Session 1P3a
Microwave Remote Sensing of Snow

Assessing the Impact of Measurement Spatial Resolution on Passive Microwave Observations of Snow from the Cold Land Processes Experiment

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The NASA Cold Land Processes Experiment (CLPX) conducted in 2002 and 2003 provides a unique opportunity for hydrologic scientists to investigate snow hydrology processes from a multitude of ground, aircraft and satellite-based measurements. Aircraft passive microwave observations at 10, 18, 21, 37 and 89 GHz frequencies from NOAA's Polarimetric Scanning Radiometer (PSR) enable studies to be conducted that investigate the microwave responses from snow fields at different spatial scales.

In this paper, a study is described that uses CLPX PSR measurements at 10, 18 and 37 GHz to characterize the spatial variability of the passive microwave response of snow within three Mesocell Study Area (MSA) at medium to coarse spatial resolution scale lengths. PSR observations are spatially averaged to simulate instantaneous field of view observations ranging from 500 m to 25 km in size. Geostatistical analysis is applied to characterize the passive microwave response of snow in the three MSAs at each spatial scale. Ground-based snow field survey measurements made by CLPX scientists, and ancillary geospatial data sets of the MSAs (such as digital elevation models and vegetation cover) are combined in a simple model to represent snow depths and snow water equivalent fields. A geostatistical characterization of the survey-based fields is conducted and compared with the geostatistics of the multi-scale passive microwave scale observations. The effect of observing snow fields at different spatial resolutions, especially with respect to the impact on representativity of snow field variability, is discussed.

Spatial Scaling Behavior of Brightness Temperatures during CLPX and Appropriate Satellite Sensor Resolution

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Accurate estimates of snow water equivalent and other properties play an important role in weather and hydrological forecasting and climate modeling over a range of scales in space and time. Such estimates also have important uses in natural hazard forecasting (e.g., melt-related floods) and water resource applications such as agriculture and hydropower, and there is a strong heritage for the retrieval of snow parameters using passive microwave remote sensing techniques.

Improving the spatial resolution of new passive microwave satellite sensors is a major desire in order to (literally) resolve subpixel heterogeneity effects on the accuracy of retrievals, but limited spacecraft and mission resources impose severe constraints and tradeoffs. In order to maximize science return while mitigating risk for a sensor concept, it is essential to understand the scaling behavior of snow in terms of what the sensor sees (brightness temperature) as well as in terms of retrieved quantities (snow water equivalent, SWE). NASA's Cold Land Processes Experiment-1 (CLPX-1: Colorado, 2002 & 2003) was designed to provide data to measure these scaling behaviors for varying snow conditions in areas with forested, alpine, and meadow/pasture land cover.

We will use observations from CLPX-1 ground, airborne, and satellite passive microwave sensors to examine and evaluate the scaling behavior of brightness temperatures and retrieved SWE across scales from meters to 10's of kilometers.

The conclusions will provide direct examples of the appropriate spatial sampling scales of new sensors for snow remote sensing. The analyses will also illustrate the roles and spatial scales of the underlying phenomena (e.g., land cover) that control subpixel heterogeneity.

SAR Remote Sensing of Snow Parameters in Norwegian Areas — Current Status and Future Perspective

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Abstract—The paper presents results from a series of European and national projects on remote sensing of snow parameters. Currently, satellite borne syntethic aperture radar (SAR) data are only available at C-band frequencies. Other frequencies such as L-band or Ku-band may be favorable in several snow applications, but current C-band SAR may still be used and further developed to a more mature level. In particular, the advent of wide swath SAR data have provided frequent data sets at medium spatial resolution, that can be used to monitor snow parameters operationally.

We will present results from a snow cover area monitoring service developed for Norway and Sweden. The service, which is based on Envisat ASAR wide swath data, produces snow cover maps on average 3-4 times per week. The resulting time series gives a unique data set for studying the snow cover as it rapidly retreats during the melting season, and is of high value to hydro power companies.

