Model-Driven Retrieval of Fractional Snow Cover Area

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Abstract— **Operational snow cover mapping by optical sensors has taken place for more than two decades, but there is still a demand for improved mapping accuracy. Most operational products are binary (snow/no-snow). In the work presented here, a new approach has been taken to achieve significant improvements in the accuracy. Current spectral BRDF characteristics of the snow and snow-free ground are modeled locally, per pixel. Spatial functions for these characteristics are established for the region to monitor. The approach opens for snow mapping combining several different sensors independently. It is a solution to the needs for long-term climate monitoring where inter-sensor calibration and introduction of new generations of sensors make it difficult achieving time consistency in the mapping. The method is currently under validation in mountain regions in Norway.**

Remote sensing of fractional snow cover area, BRDF, anisotropic reflectance, snow impurities, snow modeling

I. INTRODUCTION

Snow cover has a substantial impact on the interaction processes between the atmosphere and the surface, thus the knowledge of snow variables is important in climatology, weather forecasting, and hydrology. The seasonal snow cover is practically limited to the northern hemisphere with an average extent during the winter months ranging from 30 to 40 million km^2.

Operational snow cover area (SCA) mapping by optical sensors has taken place for more than two decades, but there is still a demand for improved accuracy. Most operational products are binary (snow/no-snow). Since snow cover is a rapidly changing phenomenon in many regions, there is a need for frequent mapping. To achieve frequent mapping sensors with medium to low spatial resolution have to be used. Thus, to achieve the details required in many applications, fractional mapping is needed. A few fractional snow cover algorithms have been developed, but there is still a gap between the accuracy needed in many cases and the accuracy obtained in practice. It is not uncommon to see errors of 30-40% SCA. This is in particular due to effects from the topography in mountainous terrain, the effects of forest, effects from the ever-changing spectral bidirectional reflectance distribution function (BRDF) of snow (due to metamorphosis and impurities) and the spectral BRDF characteristics of the snow-free surface.

The requirement of frequent mapping has limited the number of satellite sensors that is usable operationally down to the NOAA AVHRR, Terra and Aqua MODIS and a few other sensors of low and moderate spatial resolution. This situation led very early to the development of fractional SCA retrieval for the Norwegian mountain region, a region very important for hydropower production. The idea of classifying each pixel into several snow-cover categories dates back to a proposal by Østrem et al. [1]. The method was fully described by Andersen in [2]. It is based on the assumption that there is a linear relationship between snow coverage and measured radiance. The method has been applied in Norway since it was developed in the beginning of the 80'ies, and it has also been used in Canada [3]. It has later been improved with automatic training, automatic geocoding, and automatic cloud detection [4].

A relatively new approach to the problem of retrieving snow at sub-pixel level is spectral unmixing. Spectral unmixing is particularly suited for sensors having a high number of bands, but it is also possible to use sensors like Landsat Thematic Mapper. Reference [5] introduced spectral unmixing for fractional SCA retrieval using a linear mixture model. A disadvantage of the method is that it is supervised. The spectral endmembers have to be identified manually by training of the algorithm. Reference [6] proposes a method for unsupervised spectral unmixing. The method determines endmembers automatically and then compares them to a spectral library to estimate the mixture of each pixel (see also [7]).

For operationally applications, the above approaches have various drawbacks. The algorithm in [2] actually assumes that all snow-free surfaces have the same reflectance and that the snow reflectance is the same for the whole image. It also neglects BRDF effects and topographic effects. At the basin level, and for areas above the tree line, local variations may to some degree cancel out when computing totals. However, there are also large-scale variations between basins that are not compensated for (one image with one calibration covers several basins).

The spectral unmixing approach might compensate for several of these problems by decomposing more than two spectra, hopefully all endmembers in the scene. The original algorithm in [5] has, as mentioned, the problem of being supervised. The problem was solved in [6] including a spectral library, and the approach was further improved in [7] and [8]. However, it is practically impossible to have all snow reflectance classes available in a library since the snow's spectral reflectance, and specifically the BRDF, develops continuously due to snow crystal metamorphosis and

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contamination of the snow surface by impurities. Another and more general problem with spectral unmixing is that there will usually be, in particular with a high number of possible endmembers, many solutions to the set of linear equations to be solved. Hence, the high variability of the snow reflectance will with the above approaches of spectral unmixing necessarily give variable accuracy, in particular during the melting season.

