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Radiometric inter-sensor cross-calibration uncertainty using a traceable high accuracy reference hyperspectral imager

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ABSTRACT

Optical earth observation (EO) satellite sensors generally suffer from drifts and biases relative to their pre-launch calibration, caused by launch and/or time in the space environment. This places a severe limitation on the fundamental reliability and accuracy that can be assigned to satellite derived information, and is particularly critical for long time base studies for climate change and enabling interoperability and Analysis Ready Data. The proposed TRUTHS (Traceable Radiometry Underpinning Terrestrial and Helio-Studies) mission is explicitly designed to address this issue through re-calibrating itself directly to a primary standard of the international system of units (SI) in-orbit and then through the extension of this SI-traceability to other sensors through in-flight cross-calibration using a selection of Committee on Earth Observation Satellites (CEOS) recommended test sites. Where the characteristics of the sensor under test allows, this will result in a significant improvement in accuracy. This paper describes a set of tools, algorithms and methodologies that have been developed and used in order to estimate the radiometric uncertainty achievable for an indicative target sensor through in-flight cross-calibration using a well-calibrated hyperspectral SI-traceable reference sensor with observational characteristics such as TRUTHS. In this study, Multi-Spectral Imager (MSI) of Sentinel-2 and Landsat-8 Operational Land Imager (OLI) is evaluated as an example, however the analysis is readily translatable to larger-footprint sensors such as Sentinel-3 Ocean and Land Colour Instrument (OLCI) and Visible Infrared Imaging Radiometer Suite (VIIRS). This study considers the criticality of the instrumental and observational characteristics on pixel level reflectance factors, within a defined spatial region of interest (ROI) within the target site. It quantifies the main uncertainty contributors in the spectral, spatial, and temporal domains. The resultant tool will support existing sensor-to-sensor cross-calibration activities carried out under the auspices of CEOS, and is also being used to inform the design specifications for TRUTHS.

1. Introduction

TRUTHS (Traceable Radiometry Underpinning Terrestrial and Helio Studies), is a proposed satellite mission led by the National Physical Laboratory (NPL), UK. This mission is designed to have sufficient accuracy to allow the unequivocal detection of trends, from a background of natural variability, in a number of key indicators of climate change in the shortest time possible, allowing verification of climate forecast models on decadal timescales (Fox et al., 2011). This would be achieved by establishing a fiducial reference data set of spectrally resolved incoming and outgoing solar radiation. In terms of Earth viewing radiance, the characteristics of this data set are: spectrally-resolved—5–10 nm Full Width Half Maximum (FWHM))—Earth radiances, continuously sampled (spectrally and spatially) with a Ground Instantaneous Field Of View (GIFOV) of approximately 50 m over the 320–2400 nm spectral range, and the corresponding solar spectrally-resolved irradiance; both with SI-traceable radiometric uncertainties of <0.3% (Fox et al., 2011). These fiducial data sets establish a high accuracy benchmark of the Earth's spectral radiation budget in the solar spectral domain in a similar manner to its US-proposed sister mission Climate Absolute Radiance and Refractivity Observatory (CLARREO) against which future change can be detected (Wielicki et al., 2013). The chosen spectral and spatial resolutions are optimum to allow the data sets to be utilised to retrieve many Essential Climate Variables

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(ECVs)—as defined by Global Climate Observing System (GCOS)—and facilitate detailed analysis of attribution effects (GCOS, 2010) and the Earth system's cycles and processes.

It is thus not surprising that TRUTHS's observational specifications—spatially and spectrally—match/allow reconstruction of many of the current, and planned, solar domain EO sensors, such as Landsat-8 (L8) Operational Land Imager (OLI). However, the addition of high SI-traceable radiometric accuracy in the reference sensor, maintained throughout the mission lifetime, also provides a powerful opportunity to cross-calibrate other sensors through co-incident viewing of stable target scenes and in particular, the radiometric characterisation of Pseudo Invariant Calibration Sites (PICS). For target sensors, such as Copernicus Sentinel-2 (S2) Multispectral Imager (MSI) and Sentinel-3 (S3) Ocean and Land Colour Instrument (OLCI), TRUTHS allows not only an assessment of performance but also a calibration upgrade towards that needed by many climate studies, and thus leads to the prospect of a space-based climate and calibration observatory as requested by the international community (Dowell et al., 2013).

The existing on-board calibration systems of many sensors such as Sentinel-2 and 3 have significant complementary merit, allowing assessment of any short term performance variation of the sensor over its full orbital path and between reference calibrations. In these cases, TRUTHS provides the in-flight anchor to SI units and the prospect of a regular update of the on-board monitoring systems. However, for sensors whose primary objectives do not warrant an on-board calibration system, such as the UK-DMC (Disaster Monitoring Constellation) series, similar cross-calibration activities would provide the means to achieve radiometric traceability, broadening the scope of application of such sensors, even to the point where these sensors could contribute towards climate studies and services. Following this logic, a constellation of new generation, low-cost Cube-/Nano-Sats could be envisaged, also contributing to the global observing system, radiometrically-anchored to a reference sensor such as TRUTHS.

