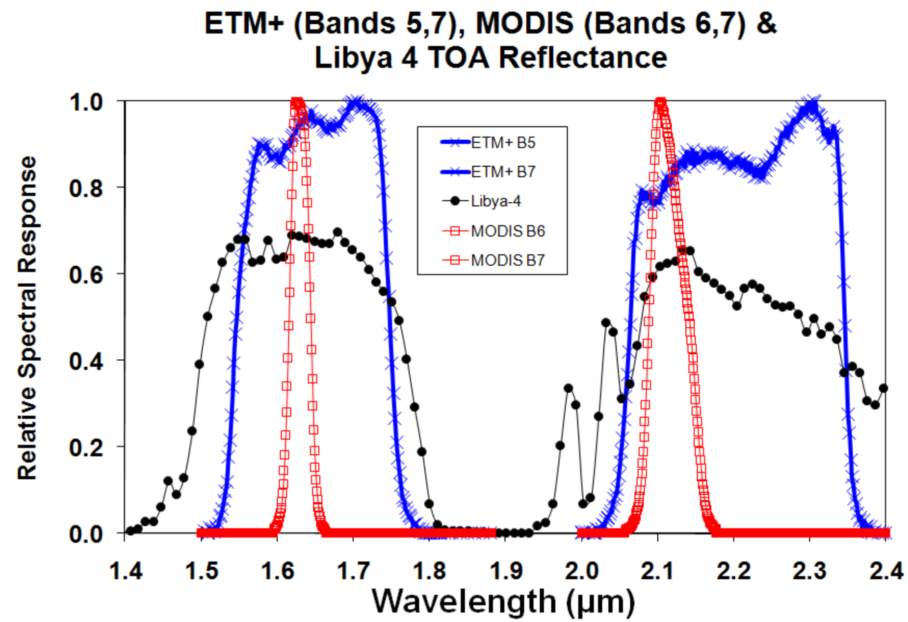


Methodology and Data Processing

- Reprojection of MODIS Level 1B (L1B) data products
- Exclusion of ETM+ SLC-off fill values and images that are contaminated due to saturation
- Selection of a homogeneous Region of Interest (ROI)
- Conversion of calibrated DN to TOA Reflectance (ρ)
- Outlier rejection conditions
  - Excluded images that were possibly contaminated with clouds using a brightness temperature threshold of 290 K
  - Excluded ROIs that have an image standard deviation (STD) greater than 0.05 reflectance units

Comparison of typical desert TOA ρ spectrum and the RSR profiles

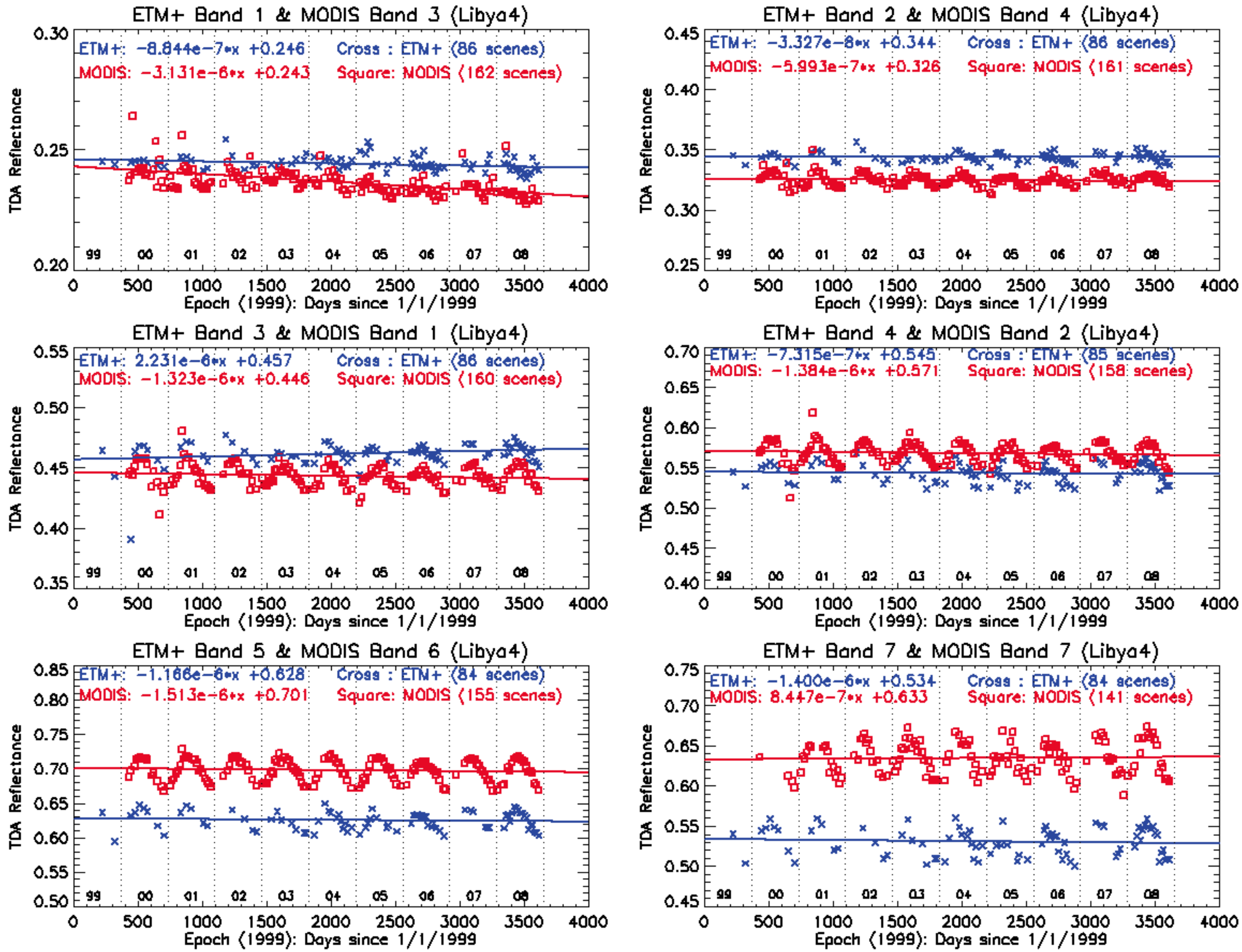




- The Libya 4 TOA ρ spectrum is increasing over the VNIR bands
  - Average ρ, as sampled by ETM+ VNIR bands, will be larger
  - Except for ETM+ B4 because of water vapor absorption feature
- In the SWIR bands, the Libya 4 TOA ρ spectrum has a Gaussian shape with the peak in the middle (near the MODIS narrow band)
  - Average ρ, as sampled by MODIS SWIR bands, will be larger

