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Research Paper

Improved estimation of leaf area index and leaf chlorophyll content of a potato crop using multi-angle spectral data – potential of unmanned aerial vehicle imagery

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ABSTRACT

In addition to single-angle reflectance data, multi-angular observations can be used as an additional information source for the retrieval of properties of an observed target surface. In this paper, we studied the potential of multi-angular reflectance data for the improvement of leaf area index (LAI) and leaf chlorophyll content (LCC) estimation by numerical inversion of the PROSAIL model. The potential for improvement of LAI and LCC was evaluated for both measured data and simulated data. The measured data was collected on 19 July 2016 by a frame-camera mounted on an unmanned aerial vehicle (UAV) over a potato field, where eight experimental plots of 30 × 30 m were designed with different fertilization levels. Dozens of viewing angles, covering the hemisphere up to around 30° from nadir, were obtained by a large forward and sideways overlap of collected images. Simultaneously to the UAV flight, *in situ* measurements of LAI and LCC were performed. Inversion of the PROSAIL model was done based on nadir data and based on multi-angular data collected by the UAV. Inversion based on the multi-angular data performed slightly better than inversion based on nadir data, indicated by the decrease in RMSE from 0.70 to 0.65 m^2/m^2 for the estimation of LAI, and from 17.35 to 17.29 $\mu g/cm^2$ for the estimation of LCC, when nadir data were used and when multi-angular data were used, respectively. In addition to inversions based on measured data, we simulated several datasets at different multi-angular configurations and compared the accuracy of the inversions of these datasets with the inversion based on data simulated at nadir position. In general, the results based on simulated (synthetic) data indicated that when more viewing angles, more well distributed viewing angles, and viewing angles up to larger zenith angles were available for inversion, the most accurate estimations were obtained. Interestingly, when using spectra simulated at multi-angular sampling configurations as were captured by the UAV platform (view zenith angles up to 30°), already a huge improvement could be obtained when compared to solely using spectra simulated at nadir position. The results of this study show that the estimation of LAI and LCC by numerical inversion of the PROSAIL model can be improved when multi-angular observations are introduced. However, for the potato crop, PROSAIL inversion for measured data only showed moderate accuracy and slight improvements.

1. Introduction

Accurate quantitative estimates of vegetation bio-physical/-chemical parameters are important for, *e.g.*, precision agriculture (Zhang and Kovacs, 2012), crop phenotyping and monitoring crop traits (Domingues Franceschini et al., 2017; Jay et al., 2017), and reduction of fertilizer usage and improvement of yield prediction (Cilia et al., 2014; Goffart et al., 2008). Inversion of radiative transfer models (RTMs) using optical remote sensing data is a commonly applied technique for the estimation of these parameters. Based on physical laws, RTMs describe how radiation interacts with vegetation canopies. RTMs allow for the computation of reflectance at arbitrary viewing and illumination geometries and a set of leaf and canopy parameters. With different inversion schemes, RTMs can be used to estimate these parameters based on a reflectance input. The accuracy of the parameter estimations depends on the used model, the applied inversion technique

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and the quality of the input data (Jacquemoud et al., 2000). PROSAIL (Jacquemoud et al., 2009) – a combination of the PROSPECT leaf model (Jacquemoud and Baret, 1990) and the SAIL canopy bidirectional reflectance model (Verhoef, 1984), is among the most widely used RTMs. By inversion of the PROSAIL model, it is possible to simultaneously estimate both leaf and canopy parameters such as leaf area index (LAI) and leaf chlorophyll content (LCC) (Darvishzadeh et al., 2008).

The inversion of RTMs is an ill-posed problem due to measurement and model uncertainties (Combal et al., 2003), and due to the issue that different combinations of parameters may result in similar reflectance spectra (Jacquemoud et al., 1995; Weiss and Baret, 1999). Therefore, inversion of a single spectrum may result in a range of possible parameter combinations that approximate a similar spectral signature. To reduce the number of possible solutions to the inversion of a RTM model, regularization needs to be applied. This can for example be done by constraining parameters, or by the use of *a priori* information on the parameters (Laurent et al., 2014; Mousivand et al., 2015). Another way to improve the estimation of vegetation parameters is by increasing the dimensionality of the input data by introducing multi-angular observations (Dorigo, 2012; Schaepman et al., 2005; Vuolo et al., 2008; Weiss et al., 2000). It has been widely accepted that multi-angular reflectance data contain additional information of vegetation targets compared to data at a single observation angle (Barnsley et al., 1994). Multi-angular measurements are sensitive to vegetation structure and can therefore provide enhanced information on the structural properties (Chen et al., 2003; Widlowski et al., 2004). For example, it has been demonstrated that the retrieval of LAI by inversion of the PROSAIL model for various crops can be improved by inclusion of just a second observation angle for the inversion (Duan et al., 2014). Moreover, using multiple viewing angles from satellites has also been demonstrated to improve the simultaneous estimation of LAI and LCC (Dorigo, 2012).

