EO-1 Science Validation Work
Final Report on:
"Inter-Sensor Calibration of Vegetation Indices for Monitoring and Continuity Studies"
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Alfredo R. Huete,
Hiroki Yoshioka,
M. Susan Moran, and
Tomoaki Miura

This project aimed to optimize vegetation index (VI) continuity across different sensors by taking advantage of EO-1 satellite technologies, namely the Hyperion and ALI sensors. In a project duration period of 2 years and 10 months, we accomplished the following objectives and tasks:

- Development of an empirical and theoretical framework to approach the problems of multi-sensor VI continuity/compatibility,
- An identification of several "key" factors that would allow for VI continuity/compatibility to be successfully accomplished, thru empirical and theoretical investigations,
- Development of a VI translation algorithm,
- An application of the developed translation algorithm to the NDVI and validation using EO-1 Hyperion and ALI data,
- A performance evaluation of the hyperspectral Hyperion sensor on land cover conversion/characterization/degradation studies in semi-arid lands and savannah,
- Development of an integrated PC and UNIX, Hyperion processing facility.

1. INTRODUCTION

Numerous satellite sensor systems useful in terrestrial Earth observation and monitoring have recently been launched and satellite-derived products from these fine and moderate resolution sensors are increasingly being used in regional and global vegetation studies. Moderate resolution sensors have coarse pixel sizes (100 m to 1000 m) but frequent revisit periods (1 – 4 days) and their observations are useful for change detection, monitoring of ecosystem seasonality, inter-annual variations for climate change studies, land cover change studies, and input to net primary and net ecosystem production (NPP, NEP) models. Fine resolution sensors are capable of capturing more detailed vegetation dynamics related to land conversion and ecosystem management with pixel sizes typically ranging from 30 m to <1 m (Landsat, Ikonos, Quickbird).

The use of multi-resolution satellite data observations can help advance our understanding and analysis of the terrestrial carbon cycle and aid in mapping ecosystem variability including land cover conversions. Multi-sensor data may be exploited by combining fine- with moderate resolution sensors for scaling studies (e.g. ASTER and MODIS) and seasonality studies (e.g. Landsat ETM+ with MODIS).

A common feature of these satellite sensor systems is their inclusion of red and near-infrared (NIR) spectral bands for vegetation studies. These two bands exhibit sensitivity to chlorophyll concentrations and leaf structure and quantity. They are typically ratioed or linearly combined to create vegetation indices (VI’s) to more accurately map spatial and temporal variations in the Earth’s vegetative cover. There is currently a 20+ year, time series data record of normalized difference vegetation index (NDVI) values from the NOAA- AVHRR series of satellite sensors which could be extended with the newer satellite data products (Los, 1993; Roderick et al., 1996). The Landsat series of sensors have also produced an archived data set that can be processed into useful information for global change studies. Vegetation index products from the AVHRR, SeaWiFS, VEGETATION, MODIS, Landsat, and other sensors are now being used to monitor both seasonal and long-term land cover changes. Consequently, there is great interest in maintaining data continuity and compatibility across the sensor-specific data sets (Gitelson and Kaufman, 1998).

Compatibility problems among the satellite data products exist due to differences in sensor characteristics and the algorithms used to process the data. The spectral characteristics of the red and NIR bands vary greatly among sensors in their filter response functions, bandwidths, and center wavelength (Fig. 1,2). There are also radiometry (signal to noise), spatial (point spread function and pixel size), and temporal (revisit times) differences as well.

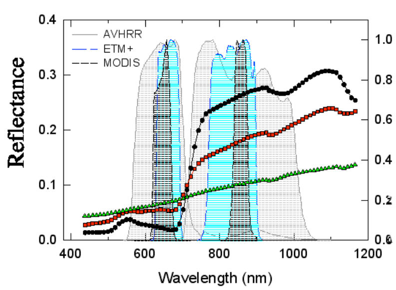

Figure 1. MODIS, Landsat ETM+, and NOAA-AVHRR normalized bandpass filters superimposed onto three hyperspectral reflectance signatures (Miura et al., 2002).

