PROGRESS AND CHALLENGES IN RADAR REMOTE SENSING OF SNOW

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ABSTRACT

The article is a review of radar remote sensing of snow, including the basics, recent progress, present challenges, and emerging technologies and methods in the field.

SYMBOL LIST

The main parameters in radar remote sensing of snow along with the corresponding symbols and abbreviations are listed in Table 1 and they are used throughout this presentation.

Table 1: Symbols and abbreviations of parameters in radar remote sensing of snow.

Parameter	Symbol or Abbreviation
Snow-covered area	SCA
Snow water equivalent	SWE
Snow wetness	SW
Permittivity	$\varepsilon = \varepsilon' - j\varepsilon''$
Backscattering coefficient	σ^0
Incidence angle	θ

Snow wetness is defined by volume and incidence angle is counted from vertical ($\theta = 0°$ for nadir).

NEED FOR SNOW INFORMATION AND PRESENT DATA COLLECTION METHODS

Most of the snow cover is located in the northern hemisphere, where the mean snow-cover extent varies from 46.5 million km^2 in January to 3.8 million km^2 in August (Robinson et al., 1993). Changes in the annual distribution of snow related to the climate change have been observed during the last decades (Serreze et al., 1999). In addition to playing a significant role in the global climate, the cryosphere is a sensitive indicator of changes in the climate system. Better understanding of the interactions and feedback mechanism of the land/cryosphere system and their adequate parameterisation in climate and hydrological models is needed) (Allison et al., 2000), (Guyenne, 1995).

The amount and timing of snowmelt runoff from snow and glaciers is valuable information for management of water resources, including flood and avalanche prediction and hydropower operation in many countries. One of the main problem with hydrological models is lack of information on the spatial distribution of model variables and parameters (Guneriussen et al., 2001a). Information on snow is needed on various temporal and spatial scales, ranging roughly from one to ten days (temporal resolution) and from 0.1 km to 100 km (spatial resolution).

Present approaches to collect information on snow range from traditional ground-based methods to airborne gamma-ray measurement and to the use of optical satellite imagery and microwave (radiometer and radar) imagery. The level of these methods varies from those purely in research phase to those used operationally.

Ground-based methods are applied operationally in many countries. In Finland the number of snow courses (a few km long paths with typical land-cover type distribution, along which snow depth and water equivalent data are collected) used operationally is about 160, scattered all over the country. The results are reliable, but derivation of regional values from these temporally and spatially sparse data is problematic.

Operational airborne snow cover mapping using gamma-ray techniques has been performed in North America since the 1980's (Carroll et al., 1989). This method provides SWE and SCA along the flight path under both dry and wet snow conditions, but calibration and use over some land-cover types is problematic.

Canada has actively developed spaceborne microwave radiometry for snow mapping since the 1980's (Goodison, 1989).

Optical satellite measurements are easy to interpret (excluding the problem with clouds) for snow-covered area, but no data are available under dark and cloudy conditions. The U.S. National Weather Service has been mapping SCA with GOES satellite data since 1983 (Allen and Mosher, 1986).

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Microwave radiometry can provide snow water equivalent of dry snow cover with adequate accuracy, assuming that regionally tuned interpretation algorithms are used, e.g. (Hallikainen and Jolma, 1992). Additionally, discrimination of wet snow from dry snow works well, when time series of data are used. The main problems are the effects of snow grain size and vegetation (forest canopies), and poor spatial resolution.

U.S. National Oceanic and Atmospheric Administration (NOAA) has measured snow cover on a weekly basis in the northern hemisphere since 1986 using a variety of sensors, including the Scanning Radiometer (SR) and the Very High Resolution Radiometer (AVHRR) (Matson, 1991). The current NOAA product is a daily snow-cover product (Ramsay and Robinson, 2000).

With the launch of the Terra satellite on 18 December 1999 new snow mapping possibilities became available. The Moderate Resolution Imaging Spectroradiometer (MODIS) has recently started providing various products for snow-covered area (SCA), Table 2.

Table 2. MODIS snow-covered area products from the U.S. National Snow and Ice Data Center (NSIDC) (http://nsidc.org/NASA/MODIS/snow_products.html).

Data Type	Coverage (km)	Spatial Resolution	Temporal Resolution
MOD10_L2	1354 by 2000	500 m	Swath (scene)
MOD10L2G	1200	500 m	Day of multiple coincident swaths
MOD10A1	1200	500 m	Day
MOD10A2	1200	500 m	8 days
MOD10C1	Global	0.25°	Day
MOD10C2	Global	0.25°	8 days

These products are considered provisional at the time. Product quality may not be optimal, and incremental product improvements are still occurring.

