Synergistic Use of Remote Sensing for Snow Cover and Snow Water Equivalent Estimation

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Abstract

An increasing number of satellites represent an opportunity for utilizing multi-sensor techniques for improving the estimation of snowpack properties using remote sensing. In this paper, the strength of a synergistic approach of leveraging optical, active and passive microwave remote sensing measurements to estimate surface snow characteristics is discussed and examples from recent work given. Each type of sensor has specific technical constraints and limitations. The optical sensors are limited to cloud free days, whereas passive microwave sensors have coarse spatial resolution and sensitivity to multiple snow properties. Therefore, the synergistic use of multi-source and multi-temporal remote sensing data holds great promise for monitoring and analysis of snow.

Keywords: Snow, Optical, Active, Passive, Microwave, Remote Sensing

1 Introduction

Snow is a key component of Earth’s energy balance, climate and environment, and also a major source of fresh water in many regions. Snow monitoring can play a significant role in seasonal flood management. One of the most common reasons for floods is rainfall over snow covered areas. During the spring, precipitation tends to occur in the form of rain rather than snow. When rain accompanies melting snow, the melting process is accelerated, causing serious floods [1,2]. Better estimation and understanding of the snowpack properties and seasonal variations therefore provide useful information for various hydrological and meteorological applications [3]. Accurate information about snow characteristics is required to increase the accuracy of water resource and flood forecasts.

Images from satellites have been used for mapping snow cover for several decades; for example, the USA National Oceanic and Atmospheric Administration (NOAA) began mapping snow using satellite-borne instruments in 1966. Snow extent is in most cases relatively straightforward to observe using visible imagery because of the high albedo of snow (up to 80% or more in the visible part of the electromagnetic spectrum) relative to most land surfaces [4]. In general, visible imagery is better at detecting snow than at quantifying surface snow characteristics like snow depth or snow water equivalent. For this reason, the primary use of optical sensors is to provide accurate and spatially detailed information on the snow cover distribution. However, limitations exist. Visible imagery is limited to that portion of the surface illuminated by sunlight, and clouds can be confused with snow. As a result, snow maps generated from visible imagery can have gaps in areal coverage.

As an alternative to visible sensors and traditional station measurements, microwave remote sensing data (active and passive) have proven their value in estimating snowpack properties. Microwave sensors do not have daylight restrictions and are capable of penetrating through cloud cover, haze, and dust. This property allows for snow cover remote sensing under almost all weather and environmental conditions. Additionally, microwave remote sensing offers a great potential for snow studies due its sensitivity to snowpack and surface properties such as density, depth, grain size, temperature, melting-refreezing cycles, surface wetness and vegetation that are not easily inferred from optical imagery. Nevertheless passive microwave products have much coarser (15-50 km) spatial resolution, poorly identify shallow and melting snow, and can confuse cold rocky surfaces with snow [5]. As result of these advantages, microwave products have not played a primary role in operational snow monitoring.

Despite the success of existing operational snow detection algorithms in mapping snow cover under most conditions, limitations in extending these to monitoring snow properties of interest, such as depth and water equivalent, suggest that more attention should be paid to making better use of microwave observations. This article reviews the synergistic use of optical, active and passive microwave to improving snow retrievals.

2 Remote Sensing of Snow

2.1 Optical Remote Sensing

Since surface snow properties and snow cover are rapidly changing phenomena in many regions, there is a need for frequent data. Satellite sensors such as the Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA satellites, Moderate Resolution Imaging Spectro-radiometer (MODIS) onboard Earth Observing System (EOS) satellites, and Imager instruments onboard Geostationary Operational Environmental Satellites (GOES) have been used for snow cover mapping. Still, most of the optical remote sensing products are binary and just divide the surface into two classes, "snow" and "no snow".

