Microwaves and snow grains:
Monitoring the changing mountain snowpack

Michael Durand
School of Earth Sciences
Ohio State University
How much snow do we have?

We don’t know.

Cline et al., 2004
Microwave measurements

Thirty+ years of global, daily measurements have been made.

Accurate retrievals could better quantify the world’s snowpack.
Microwaves are sensitive to snow grain size

Grain size has posed problems for retrieval algorithms
Scale and vegetation issues

Footprints at 37 GHz are $\sim 100 \text{ km}^2$, and vegetation transmissivities can be low.

Retrievals have struggled in mountainous areas.
1. How do microwaves interact with snow?

2. Are scale and vegetation issues tractable?

3. Can SWE be estimated from satellite microwave observations?
Snow stratigraphy
Snow grain evolution

1. 

2. 

3. 

4. 

Colbeck et al., 1998
Traditional grain size measurements have not been ideal. This has held back snow-microwave science.
Microwave slab and microstructure studies

Simple radiative transfer approach, based on data-driven structural and radiometric measurements.

\[ \frac{dT_{up}}{dz} = \gamma_a(T - T_{up}) + \gamma_s(T_{dn} - T_{up}) \]

\[ -\frac{dT_{dn}}{dz} = \gamma_a(T - T_{dn}) + \gamma_s(T_{up} - T_{dn}) \]

\( \gamma_s >> \gamma_a \)

Mätzler, 1987; Wiesmann et al., 1998
Scattering controlled by microstructure autocorrelation function

\[ A(x) = \exp\left(-\frac{x}{L}\right) \]

Autocorrelation function is lab-measurable

* departure from exponential can be significant

MEMLS ~ by Christian Mätzler, Andreas Wiesmann, 1999
Correlation length explains scattering

Wiesmann et al., 1998
The microwave emission model of layered snowpacks (MEMLS) allowed consideration of full snowpack stratigraphy.

Wiesmann & Matzler 1999
Relating objective microstructure to legacy grain size measurements

Note ~ this does not remove the issue of observer subjectivity
In-situ experiment (2003)

Part of NASA Cold Lands Processes Experiment Elder et al. 2009
MEMLS - model accuracy

Durand et al., IEEE, 2008
Stratigraphy controls brightness

Source of uncertainty in model simulation, in kelvins

19 GHz

37 GHz

Durand et al., IEEE, 2008
In-situ experiment, revisited

Experiment with new methods for measuring snow grain size

Simultaneous microwave measurements

Colorado, 2010
Lab measurement of correlation function

Snow is cast in the field, sectioned x20 and photographed in the lab, classified and $A(x)$ measured (stereology)
Field measurement of specific surface area

$$SSA = A \exp\left(\frac{r}{t}\right)$$

$$L = \frac{4(1 - \nu)}{SSA}$$

$$D = \frac{6}{SSA}$$

Matzl & Schneebeli 2010
Improved simulation accuracy

Brightness temperature model error

Model (Stereology)

Observation

Single-Layer  Hand-Lens  NIR Camera  Stereology

0  10  20  30
Using the SSA measured via µCT gave accurate $T_b$ simulations. Hand-lens measurements underestimated the scattering. The departure from exponential $A(x)$ is key here.
Remaining issues...

Photo: C. Mätzler: the Snow Grain Size Working Group, La Grave, 2013

More data: lab $A(x)$, field SSA, simultaneous $T_b$
1. How do microwaves interact with snow?

2. Are scale and vegetation issues tractable?

3. Can SWE be estimated from satellite microwave observations?
Microwave footprints are large

Footprints at 37 GHz are \(~100 \text{ km}^2\)
Cold Lands Processes Experiment

Airborne microwave measurements via the CU PSR, coincident with depth transects, LiDAR and snowpits (2002-2003)

Stankov et al., 2008
Spatial variability in depth, grain size, and stratigraphy one of four ISAs

$D_{\text{max}}$-L map used

Vander Jagt et al., 2013
Modeled $T_b$ and observed $T_b$ across four 1 km$^2$ ISAs show fairly good agreement.