Development of radar methods to collect information on snow has been slower in spite of early ground-based experiments on the effect of dry and wet snow to the backscattering coefficient of terrain (Stiles and Ulaby, 1980). The main advantages of radar-based methods over microwave radiometry and optical methods are better insensitivity to atmospheric effects (due to lower frequencies for radar) and much better spatial resolution (on the order of meters instead of kilometers), and measurement capability at night and through clouds, respectively. For example, the average cloudiness in Finland (latitude 60° to 70° N) is in winter about 70 % and, additionally, days are very short. About 70 % of the land area in Finland is covered by boreal forests, further complicating the use of optical satellite data.

In spite of the higher degree of complications for interpreting radar data, the SCA products in Table 2 are presently the reference, against which new methods should be compared. Due to the limitations of optical methods at high latitudes, an operational snow mapping method there should include the use of radar data.

MICROWAVE DIELECTRIC PROPERTIES OF SNOW AND SOILS

Water controls the dielectric properties of snow and soils. The basic investigations in this field include a study by Hallikainen et al. (1986) for wet snow, a study by Mätzler et al. (1996) for dry snow, and those by Dobson et al. (1985) and Hallikainen et al. (1985) for soils. Experimental data and theoretical models for the dielectric properties of soils at temperatures below 0°C are scarce (Hallikainen et al., 1985). Other investigations include a study by Tiuri et al. (1984) for wet snow. Recently, a new model for the microwave complex permittivity of wet snow was presented (Hallikainen and Vänskä, 2001), extending the validity range down to the MHz range.

With the possible introduction of higher frequencies for radar remote sensing of snow (Rott, 2001), studies concerning the extinction (absorption and scattering) properties of dry snow in the 10 to 30 GHz range are needed. Presently available information covers a frequency range of 18 to 90 GHz (Hallikainen et al., 1987) but the accuracy of results below 35 GHz is limited due to the measurement method.

BACKSCATTER MODELING

The backscattering coefficient of snow-covered terrain includes contributions from the snow-air interface, the snow layer (volume scattering), and the underlying ground surface. The observed backscattering coefficient is affected by several snow and soil parameters, including the following (Ulaby et al., 1986): Snow layer thickness, snow volumetric water content, snow wetness, snow temperature, snow density, surface roughness (snow-air and snow-soil interfaces), and snow layering. Depending on geographical area, the effects of boreal forest (Koskinen et al., 1997) and those of relief, aspect angle, layover, and radar shadowing (Nagler and Rott, 2000) may be important.

Based on studies by Kendra et al. (1998) and by Koskinen et al. (2000), the discrete particle model for snow volume scattering agrees with experimental data at C-band only if the snow particle size is assumed to be substantially larger than the visually observed value.

Shi and Dozier (2000b) eveloped a physically-based first-order backscatter model for dry snow. The cross-polarisation signal is only generated from the snow-ground interaction terms and it can be used to investigate co-polarisation signals. As discussed later, this model has been used to infer snow depth and particle size from SIR-C/X-SAR measurements. Previously, they developed a C-band polarimetric backscatter model for wet snow (1995), accounting for surface and volume scattering and including a total of five various coherent/incoherent scattering terms, out of which three terms represent surface-volume interaction terms. Mätzler and Wiesmann (1999) recently extended their previously developed emission and backscattering model to handle coarse-grained snow.

Ulaby et al. (1996) developed a semiempirical backscatter model for 35 and 95 GHz. The model expressions are given for each linear polarisation combination in terms of incidence angle and four snow parameters: depth, density, particle diameter, and wetness. The model accuracy was reported to be on the order of 1 to 3 dB. Other millimeter-wave backscatter models for snow include those of Mead et al. (1993) and Tjuatja et al. (1996). A review on modelling for millimeter-wave remote sensing of snow has been presented by O'Neill (1994).

Basic problems in backscatter modelling include characterisation of snow medium and vegetation (forest). The stickiness parameter is emerging to account for the effect of snow particle lumping (Ding et al., 1994). The transmissivity of boreal forest canopies has been estimated from microwave radiometer measurements at frequencies above 6.8 GHz, suggesting that the values are above 0.9 at L-band (Kruopis et al., 1999). Further studies are needed.

SNOW-COVERED AREA AND SNOW MELT

Determination of snow-covered area from radar data is a complex problem, because snow may be either wet or dry and soil may be either frozen or thawed. Moreover, the volumetric wetness of snow can have values between 0 and 5 % and that of thawed soil can have values between 5 and 30 %, changing the value of the backscattering coefficient correspondingly. Vegetation may partially mask snow and underlying ground. In practice, water authorities are mostly interested in snow melt runoff, changing the problem to that of discriminating wet snow from thawed snow-free ground within a basin.

