Developments toward an Improved Snowpack Liquid Water Content Algorithm

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Background

- Active radar observations of a snowpack that rely on the two way propagation through the snow, require accurate estimates of dielectric permittivity (ε_s) for calculations (e.g. Deeb *et al.*, 2011; Fig. 1).
- Up to 30% error in snow water equivalent (SWE) estimates can occur if snow is assumed dry and there is only 1% liquid water content (LWC) (Bradford et al., 2009).
- Multiple equations have been commonly applied to snow when LWC is present, including:
  - Roth et al. (1990)
  - Sihvola & Tiuri (1986)
  - Denoth (1997)
- These equations diverge as LWC goes up, making the results more sensitive to the equation chosen rather than snowpack properties (Fig. 2).
- It is necessary to improve upon these equations to either: a) accurately estimate LWC from radar information or b) accurately estimate SWE using radar techniques (e.g. SAR) with a modeled or observed value of LWC.

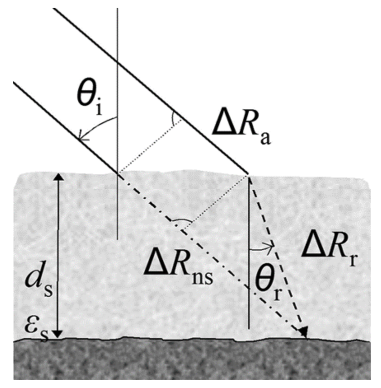


Figure 1. Radar propagation through atmosphere with no snow (ΔR_{ns}) and with snow ($\Delta R_a + \Delta R_r$). The fixed radar incidence angle (θ_i) and the refracted angle (θ_r) of the radar based on the depth (d_s) and permittivity (ε_s) of the snow pack are also shown. (from Deeb *et al.*, 2011).

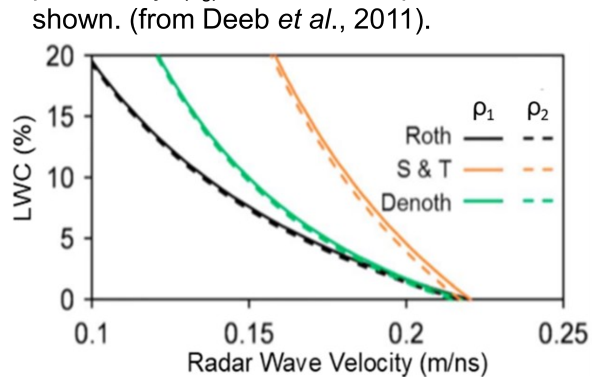


Figure 2. Comparison of common equations to calculate LWC from radar wave velocity (directly related to ε_s). Solid and dashed lines represent differences in snow density.

Research Objective

In this study, we aim to develop a new equation that relates dieletric permittivity to liquid water in snow based on in situ field data.

Methods

- In order to develop the equation, we collected independent observations of: ε_s, LWC, and snow density.
- To collect ε_s observations we used the A2 Photonics WISe sensor that has a well-constrained volume of measurement (Fig. 3).
- To collect LWC observations we used a custom-built melt calorimeter that is able to measure a sample from the same volume used for the WISe measurements (Fig. 3).
- We additionally collected bulk snow density (ρ_s) observations at 10 cm vertical increments using a 1000 cc wedge cutter and snow temperature profiles with dial stem thermometers.

Figure 3. Images of the WISe sensor (left) and the custom-built melt calorimeter and high-accuaracy thermometer (right).

- The melt calorimeter uses liquid water with a known mass (M_1) and temperature (T_1) mixed with a sample of snow with a known mass (M_2).
- The final temperature (T_2) is measured after the snow sample is melted and water is well mixed using the following equation to calculate LWC by mass (Kawashima et al., 1998):

$$\mathrm{LWC} = 100\left[1 - \frac{C}{L}\left(M_1\frac{(T_1 - T_2)}{M_2} - T_2\right)\right]$$

Where C is the specific heat of water and L is the latent heat of fusion.

- LWC by mass is converted to volumetric LWC using density observations.

