Wideband Autocorrelation Radiometry for measuring Snow and Ice thickness

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Outline

- Measurement concept
- Instrument architectures
  -- calibration
- Initial results
- Conclusions
Motivation

• Snow on the ground is a major source of fresh water around the globe
• Seasonal snow packs are changing with the climate
• Wideband Autocorrelation Radiometry (WiBAR) is
  – Microwave, and thus has all weather capability
  – Passive, and thus is relatively low power
  – Sensitive to layered structures,
    and thus responds to snow depth, and not much else.
Remote sensing of snow, today

\[
SD = k(T_{B19} - T_{B37})
\]
WiBAR Measurement Concept

\[ z = d = SD \]

\[ z = 0 \]

Atmosphere

Snow Pack

Ground

\[ \theta \]

Low Frequency Autocorrelator

\[ \varepsilon(z) \]

\[ c\tau_{\text{delay}} = 2 \int_{0}^{d} \frac{k(z)}{k_0} dz \]

direct ray w/ itself

delayed ray w/ direct ray

Autocorrelation

Delay
WiBAR Measurement Concept

For snow: \( \frac{1}{2} c \tau_{\text{delay}} \approx \left( SD + \frac{\rho_w (n_i - 1) \text{SWE}}{\rho_i} \right) \cos \theta \)
WiBAR Measurement Concept

For snow: \( \frac{1}{2}c\tau_{\text{delay}} \approx \left( SD + \frac{\rho_w}{\rho_i(n_i-1)SWE} \right) \cos \theta \)

\( z = d = SD \)

\( z = 0 \)

Atmosphere

Snow Pack

Ground

Direct Ray

Delayed Ray

\( \varepsilon(z) \)

Low Frequency Autocorrelator

\( c\tau_{\text{delay}} = 2 \int_0^d \frac{k_z(z)}{k_0} dz \)

Delay

direct ray w/ itself
delayed ray w/ direct ray
Model Assumptions

• Absorption in the slab is negligible
  – Snow must be dry

• Scattering within the slab is negligible

• Surfaces are smooth horizontally, distinct vertically
  – H-pol has higher Fresnel reflectivities than V-pol
  – Wavelength must be long: L-band (1-3GHz) for snow
Model Assumptions

• Absorption in the slab is negligible
  – Snow must be dry; ice must be freshwater ice
• Scattering within the slab is negligible
• Surfaces are smooth horizontally, distinct vertically
  – H-pol has higher Fresnel reflectivities than V-pol
  – Wavelength must be long: L-band (1-3GHz) for snow
    X-band (7-10GHz) for ice
WiBAR Measurement Concept

\[ \varepsilon(z) = \varepsilon_i = 3.18 \]

For ice:
\[ \tau_{delay} = \frac{2d}{c} \sqrt{\varepsilon_i - \sin^2 \theta} \]

For snow:
\[ \frac{1}{2} c \tau_{delay} \approx (SD + \rho_w \frac{n_i}{n_{i-1}} SWE) \cos \theta \]

\[ c \tau_{delay} = 2 \int_0^d \frac{k_z(z)}{k_0} dz \]
Instrument Concept

• Direct measurement
Instrument Problems

• Direct measurement

Problem: variable microwave delay is not readily available
Solution? Do autocorrelator digitally?
Rapid Instrument Development

- Get to time domain from frequency domain

\[ R(\tau) = \text{FFT}^{-1}\{S(f)\} \]

Antenna → Low Noise Amplifier → Band Pass Filter → Spectrum Analyzer → IFFT → \( R(\tau) = \text{FFT}^{-1}\{S(f)\} \)

Frequency, \( f \)

\( 1/\tau_{\text{delay}} \)
It’s a temporal measurement

• Relative, not absolute, power measurement
  – Don’t need fancy radiometer thermal control

Do need lots of bandwidth:
for min 10cm of snow, need $B \sim 2$GHz
Instrument Prototype
WiBAR instrument, take 2

Our X-band WiBAR for lake ice
L-band & S-band WiBARs deployed at U-Mich Bio Station
L-band WiBAR hardware

- Thermoelectric cooler (not implemented)
- RF electronics
- Horn antenna throat
- C&DH electronics (hidden from view)
- Internet hardware
- Video camera
WiBAR: the Frequency Spectrum

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

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

Calibration:

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

$K$: 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

Lake icepack
$\theta_0 = 3^\circ$
S. Sturgeon Lake, MN
2018 Mar 07
WiBAR: the Autocorrelation Function

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

\[
\Phi(\tau) = \int_{f} e(f)w(f)e^{-j2\pi f \tau} df
\]

The signal is zero padded

\( w(f) \): Hamming window

Ground truth:

\( d_{\text{ice}} = 58 - 59.5 \text{ cm} \)

\( \theta_0 = 3^\circ \)

S. Sturgeon Lake, MN
2018 Mar 07
Time Lag Angular Dependence

\[ \tau_{\text{delay}} = \frac{2d_{\text{ice}}}{c} \sqrt{\varepsilon_{\text{ice}} - \sin^2 \vartheta} \]

Douglas Lake, MI; 2016 Mar 03.

