DETERMINATION OF SNOW WATER EQUIVALENT (SWE) USING MULTI-CHANNEL AIR BORNE AND SPACE BORNE SYNTHETIC APERTURE RADAR (SAR).

Bajzak, Denes. Professor of Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland, Canada A1B 3X5.

Roberts, Bruce A. Research Scientist, Natural Resources Canada, Canadian Forest Service, P.O. Box 6028, St. John's, Newfoundland, Canada, A1C 5X8.

KEYWORDS: Snow hydrology, snow-water-equivalent (SWE), multi-channel SAR

ABSTRACT

The estimation of spring run-off is a very important aspect of the water management of reservoirs. One of the inputs to models used for this purpose is the measurement of snow accumulation on the ground during the winter months. The Churchill Falls (L) Co. uses ground measurements in several snow courses to predict snow melt through the determination of snow-water-equivalent for management of water in the reservoirs used by the hydro-electric power plant.

Researchers suggested that the SWE can be determined by the simultaneous use of multi-channel SAR. We designed a project to test this theory under field conditions at Churchill Falls, Labrador. Multi-temporal X- and C- band SAR data were obtained (one set at the fall after the freez-up and another one during the maximum snow cover) over several test sites. A detailed ground survey followed the winter SAR mission. Half of the test sites were located at 30 and the other half at 60 incidence angles. Both HH and VV polarizations were used.

The data analysis was confined only to the association of C- band winter SAR data with the ground SWE measurements because of technical difficulties. An attempt will be made to use all the multi-temporal C- band SAR data.

RESUME

L'estimation de la crue printanière est capitale pour la gestion des réservoirs hydroliques. Une des données de base dans les modèles utilisés à cette fin est la mesure de l'accumulation de la neige durant l'hivers. La Corporation Churchill Falls (L) utilise des mesures terrestres sur plusieurs transectes pour prédire le volume de la fonte par l'équivalent neige-eau (ÉNE) pour la gestion de l'eau dans les réservoirs de la centrale hydroélectrique.

Des études suggèrent que L'ÉNE peux être évalué en utilisant un radar à ouverture synthétique (ROS). Nous avons élaboré un projet visant à valider cette idée dans les conditions de terrain à Churchill Falls au Labrador. Des données multitemporelles de la bande X- et de la bande C- on été recueillient (une récolte après le gel automnal et une récolte durant la période d'accumulation maximale) pour plusieurs sites d'études. Un échantillonage terrestre a suivi la récolte de données satellites. Les sites on été observés à des angles d'incidence de 30 et 60 degrés.

L'analyse s'est limité seulement à l'association des données hivernales de la bande C- avec les mesures terrestres de l'ÉNE à cause de difficultés techniques. L'analyse de l'ensemble des données multitemporelles sera faite prochainement.

INTRODUCTION

The hydro-electric power plant at Churchill Falls, Labrador (Canada) is one of the largest power generating facility in the world with a drainage area of 69 267 km^2 containing five reservoirs. Monitoring the inflow from such a large watershed area constitutes an important part of the water management. This monitoring at the present is conducted by field observations in snow courses during the winter months. The collection of field data is very expensive as most of the snow courses can be reached only by a helicopter and the results do not provide accurate results. The field observations could be supplemented by remotely sensed data collection to improve the run-off modelling and could make the procedure less expensive and more accurate.

Researchers suggested that snow-water-equivalent can be related to multi-channel RADAR returns from the snow fields in open areas (NASA , 1981 and Shi et.al., 1990). Since the Canada Centre for Remote Sensing (CCRS) introduced a RADAR development program with the use of an air borne X- (λ=3.24 cm) and C- (λ=5.66 cm) band SAR we could designed an experiment at Churchill Falls (in situ) to investigate the usefulness of this system to derive SWE. The RADAR development program was the fore runner for the application of a new Canadian RADARSAT satellite which was launched in late 1995.

