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Radiometric comparison of multispectral imagers over a pseudo-invariant calibration site using a reference radiometric model

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ABSTRACT

A model is proposed to simulate top-of-atmosphere (TOA) observations in the visible to near-infrared (NIR) spectral range, over a pseudo-invariant calibration site, the so-called Libya-4 site. The model is based on a fully physical radiative transfer model simulating the coupling between a realistic atmosphere and a spectral surface Bidirectional Reflectance Distribution Function (BRDF) model parameterised by 4 free parameters. At first, the model is 'calibrated' on 4 years of MERIS observations by inverting the 4 free parameters of the surface BRDF model that provide the best fit to the MERIS observations. The model mimics the MERIS TOA observations with a precision of approximately 1% RMSE outside water vapour and O_2 absorption features. The inverted BRDF model parameters obtained at MERIS spectral bands are then spectrally interpolated and used as input to the radiative transfer model to simulate observations from ATSR-2, AATSR, A-MODIS, MERIS, POLDER-3 and VEGETATION-2 over the 2002 to 2012 period. Depending on the spectral band considered, AATSR radiometry appears 2% to 3% above the model 'calibrated' on MERIS radiometry, A-MODIS is 0% to 3% below, POLDER-3 is 2% to 4% below and VEGETATION-2 about 4% below. ATSR-2 data during the 2002 to early 2003 period are almost 10% below their simulations. Temporal trends between simulations and observations are also measured for all sensors. The smallest linear trends are observed for the MERIS 3rd reprocessing data (below 1%/decade). The temporal trends obtained from all sensors against the coupled surface-atmosphere model are in line with expected residual errors of instrument degradation model used in temporal extrapolation: larger in blue than in the NIR. The combined temporal trends from all sensors tend to demonstrate that the Libia-4 site is radiometrically stable in the visible to the NIR to better than 1%/decade for the 2002–2012 period, thus quantitatively confirming that it is a terrestrial target particularly adequate for the assessment of the temporal stability of Earth Observation sensors.

1. Introduction

In the last decades, many space borne optical sensors have been globally imaging the Earth radiation field at the kilometric spatial resolution scale to serve both scientific and operational applications. Both types of application generally require that these space measurements be traceable to the radiometric standards of the Système International (SI). Such traceability cannot be ensured only by means of exhaustive on-ground instrument characterisation and calibration. The harsh environmental constraints imposed by the launch and in orbit environments inevitably lead to sensor performance degradation and consequently to loss of traceability as the instrument radiometry cannot be related anymore to the SI sources available on ground. Even when onboard calibration devices, such as solar diffuser plates or reference lamps, are present on the same platform to ensure radiometric traceability to on ground SI standards, these devices can suffer from similar performance degradation issues. Each sensor performance is generally affected differently in the course of the its lifetime by space environment constraints. Such performance issues are at best partially accounted for and sometimes not identified in the instrument degradation models put in place to compensate them. This not only leads to a loss of radiometric traceability at individual sensor level but also to an overall loss of radiometric consistency between sensors and by extension of the global Earth Observation system.

Space agencies and private operators have increasingly relied on vicarious calibration methodologies and radiometric intercomparison methodologies to identify and to recover from such loss of radiometric traceability in the sensor lifetime. To support these methodologies, a set of six desert sites (referred to as Algeria 3, Algeria 5, Libya 1, Libya 4, Mauritania 1 and Mauritania 2) called the Pseudo Invariant Calibration Sites (PICS). They were selected by the Committee on Earth Observation Satellites (CEOS) among 20 sites originally identified by Cosnefroy, Leroy, and Briottet (1996) as desert sites suitable for "*multitemporal*, *multiband*, or *multiangular calibration of optical satellite sensors*". All sites are located in the Sahara and were chosen chiefly for their potential radiometric stability.

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The Sahara region radiometric stability should however not be taken for granted. Its climate changed rapidly from an arid climate to a humid climate in the early Holocene (~8500 BC) and then back to today's dry climate (~5000 BC) in response to climate forcing induced by solar insolation changes due to the Earth precession and possibly a non-linear response to it (deMenocal et al., 2000; Kuper & Kröpelin, 2006). This region of the globe is subject to the recurrent so-called African Humid Periods, following a 20,000 year precession cycle, leading to significant change in particular in vegetation cover and atmospheric regime (see deMenocal & Tierney, 2012). The growing evidence for contemporary climate change and the past record of climate variability of this region invite to caution when assuming its radiometric stability. Some of the sites originally identified by Cosnefroy et al. (1996) have also recently been subject to human induced changes such as the development of oil extraction fields. A quantitative estimate of the PICS temporal stability is necessary if they are to be used to diagnostic and correct for instrument radiometric degradation.

The present paper focuses on one of the 6 PICS, the Libya-4 site. This site has been extensively used for radiometric intercomparisons of Earth Observation (EO) sensors and their vicarious calibration (e.g., Lachérade, Fougnie, Henry, & Gamet, 2013; Smith & Cox, 2013; Sterckx, Livens, & Adriaensen, 2013). The present study proposes a model of the spectral and angular variability of the TOA reflectance over the site at a 1 nm spectral resolution in the visible to Near Infrared (NIR). This model is used as a radiometric reference against which observations from various space sensors are compared. The originality of the proposed modelling lies in that it is based on a fully physical description of the radiative transfer scattering and absorption processes on the 4 St parameters of the radiation, by a Monte Carlo model, at high spectral resolution (1 nm), with a realistic atmosphere and a full description of the surface-atmosphere coupling via a hyperspectral Bidirectional Reflectance Distribution Function (BRDF) model. Such spectral resolution allows to simulate observations from sensors with similar spectral responses and compare them whilst implicitly taking into account the slight differences between their spectral responses and thus constitutes an alternative to the use of spectral bands adjustment factors derived from hyperspectral sensor data (e.g. Chander et al., 2013).

