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# Impulse Raaar Snow Surveys – Influence of Snow Density

**A. Lundberg and H. Thunehed**
Luleå University of Technology, SE-97187 Luleå, Sweden

**J. Bergström**
Force Institut, SE-25467 Helsingborg, Sweden

Snow cover water equivalent (*SWE*) is of major importance for planning of *e.g.* hydropower production in areas where a large proportion of the annual precipitation falls as snow. Radar technique can be used to determine *SWE* from the two-way travel time (*twt*) of a radar-wave propagation through a snowpack. *SWE* is usually related to *twt* through an empirical relationship, $SWE = -b + a\ twt$, where the values of $a$ and $b$ are determined by linear regression from simultaneous measurements of *SWE* (with snow-courses) and *twt* (with radar technology). In this paper a theoretical relationship between *twt* and *SWE* is developed showing the need for introducing the density when relating *twt* to *SWE*. Use of different empirical relationships for the real dielectric constant showed that the $a$-value for dry snow with a density of 350 kg m$^{-3}$ (a typical value at the end of the accumulation season in the Nordic countries) is 0.040 m ns$^{-1}$ (*twt* given in nanoseconds). When the snow density deviates considerably from this value a corrected $a$-value has to be used. A density of 300 and 400 kg m$^{-3}$ gives $a$ = 0.036 and 0.045 m ns$^{-1}$ respectively. The $b$-value should theoretically be zero for measurements at the snow surface, non-zero values are probably due to the use of the direct wave between transmitter and receiver antennas as reference. The theoretically derived equations were confirmed by laboratory and field measurements as well as by measurements taken from literature.

## Introduction

Determination of snow cover water equivalent (*SWE*) is of great importance for *e.g.* the hydropower industry. In mountainous areas snow cover depth varies within a large range. A consequence of the highly varying snow depths is that estimates of *SWE* become difficult. Traditional snow surveys with manual density and snow depth measurements are very time and manpower consuming (*e.g.* Andersen *et al.* 1982; Sand and Killingtveit 1983; Killingtveit and Sælthun 1995; Martinec and Sevruk 1992). In order to develop more efficient and accurate methods several efforts to apply radar technology in snow surveying are made both in Norway (*e.g.* Killingtveit and Sand 1988; Andersen *et al.* 1987; Bruland and Sand 1996; Faanes and Kolberg 1996) and in Sweden (*e.g.* Ulriksen 1982; 1985; Brandt 1991; Almfors 1996). Both airborne devices (*e.g.* Ulriksen 1985; Brandt 1991; Almfors 1996) and devices pulled by snow mobiles (*e.g.* Ulriksen 1985; Killingtveit and Sand 1988; Bruland and Sand 1996) are used. With radar technology *SWE* is determined from the wave propagation time in the snowpack. The wave propagates from a transmitter located at the snow surface (for a ground-based radar) through the snowpack to the soil surface and back to a receiver at the snow surface. The propagation time is called the two-way travel time (*twt*) and is usually measured in nanoseconds. *twt* is for a given snowpack thickness a function of the dielectric constant which in turn is a function of the snow density and unfrozen liquid water content. The effect of variations in snow density has usually been regarded as small when the method is applied at the end of the accumulation period where density is expected to vary between 250-500 kg $m^{-3}$ (*e.g.* Ulriksen 1982; 1985). Empirical relationships between *SWE* and *twt* of the form