The experiment was designed such that SAR and simultaneous ground data were collected in pre-determined sites at several time intervals (with and without snow cover). Statistical analysis of the ground and RADAR data should provide an estimate of SWE that could be built in a hydrological model to predict spring run-off.

EXPERIMENTAL DESIGN

The Earth Observation System approach (NASA, 1981) uses L-, C-, and X- bands SAR simultaneously over a snow field. This provides three simultaneous equations from which the SWE can be calculated. Since we had only two bands (X- and C-) we planned to obtain SAR data without snow cover after the freeze-up and during the maximum snow cover. This would replace the use of the L- band.

Bernier and Fortin (1991) evaluated the potential of C- and X- band SAR to monitor dry and wet snow cover. More recent applications of C-band SAR for mapping melting snow (Donald et.al. 1993) and mapping of discontinuous permafrost terrain (Granberg, 1994) were reported in the Canadian Journal of Remote Sensing.

The determination of SWE requires the use of calibrated SAR data. The incidence angle is one of the most determining factor in analysis, therefore, we chose two incidence angles (30^0 and 60^0) for our data acquisition.

Since the ground data collection had to follow the SAR acquisition immediately, we could use only a limited number of test sites. These sites were chosen in open areas near to access roads. Each target area consisted of a 60 to 120 m long base line. Snow parameter data were to be obtained at 6 m intervals along the base lines to coincide with the CCRS SAR ground resolution element.

On the advice of CCRS scientist we choose a regression analysis design such that the ground data (SWE) are correlated with single band and multiple band multi-temporal SAR data.

Corner reflectors were manufactured for the absolute calibration of SAR data. Two sets of two reflectors (one for the X- and one for the C-band) were placed in locations corresponding to 30^0 and 60^0 incidence angles.

DATA ACQUISITION

Air Borne SAR.

The snow free data were collected on October 30th, 1990 after the freeze-up with minimal snow cover (less than 10 cm). This flight provided X- and C- band data with HH and VV polarizations each. The maximum snow cover data were acquired on March 20th, 1991. At this time only the C- band was available, but with polarization of HH, HC, CC, and CH. The 30^0 and 60^0 incidence angle coverage required the use of the RADAR in 'nadir' and in 'narrow' modes respectively.

Ground Data Collection.

Since the SAR imaging was carried out at the afternoon after a snow storm the ground data collection could not be started until the next day. In total 13 different sites were extensively surveyed. In each site one or two parallel lines were laid out and at 6 m intervals the snow depth, density, and SWE were measured. In addition one or two snow pits were dug along each test lines and the following data collected in the pits: number, thickness, temperature, snow density, crystal structure, hardness, and grain size of layers. All work was extensively documented with ground and large scale aerial photographs and video.

In October, 1991 detailed field work was performed to analyse the underlying surface of each test site.

DATA ANALYSIS

Digital data and pictorial output for each flight line was provided by CCRS. In addition absolute calibration functions were worked out by CCRS scientists using the images of the deployed corner reflectors.

Ground Data.

The raw field snow measurements in each station of all test lines were converted into SWE and plotted over a sketch of the underlying ground cover types. The distribution of snow depths and SWE-s (min., max. and average) are presented in Table 2. The snow pit data were analysed for snow layer structure determination. A sample pit structure is given in Figure 1.

