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Simulating arbitrary hyperspectral bandsets from multispectral observations via a generic Earth Observation-Land Data Assimilation System (EO-LDAS)

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Abstract

This paper presents results of using multi-sensor and multi-angular constraints in the generic Earth Observation-Land Data Assimilation System (EO-LDAS) for reproducing arbitrary bandsets of hyperspectral reflectance at the top-of-canopy (TOC) level by merging observations from multispectral sensors with different spectral characteristics. This is demonstrated by combining Multi-angle Imaging Spectroradiometer (MISR) and Landsat Enhanced Thematic Mapper Plus (ETM+) data to simulate the Compact High Resolution Imaging Spectrometer CHRIS/PROBA hyperspectral signal over an agricultural test site, in Barrax, Spain. However, the method can be more generally applied to any combination of spectral data, providing a tool for merging EO data to any arbitrary hyperspectral bandset.

Comparisons are presented using both synthetic and observed MISR and Landsat data, and retrieving surface biophysical properties. We find that when using simulated MISR and Landsat data, the CHRIS/PROBA hyperspectral signal is reproduced with RMSE 0.0001–0.04. LAI is retrieved with r^2 from 0.97 to 0.99 and RMSE of from 0.21 to 0.38. The results based on observed MISR and Landsat data have lower performances, with RMSE for the reproduced CHRIS/PROBA hyperspectral signal varying from 0.007 to 0.2. LAI is retrievedwith r^2 from 0.7 to 0.9 and RMSE from 0.7 to 1.4. We found that for the data considered here the main spectral variations in the visible and near infrared regions can be described by a limited number of parameters (3–4) that can be estimated from multispectral information. Results show that the method can be used to simulate arbitrary bandsets, which will be of importance to any application which requires combining new and existing streams of new EO data in the optical domain, particularly intercalibration of EO satellites in order to get continuous time series of surface reflectance, across programmes and sensors of different designs.

Keywords: MISR; Landsat; CHRIS/PROBA; EO-LDAS; Semi-discrete radiative transfer model; Barrax

1. Introduction

An understanding of surface reflectance over the solar reflective domain (with wavelengths from 400 to 2500 nm) is important in order to monitor the land surface with spaceborne passive optical sensors. Typically, these sensors acquire data in a limited set of bands (e.g. multispectral sensors, such as Landsat (6 bands), Moderate Resolution Imaging Spectroradiometer (MODIS) (7 bands) or Sentinel-2/MSI (12 bands). By contrast, the Compact High Resolution Imaging Spectrometer (CHRIS)

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instrument on board Proba-1 (Barnsley et al., 2004) collects data with a higher spectral resolution (62 bands of 1.3–12 nm width), typically referred to as a hyperspectral sensor. Although hyperspectral data are presented as airborne sensors measurements for decades, they are not so common on the space borne platforms. We note that a number of space missions are expected to be launched in the next few years with the remit of acquiring hyperspectral data. Among these missions are the Environmental Mapping and Analysis Program (EnMAP), Hyperspectral PRecursor of the Application Mission (PRISMA) and Hyperspectral Infrared Imager (HyspIRI) (Guanter et al., 2015; Candela et al., 2016; Lee et al., 2015).

Hyperspectral data are routinely collected from airborne sensors (e.g. Asner et al., 2016), on the ground and have been used for validation and calibration of space borne sensors (Gupta et al., 1998, Baccini et al., 2007, Hay et al., 1997, 2001). Hyperspectral sensors are also being mounted on automated acquisition platforms in flux towers (Porcar-Castell et al., 2015). There has been an increased interest in hyperspectral observations as a way to characterise leaf traits such as specific leaf area or leaf nitrogen content (Roelofsen, 2014, Musavi, 2016).

