Snowpack Characterization Using Low-Cost FMCW Radar

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MOTIVATION

- Snow Water Equivalent (SWE) is a vital for understanding the hydrologic cycle and predicting runoff
- Established SWE measurement systems are costly and limited in spatial resolution
- Frequency-Modulated Continuous Wave (FMCW) radar can measure SWE wirelessly
- Low-cost millimeter-wave (mmWave) FMCW devices are increasingly available
- Characterizing the performance of mmWave radar devices for SWE measurement is the first step for integration into affordable snowpack monitoring stations

THEORETICAL BACKGROUND

- FMCW radar emits a "chirp" – a wave that changes in frequency over time
- The time difference between chirp transmission and reception is measured and converted into distance
- Snow has a larger real dielectric constant (ε') than air, resulting in a larger measured distance between snow surface and ground
- The difference between the measured and actual height is related to ε' by [1]:

$$H_{\text{snow,radar}} = H_{\text{snow,actual}} \sqrt{(\epsilon'_{r,snow})}$$

- The dielectric constant is related to the relative snowpack density by [2]:

$$\epsilon'_{r,snow} = 1 + 1.7\,\rho_d + 0.7\,\rho_d^2$$

- And SWE can be calculated as [3]:

$$SWE = \rho_d * (\text{depth})\, x\, 10^3$$

- Note for wet snow (>0 °C), the imaginary component of the dielectric constant ε'' becomes significant and radar penetration depth decreases from meters to several centimeters [1]

METHODS

- Snow samples with similar densities (approx. 380 kg/m^3) and different grain properties were tested
- All experiments were done in a freezer below 0°C
- An aluminum reference plate was used
- Tests were conducted at 39.5cm above plate for SRG, and 20cm and 39.5cm for CG
- Radar set for a 2.44cm range resolution (53-63.3 GHz sweep)
- Radar ADC data was captured and processed as shown in Figure 1

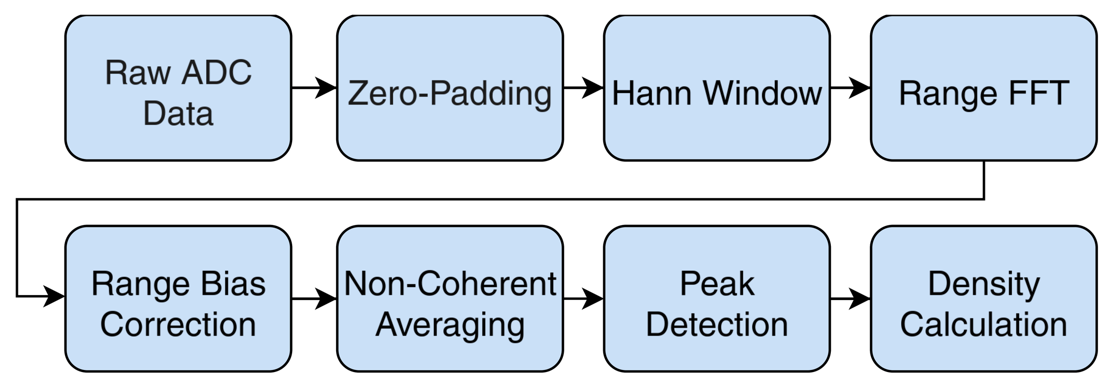

Figure 1: The implemented post-processing algorithm.

Sample Name	Snow Grain Description	Grain Size
SRG	Small rounded grains	0.25-1 mm
CG	Coarse grains	1-3 mm

Table 1: Description of the two snow types used.