The first step of the approach is to invert the 4 free parameters of a surface spectral BRDF model from 4 years of the ENVISAT MEdium Resolution Imaging Spectrometer (MERIS) observations over the site. This process can be described as the 'calibration' of the model output onto the MERIS measurements. The BRDF model parameters inverted in MERIS spectral bands are then spectrally interpolated at a 1 nm spectral sampling and used as input to the radiative transfer model in order to simulate full time series of observations from the EO sensors: ATSR-2 (on board ERS-2), AATSR (on board ENVISAT), MODIS (on board AQUA), MERIS, POLDER-3 (on board PARASOL) and VEGETATION-2 (on board SPOT-5). Finally, the question the radiometric temporal stability of the Libya-4 site is addressed and for the first time a quantitative upper estimate of its decadal stability is estimated from the analysis of all sensors radiometric temporal trends.

2. Definition of the reference dataset of TOA reflectance over Libya-4

MERIS L1 data from the 3rd reprocessing covering a 4 year period from 01/01/2006 to 31/12/2009 were extracted from the freely available Database for Imaging Multi-spectral Instruments and Tools for Radiometric Intercomparison (DIMITRI) (http://www.argans.co.uk/dimitri/). These data consist of TOA reflectances averaged over the so-called Libya-4 region of interest (ROI). The Libya-4 site is defined as per Cosnefroy et al. (1996), i.e., a latitude/longitude box between 28.05 N–29.05 N and 22.89 E–23.89 E. A description of the site and its climate can be found in Cosnefroy et al. (1996). The radiometric spatial variability of the Libyan desert is such that the choice of the ROI centre and ROI size has a significant impact on the absolute TOA radiometric level of the time series of sensor observations. Previous studies aiming at intercomparing sensors over the so-called Libya-4 site have made use of a ROI centred at about the same location than Cosnefroy et al. (1996) than the present study but with different ROI sizes (e.g., Lachérade et al., 2013; Smith & Cox, 2013; Sterckx et al., 2013). One can distinguish two typical ROI sizes being used in such studies. Firstly, the ROIs having size of about 1° latitude and longitude; they are best suited for intercomparison of sensors with spatial resolution of the order of 1 km as they provide a large number of TOA measurements (about 1000 pixels) with a low associated standard deviation around 2%. Secondly, smaller ROIs of size about 0.2° latitude and longitude; they are more likely to be fully covered by the narrow swath of high spatial resolution sensors. In the present study, the choice of the ROI first defined by Cosnefroy et al. (1996) was driven by the fact that the sensors involved have kilometric spatial resolutions.

The L1 data were corrected for the instrument smile effect (irradiance correction only following Bourg, D'Alba, & Collagrande, 2008). They were automatically cloud screened following the MERIS-GlobCarbon scheme as per Plummer (2008). Data were further visually screened using quicklooks to exclude acquisition with residual cloud contamination. 416 MERIS acquisitions are available after this data screening (see Fig. 1). Cloud contamination over the site occurs more frequently during the winter months resulting into more acquisitions being available for low sun zenith angles (SZAs) than for high SZAs. To avoid over-constraining the inversion of the surface BRDF model (described in the next section) at low SZAs at the expense of high SZAs, a sub-selection of 200 of these cloud free MERIS TOA observations is done at times randomly selected and uniformly spread across the 4-year period.

For each acquisition, the following data are automatically extracted from the DIMITRI database: the mean TOA reflectance over ROI, the standard deviation of the TOA reflectance within the ROI, the sun and viewing direction zenith and azimuth angles (SZA, VZA, SAA, VAA), the total columnar ozone (TCO) and the total column water vapour (WV)). These TCO and WV available in the DIMITRI database correspond to the meteorological data available in the MERIS L1 products. They are data from the European Center for Medium-Range Weather Forecasts (ECMWF) operational Numerical Prediction Weather (NWP) model. They were substituted by the corresponding ECMWF ERA-Interim reanalysis data (see description in Dee et al., 2011). These ERA reanalysis meteorological data present several advantages:

1. They are generated with a single NPW model throughout the entire reanalysis period (1979 to present). In contrast the ECMWF NWP operation model has gone through 23 evolutions during the ENVISAT ERA.
2. They are generated with consolidated assimilated data.
3. They are generated on a Gaussian grid with an approximately uniform 79 km spacing compared to the 125 km spacing of the data originally available with the ENVISAT data.

3. Retrieval of the surface BRDF model parameters

The retrieval of a surface BRDF model over Libya-4 is achieved by minimizing the residual error between the previously described reference dataset of MERIS TOA reflectances and their simulations. The TOA reflectance simulations are carried out with the MYSTIC radiative transfer code.

3.1. The radiative transfer modelling: MYSTIC setup

MYSTIC was first described by Mayer (1999, 2000) as a forward Monte Carlo for plane parallel atmospheres. It took part to the International Intercomparison of 3D Radiation Codes (see Cahalan et al., 2005). The addition of a backward simulation mode and simulations in spherical atmosphere are described in Emde and Mayer (2007). The model has been further extended to simulate polarised radiation. These extensions were validated against exact solutions, benchmark results and measurements by Emde, Buras, Mayer, and Blumthaler (2010). MYSTIC has