Early optical models used threshold-based criteria tests, the normalized difference between bands, and decision rules for snow cover mapping. Kyle et al. (1978) used the ratio of radiances in 1.6-0.754 μm channels and IR band to discriminate between snow and clouds. Dozier (1989) used a more sophisticated Normalized difference band ratio of spectral reflectances measured from the Landsat Thematic Mapper for snow cover mapping. Current optical algorithms for the MODIS snow-cover products were improved and enhanced from previous operational products, allowing high resolution, daily availability, and the capability to better separate snow and clouds [8]. However, detection of snow in optical wavelengths still requires clear sky conditions and sufficient daylight. For this reason and in order to mitigate these disadvantages, several authors [9] have suggested the importance of the joint use of satellite optical (visible/infrared) and microwave data to map snow extent and monitor its evolution in time and space. This is currently implemented operationally by the USA Interactive Multisensor Snow and Ice Mapping System [10], but still human and manual intervention is required.

2.2 Microwave Remote Sensing

Satellite observations in the microwave spectral range have also been used for the global monitoring of snow cover and surface snow properties for more than three decades. Several data sets from sensors like Electrically Scanning Microwave Radiometer (ESMR), Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I) and Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E) are used by the modeling community.

Models for snow-microwave interactions aim to predict the microwave radiation from a snowpack with given properties. The models describe the relationships between microwave emission and snow parameters such as mean snow grain size, density, and depth. These radiation models may be based on physical principles as well as observations, and they can be classified as empirical, semi-empirical or theoretical [11].

2.2.1 Passive Microwave Remote Sensing

Passive microwave sensors detect the weak microwave radiation that is constantly emitted from the surface and atmosphere of the earth. In the field of microwave radiometry, the microwave radiance is mostly expressed in terms of brightness temperature, TB at the measured frequency. Currently, there are many satellite sensors measuring brightness temperature in different microwave bands. These multi-frequency observations can be used to classify snow conditions, to estimate the water equivalent of dry snow, and to determine the start of the melting period.

Early studies concluded that passive microwave is very sensitive to snow wetness [12]. Later work, analyzing snowpack transitions from dry to wet through melting conditions, showed that the microwave response for seasonal snow has a large contrast between wet and dry snow [13]. It has been confirmed that the scattering from the snow pack of microwave radiation depends on many factors, like the depth of the snow pack [14], but for a given snow depth the scattering depends on snow grain size, which increases as snow ages, decreasing the brightness temperature [15]. For dry snow, scattering also decreases at higher microwave frequencies. In addition, snow grain size and snow temperatures have significant effects on the TB at the 37 and 89 GHz frequencies [13].

The results of several years of ground-based microwave observations along with the experience gained with satellite-borne microwave radiometers have facilitated the development of microwave emission models. Numerous research studies have used emission models along with brightness temperature at 19, 37 and 85/89 GHz microwave frequencies from satellite-mounted instruments, including SSM/I and AMSR-E, for estimation of snow depth and snow water equivalent [9,16–19]. Earlier snow depth retrieval algorithms [20,21] provided an "instantaneous" daily snow depth estimate based on differences in brightness temperature between microwave frequencies. The same multi-frequency approach has been used for many years to retrieve SWE. One of the best known products is the AMSR-E global SWE product (http://www.ghcc.msfc.nasa.gov/AMSR/). However in assessment of the AMSR-E SWE retrievals, Tedesco and Narvekar (2010) found large errors in SWE, likely due to the static snow density assumed in the SWE algorithm, and they suggest incorporating a spatio-temporally evolving snow density and allowing for nonlinear relationships between TB and SWE.

A number of physically based models have been proposed to describe the relationships between microwave emission and snow parameters such as mean snow grain size, density, and depth [15,18,23,24] (Table 1). Still, limited understanding of the behavior of snow-emitted microwave radiation throughout winter season means that existing models do not always accurately retrieve snow depth and snow water equivalent.

Table 1 Characteristics of commonly used microwave snow emission models for snowpack property retrieval.

Model	Model Type	Characteristics	References
Grody	Empirical	Decision tree algorithm for global snow covers map-ping from spectral gradients in SSM/I data.	Grody & Basist, (1996)
HUT	Semi-Empirical	Considers homogeneous snow or multiple layers. Includes the atmosphere, soil and vegetation.	Pulliainen et al. (1999)
MEMLS	Semi-Empirical	Considers a layered structure of the snow pack. Classical RT with Empirical scattering and absorption properties.	Wiesmann & Mätzler, (1999)
DMRT	Theoretical	Based on scattering theory. Considers snowpack as a medium consisting of scattering particles.	Tsang et al. (1992) Tsang & Kong, (2001)

