# A high-precision dynamic and adaptive BRDF and fractional snow-cover monitoring algorithm

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*Abstract*— **The aim of this work is to develop a very precise approach for monitoring the changing spectral snow Bidirectional Reflectance Distribution Function (BRDF) and Fractional Snow Cover Area (FSCA). Intended use is from local monitoring at the basin level to global monitoring. The concept assumes a day-to-day monitoring of the snow from winter conditions until all snow has melted. The developing reflectance spectrum of the snow is both observed by satellite sensors, giving samples of the BRDF, and modeled by including an empirical snow metamorphosis model and a snow impurity model giving full BRDF. Snow grain size (SGS) and snow surface impurities (SSI) are measured by indices and used to parameterize the models. The predicted snow spectrum and the local bare ground spectrum are applied in a linear spectral unmixing algorithm to estimate the area fraction of snow (SCA) and bare ground. By using predicted spectra for the current situation and not a pool of all possible spectra, the result will in general be more accurate and reliable. The area fractions and the predicted albedos of snow and bare ground are combined in order to predict the BRDF of the observed pixel.**

***Fractional Snow Cover Area; Bidirectional Reflectance Distribution Function (BRDF); spectral unmixing***

## I. INTRODUCTION

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

In order to perform sustainable management of water, one of the most important natural resources for mankind, information of the snow cover is mandatory. The understanding of the relationship between climate and the cryosphere requires the knowledge of the interactions at the snow surface. Snow is also a very sensitive indicator of climate change. In order to further increase the accuracy of weather forecasting models information on the snow coverage and snow properties is of significant importance.

The only means of frequent monitoring of snow at the regional and global level is by remote sensing instruments, as successfully demonstrated in [1] and [2]. In the future, remote sensing, mainly by polar orbiting satellites, will play a key role in deriving information about the snow operationally.

The need for frequent coverage limits the number of satellites that is usable operationally. Examples of relevant optical sensors currently are AVHRR, MODIS, AATSR and MERIS. The spatial resolution is in the range 250-1000 m. This situation lead early in the era of remote sensing to the development of a sub-pixel or fractional snow cover area retrieval algorithm for hydrology applications in the Norwegian mountains. The idea dates back to a proposal in [3]. The method is fully described in [4]. It is based on the assumption that there is a linear relationship between snow coverage and measured reflectance. When this relationship is established, it is an easy task to classify each pixel into snow cover percentage or a coverage category. Four categories were used in [4]. The relationship is established by the use of a manual interpretation of a histogram of the image (original approach) or by use of calibration areas. A population of 100% snow covered pixels is identified and determines the reflectance for 100% snow coverage. A corresponding procedure is followed for 0% snow coverage. The method has been applied in Norway since it was developed. It has later been extended by automatic training in [2], automatic geocoding, and automatic cloud detection.

A relatively new approach to the problem of measuring fractional snow cover is spectral unmixing. Spectral unmixing is particularly suited for sensors having a high number of bands, imaging spectrometers, but it is also possible to use sensors like Landsat TM. Spectral unmixing assumes that a pixel is composed of several different classes and tries to estimate the aerial coverage of each class. Hence, the method does not rely on the assumption of one "background class" like the method described above.

Paper [5] introduced spectral unmixing for snow classification using a linear mixture model. It is assumed that there is a set of spectral endmembers that are combined linearly into the resulting pixel value. One advantage with this approach is that there is a measure of the fit between the model and the data.

A disadvantage of spectral unmixing as applied in [5] and [6] is that the method is supervised. The spectral endmembers have to be identified manually by training of the algorithm. Paper [7] proposes a method for unsupervised spectral unmixing. The method determines endmembers automatically

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and then compares them to a spectral library to estimate the mixture of each pixel. The method was tested on Landsat TM data and found to have accuracy similar to aerial photography for the test area.

For operationally applications, the above approaches have various drawbacks. The algorithm in [2] actually assumes that all bare ground has the same reflectance. This is certainly not true. At the basin level, and for areas above the tree line, local variations may to some degree cancel out. 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 compensates for this problem by decomposing more than two spectra, hopefully all endmembers in the scene. The original algorithm in [5] has the problem of being supervised. The problem was solved in [7] by including a spectral library, and the approach was further improved in [8]. However, it is practically impossible to have all snow reflectance classes available in a library since the snow spectral reflectance, and specifically the BRDF, develops continuously due to snow crystal metamorphosis and contamination 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.

