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Advancing retrievals of surface reflectance and vegetation indices over forest ecosystems by combining imaging spectroscopy, digital object models, and 3D canopy modelling

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ABSTRACT

Imaging spectroscopy based methods offer unique capabilities for retrieving narrow-band vegetation indices which can be empirically related to functional traits of plants. However, in areas with complex topography, illumination effects affect the retrieval of such indices from high spatial resolution airborne or satellite data. Irradiance components at the pixel level are determined by atmospheric composition, as well as instantaneous illumination-surface-sensor geometries. An accurate pixel-wise description of direct and diffuse irradiance components is necessary to perform atmospheric corrections, finally resulting in improved surface reflectances and hence products. We assess three atmospheric correction strategies, differing in their approaches to simulate instantaneous as well as pixel-wise abundances of diffuse and direct irradiance. We use physically-based approaches in combination with either digital elevation models (DEM), fine resolution digital object models (DOM), or 3D modelling output from the Discrete Anisotropic Radiative Transfer (DART) model. The such obtained top-of-canopy reflectances at the Laegern test-site in Switzerland, are used to assess retrieval improvement for a set of indices (Normalized Difference Vegetation Index (NDVI), Photochemical Reflectance Index (PRI), as well as chlorophyll and carotenoid indices). We demonstrate that both, the DOM and the DART based approach, improve the retrievals for flat cast-shadows by $\leq 71\%$ compared to using a DEM. In dense forest areas, improvements are less significant. Remaining key issues are related to overestimating surface reflectance under extreme illumination conditions.

1. Introduction

Imaging spectroscopy is often employed to infer physiological, biochemical, and structural vegetation traits that eventually allow assessing and monitoring spatio-temporal variations in vegetation functioning, health and status. A wide range of different analytical methods (e.g. vegetation indices, model inversion techniques) are available to retrieve such quantitative information from measured radiometric signals (Kokaly et al., 2009; Schaepman et al., 2009; Ustin et al., 2009). Increasing spectral resolution of optical sensors offers new opportunities in vegetation monitoring, which were not possible before. Besides biochemical vegetation information (e.g. leaf chlorophyll content and leaf water content), functional information such as the de-epoxidation state of xanthophylls (Gamon et al., 1990) and sun-induced chlorophyll fluorescence (Damm et al., 2015a; Rascher et al., 2015) can be retrieved nowadays. The retrieval of such vegetation information is achieved by either measuring subtle changes of leaf reflectance using reflectance based approaches or exploiting narrow atmospheric absorption features using radiance based approaches. Advancements in sensor technology allow combining high spectral with high spatial resolution (Wulder et al., 2004). This information is complex in its nature, in particular due to the increasing shadow fraction for each pixel, in particular in highly vertically structured vegetation. In particular, measurements of individual species, such as trees, are always composed of a mixture of sunlit and shaded parts, complicating retrievals of surface reflectance values as well as functional traits (Gastellu-Etchegorry et al., 1999). Further, highly accurate estimates of surface irradiance are of increasing interest for specialised applications (e.g. Damm et al., 2014). Irradiance varies in intensity and spectral composition, depending on atmospheric composition (Seidel et al., 2012). Direct irradiance at

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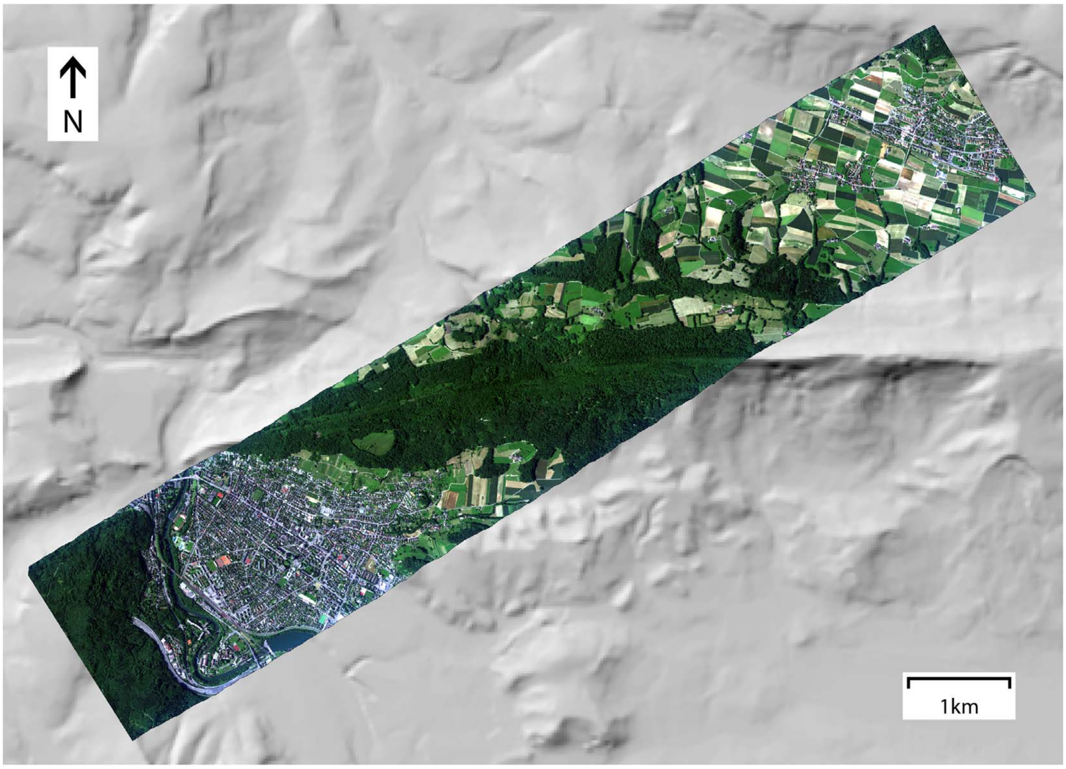