Snow water equivalent (SWE) is the key parameter for hydrological applications. Norut IT has developed a technique using repeat pass interferometry to measure SWE, based on the linear relationship between the change in SWE and the change in interferometric phase. The technique has been demonstrated, but scarceness of usable interferometric baseline pairs have so far not allowed wide spread applicability of the technique.

A future SAR using Ku-band frequency as carrier will maybe solve the problem of retrieving SWE. Since backscatter at Ku-band frequency is more sensitive to SWE, it is good hope that robust SAR methods can be invented for this purpose. It will, however, be extremely important for the scientific society to validate the retrieval algorithms against in-situ data. The authors have developed an innovative validation concept using ground-penetrating radars at the same carrier frequencies as the space borne SARs to validate EO data in an efficient manner. The concept has been studied at C-band frequencies on glaciers at Svalbard, and we hope to build a similar platform for Ku-band frequencies, and will be used to validate model based retrieval algorithms.

1. Introduction

Accurate knowledge of snow properties is essential for snow hydrology. Onset of snow melt, snow covered area, snow wetness, and snow water equivalent are variables that goes into the hydrological models to predict run-off. These predictions are used for flood forecasting and production planning in hydro power plants. Currently 98% of the Norwegian electricity production comes from hydro power and approximately 50% of this comes from melted snow. With the establishment of a common Nordic power trading market in the late nineties, the power producers, power traders and the regulatory branches have developed a need for accurate prediction of run off. This has created a market for accurately derived snow products based on satellite data. The most important parameter is the distribution of snow water equivalent (SWE). Most of the power companies and trading companies in Norway run their own HVB (Bergström, 1992) hydrological models and for the satellite products to be useful the accumulated accuracy within a catchment must be 10% or better. One will also need to know the altitude distribution of snow within the catchment. The most important period is from onset of snow melt in the spring to the end of melt (April-June in Norways mountainous regions).

2. Current Status of Operational Snow Monitoring

Currently the only fully operational satellite based snow mapping in Norway is snow covered area (SCA) maps based on optical data (AVHRR). To improve the quality and both the spatial and temporal resolutions a combined method of SCA retrieval based on both SAR and optical (ASAR and MODIS) data has been developed (Solberg et al., 2004). These methods have been incorporated into a semi-automated production line for operational use and were tested operationally at Kongsberg Satellite Services in spring 2005. The main reason for using SAR data for SCA mapping is the problem of lack of cloud free optical data. Clouds can be a very persistent problem for optical remote sensing in Norway.

For SAR data to be useful in an operational snow monitoring, the wideswath/scansar mode data has to be used to get large and frequent enough coverage. This will give a full coverage 2-3 times per week over Scandinavia.

2.1. SCA Retrieval Technique

The retrieval of SCA from SAR is based on the difference in backscatter between a reference scene in the same orbital track as the scene that will be classified, obtained during cold, dry snow conditions. We then classify wet snow based on the difference in backscatter caused by the high absorptance of the wet snow pack. A threshold of -3dB has been chosen based on comparison with field data (Nagler et al., 2000; Storvold et al., 2005). In the right panel of Figure 1 each classified pixel is assigned a quality value ranging from 0-100 depending on distance from threshold, viewing geometry, and quality of reference image (probability that the snow in the reference image is dry).

Combining the SAR data with temperature fields allows us to estimate quality of the retrieved data and make an assessment of the distribution of dry snow that is not directly detectable by SAR. The temperature fields are constructed based on more than 300 meteorological stations scattered throughout the region.

Dry snow is postulated in areas of higher elevation than the mean wet snow elevation within 20 km of the classified pixel at the same time as the air temperature is below freezing. The dry snow classification is assigned a quality number ranging from 0-70 depending on the elevation and air temperature. Figure 1 shows the differential backscatter between a cold winter reference scene and the May 5th 2004 scene covering most of the mountainous regions of South Norway (left panel), the resulting SCA map with wet and dry snow (center panel), and the corresponding confidence values (right panel).

