Dielectric Constant and Thickness Measurement of Dry Snowpack and Lake Icepack using Correlation Radiometry

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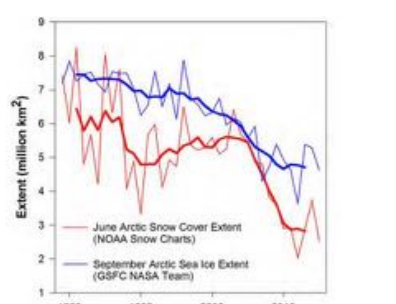
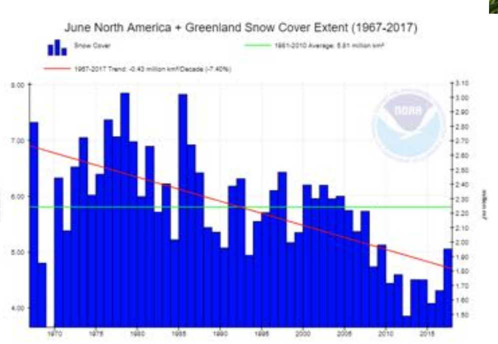
Abstract

- **Objective:**
  - NASA SnowEx's goal is to estimate the amount of water in Earth's terrestrial snow-covered regions.
  - The knowledge of the distribution of snow-water equivalent (SWE) drives the mission objective.
- **Importance of Snow and Ice:**
  - Important role in providing the water supplies for domestic, agricultural, and industrial purposes.
  - Effects on human activities, such as industrial production, building, transport of goods and winter sports.


- **Necessity of monitoring snow and ice:**
  - Significant changes in snow accumulation, timing, and melt



Sea ice and snow cover extents for the Northern Hemisphere from 1979 to 2015. The thick lines are 5-year running means (Derksen and Brown 2012) [4].



- **Method:**
  - Remotely sense the propagation time τ_{delay} of multi-path microwave emission of low-loss terrain covers at two distinct incident angles using a wideband autocorrelation radiometry (WiBAR)
- **Benefits:**
  - Passive microwave system
    - ✓ Low power (low cost) for space/air borne instruments
    - ✓ All weather operation capability
  - Deterministically measures the thickness and dielectric constant
    - ✓ No algorithm calibration needed
- **Challenges:**
  - Requires wide frequency bandwidth
  - Radio Frequency Interference (RFI) could be problematic

Wideband Autocorrelation Radiometry

- Finding the vertical extent of the pack by measuring the time delay between the brightness temperature of the ground beneath the pack and its doubly reflected signal from the lower and upper boundaries of the pack [1-3].

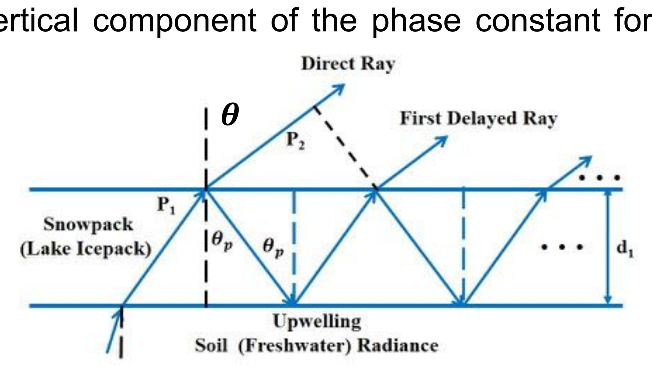
$$\tau_{delay} = \frac{2}{c}\int \sqrt{n_p^2(z) - \sin^2\theta}\, dz$$

n_p is the refractive index of the pack, and c is the speed of light in free space.

- The emissivity is given by [1-2]:

$$e = \frac{(1-|R_{01}|^2)(1-|R_{12}|^2)}{1+L_v(|R_{01}||R_{12}|)^2+2\sqrt{L_v}\,R_{01}R_{12}\cos(2k_{1z}d_1)}$$

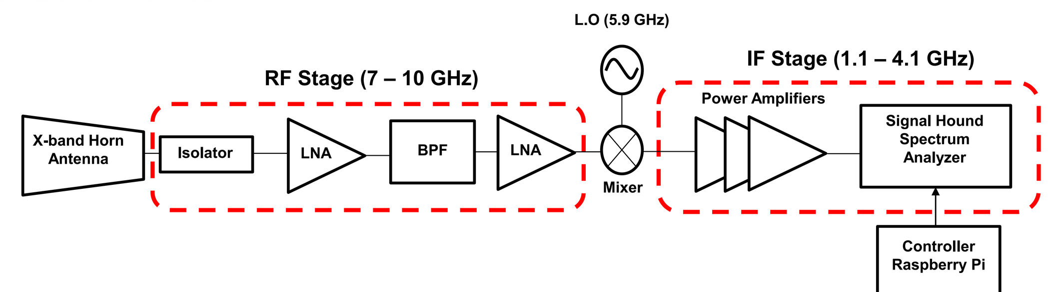
where R_{01} and R_{12} are the Fresnel reflection coefficients at the air-snow/ice and snow/ice-soil/freshwater interfaces, respectively. L_v is an attenuation factor due to volume scattering, k_{1z} is the vertical component of the phase constant for ice, and d is the ice thickness.



