Wideband Autocorrelation Radiometry for Deterministic Passive Microwave Measurement of Lake Ice and Snow Depth

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Technology under development: WiBAR

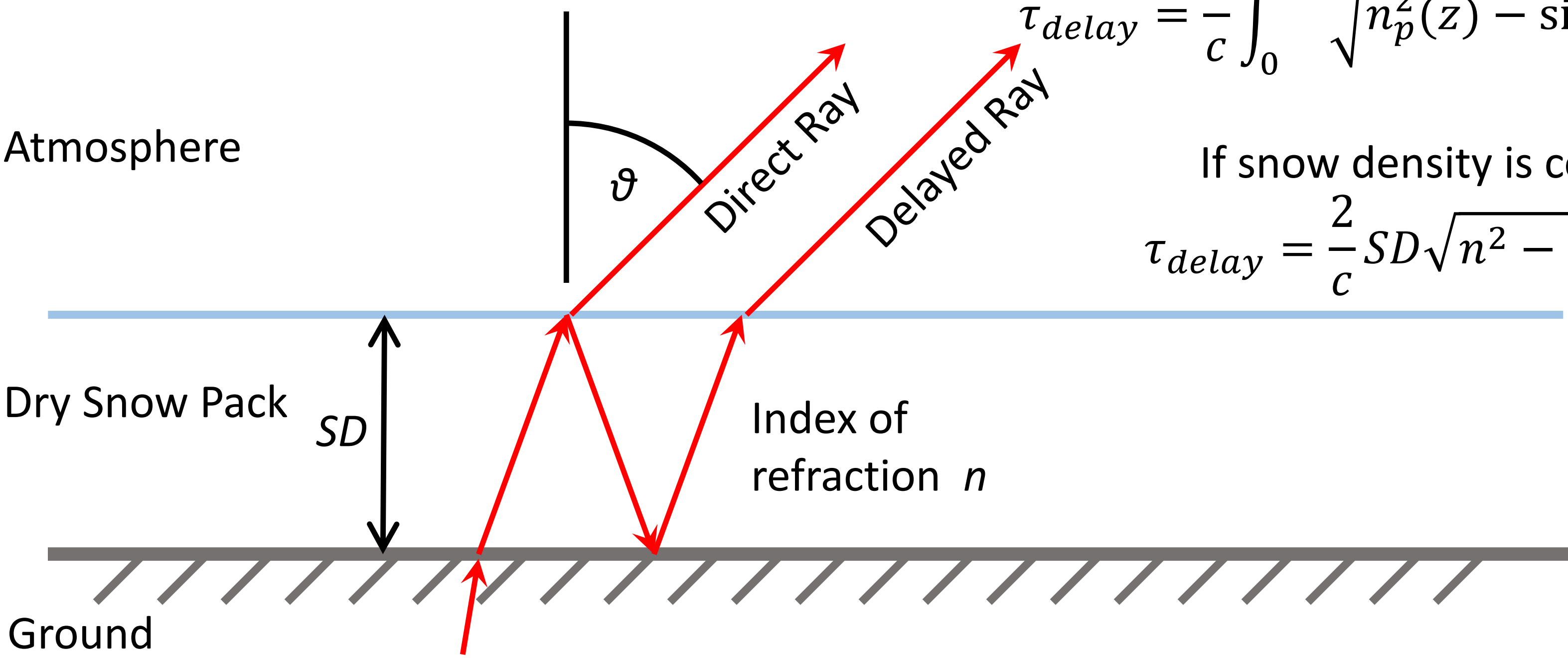
- Wideband Autocorrelation Radiometry (WiBAR)
- Passive microwave measurement
  of the electrical distance b/t two interfaces
- Geophysical applications: lake ice and dry snow pack

Integrated time delay:

$$\tau_{delay} = \frac{2}{c}\int_0^{SD} \sqrt{n_p^2(z) - \sin^2\theta}\ dz$$

If snow density is constant:

$$\tau_{delay} = \frac{2}{c} SD\sqrt{n^2 - \sin^2\vartheta}$$

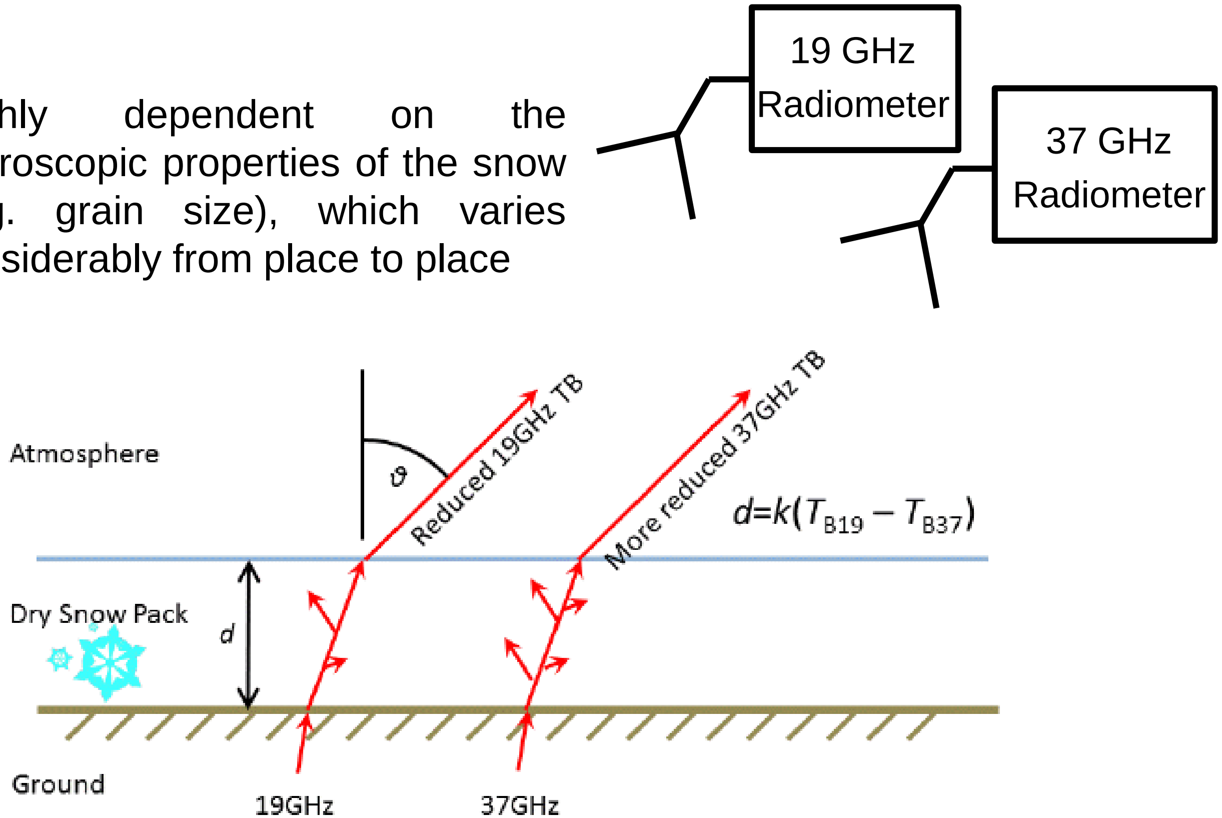


Outline

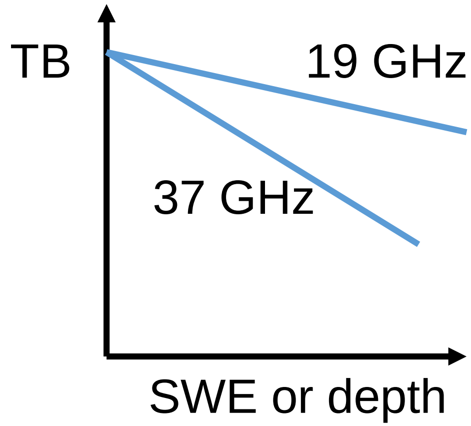
- Motivation/review: What are we doing and why?
- Introduction to
  Wideband Autocorrelation Radiometry (WiBAR)
  - WiBAR Instruments and Measurement Approach
  - Instrument calibration
  - Operational requirements
- Field Measurement Campaign/Recent accomplishments:
  - Dual pol measurements of snow over ice
  - Sub-pixel variability of the layer thickness measurement
- Conclusions

Traditional Remote Sensing of Snow

Highly dependent on the microscopic properties of the snow (e.g. grain size), which varies considerably from place to place



Planck Radiation

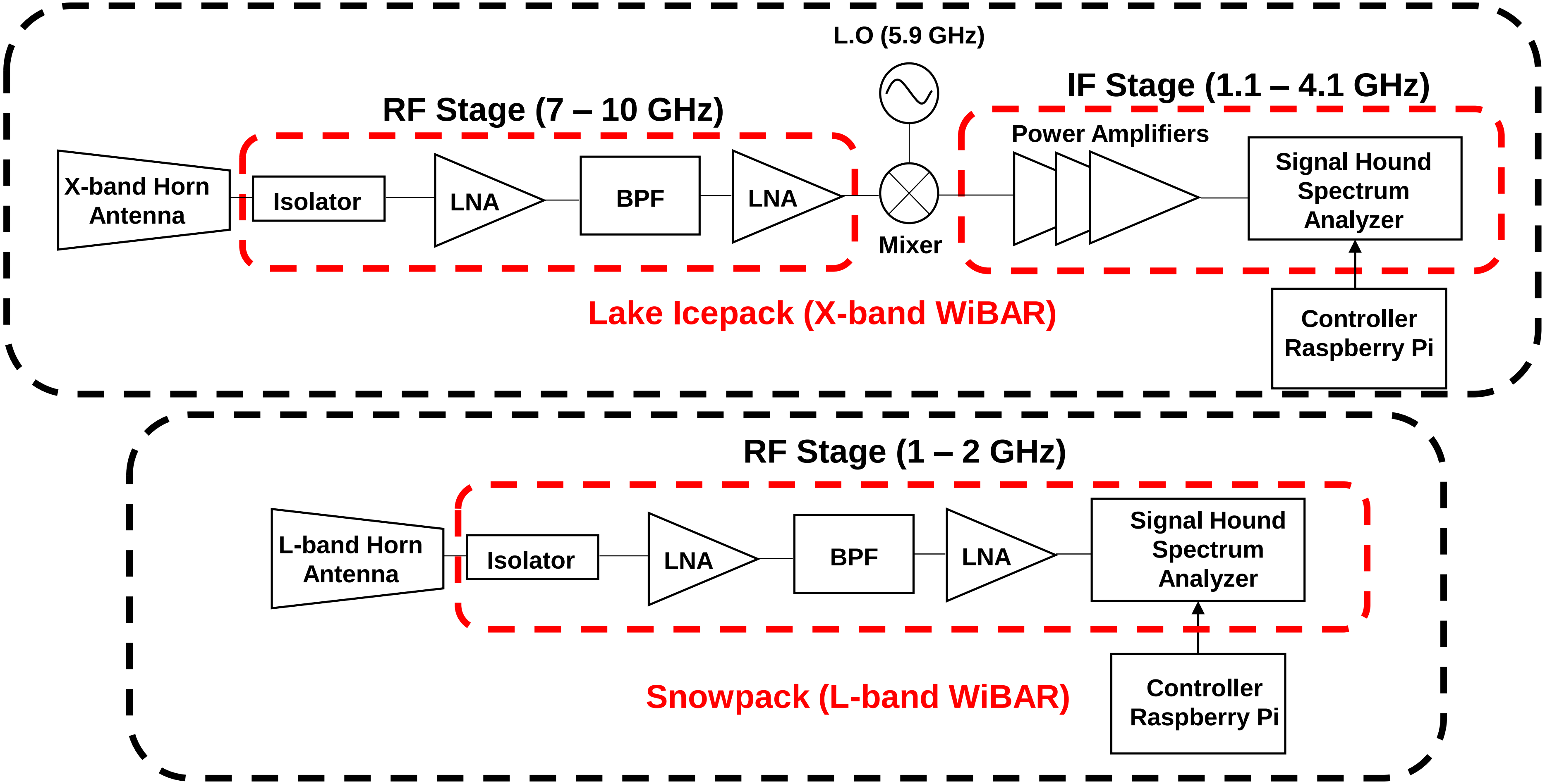


$$d = k(T_{B19} - T_{B37})$$

The theoretical explanations for constant k are very complicated, and it is typically determined via regression for different terrains.

