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Suomi NPP VIIRS reflective solar band on-orbit radiometric stability and accuracy assessment using desert and Antarctica Dome C sites

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ABSTRACT

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a key instrument flying aboard Suomi NPP satellite. It is a follow on mission for NOAA series AVHRR and NASA MODIS. The radiometric stability and accuracy of VIIRS are critical to make its data useful for weather and climate applications. This study is focused on analyzing VIIRS radiometric performance using well established calibration sites and through the inter-comparison with other satellite instruments such as AQUA MODIS and Landsat 8 OLI. The paper analyzes stability of VIIRS reflective solar bands over more than two years by using sites such as Libya 4, Sudan 1 and Dome C. VIIRS absolute radiometric accuracy is quantified using AQUA MODIS over the above mentioned sites. For VIIRS band M11 (2.1 μm), since there is no matching MODIS band pair, this study uses matching SWIR band from Landsat 8 OLI as a reference to quantify the absolute calibration accuracy of M11. The study shows that VIIRS moderate resolution reflective solar bands are stable with better than 0.5% for most of the bands with uncertainty on the order of 1%. After accounting the spectral differences, the absolute radiometric bias estimated through VIIRS and MODIS inter-calibration is within 2% for bands M1–5 and M10 and about 3% for bands M7–8. Similarly, M11 bias estimated using VIIRS and OLI inter-comparison is 5.4%.

1. Introduction

Visible Infrared Imaging Radiometer Suite (VIIRS) is a key NOAA satellite instrument onboard S-NPP satellite that provides data for the ocean, land, aerosol, and cloud applications. VIIRS instrument is equipped with onboard calibration (OBC) system that consists of solar diffuser with stability monitor for tracking the performance of Reflective Solar Bands (RSB) and blackbody for Thermal Emissive Bands (TEB). More detailed information on VIIRS instrument characteristics has been summarized by Cao, Deluccia, et al., 2013. The satellite data quality needs to be validated independently to ensure the stability and accuracy of OBC and to ensure that the satellite data from different instruments on different satellite platforms have a common radiometric scale. On-orbit radiometric stability and accuracy can be evaluated independently using different techniques such as trending and inter-calibration using vicarious calibration sites, SNO and SNO-x based inter-comparison, lunar trending, Deep Convective Clouds (DCC), etc. (Cao, Xiong, et al., 2013; Chander, Mishra, et al., 2010; Chander, Xiong, Choi, & Angal, 2010; Helder et al., 2013; Markham et al., 2014; Uprety et al., 2013; Wu, 2004; Xiong et al., 2008).

Several studies in the past have discussed different aspects of the on-orbit calibration and validation of VIIRS using independent techniques (Bhatt et al., 2014; Cao, Xiong, et al., 2013; Uprety et al., 2013; Wang & Cao, 2014; Wu, Sullivan, & Heidinger, 2011). Previous study by Uprety et al. (2013) presents the VIIRS radiometric accuracy by intercomparing with MODIS using extended simultaneous nadir overpass (SNO-x) over desert and ocean. The technique was inherited from SNO based intercomparison and it was an early assessment on VIIRS on-orbit performance using less than a year of VIIRS observation. Only VIIRS bands M1 to M8 were analyzed. Similarly, Wu, Cao, and Sun (2013) discuss VIIRS and MODIS intercomparison using high latitude polar SNOs and desert site for moderate resolution bands M1–7. Earlier study by Wang & Cao (2014) discusses VIIRS on-orbit radiometric stability for bands M5 and M7 by trending the mode of Deep Convective Cloud (DCC) pixels. Similarly the earlier study by Bhatt et al. (2014) presents the results on early assessment of VIIRS radiometric stability using Libya-4 site and DCC. Bands I1, I3 and M1–11 except M2–3 and M8 were analyzed using the VIIRS observations from early 2012 till the late 2013.