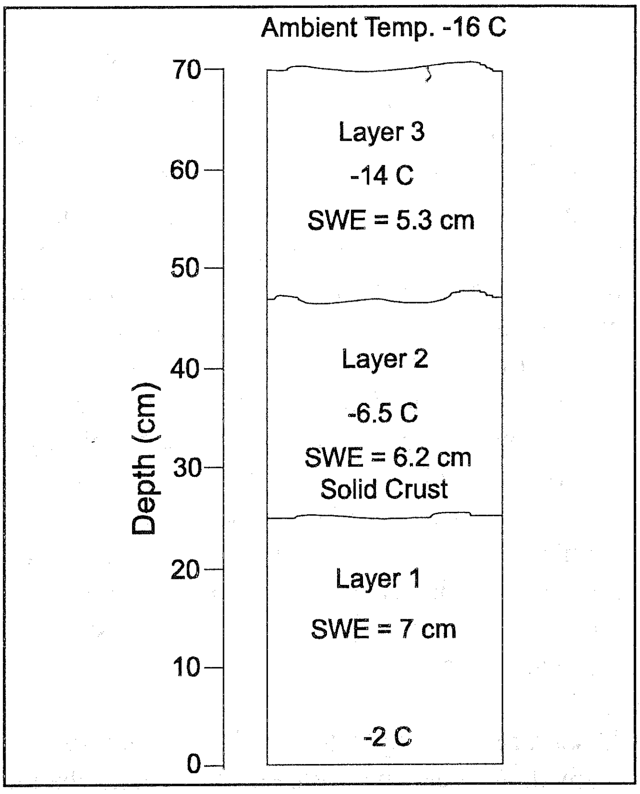

Figure 1. Profile of snow pit G 3.

SAR Data.

Based on flight recordings the incidence angles for each test sites were calculated (Table 1).
An in-house computer program was written to read, display, and dump the digital data provided by CCRS. This program involved a pictorial display of the image from which the areas of the test sites could be chosen for dumping of the digital data. Another program was prepared to carry out the conversion of digital numbers to power (σ) and average RADAR cross section (σ^0) for a selected sub sample. A third program provided the averaging of 9 neigbouring pixel values (3 by 3 kernel). As an illustration for one of the test areas (green 3), the raw and the filtered digital numbers (DN) of pixel values obtained by the SAR (nadir mode HH polarization) with the corresponding SWE data are given in Table 3.

Table 1. Incidence angles (degrees).

	Nadir Mode				Narrow Mode			
	October 30, 1990		March 20,1991		October 30,1990		March 20, 1991	
Target	C-HH X-HH	C-VV X-VV	C-HH C-HV	C-VH C-VV	C-HH X-HH	C-VV X-VV	C-HH C-HV	C-VH C-VV
B1	29.45	41.41	35.71	33.73	58.88	59.78	59.83	59.29
B2	30.06	41.77	36.15	34.19	59.05	60.03	60.00	59.55
B3	27.84	40.31	34.34	32.18	58.45	59.29	59.28	58.75
B4	29.21	41.59	35.93	33.73	58.88	59.78	59.96	59.29
B5	28.34	40.03	34.80	32.54	58.93	59.82	59.71	59.42
G1	34.97	46.01	40.45	38.57	60.87	61.55	61.48	61.27
G 2, 3, 4	34.54	45.78	40.05	38.05	60.56	61.26	61.33	61.19
G5	34.54	45.75	40.36	38.37	60.75	61.52	61.56	61.19
TFA	32.30	43.92	38.62	36.66	60.12	60.96	61.02	60.43

Table 2. Snow distribution statistics.

Target	Snow Depth (cm)			Snow-Water Equivalent (cm)		
	MIN.	MAX.	AVG.	MIN.	MAX.	AVG.
B1	47	138	67.6	12	31	20.4
B2	62	150	97.8	12	34	23.0
B3	45	115	57.2	10	26	12.9
B4	44	136	90.5	11	38	24.5
B5	118	122	120.0	22	25	23.5
G1	60	90	74.8	11	21	14.3
G2	44	104	72.2	7	22	14.4
G3	68	102	87.3	17	25	22.1
G4	31	93	61.8	7	31	17.4
G5	56	108	90.6	11	28	20.4
TFA	81	123	99.9	17	32	26.9
TFR1	40	95	51.6	9	24	13.2
TFR2	57	103	85.8	14	30	21.2

The SWE (as the dependent variable) was regressed over the raw and filtered DN-s separately (Figure 2). The analysis provided the following simple linear regression equations:

$\mathbf{SWE=17.6+0.17DN_{raw}}$ (r=0.37; SE=2.73) and

$\mathbf{SWE=16.0+0.22DN_{filtered}}$(r=0.22; SE=2.86)

Table 3. Ground and SAR Data For Target Area G3.