WiBAR measurement approach: spectrum analysis

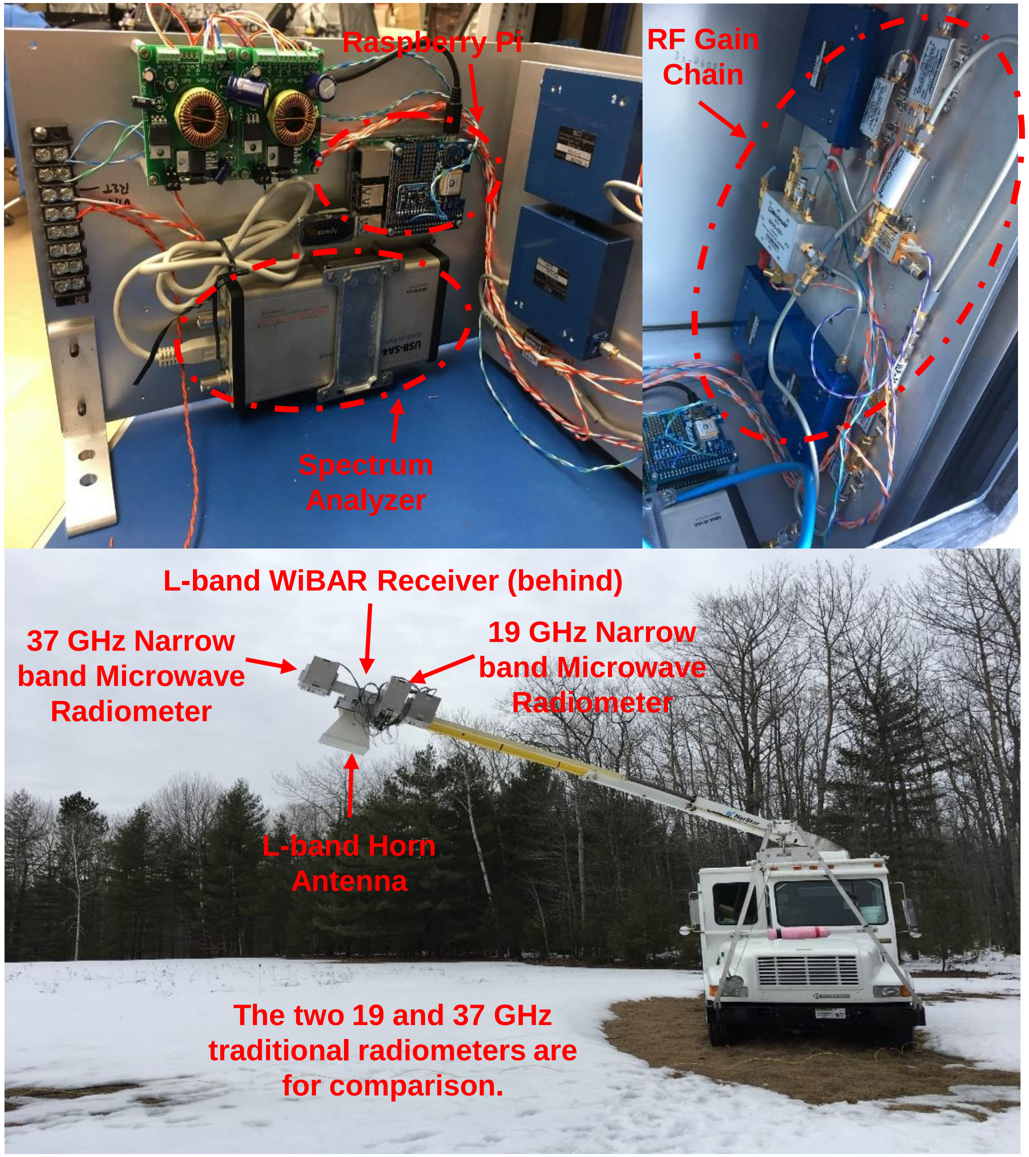
- The data are collected in frequency domain.
- The receiver is a Signal Hound spectrum analyzer (USB-SA44B)



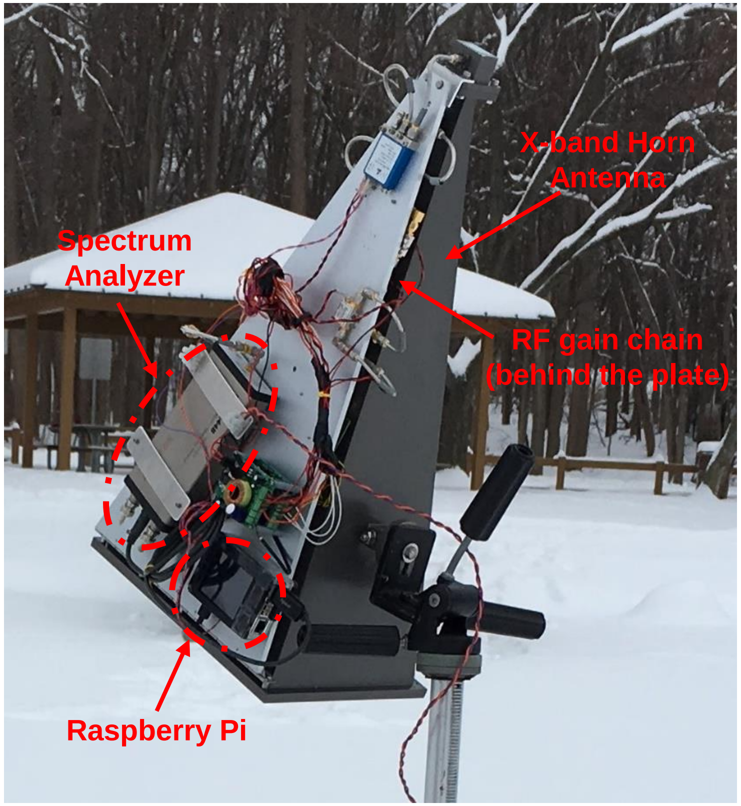
The schematic of the WiBAR receiver.

Some WiBAR instruments

Snowpack (L-band Radiometer)



Lake Icepack (X-band Radiometer)



WiBAR Measurement: Frequency Spectrum

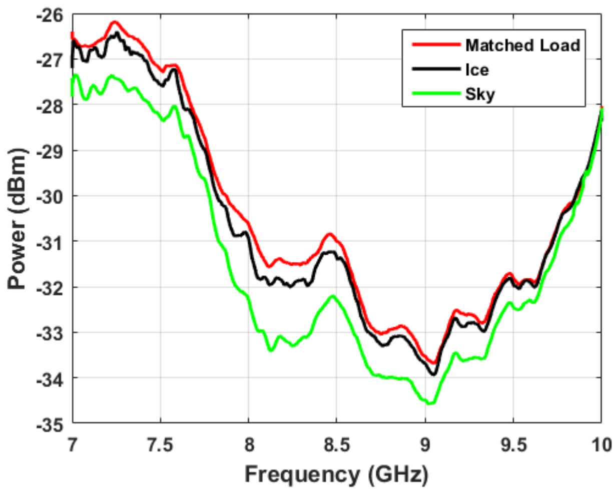
- The received power, P, at the spectrum analyzer:

$$P(f) = KT_{sys}(f)\, B\, G(f) = K\left(e(f)T_0 + T_{REC}(f)\right) B\, G(f)$$

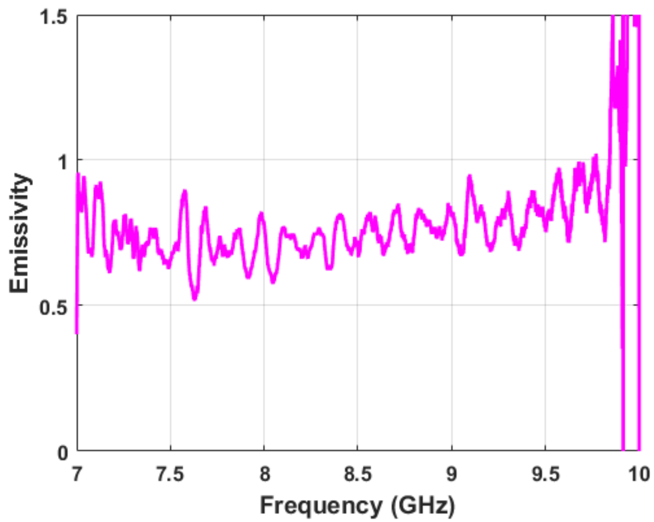
$\boldsymbol{K}$: Boltzmann's constant
$\boldsymbol{T_{SYS}(f)}$: radiometer system temperature
$\boldsymbol{G(f)}$: radiometer's gain
$\boldsymbol{T_{REC}(f)}$: receiver noise temperature
$\boldsymbol{T_0}$: physical temperature of the target

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

Power Spectrum



Emissivity



Lake icepack measurement at $\theta_0 = 3.1^o$ (South Sturgeon Lake, MN, March 07, 2018).

