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Application of Georadar for Snow Cover Surveying

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A commercial georadar was tested over in a Norwegian catchment in order to determine the areal mean snow water equivalent (*SWE*) and its spatial distribution. The methodology used and the results obtained are described. The radar was run along a number of selected snow courses, and the results were compared with manual measurements of snow depth and density. It was found that georadar is able to give accurate estimates of mean *SWE* with much less time spent in the field compared to conventional measurements. Georadar also gave a good description of the areal distribution of *SWE*.

Background

Snow is a major part of the water budget in most mountainous drainage areas in Norway. Information about snow cover is therefore of great interest for planning hydropower production. Methods for the design of snow surveys are thoroughly discussed by Andersen *et al.* (1982). Sand and Killingtveit (1983) report results from extensive snow surveys in the river Orkla catchment based on the recommendations given by Andersen *et al.* (1982). Snow in mountainous areas is very exposed to wind so it is consequently heavily redistributed by wind drift making measurement challenging. Traditional snow surveys based on manual depth measurements and gravimetric estimates of density are very time consuming and laborious. The limited number of point measurements taken and often poor representativity of these points, means that manual snow surveys often become inaccurate.

Thus, researchers in both Sweden and Norway have used radar technology in order to develop snow survey methods which are more efficient and accurate than the traditional methods (Hamran *et al.* 1986; Sand and Killingtveit 1988; Andersen *et al.* 1987; Ulriksen 1989).

The Georadar System

In this study, a GSSI SIR SYSTEM-2 georadar with a 500 MHz antenna was used. The radar system choice follows recommendations given by Kennett (1994), who did an intercomparison between four different radar systems in order to ascertain their value for snow surveying. The radar systems included in the test were:

- SIR SYSTEM-2 (Geophysical Survey Systems Inc., USA)
- SIR SYSTEM-10 (Geophysical Survey Systems Inc., USA)
- PulseEkko 1000 (Sensors and Software Inc., Canada)
- SN001 Mk2 (MIROS, Norway)

The evaluation of the different systems was based on cost; weight and volume; user friendliness (complexity of hardware system, software user interface and whether the system allowed data to be instant reviewed in the field); and data quality. Of the four systems, the SIR SYSTEM-2 was recommended as the most suitable for snow surveying along long transects.

This radar system was used here to take measurements along snow courses and was operated from a snow mobile. The system consists of a transceiver antenna, a control unit, an external marker/trigger control and a survey wheel. The antenna was fixed inside a small fibreglass sled towed behind the snow mobile while the control unit was attached to the snow mobile itself; the survey wheel was attached to the sled. The radar may be set up to sample either at regular time or distance intervals. Distance is continuously recorded by the survey wheel. The output from the radar is given in digital format and can be processed by computer in order to determine the snow/ground interface.

The Test Site

The catchment area of Lake Samsjøen, located about 40 km south of the city of Trondheim, was chosen as the test site (Fig. 1). The catchment area is 199 km^2 and the elevation ranges between 481 and 941 m asl. The surface is mainly till with bog in the low lands, and moss, lichen and fields of exposed rock at higher altitudes. The tree line is situated at about 550-600 m asl. Below tree line, the vegetation consists of coniferous species, shrubs and mountain birch. Snow depth in this area is typically between 0 and 4 m, with an average depth of around 1 m.

The catchment's runoff is utilised for hydropower production. Lake Samsjøen is the headwater reservoir for three downstream hydroelectric power stations operated by Sør-Trøndelag Kraftselskap (STK), a regional power company in central Norway. STK measures snow water equivalent at a few sites within the catchment manually each year. The reservoir storage, withdrawal and spillover are measured daily.

Measurement Strategy

For the measurements, the strategy below was followed:

- Straight line snow courses were established. These were distributed over the entire catchment area and represented all the major terrain features expected to significantly influence the spatial distribution of the snow cover, *i.e.*, latitude, longitude, elevation, slope, aspect, and vegetation.
- Snow measurements were made along all of the established snow courses.
- Snow water equivalent was estimated from the measurements and snow distribution curves for individual elevation zones were plotted.

Fig. 1 shows the snow courses established. Given this extensive sampling scheme, it could be assumed that the true snow water equivalent and the snow distribution in the catchment was observed.

