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Imaging spectrometer emulates Landsat: A case study with Airborne Visible Infrared Imaging Spectrometer (AVIRIS) and Operational Land Imager (OLI) data

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ABSTRACT

Remote sensing data are most useful if they are available with sufficient precision, accuracy, spatiotemporal and spectral sampling, as well as continuity across decades. The Landsat and Sentinel series, as well other satellites are currently covering significant parts of this observational trade space. It can be expected that growing demands and budget constraints will require new capabilities in orbit that can address as many observables as possible with a single instrument. Recent optical performance improvements of imaging spectrometers make them true alternatives to traditional multispectral imagers. However, they are much more adaptable to a wide range of Earth observation needs due to the combination of continuous high spectral sampling with spatial sampling consistent with previous sensors (e.g., Landsat). Unfortunately, there is a knowledge gap in demonstrating that imaging spectroscopy data can substitute for multi-spectral data while sustaining the long-term record. Thus, the objective of this analysis is to test the hypothesis that imaging spectroscopy data compare radiometrically with multi-spectral data to within 5%. Using a coincident Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) flight with over-passing Operational Land Imager (OLI) data on Landsat 8, we document a procedure for simulating OLI multi-spectral bands from AVIRIS data, evaluate influencing factors on the observed radiance, and assess the difference in top-of-atmosphere radiance as compared to OLI. The procedure for simulating OLI data include spectral convolution, accounting for the minimal atmospheric effects between the two sensors, and spatial resampling. The remaining differences between the simulated and the real OLI data result mainly from differences in sensor calibration, surface bi-directional reflectance, and spatial sampling. The median relative radiometric difference for each band ranges from −8.3% to 0.6%. After bias-correction to minimize potential calibration discrepancies, we find no more than a 1.2% relative difference. This analysis therefore successfully demonstrates that imaging spectrometer data can contribute to Landsat-type or other multi-spectral data records. It also shows that cross-calibration from a spectrometer to a radiometer can be easily performed as a result of the imaging spectrometer high spectral sampling and its ability to recreate multi-spectral response functions.

1. Introduction

Earth scientists and resource management decision makers have need for a long-term continuous data record of remote sensing observations of geophysical parameters (e.g., radiance, reflectance, and derived data products) (NRC, 2013, 2007). Optimally, data records should span decades while the observational technologies change on much shorter time spans. New instruments are launched to continue the land imaging record (e.g., Landsat 1-8+ or Sentinel 2; Drusch et al., 2012). Each instrument, however, has slightly different capabilities (e.g., signal to noise ratio (SNR), spatial and spectral sampling and coverage, etc. – Table 1). Those factors all affect the quality of the measurements from which geophysical data products were derived. Furthermore, even if a new sensor is built to the exact specifications of a previous sensor, observations would not align as the satellite orbit drifts (Beck et al., 2011) or the spectral response of filters can change and other sensor degradations may appear over time (Chander and Markham, 2003; Gutman, 1999). For example, Landsat 4, 5 and 7 were all built to comparable specifications and use similar surface reflectance retrieval algorithms (USGS, 2017), however differences in their retrievals at any given time may be a result of on-board calibrator drift or degradation of the imaging system (Bachmann et al., 2015; Mishra

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Table 1
Instrument specifications for Landsat 7's ETM+, the Landsat 8's Operational Land Imager (OLI) and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) instruments.

Enhanced Thematic Mapper Plus (ETM+) on Landsat 7	Operational Land Imager (OLI) on Landsat 8	Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)
Orbital, sun-synchronous, 705 km altitude		Sub-orbital, ~21 km altitude
Whiskbroom	Pushbroom	Whiskbroom
9-bit radiometric resolution (8-bit transmitted)	12-bit radiometric resolution	16-bit radiometric resolution
185 km swath, 15° FOV		11 km swath, 30° FOV
30/15 m ground sampling		15 m ground sampling
Terrain corrected with cubic convolution		Orthorectified

et al., 2016).

Resolving differences in observed radiance or derived reflectance can be even more difficult when sensors are designed differently. For example, Landsat 8's Operational Land Imager (OLI) was built to improve upon previous Landsats by improving calibration and instrument performance, specifically SNR, as well as higher radiometric resolution and spectrally narrower bands by using a pushbroom optical configuration, instead of a scanning system. These improvements affect data continuity. For example, when comparing data from Landsat 7's Enhanced Thematic Mapper Plus (ETM+) and OLI on Landsat 8 (Irons et al., 2012), Holden and Woodcock (2016) found that surface reflectance in the blue band was lower for OLI than for ETM+ and attributed this to either differences in atmospheric correction or to differences in calibration. Specific to the different scanning methods, Landsats 4–7 use oscillating mirrors that sweep the detectors' field of view *across* track (i.e., "whiskbroom"), while OLI uses long-linear detector arrays with thousands of detectors per spectral band to scan *along* track (i.e., "pushbroom"). Although the pushbroom scanning method enhances sensitivity of the instrument and reduces moving parts, thus increasing instrument life duration, cross calibrating thousands of detectors to achieve uniform sensitivity across detector arrays introduces an additional complication to data analysis. Furthermore, changes in the spectral response functions complicate direct comparisons between sensor observed values (e.g. Roy et al., 2016a).

