

Field evaluation of a new method for estimation of liquid water content and snow water equivalent of wet snowpacks with GPR

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ABSTRACT

Estimates of snow water equivalent (SWE) with ground-penetrating radar can be used to calibrate and validate measurements of SWE over large areas conducted from satellites and aircrafts. However, such radar estimates typically suffer from low accuracy in wet snowpacks due to a built-in assumption of dry snow. To remedy the problem, we suggest determining liquid water content from path-dependent attenuation. We present the results of a field evaluation of this method which demonstrate that, in a wet snowpack between 0.9 and 3 m deep and with about 5 vol% of liquid water, liquid water content is underestimated by about 50% (on average). Nevertheless, the method decreases the mean error in SWE estimates to 16% compared to 34% when the presence of liquid water in snow is ignored and 31% when SWE is determined directly from two-way travel time and calibrated for manually measured snow density.

Key words | ground-penetrating radar, liquid water content, path-dependent attenuation, radar wave propagation velocity, snow water equivalent, wet snow

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INTRODUCTION

Information on seasonal and glacier snow covers is of great interest for many reasons. A large fraction of the world's population, about 17%, depend on meltwater from glaciers or from seasonal snow covers on large mountain ranges (e.g. in the Himalaya and in the Andes; see [Barnett *et al.* \(2005\)](#)) for their water supply. In the Arctic regions, up to 80% of the river water flow emanates from snow melt ([König & Sturm 1998](#)); in the Austrian Alps, this fraction amounts to 60% ([Escher-Vetter *et al.* 2009](#)). Moreover, some of the most severe precipitation-based floods result from rain-on-snow events ([Jones & Perkins 2010](#)).

Current global warming, which mainly affects conditions at high altitudes, also actualizes the need for information about snow covers. Characterization of snowpacks has therefore become of interest in many scientific areas. It is vital, for example, for understanding climate feedback ([Bavay *et al.* 2009](#)) and frost penetration processes ([Lindström *et al.*](#)

[2002](#)); for estimation of polar and glacier ice mass budgets (e.g. [Richardson *et al.* 1997](#)); for hydropower management applications ([Laukkanen 2004](#)); for flood forecasts and flood prevention (e.g. [Jones & Perkins 2010](#)); and for avalanche risk assessment ([Bebi *et al.* 2009](#)). Snow information is also important for the prediction of various aspects of ecosystems, such as the accessibility of forage for birds of prey, small mammals, reindeers, etc. ([Jones *et al.* 2001](#)).

Distributed data on snow depth and density and snow water equivalent (SWE) with a high spatial and temporal resolution are essential for validation of snow drift models (e.g. [Prokop *et al.* 2008](#)) and runoff snow models (e.g. [Lindström *et al.* 2010](#)). At the same time, validation of regional and global climate models relies on snow information with lower demands on spatial resolution.

There is therefore a great need for distributed snow data, mainly for SWE data but also for snow depths,

density and stratigraphy, from many stakeholders. Such data can vary substantially both in space and time; for example, the spatial variability is influenced by a variety of factors such as altitude, latitude, slope angle, wind and solar radiation exposure, vegetation, etc. (Lundberg *et al.* 2010). However, today's measurement techniques do not meet the demands on distributed snow data. The traditional manual measurements are quite accurate but are typically labour intensive and time consuming. When measuring from satellites, airplanes or unmanned aircrafts, large areas can be covered quickly but the results have low accuracy; such methods are therefore dependent on ground-based measurement techniques for calibration and validation (Lundberg *et al.* 2010).

Ground-penetrating radar (GPR) has the potential to provide such ground-based measurements. In a GPR survey, electromagnetic waves propagate through the snowpack and are reflected from the snow/ground interface (or from layers within the snowpack); snow depth and density, and thereby also SWE, are traditionally estimated from the two-way travel time of the radar signal. If a radar system is operated from a vehicle such as a helicopter or a snowmobile, transects of snow depth and SWE can be obtained relatively quickly (Andréasson *et al.* 2001; Marchand *et al.* 2001; Yankielun *et al.* 2004; Marchand & Killingtveit 2005; Machguth *et al.* 2006).

When SWE is estimated from radar wave two-way travel time, the linear function used for estimation should be calibrated for density of a particular snowpack which requires one or several manual measurements (e.g. Sand & Bruland 1998; Lundberg *et al.* 2000). In addition, this method typically suffers from low accuracy when snow contains even a small amount of liquid water (Lundberg & Thunehed 2000) since radar wave propagation velocity, and hence the travel time, is highly dependent on the liquid water content. This presents a problem because, in a significant number of cases, SWE measurements have to be conducted on wet snowpacks.

To avoid laborious and time-consuming manual measurements, snow depth and density can be estimated directly from radar data if radar wave propagation velocity is known (which can be obtained, for example, with the common mid-point (CMP) method). While

snow depth can be estimated from velocity and two-way travel time, density is estimated using some empirical formula that includes ice, air and liquid water content in snow (e.g. Sihvola 1999). Hence SWE can be determined if liquid water content is known or can be assumed to be zero. It is therefore highly desirable to be able to estimate liquid water content directly from radar data.

At least two different methods have been proposed in recent years, with liquid water content estimated from radar wave attenuation in snow. One method relies on measuring the frequency-dependent attenuation of radar waves to estimate liquid water content (Bradford & Harper 2006; Bradford *et al.* 2009). Bradford *et al.* (2009) tested this method on a 1.2-m-thick snowpack with average liquid water content of 1.4 vol%, and the absolute uncertainty in liquid water content was limited to 0.5 vol%. The other method is based on comparing attenuation of two radar waves travelling along different paths through the snowpack but sharing a single reflection point on the ground (Granlund 2009; Sundström *et al.* 2012); this approach is referred to as the path-dependent attenuation (PDA) method.