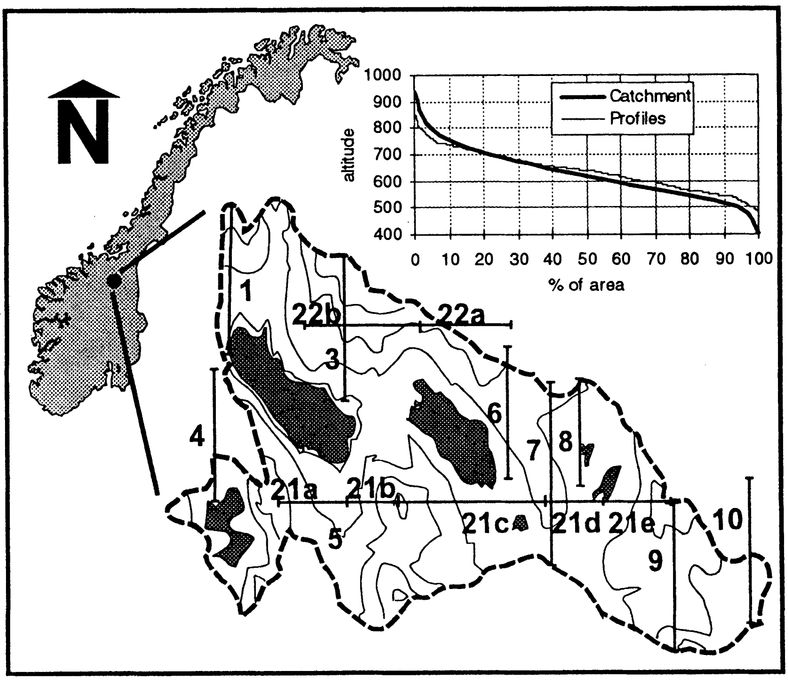

Fig. 1. Lake Samsjøen catchment. Location, measurement transects and hypsografic curve

Field work

The measurements were made during two periods, 4-7 April and 18-22 April 1995. The radar was run across all the snow courses, which covered 70 km in total (Fig. 1). The radar was set to sample every 0.20 m and with a range corresponding to approximately 4 m snow depth. Six control transects (620-1,000 m long) were measured manually to check the radar measurements. For these, snow depth was measured at 5 m intervals with a graduated snow probe. Snow density was measured at two or three locations along each transect. Vertical snow samples of the entire snow column were taken using a cylindrical tube (Songa-tube, 100 cm long and 10.0 cm diameter). Snow densities were then calculated from the weight and original length of the snow samples.

Introduction to the Impulse Radar Principle

Impulse radar is characterised by the sending of very short, wide-band signals, allowing it to determine short ranges with high resolution. The radar is capable of a sub-nanosecond resolution, the higher the frequency the greater the resolution. When the antenna is placed pointing downward onto a surface, the radar will detect echoes from different reflectors below the surface which have distinctively different dielectric properties (Table 1). The two-way-time (*TWT*), that is, the delay between the transmitted and reflected signal received by the antenna, indicates the depth to the reflector as long as the dielectric properties are fairly constant.

The delay of an electromagnetic wave travelling through a snow pack is proportional to the snow depth and inversely proportional to the average velocity of the wave (Ulriksen 1989). The average density and the liquid water content of snow determine the average velocity. In dry mediums, the (dry) bulk density primarily influences the dielectric constant. Under partially saturated or saturated conditions, it is mainly the liquid water content that determines the dielectric constant (Ulaby *et al.* 1986). The dielectric constant for dry snow normally ranges from about 1 to 2, while values up to 7 are found for saturated snow. For firn and glacier ice the value is about 4. Glen and Paren (1975) reviewed different methods to calculate the velocity of an electromagnetic wave in snow. They found the Loyenga model (Beek 1967) was easy to use and gave good results. This model is close to those found in Ulaby *et al.* (1986). For small dielectric losses and high frequencies the model can be written as (Fig. 2a)

$$\varepsilon_r = \left(1+0.469\,\frac{\rho_{snow}}{\rho_{ice}}\right)^3 \tag{1}$$

where ε_r – real part of the dielectric constant
ρ_{snow} – density of snow
ρ_{ice} – density of ice

Table 1 – Dielectric constant for different materials

Air	1	Water	81	Stone	5-10
Snow	1-2	Ice	4	Permafrost	6
Dry sands	4	Saturated sands	25	Organic soils	64
Wet clay	27	Tills	11	Peats	61