Ground truth of 14” thickness from augered hole.

\( \tau_{\text{delay}} \downarrow \) as \( \vartheta \uparrow \) is a signature of a single-layered emitter.
Bare ice

Theoretical values from ground truth and

$$\tau_{delay} = \frac{2d_{ice}}{c} \sqrt{\varepsilon_{ice} - \sin^2 \theta}$$

RMSE=0.09ns
Snow-covered ice

Theoretical values from ground truth and

\[ \tau_{\text{delay}} = \frac{2d_{\text{ice}}}{c} \sqrt{\varepsilon_{\text{ice}} - \sin^2 \theta} \]

RMSE=0.10ns
Snow, w/ RFI

Remote sensed: 62.5 cm

Ground truth: 64 cm

1-3 GHz, 100 traces
RBW=3MHz, VBW=300Hz
Sweep time 8.9s/trace
Measurement Benefits

• Direct measurement of accumulation
  – **Spread** related to sub-pixel variability?
A Measurement with Multiple Thicknesses

\[ \tau_{\text{delay}} = 3.86 \text{ ns} \]
\[ (d_{\text{ice}} \approx 38.5 \text{ cm}) \]

\[ \tau_{\text{delay}} = 4.23 \text{ ns} \]
\[ (d_{\text{ice}} \approx 42.2 \text{ cm}) \]

\( \theta_0 = 70^\circ \)

Douglas Lake, MI
2018 Mar 03

Lake icepack
(no snow)
WiBAR finds a transition in ice thickness

Location 1 (Antenna location)
Ground Truth: 39 – 40 cm
WiBAR at nadir: 40.8 cm
($\tau_{\text{delay}} = 4.8 \text{ ns}$)

Location 2
Ground Truth: 37 – 38 cm
WiBAR at nadir: 39.2 cm
($\tau_{\text{delay}} = 4.6 \text{ ns}$)

Douglas Lake, MI  2018 Mar 04
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 $\tau_{delay}$ 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 susceptibility
  - Large footprint

Wideband Autocorrelation Radiometry (WiBAR)
Backup slides
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

Remote sensing: 11.45 cm

Expected: 12 cm

7-10 GHz, 100 traces

RBW = 3 MHz, VBW = 300 Hz

Sweep time 8.9 s/trace
RFI observed
Simulated effect of RFI
Snow

7-10 GHz, 100 traces

Measured Autocorrelation
Expected Null Result
Expected + 1 std dev

Remotely sensed: 65 cm

Ground truth: 64 cm
Amplitude of ripples

Ratio of powers in delayed path to that in direct path

England, TGRS, Apr 2013
Sub-Pixel Variability of the Measured Pack Thickness

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

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

\[ \Omega_M = \iint g(\theta, \theta_0) d\Omega \]

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

WiBAR can measure multiple thicknesses in one footprint
## Measurement Field Campaign

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<th>Lake Icepack</th>
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**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
Lake Ice with Variable Thickness

Location 1 (Antenna location)
Ground Truth: 39 – 40 cm
WiBAR at nadir: 40.8 cm
($\tau_{delay} = 4.8$ ns)

Location 2
Ground Truth: 37 – 38 cm
WiBAR at nadir: 39.2 cm
($\tau_{delay} = 4.6$ ns)

Douglas Lake, MI on 2018 March 04
Spatial oversampling to mitigate large footprint?

- Low frequency radiometry: large footprint
- Rapid sampling (this 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?
Roughness: \( \exp(-2(ks \cos \vartheta)^2) \)
Coherence Reducers

Effects of **surface roughness**, **volume scattering**, and **finite beamwidth** wrt incidence angle on the peak of the ACF at the desired lag, $\tau_{\text{ice}}$

$$ACF(\tau) = \text{FFT}^{-1}(e(\omega))$$

$$e(\omega) = e_{\text{no lag}} + 2e_{\text{ice}} \cos \omega \tau_{\text{delay}}$$

$e_{\text{no lag}}$ is proportional to ACF at $\tau=0$  
$e_{\text{ice}}$ is proportional to ACF at $\tau=\tau_{\text{delay}}$

Surface Roughness appears to be the largest coherence reducer for thin layers. $ACF(\tau_{\text{delay}}) \uparrow$ as $\vartheta \uparrow$ is a signature of a thin layered emitter.
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