TOA ρ trending over the Libya 4 site

- Measured TOA ρ from MODIS (red squares) ETM+ (blue crosses)
- The slope of the fitted lines were ~10^{-7}/day, indicating very stable long-term response changing by no more than 0.02% per year (except B1) in their TOA reflectance
- Major contributions to offsets are caused by a combination of the spectral signature of the ROI, atmospheric composition, and the RSR of each sensor

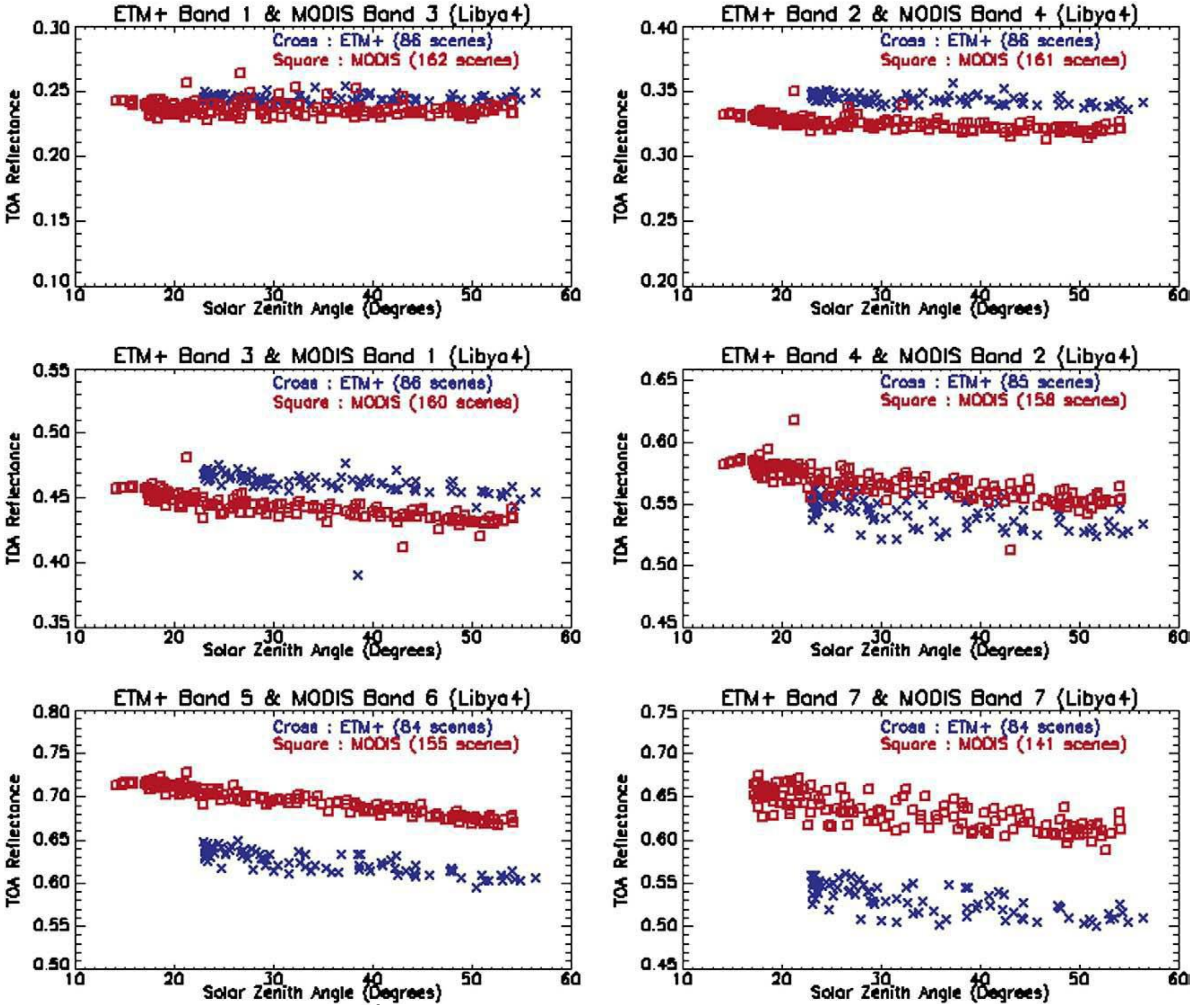


- The periodic seasonal oscillations in the TOA ρ trending is caused by the BRDF effects (while satellite zenith angle is nadir, the solar zenith angle varies significantly with season)

TOA ρ versus solar zenith angle (SZA)

- Due to 30 min difference between the overpass times, the MODIS ρ start at SZA of 14°, and the ETM+ ρ at SZA of 23°