In the work presented here, the current spectral and BRDF characteristics of the snow and the snow-free surface are modeled locally. With good predictions of local spectra established, a straightforward spectral unmixing gives the current snow fraction of each pixel.

II. Methodology

A. Overall approach

In the proposed approach for fractional SCA retrieval presented here, the actual, current spectral BRDF characteristics of the snow and snow-free ground are modeled locally, per pixel. The models are established by assimilation of remote sensing data for varying acquisition and solar geometry during the snow and snow-free seasons. To model snow metamorphosis, a "time dimension" is introduced to let the spectral BRDF develop. The assimilation technique, using sensors with moderate spectral resolution, performs modulation of an initial spectrum of high spectral resolution to establish a full high-spectral-resolution BRDF model locally.

In order to be able to handle the development of the snow spectrum also when the snow cover is patchy, metamorphosis and impurity projection functions are introduced. These functions predict the development of the snow state during the late part of the snowmelt season.

With local estimates of spectra for snow and snow-free ground established, linear spectral unmixing is applied to estimate the current snow fraction per pixel. An iterative approach is used where the predicted spectra for snow and snow-free ground are improved in each iteration, hence also giving an improved estimate for the fractional SCA.

B. Spectral BRDF model grid

The snow undergoes a process of continuous metamorphosis and reception of impurities (the theory behind this is described in [9] and [10]). Snow crystals change structure and size, mostly due to processes related to energy transfer. Impurities, small particles of organic and inorganic material (like litter from vegetation, soil and soot), will usually be deposited in a rate proportional to the amount of vegetation and snow-free surfaces in general exposed to the air in the neighborhood. Metamorphosis and increased impurity content change the reflectance spectrum. The near-infrared region of the spectrum is more sensitive to the metamorphosis than the visual part, while the visual spectrum is more sensitive to impurities.

The combined effect of terrain relief, solar illumination geometry and sensor acquisition geometry (here called geometrical effects) affects the exiting radiance for a given area on the ground (e.g., the area corresponding to a pixel). The atmosphere adds on with more effects for the observed radiance at the satellite.

Except for small experimental sites, it has proven quite hard to carry out fractional snow cover mapping through physical modeling of all or most effects mentioned. There are simply too many variables which one has no control over.

A fundamental aspect of the approach chosen here is to utilize observations as much as possible to retrieve the information needed that otherwise could have been created by complex, physical modeling. In other words, empirical models have been used as far as it is possible when remote sensing can be applied to calibrate them.

An important part of the concept is that a spectral BRDF grid is established for the region to monitor. The grid size might correspond to the pixel size, such that there is one grid element for each observed pixel on the ground (however, this is no requirement and in general not true when different sensors are applied to monitor the same region). A grid element models the spectral BRDF for all relevant acquisition angles and solar illumination angles for the terrain relief associated with the given grid position.

Two BRDF grids are established – one for snow and one for the snow-free land surface cover (senescent vegetation, vegetation in the winter state, when vegetation is present). The BRDF snow grid also has to model developing snow. Since the anisotropy of the snow reflectance changes with the metamorphosis and since the reflectance is depending on the local terrain orientation, there is no straightforward way to predict how the spectral BRDF for a snow grid element will develop with the metamorphosis. The approach taken here is to include a "time dimension" (or more correctly, a metamorphosis development dimension) to the spectral BRDF model. The metamorphosis dimension in the grid model is parameterized by the observed or effective grain size (various algorithms for retrieval of the effective grain size are presented in [11]).

The grid is calibrated using a spectral BRDF assimilation algorithm. The BRDF grid elements are built up from numerous observations, through several snow seasons, to reach full coverage of combinations of snow metamorphosis and illumination and observation geometry. Similar assimilation is done for snow-free surface conditions during late spring and autumn (with senescent vegetation). It is important to avoid any presence of bare ground in the snow grid and any presence of snow in the land surface grid. This is done by a comparison of each new observation with statistics for the corresponding grid element. If the new observation represents a spectral BRDF outlier, it is discarded. For initialization of the grid, to build up the initial statistics, special filters are applied to ensure pure observations.