2.2.2 Active Microwave Remote Sensing

Active microwave remote sensing, known as radar or SAR, is based on actively transmitting a powerful pulse of microwave radiation and measuring its backscatter from the target surface. Active microwave remote sensing has basically similar sensitivity to snow properties as passive microwave remote sensing using similar frequencies [27,28] but enables more precise retrievals because the power output is known. As well, active retrievals' typically achieve much better spatial resolution due to their higher signal-to-noise ratio, depending also on the antenna size. Active microwave measurements are very promising for snow remote sensing, but product improvements have been hindered by some complications, in that the backscattered energy is influenced by many other factors like soil type and soil moisture as well as the geometry of the microwave beam and receiver. Due to its higher resolution and stronger signal, studies have demonstrated that SAR can adequately distinguish snow covered areas during the snow melting period, discriminating between snow-free ground and melting snow [29].

The QuickSCAT active microwave scatterometer has been used to estimate the timing of snow melt across Greenland [30] and across Arctic lands [31] with accurate results. Furthermore, an algorithm for mapping wet snow in mountainous terrain using repeat passes of the Synthetic Aperture Radar (SAR) images showed very good correlations with snow cover retrievals [32].

Different algorithms for retrieving snow properties, including snow melting, snow depth and snow cover, based on active microwave sensors have been tested in different situations and regions of the world [18,33,34], in some cases giving accurate results, but in others offering poor to fair correlations when compared to in-situ measurements. Currently active microwave remote sensing of snow finds itself in the very peculiar situation of having long term experience on the field, a wide range of studied situations and very large data archives to analyze, but few verified operational products. The situation holds promise, but a lot more work has to be done; the possibility of incorporating more data types and sources, more complex algorithms or even more efficient and focused filtering may be pursued.

3 Synergistic Approach

While standalone approaches for snow estimation using individual satellite instruments have made significant progress in recent years, many of the products currently used are still based on empirical or semi-empirical relationships and are accurate only over a limited range of snow properties [35]. For this reason, some studies have explored the possibility of improving snow retrievals by incorporating the use of multi-source and multi-temporal remote sensing data. Given the technical constraints and limitations previously discussed, the synergy of satellite observations in the visible and in the microwave spectral bands is an important approach to improve the mapping and monitoring of the snow cover and snow pack properties.

3.1 Snow Cover

Snow has a high reflectivity ratio in the optical range of the electromagnetic spectrum; this characteristic makes its detection very easy using different combinations of visible and infrared wavelengths. The Normalized Difference Snow Index, for example, uses the Green and Mid Infrared radiances with a threshold to have a binary detection of Snow (Covered and Non-Covered) [7]. At the same time, visible and infrared bands have the well-known limitation of allowing only clear day detection, as neither of them can penetrate clouds. Also, snowpack properties such as the snow water content can't be derived from them. A solution to the cloud problem and to inferring properties beyond snow cover is incorporating microwave data either passive or active. Both can be acquired during night or day. Although the cloud problem is removed, interpretation of microwave imagery is much more difficult compared to optical-based indices [36,37]. An example of this approach is the case of [9,38] that developed an automatic system of snow mapping with a spatial resolution of 5 km using GOES visible and infrared data and SSM/I microwave data. The method was shown to be as precise as the IMS (Ice Mapping System) products if not better especially on the level of the consistency of the time series. In general they showed the utility of the multi-sensor techniques for the improvement of the snow detection.

To improve optical-based algorithms, the use of microwave information has increased over time. One complication is that dry snow hardly emits any microwave radiation by itself, nor does it absorb radiation emitted from the underlying ground [39]. The spectral gradient between microwave frequencies is used in most algorithms for snow cover detection with microwave data. Kunzi et al. (1982) used the spectral gradient method on SMMR data to map snow cover extent and found that they were able to delimit a level of snow cover roughly corresponding to 5 cm snow depth. This level of snow cover was defined by the threshold: $(T18H – T37H) > 3.8$ K. Properties affecting microwave response from snowpack include: snowpack depth and stratification, snow water equivalent, wetness, density, grain size and shape, temperature profile, snow age, and land cover. The most important of the disturbing factors are variations in snow grain size, and in some cold and dry regions it is actually the grain size, rather than snow depth, that is most important for the microwave signal [41].

