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The effect of boreal forest canopy to reflectance of snow covered terrain based on airborne imaging spectrometer observations

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ABSTRACT

Optical remote sensing methods for mapping of the seasonal snow cover are often obstructed by the masking effect of forest canopy. Therefore, optical algorithms tend to underestimate the amount of snow cover in forested regions. In this paper, we investigate the influence of boreal forest stand characteristics on the observed scene reflectance under full dry snow cover conditions by applying an advantageous experimental setup combining airborne hyperspectral imaging and LIDAR data sets from a test region in Sodankylä, northern Finland. This is particularly useful to the understanding of the composition of the mixed satellite scene reflectance behavior and it is relation to the natural ground targets' spectral signatures.

At first, we demonstrate the effects of varying forest stand characteristics, including Canopy Cover (CC), Tree Height (TH) and the product of the these parameters referred to as CCxTH, on the reflectance measured by airborne imaging spectrometer AisaDUAL. Then, we analyze the effects of the presence of snow on forest canopy on the observed AisaDUAL data. The analysis of the effects of canopy was enabled by the high resolution LIDAR measurements which provide reference information on forest canopy characteristics. According to the results the change in Canopy Cover, as well as in CCxTH, is related to the observed change in reflectance, as well as to changes in such spectral indices as Normalized Difference Snow Index (NDSI) and Normalized Difference Vegetation Index (NDVI). Additionally, NDSI was found to vary extensively particularly in dense forests (CC > 85%), where the relative variation was over 100%. This should be considered when applying NDSI-based snow mapping methods in the case of forested areas. One notable finding was that the relation between the forest characteristics and reflectance was nearly exponential, while with reflectance indices it was linear. Besides, the results show that NDSI was a more effective parameter in detecting snow on canopy (values deviated 0.3 on average) than NDVI (values deviated 0.3 on average) in all Canopy Cover classes. The difference in NDSI between these two cases, snow-covered and snow-free canopy, increased when the canopy coverage increased.

1. Introduction

The development of improved and accurate methods to describe satellite-based observations as a function of regionally varying scene (target) characteristics, i.e. *forward modeling*, requires extensive and reliable experimental datasets. The feasibility of geo/biophysical variable estimates retrieved from satellite-data is most of all dependent on how reliable is this *forward modeling*. Thus, e.g. in developing and improving methods for seasonal snow cover monitoring in boreal forests, high spatial and spectral resolution information on the investigated scene properties and their temporal behavior are required. Above all, it is crucial to combine the employment of in situ data of the scene characteristics, coinciding near-range remote sensing reference observations (e.g. airborne, mast- or ground-based) and satellite observations. Using optical snow mapping instruments, such as the MODIS (Moderate Resolution Imaging Spectroradiometer) aboard Terra, specifically the forest disturbs the snow covered area detection as the trees prevent the visibility of snow-covered ground. In open areas with full snow cover the error in detecting snow from a satellite is usually very tolerable, typically less than 1%, but in forested areas the error has been found to be much larger, even 76% in Metsämäki et al. (2012).

Retrieval of fraction of snow covered area (FSC) using optical data is based on the high reflectance of snow in visible (VIS) and near-infrared (NIR) wavelengths compared to other natural

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targets (Wiscombe and Warren, 1980). Spectral unmixing methods for FSC mapping are presented e.g. by Painter et al. (2003) and Vikhamar and Solberg (2003a,b). Moreover, the algorithm of NASA/Goddard Space Flight Center estimates the FSC from Normalized Difference Snow Index (NDSI) using linear regression (Hall and Riggs, 2007; Riggs et al., 2006; Salomonson and Appel, 2004, 2006). A typical defect with these methods is their weaker performance over forested areas. The semi-empirical reflectance model-based method *SCAmod* for FSC mapping in boreal forest and tundra belt using optical data was proposed by Metsämäki et al. (2005). *SCAmod* originates from radiative transfer theory and describes the scene-level reflectance as a mixture of three major constituents – opaque forest canopy, snow and snow-free ground, which are interconnected through forest canopy transmissivity and snow fraction. The method has proven to be feasible for global scale snow cover mapping and is particularly designed to give a good performance also for forested areas (Metsämäki et al., 2012). However, in *SCAmod*, the spatial and temporal variation in the utilized reflectance causes potential error in the satellite FSC retrieval when different constituents of modeled reflectance have standard constant values in the parametrization of *SCAmod* (Metsämäki et al., 2012; Niemi et al., 2012; Salminen et al., 2009). In order to quantify the magnitude of this error, high resolution measurements in controlled condition are required. The usability of satellite data can be improved (e.g. by better forward modeling) by applying more accurate snow-free ground, forest canopy and wet snow reflectances as model parameters (Metsämäki et al., 2012; Niemi et al., 2012; Salminen et al., 2009).

