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NOTE

Estimating snow density from dielectric values measured using the surface reflection method

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Abstract

The surface reflection method is a popular method for determining layer dielectrics in road pavements. However, this technique has not been applied to snow. An air-coupled 800 MHz Ground Penetrating Radar (GPR) antenna was used to image alpine snow, and comparison was made with an ideal reflector, a metal plate. Application of the surface reflection technique allowed surface snow density to be estimated based on radar amplitude variations. The estimated density showed good agreement with gravimetrically measured density. This technique introduces a simple method by which surface snow density could be rapidly estimated over large areas.

Keywords

Ground Penetrating Radar, GPR, surface reflection method, snow density, dielectric

Introduction

An estimate of snow surface density is valuable for many reasons, including the estimation of Snow Water Equivalent (SWE) for hydrological studies, mass balance estimates, or to estimate snow strength or bearing capacity. However, typically, density is laboriously calculated gravimetrically at point locations by digging snow pits and measuring snow weight and volume.

In their work on road pavement analysis used Ground Penetrating Radar (GPR), Maser and Scullion (1991) derived a simple equation that provides an estimate for the dielectric of the surface pavement.

$$\epsilon_a = \left[\frac{(1+\frac{A_1}{A_2})}{(1-\frac{A_1}{A_2})}\right]^2 \qquad \text{(Eq. 1)}$$

A graphical representation is shown in Figure 1. By comparing the relative amplitude of the electromagnetic wave reflected off the pavement surface (A_1) with that reflected off an assumed perfect reflector (steel plate, A_2) the relative dielectric of the surface (ε_a) can be estimated. Amplitude is normally measured in volts or millivolts, however, because of the comparative nature of this assessment, it is not the units but the magnitude of the amplitude that is important.

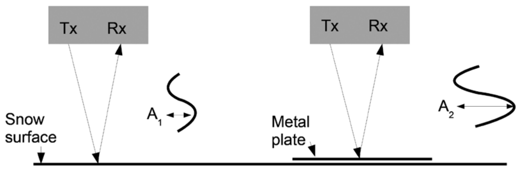

Figure 1 – The surface reflection method compares the amplitude of reflection from the medium surface (A_1) with that from an assumed ideal reflector (metal plate) (A_2).

Although GPR is routinely used to image snow subsurface stratigraphy, and amplitude comparison with an ideal reflector has been used to determine the radar wave velocity in firn (Jezek and Roeloffs, 1983), the surface reflection method described by Maser and Scullion (1991) has not previously been used to estimate the surface dielectric of snow using an air-coupled impulse GPR antenna. Application of this technique to snow could allow the rapid estimation of snow surface dielectric and density over large areas using mobile surface or air-mounted GPR systems.

Investigations have been carried out on the relationship between snow density and dielectric (Stiles and Ulaby, 1981; Kovacs *et al.*, 1993) and Kovacs *et al.* (1993) and Marshall *et al.* (2005) both provide useful synopses of quantitative interpretation of radar measurements. A simple equation to derive dielectric constant from the density of an air-ice mixture was proposed by Kovacs *et al.* (1993):

$$\epsilon_r{}' = (1 + 0.845\rho)^2 \quad \text{(Eq. 2)}$$

where ε_r' is the dielectric constant and ρ is snow density (kgm^{-3}).

This equation was derived from measurements in polar snow. The dielectric properties of alpine snow may be additionally affected by factors such as temperature, water content, snow chemistry and crystal orientation. However, Kovacs *et al.* (1993) applied this expression to numerous data-sets comparing dielectric constant and density, across numerous air-ice mixtures, including alpine snow, and still obtained a fit with a correlation of $r^2 = 0.999$ and a standard error of ± 0.031.

This short note outlines the application of the surface reflection technique to alpine snow. It shows that by simply estimating surface dielectric using GPR and then applying general dielectric/density relationships, an estimate for surface snow density can be obtained.

Method

A snow bank approximately 1 m high was selected, by the roadside at Perisher Valley ski resort in the Australian Alps. After 'squaring' of the bank using a shovel and snow saw, layers were identified and layer density was determined gravimetrically; three density measurements were made of each layer and an average value was used. Average density data and layer thickness (measured using a ruler) are presented in Table 1.

Table 1 – Gravimetric snow density data

Layer	Depth (m)	Density (kgm^{-3})
1	0–0.6 m	587
2	0.6–0.8 m	555
3	0.8–0.9 m	Not measured

After density had been assessed, the antenna with a central frequency of 800 MHz was configured and GPR imaging began. Discrete repeat measurements were made with:

1) the antenna on the snow surface (ground coupled, for comparison),
2) the antenna placed on a non-reflective inverted plastic box, at a height of 270 mm above the snow surface, and
3) as in 2), but with a 0.6 m × 0.6 m, 2-mm thick metal plate slid under the box, on top of the snow surface.