$$SWE = -b + a\,twt \tag{1}$$

are established for each measurement period (*e.g.* Ulriksen 1982; 1985). The assumption of negligible influence of snow density is too simplified as can be seen from the reported variations in the *a*-value. The values of *b* and *a* vary within a large range. Ulriksen (1985) *e.g.* observed *a*-values from 0.033 to 0.050 m $ns^{-1}$ and *b*-values from 0.206 to 0.0018 m and Brandt (1991), reports *a*-values ranging from 0.020 m $ns^{-1}$ in forested areas to 0.050 m $ns^{-1}$ in mountainous areas. Ulriksen (1982), Bruland and Sand (1996) and Almfors (1996) used a relationship between relative dielectric constant $K_{DS}$ of dry *s*now and snow density $\rho_s$ (found in Looyenga 1965) to illustrate that *twt* is only vaguely dependent on $\rho_s$ for high snow densities (Fig. 1). Bruland and Sand (1996) however showed that the *a*-value in Eq. (1) could be related to snow density $\rho_s$ according to $a = 1.455 \times 10^{-5} \times \rho_s - 0.00213$ m $ns^{-1}$ (empirical relationship). There are many reports where the influence of snow density and liquid water content on the dielectric constant are discussed (*e.g.* Hallikainen *et al.* 1982; Tiuri *et al.* 1984; Sihvola and Tiuri 1986; Denoth 1989; Denoth *et al.* 1984; Lundberg 1997). Almfors (1996) strongly advised an annual calibration of the *SWE/twt*

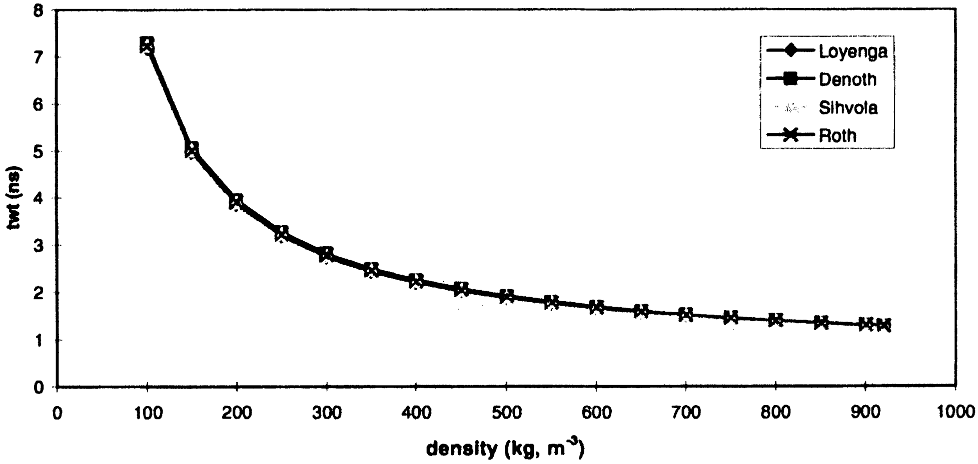

Fig. 1. Relationship between two-way travel time *twt* and dry snow density $\rho_s$ for $SWE$ = 0.1 m calculated using different relationships for the dielectric constant $K_{DS}$ of dry snow. $K_{DS}$ was calculated using the mixing model of Roth *et al.* (1990) and empirical relationships by Looyenga (1965), Denoth (1989; 94) and Sihovola *et al.* (1986) respectively.

relationship in Eq. (1). Thus both empirical results and theoretical reasons indicate that snow density $\rho_s$ and liquid water content should be included in the *a*-value (Eq. (1)).

The aim of this study was: a) Theoretically discuss the effects of snow density on the *a*-value and thus on the relationship between *SWE* and *twt* b) Compare *SWE*-values measured with snow surveys with *SWE* determined with radar technology using an *a*-value calibrated for snow density variations as well a constant *a*-value. Laboratory and field measurements as well as data from other studies were used in this work.

## Material and Methods

In this study a relationship between *twt* and *SWE* was established using theoretical relationships between radar wave velocity, the relative dielectric constant, snowpack height and snow density. Several different models for calculation of the relative dielectric constant for dry snow $K_{DS}$ were tried. The effect of density variations on *twt* and the *a*-value (in Eq. (1)) was investigated. Comparisons were made between *SWE* determined by snow survey measurements ($SWE_{\mathrm{SURV}}$) and *SWE* calculated from *twt*-measurements with radar technology ($SWE_{\mathrm{RAD}}$). The calculations of $SWE_{\mathrm{RAD}}$ were made using a) a constant *a*-value and b) a density-dependent *a*-value. The comparisons were made using laboratory measurements and a small field study.