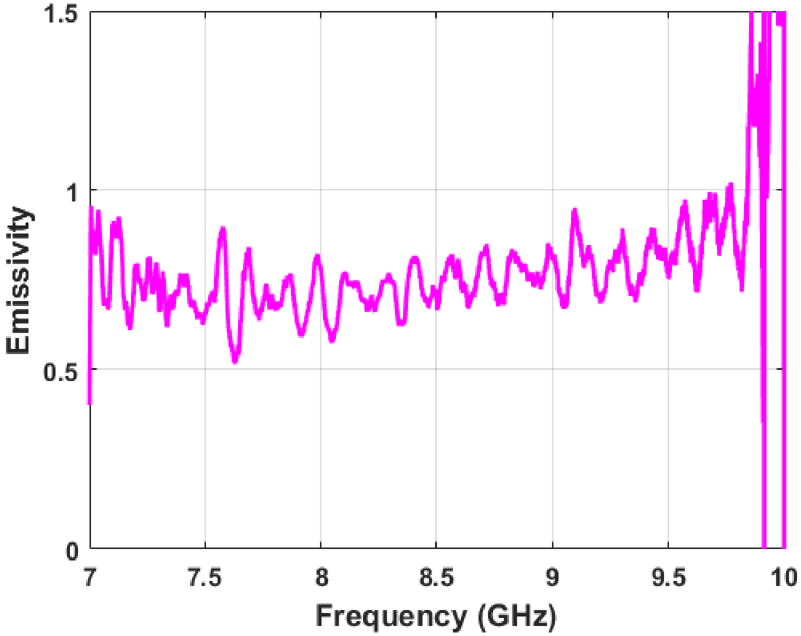
WiBAR Measurement: the Autocorrelation Function

- Using the Wiener Khinchin theorem, the autocorrelation function, $\Phi(f)$, is:

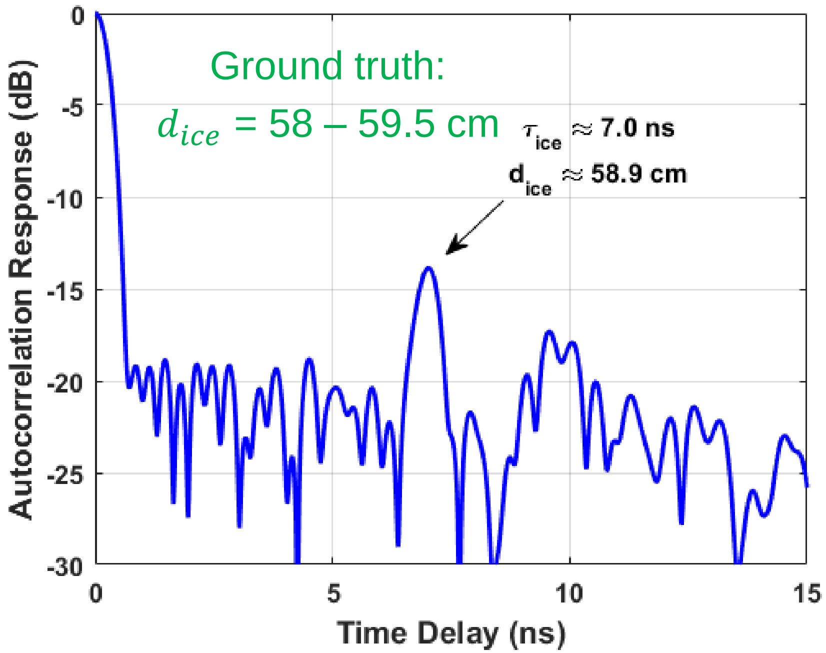
$$\Phi(\tau) = \int_f e(f)w(f)e^{-j2\pi f\,\tau}\,df$$

$w(f)$: window function

Emissivity



Autocorrelation Function



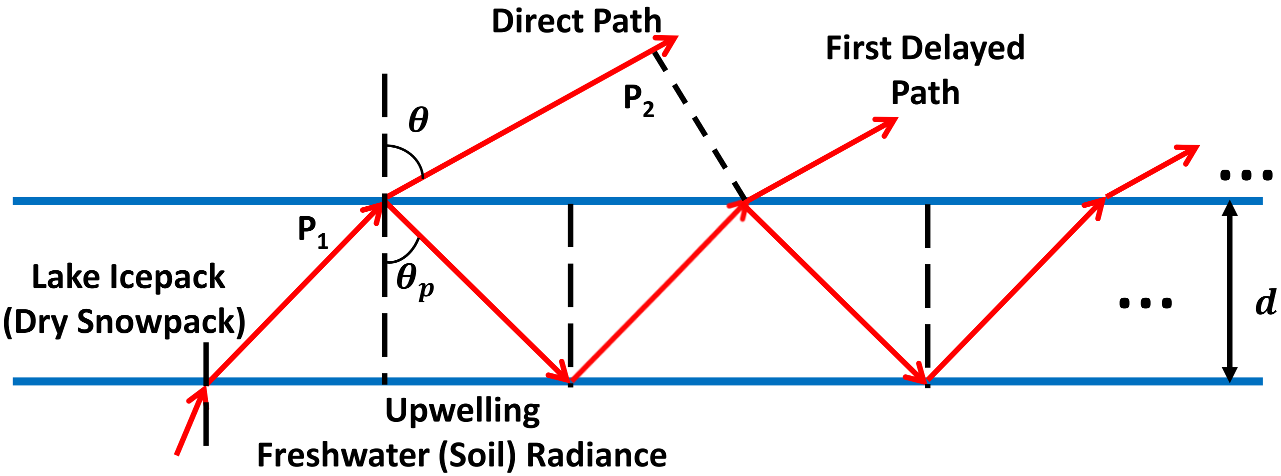
The signal is zero padded and a Hamming window is used for $w(f)$.
Lake icepack measurement on South Sturgeon Lake at $\theta_0 = 3.2^o$ (March 2018).

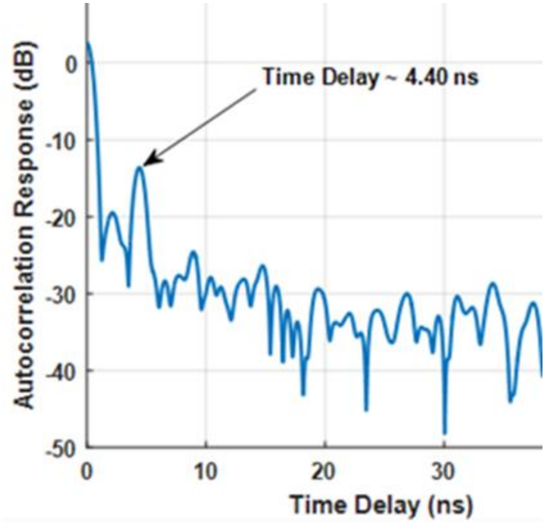
WiBAR Operational Requirements

- Multi-path delays are nanoseconds: } Need ~ 1 GHz bandwidth
- Absorption in the pack is negligible:
  - ✓ Dry snowpack
  - ✓ Freshwater icepack (lake icepack)