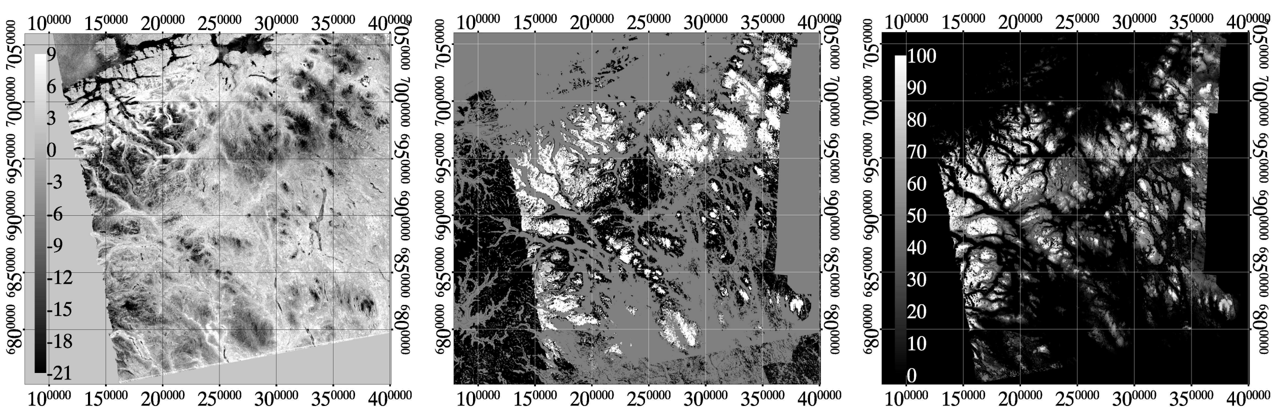

Figure 1: The left panel shows the differential backscatter on May 1st 2004. The center panel shows classified snow covered area map for May 1st 2004. Black indicates bare ground, white-wet snow, light grey-dry snow, and grey are unclassified pixels due to forest, lakes, lay-over and shadow. The right panel show the corresponding classification confidence map. (The map resolution is 100 meter and map coordinates are given in the UTM zone 33 grid, WGS-84 datum.)

2.2. SCA Retrieval Results 2004

The SAR wideswath scenes are georeferenced within a fraction of a pixel accurcy with Norut IT's automated geocoding routine (Lauknes et al., 2005). The difference between South Norway SCA classifications based on SAR and optical data (MODIS), for the 2004 season, is shown in Table **??**. Only cloud free pixels are compared and this causes the apparent large day to day variation in total SCA shown in the table. We see from Table **??** that the total snow covered area is on average approximately 4-5% larger for the Modis retrievals than for the SAR retrievals. The largest difference coinsided with a late May cold period with approximately 5 cm of new dry snow.

2.3. Current Pittfalls in SAR SCA Retrievals

The main uncertainties in todays SAR based snow covered area algorithms lies in the dry snow cover estimate, which currently are based on air temperature and presence of wet snow from which a lower altitude boundary for the dry snow coverage is derived. This causes occasional problems in early spring when there are no wet snow present within the preset distance of the pixel that is to be classified, causing the algorithm to predict bare ground. The preset distance is choosen based on the climatic scales of the region. In the late season scattered wet snow pixels can cause false classifications of dry snow pixels during short cold spells.

The algorithm currently in use does not work in forested areas. Algorithms for estimation of snow cover in forested areas has been demonstrated in Finland (Koskinen et al., 1999) but these cannot easily be used in Norway due to the different climate regime (Norway has a costal climate with multiple freeze thaw cycles throughout the winter).

Compared with SCA retrieval from optical data, the SAR derived algorithm is binary (snow/no snow) and tend to underestimate the snowcover when pixels are partially snow covered. This is due to the high sensitivity to strong scatters (rocks and vegetation) that is often exposed early in the melt.

Table 1: Comparison between SCA classification of South Norway based on Envisat ASAR Wideswath and MODIS in spring 2004.