We present the results of a field experiment conducted to investigate applicability of the PDA method during snowmelt, which was the first field evaluation of the method (for earlier simulations of the method see Sundström *et al.* (2012)). The snowpack in the experiment was characterized by liquid water content of around 5 vol% and the snow depth varied from about 0.9–3 m. Radar data were collected using a multi-channel GPR system with ground-coupled antennas with nominal frequencies of 800 MHz; this radar setup allowed us to obtain a CMP gather at each measurement point. Evaluation of the method was performed by comparing the values of SWE (i.e. snow depth and density) estimated with the PDA method (method A), radar-only estimation with liquid water content assumed to be zero (method B) and the traditional method based on a linear relationship between SWE and two-way travel time, calibrated for manually measured snow density (method C). Estimated values of SWE were also compared to reference values obtained by manual measurements with a snow tube.

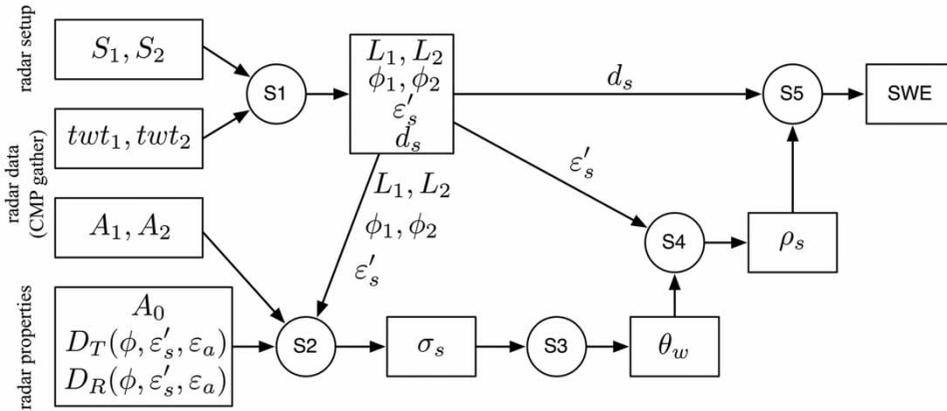


Figure 1 | SWE estimation with the PDA method for a particular measurement point, from two radar waves travelling different paths through the snow but sharing the same reflection point at the ground (S1–S5: calculation steps 1–5).

ESTIMATING SWE WITH GROUND-PENETRATING RADAR

This section describes how SWE of a wet snowpack can be determined from radar wave data using the three different methods compared in the field experiment.

Method A: PDA

For each measurement point, SWE is estimated with the PDA method as follows (see also Figure 1).

Step 0: determining two-way travel time and amplitude from radar data

Two-way travel time twt (ns) of a radar wave is determined for each trace by identifying the maximum of the main lobe (Figure 2) of the snow/ground reflection in a radargram (Figure 3) and then performing time-zero correction.

The amplitude A of a radar wave (an input to the PDA method) is determined from the analytic signal (AS) of each radar trace $f(t)$:

$$AS(t) = f(t) + i.H(f)(t) \tag{1}$$

i.e. the real part of AS is the trace itself and the imaginary part is its Hilbert transform. The instantaneous amplitude $A_{inst}(t)$ (also called amplitude envelope or reflection

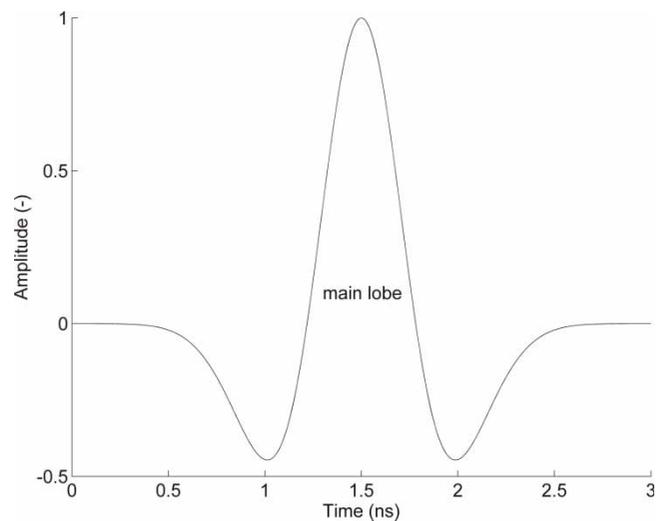


Figure 2 | The main lobe of the Ricker wavelet, which is a good approximation of a typical impulse radar signal.

strength) is calculated as the absolute value of AS :

$$A_{inst}(t) = |AS(t)| \tag{2}$$

The instantaneous amplitude (which is equivalent to the envelope function of the radar trace) is a robust, smoothed, polarity-independent measure of the energy in the trace at a given time (Robertson & Nogami 1984). The amplitude of a radar wave is therefore defined as the instantaneous amplitude picked at the peak (t_{peak}) of the envelope function within a time gate ($t_0 - \delta, t_0 + \delta$) around t_0 , the location of the main lobe of the reflected