## Theory

The velocity $v$ of a radar-wave propagating through a non-magnetic medium can be calculated from the relative dielectric constant $K$ of the medium (here snow dielectric constant $K_S$) and the radar-wave velocity in vacuum $c$ according to

$$v = \frac{c}{\sqrt{K_S}} \tag{2}$$

The two-way travel time $twt$ is related to the snowpack thickness $d$ and the radar-wave velocity $v$ as

$$twt = \frac{2d}{v} \tag{3}$$

Combining Eq. (2) and (3) gives

$$twt = \frac{2d\sqrt{K_S}}{c} \tag{4}$$

$SWE$ is defined as

$$SWE = \frac{\rho_S d}{\rho_w} \tag{5}$$

where $\rho_s$ and $\rho_W$ are the densities of snow and water respectively. Combining Eqs. (4) and (5) give a relationship between the $SWE$ and $twt$

$$SWE = \frac{\rho_S\, c\ twt}{\rho_w\, 2\sqrt{K_S}} \tag{6}$$

Which with numerical values of $c$ ($3 \times 10^8$ m s$^{-1}$) and $\rho_W$ (1,000 kg m$^{-3}$) becomes

$$SWE \equiv \frac{\rho_S\, 1.5\times 10^{-4}\, twt}{\sqrt{K_S}} = f(\rho_S, \sqrt{K_S})\, twt \quad (twt \text{ in nanoseconds}) \tag{7}$$

The function $f(\rho_s, \sqrt{K_s})$ corresponds to the $a$-value derived empirically from simultaneous measurements of $SWE$ and $twt$ in Eq. (1).

The relative dielectric constant $K$ of a mixture can be calculated with a dielectric mixing model using $K$ and the volume fractions $\Theta$ of the constituents (*e.g.* Roth *et al.* 1990; Lundberg 1997). The dielectric constant of wet snow $K_{WS}$ becomes

$$K_{WS} = (\Theta_W K_W^{\alpha} + \Theta_I K_I^{\alpha} + \Theta_A K_A^{\alpha})^{1/\alpha} \tag{8}$$

where subscripts $_{W,\, I,\, A}$ denotes water, ice and air respectively. Many authors have found good agreement in geological media using $\alpha = 0.5$ (*e.g.* Roth *et al.* 1990; Bergström 1997) and Lundberg (1997) who used $\alpha = 0.5$ for wet snow found fair agreement between measured and calculated water contents. Assuming $\alpha = 0.5$ Eq. (8) can be written

$$\sqrt{K_{WS}} \equiv \Theta_W\sqrt{K_W} + \Theta_I\sqrt{K_I} + \Theta_A\sqrt{K_A} \tag{9}$$

Applying $\Theta_A = 1 - \Theta_I - \Theta_W$ and rearranging the terms gives

$$\sqrt{K_{WS}} = \sqrt{K_A} + \Theta_I(\sqrt{K_I} - \sqrt{K_A}) + \Theta_W(\sqrt{K_W} - \sqrt{K_A}) \tag{10}$$

Using the relation between $\rho_s$ and $\Theta$ and $\rho$ of water, ice and air respectively

$$\rho_S = (\Theta_W\rho_W + \Theta_I\rho_I + \Theta_A\rho_A) \tag{11}$$

and neglecting the last term ($\rho_A << \rho_W$ and $\rho_I$) gives

$$\Theta_I = \frac{\rho_S - \Theta_W\rho_W}{\rho_I} \tag{12}$$

By inserting Eqs. (11) and (12) into Eq. (10) we get

$$\sqrt{K_{WS}} = \sqrt{K_A} + \frac{\rho_S}{\rho_I}(\sqrt{K_I} - \sqrt{K_A}) + \Theta_W(\sqrt{K_W} - \sqrt{K_A} - \frac{\rho_W}{\rho_I}(\sqrt{K_I} - \sqrt{K_A}) \tag{13}$$