ASAR		MODIS		Snow Cover
Date	Snow Cover [%]	Date	Snow Cover [%]	Difference [%]
20040501	58.8	20040501	58.9	0.1
20040510	65.6	20040510	68.2	2.6
20040523	29.4	20040523	36.1	6.7
20040526	55.1	20040527	54.5	-0.6
20040528	39.2	20040527	40.0	0.8
20040529	28.5	20040530	35.7	7.2
20040531	26.1	20040531	41.8	15.7
20040601	24.9	20040601	27.0	2.1
20040601	25.9	20040602	29.0	3.1
20040604	3.0	20040603	4.3	1.3

3. Snow Water Equivalent

3.1. Repeat Pass Interferometry

Use of repeat pass interferometry can be used to detect changes in SWE between successive passes (Guneriusen et al., 2001). Main limitation on this method currently is the problem of unwrapping the phase change when the change in snow water equivalent is larger than typically 1-2 wavelengths. The equation below relates the phase change with the change in SWE (Guneriusen et al., 2001)

$$\Delta\Phi_s \approx \frac{1.6}{\cos\theta_i} k\rho\Delta Z_s = \frac{1.6k}{\cos\theta_i}\Delta SWE \ , \tag{1}$$

where $SWE = \rho Z_s$. For currently available SAR data (C-band) and repeat cycles (35 days Envisat) this is not a feasable approach, but with the launch of ALOS L-Band SAR this method is likely to become more useful. Still there are problems with large snowfalls and with high absorption if the snow is wet. Wet snow absorption limits the usefulness of this method in the most interesting period, which is during the snow melt.

3.2. Δk Repeat Pass Interferometry

For a snow density of $0.3\,\mathrm{kg/dm^3}$, radar wavelength of 5.62 cm (Envisat), a nd an incidence angle $\theta_i = 23°$, phase wrapping occurs at a snow depth of only 10.7 cm. Retrieval of SWE from C-band SAR can be performed using repeat pass interferometry and delta-K processing. This method was demonstrated using ERS data (Engen et al., 2004) and Envisat ASAR data (Larsen et al., 2005). Based on the delta-k principle known from the radar literature (T. Hagfors, 1961), it has been proposed to handle the phase unwrapping problem by splitting the bands of both the summer and the winter image into two subbands in the slant range dimension. This results in two bands with slightly different carrier frequencies. By forming interferograms for each of the subbands, we get two interferograms with a different phase, due to the different carrier frequencies. This phase difference, the delta-k interferometric phase, is given by

$$\Delta\Delta\Phi_s = \frac{1.6}{\cos\theta_i}(k_2 - k_1)\Delta SWE = \frac{1.6}{\cos\theta_i}\Delta k \Delta SWE \ , \quad (2)$$

where $\Delta k = k_2 - k_1$ is the difference in wavenumbers between the two subbands. For Envisat ASAR data with a maximum bandwith of 15 MHz, we split the band into two subbands with a carrier frequency difference of about 6.5 MHz. This results in phase wrapping at a snowdepth of about 85 m. Thus, the phase unwrapping problem is effectively avoided. The largest drawback of this method is the course resolution of the SWE product due to the need for averaging to improve the signal to noise (5×5 km for Envisat). In Figure 2 we show a comparison between field measurements of SWE and SWE derived from Envisat.

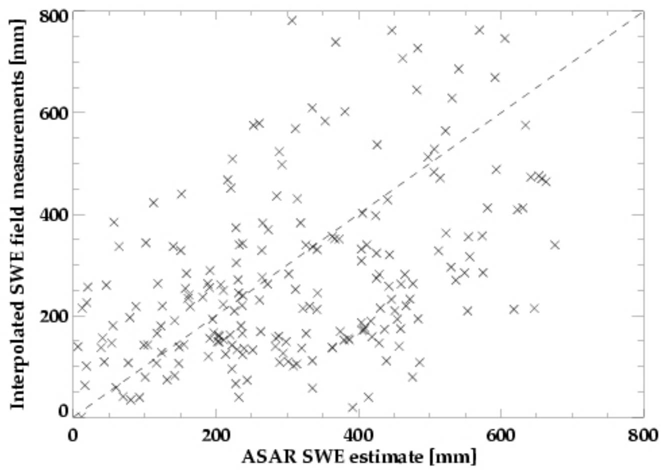

Figure 2: Interpolated SWE field data versus ASAR SWE result. Outliers are eliminated.