In Fig. 1, the normalized red and NIR spectral response functions of the AVHRR, ETM+, and MODIS bands are shown over three typical spectral reflectance signatures of soil, medium- and dense vegetation. The MODIS bands are very narrow in comparison with the coarse AVHRR bands, while the ETM+ bands are intermediate in width. The red and NIR band centers, as well as bandwidths are shown for 14 moderate and fine resolution sensors in Fig. 2. There appears to be an inverse trend of red bandwidth vs. center wavelength (Fig. 2a). The sensor contrasts, or distance, between the center NIR and red wavelengths are as short as 150 nm (ASTER) to as far apart as 300 nm (Landsat MSS).

The goal of VI continuity is to normalize the spectral, temporal, spatial, and radiometric differences among sensors for the purposes of (1) extension of stable time series data sets for monitoring ecosystem change; and (2) for scaling studies from fine resolution to moderate resolution satellite data sets. We consider VI continuity to be attained when the VI values computed from the reflectance data produced by the different sensors become the same for the same target under identical conditions (Yoshioka et al., 2002). The issue of data product continuity is particularly relevant to the inter-relationships between the AVHRR time series record (1981-) with MODIS (2000 -) and other moderate resolution sensors; the extension of AVHRR and MODIS data records to the NPOESS Preparatory Project (NPP); and the synergistic use of fine (Landsat, ASTER) and moderate (MODIS, SeaWiFS, AVHRR, GLI, VEGETATION) resolution sensors.

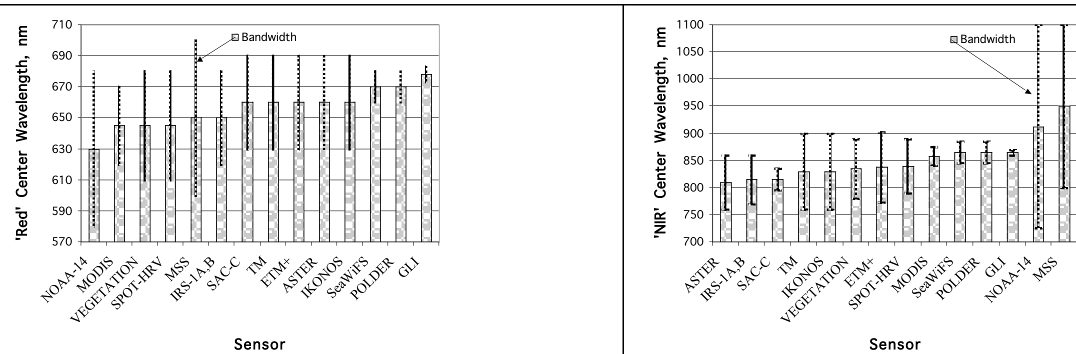

Figure 2. Variations in red (left) and NIR (right) wavelength centers and bandwidths for a variety of satellite sensors ranked in order of increasing wavelength center.

2. APPROACHES TO THE ISSUES OF DATA CONTINUITY

Throughout our work, we considered VI continuity/compatibility to be attained when the VI values computed from the reflectance data produced by the different sensors become the same for the same target under identical conditions.

Our VI continuity analysis was based on a multi-tier approach:

- Multi-scale extension involving simultaneous coarse to fine scale acquisitions: vertical (multi-scale) extension in VI's, such as continuity between MODIS and ETM+ (or ASTER and SPOT),
- Horizontal continuity across moderate/coarse resolution sensors: horizontal continuity across a series of moderate/coarse resolution sensors including MODIS, SeaWiFS, GLI, and AVHRR,
- Historical continuity couple to the AVHRR-NDVI time series record: 'historical' continuity through a coupling of MODIS and the AVHRR-NDVI time-series data record

We have taken four ways to approach the multi-sensor data continuity and to provide inter-sensor translation coefficients:

1) Use 'real' satellite sensor observations from multiple instruments. The advantages are that this the real data from which we wish to establish translation and encompasses all

sources of uncertainty, including filter degradation and calibration drift. With this approach, one can also encompass a global set of land cover and seasonal surface conditions for the sensor comparisons. The main disadvantages include the time intervals between different sensor 'looks' to the same target with possible variations resulting from sun angle and atmosphere differences. One must also be precise in co-registration of the two sensor data sets with uncertainties resulting from geolocation error.