An operational snow melt monitoring system was adopted for use in Finland recently (Metsämäki et al., 2001), (Koskinen et al., 1999). It employs AVHRR images, weather permitting, and ERS-2 SAR images, when available. The system supports run off prediction. The SAR method is based on pixel-wise comparison of present image with reference image(s) for wet snow-free ground, e.g. from the previous snow season (Koskinen et al., 1997). The change in the value of the backscattering coefficient from that for wet snow to that for snow-free ground (about 3 dB at C-band, depending on land-use category) is assumed to depend linearly on the fraction of snow-covered ground within a pixel. The effect of boreal forest canopies is compensated using the method presented in (Pulliainen et al., 2001). Using their modelling approach, verified by comparisons of computed results with ERS SAR data and airborne HUTSCAT scatterometer data, Koskinen et al. concluded that the SCA algorithm relying on reference images for snow-free ground works better than that employing reference images for dry snow (2000).

Similar SAR-based methods for have been developed for other geographical areas. The method relying on ERS-2 SAR and RADARSAT data was demonstrated in Austria (Nagler and Rott, 2000). In Canada Baghdadi et al. demonstrated the use of C-band SAR data for mapping of wet snow, employing ERS-1 SAR data (1997) and airborne polarimetric data (1998) and, additionally, they investigated the potential and limitations of RADARSAT data for wet snow monitoring (2000). Experiments on snow melt monitoring with RADARSAT SAR images were conducted also by Li, S. et al. (2000). Bernier et al. (1998) studied the use of ERS SAR time series to monitor dry and shallow snow cover. The use of a high incidence angle was observed to help in the discrimination of wet snow from snow-free ground; the same was confirmed by Guneriussen et al. (2001b).

The use of airborne L- and C-band polarimetric data was tested in Norway for discrimination of wet snow from bare snow-free ground and vegetated snow-free ground (Holden et al, 1998). The best classification accuracy for discriminating wet snow from bare snow-free ground was obtained with the C-band span (87 %), followed by C-band VV and HH polarisations. In the case of vegetated snow-free ground C-band HV and VH polarisations gave the best accuracy (95 %), closely followed by corresponding L-band channels.

The results from airborne C-band polarimetric radar experiment in the Alps under summer melt and rainstorm conditions showed that the best separabilities between wet snow, glacier ice and other surfaces (rock, moraine, grassland) are obtained with three polarimetric parameters (Shi et al., 1994). They are the degree of polarisation, depolarisation factor ($\sigma^0_{hv}/\sigma^0_{vv}$), and total power in VV polarisation. For discrimination of wet snow-covered areas from snow-free areas the separabilities (difference between class mean values divided by sum of standard deviations) ranged from 1.4 to 2.1.

One of the present challenges is to examine the use of SAR systems operating above X-band to further improve determination of snow-covered area.

CLASSIFICATION OF WET SNOW, DRY SNOW, AND SNOW-FREE GROUND

Hallikainen et al. (1995) used data sets from ERS-1 SAR, airborne HUTSCAT scatterometer (C- and X-band, 4 linear polarisations), and airborne microwave radiometer data at 24, 35, 48 and 94 GHz to discriminate dry snow, wet snow, frozen snow-free ground and wet snow-free ground. A specific combination of radar and radiometer data for discriminating each parameter in the case of several land-use categories and forest types was determined.

Stiles and Ulaby (1980) demonstrated that the capability of radar to discriminate wet snow from dry snow by radar improves with increasing frequency. Since the highest frequency of a satellite-borne SAR system so far is 5.3 GHz, Nghiem et al. (2001) used data from the Ku-band SeaWinds scatterometer onboard the QuikSCAT satellite to investigate snow signatures. They carried out a ground-based Ku-band scatterometer campaign in Alaska and applied its results to the satellite data. The final outcome was daily global snow cover maps with four separate categories: Snow, melting snow, refrozen snow, and snow-free ground. They also showed the evolution of seasonal snow cover over the northern hemisphere in 1999-2001 with time-series SeaWinds imagery.

Methods based on airborne radar polarimetry were suggested for studying changes in L- and C-band polarimetric descriptors (entropy, alpha angle, and anisotropy) due to seasonal changes in snow-covered areas in the Alps (Ferro-Famil et al., 1999).