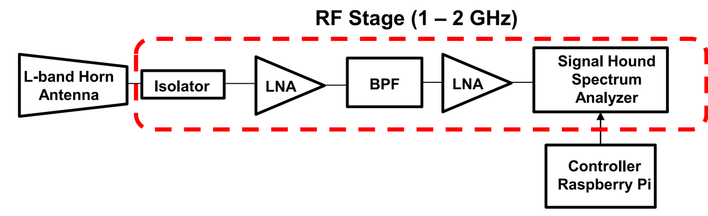
Remote sensing of microwave travel time within the pack using Wideband Autocorrelation Radiometry.

Instruments and Measurement Approach

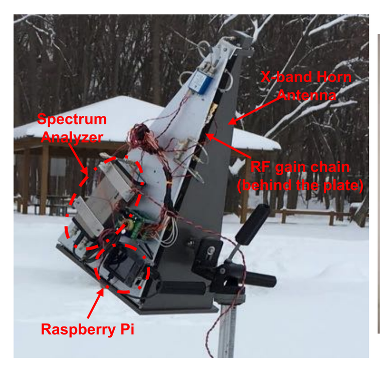
- **Instruments:**



The schematic of the X-band receiver gain chain.

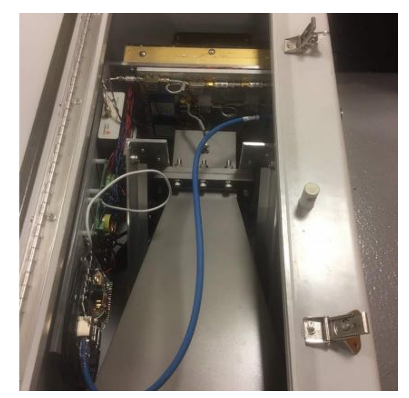


The schematic of the L- or S-band receiver gain chain.



X-band WiBAR.

L-band WiBAR.



S-band WiBAR

- **Measurement Approach:**

Truck Mounted Radiometers

- The received power:

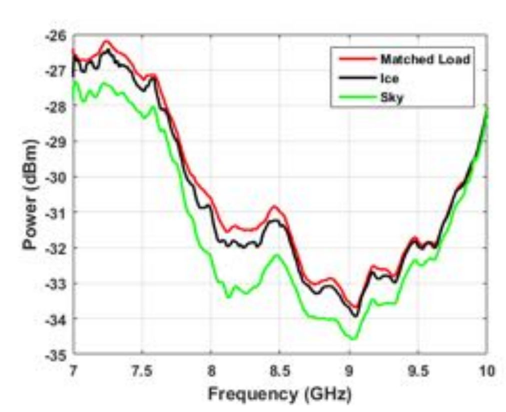
$$P(f) = KT_{SYS}BG(f) = K\big(e(f)T_0 + T_{REC}(f)\big)BG(f)$$

K: Boltzmann's constant
$T_{SYS}(f)$: radiometer system temperature
$G(f)$: radiometer's gain
$T_{REC}(f)$: receiver noise temperature
T_0: physical temperature of the target

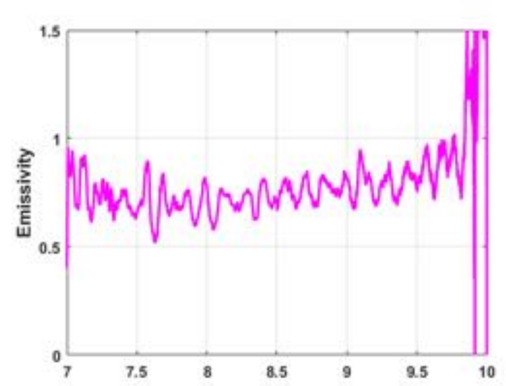
- Calibration:

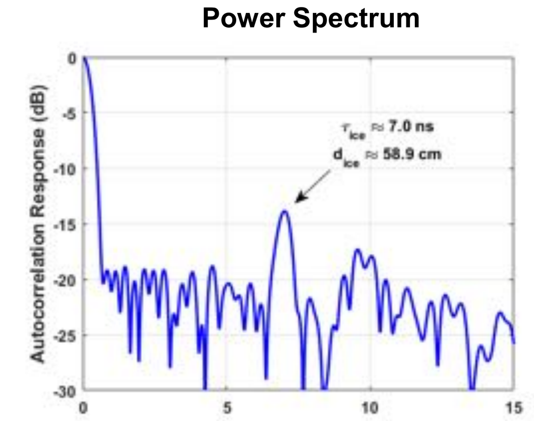
$$\hat{e}(f) = \frac{P_{pack}(f) - P_{sky}(f)}{P_{Matched\ Load}(f) - P_{sky}(f)}$$

$$ACF(\tau) = \int_f e(f)w(f)e^{-j2\pi f\tau}\,df$$



Power Spectrum





Emissivity (left) and autocorrelation function (right) of the lake icepack measured on South Sturgeon Lake on March 07, 2018. The Hamming window was used for $w(f)$ and $\theta = 3.2^o$.

Dielectric Constant and Thickness Measurement using WiBAR

- Measured time delay by WiBAR at two distinct incidence angles:

$$\begin{cases}\tau_1 = \tau_{delay}(\theta_1) = \frac{2d_p}{c}\sqrt{\epsilon_p - \sin^2\theta_1} \\ \tau_2 = \tau_{delay}(\theta_2) = \frac{2d_p}{c}\sqrt{\epsilon_p - \sin^2\theta_2}\end{cases} \Rightarrow d_p \text{ and } \epsilon_p \text{ can be found}$$

- Assuming ϵ_p is real (low-loss pack):

$$\epsilon_p = \frac{\tau_1^2\sin^2\theta_2 - \tau_2^2\sin^2\theta_1}{\tau_1^2 - \tau_2^2}$$

- Using the measured ϵ_p:

$$d_p = \frac{c\tau_i}{2\sqrt{\epsilon_p - \sin^2\theta_i}}, \quad i = 1,2$$

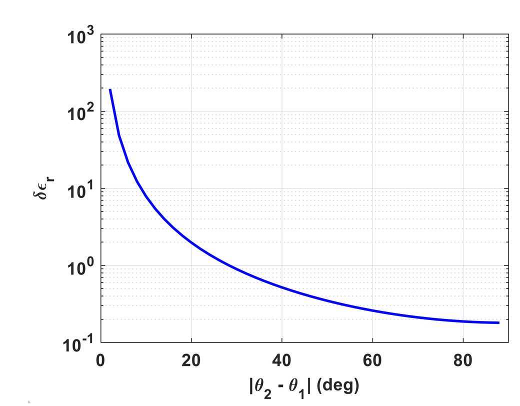
- Assuming pencil beam antenna and ideal conditions of the target, the error is mainly due to the error in the measured time delay ($\delta\tau$), and using the error propagation rule:

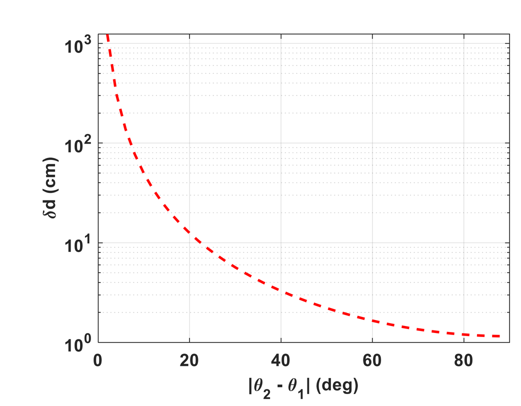
$$\delta\epsilon_p = \frac{2\delta\tau\,|\tau_1^2\sin^2\theta_2 - \sin^2\theta_1|\,\tau_1\tau_2}{(\tau_1^2 - \tau_2^2)^2}\cdot\sqrt{\tau_1^2 + \tau_2^2}$$

$$\delta d_p = d_p\cdot\sqrt{\left(\frac{\delta\tau_i}{\tau_i}\right)^2 + \left(\frac{\delta\epsilon_p}{\epsilon_p - \sin^2\theta_i}\right)^2}$$

where $i = 1$ or 2, and $\delta\tau_1 = \delta\tau_2 = \delta\tau$.

- We also investigated the effect of the incidence angles separation:





The error in the measured ϵ_r (left) and d (right) of a 20 cm icepack. The error in the measured time delay is assumed to be $\delta\tau = 20$ ps.