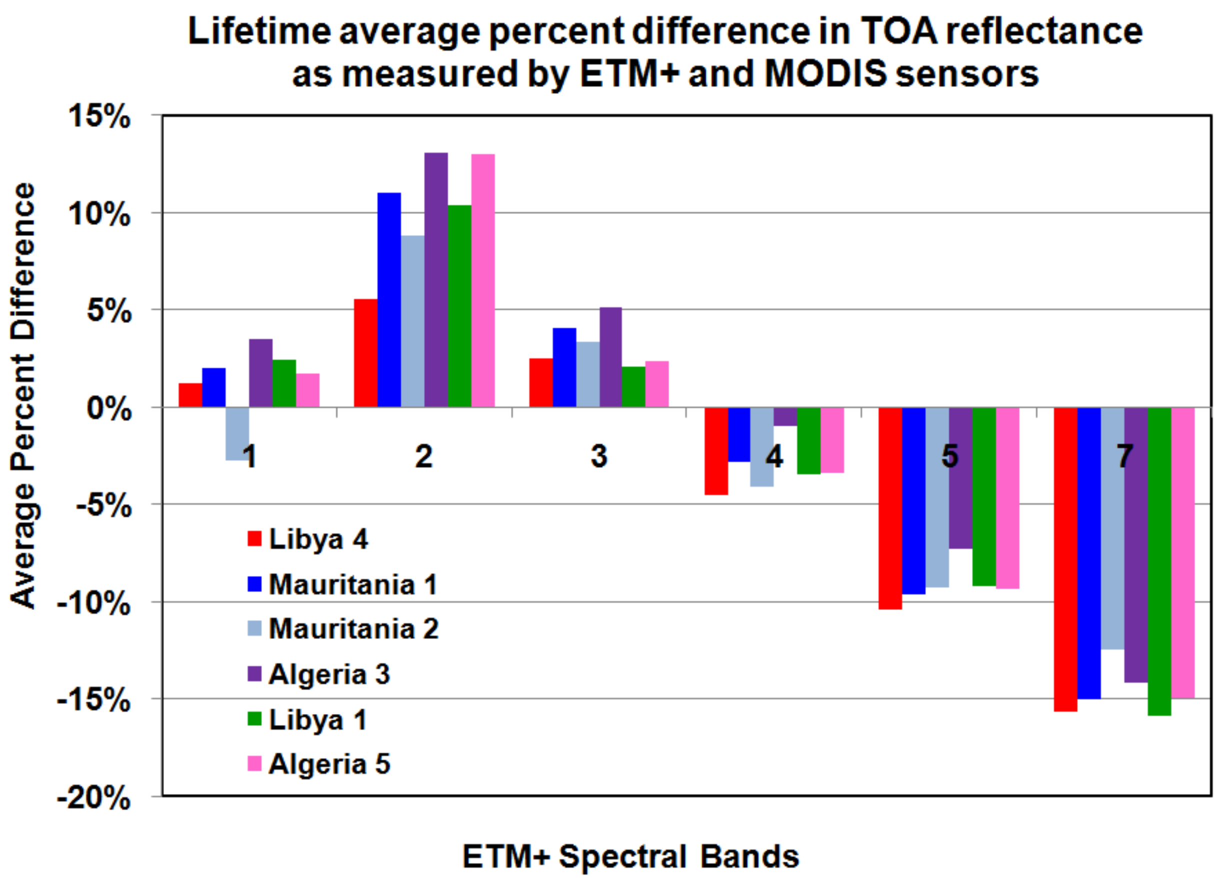
- The BRDF effect is caused by changes in the illumination geometry due to varying SZAs



Average percent difference between ETM+ and MODIS TOA ρ

- The first order cross-cal compared the TOA ρ between the two sensors without taking into account the spectral differences
- The differences in RSR leads to a systematic band offset when comparing data from two sensors over the same target

- For the Libya 4 site, the percent difference between the ETM+ and MODIS TOA ρ
  - in Band 1, is 1.23%;
  - in Band 2, 5.52%;
  - in Band 3, 2.47%;
  - in Band 4, –4.55%;
  - in Band 5, –10.41%; and
  - in Band 7, –15.64%
- For the PICS, the average percent difference in intercept from long-term trends range from 2% to 15%



Formulation for Spectral Band Adjustment Factor (SBAF)

- A compensation for differences in RSR can be made after having some prior knowledge of the spectral signature of the target
  - This adjustment factor needed to compensate for the RSR differences is named as SBAF

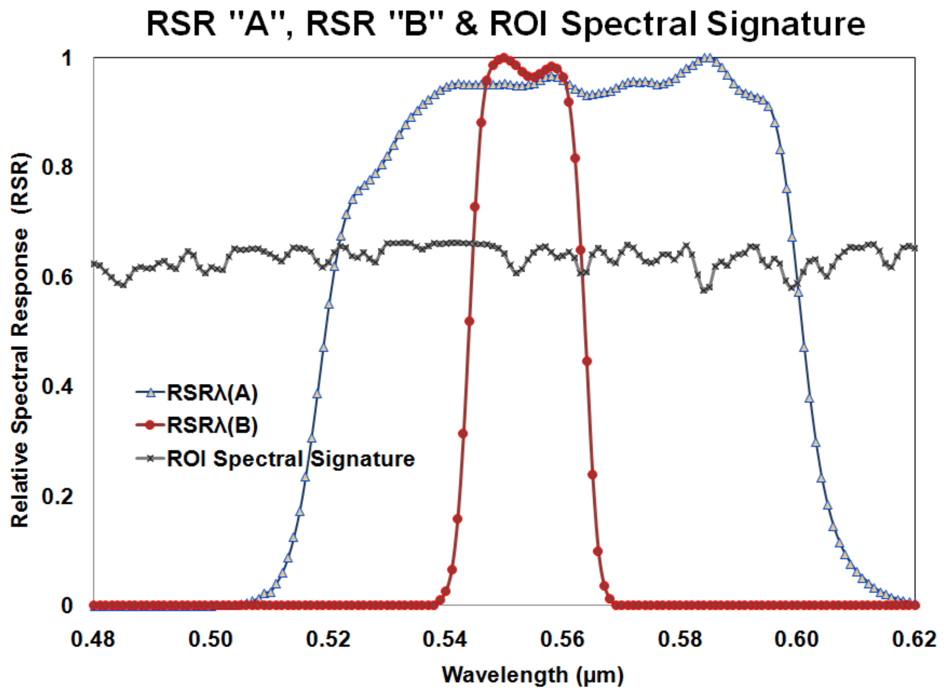
- The simulated ρ can be calculated by integrating the RSR of the sensor with the spectral signature of the target at each sampled wavelength, weighted by the respective RSR