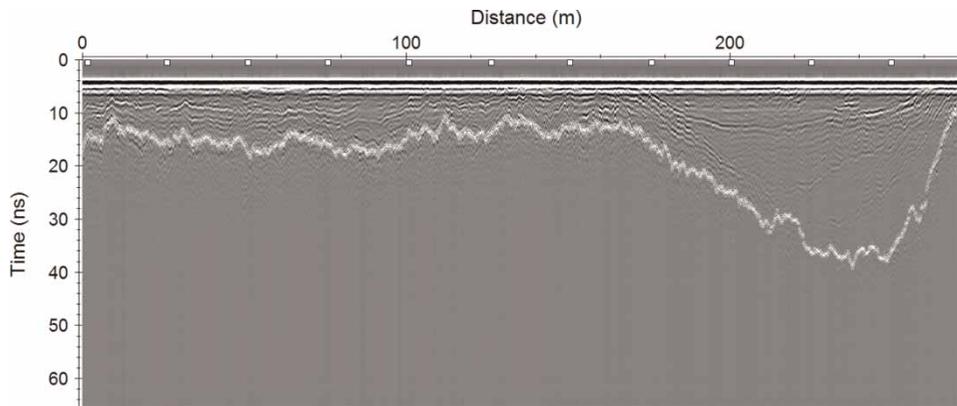


Figure 3 | A radargram from the field experiment, with reflection from the snow/ground interface marked in white.

wave, with the time gate chosen so that it roughly corresponds to the size of the main lobe.

Note that t_{peak} , the location of the peak of the envelope function, is determined from AS which is calculated after an approximate correction for spherical spreading of the wave, performed by scaling the amplitudes by time (Bradford *et al.* 2009). However, the actual input to the PDA method is chosen as the instantaneous amplitude at the same location t_{peak} but taken from the envelope function calculated without such correction, since the PDA method itself includes a more accurate correction for geometrical spreading.

Step 1: calculating snow depth, travel path lengths, incidence angle at the snow/ground interface and the real part of electrical permittivity of snow from a CMP gather

From distances between the antennas S_1 and S_2 (m) and from two-way travel times of radar waves in the CMP gather at each measurement point along a transect, the effective radar wave propagation velocity v (m s^{-1}) and the snow depth d (m) can be estimated with the CMP method under the assumption of a single-layered snowpack with parallel snow and ground surfaces. Under the same assumption, the travel path lengths L_1 and L_2 (m) and the incidence angles at the snow/ground interface ϕ_1 and ϕ_2 (rad) for each radar measurement in the CMP gather is obtained from the geometry of the ray path. Finally, the real part of the effective relative electrical permittivity

of snow is calculated as $\epsilon'_s = c^2 / (v^2 \mu_s)$ where c is the speed of light in vacuum (m s^{-1}) and $\mu_s \approx 1$ is the relative magnetic permeability of snow.

Step 2: calculating electrical conductivity of snow from two radar signals

For ground-coupled radar antennas (placed directly on the snow surface) and with relative magnetic permeability of snow assumed to be equal to unity, the resulting amplitude of a wave travelling through a homogeneous snowpack to the ground and back can be expressed as (Cai & McMechan 1995):

$$A = \frac{A_0 D_T D_R R}{G} e^{-\alpha L} \quad \text{where} \quad \alpha \approx \frac{\sigma_s}{2} \sqrt{\frac{\mu_0}{\epsilon_0 \epsilon'_s}} \quad (3)$$

A_0 is effective source amplitude; D_T and D_R are directivity of the transmitter and receiver antennas; G is geometrical spreading of radar waves; R is reflectivity of the snow/ground interface; L is the length of radar wave travel path in snow (m); ϵ'_s is the real part of effective relative electrical permittivity of snow; and σ_s is real effective electrical conductivity of snow (S m^{-1}) (effective values are used to account for possible inhomogeneity). The constants μ_0 ($\text{Vs A}^{-1} \text{m}^{-1}$) and ϵ_0 ($\text{As V}^{-1} \text{m}^{-1}$) are magnetic permeability and electrical permittivity of free space, respectively.

The directivity terms for the transmitter and receiver antenna together with the effective source amplitude should be derived experimentally for specific radar

equipment as a function of the transmission/reception angle and the electrical permittivity of snow. This can be done by establishing the corresponding term in air $A_0D[\text{air}]$ and correcting for focusing or dispersion that occurs when antennas are placed directly on the snow surface. Using a simple model obtained from Snell's law, for a spherical radar wave we have:

$$A_0D = \begin{cases} A_0D[\text{air}] \frac{1}{\sqrt{1 - \cos(\arcsin \sqrt{\varepsilon_a/\varepsilon'_s})}} & \text{for } \varepsilon'_s > \varepsilon_a \\ A_0D[\text{air}] \sqrt{1 - \cos(\arcsin \sqrt{\varepsilon_a/\varepsilon'_s})} & \text{for } \varepsilon'_s \leq \varepsilon_a \end{cases} \quad (4)$$

where ε_a is the electrical permittivity of the antenna housing.

Geometrical spreading in a homogeneous medium is usually assumed to be proportional to the distance travelled from the transmitter; we assume $G = 2\sqrt{\pi}L$. The reflectivity of the snow/ground interface is given by Fresnel's equations, separately for *s*- and *p*-polarized radar waves. (Electric field vectors of *p*-polarized waves are parallel to the plane of incidence and those of *s*-polarized waves are perpendicular to the plane of incidence; Reitz *et al.* (1993). In radar applications, polarization depends on the radar antenna setup.) Using Snell's law, geometrical spreading can be expressed as a function of the incidence angle at the snow/ground interface ϕ (rad) and relative electrical permittivity of the ground $\varepsilon_{\text{ground}}$ (Reitz *et al.* 1993). Combining the equation for *s*-polarized waves (which was the case for the radar setup in our field experiment) with Equation (3), effective electrical conductivity of snow can be expressed as a function of relative electrical permittivity of the ground:

$$\sigma_s = -\frac{2}{L} \sqrt{\frac{\varepsilon_0 \varepsilon'_s}{\mu_0}} \ln \left(\frac{AG}{A_0 D_T D_R} \left| \frac{\cos \phi + \sqrt{\varepsilon_{\text{ground}}/\varepsilon'_s - \sin^2 \phi}}{\cos \phi - \sqrt{\varepsilon_{\text{ground}}/\varepsilon'_s - \sin^2 \phi}} \right| \right) \quad (5)$$