  } Target must be below 0ºC
- Volume scattering is negligible:
- Surfaces are electrically smooth:
  - ✓ **Ice**: 7 – 10 GHz (X-band)
  - ✓ **Snow**: 1- 3 GHz (L-band)

} Use long wavelength





Measurement Field Campaign

	Lake Icepack
Frequency Range	7 – 10 GHz
Measurement Location and Time	Douglas Lake at the UMBS in March, 2018
View Angle	Nadir to 70.2°
Antenna	ATM 112-443-6 X-band horn w/ 10^{o} beamwidth
Calibration Targets	Sky (e~0) and Matched Load (e~1)

Lake Icepack Measurement

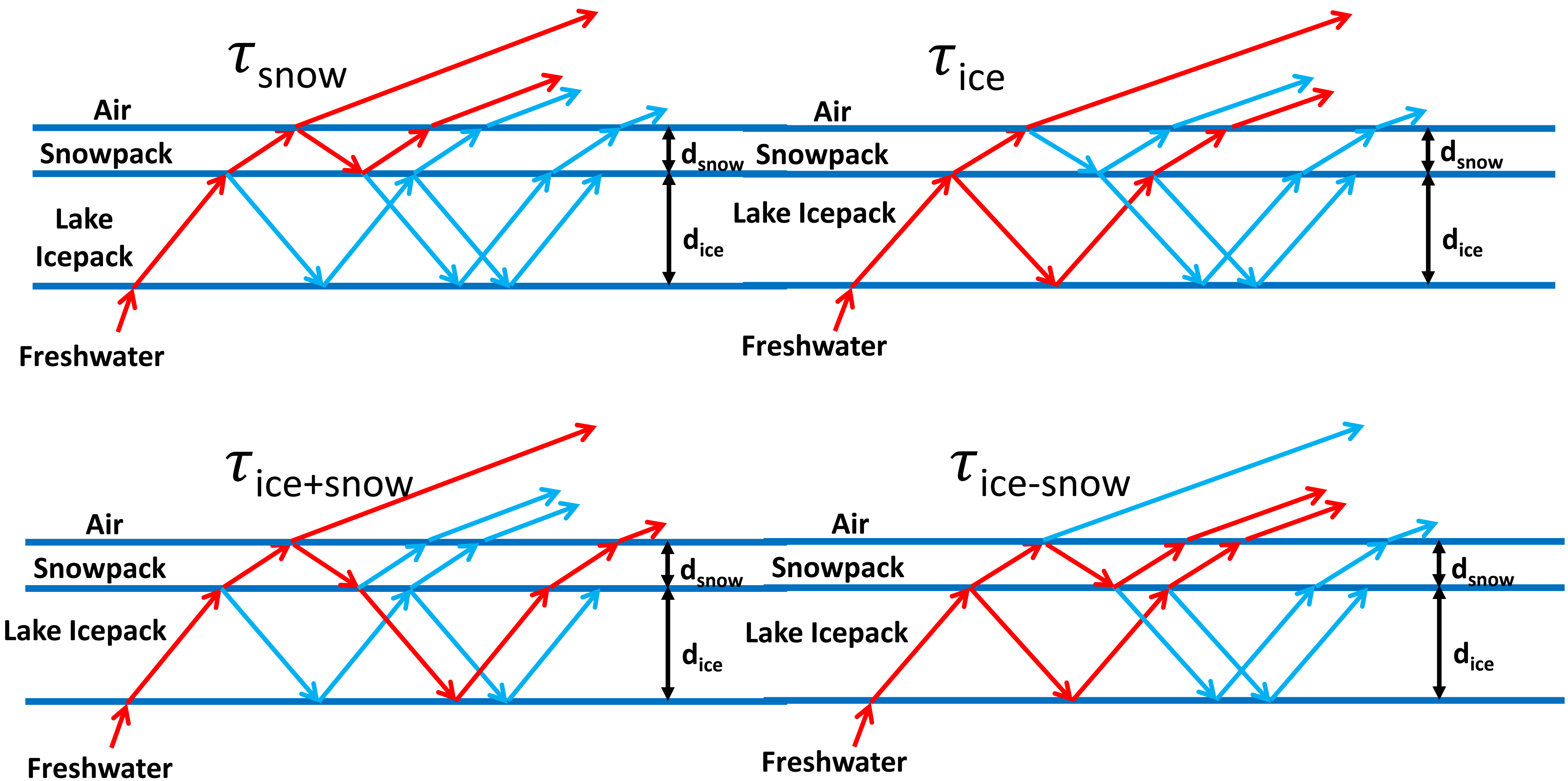
Purpose: assess WiBAR measurement concept over wide variety of conditions.

Lake ice has large signal compared to snow pack.

