SPECTRO-DIRECTIONAL CHRIS/PROBA DATA OVER TWO SWISS TEST SITES FOR IMPROVED ESTIMATION OF BIOPHYSICAL AND –CHEMICAL VARIABLES – FIVE YEARS OF ACTIVITIES

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ABSTRACT:

The spaceborne ESA-mission CHRIS (Compact High Resolution Imaging Spectrometer) on-board PROBA-1 (Project for On-board Autonomy) delivers multi-directional data sets that contain spectral, directional, spatial and multi-temporal information. CHRIS/PROBA data have been acquired over two well documented test sites in Switzerland (Swiss National Park (SNP) and Vordemwald (VOR) since 2003 and allow for the monitoring of complex and dynamic vegetation canopies of forests and agricultural crops. For vegetated surfaces, the spectral information content of CHRIS/PROBA may yield the biochemical and biophysical properties of vegetation canopies, while the directional component may deliver additional information on canopy structure. The CHRIS instrument offers the possibility to combine independent information sources, such as spectral and directional observations, for a complete and robust characterization of a vegetation canopy. Such an integrated approach bears the potential to improve the estimation of biophysical and biochemical canopy characteristics relevant for applications such as ecological modeling and precision agriculture. A full pre-processing scheme for CHRIS/PROBA data for geometric and atmospheric processing over mountainous and hilly terrain, which is a pre-requisite for the subsequent spectro-directional data analysis, has been established. The three case studies presented in this paper deal with a) the assessment of canopy structure and heterogeneity from multi-angular data, b) the contribution of directional data for the estimation of canopy biochemistry and c) the estimation of leaf area index (LAI) from multi-temporal CHRIS/PROBA data. Concerning the first case study, the structure and heterogeneity of a coniferous canopy based on its degree of reflectance anisotropy is addressed using multi-angular CHRIS data and the parametric Rahman-Pinty-Verstraete (RPV) model. The second case study aims at an improved retrieval of foliar nitrogen concentration (C_N) and water content (C_W) using multi-angular CHRIS data and ground truth in multiple linear regression analyses limited by a statistical variable selection method. In the third case study, a radiative transfer model (RTM) is coupled to a canopy structure dynamics model (CSDM) for provision of a continuous LAI time course of maize over the season. The resulting estimation of the temporal and spatial variation of LAI is improved by integrating multi-temporal CHRIS/PROBA data and ground meteorological observations. The paper shows the potential and value of spectro-directional Earth observations, as provided by an innovative system like CHRIS/PROBA for Earth system studies.

1. INTRODUCTION

This paper presents three case studies that deal with the exploitation of spectral, directional, spatial and multi-temporal information contained in CHRIS/PROBA observations. The case studies present exemplarily the information content and thus the potential for improved vegetation characterization provided by an Earth observation mission such as CHRIS/PROBA sampling multiple information dimensions at Landsat-like spatial resolution. The work was carried out within the two well documented CHRIS/PROBA study sites that exist in Switzerland, namely the alpine Swiss National Park (SNP) and the Swiss Plateau study site Vordemwald (VOR) since 2003. The three case studies presented in this paper deal with 1) the assessment of canopy structure and heterogeneity from multi-angular data, 2) the contribution of directional data for the estimation of canopy biochemistry and 3) the estimation of leaf area index, being a key variable for the understanding and modelling of several eco-physiological processes. The results clearly show the potential and value of spectro-directional Earth observations at regional scale for ecological monitoring and modeling studies. CHRIS/PROBA represents a rich source of information of Earth observation data specifically adapted for monitoring complex and dynamic vegetation canopies particularly in ecotones at the regional scale.

2. DATA AND METHODS

2.1 CHRIS/PROBA Data

The CHRIS sensor on PROBA-1 provides spectral data over the visible/near-infrared spectral region from 400-1050 nm, and it can be operated at different modes reflecting on the one hand user needs and on the other hand a necessary compromise between spatial resolution and the number of spectral bands that can be stored onboard. The CHRIS sensor captures along-track five separate images of a given target area, whereas each image is recorded at a different sensor viewing angle (nominally listed at -/+55°, -/+36°, 0°, (Barnsley et al., 2004)). A total of 16 multi-angular data acquistions between winter 2003 - 2007 have been performed over the SNP site and nine acquisitions over VOR, respectively, the latter mainly acquired during the growing seasons of 2005 and 2006. We have set up a full pre-processing scheme for CHRIS/PROBA data for geometric and atmospheric processing over mountainous terrain (Kneubühler et al., 2005), which is a pre-requisite for subsequent spectro-directional data analyses.

