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# Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity

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ABSTRACT

At over 40 years, the Landsat satellites provide the longest temporal record of space-based land surface observations, and the successful 2013 launch of the Landsat-8 is continuing this legacy. Ideally, the Landsat data record should be consistent over the Landsat sensor series. The Landsat-8 Operational Land Imager (OLI) has improved calibration, signal to noise characteristics, higher 12-bit radiometric resolution, and spectrally narrower wavebands than the previous Landsat-7 Enhanced Thematic Mapper (ETM+). Reflective wavelength differences between the two Landsat sensors depend also on the surface reflectance and atmospheric state which are difficult to model comprehensively. The orbit and sensing geometries of the Landsat-8 OLI and Landsat-7 ETM+ provide swath edge overlapping paths sensed only one day apart. The overlap regions are sensed in alternating backscatter and forward scattering orientations so Landsat bi-directional reflectance effects are evident but approximately balanced between the two sensors when large amounts of time series data are considered. Taking advantage of this configuration a total of 59 million 30 m corresponding sensor observations extracted from 6317 Landsat-7 ETM+ and Landsat-8 OLI images acquired over three winter and three summer months for all the conterminous United States (CONUS) are compared. Results considering different stages of cloud and saturation filtering, and filtering to reduce one day surface state differences, demonstrate the importance of appropriate per-pixel data screening. Top of atmosphere (TOA) and atmospherically corrected surface reflectance for the spectrally corresponding visible, near infrared and shortwave infrared bands, and derived normalized difference vegetation index (NDVI), are compared and their differences quantified. On average the OLI TOA reflectance is greater than the ETM+ TOA reflectance for all bands, with greatest differences in the near-infrared (NIR) and the shortwave infrared bands due to the quite different spectral response functions between the sensors. The atmospheric correction reduces the mean difference in the NIR and shortwave infrared but increases the mean difference in the visible bands. Regardless of whether TOA or surface reflectance are used to generate NDVI, on average, for vegetated soil and vegetation surfaces ($0 \le \text{NDVI} \le 1$), the OLI NDVI is greater than the ETM+ NDVI. Statistical functions to transform between the comparable sensor bands and sensor NDVI values are presented so that the user community may apply them in their own research to improve temporal continuity between the Landsat-7 ETM+ and Landsat-8 OLI sensor data. The transformation functions were developed using ordinary least squares (OLS) regression and were fit quite reliably ($r^2$ values > 0.7 for the reflectance data and >0.9 for the NDVI data, p-values < 0.0001).



## 1. Introduction

At over 40 years, the Landsat satellites provide the longest temporal record of space-based land surface observations, and the successful 2013 launch of Landsat-8 carrying the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) is continuing this legacy (Irons, Dwyer, & Barsi, 2012; Roy, Wulder, et al., 2014). Multi-temporal optical wavelength satellite data acquired under different acquisition conditions and by different sensors may have reflectance inconsistencies introduced by factors including atmospheric and cloud contamination (Kaufman, 1987, Masek et al., 2006), variable sun-surface-sensor geometry (Roy et al., 2008, Nagol et al., 2015, Ju et al., 2010), sensor degradation and calibration changes (Markham & Helder, 2012), between sensor spectral band pass and spatial resolution differences (Steven, Malthus, Baret, Xu, & Chopping, 2003; Tucker et al., 2005), and data processing issues (Roy et al., 2002). The need for multi-year consistent data records for both research and applications is well established. For example, the global coverage Moderate Resolution Imaging Spectroradiometer (MODIS) products have been generated

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from 2000 to present (Justice et al., 1998) and have been reprocessed several times using improved calibration and geometric knowledge and refined product generation algorithms (Masuoka et al., 2011). Similarly, substantial research effort has been developed to generate global long term data records derived from coarse resolution Advanced Very High Resolution Radiometer (AVHRR) observations available since 1981, although those that are publically available are subject to scientific debate (Myneni, Tucker, Asrar, & Keeling, 1998; Pedelty et al., 2007; Beck et al., 2011; Fensholt & Proud, 2012; Pinzon & Tucker, 2014). Unlike past AVHRR sensors, which carried no onboard reflective wavelength calibration capability, the Landsat Thematic Mapper, ETM + and OLI sensors are well calibrated (Markham & Helder, 2012) and with the free Landsat data availability the systematic generation of consistent global long-term Landsat products has been advocated (Roy, Wulder, et al., 2014).