Advantage: small, portable, wide (3 GHz) bandwidth

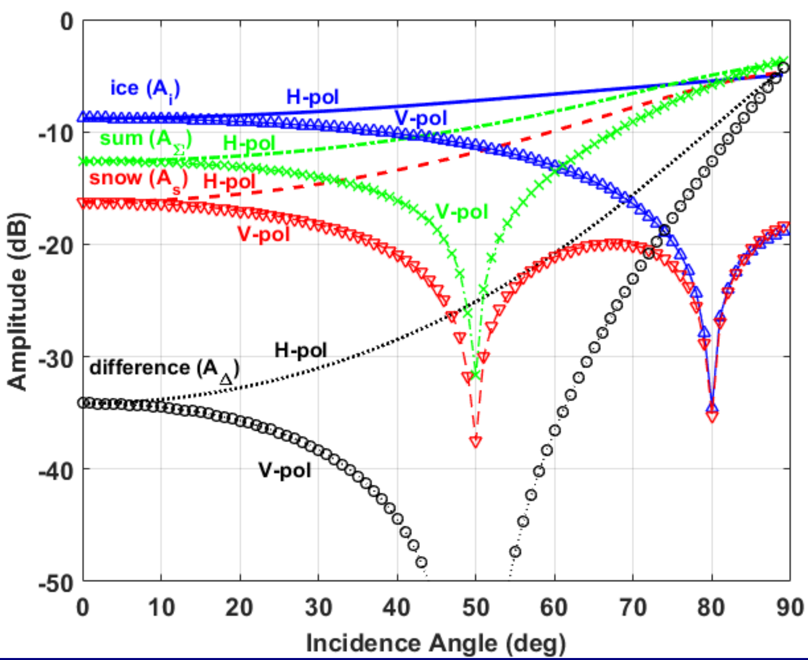
Sky Measurement

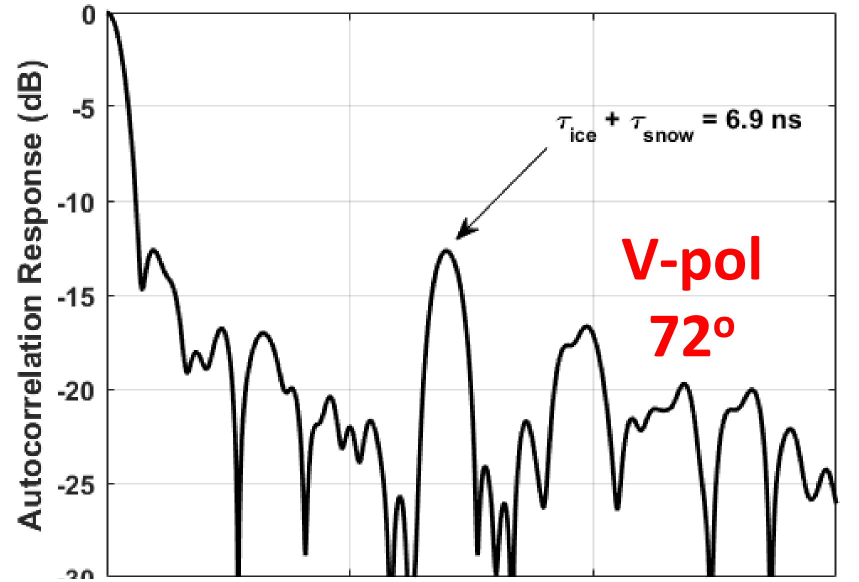
Clear cut multiple layers: snow over ice

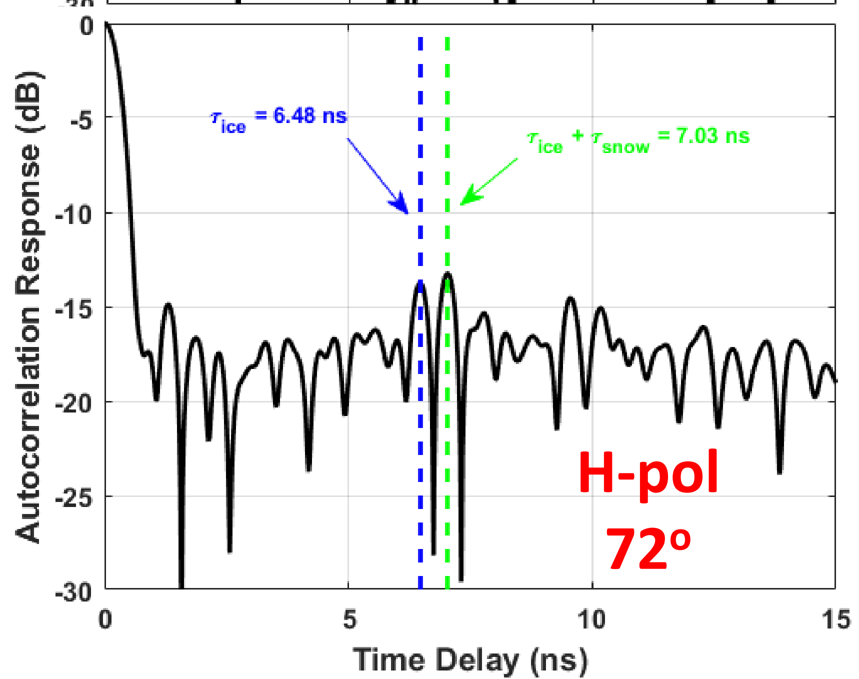


Dual pol with snow over ice

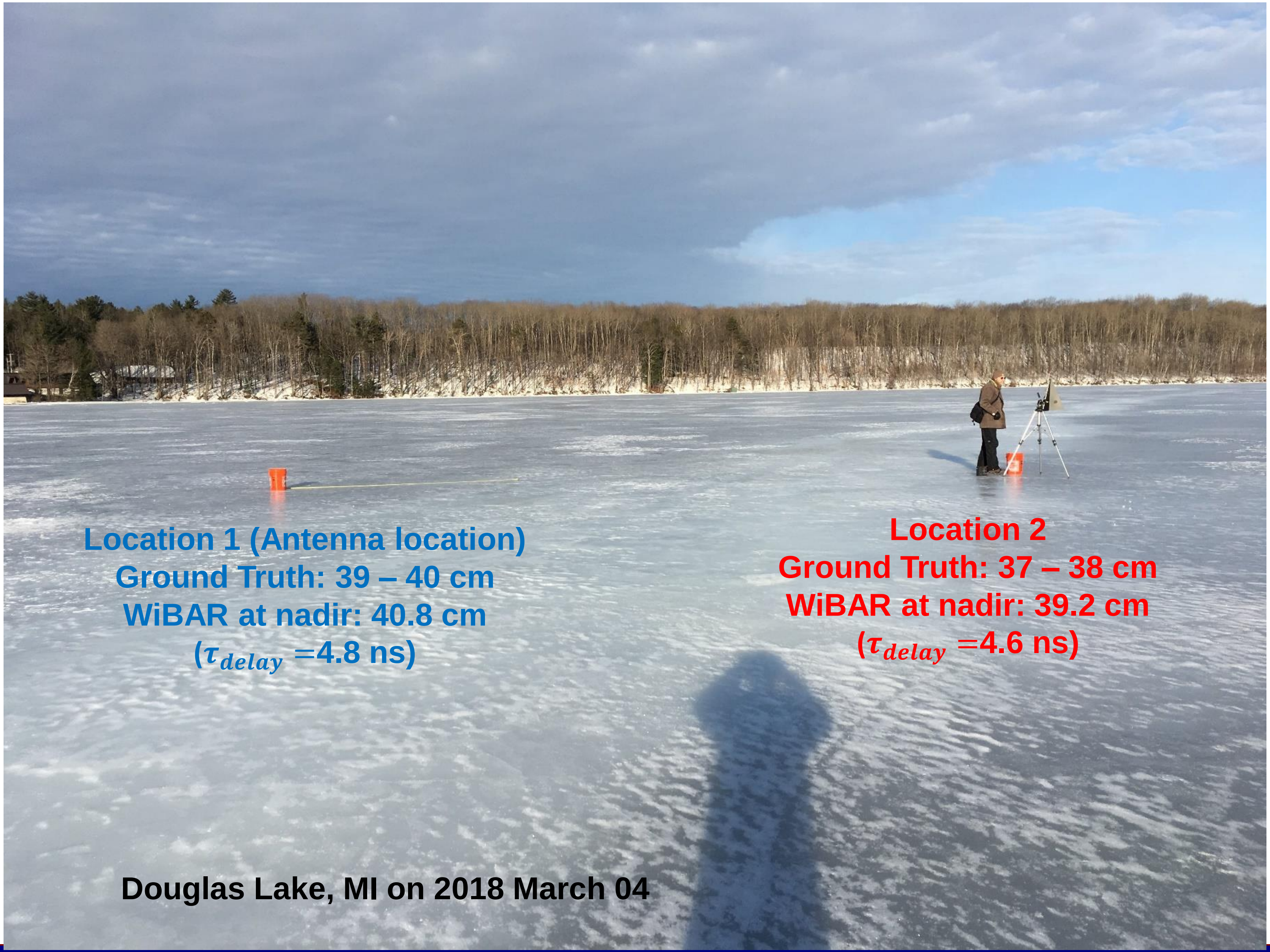
- S. Sturgeon Lake, MN
  2018 Mar 07
- Snow too thin by itself (19cm) to distinguish from zero-lag
- Snow+ice can be seen distinct from ice alone (59cm) in H-pol