Equation (5) contains two unknowns: effective electrical conductivity of snow and electrical permittivity of the ground. With resulting amplitude, travel path length and incidence angle at the snow/ground interface determined in steps 0 and 1 for two different radar signals in a CMP gather, a

system of two equations is obtained for each measurement point. This system can be solved numerically to determine σ_s by investigating $\varepsilon_{\text{ground}}$ in the expected range from 3 (frozen ground) to 87 (liquid water at 0 °C), in steps of 0.1, choosing the value with the minimum error in σ_s .

Step 3: calculating liquid water content

We know that $\sigma_s = \sigma_{\text{dc}} + \varepsilon''_s \omega$, where σ_{dc} is the direct-current electrical conductivity, ε''_s is the imaginary part of electrical permittivity of snow and ω is the angular frequency of a radar wave (rad s^{-1}). In GPR studies of snow, it is generally assumed that $\sigma_{\text{dc}} \approx 0$. Liquid water content can then be determined from ε''_s and the imaginary part of electrical permittivity of water ε''_w (Tiuri *et al.* 1984):

$$\varepsilon''_s = (0.10 \theta_w + 0.80 \theta_w^2) \varepsilon''_w \quad (6)$$

where θ_w is volumetric liquid water content.

Equation (6) is valid for the radar frequency of 1 GHz, where $\varepsilon''_w = 9$, but it can also be used with other frequencies if the electrical permittivity of snow is scaled to 1 GHz (Tiuri *et al.* 1984). An alternative to using Equation (6) is to use another experimentally obtained relationship between electrical conductivity of snow and liquid water content, for example one established for a nominal frequency of 800 MHz by Granlund *et al.* (2010).

Step 4: calculating snow density

A number of empirical equations have been suggested for the relation between electrical permittivity and density of wet snow, and the review by Frolov & Macheret (1999) showed that most of them are comparable. Using the equations by Tiuri *et al.* (1984), density of snow in the pendular regime (i.e. snow with the presence of liquid water where air exists in continuous paths and the grain-grain bounds are strong; Singh & Singh (2001)) can be determined from volumetric liquid water content θ_w (vol%) and the real part of electrical permittivity of snow via 'dry density' of snow ρ_d (relative density of dry snow compared to water) and equivalent dry snow permittivity ε'_d :

$$\rho_s = (\rho_d + \theta_w) \rho_w \quad (7)$$

$$\varepsilon'_d = 1 + 1.7\rho_d + 0.7\rho_d^2 \quad (8)$$

$$\varepsilon'_s = (0.10\theta_w + 0.80\theta_w^2)\varepsilon'_w + \varepsilon'_d \quad (9)$$

where ε'_w is the real part of electrical permittivity of water; ρ_w is water density (kg m^{-3}); and ρ_s is snow density (kg m^{-3}). Similarly to Equation (6), Equation (9) is valid for the radar frequency of 1 GHz where $\varepsilon'_w = 87$ at 0°C , but it can also be used for other frequencies if the measured electrical permittivity of snow is scaled to 1 GHz (Tiuri *et al.* 1984). Note that in the range from 1 MHz to 2 GHz, the real part of electrical permittivity is approximately frequency independent (Bradford *et al.* 2009).

Step 5: calculating SWE

With snow depth and density known, SWE (m) is calculated as:

$$\text{SWE} = \frac{d\rho_s}{\rho_w} \quad (10)$$

Method B: estimation of SWE under the assumption of dry snow

This method is very similar to the PDA method but the liquid water content is set to zero:

- two-way travel time is determined from radar data;
- snow depth and the real part of electrical permittivity of snow are obtained from a CMP gather;
- snow density is calculated using Equations (7)–(9) with liquid water content set to 0; and
- SWE is calculated using Equation (10).

Method C: estimation of SWE from radar wave two-way travel time (with calibration for snow density)

This method represents a group of traditional methods where SWE (m) is estimated directly from radar wave two-way travel time twt (ns), which requires only one radar channel. We use the linear formula from Lundberg *et al.* (2000),

further investigated by Lundberg & Thunehed (2000):

$$\text{SWE} = \frac{1.5 \times 10^{-4} \rho_s}{1 + (8.51 \times 10^{-4} \rho_s)} twt \quad (11)$$

The relation between SWE and two-way travel time should therefore be calibrated for snow density ρ_s (kg m^{-3}) which can be obtained, for example, with one or several manual measurements per measurement line; it could also be estimated from radar wave propagation velocity using mixture formulae such as Equations (7)–(9). In the experiment, ρ_s was calculated as the mean value of manually measured snow density at eleven reference points.

THE FIELD EXPERIMENT

The location of the experiment was in the watershed of the Lake Korsvattnet ($63^\circ 50' \text{ N}$; $13^\circ 30' \text{ E}$) in the Swedish mountains in the county of Jämtland (in sub-Arctic). The measurement site was well above the tree line at about 750 m above sea level. The measurement line was 250 m long, heading uphill on the southeast side of a mountain. The slope was very moderate along the first 150 m and the snow depth was around 1 m. The slope was steeper at the end of the line, but a snowmobile could still easily be driven at a constant low speed. Further, it was obvious that the maximum snow depth in the last third of the line was quite large (several metres), allowing for testing of the PDA method at larger snow depths.