$$\bar{\rho}_{\lambda(sensor)} = \frac{\int \rho_\lambda \, RSR_\lambda d\lambda}{\int RSR_\lambda d\lambda}$$

$$SBAF = \frac{\bar{\rho}_{\lambda(A)}}{\bar{\rho}_{\lambda(A)}} = \frac{\left(\int \rho_\lambda \, RSR_{\lambda(A)} d\lambda\right) / \left(\int RSR_{\lambda(A)} d\lambda\right)}{\left(\int \rho_\lambda \, RSR_{\lambda(B)} d\lambda\right) / \left(\int RSR_{\lambda(B)} d\lambda\right)}$$

$$SBAF = \frac{\bar{\rho}_{\lambda(ETM+)}}{\bar{\rho}_{\lambda(MODIS)}} = \frac{\left(\int \rho_\lambda \, RSR_{\lambda(ETM+)} d\lambda\right) \; / \; \left(\int RSR_{\lambda(ETM+)} d\lambda\right)}{\left(\int \rho_\lambda \, RSR_{\lambda(MODIS)} d\lambda\right) \; / \; \left(\int RSR_{\lambda(MODIS)} d\lambda\right)}$$

$$\bar{\rho}^*_{\lambda(ETM+)} = \bar{\rho}_{\lambda(ETM+)} \, / \, SBAF$$



EO-1 Hyperion Overview

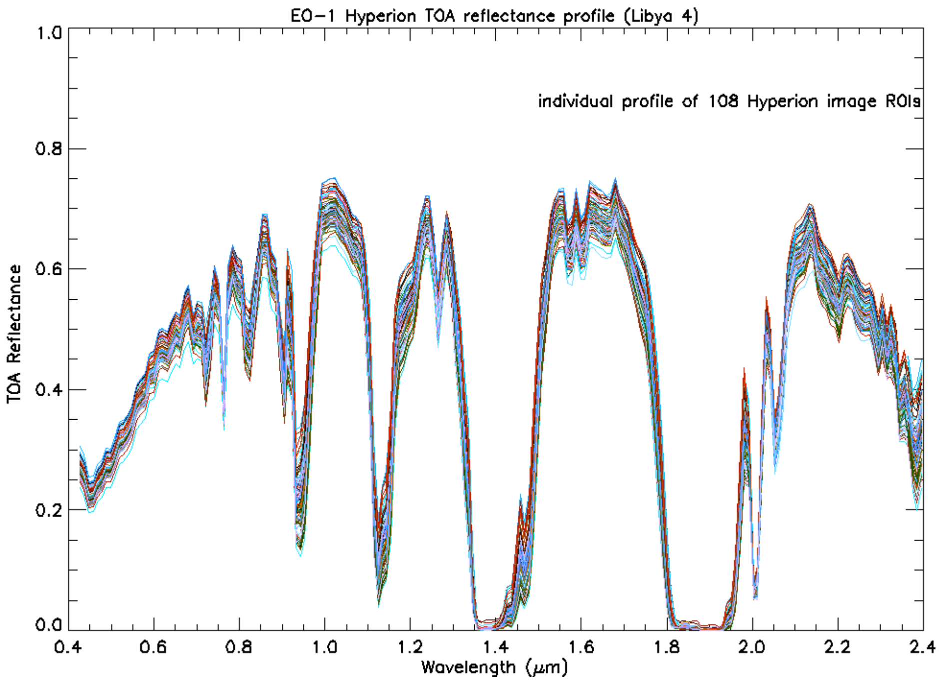
- The NASA EO-1 satellite was launched on Nov 21, 2000, as part of a one-year technology demonstration mission

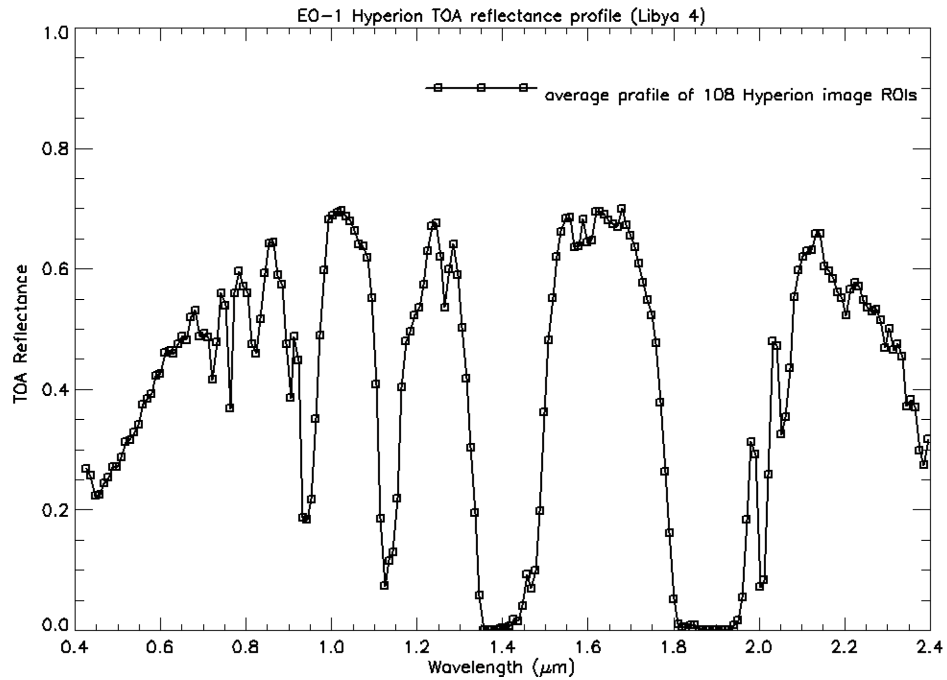
- Hyperion is a push-broom satellite hyperspectral sensor
  - Spectral range: 0.4 to 2.5 μm
  - Spectral bands: 242
  - Spectral resolution: ~10 nm
  - Spatial resolution: 30 m
  - Swath Width: 7.7 km