The ideal configuration for vicarious target inter-calibration is that the two instruments should make matched measurements viewing the same target at the same time; with the same spatial and spectral responses at the same viewing geometry. Since these idealized conditions never occur in reality, there will always be some additional compensatory steps needed to allow comparison of the two instruments. The accuracy achievable by the target sensor via the inter-sensor cross-calibration is ultimately limited by the reference sensor accuracy and the inability to fully account for the differences from the ideal comparison conditions. These differences include the instrument spectral response, target site spectral signature and the radiometric properties of the selected target site for the calibration process, including effects of solar illumination and sensor view angles and any variance in the atmosphere transmittance between the observations by the two sensors. Similar conditions apply even when the reference sensor measurements are used only as an input for the radiometric characterisation of PICS. In that situation, the longer term temporal radiometric properties of the site and its atmosphere become relevant factors.

In a recent study by Chander et al. (2013a), the uncertainty introduced by the main effects inherent in the cross-calibration transfer using a calibration target site was assessed to fall well below an uncertainty level of 0.3% ($k = 1$) with the exception of a spectral shift in SBAF. In that case, the use of filters such as those used in the Moderate Resolution Imaging Spectrometers (MODIS) (often used as a reference sensor) have suggested worst-case tolerances/shifts of 5 nm in the bands would produce larger differences. As a result, the uncertainty associated with the calibration of the reference sensor is now often the dominant component in the final uncertainty achieved for the test sensor.

The calibration accuracy of sensors measuring in the visible/near infrared (VNIR) and shortwave infrared (SWIR) spectral regions increased notably in the last decades. MODIS on board the Terra and Aqua satellites, or the recently launched S3 OLCI, have requirements for calibration accuracy of below 2% ($k = 1$) relative to the sun (Donlon et al., 2012; Xiong and Barnes, 2006). Instruments such as the Clouds and the Earth's Radiant Energy System (CERES) have even more stringent calibration accuracy requirements—calibration accuracy below 1% ($k = 1$)—have highlighted the need for a reliable inter-calibration with an instrument like TRUTHS or CLARREO to overcome the data gap between the CERES mission instruments, to maintain the demanding stability requirements needed for climate (Loeb et al., 2016). Even If these well-calibrated instruments are used for cross-calibration their accuracy levels remain the dominant contribution to the total uncertainty in the cross-calibration process compared to the ones described in Chander et al. (2013a). Thus, the possibility of a reference instrument like TRUTHS or CLARREO with a radiometric uncertainty below 0.3% ($k = 2$) would be of a large benefit to reduce the total uncertainty in a cross-calibration over PICS.

This paper addresses the uncertainty contributions affecting typical CEOS WGCV recommended land-based reference sites in its use for cross-calibration of satellite imagers in the three main domains: spectral, spatial, and temporal. The aims of this paper are to: (1) evaluate the "inherent" uncertainty contributions with case studies (2) set up a suite of tools and methodologies useful for the exploitation and design of missions like TRUTHS or CLARREO, and (3) define the uncertainty contributions in a cross-calibration using rigorous metrology. Spectral, spatial and temporal contributors are all considered separately in Section 2.

For the latter point, the uncertainty propagation is based on the Monte-Carlo Method (MCM) as described in Supplement 1 to the Guide to the Expression of Uncertainty in Measurement (GUM) (BIPM et al., 2008b), the use of which is explicitly encouraged in the Quality Assurance Framework for Earth Observation (QA4EO) (http://www.QA4EO.org). Thus, the cross-calibration uncertainty estimates are presented in terms of a probability distribution function (pdf) of the associated parameters. The uncertainty is reported as the interval around the best estimate that approximates a coverage of 68.27% (which is expressed as $k = 1$). The coverage factor, k, is a numerical factor that multiplies the combined standard uncertainty in order to specify the fraction of the probability distribution that the uncertainty represents.

The MCM uncertainty propagation is a well-described technique which has historically been limited by the computing resources available. The rapid development of computing capabilities in recent years has made it more accessible to the EO community. The quantification and analysis of the uncertainty contributors developed as a software tool here require access to a large amount of memory and CPU time and have thus utilised the UK's JASMIN supercomputer facility (Lawrence et al., 2013). The high-performance of the computer nodes permits the management of large quantities of memory, while a cluster of virtual and physical machines sharing a dedicated network, permits the parallel processing of the MCM algorithm.

The terms uncertainty, error and bias appear throughout this paper and are extensively analysed. We briefly define these terms here for clarity. Uncertainty expresses the degree of doubt around the measured value and can be reduced by thorough identification and correction of measurement errors. Error is the effect of measurement imperfection and can be systematic or random in nature. The random error can be minimised by using a large statistical sample. Bias is an estimate of a systematic error. These two terms will be used through the document and, in many cases, the difference between them will lead to a slightly different interpretation. The major biases in satellite cross comparison are introduced by