A Constrained Spectral Unmixing Approach to Snow-Cover Mapping in Forests using MODIS Data

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Abstract— **A snow-cover mapping method accounting for forests (*SnowFrac*) is presented. *SnowFrac* uses spectral unmixing and endmember constraints to estimate the snow-cover fraction of a pixel. The unmixing is based on a linear spectral mixture model, which includes endmembers for snow, coniferous trees, branches of leafless deciduous trees and snow-free ground. Model input consists of a land-cover fraction map and endmember spectra. The land-cover fraction map is applied in the unmixing procedure to identify the number and types of endmembers for every pixel, but also to set constraints on the area fractions of the forest endmembers. Results are presented for non-forested areas, deciduous forests, coniferous forests and mixed deciduous/coniferous forests. Results are also compared to the MODIS L2 500 m snow product.**

Keywords-component; snow-cover mapping, forest, optical remote sensing, MODIS.

I. INTRODUCTION

Large regions of the Earth's land surface are seasonally snow-covered, of which forested areas constitute a significant part. The snow-cover affects climatic conditions and hydrological processes. Hence, information about the snow-cover extent and duration is important for climate modeling and hydrological applications. Hydrological applications include hydropower production and flood prediction, for which accurate estimates of the runoff are very valuable.

Different classification techniques have been developed and/or applied for snow-cover mapping by optical remote sensing data. Examples of approaches include conventional unsupervised and supervised classification, linear interpolation techniques [1, 2], spectral ratios combined with thresholds [3, 4] and spectral unmixing [5]. Presently, global snow maps are produced regularly from MODIS images based on the normalized difference snow index (NDSI) [6]. Criteria tests are included to improve the mapping of snow in forested areas. Snow-covered areas are often located in mountains or in high latitudes, areas which often suffer from frequent cloud coverage. Therefore, due to its daily coverage the MODIS sensor is favorable for operational snow-cover mapping.

Snow in forests is challenging to map with optical remote sensing, and also with radar images. The difficulties are related to snow being masked out by the tree canopy and the additional spectral contribution from the trees. Generally, snow-cover mapping in forests using optical remote sensing has not been thoroughly studied, and the topic has come more into focus in recent years.

The aim of this work has been to develop a snow-cover mapping method accounting for forests (*SnowFrac*) which uses optical remote sensing data. The method is based on linear spectral mixture modeling and prior land-cover information for each pixel. The prior data is used to select spectra and to set constraints during the spectral unmixing of a pixel.

II. SNOWFRAC – A METHOD FOR MAPPING SNOW-COVER IN FORESTS

SnowFrac has been developed through several studies where the general philosophy first was to perform reflectance modeling and compare modeled pixel reflectance with satellite measured pixel reflectance. Secondly, a spectral unmixing approach was applied to decompose the satellite measured pixel reflectance into individual reflectance components. By doing so the reflectance model is inverted to map the snow-covered fraction within a multispectral satellite image. The spectral unmixing approach is treated in this paper.

A generalized linear spectral mixture model (generalized SnowFor model) constitutes the core of the SnowFrac method. Based on experiences from previous studies [7] the SnowFor model was simplified by keeping important components and effects, and thereby reduce the number of input data sets. This lead to a generalized SnowFor model including the four main components: snow, conifer trees, branches of leafless trees and snow-free bare ground:

$$\hat{R} = A_{\mathrm{C}} R_{\mathrm{C}} + A_{\mathrm{BR}} R_{\mathrm{BR}} + A_{\mathrm{SW}} R_{\mathrm{SW}} + A_{\mathrm{BG}} R_{\mathrm{BG}}, \qquad (1)$$

where $\hat{R}$ is the modelled pixel reflectance for a given wavelength λ and $A_C + A_{BR} + A_{SW} + A_{BG} = 1$. The subscripts C and BR refer to conifer and branches of leafless deciduous trees, respectively, while the subscripts SW and BG refer to snow and bare ground, respectively. A model to estimate the ground coverage of branches of leafless trees was also kept.

Figure 1 illustrates conceptually how the SnowFrac method estimates snow-cover fraction for a pixel. A land-cover fraction map and endmember spectra are input data. The land-cover fraction map contains information of the land-cover types inside every pixel. This map is first used for identifying endmembers within a pixel. As a consequence the number and types of endmembers, and therefore also the spectra, vary from pixel to pixel. Secondly, for pixels containing forests, the land-cover fraction map is used to set constraints on the area fractions of conifers and deciduous trees during the unmixing computation. The procedure is here referred to as constrained spectral unmixing. The overall aim of using a land-cover map is to reduce the number of unknown variables in the equation system, and thereby improving the snow-cover fraction estimate. The bounded variables least-squares algorithm by Stark and Parker [8] allows setting different constraints on each of the endmember fractions, and was therefore applied for the mixture decomposition.