ETM+ bands	Bandpass (μm)	Number of Hyperion bands	MODIS bands	Bandpass (μm)	Number of Hyperion bands
1	0.45-0.52	7 (B11 - B17)	3	0.459-0.479	2 (B12 - B15)
2	0.53-0.61	8 (B19 - B26)	4	0.545-0.565	2(B20 - B21)
3	0.63-0.69	6 (B28 - B33)	1	0.620-0.670	5 (B28 - B32)
4	0.78-0.90	12 (B43 - B54)	2	0.841-0.876	4 (B49 - B52)
5	1.55-1.75	20 (B141 - B160)	6	1.628-1.652	3 (B148 - B150)
7	2.09-2.35	26 (B194 - B219)	7	2.105-2.155	5 (B196 - B200)

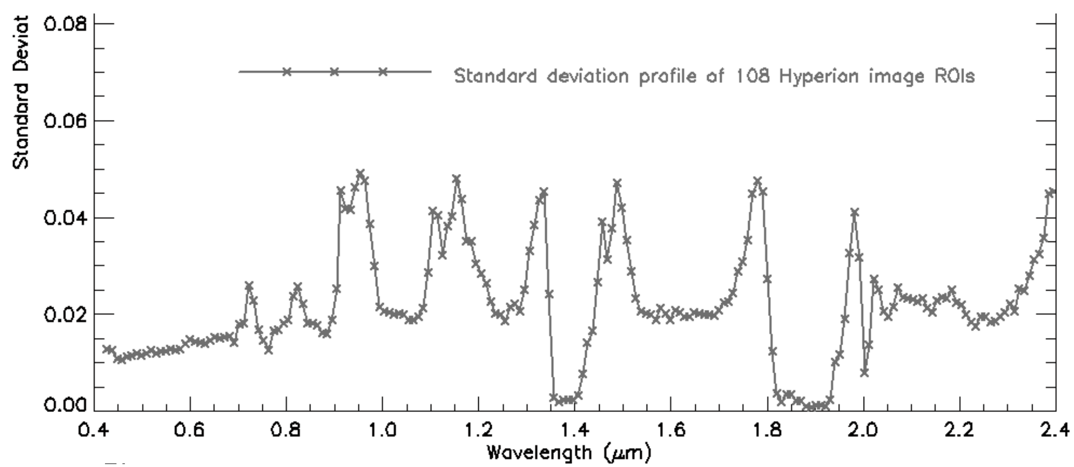
- The Level 1 Hyperion product is generated by the USGS EO-1 Product Generation System (EPGS)
  - The EPGS uses the Hyperion pre-launch calibration coefficients to radiometrically process the data

TOA ρ Profile of 108 Libya 4 Images





- Individual profiles over the Hyperion ROI
- Average TOA ρ profile of 108 Hyperion images acquired over the Libya 4 site at every 10 nm Hyperion center wavelength
- Temporal STD of the TOA ρ over the 108 profiles



SBAF with Lifetime Hyperion Data

- A 5% STD in the lifetime TOA ρ profiles from the Hyperion sensors over Libya 4 was reduced to <1% STD in SBAFs

ETM+ Bands	Simulated TOA ρ_{ETM+}	Simulated TOA ρ_{MODIS}	SBAF Average	STD of 108 SBAF
1	0.253	0.236	1.071	0.29%
2	0.368	0.356	1.034	0.22%
3	0.495	0.479	1.033	0.11%
4	0.561	0.611	0.917	0.68%
5	0.648	0.684	0.947	0.88%
7	0.539	0.618	0.871	0.61%

- Summarizes the SBAF for the PICS
- Even for similar desert land cover types, the SBAFs are not identical from site to site

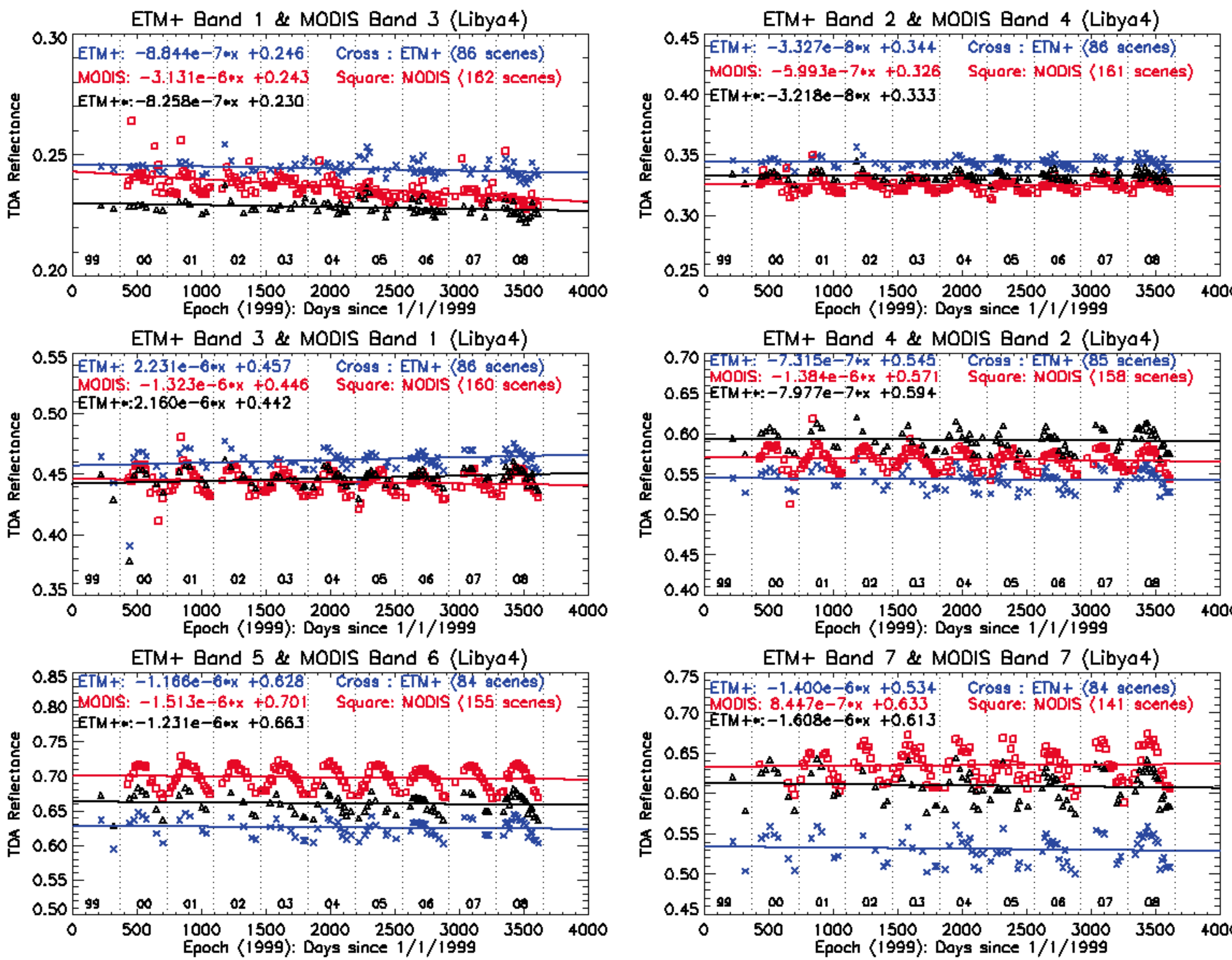
ETM+ Bands	Libya 4	Mauritania 1	Mauritania 2	Algeria 3	Algeria 5
1	1.071	1.062	1.059	1.054	1.055
2	1.034	1.084	1.084	1.065	1.086
3	1.033	1.036	1.036	1.040	1.044
4	0.917	0.929	0.926	0.927	0.920
5	0.947	0.958	0.957	0.953	0.949
7	0.871	0.874	0.879	0.871	0.861