Results

- Due to COVID-19 limitations on data collection and SnowEx field activities, observations were only collected in the Sandia Mountains outside of Albuquerque, NM.
- A total of 64 observations were used after QA/QC. Most observations were not used if the temperature of the snowpack was not isothermal as the calorimeter equation does not take snow temperatures other than 0°C into account.
- A new equation relating permittivity to snow density and volumetric LWC (Fig. 4) was developed using MATLAB. The equation has an R^2 = 0.68 and RMSE of 0.018 volumetric LWC. The equation is:

$$\mathrm{LWC} = 0.037\varepsilon_s + \frac{\varepsilon_s + 0.051\rho_s - (3.17\times10^{-5})\rho_s^2}{158.8} - 0.08$$

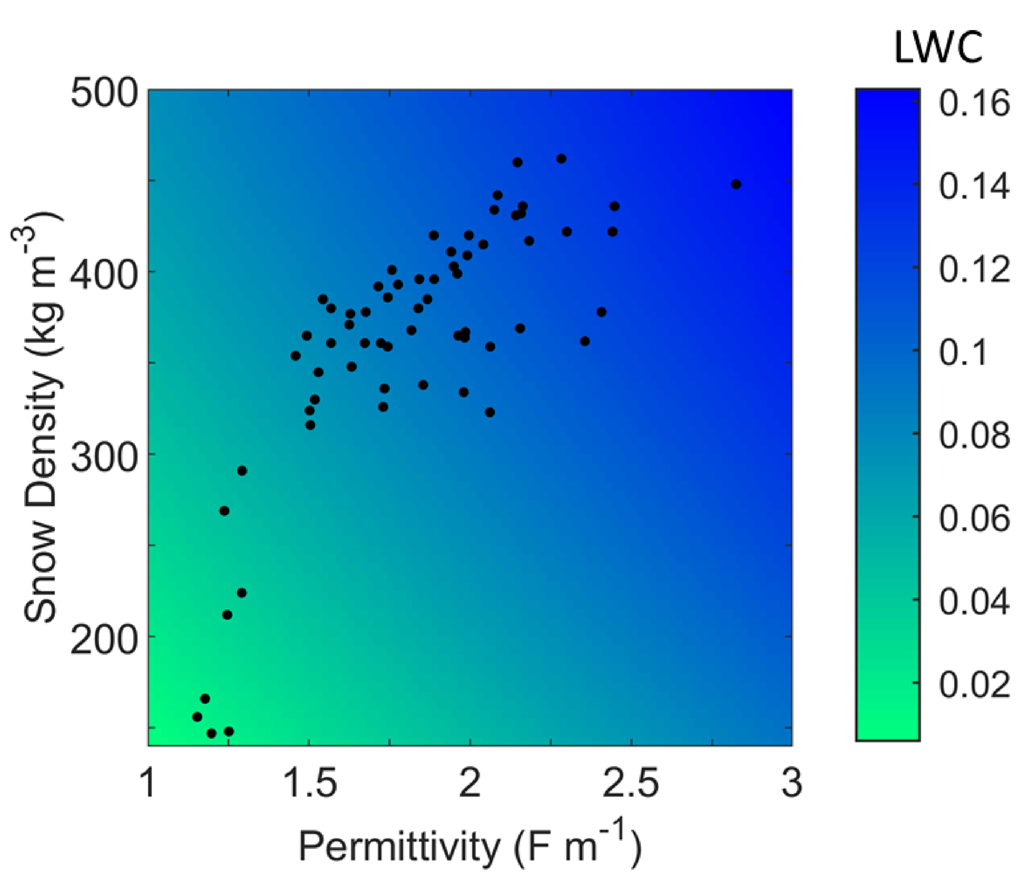


Figure 4. Color plot of the volumetric LWC equation developed. Black dots represent data points used to develop the equation

- The equation was compared to Roth et al. (1990), Sihvola & Tiuri (1986), and Denoth (1997) as well as the equations used by the WISe and SLF snow LWC sensors (Fig. 5).