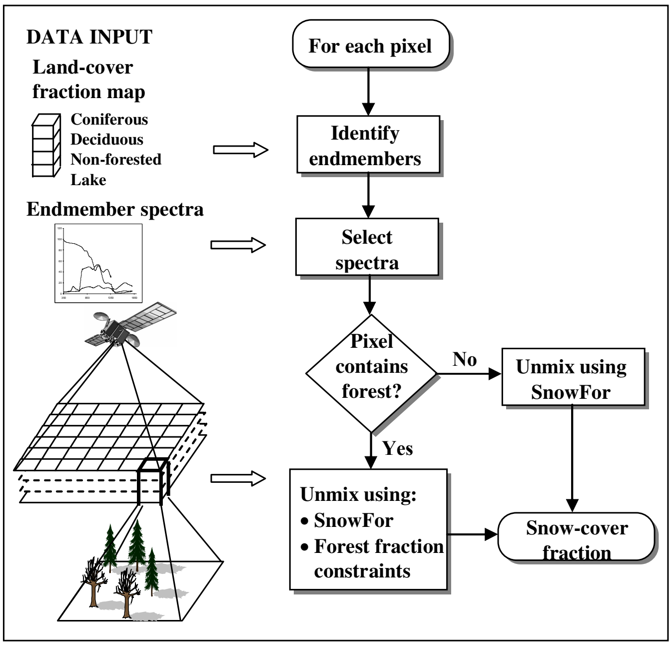

Figure 1. Conceptual illustration of the SnowFrac method applied on a multispectral satellite image pixel.

III. DATA SET AND EXPERIMENTS

A study area of 56 km × 50 km located 10 km north of Lillehammer city in Southern Norway was selected for experiments. The data set consisted of Terra MODIS scenes (MOD02HKM: level 1b calibrated radiances, channels 1-7, 500 × 500 m spatial resolution) from 4 Mai 2000 and 7 Mai 2001. There was extensive snow coverage on 7 Mai 2001, while on 4 Mai 2000 the snow coverage was thin and patchy. Both days were characterized by wet snow conditions. Snow reference maps of 500 m pixel resolution were derived from simultaneously acquired Landsat ETM+ images for both dates, by combining supervised classification and the NDSI. The snow-cover fraction (SCF) estimate from SnowFrac represents the snow coverage around the trees, as seen from above. To be consistent, the forest coverage was therefore subtracted from the snow reference maps, using the land-cover fraction maps. In-situ snow parameter measurements (reflectance, grain size, water content, impurities, density) were carried out on 6-7 Mai 2001.

Endmember spectra were selected from two sources: MODIS images and a spectral library. Calibration areas in the MODIS images served to derive spectra for the snow and conifer forest endmembers. Multiple spectra for snow were used to account for the large reflectance variability of snow within a scene. Average and standard deviation of observed MODIS snow spectra were evaluated for each pixel by the root-mean-square of the errors. The unmixing result with the lowest rms error for a pixel was selected as the output snow-cover fraction. Spectra for branches of leafless deciduous trees were collected by field measurements. Snow-free bare ground spectrum was a mixture of grass and soil spectra. Forest area fractions were constrained to be nearly equal to the land-cover fraction map by including some flexibility with a deviation of ±0.1. The other endmember area fractions were constrained to vary between 0 and 1.

SCF estimates from SnowFrac applied on the MODIS images were compared to the snow reference maps derived from the Landsat ETM+ images. Additionally, the results obtained with SnowFrac were compared to MODIS L2 500 m snow product (Version 3) of the same swaths [9]. Results are presented in Figures 2-4.

IV. RESULTS AND DISCUSSION

A. *Snow-cover mapping results using SnowFrac*

Experiments show that the use of a land-cover fraction map in the SnowFrac algorithm highly improves the results, as compared to conventional linear spectral unmixing when the same number and types of endmember spectra are used for all pixels.

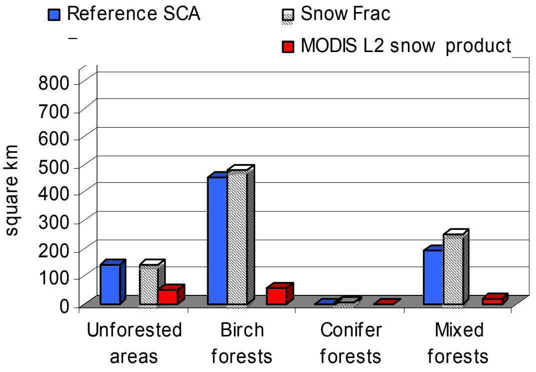

Figure 2. Area estimates of snow for individual forest types: 4 Mai 2000.