Numerical values of $K_W = 80$, $K_I = 3.17$, $K_A = 1.0$ and $\rho_I = 917$ kg m$^{-3}$ gives

$$\sqrt{K_{WS}} = 1 + \frac{\rho_S}{917}(1.78045 - 1) + \Theta_W\left(9.0 - 1 - \frac{1000}{917}(1.78045 - 1)\right) \tag{14}$$

or

$$\sqrt{K_{WS}} = 1 + c_1\rho_S + c_2\Theta_W \tag{15}$$

where $c_1 \equiv 0.000851$ and $c_2 \equiv 7.09318$. Restricting the study to dry snow we get

$$\sqrt{K_{DS}} = 1 + 0.000851\,\rho_S \tag{16}$$

Which combined with Eq. (7) gives

$$SWE = \frac{\rho_S\, 1.5\times10^{-4}\, twt}{1+0.000851\,\rho_S} \qquad (twt \text{ in nanoseconds}) \tag{17}$$

## Measurements

### Laboratory Measurements

A small laboratory experiment was designed to illustrate the effect of density on the measured *twt*. A plywood box with 1 m height and a cross-sectional area of 0.5 m$^2$ was filled with dry snow. The snow was first left in a climate chamber, keeping an air temperature -1°C, for a couple of days. This was made in order to keep snow and air temperature just below zero during the experiments. The initial snow density (400 kg m$^{-3}$) was determined by weighing the empty and the filled box. Radar measurements were conducted using the Sensor & Software Pulse Ekko 1000, 450 MHz antenna. The one way travel time *(owt)* was measured by placing the transmitting antenna on top of the snowpack and the receiving antenna below the snowpack. The measurements were compared with corresponding measurements in air. Difference in arrival time between snow and air measurements were added to the beforehand known *owt* in air in order to get *owt* in snow. This procedure will eliminate errors due to offset in zero time. The snow density was step-wise increased by packing the snow until a final density of 635 kg m$^{-3}$ was reached. The *SWE* was kept constant during the whole experiment. The theoretically calculated $owt/\rho_S$ relationship (Eq. (17)) was compared with the measured relationship. Those measurements were later complemented with additional measurements of *SWE*, *owt* and $\rho_S$ for a range of initial *SWE* and $\rho_S$. To make the measurements comparable with the first measurements, where SWE was kept 0.4 m, the latter *owt*-values were normalised to *SWE* 0.4 m.

### Field Measurements

A small field test was performed at a suburban lawn where most of the lawn was covered with natural dry snow (A; depth $d = 0.7$ m, $\rho_S = 265$ kg m$^{-3}$, $SWE = 0.186$ m, Fig. 3a). Closer to the house the snow was denser (B; $d = 0.88$ m, $\rho_S = 394$ kg m$^{-3}$, $SWE = 0.347$ m) since snow had slided down from the roof of the house. *twt* was determined with radar technology (Pulse Ekko 1000, 1200 MHz antennae) and *SWE* was calculated with Eq. (17) using both the average density (330 kg m$^{-3}$) and the actual measured densities at the two locations A and B.

#### *Comparison with other published empirical $K_{SD}/\rho_S$ relationships*

The $twt/\rho_S$ relationship calculated with Eq. (17) for $SWE = 0.1$ m was compared with the $twt/\rho_S$ relationship calculated using other empirical relationships between $K_{DS}$ and $\rho_S$ (Looyenga 1971; Denoth 1989; 1994; Sihvola and Tiuri 1986). The *a*-values calculated for varying $\rho_S$ using Eq. (17) were compared with *a*-values calculated using the other relationships between $K_{SD}$ and $\rho_S$ mentioned above.

## Results and Discussion

### Laboratory Measurements

The laboratory measurements showed a distinct relationship between measured *owt* and $\rho_S$ (Fig. 2). The experimentally measured *owt* agrees fairly well with the theoretical relationship.

## Field Measurements

*twt* determined at the suburban lawn are shown in Fig. 3a. The correlation between $SWE_{\mathrm{SURV}}$ at the suburban lawn and $SWE_{\mathrm{RAD}}$ was clearly better when the effects of density variations were taken into account (relative error 4% and 5%) compared with calculating $SWE_{RAD}$ using the average density (relative error 24% and 10%) as illustrated in Fig. 3b.