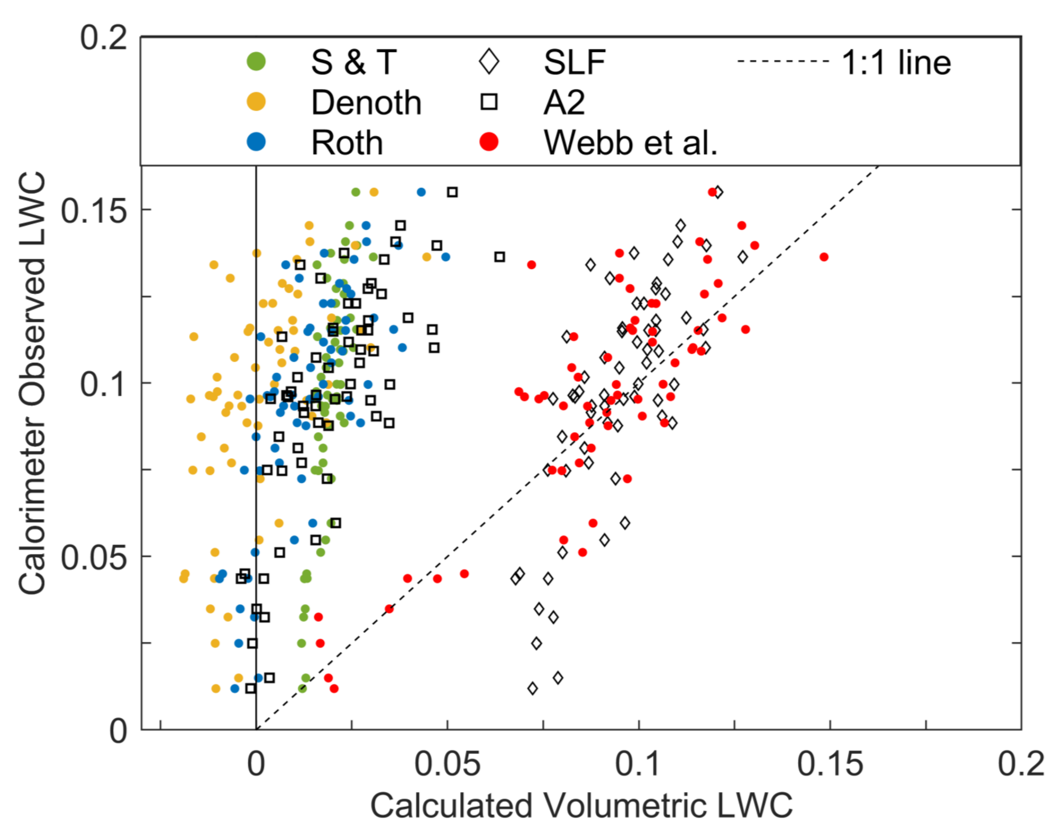
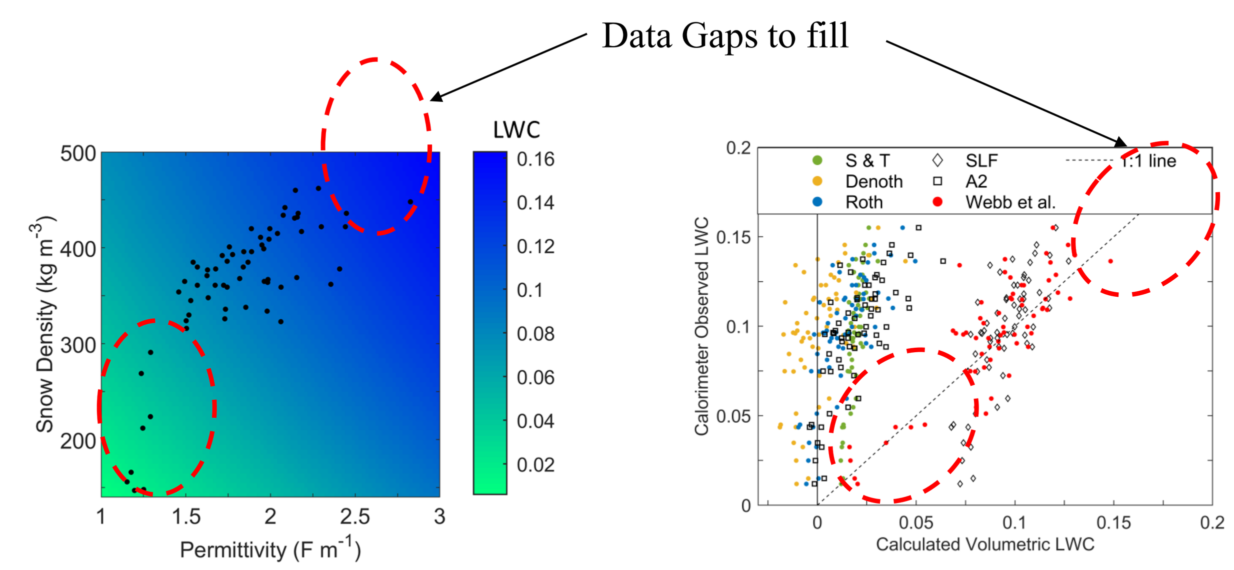


Figure 5. Scatter plot of calorimeter observed LWC compared to the calculated LWC using common equations, sensor specific equations, and the currently developed equation by Webb et al.. All LWC values are volumetric.

Discussion

- Our observations provide new information towards the need for improved equations for radar based techniques in snow when liquid water is present.
- Many of the commonly applied equations did not compare well to calorimeter observations, with a number of calculated LWCs being negative (Fig. 5).
- Most of these common equations are based on theoretical or laboratory work under idealized conditions.
- More observations are necessary of varying snowpack climates to determine what conditions this equation works for.
- Further data collection to fill in the gaps in the current dataset will improve this equation for more accurate estimates.



- Initial estimates of error in calorimeter observations is ~1.5% volumetric LWC
- Experiments are planned in the coming weeks/months to better define error bars of melt calorimeter, including:
  - Mixing of 2 masses of water to estimate heat loss to calorimeter
  - Use of freezer to impose temperature gradients and observe heat loss with time.

Acknowledgements

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