Vander Jagt et al., 2013

MEMLS used to model $T_b$ from measured snow properties.
Snow depth at 10 m derived from repeat LiDAR flights
Stratigraphy estimated via stochastic snowpit interpolation

Given grain size and stratigraphy variability, how much does the average $T_b$ change as a function of average depth?

Vander Jagt et al., 2013
For all four ISAs there is still a (modeled) sensitivity of the average $T_b$ to the average depth.

What happens when this is sampled by a coarse non-linear antenna pattern?

Vander Jagt et al., 2013
There is little change in the sensitivity of depth to $T_b$ as a function of scale of the microwave measurement.

Vander Jagt et al., 2013
Remaining issues...

Sensitivity to average depth does not give hi-res SWE.
Also, vegetation attenuates microwaves.
Vegetation absorbs attenuates microwaves, reducing sensitivity of $T_b$ to depth.

How much of the global SWE is measurable using microwaves?

Vander Jagt et al., 2013
A function for vegetation transmissivity as a function of LAI was used to calculate transmissivity, and overlaid on SNODAS SWE.
Measurable fraction of total SWE in select basins in the Rockies ranges from 35-60% at airborne resolution: less at satellite.
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Microwave spatial patterns from space

37 GHz measurements over Sierra Nevada
Kern River, Sierra Nevada, California

How well does the $T_b$ correlate with snow pillow snow water equivalent?
Microwave measurements of the upper Kern

AMSR-E measurements & variable scan geometry

Li et al., 2012
Microwave sensitivity to SWE

Lowest $T_b$ value of each year is highly correlated with snow accumulation
2006 is an outlier in several basins. Kern shows one of the best correlations. $r^2$ shown exclude 2006
For basins with less than 20% tree cover, there is snow information in the AMSR-E $T_b$. But how best to solve the inverse problem, and map SWE from $T_b$?
SWE estimation
A data assimilation framework

Operating principle is calculation of an empirical covariance between coarse $T_b$ and SWE at higher resolution.

\[ y_{\text{posterior}} = y_{\text{prior}} - K[z_{\text{predicted}} - (z + v)] \]
Sequential data assimilation

1) Propagate forward in time
Need state model

2) Update with new measurement \( z_{i+1} \)

Need measurement model to relate measurement to states
In situ assimilation experiment

Durand et al., GRL, 2009
Assimilation framework applied to point measurements

Flanner & Zender [2006] parameterized model for grain growth used to accurately model SSA and L

\[
\frac{\partial D}{\partial t} = \left. \frac{\partial D}{\partial t} \right|_{t_0} \left[ \frac{\tau}{2 (D - D_t + \tau)} \right]^{1/\kappa}
\]
Water resources monitoring

Data assimilation results

Durand et al., GRL, 2009
Synthetic Experiment:
True simulation, and synthetic measurements
Open-loop simulation vs. Assimilation
Operational estimate

Synthetic Observations: Microwave (25 km) and NIR (1 km)

Durand et al., JGR, 2007
True snow depth is recovered

Model used to predict spatial SWE pattern

True
Assimilation
Model
Operational
Basin-scale AMSR-E experiment

First guess: SWE from 3-layer SAST at 90 m forced with disaggregated NLDAS (UCLA)

Predicted $T_b$ from MEMLS using improved Born approximation

We're just treating grain size as a "nuisance variable" with very high uncertainty in the model

Aggregated $T_b$ (right)
AMSR-E (left)

Difference used to update SWE

Li et al., in prep
SWE compared to snow courses improved for CBT, UTY. Slightly degraded at UTY. Melt timing still needs significant improvement.

Additional years, model improvements, validation against streamflow all in the works.

Li et al., in prep
Remaining issues...