The experiment was conducted on 19 April 2011 from 10:00 to 12:30 and included one set of radar measurements and manual measurements at reference points. The relatively short time frame should decrease the risk of a change in snow properties between radar and manual measurements. The sun was shining during the whole experiment and the air temperature was about 5°C . The air temperature had been above zero at daytime for several weeks, but the night before the experiment the temperature dropped below zero. This resulted in a wet snowpack (the average value of liquid water content at each reference point was about 5–7 vol% according to snow fork measurements) with drier snow at the top (about 2 vol%). The

snowpack was assumed to be in the pendular regime (liquid water content in the range 3–8 vol%; see Singh & Singh (2001)). It should however be noted that some measurements of liquid water content at each reference point were outside this range.

Radar measurements were conducted along a single line with total measurement time of about 5 minutes; the measurements can therefore be assumed to have been conducted at the same time. In addition, at the start of the experiment the sledge was lifted in the air to obtain reference radar measurements for time-zero correction (the time of the first arrival is unknown in raw radar data and has to be determined).

Reference measurements of SWE and liquid water content were conducted along the measurement line at points separated by 25 m. Snow depth and density were measured with a snow tube (Federal Snow Sampler), with three measurements conducted in near proximity of each reference point and average values used in calculations of SWE.

Reference measurements of liquid water content were taken using a snow fork which, for the range of liquid water content in the experiment, has relative error of less than 5% (Sihvola & Tiuri 1986). Measurements were taken in vertical steps of 2 cm for the first 20 cm from the top and then in steps of 5 cm. The length of the snow fork was 1.5 m and hence no liquid water content measurements beneath that depth were obtained. At the last three points along the profile (at 200, 225 and 250 m), the deepest measured value of liquid water content was used for the whole segment below 1.5 m. This probably resulted in an overestimation of the total liquid water content, as we would expect the snow to be drier at larger depths. The values of liquid water content at different depths were aggregated into a single value representing the whole snowpack. Only one measurement profile was taken at each reference point, since performing multiple measurements would substantially increase the total measurement time and hence the risk of a change in snow properties between radar and manual measurements.

Radar setup and properties

Radar measurements were conducted on four radar channels using a multi-channel RAMAC/GPR system from

Malå Geoscience, with shielded antennas with a nominal frequency of 800 MHz. Sampling frequencies of about 16 GHz and time windows of about 65 ns were used; these settings were chosen to achieve the best possible resolution of radar data without risking overloading the system or missing the snow/ground reflection.

The antennas were placed in a wooden sledge to form a multi-offset antenna array. The setup allowed us to conduct CMP measurements with antenna offsets of 14, 60, 124 and 198 cm. The measurements were conducted by drawing the sledge behind a snowmobile at a constant low speed and were triggered with a hip chain every 23 cm. There was therefore a potential deviation between the points of the manual measurements and the corresponding GPR measurement of up to 23 cm. However, with a radar footprint of about 80–90% of snow depth, this should not substantially affect our results.

For the radar equipment used in the experiment, relative electrical permittivity of the antenna housing (ABS plastic) was $\epsilon_a = 3.8$. The term combining the effective source amplitude with the transmitter and receiver directivity in air A_0D [air] had been determined in a separate experiment as a function of the transmission/reception angle ϕ (rad) in the interval (0° , 60°):

$$A_0D[\text{air}](\phi) = 10^3(75\phi^3 - 163\phi^2 + 22\phi + 112) \quad (12)$$

(see Figure 4 and Equation (12); Granlund (2009)). The transmission and the reception angles are assumed to be equal in the PDA method; they were also equal in our experiment.

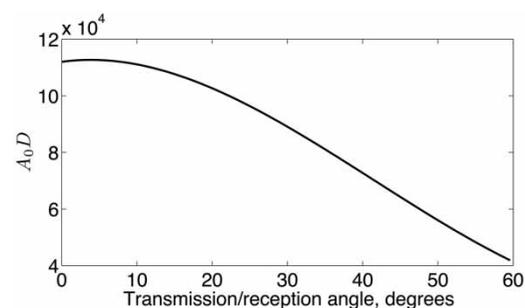


Figure 4 | The term combining effective source amplitude and directivity as a function of the angle of transmission and reception, obtained for radar waves travelling through air.

Analysis of radar data

Both the PDA method (method A) and method B include determination of *both* radar wave propagation velocity and snow depth from radar data using the CMP method. However, in our evaluation of the PDA method we only considered the points where manual measurements of snow depth were conducted. This allowed us to obtain a more accurate estimate of velocity by considering two-way travel time from the four available radar channels; the value of velocity that gave the least-square error sum in snow depth (compared to the manually measured depth) was chosen. Snow depth (used as an input to methods A and B) was then determined from the radar wave propagation velocity and the travel time for the radar channel with an antenna separation of 0.14 m. This approach allowed us to exclude errors due to CMP measurements and focus on how the accuracy of the obtained liquid water content influences the SWE estimates. Note also that to attenuate noise in two-way travel time, a running average over five consecutive measurement points (spanning a distance of 92 cm) was applied (this was done for all three methods).

SWE (and liquid water content for the PDA method) were determined as described in ‘Estimating SWE with GPR’ with the following additions.