High resolution airborne optical measurements of snow-covered forests accompanied with LIDAR (Light Detection and Ranging) data-derived detailed forest canopy characteristics enable an advanced analysis of forest cover effects on space-borne observations, which is the key novelty of this investigation. The use of extensive data sets from Sodankylä test region, northern Finland, enables the development of optical snow mapping method, and their further validation and regional parameterization. Additionally, the mast-based spectral observations are particularly useful for determining the temporal behavior of forest scene reflectance (Niemi et al., 2012; Salminen et al., 2009). The effects of tree characteristics on the observed reflectance have been investigated earlier, while there is less information available on the spectral differences between various coniferous forest stands in snow-covered conditions (e.g. Betts and Ball, 1997; Ni and Woodcock, 2000; Rautiainen et al., 2004). The combined utilization of the airborne AisaDUAL (Airborne Imaging Spectrometer for Applications) hyperspectral data and LIDAR data with full dry snow cover enables the detailed examination of the effects of the forest stand properties, such as Canopy Cover (CC) and Tree Height (TH), to the observed scene reflectance. Moreover, the exploitation of the high spatial resolution airborne and ground based reflectances acquired under homogeneous dry snow cover conditions is beneficial for the modeling of the scene reflectance of forested terrain. Additionally, the airborne AISA and LIDAR data were utilized in the investigation of the effects of snow on canopy on scene reflectance in different types of forest. This is a further contribution to earlier work that indicates the significant influence of snow on canopy to boreal forest albedo (Kuusinen et al., 2012; Manninen and Stenberg, 2009; Niemi et al., 2012).

The scope of this research is the modeling of the effect of tree canopy on snow mapping in boreal forests. In the next step of the research the results will be used in the developing spectral un-mixing methods and reflectance model-based snow monitoring. Furthermore, the obtained full spectrum dataset facilitates the adaptation and development of snow mapping methods for current and future optical satellite sensors with different optical channels. To summarize, we apply scene-level observations from aerial campaigns to provide information on the behavior of optical spectral signatures relevant to the parameterization of forward models including canopy and ground components.

Table 1
The measurement conditions on 18 March 2010 when the canopy was snow-free and on 21 March 2010 when the canopy was snow-covered. The proportions are from the area monitored by mast-borne spectrometer analyzed from digital image.

	18 March 2010 at 10:05 UTC	21 March 2010 at 10:05 UTC
Solar azimuth (°)	175.5	175.7
Solar elevation (°)	21.7	22.9
Snow depth (cm)	77	83
Grain size (mm)	0.54	0.38
Proportion of snow-free canopy (%)	62.4	39.5
Proportion of directly illuminated snow at ground and on canopy (%)	3.8	11.9
Proportion of shadowed snow at ground and on canopy (%)	34.0	48.6
Snow surface temperature (°C)	−6	−7
Air temperature (°C)	−4	−5

2. Material and methods

2.1. Study area

Sparse coniferous forest dominates the study area in the surroundings of the Arctic Research Center of the Finnish Meteorological Institute (FMI-ARC) in Sodankylä located in southern Lapland of Finland at 26.6°E 67.4°N, about 100 km north of the Arctic Circle and 180 m above the sea level. This sub-arctic environment has long, cold continental winters, and it is characterized by seasonally snow covered forests and open wetlands. In general, snow layer in Lapland is rather homogenous until the spring melt-freeze metamorphosis starts. The Scots Pine (*Pinus sylvestris*) dominated forests are characteristic for the area as overall 92% of forests in southern Lapland are dominated by Scots Pines (fraction of pines > 75%) (METLA, 2010).

2.2. Airborne spectrometer data and processing

The airborne hyperspectral data was acquired utilizing AisaDUAL, which combines two sensors. It provides very high spatial and spectral resolution data covering with VNIR sensor the spectral range of 400–970 nm and with SWIR sensor the range of 970–2500 nm. The campaign was carried out in Sodankylä during full dry snow cover and ideal weather conditions, i.e. several minus degrees and cloudless sky, on 18 March and on 21 March 2010 (Table 1). On 18 March, the trees were snow-free and snow cover on ground was several days old, while on 21 March, the trees were snow-covered and the snow on trees and ground was newly fallen (Fig. 1). The hyperspectral data was acquired from helicopter at the altitude of 800 m producing a spatial resolution of 0.8 m. The spectral resolution for the VNIR bands was 5 nm and for SWIR bands 6 nm totaling to 359 spectral bands. The image swath was 240 m and flight lines were several kilometers long. All measurements were carried out in direct illumination (i.e., clear sky: 0/8 to 2/8 cloud cover). In both campaigns, Oxford Technical Solutions RT4000 GPS/INS was used, which enables high accuracy measurements with low drift rates. The instrument foreoptics unit was set to look at nadir (0°) direction and the field of view (FOV) was 17°. The data was radiometrically and geometrically corrected by using CaliGeo tool by SPECIM in the ENVI software. The AISA data was first filtered with mean filter using 12 × 12 window corresponding to pixel size of 10 m and then reprojected to the same grid with