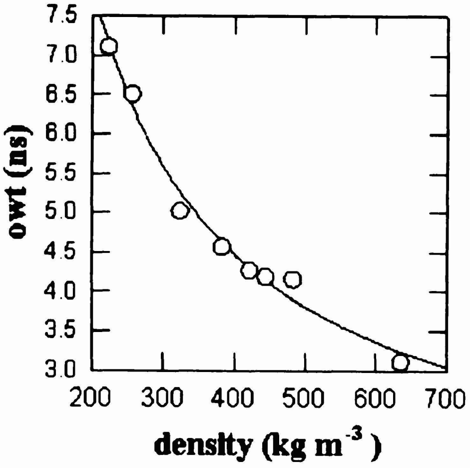

Fig. 2. One way travel time *owt* determined by radar measurements in laboratory for *SWE* = 0.4 m as a function of snow density. Open circles measured values, line theoretically determined relationship using Eq. (17).

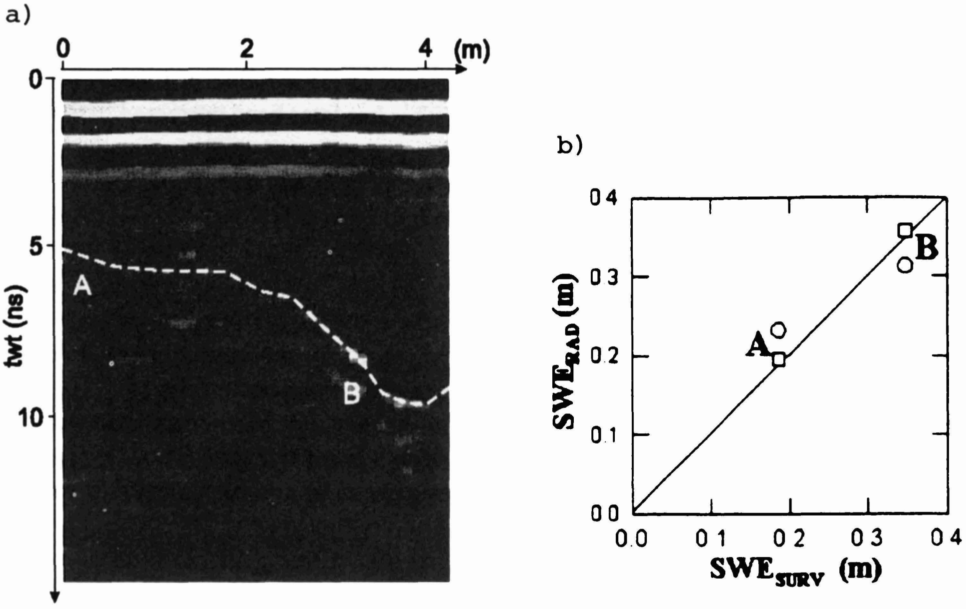

Fig. 3. a) Two way travel time *twt* at the suburban lawn. Snow water equivalent *SWE* determined with depth and density measurements at the point A (normal snow) and B (compacted snow).

b) Measured and calculated snow water equivalent *SWE* at lawn. Rectangulars and circles denote calculated *SWE* using variable and average density respectively.

## Comparison with Published Data

The relationships between *twt* and $\rho_S$ calculated for $SWE = 0.1$ m are roughly independent of chosen relationship between $K_{DS}$ and $\rho_S$ but small deviations between the different investigations exist (Fig. 1). This could be due to the fact that different types of probes were used in the different studies and Schneebeli *et al.* (1998) conclude that the combined effect of compaction and distribution of electromagnetic field caused by different sensors are important for the measurement of the dielectric constant in snow. The choice of relationship between $K_{DS}$ and $\rho_S$ thus seems unimportant. The simplicity of Eq. (16) and the direct correlation between the square root of $K_{DS}$ and $\rho_S$ makes Eq. (16) suitable for inclusion of density variations into the calculation of *a*. The agreement between the *a*-values determined by the mixing model and by the other empirical relationships between snow density $\rho_S$ and $K_{DS}$ was good (Table 1). The sensitivity to variations in $\rho_S$ in the *a*-value was much larger than the sensitivity to different approaches to model the $K_{DS}$ (Table 1 and Fig. 4). Eq. (16) is identical with an equation (based on empirical measurements) first proposed by Robin *et al.* (1969) and Robin (1975). Their findings were first questioned due to lack of agreement between $K_{DS}$-values determined in laboratory and with radar field measurements. Kovacs *et al.* (1993) however showed that Eq. (16) well described the relationship between $K_{SD}$ and $\rho_S$ but suggested a slightly modified $c_1 \equiv 0.000845$.