Ground Sheet #	SWE (cm)	Digital Number	
		Raw	Filtered
	reflectors	65	
		103	
		43	
		22	
		22	
1	21	24	30.0
2	19	36	31.2
3	23	31	28.4
4	22	23	25.3
5	24	22	28.8
6	25	41	33.0
7	25	35	34.1
8	24	25	30.7
9	17	23	27.7
10	25	25	26.7
11	24	29	26.2
12	21	24	25.4
13	20	24	25.1
14	26	24	25.8
15	22	30	25.9
16	17	17	27.1
		17	
		25	
	reflectors	39	
		126	
		108	

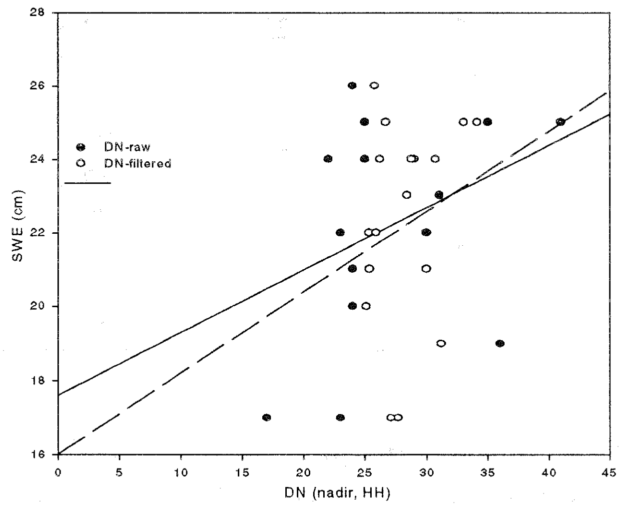

Figure 2. Linear regression of SWE vs.DN-s

Similar equations were developed for each test area, both with HH and VV polarizations.

RESULTS

The ground survey gave detailed information on snow distribution (depth, density, SWE) and on the underlying ground cover (soil, rock, ice, vegetation type). The SAR data must be correlated with all of the snow parameters, the underlying surface conditions and with the incidence angle and polarization of the RADAR. Since the preparation of the necessary computer programs and the development of the absolute calibration procedure took a very long time, the data has only been partially analysed to date.

Ground Data.

We had a very good distribution of SWE within and between test lines (Table 2). The snow depth should be over 20 cm to have an effect on the SAR return. In our case this varied between 31 and 138 cm. The SWE values had a range of 9 to 38 cm with averages of 12.9 to 24.5 cm of individual test lines.

The snow pit data provided detailed information on snow layering characteristics. All 22 detailed snow pits had at least 3 distinct snow layers. Thirty two per cent had four distinct layers and only one pit had five distinct snow layers. The mean thickness of the three main snow layers from the bottom of the pit to the surface was 22, 25, and 24 cm respectively. In the snow layer closest to the substrate, the snow temperature showed the least variation and averaged -1.5 ^{0}C. The temperature of the snow in layer three near the surface was very close to the ambient temperature. The SWE variation was minimal in the layer close to the substrate and highest in the second snow layer with variation further decreasing in the newer snow on top of the profile.

SAR Data Correlation With Ground Data.

The C- band SAR return from snow covered areas is made up of volume scatter from the snow and of return from the snow-soil interface, with the incidence angle being the most important factor affecting the strength of the signal. Since the test sites in this study were selected after the ground was covered with snow, in most cases we did not have uniform underlying soil surfaces. In order to obtain all of the required SAR data (two different modes and polarizations), the aircraft needed four passes each during the fall and winter. Table 1 shows that the incidence angles for a particular test site varied significantly. In addition, the X-band data were not collected during the maximum snow cover period which forced us to use only the C-band data. Another problem was encountered with the exact location of the test lines on the various SAR imagery.