Fig. 1. APEX flight line (at-sensor radiance, RGB colour composite) of the Laegern study site (June 26, 2010, 15:30 UTC). The background is a hillshaded DEM illustrating scene topography (DHM25 from Swisstopo, Switzerland). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

surface level represents radiation which remains un-scattered while diffuse irradiance contains radiation which was previously scattered by gases or aerosols in the atmosphere and by the surroundings of the target surface. Multiple scattering within the atmosphere leads to a wavelength dependent increase of the atmospheric pathway and thus an increase of atmospheric molecular absorption compared to the direct path. It has been demonstrated that these wavelength dependent differences between direct and diffuse irradiance lead to considerable errors in retrieved surface reflectance and subsequently derived vegetation information if pixel-wise estimates of direct and diffuse irradiance are uncertain (Damm et al., 2015b). Accurate and instantaneous atmospheric corrections of high spectral and spatial resolution data are challenging (Matthew et al., 2002; Seidel et al., 2010). The state of the atmosphere at acquisition time plays a vital role because local and temporal variations in water vapour and aerosol loadings impact spectral irradiance estimates (Cho et al., 2003). To overcome this limitation, a precise parameterization of the atmosphere for radiative transfer codes is required (Key and Schweiger, 1998). In order to properly describe these complex irradiance fields, one can no longer assume uniformly flat Earth surfaces or use coarse digital elevation models (DEM) which do not resolve small scale height differences for correction (Richter, 1990, 1998). Several approaches have been discussed to minimize those uncertainties. Minimizing varying illumination effects can be achieved by only considering sunlit pixels (Asner et al., 2015; Malenovský et al., 2013). Other methods include the use of matched filtering of reflectance data to detect and correct shadows (Adler-Golden et al., 2002). More sophisticated approaches make intensive use of auxiliary data. Digital object models (DOM) derived from LiDAR data are used to better represent the surface (Friman et al., 2011). Other approaches involving ray tracing through LiDAR based voxel grids have been proposed (Schläpfer et al., 2003; Kükenbrink et al., 2016). In this study, we hypothesize that (1) more accurate irradiance fields can be modelled by using auxiliary, scene specific data and that (2) these irradiance fields can be integrated in the atmospheric correction process to minimize product sensitivity to illumination effects. This will finally lead to (3) retrievals of vegetation indices showing a substantially reduced sensitivity to surface illumination. We evaluate three approaches for atmospheric correction that are all using four-stream theory (Verhoef and Bach, 2003) and account for direct and diffuse irradiance variations by employing different auxiliary data. All approaches are applied to data acquired with the Airborne Prism Experiment (APEX) imaging spectrometer (Schaepman et al., 2015), allowing an evaluation based on commonly encountered illumination situations. We derive vegetation indices (Normalized Difference Vegetation Index (NDVI), Photochemical Reflectance Index (PRI) and two pigment indices for chlorophyll (CHL) and carotenoids (CAR)) to demonstrate the impact of the correction methods on remote sensing products.

2. Study site and data

2.1. Study site

The Laegern study site is a limestone hill northwest of Zurich, Switzerland (47° 28′ 54.75″ N 8° 23′ 37.82″ E, 866 m a.s.l.), stretching West to East. The site is mainly covered by a temperate mixed forest with a high diversity of tree species (dominated by beech, ash, sycamore and spruce) of different ages and sizes (Eugster et al., 2007). The Laegern is a well-studied site and contains a flux tower which is part of the AERONET (Holben et al., 1998) and FLUXNET (Baldocchi et al., 2001) measurement networks. The extent of the study site used here contains the Laegern forest as well as surrounding agricultural areas.

2.2. Imaging spectrometer data

The main data sets used are two flight lines covering the study site (Fig. 1). They were acquired by APEX on the 26th of June 2010 at 15:30 UTC and on the 29th of June 2010 at 10:00 UTC. The solar zenith and azimuth angles at acquisition time are listed in Table 1. APEX is an airborne pushbroom imaging spectrometer covering the 372 nm to