## II. METHODOLOGY

### A. *Overall approach*

The aim of the approach proposed in this paper is to obtain very high accuracy of fractional snow cover area (FSCA) through a totally automatic approach. A driving idea behind the development of the algorithm has been to utilize observations as far as possible and try not to model more than strictly necessary. The general problem of modeling a remotely sensed scene is that the variability is so large that very high accuracy is seldom obtainable in general. A bi-product of the algorithm is actually an estimate of the Bidirectional Reflectance Distribution Function (BRDF) for each pixel.

The concept assumes a day-to-day monitoring situation of the snow from winter conditions until all the snow has melted. The developing reflectance spectrum of the snow is both observed by satellite sensors, giving samples of the BRDF, and modeled by including an empirical snow metamorphosis model and a snow impurity model giving full BRDF. Snow grain size (SGS) and snow surface impurities (SSI) are measured by indices and used to parameterize the models. The appearance of bare ground in the time series is measured as a rapid increase in the SSI index. With a mixture of bare ground and snow in the snowmelt season, the SSI and SGS indices do not give useful results any more. From this stage and on, snow impurity development and snow metamorphosis models are used to infer the change of snow albedo. The impurity model is taking into account the typical impurity development based on time, land surface cover type and bare-ground fraction. The metamorphosis model follows a similar scheme based on time.

The predicted snow spectrum and the local bare ground spectrum are applied in a linear spectral unmixing algorithm to estimate the area fraction of snow (FSCA) and bare ground. By using predicted spectra for the current situation and not a pool of all possible spectra, the result will in general be more accurate and reliable. The area fractions and the predicted albedos of snow and bare ground are combined to predict the BRDF of the observed pixel. A weighting algorithm is applied to combine the current single-angle observation of the pixel and the full BRDF spectrum predicted.

### B. *Assimilation algorithm*

The FSCA algorithm requires a local (per pixel) estimate of the BRDF for a snow winter situation and the bare ground under winter conditions (no or little chlorophyll for most vegetation types). The only practical means of establishing precise local BRDF models at the pixel level is empirically by direct measurements of the true BRDF. This is due to the high local variability and many influencing factors.

The approach of the proposed assimilation algorithm is to generate a pixel-wise BRDF model automatically from satellite observations. The BRDF model established is actually only partial as only relevant combinations of observation angles and solar illumination angles are covered. Across-track observations of a given point on the ground is aggregated and represented in a compact BRDF data structure allowing quick access to values in various applications.

The variation of observation angle combined with solar elevation angle gives samples of the local BRDF function. Not all angles will be covered but is not necessary, as the models will be applied with new observations later using satellites in polar orbit with approximately the same inclination. Across-track observations of a given point on the ground is aggregated and represented in a compact BRDF data structure allowing