A typical application of Earth Observation (EO) data in the optical domain over the land surface is the retrieval of biophysical parameters, often carried out through the inversion of a radiative transfer (RT) model. The resulting derived parameters are usually 'validated' by comparisons with ground based measurements (Baret et al., 2006) and/or comparisons among different products (Disney et al., 2016). These validation methods have a number of shortcomings, as detailed for leaf area index (LAI) in e.g. (Disney et al., 2016), which mentions that a number of incompatible assumptions can be made when gathering "ground truth" data and the retrieval scheme chosen (or among different products). The issue of the scale of the measurements is also important (Pfeifer et al., 2012; Widlowski et al., 2005). Validation of other parameters that describe leaf optical properties is also fraught with complications due to similar reasons. An additional, independent, test of an inversion scheme is that the results obtained from the inversion ought to allow one to predict observations from a different sensor, with arbitrary angular and spectral properties. In this respect, hyperspectral sensors present a spectrally comprehensive dataset to compare against.

Data assimilation (DA) schemes, such as the Earth Observation Land Data Assimilation System (EO-LDAS) of Lewis et al. (2012) and Gomez-Dans et al. (2016) produce inferences of land surface parameters based on EO data combined with a number of *a priori* additional constraints. The EO-LDAS approach maps land surface parameters (such as LAI, or leaf and soil optical properties) to surface directional reflectance by means of an RT model scheme. Thus, if the land surface parameters are known, the RT model can be used to predict observations from another sensor, with different acquisition geometries, spectral characteristics, etc. Additionally, the ability to produce a complete time series of parameters allows the prediction of observations when no other sensor data is available.

An example of this approach is provided in Verhoef and Bach (2003), where estimates of LAI, fraction of brown leaves and soil moisture derived from inverting Landsat data, were used to forward model HyMap imaging spectrometer observations. Verhoef and Bach (2007) concentrate on simulation of Top Of Atmosphere (TOA) multi-angular hyperspectral signal by coupling soil-leaf-canopy and atmosphere RT models. In order to validate the RT model results, they simulate hyperspectral signal of CHRIS/PROBA at the bottom-of-atmosphere (BOA) level for bare soil, maize, dense and sparse forest. Comparison of results between real and simulated CHRIS/Proba measurements show RMSE from 0.011 to 0.027.

The inverse problem is known to be ill-posed (Kimes et al., 2000), in practice meaning that there may be infinite solutions that fit the observations equally well. One way around this is to use prior constraints (Combal et al., 2003), complemented by regularisation approaches (Lewis et al., 2012) or by models of the parameter evolution (Koetz et al., 2005; Quaife et al., 2007; Gomez-Dans et al., 2016). Adding more (independent) observations is also an obvious way to add more constraints to the problem. In all these cases, the original set of observations are being complemented by extra information that restricts the solution space.

Several studies have shown that multi-angular information can improve retrieval of land parameters such as LAI. For instance, Knyazikhin et al. (1998) describe the algorithm for synergistic retrieval of LAI and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) from MODIS and MISR measurements. Gobron et al., (2000) demonstrate that using multiple observational angles from MISR reduces the number of solutions when inverting a canopy RT model. Other studies have demonstrated that MISR can also provide information on structure and heterogeneity of vegetation (Pinty et al., 2002; Gobron et al., 2000; Widlowski et al., 2004).

There are currently in excess of 100 EO sensors acquiring data over the land surface. Products that combine observations from different sensors are still relatively rare, as the different spectral, spatial, angular and temporal characteristics of the data, as well as artefacts introduced by parts of the processing, result in a challenging problem. The identification of so-called essential climate variables (ECVs) (Hollman et al., 2013, Bojinksy et al., 2014) is providing a push towards datasets of scientific parameters that use observations from all available satellites, resulting in consistent, uncertainty-quantified, long term records.

In this paper, we aim to advance the development of multi-sensor products by demonstrating a method for using data from a sensor with relatively few spectral bands can be used to predict data from a hyperspectral sensor, via a DA approach. To achieve this we use data from the