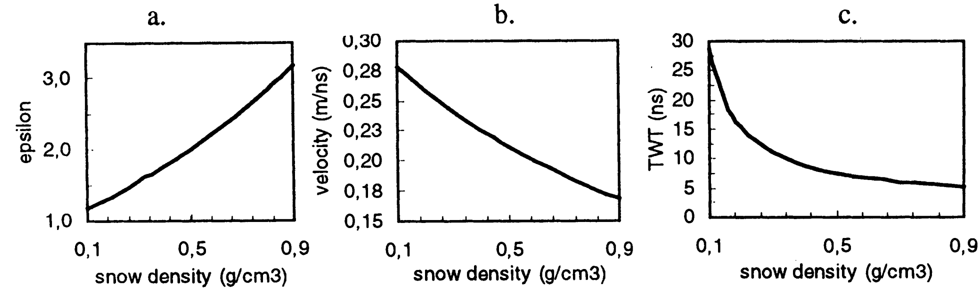

Fig. 2. a. The relative dielectric constant as a function of snow density,
b. The wave propagation speed as a function of snow density,
c. The wave two-way-time as a function of snow density.

The wave propagation speed *V*, can be calculated as

$$V = c\,\varepsilon_r^{-1/2} \tag{2}$$

where V – wave propagation speed
c – speed of light in vacuum (0.3 m/ns)
ε_r – real part of the dielectric constant

Fig. 2b shows the wave propagation speed in snow as a function of snow density according to Eqs. (1) and (2). Fig. 2c shows two-way-time as a function of snow density in a snowpack of 400 mm water equivalent when the density changes from 0.10 to 0.90 g/cm^3. Fig. 2c shows that two-way-time is not very sensitive to changes in snow density when the density is greater than about 0.4 g/cm^3; the lesser the sensitivity the greater the snow density.

The propagation velocity may also be expressed as

$$V = \frac{2d}{TWT} = \frac{2\,SWE}{TWT\,\rho_{snow}} \tag{3}$$

where d – snow depth
TWT – two-way-time
SWE – snow water equivalent
ρ_{snow} – bulk density of snow

Combining Eqs. (1), (2) and (3) gives the following expression for *SWE*

$$SWE = \frac{c}{2}\ \rho_{snow}\ (1 + 0.469\ \frac{\rho_{snow}}{\rho_{ice}}\ )^{-3/2}\ TWT \tag{4}$$

If the expression within the parenthesis of Eq. (4) is assumed to be constant, *SWE* is directly proportional to *TWT*, in practice, some correction must be introduced so that

$$SWE = a\ TWT + b \tag{5}$$

where: a – conversion factor
b – constant

The conversion factor a is thus a linear function of ρ_{snow}. The constant b should reflect any offset due to the distance between the centre of the antenna and the snow surface. The assumption made for Eq. (5) requires that the variation in snow density is small. Snow density may vary temporally and spatially over long distances. However, along snow courses within a limited survey area at a fixed time, the variability is very low. Thus the assumption should be acceptable for the normal ranges of densities found in natural snow covers at the end of the accumulation period.

Calibration of Radar Data

To establish the relationship between *TWT* and *SWE*, manually collected depth and density data was compared to the radar samples from along the same six control transect lines. The values of the parameters a and b in Eq. (5) which gave the best fit between the *SWE* curves sampled manually and by radar, are shown in Fig. 3. One parameter set was obtained from the average snow density for each snow course. Variability of the a values between the snow courses is due to differences in snow density.

Based on the calibration analyses from the six control transects, the relationship between the conversion factor a in Eq. (5) and snow density relative to the density of water could be expressed as

$$a = 151.4\ \rho_{snow} - 22.6 \quad (\mathrm{mm/ns}) \tag{6}$$

Within the range of densities measured during our fieldwork (0.29 to 0.43 g/cm^3), Eq. (5) gives lower values for *SWE* than Eq. (4) (the constant b in Eq. (4) is 0). The differences vary from -40% for the lowest density to -10% for the highest density. This shows that the Loyenga model does not fit the field data very well, especially in the lower end of the density range.