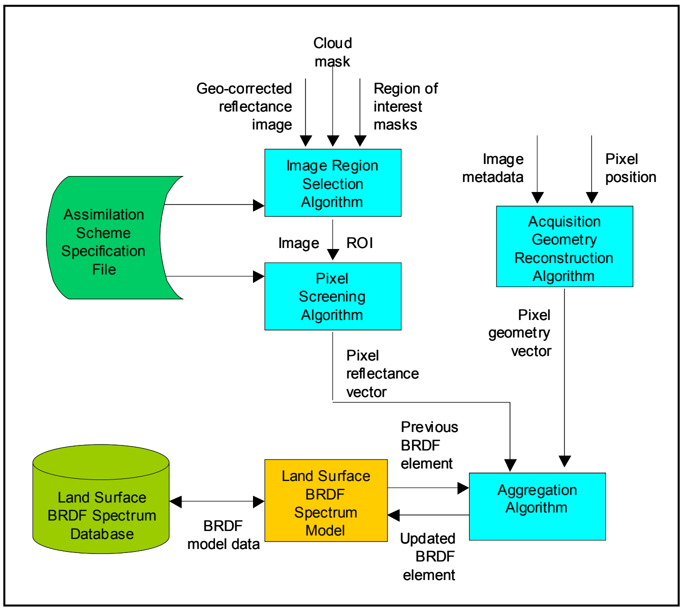


Figure 1. Conceptual design of the assimilation approach

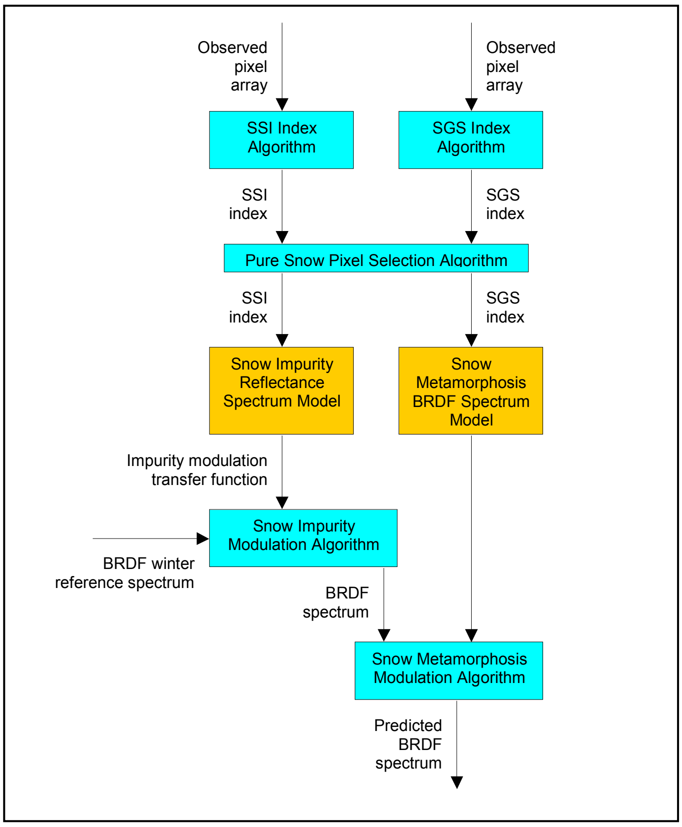


Figure 4. Conceptual design of the snow development algorithm

quick access to the values.

The assimilation algorithm includes a pre-screening of each observation in order to make an unbiased estimate of the true local BRDF. For winter snow referencing it is checked that the SSI and SGS values are low. For bare ground early-spring conditions, it is checked that autumn image pixels have low chlorophyll content and no snow present. The development has taken into account practical needs and limitations for applying the approach to global monitoring, e.g. associated to environmental and climate-change monitoring.

### C. *Snow development algorithm*

The objective of this algorithm is to extend the assimilation algorithm and BRDF model representation to dynamic BRDF where a model for developing spectral reflectance of the local ground surface cover is included. Snow is used as the study case.

The local BRDF spectrum from the relatively stable winter conditions at high latitudes is applied as a reference spectrum. This spectrum includes the effect of the terrain and tall vegetation. The developing spectrum is modeled by including an empirical snow metamorphosis model and a snow impurity model. Snow grain size (SGS) and snow surface impurities (SSI) are measured by indices and used to parameterize the two functions, respectively. Both functions give a new spectrum. The spectra are fused into an estimate of the current partial BRDF.

### D. *Snow cover and BRDF algorithm*

The snow cover and BRDF algorithm is based on the two previous algorithms. It is assumed that a snow and bare ground BRDF database has been build up by the assimilation algorithm. The snow development model is then applied for prediction of new spectra based on current observations of the grain size and the contents of impurities.

When bare ground appears in the melting season, it is detected by an abrupt increase of the SSI index. The outlined snow development model will then fail so another model is applied during this phase of the melting season. The model predicts SGS and SSI based on the nominal development in the melting season for partial snow cover. The impurity model applied is parameterized by the general type of land cover, which to a large degree determines the type and amount of impurities transported.

For full or partial snow cover the predicted BRDF of snow (and bare ground when relevant) is input to the conditional spectral unmixing algorithm. By using "most likely spectra", a more reliable result should be obtained as linear spectral unmixing in general gives many solutions. The true solution cannot easily be selected without additional information. Based of the surface area of the two predicted spectral components, a full BRDF model for the mixed snow and bare ground classes can be predicted for the local pixel.

## III. Validation of the Concept

A series of experiments is currently ongoing in order to verify the concept of snow cover and BRDF retrieval described above. In particular, the following set of hypothesis has to be proved:

*1. It is possible to filter out non-relevant pixels such that bare ground and winter snow BRDF references can be established.* This a requirement for the assimilation algorithm in order to establish accurate reference spectra for new winter snow and bare ground before the leafing of the ground