An objective of the spectral BRDF grid is to ensure compatibility with different optical sensors, including sensors of high spectral resolution. The approach currently tested out is to initialize the grid with data from a hyperspectral sensor. Only one or a few hyperspectral observations of each grid element are applied. Following observations, with sensors of moderate or low spectral resolution, are then modulating the original high-resolution spectrum.

C. *Metamorposis and impurity projection*

For fractional snow cover conditions, snow metamorphosis and the level of impurities cannot be directly measured due to the spectral mixture of snow-free ground and snow. The terminal full snow cover conditions are here used as a baseline for projection algorithms. There is one model for nominal development of metamorphosis and several models for nominal development of the impurity concentration. The metamorphosis model builds on a degree-day approach to simulate the metamorphosis (similar approach is often taken in snowmelt models). Since the temperature normally will not be available, nominal development for the given region is applied.

The process of impurity deposition in the snow is mostly driven by wind for areas with low vegetation, and most of the deposition takes place when snow-free ground appears in the neighborhood. The deposition process has been measured in the field for the development of fractional snow cover for several land cover types. The measurements are the basis for empirical functions parameterized by snow cover fraction. There is one function for each general land cover type.

D. *Fractional snow cover algorithm*

The overall approach for the fractional snow cover algorithm is illustrated in Figure 1. The algorithm starts to calculate an initial estimate for the snow cover fraction. A simple two-spectra linear mixture model is applied, where the two spectra represent the terminal full snow coverage as determined by the snow spectral BRDF grid and the snow-free surface as determined by the snow-free surface spectral BRDF grid.

The algorithm proceeds with metamorphosis modeling, parameterized by the estimate of the snow cover fraction. The terminal full-snow-coverage snow spectrum is modulated accordingly. The next step is to model impurity deposition. A map of local land cover type is used to select the relevant model, and snow cover fraction is used to parameterize the model. The estimated impurity content is used to further modulate the snow spectrum.

The next step is to apply the modulated snow spectrum, i.e. the predicted snow spectrum, and the corresponding grid element for the snow-free surface in a linear spectral unmixing algorithm. This gives a new and more accurate estimate for the snow cover area fraction for the current pixel.

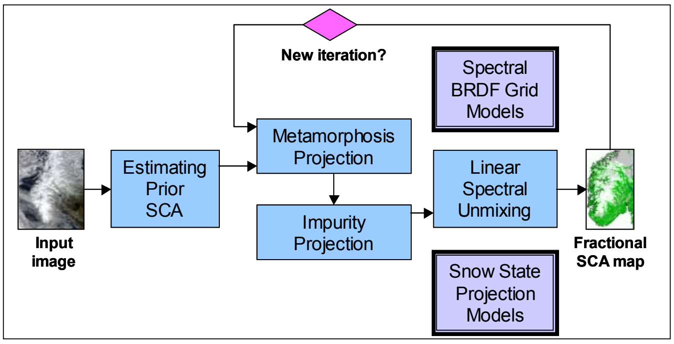

Figure 1. Overall approach for the new fractional SCA algorithm

The algorithm proceeds in an iterative manner applying the new estimate of the snow cover fraction to make a new, and hopefully better, estimate of the snow spectrum, which is again applied in the linear spectral unmixing algorithm. The process is repeated until the change between two iterations is marginal or an upper limit for the number of iterations is reached.

III. FIRST EXPERIMENTAL RESULTS

The proposed approach is just in the first stage of validation. Therefore, only results from the first few and limited experiments are presented here. The quantitative results should be interpreted cautiously as larger experiments for a broader variety of snow conditions need to be carried out to understand how the algorithm performs in general.

The first experiments have been carried out in the Heimdalen-Valdresflya test site in the Jotunheimen mountain region in the central part of southern Norway (9.0° E; 61.4° N). The area is of about 200 km^2 with an elevation range of 1050 to 1840 m a.s.l. The area is free of tall vegetation except for some birch in the lowest locations.