- The STD generated using lifetime Hyperion profiles was less than 1%
  - Higher in SWIR bands because of absorption features

ETM+ Bands	Libya 4	Mauritania 1	Mauritania 2	Algeria 3	Algeria 5
1	0.29%	0.22%	0.20%	0.48%	0.38%
2	0.22%	0.55%	0.60%	0.41%	0.35%
3	0.11%	0.17%	0.13%	0.16%	0.09%
4	0.68%	1.08%	0.82%	0.71%	0.74%
5	0.88%	1.28%	1.04%	0.92%	0.99%
7	0.61%	0.87%	0.61%	0.66%	0.79%

TOA ρ trending after SBAF compensation over the Libya 4 site

ETM+ Bands	1	2	3	4	5	7
% difference before SBAF	1.23%	5.52%	2.47%	-4.55%	-10.41%	-15.64%
% difference after SBAF	-5.51%	2.04%	-0.83%	4.06%	-5.42%	-3.18%



ENVISAT SCIAMACHY Overview

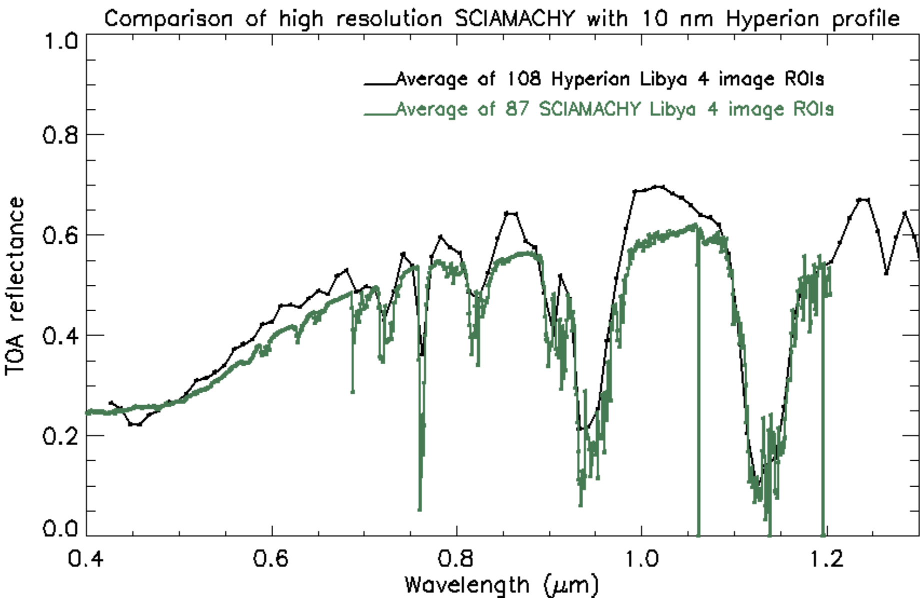
- The SCanning Imaging Absorption SpectroMeter for Atmospheric CartograpHY (SCIAMACHY) is an atmospheric sensor aboard the European Environmental Satellite (ENVISAT) launched in March 2002