Method A: PDA

- To attenuate noise in the amplitude, a running average over five consecutive measurement points (spanning a distance of 92 cm) was applied; this roughly corresponds to the minimum radar footprint on the snow/ground interface in this particular experiment.
- For each point along the measurement line, a system of two equations (Equation (5)) was set up for two measurements in a CMP gather with antenna offset of 14 and 198 cm.
- The value of 1 GHz was used as the radar frequency since the mean frequency of the transmitters and the receivers was close to 1 GHz. No scaling of the real or the imaginary part of electrical permittivity was therefore performed.
- Any negative values of liquid water content were set to zero before calculating SWE.

Method B: estimation of SWE under the assumption of dry snow

Since the mean frequency of the transmitters and the receivers was close to 1 GHz, no scaling of the real part of electrical permittivity was performed.

Method C: estimation of SWE from radar wave two-way travel time (with calibration for snow density)

To calibrate the relationship between SWE and two-way travel time (Equation (11)), the mean value of all the manually measured snow densities at the reference points was used.

Errors in SWE estimated with the PDA method are likely to be caused by incorrectly determined velocity, approximation errors in the mixture formulae, i.e. Equations (7)–(9), or otherwise incorrectly determined liquid water content (due to invalid assumptions about the snow surface being parallel to the ground surface and a single-layered snowpack; Sundström *et al.* (2012)). To investigate the origin of errors, two additional tests were conducted. In the first test, snow density for each reference point was determined using Equations (7)–(9) from liquid water content measured with the snow fork, SWE was calculated from snow density and the error in SWE (compared to reference measurements of SWE) was determined. In the second test, we used Equations (7)–(9) to determine the liquid water content at each reference point that would produce the correct value of SWE.

RESULTS

With radar wave propagation velocity obtained from manually measured snow depth and two-way travel times (for the four available radar channels), the error in snow depth varies from –2 to 1% (Table 1). Snow depth is estimated from the velocity and two-way travel time for the radar channel with antenna separation 0.14 m. The propagation velocity is generally in the range 0.19–0.20 m ns⁻¹ except for two points (at 25 and 150 m) where the velocity is 0.22 and 0.21 m ns⁻¹, respectively (Table 1).

Table 1 | Radar wave propagation velocity at the reference points obtained from manually measured snow depth and two-way travel times for the four available radar channels. Snow depth estimated from the velocity and the two-way travel time for the radar channel with antenna separation 0.14 m is also given, together with the relative error in snow depth (compared to the reference values)

Point (m)	Reference depth (m)	Estimated velocity (m ns ⁻¹)	Estimated depth (m)	Relative error in depth (%)
0	1.01	0.19	1.01	0
25	1.30	0.22	1.27	-2
50	1.30	0.19	1.31	1
75	1.12	0.19	1.12	1
100	1.00	0.20	1.00	0
125	0.89	0.19	0.90	0
150	0.86	0.21	0.87	1
175	1.15	0.19	1.15	1
200	2.01	0.19	2.00	-1
225	3.20	0.20	3.20	0
250	3.06	0.19	3.06	0

Manual snow tube measurements of snow density are in the range 377–536 kg m⁻³, while the range of density estimates obtained with the PDA method is much wider: 304–646 kg m⁻³ (Table 2). Manual snow fork measurements of

liquid water content are in the range 2.6–7 vol%, while most estimates with the PDA method are in the range 1.7–4 vol% with 3 out of 11 measurements producing values equal or close to 0 vol% (Table 2). Notably, while the estimates of snow densities are both over- and underestimated compared to the reference measurements, all values of liquid water content are underestimated (Table 2 and Figure 5). On average, the PDA method overestimates snow density by 16% and underestimates liquid water content by 51%.

Table 2 also includes the values of liquid water content that, combined with radar wave propagation velocity obtained using all available radar channels and manually measured snow depth, produce correct values of SWE for each measurement point. In this case, the difference between the calculated liquid water content and the snow fork measurements is much smaller (about -12% on average). Moreover, if the two points where the calculated water content is negative are excluded, the average difference is only about 6%. This suggests that the main error in the estimates of SWE with the PDA method lies in the liquid water content determination. However, since the radar wave propagation velocities were estimated using

Table 2 | Reference values of snow depth, density and liquid water content (LWC); snow density and liquid water content estimated using the PDA method; and relative estimation errors. For depth and density, an average of three manual measurements is presented for each reference point together with the standard deviation

Point (m)	Reference measurements					Estimation from radar data					
	Depth (m)	Std dev (cm)	Density (kg m ⁻³)	Std dev (kg m ⁻³)	LWC (vol%)	Density (kg m ⁻³)	Rel. error in density (%)	LWC (vol%)	Rel. error in LWC (%)	LWC ^b (vol%)	Rel. error in LWC ^b (%)
0	1.01	0.5	512	14	5.3	568	11	2.5	-53	3.8	-21
25	1.30	0.5	446	11	4.0	304	-32	3.2	-21	-1.1	-129
50	1.30	0.8	491	31	7.0	643	31	2.4	-66	5.6	-20
75	1.12	0.5	454	11	4.8	601	32	3.4	-28	6.2	30
100	1.00	2.6	377	22	5.2	581	40	0 ^a	-100	4.2	-20
125	0.89	3.3	417	15	5.2	479	15	4.9	-6	5.9	14
150	0.86	2.9	536	18	4.2	346	-35	4.4	-6	-0.1	-101
175	1.15	0.9	471	11	4.9	597	27	3.8	-22	6.1	26
200	2.01	0.9	468	11	5.2	633	35	2.1	-60	5.5	7
225	3.20	4.9	472	10	3.8	609	29	0 ^a	-100	3.8	1
250	3.06	1.4	527	15	2.6	647	23	0.1	-97	3.5	39
Mean error							16		-51		-12

^aNegative values of liquid water content are set to zero.