Spherical spreading of the transmitted electromagnetic wave means that reflection occurs from an area beneath the radar. For the 800 MHz antenna used in this study, the size of this footprint at a distance of 270 mm from the transmitter is estimated to be about 0.4 m × 0.2 m (Annan, 1996) so the metal plate is expected to reflect most of the transmitted energy.

Figure 2 shows a photograph of the snow bank with the 800 MHz antenna mounted in air-coupled mode upon an upturned plastic box, which is sitting upon the 2-mm thick metal plate.

Figure 2 – A snow bank that is about 1 m high with 800 MHz GPR antenna shown in air-coupled configuration, sitting on an upturned plastic box some 270 mm above a 2-mm thick, 0.6 m × 0.6 m metal plate, resting upon the snow surface.

Data were recorded using proprietary MALA Ground Vision 2 software (MALA Geoscience, 2012) on a Panasonic Toughbook. Upon returning from the field, no processing was applied to collected radargrams; amplitudes were compared as collected.

Results

Figure 3 shows a representative 'wiggle' trace obtained from the air-coupled 800 MHz antenna suspended over the snow surface with a representative 'wiggle' trace from the same antenna in the same position imaging the metal plate. The first three –'ve/+'ve cycles evident within each trace represent the direct radar wave and are not reflections. The returns from both the snow surface and the metal plate are identified by arrows. The X-axis is normalised received pulse amplitude, and *y*-axis is return travel time in nanoseconds.

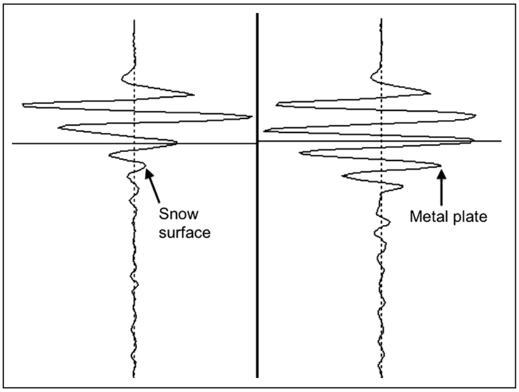

Figure 3 – 'Wiggle' trace obtained from the air-coupled 800 MHz antenna suspended over the snow surface alongside the trace obtained from the antenna in the same configuration over a metal plate on the snow surface; the traces have not been filtered.

It is these amplitudes that are compared in applying the surface reflection method.

Discussion

The reflection amplitude from both the snow surface and the metal plate were obtained manually from the images presented in Figure 3 using Reflex2DQuick software (Sandmeier, 2012); the WiggleWindow was activated and visually determined maximum amplitude was recorded for each trace. Amplitude values are not in volts but are normalised relative to the 16-bit Analog/Digital converter within the GPR acquisition system. These amplitudes are shown in Table 2:

Table 2 – Absolute radar reflection amplitude data

Reflector	Normalised Amplitude
Snow surface	3,850
Metal plate	21,000

Inputting these values into Equation 1 results in an estimated surface dielectric of ~ 2.1. This estimate can then be input into Equation 2 relating snow dielectric constant and snow density.

This results in an estimated surface snow density of 531 kgm^{-3}. This compares reasonably well with the gravimetrically determined surface snow density of 587 kgm^{-3}. If a different simple equation relating dielectric constant and snow density is used (Equation 3, Ulaby *et al.*, 1986) then a density of 578 kgm^{-3} is obtained, differing by <2 %.

$$\epsilon_r = (1 + 1.9\rho) \quad \text{(Equ. 3)}$$

where ε_r is the dielectric constant and ρ is bulk snow density (kgm^{-3}).

Comparison with two simple empirically-derived relationships, applicable to a broad range of snow types, shows good agreement between estimated and measured snow density.

A question remains: what depth does this density estimate represent? The theoretical range resolution of the 800 MHz antenna used in this experiment is approximately one quarter of the wavelength or ~ 90 mm. However, in this particular experiment, maximum amplitudes for comparison (the basis of the surface reflection method) were extracted from the discrete 'wiggle' traces, as shown in Figure 3. It is assumed that these traces represent maximum reflected wave amplitudes, representative of the maximum permittivity contrast, at the air/metal plate interface and the air/snow surface interface. The assumption is, therefore, that the estimate of snow density is for the absolute surface of the snow.

This simple application of the road pavement surface reflection method to snow shows agreement between average surface density estimated using GPR and measured snow density. Additional research is necessary to quantify factors affecting this estimate, validate spatial applicability and depth resolution, and investigate potential for assessment of deeper layers. However, a simple method by which surface snow density may be remotely estimated using commercial GPR equipment has been presented.

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