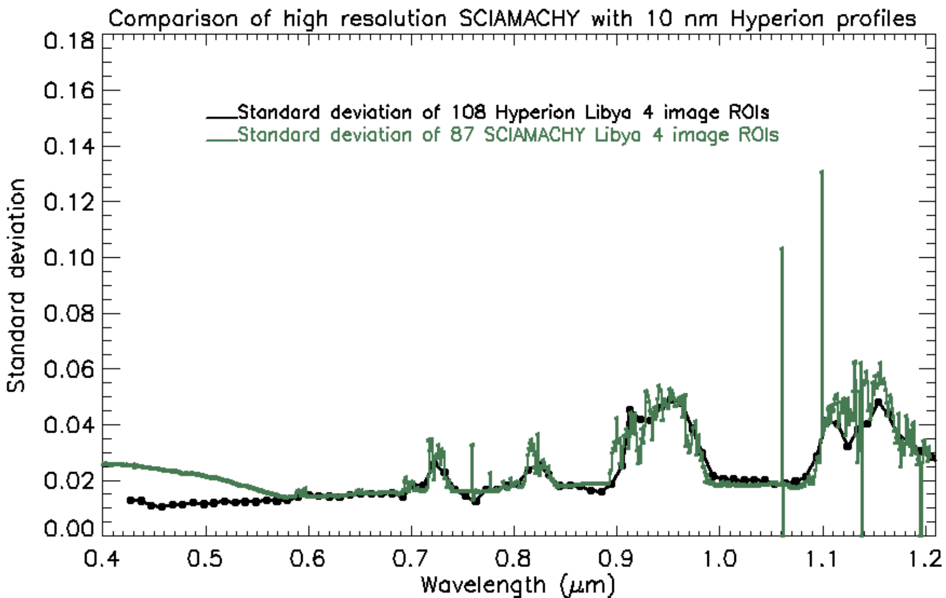
- The solar radiation transmitted, backscattered, and reflected from the atmosphere is recorded at relatively high resolution (0.2 to 0.5 nm) over the range 0.24 to 1.7 µm, and in selected regions between 2.0 and 2.38 µm

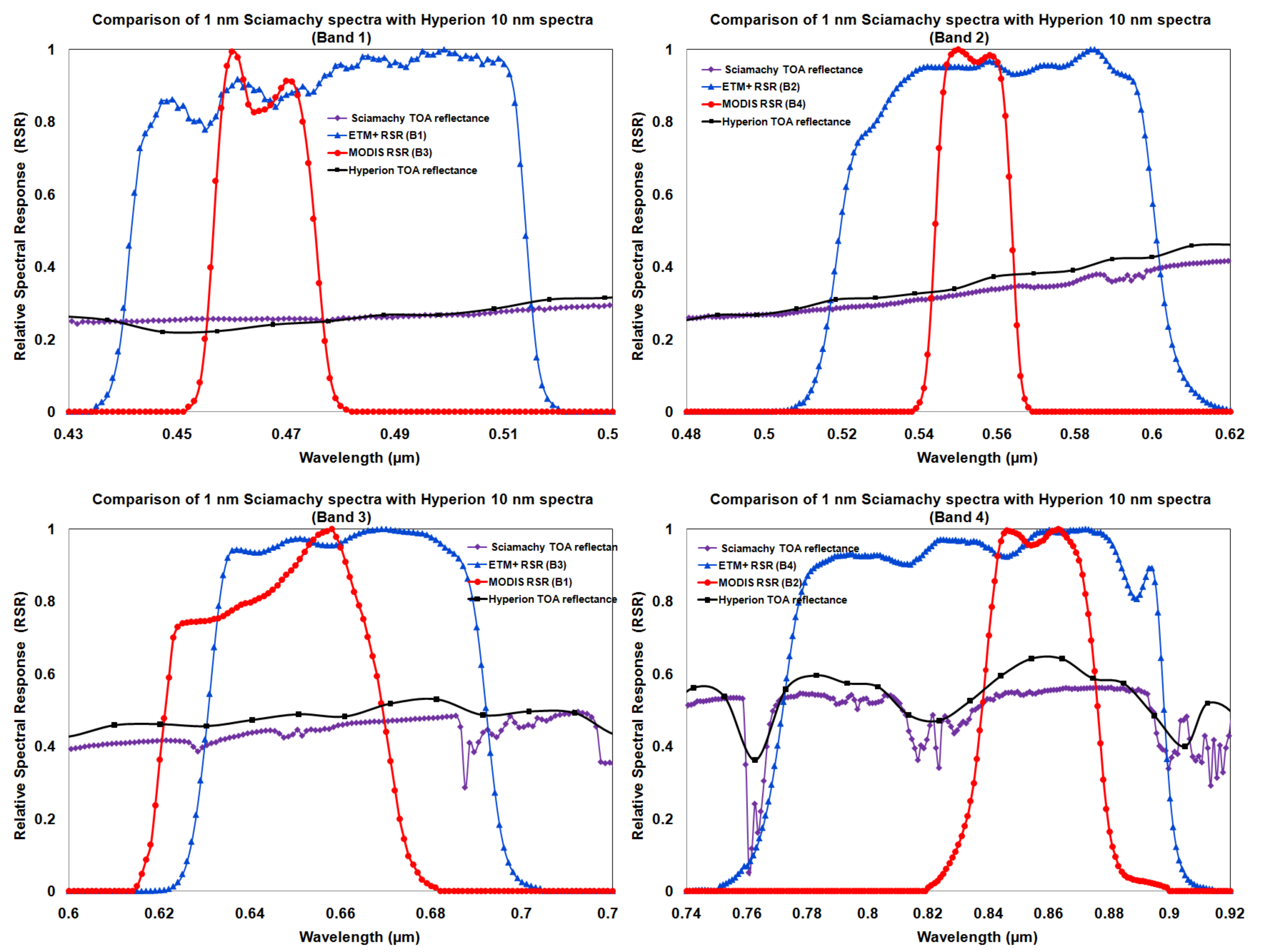
- The SCIAMACHY mission objective is to perform global measurements of trace gases in the troposphere and in the stratosphere

Comparison of SCIAMACHY and Hyperion derived TOA ρ profile

- The fine spectral resolution SCIAMACHY profile captures the absorption features better in the strong absorption bands
- The TOA ρ measured by Hyperion is higher than SCIAMACHY
- Both the Hyperion and SCIAMACHY profiles have identical temporal STD of <3% for most wavelengths used by LRS
- In the wavelengths corresponding to ETM+ and MODIS bands, the SCIAMACHY profile is spectrally smoother than the Hyperion