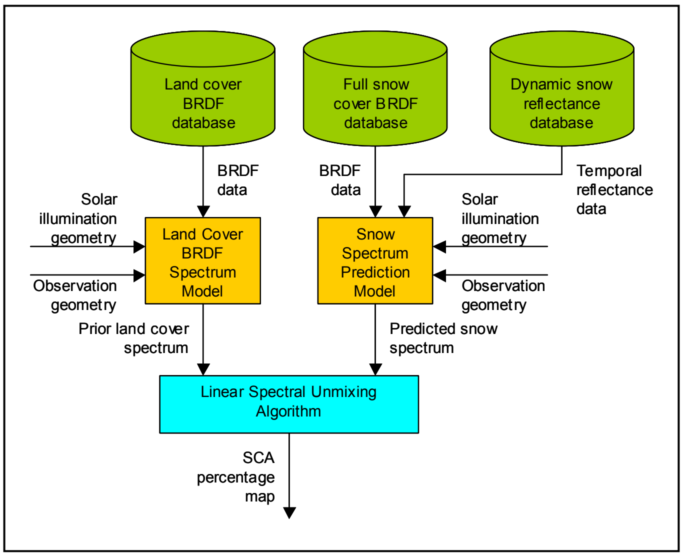


Figure 2. Conceptual design of the FSCA and BRDF overall algorithm

vegetation. This is will be done by SGS and NDVI filters, correspondingly.

*2. A land surface BRDF spectrum model can be established by aggregation and with performance for global applications.* Smart storage and processing approaches are needed to be able to handle a BRDF spectrum for each pixel in the area to be monitored, even for global applications. The design goal is to handle 1 km data globally (for seasonally snow-covered areas).

*3. It is possible to design an index that uniquely parameterises an impurity effect function through the spectrum.* The index has to work independently of grain size and illumination (i.e., in spectral or time domain; terrain independent). There might be different impurity functions for different types of impurities.

*4. It is possible to design an index vector that uniquely parameterises a metamorphosis function through the BRDF spectrum.* A set of indices (index vector) has to uniquely determine the metamorphosis stage of the snow. Must take into consideration that the actual terrain surface in the pixel gives a multitude of illumination and observation angles, which cannot be generated by any simple tilted flat surface.

*5. For partial snow cover, nominal development functions for snow metamorphosis and impurity are sufficiently accurate.* In particular, the functions have to give predictions which are sufficient for accurate SCA retrieval, also for low snow-cover fractions.

## IV. Concluding Remarks

A concept for high-precision fractional snow cover area and BRDF prediction is proposed. Algorithms for the various components of the approach have been outlined together with a set of hypothesis that has to be verified in order to prove that the concept is feasible. Field data for development of the empirical models has been collected for two field seasons and are currently being prepared for the validation-of-concept experiments.

Furthermore, the plan is to implement the concept in a general snow parameter retrieval production line developed recently. The system will be run on data for the winter and melting seasons of 2003 and 2004. Validation data for the FSCA and BRDF products has been established, like aerial photography from both seasons and acquisition of high-resolution satellite data. The production line is to be demonstrated in the winter and melting season of 2005.

## References


[1] R. Kuttinen, Remote Sensing for Hydrology Progress and Prospects, WMO Operational Hydrology report, No. 36, 1992, WMO-No. 773, Geneva-Switzerland.

[2] R. Solberg and T. Andersen, "An automatic system for operational snow-cover monitoring in the Norwegian mountain regions," IGARSS 1994, Pasadena, California, USA.

[3] G. Østrem, T. Andersen and H. Ødegaard, "Operational use of satellite data for snow inventory and runoff forecasting," Satellite hydrology, Proceedings of Pecora Symposium, June 1979, American Water Resources Association, pp. 230-234.

[4] T. Andersen, "Operational snow mapping by satellites," Hydrological aspects of alpine and high mountain areas, Proceedings of the Exeter symposium, July 1982, IAHS publ. no. 138, 1982, pp. 149-154.

[5] A.W. Nolin, Radiative heating in alpine snow, Ph.D. Theses, University of California, Santa Barbara, September 1993.

[6] A.W. Nolin, "Snowcover mapping with the Airborne Visible/Infrared Imaging Spectrometer," Proceedings of International Geoscience and Remote Sensing Symposium (IGARSS), Pasadena, California, USA, 8-12 August 1994, pp. 2081-2083.

[7] W. Rosenthal, "Estimating alpine snow cover with unsupervised spectral unmixing," Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS), 27-31 May 1996, Lincoln, Nebraska, USA, pp. 2252-2254.

[8] T.H. Painter, J. Dozier, D.A. Roberts, R.E. Davis and R..O. Green, “Retrieval of subpixel snow-covered area and grain size from imaging spectrometer data,” Remote Sensing of Environment, Vol. 85, 2003, pp. 64-77.