It has been shown that satellite microwave data, even at very poor resolution, can be used to obtain information about average basin snow water equivalent and snow cover. In hydrology applications, a combination of passive sensors for mapping dry snow, snow water equivalent and onset of snowmelt and active sensors for mapping wet snow with better areal resolution could give the optimum information content, since the coarse resolution of passive microwave sensing can lead to large biases on very mountainous or marshy places. Venkataraman et al. (2004) combined statistically IRS LISS-III (optical) and Radarsat-1 SAR (active microwave) to improve on their already operational snow cover products, achieving better classification accuracy compared to each product individually, reducing shadow effects and correcting some errors in both products.

Goals for future work are to improve night and cloudy day detection, downscaling to better spatial resolutions, and the use of multiple instruments in different orbits in order to have better time resolution. As snow cover is currently showing rapid changes because of the climate change and it is impossible to estimate it based on ground measurements because its area is so wide globally, hydrologists are very interested in remote sensing for snow mapping, but removing biases and limitations of existing satellite products remains a challenge.

3.2 Snow Water Equivalent

Passive microwave data at 19 and 37 GHz (or similar frequencies) have been historically used to retrieve snow parameters such as snow water equivalent (SWE) and snow depth. Meanwhile, studies using active microwave data collected from space for snow applications have concentrated on the separation between wet and dry snow. However, a sensitivity of active microwave also exists to other parameters such as mean grain size and SWE, as has been demonstrated both theoretically and experimentally. The explicit combination of active and passive microwave data for remote sensing of snow offers therefore a strong potential for improving the retrieval of snow parameters. Hallikainen et al. (2003) combined active (QuikSCAT/SeaWinds) and passive (SSMI/DMSP) data for monitoring key snow parameters in Finland. The results show that combined active and passive microwave sensors provide useful information on diurnal and seasonal variability. These results were more accurate than those obtained by only passive microwave.

Synthetic Aperture Radar (SAR), particularly C-band SAR, has been used for monitoring snow and ice for more than two decades. In research comparing passive and active airborne microwave remote sensing of snow cover, Sokol et al., (2003) showed that SAR sensors are highly sensitive to changes in the dielectric constant and have better spatial resolution than their passive counterparts. They concluded that passive techniques estimate SWE most accurately under dry snow conditions with minimal stratified snow structures [43]. Other studies also showed that adding NDVI and QuikSCAT-ku data can increases the correlation between microwave based product and SWE [44]. Overall, there is evidence that the combination of active and passive microwave data to retrieve SWE may improve the results from those obtained just using passive microwave. Adding visible and infrared measures of snow cover may improve the spatial and temporal resolution of the retrievals further.

4 Summary

Unbiased estimates of snow properties could lead to much better understanding of hydrological processes in snow covered watersheds. This understanding is important not only for long term processes like snowmelt dependent water supply systems or snow-atmosphere interactions, but for predicting flash floods that can be caused by rapid changes in snowpack properties.

Even though significant improvements have been made to microwave emission models for snowpack properties retrieval in the last 45 years, the accuracy of the models and the retrieved data from both passive and active microwave sensors is relatively poor compared to what is needed for hydrological applications. Great advances have been achieved with combinations of different frequencies and even from data from both passive and active sensors [43]. Numbers of climate and snowpack parameters that influence brightness temperatures in the microwave range make it very difficult to estimate accurate relationships from any one frequency.

For example, it has been demonstrated that passive techniques can give very good estimates of SWE, and that polarimetric Synthetic Aperture Radar (SAR) can identify complex snow structures but is affected by the SWE. Using the strength of both (passive microwave and SAR), snowpack properties can be monitored under many conditions more accurately. Azar et al. (2006) show an improvement in SWE estimation by the combination of the retrievals from both types of sensors, even though the correlation with SWE using only SAR was very low.

Future improvements include refinement of snow-cover extent measurements, minimizing SWE errors, and improving our ability to ingest remote sensing data into snow models. Also useful will be a more complete analysis of available and planned datasets from both passive and active microwave remote sensing, taking into account more parameters to improve the accuracy and temporal and spatial resolution of retrievals. These steps will help achieve a better understanding of gradual and rapid changes in the snowpack.

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