Comparison of 1 nm Sciamachy spectra with Hyperion 10 nm spectra (Band 1)
Sciamachy TOA reflectance
ETM+ RSR (B1)
MODIS RSR (B3)
Hyperion TOA reflectance
Relative Spectral Response (RSR)
Wavelength (µm)
0
0.2
0.4
0.6
0.8
1
0.43
0.45
0.47
0.49
0.51
0.5
Comparison of 1 nm Sciamachy spectra with Hyperion 10 nm spectra (Band 2)
Sciamachy TOA reflectance
ETM+ RSR (B2)
MODIS RSR (B4)
Hyperion TOA reflectance
Relative Spectral Response (RSR)
Wavelength (µm)
0.48
0.5
0.52
0.54
0.56
0.58
0.6
0.62
Comparison of 1 nm Sciamachy spectra with Hyperion 10 nm spectra (Band 3)
Sciamachy TOA reflectan
ETM+ RSR (B3)
MODIS RSR (B1)
Hyperion TOA reflectance
Relative Spectral Response (RSR)
Wavelength (µm)
0.6
0.62
0.64
0.66
0.68
0.7
0.7
Comparison of 1 nm Sciamachy spectra with Hyperion 10 nm spectra (Band 4)
Sciamachy TOA reflectance
ETM+ RSR (B4)
MODIS RSR (B2)
Hyperion TOA reflectance
Relative Spectral Response (RSR)
Wavelength (µm)
0.74
0.76
0.78
0.8
0.82
0.84
0.86
0.88
0.9
0.92

Hyperion 10 nm, SCIAMACHY 1 nm and SCIAMACHY 10 nm spectra

Simulated TOA ρ_{ETM+}

	Simulated TOA ρ_{ETM+}			Pecentage Difference		
ETM+ Bands	Hyperion 10 nm	SCIAMACHY 1 nm	SCIAMACHY 10 nm	HYP 10 nm and SCI 1 nm	SCI 1 nm and SCI 10 nm	HYP 10 nm and SCI 10 nm
1	0.253	0.261	0.261	-3.10%	-0.01%	-3.11%
2	0.368	0.336	0.336	9.51%	-0.03%	9.48%
3	0.495	0.448	0.448	10.33%	-0.04%	10.28%
4	0.561	0.517	0.515	8.46%	0.33%	8.83%

Simulated TOA ρ_{MODIS}

	Simulated TOA ρ_{MODIS}			Pecentage Difference		
ETM+ Bands	Hyperion 10 nm	SCIAMACHY 1 nm	SCIAMACHY 10 nm	HYP 10 nm and SCI 1 nm	SCI 1 nm and SCI 10 nm	HYP 10 nm and SCI 10 nm
1	0.236	0.256	0.256	-7.88%	0.10%	-7.79%
2	0.356	0.329	0.329	8.22%	0.02%	8.24%
3	0.479	0.438	0.438	9.31%	-0.09%	9.21%
4	0.611	0.547	0.546	11.83%	0.12%	11.96%

SBAF

	SBAF Average			Pecentage Difference		
ETM+ Bands	Hyperion 10 nm	SCIAMACHY 1 nm	SCIAMACHY 10 nm	HYP 10 nm and SCI 1 nm	SCI 1 nm and SCI 10 nm	HYP 10 nm and SCI 10 nm
1	1.071	1.019	1.020	5.18%	-0.11%	5.07%
2	1.034	1.022	1.022	1.19%	-0.05%	1.15%
3	1.033	1.024	1.023	0.93%	0.04%	0.97%
4	0.917	0.946	0.944	-3.01%	0.21%	-2.80%

Effects of SBAF on lifetime Libya 4

ETM+ Bands	Measured TOA ρ_{ETM+} (E)	Measured TOA ρ_{MODIS} (M)	Adjusted TOA ETM+ (E*)	% difference (E-M)/M% before SBAF	% difference (E*-M)/M% after SBAF
1	0.246	0.243	0.230	1.23%	-5.51%
2	0.344	0.326	0.333	5.52%	2.04%
3	0.457	0.446	0.442	2.47%	-0.83%
4	0.545	0.571	0.594	-4.55%	4.06%

Results using an average lifetime Hyperion 10 nm derived SBAFs

ETM+ Bands	Measured TOA ρ_{ETM+} (E)	Measured TOA ρ_{MODIS} (M)	Adjusted TOA ETM+ (E*)	% difference (E-M)/M% before SBAF	% difference (E*-M)/M% after SBAF
1	0.246	0.243	0.241	1.23%	-0.62%
2	0.344	0.326	0.337	5.52%	3.26%
3	0.457	0.446	0.446	2.47%	0.09%
4	0.545	0.571	0.576	-4.55%	0.93%

Results using an average lifetime SCIAMACHY 1 nm derived SBAFs

ETM+ Bands	Measured TOA ρ_{ETM+} (E)	Measured TOA ρ_{MODIS} (M)	Adjusted TOA ETM+ (E*)	% difference (E-M)/M% before SBAF	% difference (E*-M)/M% after SBAF
1	0.246	0.243	0.241	1.23%	-0.72%
2	0.344	0.326	0.336	5.52%	3.21%
3	0.457	0.446	0.447	2.47%	0.13%
4	0.545	0.571	0.578	-4.55%	1.14%

Results using an average lifetime SCIAMACHY 10 nm derived SBAFs

Summary and Lessons Learned

- This study focused on using near-simultaneous observations from ETM+ and MODIS sensors in the reflective solar band spectral domain
- Cross-cal based on TOA reflectances ranged from 2% to 15% (without taking into RSR differences)
- Spectral issues with this cross-cal approach were investigated
  - The RSR adjusted ETM+* TOA ρ were found to agree with MODIS TOA ρ to within 6% or better for all bands using Hyperion derived SBAFs
  - These differences were reduced to less than 1% for all VNIR bands (except Band 2) by using SCIAMACHY derived SBAFs

Lessons Learned from SBAF

- Relative spectral radiometric calibration of the hyperspectral sensor is more critical than its spectral resolution
- SBAFs are more affected by the shape of the spectral profile of the target than by the magnitude the profile
- Even for similar land cover types, the SBAFs are not identical from site to site