This paper presents the comprehensive study and analysis on VIIRS radiometric performance for bands M1 (0.4 μm) through M11 (2.1 μm) (except bands M6 and M9 (1.37 μm)) characterized using the two Saharan desert calibration sites, Libya-4 and Sudan-1 and Antarctica Dome C site. In addition, inter-comparison of VIIRS with

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AQUA MODIS and Landsat 8 Operational Land Imager (OLI) is performed to quantify the radiometric accuracy of VIIRS. Both Libya-4 and Dome C are CEOS endorsed calibration sites. The temporal trends of TOA reflectance observed at nadir are used to quantify the radiometric stability. VIIRS radiometric accuracy can be achieved by continuously monitoring, characterizing and comparing VIIRS instrument to other well calibrated radiometers such as MODIS whose absolute calibration uncertainty is estimated to be within 2% (Xiong et al., 2007). This paper shows absolute radiometric bias of VIIRS estimated for moderate resolution radiometric bands by comparing top of atmosphere (TOA) reflectance with MODIS and OLI. The spectral coverage of one of the VIIRS moderate resolution bands M11 (2.2 μm) doesn't overlap with MODIS. Hence we have used Landsat 8 OLI SWIR band 2 (2.11–2.29 μm), a new generation Landsat sensor, to perform the intercomparison over Libya-4 and evaluate the radiometric accuracy. VIIRS M11 signal strength over desert (~7–8 W/m^2-sr-um) is more than 10 times higher than over ocean. Typical radiance observed by M11 over ocean is less than 0.5 W/m^2-sr-um. This very small signal strength over ocean can significantly increase the noise level in measurements and makes the band more challenging for calibration in absolute scale. Assuming that the detector gain is linear, we have chosen desert sites to study its radiometric performance. In addition, we have used OLI to evaluate the radiometric performance of VIIRS M7. This helps to compare the results from VIIRS, MODIS intercomparison for band M7 and analyze any discrepancy and its root cause. The uncertainties in the VIIRS bias are mainly due to the spectral difference between the instruments matching bands, BRDF, cloud contamination, calibration issues, and registration errors. Uncertainty in bias caused by mismatch in relative spectral response (RSR) of the instruments is quantified using EO-1 Hyperion and radiative transfer models such as MODTRAN (Uprety et al., 2013). After accounting spectral differences, the residual bias observed at different sites is compared and analyzed. Unlike the previous studies that analyzed the VIIRS stability for only few bands, this study analyzes more VIIRS bands that include all SWIR bands except M9 and for a longer time interval ranging from early 2012 to the end of 2014. Further, in addition to Libya-4, it utilizes Sudan-1 and Dome C sites to supplement and validate the radiometric stability and accuracy results. Also, besides Aqua MODIS, it uses OLI to compare VIIRS M7 and M11 thus providing further opportunities to better understand and improve the calibration accuracy of these bands. This comprehensive analysis on VIIRS radiometric performance helps to build the confidence to users working on EDR products.

2. Methodology

There exist Earth locations which are temporally stable and are capable of tracking the changes in satellite instrument response over time. These are usually high altitude arid regions with little rainfall, mostly clear sky with no human activities. Since it is almost impossible to find a single site with all above ideal characteristics, the term Pseudo Invariant Calibration Sites (PICS) has been commonly used for these sites which have been identified and characterized to be suitable to detect the radiometric stability of satellite sensors. More details on PICS and its optimized identification criteria can be found in earlier studies such as Helder, Basnet, and Morstad (2010). Saharan desert calibration sites have been used in trending the satellite sensors for more than a decade (Helder et al., 2008, 2010, 2013; Markham et al., 2004, 2012; Barsi, Markham, Helder, & Chander, 2007; Rao & Chen, 1995, 1999; Wu, 2004, Wu, Sullivan, & Heidinger, 2011). In addition, the potential of these sites for absolute calibration has been successfully demonstrated by several studies in the past (Helder et al., 2013; Mishra, Haque, et al., 2014; Mishra, Helder, Angal, Choi, & Xiong, 2014). PICS can be used reliably to analyze radiometric performance of the instruments as long as the sites have been rigorously characterized to ensure the long term stability.