Our example, presented in this paper, shows that the C-band SAR alone cannot give a good indication on the SWE value of snow pack (low correlation coefficient). Although the regression line has a positive slope, the individual observations are widely scattered. This scatter is due not only to the variation of the snow properties and of the ground surface coverage, but also to the inherent 'speckle' of the SAR even over uniform surfaces. To obtain a more precise result, the averaging of more pixels is required. However, this would involve a more detailed observation of SWE on the ground as it also can vary on a short distance. Our general observation is that raw DN-s of C-band VV polarization provides a better result than the data of HH polarization. We also conclude that the averaging filter (3 by 3 kernel) provides poorer results than the use of raw DN-s. We hope to improve on our results with the analysis of the multi-temporal SAR data.

CONCLUSIONS

At the time of the initiation of the project, very limited information was available in the literature concerning the prediction of SWE using SAR data (NASA, 1981). We received diverging and sometimes contradicting advice from experts concerning our experimental design. Finally we adapted a simple linear regression design for the establishment of relationships between SAR and SWE data. As we collected a very large amount of ground data on snow parameters and of SAR data (two incidence angles, two SAR bands, four different polarizations), the data analysis consumed a lot of time. In addition, we had to write our own computer program for the data analysis. We also encountered numerous technical difficulties, most of them out of our control, which made the data analysis a difficult task. We are currently in the process of using the fall C-band SAR data in combination with the winter SAR DN-s.

Our overall conclusion is that the C-band VV polarization provided a better estimate of SWE than the HH polarization. The use of a 3 by 3 averaging filter does not improve the precision of SWE estimation but actually decreases it. Although our results are not fully conclusive, we learned a great deal concerning the pitfalls of data collection and analysis.

Our final conclusion is that the field data collection and the SAR data acquisition requires extreme precision. We are now in the position to conduct further experiments which would yield more conclusive results. We are planning to use the Canadian RADARSAT and the Japanese JERS satellite data to refine our procedure of SWE estimation.

ACKNOWLEDGEMENTS

We would like to thank the Canada Center for Remote Sensing (CCRS) for providing the SAR data acquisition under very adverse conditions. We acknowledge all the help we received from various scientists of CCRS, especially Dr. T. Lukowski for working out the absolute calibration procedure. Thanks are also extended to Mr. W. Smith, Site Service Manager, Churchill Falls (L) Co. for the logistic help and members of the Water Resources Management Section for their help in the field data collection. The Faculty of Engineering and Applied Science of the Memorial University of Newfoundland (MUN) and the Canadian Forest Service (CFS, Newfoundland and Labrador Region) materially aided our research efforts. The image analysis programs were written by Mr. A. Galloway of MUN which we gratefully acknowledge. Special thanks are also due to K. Deering (Forest Ecology Section, CFS) for his help in the preparation of the manuscript of the paper.

REFERENCES

Bernier, M and J.P. Fortin, 1991. Evaluation of the potential of C- and X-band SAR data to monitor dry and wet snow cover. Proceedings of IGARSS'91, Espoo, Finland, June 3-6, pp. 2315-2318.

Donald, J.R., F.R. Seglenieks, E.D. Soulis, N. Kowen, and D.W. Mullins.1993. Mapping partial snow cover during the melt season using C-band SAR imagery. Can. Jour. of Rem. Sens. Vol.19,No.1 pp. 68-76.

Granberg, H.B., A.S. Judge, K.Fadaie and R. Simard, 1994. C-band SAR backscatter from northern terrain with discontinuous permafrost: The Schefferville digital transect. Can. Jour. Of Rem. Sens. Vol. 20, No. 3. Pp 245-256.

National Aeronautic and Space Administration. 1981. Remote sensing of snow parameters from space-synthetic aperture RADAR earth observation system instrument panel report. Vol. II f. Appendix A: glaciology-additional information. pp.177-181.

Shi, Jian Cheng, J. Dozier and E. Davis, 1990. Simulation of snow depth estimation from multi-frequency RADAR. IEEE IGARSSI 90. Remote sensing science for the nineties symposium, College Park, MD.,USA, May 20-24, 1990. Digest Vol. 1. pp. 1129-1132.