Bruland and Sand (1996) reported an increase in the *a*-value of 0.08 m ns$^{-1}$ for densities increasing from 330 to 400 kg m$^{-3}$. This has later been corrected to 0.008 m ns$^{-1}$ (Sand and Bruland 1998). The latter figure agrees well with the increase in *a*-value (in the same density range) of 0.006 m ns$^{-1}$ calculated with Eq. (17).

Different antennas were used for the field and laboratory experiment. High frequency antennas are preferable for moderate and low *SWE*-values since they give high resolution and 1200 MHz antennas were used for the field experiment. The laboratory experiment required separate transmitter and receiver antennas and the 1200 antennas were built in one unit. We used separate transmitter and receiver antennas with 450 MHz for the laboratory experiment. The frequencies used by Ulriksen (1982; 85) and Bruland and Sand (1996) were 900 and 500 MHz respectively. Since $K_{DS}$ is almost independent of frequency between a few MHz and ≈10 GHz (Denoth 1994) there should not be any discrepancies caused by the differences in radar - wave frequency.

Annan *et al.* (1994) also sketched a method to determine *SWE* from radar measurements. They used a mixing model called CRIM (Complex Refractive Index Model) described by Birchak *et al.* (1974).

Killingtveit and Sand (1988) investigated the effect of snow density and liquid water content on *SWE* determined with radar technology. They studied the discrepancies $\Delta SWE$ between $SWE_{RAD}$ determined with Eq. (1) and $SWE_{SURV}$. They failed to establish relationships between D*SWE* and $\rho_S$ or $\Theta_W$. The *a*-value increases when

Table 1 – Calculated *a*-values for dry snow with different densities using different expressions for the dry snow dielectric constant $K_{DS}$. Average *a*-value and range of variation between the different expressions.

| density (kg m$^{-3}$) | $K_{DS}$-value from Looyenga (1965) | Denoth (1989; 94) | Sihovola & Tiuri (1986) | Roth *et al.* (1990) | Average and range |
|---|---|---|---|---|---|
| 300 | 0.0363 | 0.0354 | 0.0358 | 0.0359 | 0.0359 ± 0.0004 |
| 350 | 0.0410 | 0.0400 | 0.0405 | 0.0405 | 0.0405 ± 0.0005 |
| 400 | 0.0454 | 0.0443 | 0.0448 | 0.0448 | 0.0448 ± 0.0006 |
| 450 | 0.0495 | 0.0483 | 0.0488 | 0.0489 | 0.0489 ± 0.0006 |
| 500 | 0.0533 | 0.0521 | 0.0526 | 0.0527 | 0.0527 ± 0.0006 |
| 550 | 0.0569 | 0.0558 | 0.0562 | 0.0563 | 0.0563 ± 0.0006 |
| 600 | 0.0603 | 0.0592 | 0.0596 | 0.0597 | 0.0597 ± 0.0006 |