The use of (a) Ku-band and even higher frequencies, (b) SAR polarimetry, and (c) combined radar and microwave radiometer measurements for large-scale applications are some of the present challenges.

SNOW WATER EQUIVALENT

Opposing results on the dependence of the backscattering coefficient vs. snow water equivalent have been presented over a period of 20 years. Ulaby and Stiles (1980) showed that the correlation between σ^0 and SWE is positive at 8.2 and 17 GHz. Based on their experimental results they developed a semiempirical model to characterise the relationship. They considered the direct volume backscattering component from the snow volume and the surface backscattering component from the snow-ground interface. Kendra et al. (1998) also found a positive correlation between the two quantities from their data over a smooth subsurface. However, this positive correlation only existed over a frozen subsurface, whereas there was no correlation over the thawed subsurface (Bernier and Fortin, 1998). On the other hand, Strozzi (1996) observed a negative correlation between σ^0 and SWE at 5.3 GHz. Rott and Mätzler (1987) observed no particular difference between dry snow-covered and snow-free areas at 10.4 GHz.

This dispute was explained by Shi and Dozier (2000b); they concluded from their theoretical studies that the correlation between σ^0 and SWE for a given incidence angle and polarisation may vary from positive to negative, depending on snow and soil characteristics.

Shi and Dozier (2000a, 2000b) estimated snow water equivalent for a test site (snow depths up to 5 m) using SIR-C/X-SAR data at L-band, C-band, and X-band. They first inferred snow density with L-band VV and HH data and then determined snow depth and particle size with C-band and X-band data. This algorithm is based on a polarimetric dry snow backscatter model and consequent characterisations and parameterisations of various terms and relationships in order to decrease the number of unknown components in backscatter contributions. The algorithm performs well for incidence angles higher than 30°. The density of snow for a test site in China was determined with L-band polarimetric data using a similar approach (Li, Z. et al., 2000).

Arslan et al. (2001) investigated retrieval of SWE of dry snow form airborne SAR C-band data during the ESA EMAC'95 Snow and Ice Campaign in northern Finland. They used an empirical model and data for non-forested areas. This approach provided good results only after massive spatial averaging of radar data. This is likely to be caused by the large variability in soil type (agricultural land, clear cut, and bogs) and, consequently, in surface roughness.

The use of polarimetric descriptors for retrieval of snow information from airborne L- and C-band data in the boreal forest zone was tested by Praks et al. (1998). Their study showed that entropy of natural targets is high and the amount of polarimetric information in backscatter is low. The alpha angle (related to the backscatter mechanism) increases with increasing snow depth, but has considerable scatter and is also affected by forest stem volume.

Obviously, polarimetric multifrequency SAR data will not be available from satellites in the near future. Another new technique, SAR interferometry, already proven in space, was recently applied to snow studies. Guneriussen et al. (2001c) determined a relationship between the InSAR phase and SWE. The results imply that small changes in snow characteristics between InSAR image acquisitions may introduce an increase in the DEM height error. Li and Sturm (2001) had a similar approach. They constructed an interferogram from a pair of SAR images spanning a snow precipitation event, and another SAR interferogram from a pair of SAR images acquired a week earlier. The second pair was used to remove the topographic component, revealing the spatial distribution of the snow precipitation event, obviously with reasonable accuracy.

Koskinen (2001) investigated the feasibility of using interferometric L- and C-band SAR imagery for determining the extent and depth of wet snow cover. He was able to determine the snow extent using SAR intensity and Landsat imagery; however, the accuracy of the digital elevation model (DEM) available for interferometric height calibration was not adequate. A reference interferometric height measurement would be needed for the purpose.

The use of SAR interferometry for SWE mapping is no doubt one of the major challenges in this area.

SNOW WETNESS

Investigations have shown both negative and positive correlations between the backscattering coefficient and snow wetness (Stiles and Ulaby, 1980), (Shi and Dozier, 1992), possibly due to different surface roughness values. On the other hand, European SAR algorithms for retrieval of snow-covered area employ observed negative correlation between σ^0 and wetness for reasonable snow wetness and depth values (Koskinen et al., 1997), (Nagler and Rott, 2000), (Guneriussen et al., 2001b).

Shi and Dozier (1995) applied their backscatter model for wet snow in a test site with an average annual SWE of 800 mm, showing that the relationship between σ^0 and SW is controlled by the relative contribution of volume and surface scattering mechanisms. Their results indicate that rough surface tends to cause positive correlation and smooth surface negative correlation depending, additionally, on snow characteristics and incidence angle.