Some satellite-borne sensors have been specifically designed to make multi-angular observations, such as the Compact High Resolution Imaging Spectrometer on-board the Project for On-Board Autonomy (CHRIS-PROBA) (Barnsley et al., 2004) or the Multi-angle Imaging Spectrometer (MISR) (Diner et al., 1998). These sensors are capable of viewing an area of interest from several different angles during their overpass, providing information on the anisotropic characteristics of the target's reflectance. Although these sensors are capable of collecting data up to large view zenith angles (VZAs) [five viewing angles up to a VZA of ± 55° for CHRIS and nine viewing angles up to a VZA ± 70.5° for MISR], their relative coarse spatial resolution (18–36 m for CHRIS and 275 m − 1.1 km for MISR) hinders detailed analysis for, *e.g.*, precision agriculture.

In addition to satellite-based measurements, multi-angular observations are typically collected using goniometers. On the one hand, goniometers provide a high angular sampling in general with accurate control of the observation angles (Sandmeier et al., 1998; Sandmeier, 2000). Moreover, depending on the sensor mounted on the goniometer, measurements with high spectral resolution can be acquired. On the other hand, goniometer measurements are relatively time consuming. Especially for measurements in the field this can be a serious issue due to several factors including movement of the sun and possible changes in atmospheric conditions during a measurement sequence (Milton et al., 2009). Moreover, most goniometer systems only sample a single point and thus lack information on the spatial distribution of anisotropy effects.

Recently, multi-angular measurements have also been performed using unmanned aerial vehicles (UAVs). Several researchers have shown that these agile platforms are capable of collecting multi-angular observations in a relatively short amount of time (Burkart et al., 2015; Grenzdörffer and Niemeyer, 2011; Roosjen et al., 2017; Roosjen et al., 2016). Moreover, due to the relatively low flight height of UAVs, a good ground sampling distance (GSD) can be achieved, making UAV-based methods valuable for detailed studies on anisotropy effects at the individual plant level (Roosjen et al., 2017). UAV based methods where a gimbal is used to hold a spectrometer at different viewing angles can provide a good angular coverage of an area of interest (Burkart et al., 2015; Grenzdörffer and Niemeyer, 2011). However, to capture viewing angles covering all azimuth directions around a target requires complicated flight patterns, making it difficult to apply such a measurement strategy. Moreover, most professional UAVs have downward pointing sensors and do not have the flexibility to change their orientation during the flight.

In a recent study we demonstrated that multi-angular views can easily be obtained by exploiting the overlap of images that are collected by a frame-camera mounted on a UAV (Roosjen et al., 2017). This method is very attractive for studying pixel wise anisotropy effects, since every georeferenced pixel is captured from multiple camera positions and thus observed from different viewing angles. Using this method it was shown that different fertilization regimes within a potato field resulted in significantly different anisotropy signals due to variation in the development of the potato plants as a result of the differences in fertilization level. In that study, these differences in anisotropy were quantified using the parameters of the Rahman-Pinty-Verstraete (RPV) model (Rahman et al., 1993). A correlation between RPV and canopy parameters pointed at the information content of the anisotropy signal. A follow-up step is to explore the use of these multi-angular views in combination with physically based RTMs to explore their use for the estimation of vegetation parameters. Currently, only a limited number of research papers focus on the retrieval of biophysical vegetation parameters using data collected by UAVs. Moreover, especially parameter retrieval using multi-angular data collected by UAV is underrepresented.

The aim of this paper is to study the potential of multi-angular measurements collected by UAVs for the retrieval of LAI and leaf LCC by inversion of the PROSAIL model. We studied three cases: In the first case we used the data that were collected during the study of Roosjen et al. (2017) for inversion of the PROSAIL model to estimate LAI and LCC, which were simultaneously measured in the field during the UAV flight. However, a mismatch between the measured multi-angular reflectance data and the ability of the used model to reproduce this, which can be either caused by the quality of the RTM model or by the quality of the spectral measurements, might provide poor results (Dorigo, 2012). Therefore, in a second case, we used the configuration of viewing angles that was captured during the same study and simulated reflectance data at these angles, which we then used as input for the inversion of the PROSAIL model to estimate LAI and LCC. This case represents the situation where a realistic range and distribution of viewing angles is available for inversion, and where we were sure that the model used can reproduce the input data. In the third case, we simulated multi-angular reflectance data for inversion of the PROSAIL model based on several configurations of viewing angles that are typically collected with goniometer setups. This case represents the ideal situation where a wide range of well-distributed viewing angles is available. For all cases, the inversion accuracies based on the multi-angular data were compared with inversions based on nadir viewing data, in order to assess the improvement of LAI and LCC estimations when multi-angular observations were used.

2. Methods

2.1. Study area

The study area that was used for our UAV experiment and data simulations, was a potato field (*Solanum tuberosum* L., cultivar Fontane. Planting date: 16 April 2016) located south of the village Reusel (51°59′47.9″N, 5°9′34.5″E) on the Dutch–Belgian border, in the province of Noord-Brabant (The Netherlands). In this field, an experiment was performed to evaluate the effect of split-level fertilization on potato yield. Eight 30 × 30 m plots, labelled A-H, were marked in the different fertilization zones (Fig. 1). Varying initial nitrogen (N) fertilization was