2) One can utilize a finer resolution sensor data set to simulate the responses of a coarser resolution sensor data set. Thus, we can utilize hypersepctral and fine spatial resolution Hyperion data to simulate a MODIS, SeaWiFS, AVHRR, and GLI pixel. The advantage is that only a single atmosphere is involved and there are no spatial registration errors. The disadvantage is that the data is synthetic and the spectral response functions and modulation transfer function (MTF) need to be approximated.
3) One can also utilize low level airborne and field-based field ratiometery, such as Analytical Spectral Devices (ASD) data. This has the advantage of eliminating the sensor-dependent atmosphere effects enabling one to focus on inter-sensor comparisons related to the ecosystem targets of interest. This is useful from a spectral standpoint but has less utility in studying the spatial pixel size inter-dependencies between sensors.
4) Finally, one can mathematically derive inter-relationships among sensors through models, including leaf biochemical models, soil models, canopy radiative transfer models, and atmosphere radiative transfer models. This has the advantage of complete control of surface, atmosphere, and sensor effects. The main limitation concerns the extent to which modeled data depicts actual sensor-target results, particularly over heterogeneous surfaces.

2. SUMMARY OF RESEARCH RESULTS

2-1. Empirical and Theoretical Investigations of the Continuity/Compatibility of the Broadband Reflectances and VIs

We investigated continuity/compatibility of the broadband reflectances and VIs across sensors. Data sets from various sources were used, including EO-1 Hyperion and ALI data, low-altitude airborne, "top-of-canopy" ASD reflectance data, soil-canopy-atmosphere radiative transfer modeling, near simultaneously-acquired, "real" ETM+, AVHRR, and MODIS data. VIs analyzed included the NDVI and EVI. Our analyses focused on the spectral issue (spectral characteristics of multiple sensors and their influences on the derived VI values). The sensors considered in spectral syntheses were MODIS, AVHRR series, SeaWiFS, VEGETATION, GLI, MSS, ETM+, and ALI. The major findings were that:

- VI relationships among sensors were neither linear nor unique and were found to exhibit complex patterns and dependencies on spectral bandpasses.
- From the radiometric point of view, an inclusion of the "red-NIR transitional" zone, a diagnostic spectral feature of photosynthetically-active vegetation (PV), to either red or NIR bandpasses is the "key" in producing the complex patterns in across-sensor VI relationships. Thus, simply taking a weighted average of several narrow bands of one sensor does not approximate any broad band of another sensor (e.g., an average of MODIS green and red band for AVHRR channel 1) for VI continuity purposes, given atmospheric effects have been corrected.

- From the biophysical point of view, inter-sensor VI relationships varied with land cover types and surface compositions. Thus, a prior knowledge of such ecosystem parameters as leaf area index (LAI) and soil brightness are needed for exact translation.
- Atmospheric contaminations were found to increase the discrepancies and land cover dependencies of inter-sensor VI relationships, of which magnitudes depends both on level of atmospheric contaminations and on amount of PV (e.g., LAI).
- Other factors of cloud and BRDF-related influences might affect the resulting NDVI values to a much greater extent than spectral bandpass differences.

2-2. Development and Validation of a VI Translation Algorithm

An algorithm for exact translation of multi-sensor VIs was developed based on the "vegetation isoline" concept. The algorithm has been designed to take ecosystem parameters (i.e., LAI and soil brightness) of targets into account, and reduce systematic differences of the index values. Likewise, it can be applied to any two-bands spectral vegetation indices. The algorithm was applied to exact translation of the NDVI across sensors. Its performance was tested with Hyperion, ALI, and ETM+ data, and compared with non-translated NDVI differences and translation results by simply fitting linear equations. The developed NDVI translation algorithm resulted in a significant reduction of systematic differences of the index values due to spectral band pass differences, e.g., between MODIS and ETM+ from .03 to .0004.