Based on their modelling approach, Koskinen et al. (2000) concluded that, for snow and land-use conditions typical of the boreal forest zone, the difference in the C-band VV-polarisation (ERS SAR) backscattering coefficient between dry and wet snow increases with increasing wetness. It finally saturates to a value of about 7 dB at SW = 4 %; typical scatter due to varying snow and land-use conditions is of the order of 5 dB. The corresponding difference between snow-free ground and wet snow was determined to be practically the same, with substantially smaller scatter.

Ulaby et al. (1996) investigated the use of 35 and 95 GHz for retrieval of snow characteristics. Although the role of snow particle size is substantial even at 35 GHz (as in microwave radiometry), the backscattering coefficient is highly sensitive to snow wetness, exhibiting a dynamic range of about 20 dB for the wetness range of 0 to 6 % for HV polarisation, incidence angle 40 degrees.

The use of higher frequencies for SW mapping is a challenge for near-future research.

MILLIMETERWAVE RADAR STUDIES OF SNOW

Millimeter-wave backscatter from snow has been discussed to some degree in previous sections. Additional work includes measurements at 35, 95, and 225 GHz (Chang et al., 1994) and analysis of 215 GHz measurements and a geometrical optics model development (Narayanan and McIntosh, 1990).

EMERGING METHODS AND SENSORS

New methods for radar sensing of snow include SAR polarimetry, SAR interferometry, and high-frequency SAR. Although various decomposition techniques have been introduced (Cloude and Potier, 1996), the covariance matrix eigenvalue-based decomposition theory proposed by Cloude (1992), has been generally adopted for use in remote sensing. Few studies have been conducted so far to thoroughly test the feasibility of SAR polarimetry and interferometry for retrieval of snow characteristics. The proposal for a space-borne high-frequency SAR (Rott, 2001) is an interesting initiative that, if successful, will lead to a dedicated SAR mission for global snow mapping.

REFERENCES

Allen, M. W. and Mosher, F. R. (1986): Monitoring snow pack conditions with an interactive geostationary satellite system. *Proc. 54th Annual Western Snow Conference*, pp. 51-60, Phoenix, AZ, USA, 15-17 April 1986.

Allison, I., Barry, R. G., and Goodison, B. E. (2000): World Climate Research Programme Climate and Cryosphere (CLIC) Project – Initial Sequence and Coordination Plan (*http://www.np.no/clic*).

Arslan, A.N., Praks, J., Koskinen, J., and Hallikainen, M. (2001): An empirical model for retrieving snow water equivalent from C-band polarimetric SAR data. *Report 45, Laboratory of Space Technology, Helsinki University of Technology*, 35 pp., 2001.

Baghdadi, N., Gauthier, Y., and Bernier, M. (1997): Capability of multitemporal ERS-1 SAR data for wet snow mapping. *Remote Sens. Environ.*, vol. 60, pp. 174-186, 1997.

Baghdadi, N., Livingstone, C. E., and Bernier, M. (1998): Airborne C-band SAR measurements of wet snow areas. *IEEE Trans. Geosci. Remote Sensing*, vol. 36, pp. 1977-1981, Nov. 1998.

Baghdadi, N., Gauthier, Y., Bernier, M., and Fortier, J.-P. (2000): Potential and limitations of RADARSAT SAR data for wet snow monitoring. *IEEE Trans. Geosci. Remote Sensing*, vol. 38, pp. 316-320, Jan. 2000.

Bernier, M. and Fortin, J-P. (1998): The potential of times series of C-band SAR data to monitor dry and shallow snow cover. *IEEE Trans. Geosci. Remote Sensing*, vol. 36, no. 1, pp. 226-243, Jan. 1998.

Carroll, T. R., Baglio, J. V., Verdin, J. P., and Holroyd, E. W. III (1989): Operational mapping of snow cover in the United States and Canada using airborne and satellite data. *Proc. 15th Canadian Symposium on Remote Sensing and IGARSS'89*, pp. 1257-1259, Vancouver, B.C., Canada, 10-14 July 1989.

Chang, P., Mead, J., McIntosh, R., Davis, R., and Boyne, H. (1994): A detailed study of the backscatter characteristics of snowcover measured at 35, 95 and 225 GHz. *Proc. IEEE 1994 Int. Geoscience and Remote Sensing Symposium (IGARSS'94)*, pp. 1932-1934, Pasadena, CA, USA, 8-12 Aug. 1994.

Cloude, S. R. (1992): Uniqueness of target decomposition theorems in radar polarimetry. In: *"Direct and Inverse Methods in Radar Polarimetry,"* Editors: Boerner, W. M. et al., Kluwer Academic Publishers, pp. 773-791, 1992.