The radar receives signals from different reflectors in the snowpack. The snow/ground interface must be identified and separated from internal reflectors in the snowpack during data processing. *TWT* is measured with sub-nanosecond resolution and accuracy. The accuracy of the *SWE* calculations depends on the accuracy of the wave propagation speed estimate in the snow, which, in turn, is a function of the

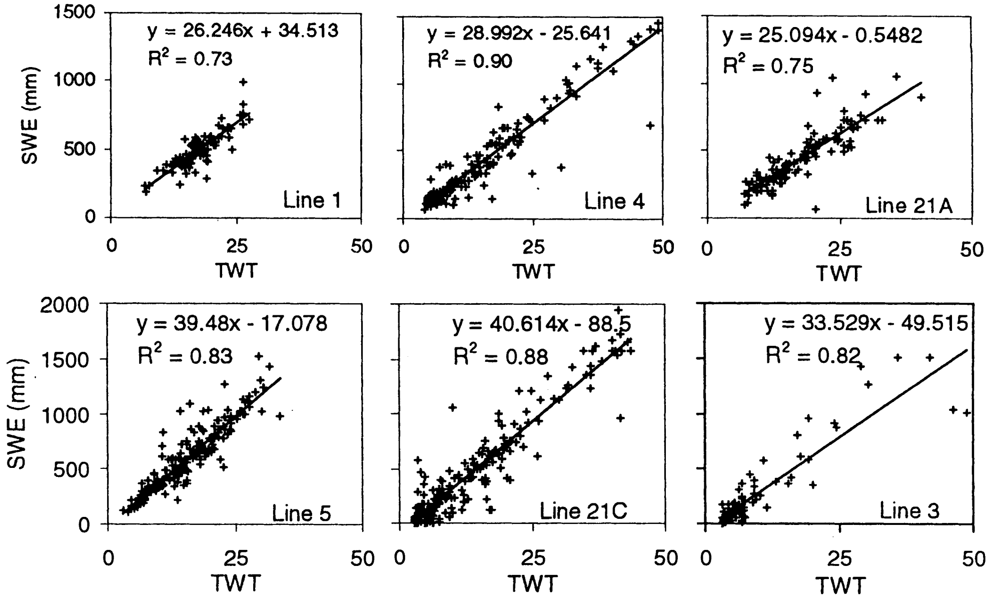

Fig. 3. The relationship between two-way-time (TWT) and snow water equivalent *SWE* at the control transects.

density. The density varies both in depth due to stratification and along the snow course due to different degrees of exposure. The snow densities were measured at two locations along each snow course and the average snow density for the calculation of the average wave propagation velocity along each transect was used. The radar wave propagates as a conic beam from the antenna. For the SIR-2/500 MHz antenna , the view angle is approximately 90 degrees in the longitudinal direction and 60 degrees in the perpendicular direction. The signal is therefore reflected from an elliptical footprint, the area of which increases with snow depth. Though the strongest reflection is from the central part of the footprint area, the roughness of the ground surface influences the signal received and, hence, the accuracy of the *SWE* estimate. Smaller sampling intervals where surfaces are rough will reduce this error.

Results and Discussion

Using the calibrated parameters, the radar data (*TWT*) were converted to snow water equivalent (*SWE*) for all snow courses. Snow depths varied from 0 to more than 400 cm. Fig. 4 shows one section (700 m) of snow course 21A with *SWE* values ranging from less than 200 mm to more than 1,000 mm (corresponding to snow depths of approximately 60-300 cm). This figure shows good agreement between the radar measurements and the manual control measurements (R^2 =0.76).The correlation co-

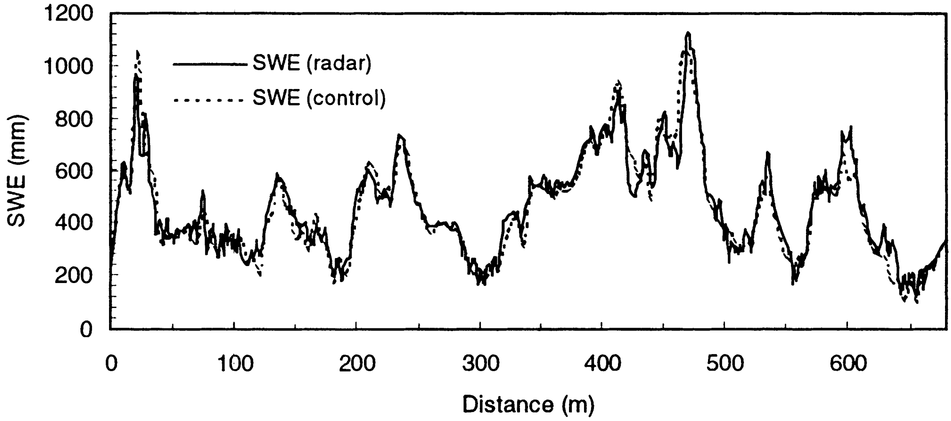

Fig. 4. Snow water equivalent at transect 21A. Radar measurements compared with manual control measurements.