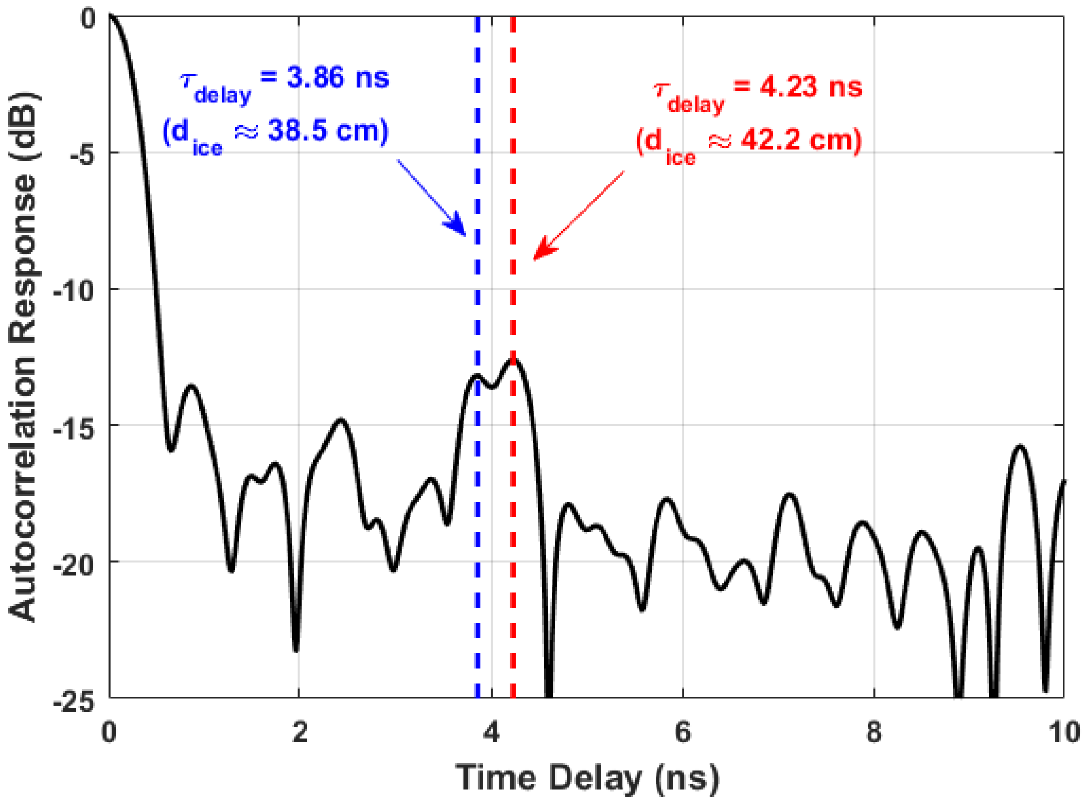


Lake Ice with Variable Thickness



A Measurement with Multiple Thicknesses in FOV

- Measurement is done at $\theta = 70.2^o$ on Douglas Lake on March 03, 2018 around 10:00 AM
- There was no snow on the ice.
- The ice-air boundary was a little rough (there is no surface profile).
- The air temperature was -7.0 ºC at 9:28 AM and -0.8 ºC at 11:41 AM.



Sub-pixel variability of about 3 cm with 3 GHz bandwidth.

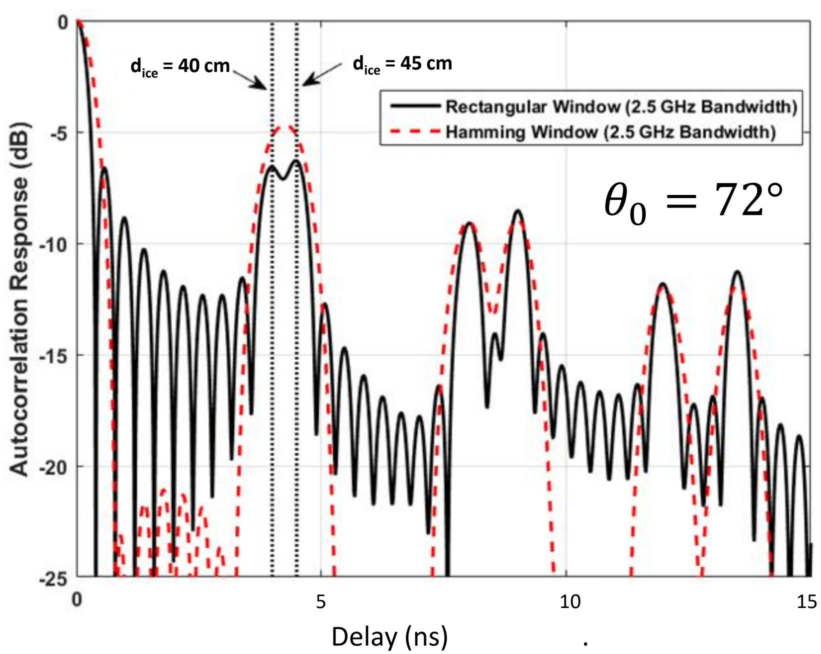
The autocorrelation response of the lake icepack measured on Douglas Lake, MI on 2018 March 03

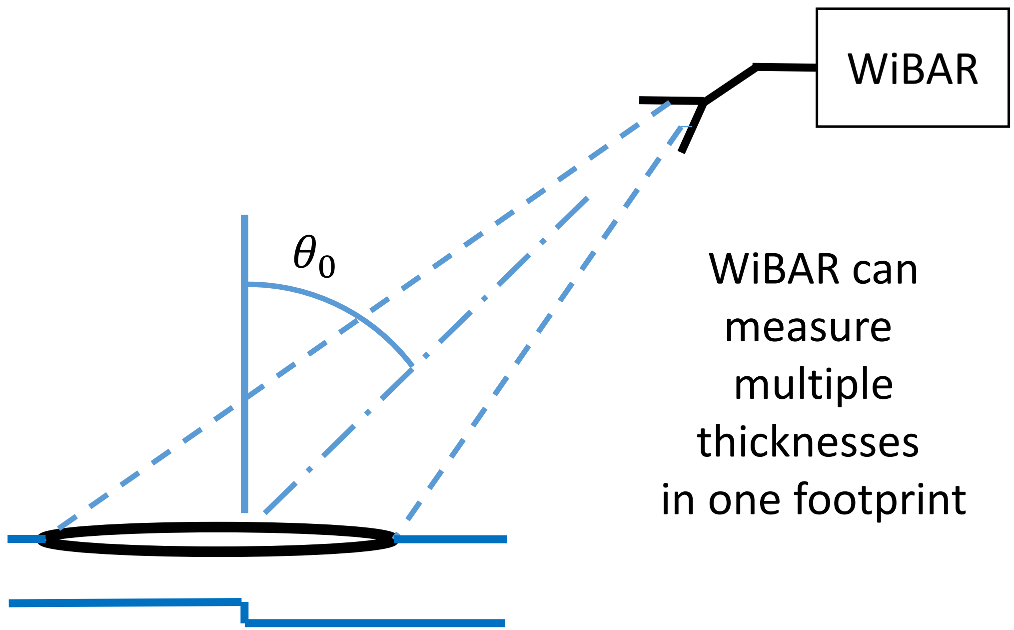
Sub-Pixel Variability of the Measured Pack Thickness