Cloude, S. R., Potier, E., (1996) A review of target decomposition theorems in radar polarimetry. *IEEE Trans. Geosci. Remote Sensing*, vol. 34, pp. 498-518, March 1996.

Ding, K., Zurk, L., and Tsang, L. (1994): Pair distribution functions and attenuation rates for sticky particles in dense media. *J. Electromagn. Waves Applicat.*, vol. 8, 1585-1604, 1994.

Dobson, M.C., Ulaby, F.T., Hallikainen, M., and El-Rayes, M.(1985): Microwave dielectric behavior of wet soil - Part II: Dielectric mixing models. *IEEE Trans. Geosci. Remote Sensing*, vol. GE-23, pp. 35-46, Jan. 1985.

Ferro-Famil, L., Pottier, E., Saillard, J., Dedieu, J., Bernier, M., and Fortin, J. (2000): The potential of full polarimetric SAR data to classify dry snowcover. *Proc. IEEE 1999 Int. Geoscience and Remote Sensing Symposium (IGARSS'99)*, pp. 1792-1794, Hamburg, Germany, 28 June - 2 July 1999.

Goodison, B. (1989): Determination of areal snow water equivalent on the Canadian prairies using passive microwave satellite data. *Proc. Joint 15th Canadian Symposium on Remote Sensing and IGARSS'89*, pp. 1243-1246, Vancouver, Canada, 10-14 July 1989.

Guneriussen, T. et al. (2001a): Description of Work; Development of Generic Earth Observation Based Snow Parameter Retrieval Algorithms. *Project Proposal to European Union*, EESD Programme, 2001.

Guneriussen, T., Johnsen, H., and Lauknes, I. (2001b): Snow cover mapping capabilities using RADARSAT standard mode data. *Canadian J. Remote Sensing*, vol. 27, pp. 109-117, April 2001.

Guneriussen, T., Hogda, K. A., Johnsen, H., and Lauknes, I. (2001c): InSAR for estimation of changes in snow water equivalent of dry snow. *IEEE Trans. Geosci. Remote Sensing*, in press, to appear in Oct. 2001.

Guyenne, T. (editor) (1995): Scientific Achievements of ERS-1. *ESA SP-1176/1*, ESA-ESTEC, 162 pp., Noordwijk, The Netherlands, 1995.

Hallikainen, M., Ulaby, F.T., Dobson, M.C., and El-Rayes, M. (1985): Microwave dielectric behavior of wet soil - Part I: Empirical models and experimental observations. *IEEE Trans. Geosci. Remote Sensing*, vol. GE-23, pp. 25-34, Jan. 1985.

Hallikainen, M., Ulaby, F.T., and Abdelrazik, M. (1986): Dielectric properties of snow in the 3 to 37 GHz range. *IEEE Trans. Ant. Propagat.*, vol. AP-34, pp. 1329-1340, Nov. 1986.

Hallikainen, M., Ulaby, F.T., and Van Deventer, T.E. (1987): Extinction behavior of dry snow in the 18 to 90 GHz range. *IEEE Trans. Geosci. Remote Sensing*, vol. GE-25, pp. 737-745, Nov. 1987.

Hallikainen, M. and Jolma, A. (1992): Comparison of algorithms for retrieval of snow water equivalent from Nimbus-7 SMMR data in Finland. *IEEE Trans. Geosci. Remote Sensing*, vol. 30, no. 1, pp. 124-131, 1992.

Hallikainen, M., Kurvonen, L., Koskinen, J., Jääskeläinen, V., and Mäkynen, M. (1995): Combined use of radar and microwave radiometer in retrieval of snow characteristics. *Proc. IEEE 1995 Int. Geoscience and Remote Sensing Symposium (IGARSS'95)*, pp. 1511-1514, Florence, Italy, 10-14 July 1995.

Hallikainen, M. and Vänskä, T. (2001): A new model for the microwave dielectric properties of wet snow. *Unpublished.*

Holden M., Schistad, A., and Solberg, R. (1998): Wet snow-cover mapping by L-and C-band polarimetric SAR. *Proc. IEEE 1998 Int. Geoscience and Remote Sensing Symposium (IGARSS'99)*, pp. 1533-1537, Seattle, WA, USA, 6-10 July 1998.

Kendra, J. R., Sarabandi, K., and Ulaby, F. T. (1998): Radar measurements of snow: Experiment and analysis. *IEEE Trans. Geosci. Remote Sensing*, vol. 36, pp. 864-879, May 1998.