The primary Landsat-8 mission objective is to extend the Landsat record into the future and maintain continuity of observations so that Landsat-8 data are consistent and comparable with those from the previous Landsat systems (Roy, Wulder, et al., 2014). Because of the importance of continuity, the Landsat legacy is one in which there has been relatively consistent mission objectives, but with capabilities modified by incremental improvements in satellite, sensor, transmission, reception and data processing and storage technologies (Irons & Masek, 2006; Irons et al., 2012). There is a need to define quantitative spectral reflectance transformations between all the Landsat sensors to provide consistent long term Landsat reflectance data. This paper is limited to the Landsat-7 and Landsat-8 sensors and compares their spectrally overlapping reflective wavelength bands and develops statistical functions to transform between them. In addition, between sensor transformations for the normalized difference vegetation index (NDVI) are developed as the NDVI is one of the most commonly used remote sensing indices. The transformations are developed by statistical comparison of contemporaneous sensor satellite observations which is quite a common approach (Brown, Pinzón, Didan, Morisette, & Tucker, 2006, Gallo, Ji, Reed, Eidenshink, & Dwyer, 2005, Miura, Huete, & Yoshioka, 2006). However, this is challenging for several reasons. First, spectral response differences between the sensors mean that the observed sensor radiances differ in a way that is dependent on the observed surface components (Steven et al., 2003) except when the surface reflectance changes linearly over the band passes which is not usually the case for Landsat (Miura et al., 2006; Zhang & Roy, 2015). Second, top of atmosphere (TOA) reflective wavelength differences between the sensors depend on the atmospheric state and at reflective wavelengths atmospheric effects are coupled to the surface reflectance (Tanre, Herman, & Deschamps, 1981). Third, Landsat atmospheric correction algorithms are imperfect, particularly at shorter visible wavelengths (Ju, Roy, Vermote, Masek, & Kovalskyy, 2012; Vermote, Justice, Claverie, & Franch, submitted for publication). Fourth, despite the relatively narrow 15° Landsat sensor field of view, Landsat bidirectional reflectance effects occur (Roy et al., 2008; Li et al., 2010; Nagol et al., 2015; Gao et al., 2014) and so comparison of Landsat data with different solar and view zenith geometry may introduce differences when surfaces are non-Lambertian. Fifth, unless the sensor data are observed closely together in time, the surface state and condition may change due to anthropogenic factors (e.g., land cover change and agricultural harvesting) and natural factors (e.g., phenology, moisture changes due to precipitation, fire and wind disturbances) which can be difficult to detect reliably using Landsat data (Huang et al., 2010; Kennedy, Yang, & Cohen, 2010; Hansen et al., 2014; Zhu & Woodcock, 2014). For these reasons, reliable and representative determination of statistical functions to transform between sensor bands requires a comparison of data sensed over a wide range of surface conditions. Previous researchers have reported comparisons between Landsat-7 ETM + and Landsat-8 OLI data but considered only a relatively small (compared to this study) amount of data in Australia (Flood, 2014) and in China and Korea (Ke, Im, Lee, Gong, & Ryu, 2015) and did not take into account the per-pixel spectral saturation status that we show is important.

In this study, a total of 59 million 30 m corresponding sensor observations extracted from 6316 Landsat-7 ETM + and Landsat-8 OLI images acquired over three winter and three summer months for all the conterminous United States (CONUS) are examined. Statistical calibrations are derived to document between sensor differences for TOA and also surface reflectance and derived NDVI. The transformations are provided so that the user community may apply them in their own research to improve temporal continuity of reflectance and NDVI between the Landsat OLI and ETM + sensors. First, the Landsat data and pre-processing required to allow their meaningful comparison are described, then the analysis methodology and results are described, followed by concluding remarks with implications and recommendations.

## 2. Data

The Landsat-8 OLI has narrower spectral bands, improved calibration and signal to noise characteristics, higher 12-bit radiometric resolution, and more precise geometry, compared to the Landsat-7 ETM + (Irons et al., 2012). The OLI dynamic range is improved, reducing band saturation over highly reflective surfaces, and the greater 12-bit quantization permits improved measurement of subtle variability in surface conditions (Roy, Wulder, et al., 2014). The Landsat-7 ETM + has a 5% absolute radiometric calibration uncertainty (Markham & Helder, 2012) and the Landsat-8 OLI has a 3% absolute radiometric calibration uncertainty (Markham et al., 2014). The OLI has two new reflective wavelength bands, a shorter wavelength blue band (0.43–0.45 μm) and a shortwave infrared cirrus band (1.36–1.39 μm), but these are not considered in this study as they have no direct ETM + equivalent. Comparison of thermal wavelength sensor data is complex because the processes controlling thermal emittance are highly variable in space and time (Moran, Clarke, Inoue, & Vidal, 1994; Norman, Divakarla, & Goel, 1995) and because of this, and the stray light contamination in one of the two TIRS bands (Montanaro, Gerace, Lunsford, & Reuter, 2014), the Landsat thermal bands are also not considered in this study.

The OLI bands are defined at 30 m like the ETM + but are spectrally narrower and cover different spectral ranges (Fig. 1). The OLI and ETM + spectral band passes are tabulated in Roy, Wulder, et al. (2014). The blue, green and red OLI band spectral response functions intersect with 82.76%, 71.08% and 60.63% of the corresponding ETM + band spectral response functions. Conversely, the blue, green and red ETM + band spectral response functions intersect with 98.83%, 98.30% and 98.90% of the corresponding OLI band spectral response functions. Notably, the OLI near-infrared (NIR) band (~0.85 μm) avoids a water absorption feature that occurs in the ETM + NIR band (Irons et al., 2012). The OLI NIR and the shortwave infrared band (~1.16 μm and ~2.11 μm) spectral response functions fall entirely within the ETM + spectral response functions and occupy only 23.14%, 42.22% and 66.69% of the ETM + spectral response functions respectively.

The Landsat-8 is in the (now decommissioned) Landsat 5 orbit and so Landsat-8 and 7 have the same approximately 710 km sun-synchronous circular 98.2° inclined orbit and overpass every Earth location every 16 days but are offset from each other by 8 days (Teillet et al., 2001; Loveland & Dwyer, 2012). Both Landsat sensors have 15° fields of view and their data are available in approximately 185 km × 180 km scenes defined in a Worldwide Reference System (WRS) of path (groundtrack parallel) and row (latitude parallel) coordinates (Arvidson, Goward, Gasch, & Williams, 2006; Loveland & Dwyer, 2012). Every daytime sunlit Landsat-7 and 8 overpass of the CONUS is ingested into the U.S. Landsat archive, located at the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS), with an annual maximum of 22 or 23 acquisitions per path/row. In May 2003 the Landsat-7 ETM + scan line

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