Computationally expensive, issues remain with modeling grain size, especially during large snowfall events. It is hard to model covariance functions during snowmelt.
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Summary

• How do microwaves interact with snow? 
Correlation length and stratigraphy are key

• Are scale and vegetation issues tractable? 
Coarse $T_b$ sensitive to average depth. Much SWE measurable despite vegetation

• How to extract information on SWE from $T_b$? 
Modeling grain growth and data assimilation provide a path forward
Thank you
Additional and Removed Slides
Scattering controlled by microstructure autocorrelation function

\[ I = \int_{0}^{\infty} A(x) x \sin(\alpha x) dx \]

\[ \gamma^{bi}(\hat{o}, \hat{i}) = v(1 - v)(\epsilon_2 - \epsilon_1)K^2Ik^4 \sin^2 \chi \]

MEMLS ~ by Christian Mätzler, Andreas Wiesmann, 1999
**Theory:**

\[ L_o = \frac{4(1 - v)}{SSA} \]

\[ L_o = \left( - \frac{dA}{dx} \right)_{x=0} \]

SSA is field-measurable*

Scattering coefficient requires \( A(x) \) parameterization

\[ I = \int_0^\infty A(x)x \sin(\alpha x) \, dx \]

An exponential fit is usually assumed, but \( A(x) \) usually not exponential

\[ L_e = \beta L_o \]
Confirmation that the relationship between $T_b$ and snow depth is far from simple or univariate: note that this includes the model results

Departure from one-one relationship due to vegetation and grain size

Vander Jagt et al., 2013
Microwave frequencies

- Sensitive only to ground temperature
- Sensitive to snow depth and grain size
- Sensitive only to snow grain size

Increasing Frequency

- 6.9 GHz (AMSR-E)
- 89 GHz (MODIS, 0.4 µm)

6.9 GHz ~ 4.3 cm
89 GHz ~ 0.33 cm

Snow grains
True grain size is recovered

True

Assimilation

Model

Vegetation

Durand et al., JGR, 2007
Grain size profiles

Grain radius, µm

Molotch et al., in prep.
The current NASA product

Algorithms matter.

Tedesco and Narvekar, 2010
What do we want to measure?

Theory: scattering in the microwave is controlled by surface-area-volume ratio:

\[ SSA = A/V \]

SSA is the ratio of total ice surface to ice volume

The “optical equivalent” grain diameter is the diameter of a sphere with the same SSA as the irregular snow

For a sphere: \[ D = 6/SSA \]
Stereology samples
Field microwave measurements
Temperature gradient growth

Vapor Diffusion, $D$

Grain growth rate $\propto D \propto \frac{\partial T}{\partial z}$
Measuring grain size

Traditional grain size measurements

Spectrometer grain size measurements
Microwave scattering

Rayleigh: \[ \gamma_s \propto D^6 f^4 \]

Snow: \[ \gamma_s \propto I(D) f^4 \]
MEASUREMENTS

Microwave (three days) at 37 and 19 v-pol, NIR camera, stereology, density, temperature, stratigraphy (two pits):
1. February 22, 2010
2. February 23, 2010
Samples were cast with dimethyl phthalate and shipped to CRREL. Photos by Zoe Courville.
GRAIN SIZE RESULTS

NIR camera compares fairly well to the stereology
Photographs from left: Valley floor, Thunderhead, and Stormpeak Laboratory sites (Photographs courtesy Danielle Perrot).

Below: digital elevation models via USGS of the Rabbit Ears Mesocell Study Area of CLPX (left), and a wireframe model of the area (right).
**Valley Floor**
Snow was isothermal, with some liquid water held in pore spaces in the top part of the pack. NIR photography was used to characterize the profile of De. Below 17 cm depth, values of De decrease below 1.0 mm. The De for the ice layer visible in the photograph below was 1.6 mm estimated via stereology, and over 3.0 mm estimated via photography. Scalebars in the snow cast photos (right) are 1,000 μm.

**Christie Peak**
The bottom 80 cm of the pack had De of approximately 500 μm, increasing to 1,000 μm for the top twenty cm. Densities ranged from 370 kg m⁻³ near the bottom of the pack to 400 kg m⁻³ near the top (measured via both cutter and stereology). Snow was nearly isothermal, but showed no signs of liquid water. Values of De are approximately a factor of two less than at Valley Floor.

**Thunderhead**
Melt had not yet begun, with typical daytime mid-winter snow temperature profiles observed. Snow depth at this elevation was nearly twice that at Christie Peak. Values of De measured via stereology decreased from 770 μm near the bottom of the pack to 361 μm near the top, with the exception of the crust: 828 μm via stereology.

A melt refreeze crust of approximately 5 mm in thickness has been buried under several centimeters of new precipitation.