3.3. Snow Volume Backscatter

Ku-band SAR instruments have the potential to overcome some of the problems that L-X-band radars have in retrieving SWE. The main advantage of Ku-Band is the large sensitivity to dry snow. Ku-band signal has sufficient penetration in most snow packs, at the same time as the volume scattering signal is detectable for dry snow. Higher frequencies have shorter penetration depths, lower frequencies have less sensitivity. According to Shi et al., [2003] Ku-band is thus the optimal sensor frequency for estimation of SWE due to the balance of detectability vs. penetration depth. Repeat pass corrections will allow for removal of topographic and terrain effects and polarimetric measurements will enable decoupling of the snow volume scattering and snow surface scattering contributions.

4. Future Snow Monitoring

Table 2: Future and current SAR sensors for research and operational use.

Sensor	Satellite	f[GHz]/Polarization	Resolution [m]	Swath [km]
SAR	Radarsat1(1995-)	5.3 VV	10, 30, 100	100-500
ASAR	Envisat (2002-)	5.3 HH,VV,HV	30, 100	100-400
PALSAR	ALOS (2006-)	1.2 PP	15/100	40-350
TerraSAR-X	TerraSAR(2006-)	9.6 PP	1, 3, 16	5, 30, 100
SAR	Radarsat2(2006-)	5.3 PP	3, 10, 25, 50, 100	20-500
C-SAR	3-Constellation	5.3 VV	50	350
Sentinel-1	GMES, ESA-EC	5.3 PP ?	25-50 ?	350-500 ?

PP - Polarimetric; Source: H. Rott, personal correspondance

There are several new upcomming SAR missions (see Table 2) over the next couple of years that yield new possibilities in snow property retrieval and have potensial in operational snow monitoring. The introduction of polarimetric sensors as well as new frequencies opens new possibilities in particular in regard to operational retrieval of SWE.

4.1. Users and Requirements

Snow properties are particularly important for hydropower producers, power traders and regulators. Both for optimizing hydopower production and for avoiding flooding. For the data to be useful for this group the quality of the products has to be good (within 10% on a basin wide scale) and the coverage frequent, in particular in melting season (at least weekly).

5. Conclusion

Future sensors and new retrieval methods will allow for establishment of operational monitoring of SCA and SWE, for hydrological purposes based on SAR, that will meet the user requirements on quality and coverage. Main obstacle today is lack of operational sensors, in particular for the retrieval of SWE. Scheduled missions within the next couple of years will change this. Wet snow remains a challenge preventing melt season estimates of SWE.

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Electromagnetic Models for Passive Microwave Remote Sensing of Snow and Application to Experimental Data

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Several electromagnetic models have been described in the literature for modeling radiometric signatures of snow-covered terrains. Understanding how each model simulates the radiometric behavior of a snowpack, exploring the conditions under which the different models display the best agreement can provide insights for developing retrieval techniques, as well as possible model improvements.

In this study, we use four widely-used electromagnetic models to simulate the brightness temperatures of six different snow classes at different frequencies and observation angles. The snow classes considered here account for a majority of the types of snow occurring in the northern hemisphere. The models considered are the following: a model based on Dense Media Radiative Transfer Theory, a model based on the Strong Fluctuation Theory, the Helsinki University of Technology (HUT) model and the Microwave Emission of Microwave Layered Snowpacks (MEMLS) of the Institute of the Applied Physics, Berne.

We discuss the different approaches taken by each model, the required input parameters and the sensitivity of the electromagnetic quantities involved (e.g., brightness temperatures, extinction coefficient) to the input parameters. We compare the brightness temperatures simulated by means of the electromagnetic models for the six classes and analyze the causes of the observed differences.

Finally, we drive all four models with snow parameters derived from recent field data (e.g., the NASA Cold Land Processes experiment) and evaluate the outputs against observed brightness temperatures observations.