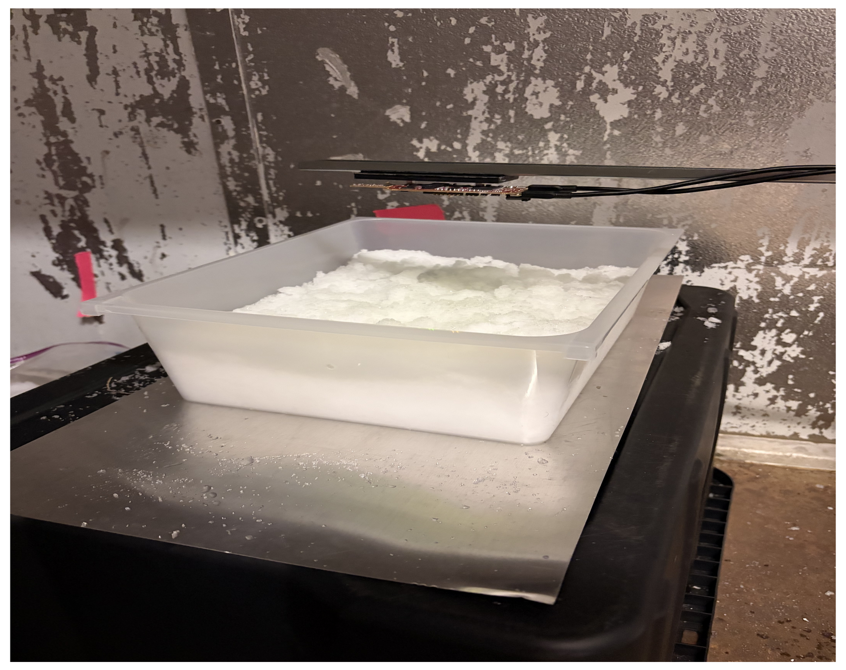

Figure 2: The experimental setup with the radar, snow, and aluminum plate.

PRELIMINARY RESULTS

- Range profile varied widely between trials
- Significant error in calculated densities
- Snow-air interface only detected in some trials
- Thin ice layer was observed in initial trials of SRG

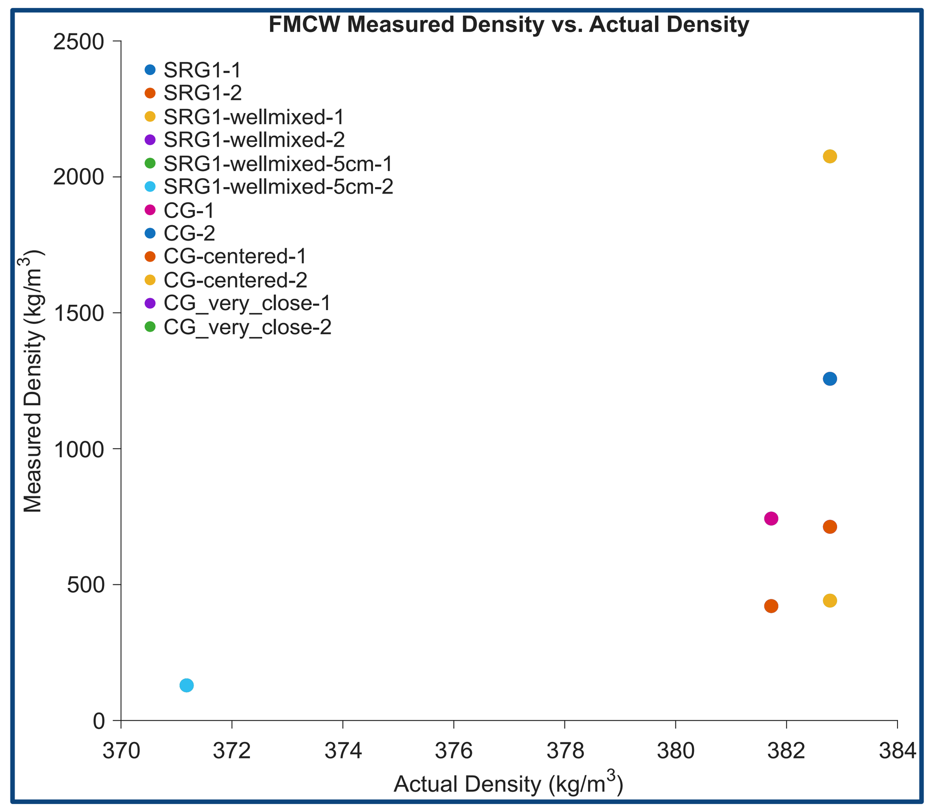

Figure 3: Measured vs. actual snow density.