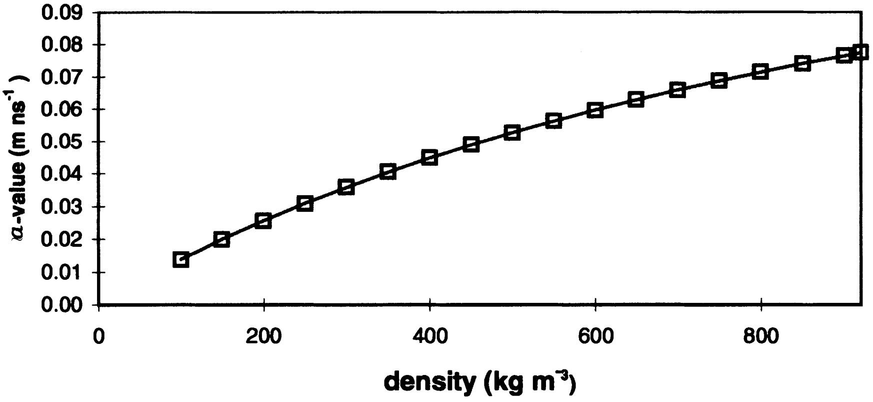

Fig. 4. The *a*-value in Eq. (1) as function of dry snow density derived from the dielectric mixing model (Eq. (8)) used by Roth *et al.* (1990) with $\alpha = 0.5$

the density increases but the *a*-value decreases when the liquid water content increases (this can be derived from Eqs. (7) and (15)). Since melt of the snowpack is often associated with compacting these two effects may partly cancel each other. This might be an explanation to the difficulties for Killingtveit and Sand (1988) to establish relationships between $\Delta SWE$ and $\rho_S$ or $\Theta_W$.

## Conclusions

The dielectric constant of dry snow can be estimated as: $K_{SD} = (1 + c_1\rho_S)^2$ where the constant $c_1 = 0.000851$ was calculated from $\rho_I$ and $K_I$ according to $c_1 = (\sqrt{K_I} - 1)/\rho_I$. *SWE* for dry snow (measurements from snow surface) can be calculated from *twt* us-

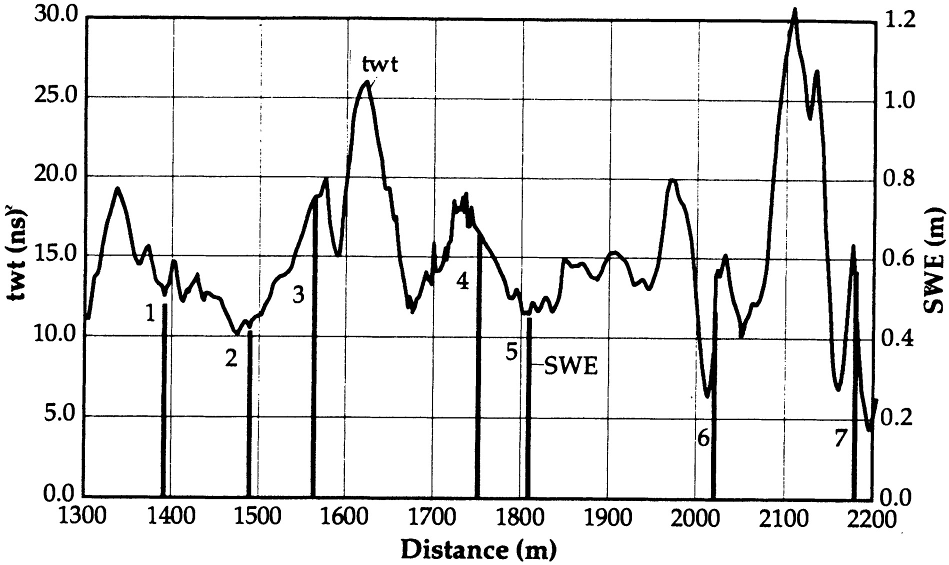

Fig. 5. Measured $twt$ and $SWE_{RAD}$ calculated from $twt$ with $a$ = 0.040 m ns$^{-1}$ compared with $SWE_{SURV}$ determined with snow-surveys at 7 points. (Wikström 1998, personal communication).