^bLiquid water content that results in a correct value of SWE.

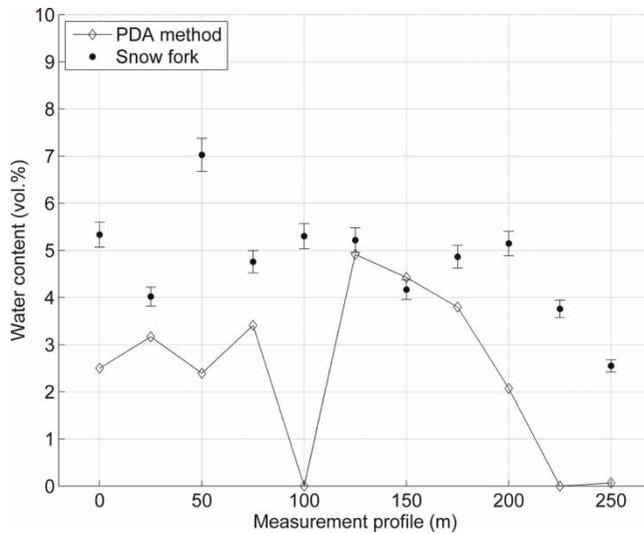


Figure 5 | Estimates of liquid water content (LWC) at the reference points obtained using the PDA method, compared to manual measurements. Negative values of LWC are set to zero. The error bars show the specified measurement accuracy of the snow fork (5%).

the manual snow depth measurements and not with the CMP method, it is also important to recognize that the PDA method is highly sensitive to errors in velocity estimates.

The obtained values of SWE are presented in Figure 6. The mean error in SWE obtained with the PDA method (16%) is smaller than the mean error in SWE calculated based on the assumption of dry snow (method B, 34%) or determined directly from the two-way travel time (method C, 31%) (Table 3). If we consider the differences between the errors at each measurement point and calculate the mean difference between the methods, we can see that:

- the PDA method offers a definite improvement compared to method B; the error in SWE is decreased on average by 18% from 34 to 16%, with 95% confidence interval (8%, 28%); and
- the PDA method's improvement compared to method C is less statistically significant; the error in SWE is decreased by 14% from 31 to 16%, but the 95% confidence interval (1%, 29%) is close to 0.

SWE calculated with the PDA method from manually measured liquid water content is also presented in

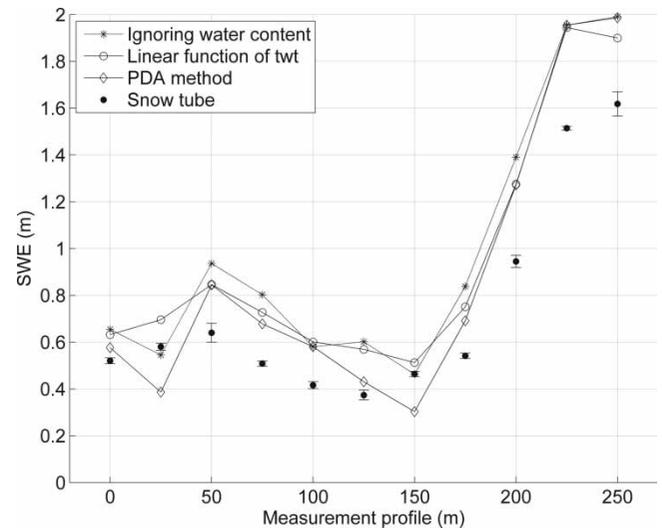


Figure 6 | Reference values and estimates of SWE at the reference points, with SWE estimated with 3 methods: the PDA method; based on the dry snow assumption; and from two-way travel time. The error bars show the standard deviation of the manual snow tube measurements conducted at each reference point.

Table 3. The mean relative error is -6% with a confidence interval from -20 to 8% , which is in line with the previous results that showed how liquid water content estimated to optimize the SWE estimates were close but slightly lower than the snow fork measurements (Table 2). This is further support for the conclusion that the main error in the PDA method is in determination of liquid water content. If water content estimates could be improved, the current accuracy in determining depth and radar wave velocity from the radar data would be adequate to reduce the errors in SWE estimates to below 10% . However, we still need to be able to improve velocity estimates without using manual snow depth data.

DISCUSSION

The results of this study clearly show that neglecting or underestimating liquid water content leads to an overestimation of snow density and SWE when estimated from GPR propagation velocity and two-way travel time. The new PDA method largely improved the SWE estimates compared to the methods neglecting liquid water content. Still, the liquid water content was underestimated by about 51% with the PDA method compared to the snow fork

Table 3 | Reference values of snow depth and SWE at the reference points and relative errors in SWE estimates obtained with the different estimation methods. (A) PDA: SWE estimated with the PDA method investigated in this paper; (B) 'dry snow': SWE calculated with liquid water content set to zero; (C) TWT: SWE obtained using a linear function of two-way travel time; and finally PDA with reference LWC: SWE calculated with manually measured liquid water content as input

Point (m)	Reference measurements		Relative error in SWE (%)			
	Depth (m)	SWE (m)	PDA (Method A)	'Dry snow' (Method B)	TWT (Method C)	PDA with reference LWC
0	1.01	0.52	11	26	21	-13
25	1.30	0.58	-33	-6	20	-44
50	1.30	0.64	32	46	32	-20
75	1.12	0.51	33	58	43	19
100	1.00	0.42	40	40	44	-15
125	0.89	0.37	15	61	52	11
150	0.86	0.46	-35	0	10	-32
175	1.15	0.54	28	55	39	16
200	2.01	0.95	35	47	35	5
225	3.20	1.51	29	29	28	0
250	3.06	1.62	23	23	17	8
Mean error			16	34	31	-6
with 95% confidence interval			(-1, 34)	(19, 49)	(22, 40)	(-20, 8)

measurements, which resulted in a consequent overestimation of snow density and SWE by about 16% (Table 2). Potentially, the remaining errors in liquid water content, snow density and SWE could be due to many reasons such as: incorrectly determined radar wave propagation velocity; absence of common reflection points for the CMP analysis; mixing formula errors; or manual snow depth and snow fork measurement errors. It is important to discuss and eliminate the uncertainty in these aspects as much as possible in order to evaluate the efficiency of the PDA method itself.