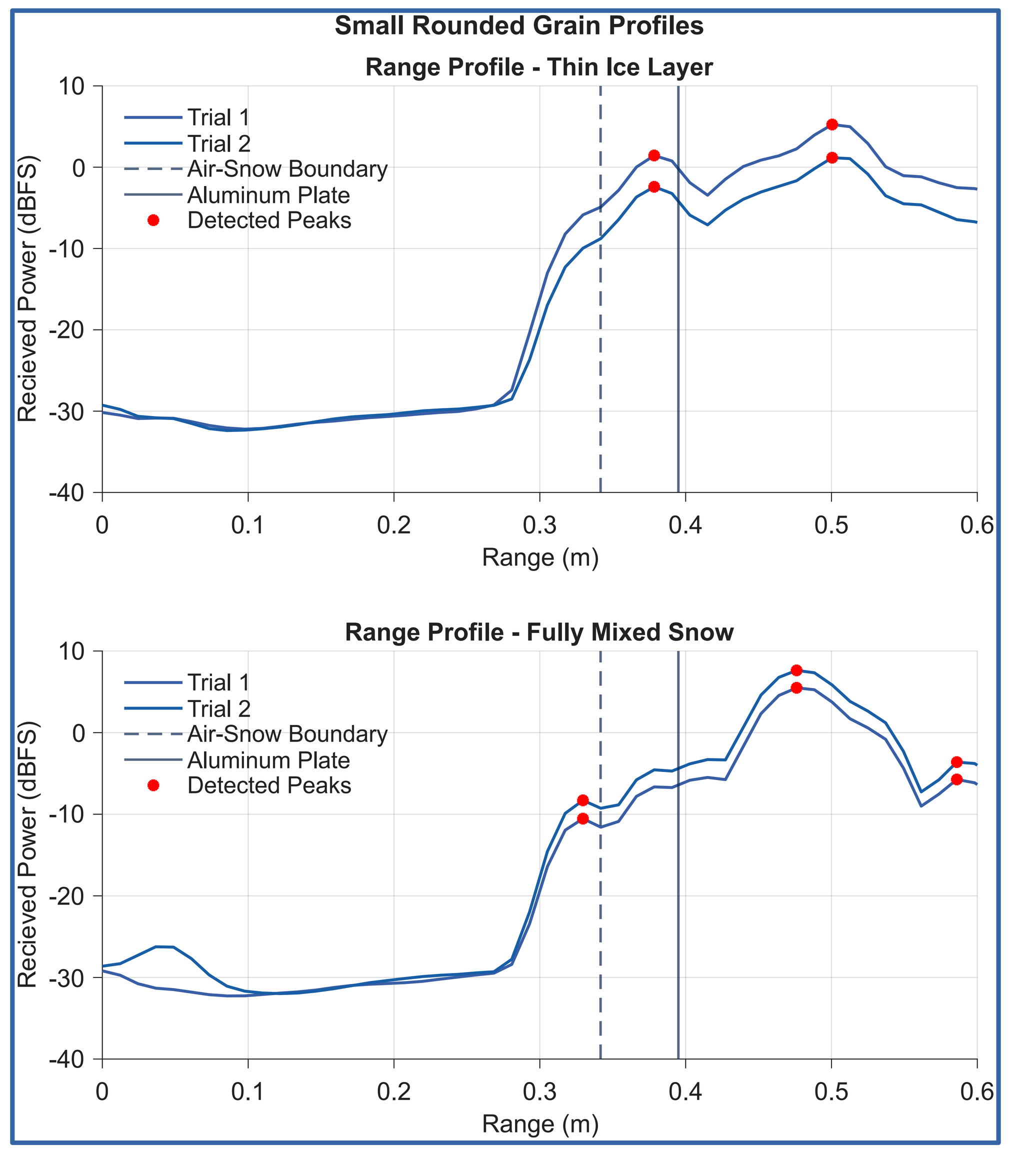

Figure 4: Range FFT for SRG trials.