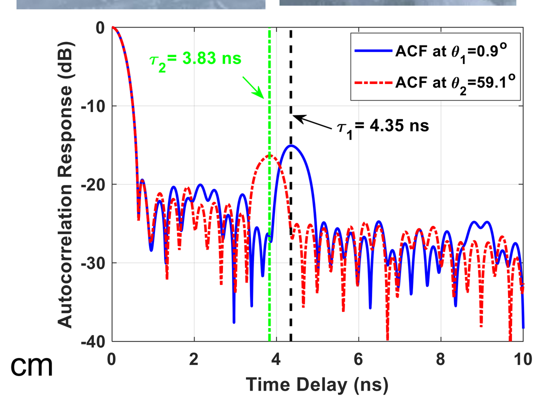
Measurements and Results

- The measurement was performed on Douglas Lake at the University of Michigan Biological Station (UMBS) in March 2016.
- We used an ice augur to drill a hole in ice and measure the thickness using measuring tape.
- The ground truth value of ice thickness is about 35.56 cm.

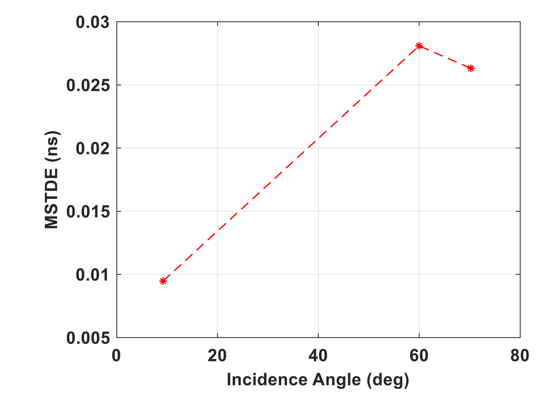
- Using the time delays measured by WiBAR at two distinct incidence angles:

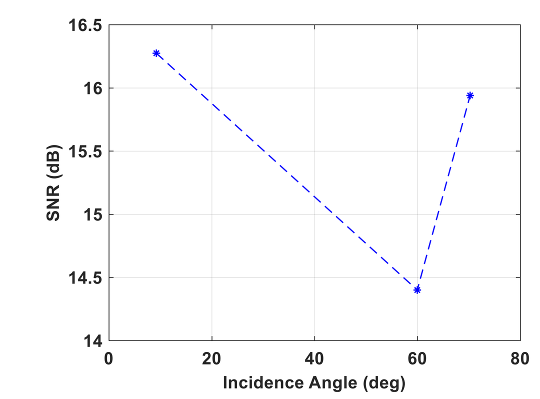
$$\epsilon_{ice} = \frac{\tau_1^2\sin^2\theta_2 - \tau_2^2\sin^2\theta_1}{\tau_1^2 - \tau_2^2} = 3.24$$

$$d_{ice} = \frac{c\tau_1}{2\sqrt{\epsilon_p - \sin^2\theta_1}} = 36.24\ cm$$



- The measured thickness by this method is less than 1 cm different from the ground truth value of 35.56 cm.
- The measured dielectric constant of freshwater ice is about 0.06 higher than the reported value of 3.18 over microwave frequencies by Matzler and Wegmuller [5].
- Due to the access to single of traces in Winter 2018 measurements, we are only able to extract the mean square time delay error (MSTDE) from these set of measurements:





THE MSTDE (left) and the SNR (right) of the measured delay peak as a function of incidence angle. The measurements were performed on Douglas Lake on March 03, 2018. The bandwidth was 3 GHz, and the Hamming window was used.

- Assuming $\delta\tau \approx 10$ ps, $\delta\epsilon_p \approx 0.1$ and $\delta d_p \approx 1.7$ cm.
- The error in the measured values of dielectric constant and thickness of the icepack are close to the difference between the measured and ground truth values, which are $|\epsilon_{ice_{measured}} - \epsilon_{ice_{ground\ truth}}| \approx 0.06$ and $|d_{ice_{measured}} - d_{ice_{ground\ truth}}| \approx 1$ cm.

Conclusion

- The potential of the WiBAR technique as for material characterization was demonstrated
- This technique can also be used to measure snowpack depth, density, and thus snow water equivalent (SWE), by itself
- The effect of the incident angles separation on the retrieved refractive index and thickness of a loss-less slab were demonstrated. For example, for the angle separations of more than 55^o, $\frac{\delta d}{d} \leq 10\%$ and $\frac{\delta\epsilon_r}{\epsilon_r} \leq 3\%$ ($\delta\tau \approx 20$ ps, $d_{ice} = 20$ cm, $\epsilon_{ice} = 3.18$).
- The measured refractive index and thickness of the freshwater icepack by WiBAR was 3.24 and 36.24 cm ($\frac{\delta d}{d} \approx 2\%$, $\frac{\delta\epsilon_r}{\epsilon_r} \approx 1.8\%$). The ground truth was about 35.56 cm.

Acknowledgements

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References

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[5] C. Matzler and U. Wegmuller, ``The dielectric properties of fresh-water ice at microwave frequencies,'' Journal of Physics, D: Applied Physics, vol. 20, pp. 1623-1630, 14 Dec. 1987.