2.2 Swiss National Park

The study site covered by CHRIS/PROBA data is located near Ofenpass within the Swiss National Park (10° 14' E, 46° 40' N). The Ofenpass represents an inner-alpine valley at an average altitude of about 1900 m a.s.l. with an annual precipitation of 900-1100 mm. Embedded in this environment are dry, boreal type subalpine forests. The south-facing floor of the Ofenpass valley is considered as the core test site (Figure 1). It has long been subject to ecological studies (Kötz et al., 2004) and is described extensively in Schaepman et al. (2005). The forests are largely dominated by mountain pine (*Pinus montana ssp. arborea*) and some stone pine (*Pinus cembra*) as a second tree species.

Figure 1: Subset of the geometrically and atmospherically corrected CHRIS/PROBA nadir scene acquired over the Swiss National Park study site on 17 February 2004. The Ofenpass valley stretches from left to right in the central part of the image.

2.3 Vordemwald

The study site Vordemwald (7° 53' E, 47° 16' N) is located on the Swiss Plateau in central Switzerland (Figure 2). The hilly area is dominated by agricultural fields in the lower parts (450-500 m a.s.l.) and forests mainly on the hilltops (elevations up to 700 m a.s.l.) Agriculture concentrates on barley, wheat, maize, sugar beet and pasture land (Kneubühler et al., 2006). The forest canopy is composed of a mixture of needle-leaf and broadleaf species, dominated usually by European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L.). In total, nine different species can be found belonging to two plant functional groups (coniferous (evergreen) and broadleaf (deciduous) species).

Figure 2: Subset of the geometrically and atmospherically corrected CHRIS/PROBA nadir scene acquired over the study site Vordemwald on the Swiss Plateau on 26 May 2005.

2.4 Geometric Processing

Since both the SNP and VOR study sites are located in either high mountainous, rugged or at least hilly terrain, a parametric approach for geometric correction of each data set of a CHRIS/PROBA acquisition scenario (up to five viewing angles) was applied. This approach is based on a three-dimensional (3-D) physical model (Toutin, 2004) which is implemented in the commercially available image processing software PCI/Geomatica (PCI Geomatics, 2006). The method allows us to achieve a high geometric accuracy with resulting root mean square errors (RMSE) derived from GCPs at 0.46-0.79 pixels along track and 0.39-0.73 pixels across track when using a digital surface model (DSM) (© swisstopo) with 2 m resolution.

2.5 Atmospheric Processing

Atmospheric correction of the CHRIS radiance data was performed using ATCOR-2/3 (Richter, 1998) which is based on MODTRAN-4. ATCOR-3 is suitable for atmospheric correction of sensor data acquired over rugged terrain. The software has recently been adapted to include the option to process tilted sensors by accounting for varying path lengths through the atmosphere and varying transmittance. Validation showed a good agreement between atmospherically corrected CHRIS/PROBA data and spectral ground measurements with deviations within ±1 stdev of the ground measurements of homogenous targets for most bands. The CHRIS/PROBA data are geo-corrected Hemispherical-Directional-Reflectance-Factor (HDRF) data.

3. CASE STUDIES

3.1 Canopy Structure and Heterogeneity Assessment

Multi-angular observations of the reflectance anisotropy have proven to be diagnostic for structural surface properties, which are helpful to complement the spectral measurements for a complete and robust characterization of vegetation canopies and heterogeneity of a coniferous canopy based on its degree of reflectance anisotropy as observed by the multi-angular imaging spectrometer CHRIS. This study was performed on the Swiss National Park (SNP) study site using a four-angle CHRIS/PROBA data set that was acquired over the SNP on 17 February 2004 (sun zenith: 59.7°, azimuth: 165.4°) under cloud free conditions. The data set was subsequently geometrically and atmospherically corrected following the approach described in the preceding chapter.

CHRIS/PROBA observations were investigated and related to surface structure using the parametric Rahman-Pinty-Verstraete (RPV) model (Rahman et al., 1993), which simulates the anisotropy of a surface reflectance as a function of four parameters. It has been shown that the RPV Minnaert function parameter *k*, describing the degree of anisotropy, is related to canopy structure and subpixel heterogeneity (Pinty et al., 2002; Widlowski et al., 2004). Hence, the Minnaert function parameter *k*, which quantifies the overall shape of the surface Bidirectional Reflectance Factor (BRF) is of particular interest. Based on the *k* values, the anisotropy of the observed HDRF can be classified into a bell- (k>1) or bowl-shaped (k<1) pattern. Bell-shaped BRFs are associated to heterogeneous canopies of medium density over a bright background. The inversion of the RPV model against the multi-angular data over a subset of the pre-processed CHRIS/PROBA scene provided spatial fields of the RPV model parameters describing the anisotropy of the observed surface reflectance. The performance of the inversion was affected by errors due to sloping terrain (i.e., topography). Thus, the subsequent interpretation of the retrieved model parameters was restricted to areas with slopes of up to 10° and inversion uncertainties below 10%. For those conditions measured multi-angular data were fitted well by simulated BRF based on the retrieved RPV parameter sets.
This case study demonstrated the successful inversion of the parametric RPV model against the independent information source of multi-angular CHRIS/PROBA observations. The RPV inversion allowed discriminating between different surface types based on their inherent anisotropy. Results showed the potential to distinguish within a forest stand between closed canopies and ones of medium density, thus delivering quantitative surface structural information.