- The measured Autocorrelation Function is a weighted sum of all local Autocorrelation Functions within the footprint

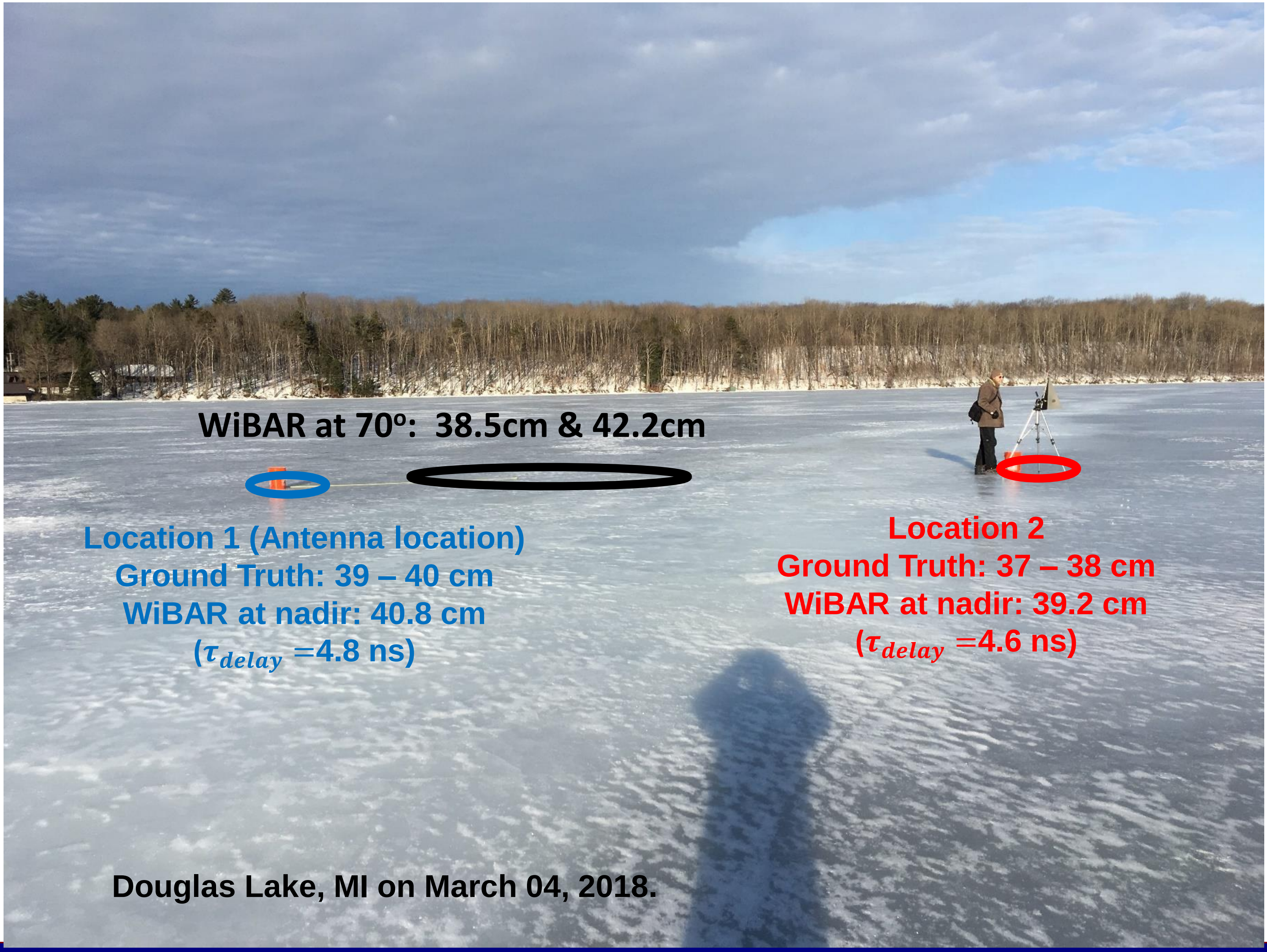
$$ACF_{meas}(\tau) = \frac{1}{\Omega_M} \iint ACF(\tau)\, g(\theta, \theta_0) d\Omega \qquad \Omega_M = \iint g(\theta, \theta_0)\, d\Omega$$

- The weighting is provided by the antenna gain pattern $g(\theta, \theta_0)$
- Finite bandwidth allows smearing: autocorrelation peak broadens





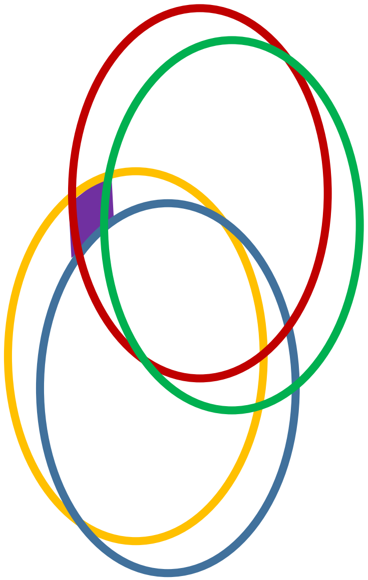
WiBAR finds a transition in ice thickness



Spatial oversampling to mitigate large footprint?

- Low frequency radiometry: large footprint
- Rapid sampling (this IIP project): oversampling possible

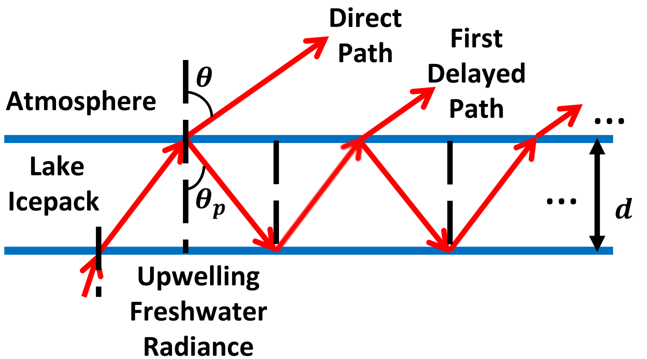
- Each measurement contains not one average value, but information on the pdf of the thicknesses
- The purple area contributes to the red and yellow footprints, but not to the green or blue
- Can a modified Backus-Gilbert help us recover a best estimate for the small purple area?



WiBAR: conclusions

- **Objective:**
  - To remotely sense the vertical extent of dry snowpack and lake icepack
- **Method:**
  - Observe coherent effects to remotely sense the propagation time τ_{delay} of multi-path microwave emission
- **Benefits:**
  - Passive: Low power (=low cost)
  - Microwave: All weather operation capability
  - Deterministic: No algorithm calibration
  - Linear: signal variability contains information
- **Challenges:**
  - Wide bandwidth: RFI succeptability
  - Large footprint

Lake icepack



Wideband Autocorrelation Radiometry (WiBAR)

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