efficient, R^2, for the six control transects varied between 0.74 and 0.90. The *SWE* estimates determined by the radar were between 1% and 5% different from those calculated from the manually collected control measurements. Water balance calculations based on measurements of runoff, precipitation and changes in water level in the Lake Samsjøen reservoir during the snowmelt runoff season, show that snowmelt contributed 112 million m^3 of water, corresponding to an average *SWE* for the entire catchments of 530 mm. By contrast, the radar survey and density measurements give an average *SWE* of 506 mm in late April prior to any snowmelt.

In case of few or no snow density measurements, the estimated *a* factor in Eq. (6) would be less accurate, and hence reduce the accuracy of the determination of *SWE*. For instance, assuming a true snow density of 0.40 g/cm^3, a 10% error in the snow density measurement will lead to a 16% error in the determination of *SWE* according to Eq. (5). The results presented here are achieved by using manual measurements of densities and snow depths for calibration of the radar measurements.

Less labour intensive calibration is possible if equations, such as Eqs. (1) and (2), are used to calculate bulk densities. By comparing *TWT* and manually measured snow depth at the same spot, wave propagation velocity can be calculated and bulk snow density derived from these equations. The accuracy of the measurements would then depend on the ability of these equations to describe reality. In the study presented here there was significant disagreement between measured values and these equations. These would lead to an *SWE* underestimation of 40% for the lowest snow density measurement (0.29 g/cm^3). Finally, the accuracy of the mean areal *SWE* estimate based on a single point or an average value for snow density will depend on the spatial variability of the density in the survey area.

The radar data was linked to a digital terrain model (DTM) in order to classify the measurements with respect to topographic parameters. We used the DTM to extract

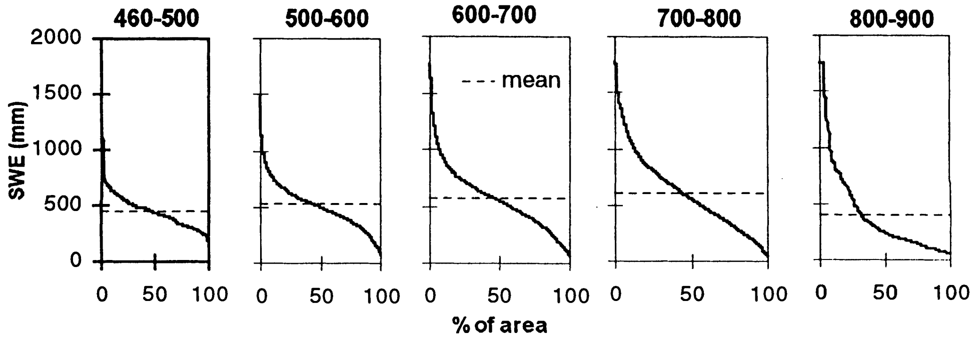

Fig. 5. Spatial snow distribution curves derived from the radar measurement and DTM of the catchment. The figure also shows the mean *SWE* in each elevation zone.

the measurement points within individual elevation zones in the catchment and established spatial snow distribution curves for the different elevation zones. Fig. 5 shows the snow distribution curves for each elevation zone derived from the snow radar data. The curves have an increase in slope with increased elevation, illustrating that snow cover is more heavily redistributed at high elevations than at low elevations. It can also be seen that the mean *SWE* increases with increasing elevation up to the 800-900 m asl zone. However, there is less snow at the highest elevation zone as it contains all the high ridges and peaks in the area. These are very exposed to wind and the snow is very easily swept away to be deposited at lower elevations.

Conclusions

A preliminary conclusion is that the GSSI SIR SYSTEM-2 georadar is a suitable tool for snow surveying. The conversion of the radar data to snow water equivalent is sensitive to snow density. Hence, good quality assessments of snow water equivalent require reliable estimates of snow density. The observations suggest that the radar is capable of measuring snow cover at least as thick as 4 m snow depth or about 1,600 mm water equivalent very satisfactorily. Also, the radar has demonstrated its ability as a tool to perform good quality snow surveys within very short time periods and with minimal labour requirements.

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