The previously developed vegetation isoline equation for a canopy-soil system was also extended to include atmosphere in the system (i.e., an atmosphere-canopy-soil system) and successfully used for a continuity analysis from AVHRR and MODIS to GLI sensors in quantifying the impact of water vapor contents and LAI values on the discrepancies between MODIS/GLI and AVHRR.

2-3. Land Cover Conversion and Degradation Analyses in the Ñacuñán Reserve, Argentina Using EO-1 Hyperion

Land degradation in arid and semi-arid areas result from various factors, including climate variations and human activity, and can lead to desertification. The process of degradation results in simultaneous and complex variations of many interrelated soil and vegetation biophysical parameters rendering it difficult to develop simple and robust remote sensing mapping and monitoring approaches. In this study we tested the use of EO-1 Hyperion hyperspectral data to analyze land conversion and degradation patterns within the protected Ñ acuñán Biosphere Reserve and surrounding degraded areas within the Mendoza region of Argentina. The floristically diverse vegetation communities included mesquite forest (algarrobal), sand-dune (medanal), creosotebush (jarillal), and severely degraded (peladal) sites. Various optical measures of land degradation were employed, including vegetation indices, spectral derivatives, albedo, and fractional multi-component images derived from spectral mixture analysis. Broadband-based spectral vegetation indices and narrowband spectral derivative indices were found to be limited in characterization of land degradation. Spectral mixture analysis provided a means to simultaneously analyze spatial variations in photosynthetic-active vegetation (PV), non-photosynthetic vegetation (NPV), and soil brightness provided a useful basis for characterizing the unstable and spatially variable landscape dynamics found at the Ñacuñán Biosphere Reserve. Overall, the hyperspectral information obtained from the Hyperion sensor was more useful in characterizing land degradation than the methods more commonly employed from current broadband sensors.

2-4. Discrimination and Characterization of Land Cover Types and Conversions in Brazilian Savannah Using EO-1 Hyperion

The savanna, typically found in the sub-tropics and seasonal tropics, are the dominant vegetation biome type in the southern hemisphere, covering approximately 45 % of the South America. In Brazil, the savanna, locally known as "cerrado", is the most intensely stressed biome with rapid and aggressive land use conversions. Better characterization and discrimination of cerrado land cover types are needed in order to improve assessments of the impact of these land cover conversions on carbon storage, nutrient dynamics, and the prospect for sustainable land use in the Amazon region. In this study, we explored the utility of hyperspectral remote sensing in improving discrimination and biophysical/biochemical characterization of the cerrado land cover types by taking advantage of a newly available satellite-based, hyperspectral imaging sensor, "EO-1 Hyperion". A Hyperion image was acquired over the Brasilia National Park (BNP) and surrounding areas in Brasilia on July 20, 2001. Two commonly-used techniques, spectral derivatives and spectral mixture modeling, were applied to the atmospherically-corrected Hyperion scene. Derivative spectroscopy was useful in analyzing variations in spectral signatures and absorption depths, while spectral mixture modeling provided a means to simultaneously analyze variations in component fractions of photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV), and soil brightness. Data sets were extracted over a range of land cover types typically found in the Brazilian Cerrado. These included cerrado grassland, shrub cerrado, wooded cerrado, and cerrado woodland as undisturbed cerrado land cover types, and gallery forest as an undisturbed forest cover type in the Cerrado domain, and cultivated pasture as a converted land cover. In the derivative spectra analysis, both the position and magnitude of the red edge peak, and the ligno-cellulose absorptions at 2090nm and around 2300nm wavelengths showed large differences among the land cover types with the absorption depth of the latter correlating well with ground-measured % NPV cover. The multi-component fractional estimates successfully discriminated pasture and gallery forest from other cerrado land cover types. Likewise, PV and NPV fractional estimates for cerrado land cover types correlated well with ground-measured % green and NPV covers, respectively. These analyses showed a great potential of hyperspectral data in biophysical/biochemical characterization as well as discrimination of the land cover types in the Brazilian cerrado.