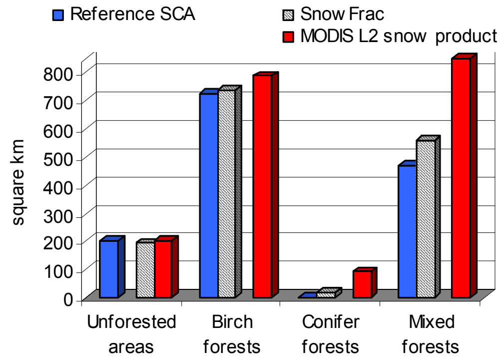

Figure 3. Area estimates of snow for individual forest types: 7 Mai 2001.

B. *Comparison with MODIS L2 500 m snow product (Version 3)*

Generally, the MODIS snow product estimates more snow than SnowFrac on 7 Mai 2001 and less snow than SnowFrac on 4 Mai 2000. Unforested areas are best modeled on 7 Mai 2001, with increasing bias with denser forest coverage.

C. *Future perspectives*

Promising results are obtained using SnowFrac. More evaluation is needed using a test area where accurate and extensive snow reference data are available. The use of prior land-cover data in the algorithm improves the results. The SnowFrac method may be used with any sensor having a high number of channels. The method may have large potential for regional operational hydrological use.

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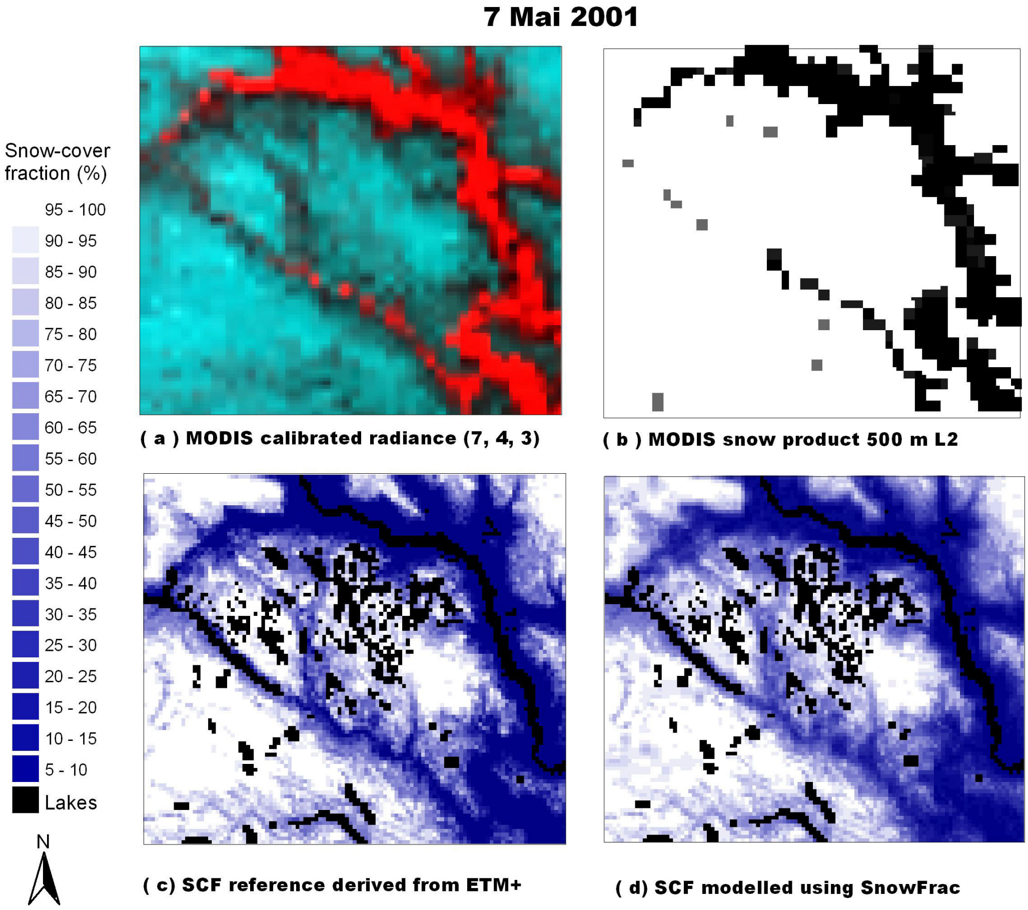

(a) MODIS calibrated radiance (7, 4, 3)

(b) MODIS snow product 500 m L2

(c) SCF reference derived from ETM+

(d) SCF modelled using SnowFrac

Figure 4. Snow-cover mapping results for 7 Mai 2001. a) original MODIS image; b) MODIS snow product 500 m L2, Version 3. Snow (white), no snow (black), lake (gray); c) ETM+ derived snow reference map; and d) SnowFrac estimated snow-cover fractions.