Koskinen, J., Pulliainen, J., and Hallikainen, M. (1997): The use of ERS-1 SAR data in snow melt monitoring. *IEEE Trans. Geosci. Remote Sensing*, vol. GE-35, pp. 601-610, May 1997.

Koskinen, J., Metsämäki, S., Grandell, J., Jänne, S., Matikainen, L., and Hallikainen, M. (1999): Snow monitoring using radar and optical satellite data. *Remote Sens. Environ.*, vol. 69, pp. 16-29, 1999.

Koskinen, J., Pulliainen, J., and Hallikainen, M. (2000): Effect of snow wetness to C-band backscatter – a modeling approach. *Report 41, Laboratory of Space Technology, Helsinki University of Technology*, 20 pp., 2000.

Koskinen, J. (2001): Snow monitoring using interferometric TOPSAR data. *Proc. IEEE 2001 Int. Geoscience and Remote Sensing Symposium (IGARSS'01)*, 3 pp., Sydney, Australia, 9-13 July 2001.

Kruopis, N., Praks, J., Arslan, A.N., Alasalmi, H., Koskinen, J., and Hallikainen, M., (1999): Passive microwave measurements of snow-covered forest areas in EMAC'95. *IEEE Trans. Geosci. Remote Sensing*, vol. 37, pp. 2699-2705, 1999.

Li, S., Sturm, M., Kyriazis, S., and Logan, T. (2000): Mapping snowmelt sequence at Ivotuk, Alaska, using RADARSAT SAR images acquired with different standard beams. *Proc. IEEE 2000 Int. Geoscience and Remote Sensing Symposium (IGARSS'2000)*, pp. 481-483, Honolulu, Hawaii, USA, 24-28 July 2000

Li, S. and Sturm, M. (2001): Derivation of spatial distribution of snow precipitation using interferometric SAR technique. *Proc. IEEE 2001 Int. Geoscience and Remote Sensing Symposium (IGARSS'01)*, 3 pp., Sydney, Australia, 9-13 July 2001.

Li, Z., Guo, H., and Shi, J. (2000): Estimation of snow density with L-band polarimetric SAR data. *Proc. IEEE 2000 Int. Geoscience and Remote Sensing Symposium (IGARSS'2000)*, pp. 1757-1759, Honolulu, Hawaii, USA, 24-28 July 2000.

Matson, M. (1991) NOAA satellite snow cover data. *Paleogeography and Paleoecology*, vol. 90, pp. 213-280, 1991.

Mead, J. B., Chang, P. S., Lohmeier, S. P., Langlois, P. M., and McIntosh, R. (1993): Polarimetric observations and theory of millimeter-wave backscatter from snow cover. *IEEE Trans. Geosci. Remote Sensing*, vol. 31, pp. 38-46, Jan. 1993.

Metsämäki, S., Vepsäläinen, J., Pulliainen, J., Koskinen, J., Huttunen, M., and Hallikainen, M. (2001): The applicability of C-band SAR and optical data for snow monitoring in Boreal forest. *Proc. Third Int. Workshop on Retrieval of Bio- & Geo-physical Parameters from SAR Data for Land Applications*, 6 pp., Sheffield, UK, 11-14 Sept. 2001.

Mätzler, C. (1996): Microwave permittivity of dry snow, *IEEE Trans. Geosci. Remote Sensing*, vol. 34, pp. 573-581, March 1996.

Mätzler, C. and Wiesmann, A. (1999): Extension of the microwave emission model of layered snowpacks to coarse-grained snow. *Remote Sens. Environ.*, vol. 70, pp. 317-325, 1999.

Nagler, T. and Rott, H. (2000): Retrieval of wet snow by means of multitemporal SAR data. *IEEE Trans. Geosci. Remote Sensing*, vol. 38, pp. 754-765, March 2000.

Narayanan, R. M. and McIntosh, R. E. (1990): Millimeter-wave backscatter characteristics of multilayered snow surfaces. *IEEE Trans. Geosci. Remote Sensing*, vol. 28, pp. 693-703, May 1990.

Nghiem, S. V., Tsai, W.-Y., Neumann, G., Sturm, M., Taras, B., Perovich, D. K., and Elder, B. (20001): Remote sensing of snow with SeaWinds scatterometer. *Proc. IEEE 2001 Int. Geoscience and Remote Sensing Symposium (IGARSS'01)*, 3 pp., Sydney, Australia, 9-13 July 2001.

O'Neill, K. (1994): A review of modeling for millimeter wave remote sensing of snow. *Proc. IEEE 1994 Int. Geoscience and Remote Sensing Symposium (IGARSS'94)*, pp. 1925-1928, Pasadena, CA, USA, 8-12 Aug. 1994.