The experiments so far have concentrated on the snowmelt season in 2004, for the period April-June. The site is usually fully snow covered in most of April, and snow patches may remain until late June. Fractional snow cover area has been retrieved from Terra MODIS data and compared to Landsat 5 Thematic Mapper (TM) images and one aerial orthophoto mosaic. The available TM images were acquired 23 May and 30 May, while the aerial photos were acquired 13 June. The TM images have been classified interactively using a clustering algorithm. The 30 m classified pixels were then converted to 250 m pixels of fractional snow cover for direct comparison with the maps derived from MODIS data with the new algorithm. The orthophoto mosaic with 1 m spatial resolution is quite hard to classify due to radiometric effects from the varying viewing geometry within each original image, so the mosaic has so far only been used for comparison of small areas.

The snow maps have also been compared to maps generated by the classical algorithm in [2] still in operational use. The classical algorithm has previously been compared to the NASA GSFC MODIS algorithm in [12], where the algorithms were shown to give quite consistent results.

The snow cover was quite patchy on 13 June. Field measurements also showed that there was a significant amount of impurities in the snow. The classical fractional snow cover algorithm gave too low values in the area, typically 25-20% less SCA than the orthophoto shows. The new algorithm gave values typically within 5% of the orthophoto.

The comparison with snow maps derived from the TM images included studies of mountain slopes in various directions (see Figure 2). The classical algorithm might in many cases give snow fractions up to 30-40% higher than the actual value for slopes oriented towards the sun and, similarly, 30-40% lower values for slopes oriented away from the sun.

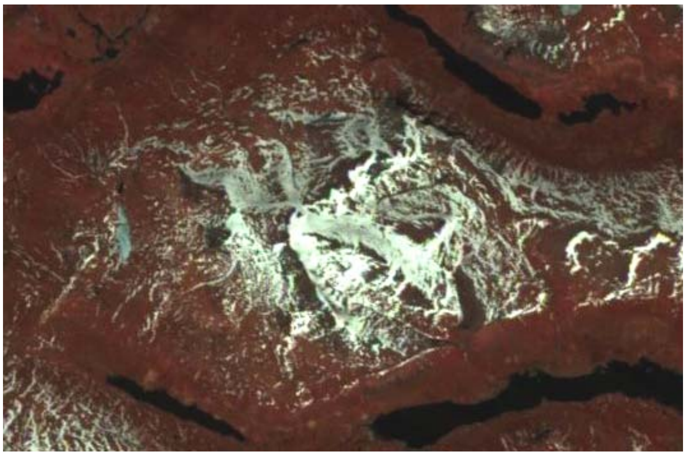

Figure 2. Landsat TM image acquired 30 May 2004 showing Heimdalshø mountain in the Heimdalen-Valdresflya test site. The classical fractional SCA algorithm gave much too low values in the northernly oriented slopes, up to 40% too low SCA was found in this example. The new method gave errors within about 5% for the same slopes

The new algorithm, which indirectly compensates for the terrain orientation relative to the sun, gave values within approximately 5% of the values derived from TM.

IV. Discussion and Conclusions

Operational snow cover mapping by optical sensors has taken place for more than two decades, but there is still a demand for improved mapping accuracy. Even if the contrast between snow and snow-free ground is quite high in general, accurate mapping of the snow cover is not straightforward. This is partly due to the situation that the snow fraction at the sub-pixel level is needed to obtain the required level of detail for the snow maps. Combined with the fact that the snow spectrum changes continuously and that the regions to monitor frequently has complex terrain relief, this has resulted in a failure to obtain very accurate operational fractional snow cover monitoring for larger regions.

For smaller regions, high accuracy has been obtained at the sub-pixel level by a few authors (like in [8]). It is characteristic for such experiments that detailed knowledge and models have been established for the region at hand. For large-scale mapping, it is practically hard to apply the same approaches.

The approach taken here is to avoid using detailed local ancillary data and complex physical models, and instead deriving local information from time series of remote sensing data to establish or parameterize empirical models. This makes it feasible to apply the method on larger regions. However, a data assimilation period is required to build up the necessary local models.

The limited experiments performed so far with the new approach confirm that significantly higher accuracy, compared to classical, operational approaches, is achievable. Errors seem to deviate with less than 5% from SCA in the reference data (Landsat TM and aerial images) for regions with terrain relief and snow states where classical methods typically give large errors. If the high accuracy can be proved to be valid in general, the method should be attractive for local applications (like hydropower hydrology) as well as for global applications (like climate change monitoring) where high accuracy is a requirement.

Future plans include large-scale validation for a variety of snow states and adaptation of the method to snow monitoring in forested regions.

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