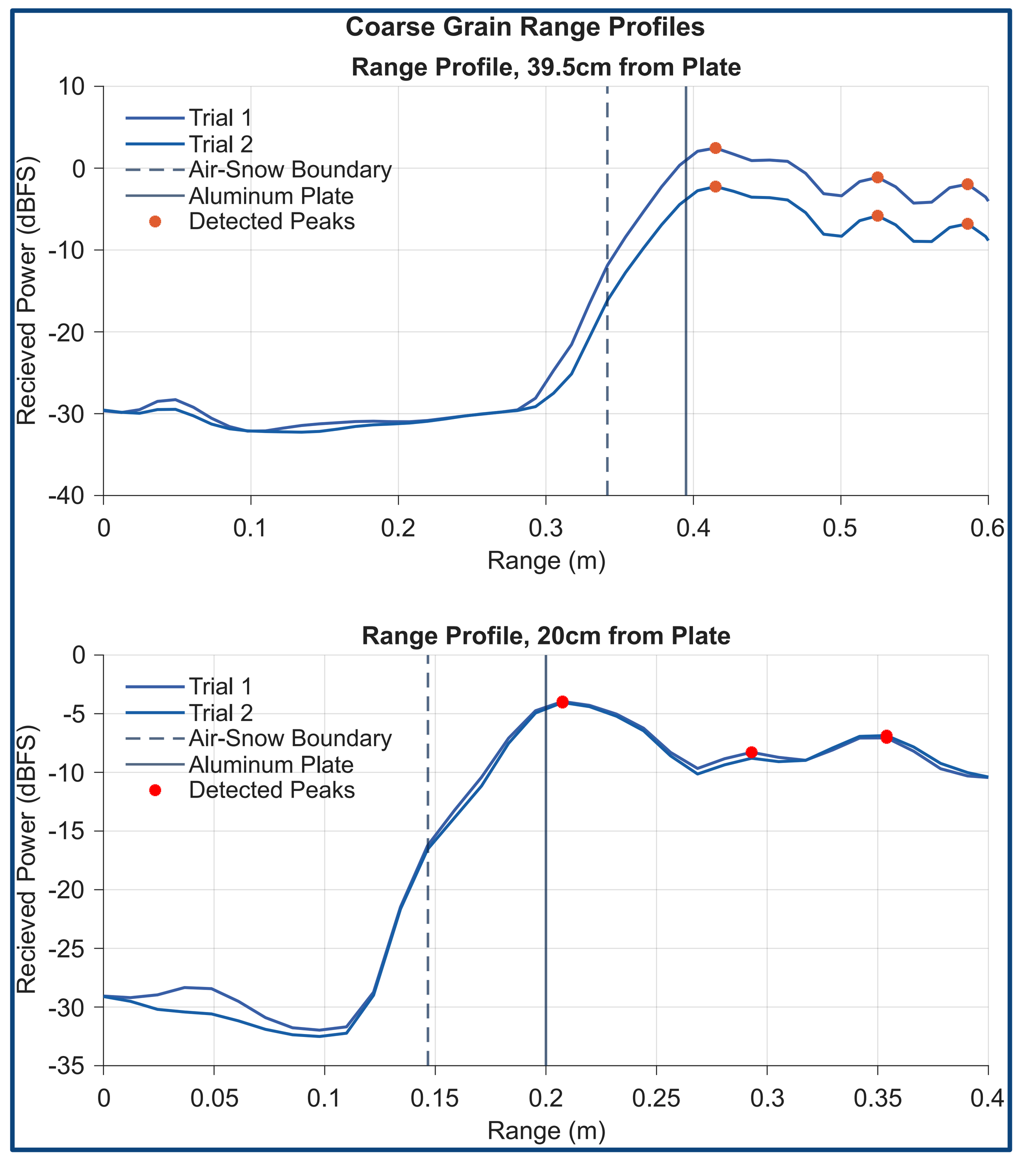

Figure 5: Range FFT for CG trials.

DISCUSSION AND NEXT STEPS

- The snow-air interface was much more defined for SRG snow than for CG snow
- This may be due to the smoother snow surface reducing scattering
- When the snow-air interface did not have a significant peak, the density algorithm failed
- The stronger plate return vs. air-snow return may be due to interference from the bare aluminum plate overpowering the air-snow peak
- The detected peak in the SRG – Thin Ice Layer plot appears to demonstrate detection of the ice layer, showing a potential for snow stratigraphy measurement

Future Work

- Refine test setup to mitigate effect of external reflections
- Tune FMCW device and post-processing algorithm for low power consumption
- Integrate into remote, power-contained meteorological sites to measure SWE in the Hubbard Brook watershed and beyond
- Implement onto a UAV for high spatial resolution SWE measurement
- Examine ability to measure snow stratigraphy

CONCLUSION

- Preliminary experimentation with a mmWave FMCW device to measure SWE is presented
- Results indicate potential to measure SWE, but variability between experiments
- Hypothesized that density measurement error is due to erroneous aluminum plate reflections rather than an issue with the radar theory

WORKS CITED

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[2]M. Tiuri, A. Sihvola, E. Nyfors, and M. Hallikaiken, "The complex dielectric constant of snow at microwave frequencies," IEEE Journal of Oceanic Engineering, vol. 9, no. 5, pp. 377–382, Dec. 1984, doi: 10.1109/JOE.1984.1145645.

[3]S. Wielandt et al., "Characterizing Snowpack with 60 GHz FMCW Millimeter-Wave Radar Sensors," in 2023 57th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA: IEEE, Oct. 2023, pp. 1245–1250. doi: 10.1109/IEEECONF59524.2023.10476846.