2.1. Calibration sites

This study uses Saharan desert sites and Antarctica Dome C (75.1°S, 123.39°E) site. The desert sites used are Libya-4 (28.55°N, 23.39°E) and Sudan-1 (21.74°N, 28.22°E). Libya-4 is one of the Committee on Earth Observation Satellites (CEOS) endorsed calibration sites and has been widely used in calibration and validation of medium and high resolution satellites (Chander, Mishra, et al., 2010; Chander, Xiong, et al., 2010; Cosnefroy, Leroy, & Briottet, 2014; Helder et al., 2010; Helder et al., 2013, Markham and Helder, 2012; Wu, Xiong, Cao, & Angal, 2008). Libya-4 is one of the best desert reference sites recommended by CEOS. More detailed analysis on the radiometric quality of Saharan desert sites can be found in Helder et al. (2010) and Teillet, Barsi, Chander, and Thome (2007), Teillet, Fedosejevs, Thome, and Barker (2007). Fig. 1 shows VIIRS image with Libya-4 and Sudan-1 sites. The reason behind choosing Sudan 1 site is that NOAA series AVHRR sensors use this site for on-orbit relative calibration (Wu, 2004). In recent years some of the areas near the Sudan-1 site started to suffer from human activities that include irrigation (Yu & Wu, 2009) however, the region of interest chosen for this study avoided the areas impacted by human activities.

Antarctica Dome C (−75.1°, 123.39°) is a large snow flat surface located at an altitude of 3.2 km from sea level. It is a CEOS endorsed calibration site. The site has excellent temporal stability and spatial uniformity (Cao et al., 2010; Uprety & Cao, 2011, 2012). It has been studied rigorously due to its unique characteristics such as, high altitude; high reflectance; high percentage of cloud-free time; atmosphere with very low infrared sky emission, low water vapor content and low aerosol and dust content. Some of the limitations of this site include: it receives sunlight only for about four months every year (austral summer only), there is a large BRDF from snow, accessibility issues for ground truth measurements, early launch cal/val activities may not be possible for RSB if the satellite is launched during the other 8 month period. The site is observed more frequently by polar orbiting satellites however it is not visible for current GOES and future GOES-R instruments.

2.2. Sensor overview

S-NPP is a sun-synchronous polar orbiting satellite launched in October 2011 with VIIRS as one of the payloads. VIIRS has full global coverage of Earth daily (one at daytime and the other at nighttime) from a nominal altitude of 829 km. It is a multispectral scanning radiometer with 16 moderate resolution bands (0.4 μm to 12 μm), 5 Imagery bands (0.6 μm to 12 μm) and 1 day night band (DNB). This is a wide-swath (3000 km) scanning radiometer with spatial resolution: 750 m for moderate resolution bands and DNB, 375 m for imagery bands. It is a follow-on mission for Advanced Very High Resolution Radiometer (AVHRR) on NOAA and MetOp series satellites and Moderate-Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua. More detailed explanation on VIIRS instrument and onboard calibrators can be found in Cao, Deluccia, et al. (2013).

MODIS is a NASA instrument launched aboard Terra (1999) and Aqua (2002) satellites. It has 36 spectral bands with wavelengths ranging from 0.4 to 14.4 μm. The spatial resolution varies from 0.25 km for the first two bands, 0.5 km for 5 bands and 1 km for the remaining 29 bands. A complete scan covers a swath width of 10 km (along track) and 2330 km (cross track) with +/−55° scan angle. Absolute radiometric calibration for both VIIRS and MODIS is achieved by using onboard calibration system that mainly includes solar diffuser and solar diffuser stability monitor for the calibration of reflective solar bands (RSBs) and blackbody for the thermal emissive bands. More detailed explanation on MODIS instrument can be found in Xiong and Barnes (2006).

The Operational Land Imager (OLI) is a pushbroom sensor launched onboard Landsat 8 on 11 February 2013. Detail explanations on the instrument design including onboard calibration, characterization and performance can be found in earlier studies such as Irons, Dwyer, and