3.2 Canopy Biochemistry Estimation

Knowledge about plant biochemistry is important for a range of environmental applications (Asner and Vitousek, 2005; Curran, 2001; Ustin et al., 2004).

The objective of the second case study was the investigation of directional CHRIS/PROBA data for an improved estimation of foliar nitrogen concentration (C_N) and water content (C_W). We investigated a) whether the added information in remotely sensed multi-angular data can improve C_N and C_W estimates and b) whether certain sensor viewing angles emerge to be beneficial for estimating C_N and C_W. The study was performed on the forests of the Swiss Plateau study site Vordemwald (VOR) as described above. In July 2004, an extensive field data campaign took place covering 15 subplots that were chosen according to their species composition. At each subplot 3–10 tree crowns were determined for foliar sampling. The trunk position of each tree was measured with a Trimble GeoXT GPS receiver. A complete CHRIS/PROBA scene (five viewing angles) acquired on 1 July 2006 over the VOR study site was geometrically and atmospherically corrected following the pre-processing methodology described earlier in this paper. In total, spectra of 60 field-sampled crowns were extracted from the five CHRIS/PROBA images by using the geographical trunk positions (vector data) of the sampled trees to locate the crown pixels in the images (Gorodetzky, 2005). CHRIS/PROBA data acquisition was two years after field data collection but during the same phenological period (July). We assumed a stable C_N and C_W level during July and only small inter-annual variability for nitrogen concentration and for leaf water status due to similar climatic conditions in the years 2004 and 2006.

Multiple linear regression analysis was applied to fit models between the dependent variables (C_N and C_W) and all possible viewing angle combinations of four spectral data sets: SPEC, BNC, CRDR, NBDI. SPEC includes original reflectance values; BNC includes band depths normalized to the waveband at the center of the absorption feature (Curran et al., 2001; Kokaly and Clark, 1999); CRDR includes continuum-removed derivative reflectance (Mutanga et al., 2004; Tsai and Philpot, 1998) and NBDI includes normalized band depth index values (Mutanga et al., 2004). To limit the number of spectral wavebands used in the regression models, this study employed a statistical variable selection method, namely an enumerative branch-and-bound (B&B) search procedure (Miller, 2002).

To summarize the findings of this case study, the following conclusions can be drawn: 1) additional information contained in multi-angular data improved regression models for C_N and C_W estimates and lowered cross-validated RMSEs considerably, 2) strongest effects upon R^2 for each data set (SPEC, BNC, CRDR, NBDI) yielded from models with the same number of viewing angles can be achieved when adding a second and third viewing angle (Figure 3 and Figure 4), 3) monodirectional models developed on backward scattering viewing directions were generally superior to models based on forward scattering data and 4) untransformed reflectance data (SPEC) often outperformed continuum-removed data when using only one viewing zenith angle (Huber et al., 2008).

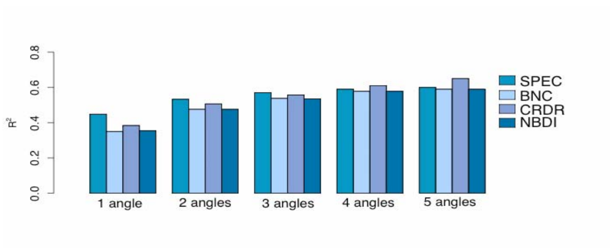

Figure 3: Model coefficient of determination (R^2) of nitrogen concentration regressed on the data sets SPEC, BNC, CRDR and NBDI, respectively. R^2 represents the mean of all models with the same number of viewing zenith angles involved. For instance R^2 of one angle stands for the mean of five monodirectional models (± 36°, ±55° and nadir).

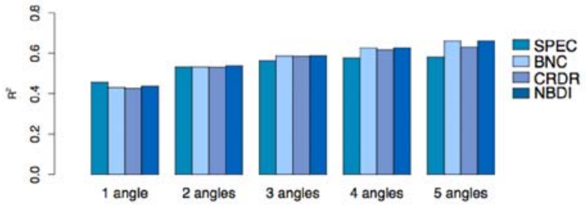

Figure 4: Model coefficient of determination (R^2) of water content regressed on the data sets SPEC, BNC, CRDR and NBDI, respectively. R^2 represents the mean of all models with the same number of viewing zenith angles involved. For instance R^2 of one angle stands for the mean of five monodirectional models (± 36°, ±55° and nadir).