Praks, J., Koskinen, J., Arslan, A., Kruopis, N., Alasalmi, H, and Hallikainen, M. (1998): Cloude's target decomposition theorems applied to EMISAR data acquired during EMAC'95 snow campaign. *IEEE 1998 Int. Geoscience and Remote Sensing Symposium (IGARSS'98)*, pp. 1538-1540, Seattle, WA, USA, 6-10 July 1998.

Pulliainen, J., Koskinen, J., and Hallikainen, M. (2001): Compensation of forest canopy effects in the estimation of snow covered area from SAR data. *Proc. IEEE 2001 Int. Geoscience and Remote Sensing Symposium (IGARSS'01)*, 3 pp., Sydney, Australia, 9-13 July 2001.

Ramsay, B. H. and Robinson, D. (2000): Prospects for the Interactive Multisensor Snow and Ice Mapping System. *Proc. 57th Eastern Snow Conference*, Syracuse, N.Y., USA, 17-19 May 2000.

Rott, H. (2001): Requirements for a high frequency spaceborne SAR mission to measure the extent and properties of the seasonal snow cover. *Proc. Third Int. Workshop on Retrieval of Bio- & Geo-physical Parameters from SAR Data for Land Applications*, 6 pp., Sheffield, UK, 11-14 Sept. 2001.

Rott, H. and Mätzler, C. (1987): Possibilities and limits of synthetic aperture radar for snow and glacier surveying. *Ann. Glaciol.*, vol. 9, pp. 195-199, 1987.

Shi, J. and Dozier, J. (1992): Radar response to snow wetness. *Proc. IEEE 1992 Int. Geoscience and Remote Sensing Symposium (IGARSS'92)*, pp. 927-929, Houston, TX, USA, 26-29 May 1992.

Shi, J., Dozier, J., and Rott, H. (1994): Snow mapping in Alpine regions with synthetic aperture radar. *IEEE Trans. Geosci. Remote Sensing*, vol. 32, pp. 152-158, Jan. 1994.

Shi, J. and Dozier, J. (1995): Inferring snow wetness using C-band data from SIR-C's polarimetric synthetic aperture radar. *IEEE Trans. Geosci. Remote Sensing*, vol. 33, pp. 905-914, July 1994.

Shi, J. and Dozier, J. (2000a): Estimation of snow water equivalence using SIR-C/X-SAR, part I: Inferring snow density and subsurface properties. *IEEE Trans. Geosci. Remote Sensing*, vol. 38, pp. 2465-2474, Nov. 2000.

Shi, J. and Dozier, J. (2000b): Estimation of snow water equivalence using SIR-C/X-SAR, part II: Inferring snow depth and particle size. IEEE *Trans. Geosci. Remote Sensing*, vol. 38, pp. 2475-2488, Nov. 2000.

Stiles, W. H. and Ulaby, F. T. (1980): The active and passive microwave response to snow parameters. 1. Wetness. *J. Geophys. Res.* Vol. 85, no. C2, pp. 1037-1044, 1980.

Strozzi, T. (1996): Backscattering measurements of snow covers at 5.3 and 35 GHz. *Ph.D. dissertation*, Inst. Applied Physics, Univ. Bern, Bern, Switzerland, 1996.

Tiuri, M., A. Sihvola, E. Nyfors, and M. Hallikainen, (1984): The complex dielectric constant of snow at microwave frequencies. *IEEE J. Oceanic Engin.*, vol. OE-9, pp. 377-382, 1984.

Tjuatja, S., Fung, A. K., Comiso, J. C. (1996): Scattering and emission from dry snow in the range 35-140 GHz. *Proc. IEEE 1996 Int. Geoscience and Remote Sensing Symposium (IGARSS'96)*, pp. 2008-2010, Lincoln, USA, 27-31 May 1996.

Ulaby, F. T. and Stiles, W. H. (1980): The active and passive microwave response to snow parameters. 2. Water equivalent of dry snow. *J. Geophys. Res.* Vol. 85, no. C2, pp. 1045-1049, 1980.

Ulaby, F. T., Moore, R. K., and Fung, A. K. (1986): *Microwave Remote Sensing – Active and Passive, vol. III: From Theory to Applications.* Artech House, 1100 pp., 1986.

Ulaby, F., Siqueira, P., Nashashibi, A., and Sarabandi, K. (1996): Semi-empirical model for radar backscatter from snow at 35 and 95 GHz. *IEEE Trans. Geosci. Remote Sensing*, vol. 34, no. 5, pp. 1059-1065, Sept. 1996.