Point no 1: $SWE_{SURV}$ = 0.483 m; $twt$ = 12.54 ns; $\rho_s$ = 325 kg m$^{-3}$; $d$ = 1.47m; $SWE_{RAD}$ = 0.478 m;
Point no 2: $SWE_{SURV}$ = 0.417 m; $twt$ = 10.55 ns; $\rho_s$ = 329 kg m$^{-3}$; $d$ = 1.27 m; $SWE_{RAD}$ = 0.418 m;
Point no 3: $SWE_{SURV}$ ≡ 0.756 m; $twt$ ≡ 18.79 ns; $\rho_s$ ≡ 436 kg m$^{-3}$; $d$ ≡ 1.73 m; $SWE_{RAD}$ ≡ 0.754 m;
Point no 4: $SWE_{SURV}$ = 0.658 m; $twt$ = 16.45 ns; $\rho_s$ = 372 kg m$^{-3}$; $d$ = 1.77 m; $SWE_{RAD}$ = 0.658 m;
Point no 5: $SWE_{SURV}$ = 0.451 m; $twt$ = 11.34 ns; $\rho_s$ = 347 kg m$^{-3}$; $d$ = 1.30 m; $SWE_{RAD}$ = 0.451 m;
Point no 6: $SWE_{SURV}$ ≡ 0.471 m; $twt$ ≡ 11.78 ns; $\rho_s$ ≡ 337 kg m$^{-3}$; $d$ ≡ 1.40 m; $SWE_{RAD}$ ≡ 0.472 m;
Point no 7: $SWE_{SURV}$ = 0.598 m; $twt$ = 14.69 ns; $\rho_s$ = 353 kg m$^{-3}$; $d$ = 1.70 m; $SWE_{RAD}$ = 0.600 m.

ing the relationship: $SWE = a\,twt$ (m), where $a = 1.5 \times 10^{-4}\,\rho_S/(1 + c_1\rho_S)$ m ns$^{-1}$ with $twt$ given in nanoseconds. For dry snow with a density of 350 kg m$^{-3}$ (a typical value at the end of the accumulation season in the Nordic countries) $a$ becomes 0.0040 m ns$^{-1}$. A density of 300 and 400 kg m$^{-3}$ gives $a$ = 0.036 m ns$^{-1}$ and 0.045 m ns$^{-1}$ respectively. The $b$-value in Eq. (1) determined from regression analysis of simultaneous measurements of $SWE$ and $twt$ should equal zero when the determination of radar-wave entrance into snowpack is accurate.

One of the advantages with using radar technology to determine $SWE$ is that time and manpower consuming manual methods to determine snow depth and density can be avoided. If density measurements need to be included this advantage is partly lost. However since density variations are much smaller than depth variations (Fig. 5) the radar technology is still of large use but a few density determinations should be made in conjunction with the radar measurement in order to increase the accuracy of the predictions of $SWE$. The superiority of radar measurements compared to snow surveys can be illustrated by Fig. 5. It is obvious that the large variation in snow depth and *SWE* can not be described by a few manual measurements. A line average determined from the 7 measurement points gave an average *SWE* of 0.550 m for the radar measurements and 0.548 m from the snow surveys, while the 900 digitised radar measurements gave *SWE* = 0.604 m. It is not surprising that an average based on 900 measurements is much better than an average based on 7 measurements when working with highly varying snow-depths. A typical value of snow-depth autocorrelation in mountainous terrain for a distance of 0.25 m is ≈ 0.4 (Faanes and Kolberg 1996). For the survey presented in Fig. 5 the *twt*-values were determined using an automatic ground probing radar system (COBRA-SNOW) developed for airborne snow-pack surveys (Wikström 1998, personal communication). For this survey an average density of 350 kg m$^{-3}$ ($a \equiv 0.040$ m ns$^{-1}$) was used and no improvement in fit between measured and calculated *SWE*-values was achieved by using measured densities (*e.g.* $\rho_S$ for point 3 seems unrealistically high).

If possible, snow radar measurements should be restricted to periods with no liquid water in the snow since also rather small $\Theta_W$ will influence the *a*-value and hence the measured *SWE*. If this is not possible the *a*-value should be corrected for the liquid content. A further study where the influence of liquid water content on *twt*, *a*-value and *SWE* will be investigated is planned.

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**Address:**
A. Lundberg, Water Res. Eng.,
H. Thunehed, Applied Geophysics,
Luleå University of Technology,
SE-97187 Luleå, Sweden

Email: angela.lundberg@sb.luth.se

J. Bergström,
Force Institut,
Karbingatan 30,
SE-25467 Helsingborg,
Sweden.