Although much attention has been given to the consistency of multi-spectral sensor retrievals through time, less attention has been given to the consistency between multi-spectral and imaging spectroscopic data. Although historic imaging spectrometers (i.e., Hyperion, Chris, HJ-1A) had relatively low sensor performances (e.g. SNR, spatial sampling and coverage), technology has much improved and future imaging spectrometers in space (i.e., Resurs-P, DESIS, CCRSS, PRISMA, CartoSat-3, EnMAP, HISUI, HYPXIM, Shalom, Sentinel-10, as well as HyspIRI) can be expected to prove valuable for augmenting the multi-spectral record with their enhanced information content.

Multiple studies have demonstrated the value added (Table 2) and significant improvement of an imaging spectrometer over a multi-spectral radiometer for many applications. Value added from an imaging spectrometer comes from both high-dimensionality (Moskal et al., 2001; Platt and Goetz, 2004; Schimel et al., 2013; Veraverbeke et al., 2014; Thompson et al., 2017) and use of narrow bands that capture specific spectral traits (Lee and Cohen, 2002; Ustin and Gamon, 2010). Lastly, using high-spectral resolution to retrieve leaf traits outperforms the use of broad spectral bands (Shiklomanov et al., 2016).

To demonstrate that imaging spectroscopy data can augment observations from broadband multi-spectral sensors in time and space, we need to show that imaging spectroscopy data can be converted to be fully compatible with multi-spectral observations. Although there have been some studies with coincident acquisition (i.e., same solar geometries) between a multispectral radiometer and imaging spectrometer with the similar nadir viewing geometries (SPARC, 2004), no studies have been conducted using the same solar and viewing geometries to assess the independent ability of either sensor for a specific application. Thus, this work tests the hypothesis that imaging spectroscopy spectral data were compatible with a multi-spectral sensor to within ± 5% difference in radiance to OLI, as desired to continue the long-term Landsat record (Chander and Markham, 2003; Masek et al., 2006). To test this hypothesis, we simulate OLI (SOLI) using the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) classic, which has 10 nm spectral resolution and 224 contiguous bands from the visible to shortwave infrared at 380–2500 nm (Green et al., 1998) and compare those spectral data with actual OLI data. In testing this hypothesis, our objectives are to document a procedure for simulating OLI data from AVIRIS data, evaluate influencing factors on the observed radiance, and assess simulated OLI radiance (from AVIRIS) radiance compared to OLI radiance. To meet these objectives, we focus the analysis on an area where AVIRIS-classic was flown on NASA's ER-2 high-altitude research aircraft coincident in time and space along the track of the Landsat 8 satellite overpass. The influence of differences in solar irradiance and geometry, as well as atmospheric and surface conditions are herewith reduced as far as possible. The only remaining difference, over which we have no control, is the viewing geometry (view zenith angle, VZA) due to the large difference in altitude of the sensor platforms (i.e. 705 km vs. 20 km).

2. Methods

2.1. Datasets

This analysis uses data collected on October 21, 2014 from the OLI instrument on the Landsat 8 satellite and the AVIRIS instrument on NASA's ER-2 high-altitude research aircraft (Fig. 1) on a NE to SW transect about half way between Fresno, California and San Jose, California. The OLI radiance data have 30 m × 30 m pixel resolution and is from Path 43, rows 34–35. The AVIRIS image data (f141021t01p00r07rdn_b_sc01_ort_img) have 16 m × 16 m pixel

Table 2
Overview of applications enabled or augmented by the use of imaging spectroscopy data.

Application	References
Identification of invasive species	Underwood et al., 2003, 2006, 2007; Asner and Vitousek, 2005; Noujdina and Ustin, 2008; Khanna et al., 2011, 2012; Hestir et al., 2012; Beland et al., 2016; Santos et al., 2016a, 2016b
Habitat mapping and habitat suitability: including species and biodiversity mapping	Beland et al., 2016; Fagan et al., 2015; Féret and Asner, 2011; Ferreira et al., 2016; Gu et al., 2015; Roberts et al., 1998; Santos et al., 2016a, 2016b
Vegetation functional traits and diversity	Asner et al., 2015; Féret and Asner, 2014; Jetz et al., 2016; Singh et al., 2015; Ustin and Gamon, 2010
Mapping ecosystem condition (e.g., mortality/dormancy and stress)	Coates et al., 2015; Roberts et al., 2015
Phytoplankton diversity, such as algal blooms, which require information from pigment- or spectra shape-specific (i.e., not band ratio) analysis	Kudela et al., 2015; Palacios et al., 2015; Ryan et al., 2014
Mapping coral reef benthic communities	Hochberg and Atkinson, 2003, 2000
Geology and surface mineral mapping	Hook and Watanabe, 1991; Kruse, 2015; Kruse et al., 2003; Swayze et al., 2014