3. Summary of Major Findings (Vegetation Indices)

VI compatibility between any two sensors includes the issue of VI continuity, since the compatibility problems come from the differences in sensor characteristics and algorithms. If one has a technique to solve VI compatibility issues, one can also solve VI continuity problems. In this proposal, we represent the whole VI compatibility issues as VI continuity. In order to clarify the issue of VI continuity and the uniqueness of our proposed approach, we start with a definition of VI continuity:

> **Definition**. A VI is continuous if the VI values computed from the reflectance data produced by the two different sensors, become the same for the same target under the identical condition.

Two approaches have mainly been used to ensure the continuity of reflectance and VI products. The first approach is to cross-calibrate the reflectance values, hence VIs, from one sensor to another on a per-band basis. This approach is quite useful and met with a great success for the sensors from a similar series, such as the NOAA-AVHRR sensor series and the Landsat MSS, TM and ETM+ sensor series. The second approach, which was proposed for the AVHRR-MODIS NDVI continuity, is to reproduce and simulate broad band AVHRR reflectance by taking a weighted average of two or more narrow MODIS bands so that VI values from the two sensors become the same. We note that, in these "empirical" techniques, the reflectance and VI products from the new sensor may need to be 'degraded' to the same level of the previous products through adjustment of better sensors' reflectance and VI values to that of worse sensors. Thus, one can not possibly take full advantages of enhanced sensor capabilities.

We investigated the continuity issues of reflectance and VI products using model simulations, field measurements, hyperspectral imagery, and "real" satellite observations. The major findings are listed below:

- VI relationships among sensors were neither linear nor unique and were found to exhibit complex patterns and dependencies on spectral bandpasses (Miura et al., 2002, 2003; Huete et al., 2002b).
- From the radiometric point of view, an inclusion of the green peak at around 550 nm and "red-NIR transitional" zone from 680 nm to 780 nm, diagnostic spectral features of photosynthetically-active vegetation (PV), to either red or NIR bandpasses are the "key" in producing the complex patterns in across-sensor VI relationships. Thus, simply taking a weighted average of several narrow bands of one sensor does not approximate any broad band of another sensor (e.g., an average of MODIS green and red band for AVHRR channel 1) for VI continuity purposes unless the narrow bands used are properly positioned and have widths to include specific part of the green peak and red-NIR transitional regions (Miura et al., 2003).
- From the biophysical point of view, inter-sensor VI relationships showed "target-dependencies", varying with land cover types and surface compositions. Thus, a prior knowledge of such ecosystem parameters as leaf area index (LAI) and soil brightness are

needed for exact translation (Yoshioka et al., 2003; Huete et al., 2002b; Miura et al., 2002, 2003).

- Atmospheric contaminations were found to increase the discrepancies and land cover dependencies of inter-sensor VI relationships, of which magnitudes depends both on level of atmospheric contaminations and on amount of green vegetation (e.g., LAI) (Miura et al., 2002; Huete et al., 2002b).
- Other factors of cloud and BRDF-related influences might affect the resulting VI values to a much greater extent than spectral bandpass differences (Huete et al., 2002b).
- Landsat TM sensor series and ETM+ sensor data were proven to be inter-changeably useable without translations (Bryant et al., 2003).

These findings led to the development of a theoretical approach to take into account ecosystem parameters (e.g., LAI and soil brightness) and to develop algorithms that will theoretically guarantee 'exact' translations (Yoshioka, 2003a; Yoshioka et al., 2003). Using our recently developed approach of Yoshioka (2003a), we have theoretically justified the existence of and derived the functional shape of inter-relating VIs from two sensors based on the physics of atmosphere-vegetation-photon interactions.

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