From previous studies it is known that CMP estimates of radar wave propagation velocity, and hence relative electric permittivity, are largely uncertain when snow depth is equal to or larger than the maximum antenna separation in a CMP gather. The errors can be both negative or positive (as also shown by the results in this study), but it is more common to get too-low velocities if the CMP analysis involves minimizing the difference in estimated depth between the channels (low velocity results in smaller depth values and thus smaller differences).

In the current analysis, the radar wave propagation velocity was estimated using the observed snow depths; the uncertainty in the velocities thus depends both on the

manual snow depth measurements and on the two-way travel time determination. The estimated velocities at the measurement points 25 and 150 m were somewhat higher than at the other points (0.22 and 0.21 m ns⁻¹, respectively, compared to 0.19–0.20 m ns⁻¹ at the other points); these were also the points with underestimated SWE values, which goes against the general trend of overestimating SWE. Too-high velocity estimates can be due to either too-large snow depth observations or too-low two-way travel time values. The manual snow depth observations were taken as the mean of three snow tube measurements close to the reference points. Even if it is more difficult to drive a snow tube into the soil than, for instance, an avalanche probe, it is still possible if the topsoil is soft. There were in fact patches with soft wetlands along the measurement profile. Alternatively, a too-large snow depth observation can be due to radar waves reflected from some other, closer point at the snow/ground interface than the point of the corresponding manual measurements. Too-low two-way travel times were also possible, for instance if there were strong reflections from interfaces between wet and dry snow. Even if we do not have any strong evidence, it is quite likely that the errors in SWE and LWC associated with reference points at 25 and 150 m could be explained by problems in

the velocity estimates caused by errors either in the snow depth measurements or in the two-way travel time determination.

Replacing the estimated liquid water content with the snow fork measurements resulted in snow density and SWE values that were much closer to the observed values than the PDA estimates. The SWE estimates were in fact slightly lower than the manual data (−6% relative error on average). Similarly, if the values of liquid water content were chosen to optimize the SWE estimates, they were much closer to the snow fork measurements than the corresponding PDA measurements (again, the points at 25 and 150 m were the exceptions).

Firstly, these results show that if propagation velocity is correct (it should be, since we used the observed depth to derive it) and the liquid water content is correct (assuming that the snow fork data is correct), the applied mixing formulae (Tiuri *et al.* 1984) are reasonable and result in good estimates of snow density and SWE. Secondly, this indicates that the remaining error found in the PDA results (51% too-low LWC and 16% too-high density and SWE) cannot be explained by errors in the velocity or in the mixing formulae, but are more likely to be found within the PDA method itself. These errors have been discussed and quantified by Sundström *et al.* (2012).

We should also consider possible errors in our experiment setup that can lead to incorrect estimates and therefore give grounds for questioning our conclusions. One of the factors affecting our results is the accuracy of our estimates of radar wave propagation velocity. The estimates of liquid water content, snow depth and density and SWE are highly dependent on the propagation velocity, which in our experiment was obtained as the velocity giving the least-squares error sum of snow depth estimated from radar data for the four available radar channels. This approach was chosen to eliminate possible errors in the CMP method, since its reliability is known to decrease when snow depth is larger than half the largest antenna offset (1 m in our antenna setup, compared to the larger snow depth of 2–3 m in the last two reference points) or if the assumption of parallel ground and snow surfaces is invalid. The results of the method's application in field conditions can therefore be further affected by errors in velocity obtained with the CMP method, although no conclusion can

be drawn on whether the effect on SWE estimates would be negative or positive.

CONCLUSION

The presented results suggest that for a wet snowpack (liquid water content of 3–8 vol%), the PDA method underestimates liquid water content by about 50% on average. This improves the accuracy of SWE estimates compared to calculations that simply ignore liquid water content in snow or when SWE is estimated via a linear function of two-way travel time that is calibrated with manual measurements of snow density (method C). In our experiment, the mean relative error in SWE estimated with the PDA method was about 16%, compared to 31% for method C and 34% for 'dry snow' calculations (method B).

These methods can also be compared from a more practical point of view. The PDA method requires measurements on at least two measuring channels, which makes the data interpretation more time-consuming than for the other two methods, and the equipment could be heavier and more expensive. On the other hand, using the PDA method (method A) or assuming dry snow (method B) does not require any manual measurements, which are necessary if SWE is estimated via a linear formula calibrated for snow density (method C).

Another method for determining liquid water content of a wet snowpack, based on measuring frequency-dependent attenuation of radar wave, was shown to achieve an absolute uncertainty in liquid water content less than 0.5 vol% (Bradford *et al.* 2009). This accuracy, however, was obtained on a thinner snowpack than in our experiment (1.2 m compared to 0.9–3 m) and with a substantially smaller average liquid water content (1.4 vol% compared to 5 vol%).

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