3.3 Multi-temporal LAI Estimation

The third case study aimed at exploiting synergistically the spectral, spatial and temporal information dimensions contained in multi-temporal CHRIS/PROBA observations. Such Earth observations represent a rich source of information for monitoring the dynamic vegetation status. For the assessment of vegetation phenology the leaf area index (LAI) is essential as it is a key variable for the understanding and modeling of several eco-physiological processes within a vegetation canopy (eg. (Myneni, 1997). In this study, a radiative transfer model (RTM) is coupled to a canopy structure dynamics model (CSDM). The coupled models are used to exploit the complementary content of the spectral and temporal information dimensions for LAI estimation over a maize canopy. The resulting estimation of the temporal and spatial variation of LAI is improved by integrating multi-temporal CHRIS/PROBA data and ground meteorological observations. Further, the presented method provides the continuous LAI time course over the season. CHRIS/PROBA multi-angular data sets were acquired in Mode 5 over the earlier described study site Vordemwald (VOR) on eight different dates between 26 May 2005 and 22 September 2005. Out of these data sets, four dates that represent major steps in phenology of the selected agricultural fields were selected for further processing and data exploitation. The selected dates are 26 May 2005 (day of year (DOY) 171), 20 June 2005 (DOY 196), 17 August 2005 (DOY 229) and 22 September 2005 (DOY 265). The data sets were geometrically and atmospherically corrected.
A coupling scheme to combine two models, the joint radiative transfer models (RTM) PROSPECT/SAIL and the canopy structure dynamics model (CSDM), was implemented to estimate LAI based on the multi-temporal remote sensing observations (Koetz et al., 2005). The joint RTM provide an explicit connection between the canopy biophysical variables, the view and illumination geometry and the resulting canopy reflectance by exploiting our knowledge of the involved physical processes (Baret et al., 2000). The RTM have to be inverted to retrieve the biophysical variables from the measured canopy reflectance (Bacour et al., 2002; Kimes et al., 2000; Weiss et al., 2000).

The use of a canopy structure dynamics model (CSDM) allows us also to derive a continuous estimation of LAI which is required in some applications, particularly those based on the forcing of agricultural growth or land surface models (Delecolle et al., 1992; Moulin et al., 1998). The used CSDM is a simple semi-meachanistic model describing the LAI dynamics (Baret, 1986). Concerning the radiative transfer models in this study, the turbid medium radiative transfer model SAIL (Scattering from Arbitrarily Inclined Leaves (Verhoef, 1984; Verhoef, 1985)) was used to describe the canopy structure. The PROSPECT model (Jacquemoud and Baret, 1990) was used to describe leaf optical properties. The coupling of the RTM and CSDM models was based on the hypothesis that the remotely sensed observations of LAI had to be consistent with the time profile of LAI generated by the CSDM. Consequently, the remotely sensed LAI was recalibrated, where necessary, relative to the phenologically sound LAI provided by the CSDM. The integration of the CSDM to the retrieval algorithm allowed a continuous description of the LAI time course over the growing season. For the evaluation of the LAI retrieval performance estimated LAI was compared to field measured LAI.

This case study showed the successful coupling of a joint RTM to a CSDM to exploit the complementary content in the spectral and temporal information dimensions for the LAI estimation over a maize canopy. The knowledge of the canopy structure dynamic provided by the CSDM is used as ancillary information to achieve an improved robustness of the RTM inversion. Further, the presented coupled models integrate spaceborne remote sensing data with ground meteorological observations providing a continuous LAI time course over the season along with start, end and length of the growing period. Crop growth as well as surface process models require such a continuous description of the vegetation evolution. The proposed methodology prepares for the assimilation of remote sensing observations into land surface process models.

4. CONCLUSIONS AND OUTLOOK

The above discussed case studies in Switzerland all present improved use of spectro-directional (and in one case multi-temporal) measurements exceeding the classical use of the directional dimension for canopy structure retrieval and the spectral dimension for biochemistry. In particular improved measures for canopy heterogeneity (Minnaert's *k*), unprecedented estimates of C_W and C_N, and temporal evolution of vegetation structure for integration in dynamic vegetation models have been demonstrated. The six years of CHRIS/PROBA operation in space have fostered closer collaboration of various Earth System sciences and allowed working at various scales that could be validated in the field. However, the realization of further spectro-directional imagers in space remains a challenge. Proposed missions had generally not found a majority for support (e.g. SPECTRA (Rast, 2004)). Currently, combined instrumented approaches (e.g. FLORA, FLEX) or approaches with more flexible acquisition pointing have been suggested (e.g. EnMAP), but true spectro-directional concepts to widen the fields of ecological monitoring and modeling remain sparse also in the future.

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