Development of a New Satellite Radar Mission for Snow Mass

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- Mission drivers
- Why Ku-band radar for snow?
- Technical concept
- Field support for retrieval development
- Next steps and SnowEx synergy

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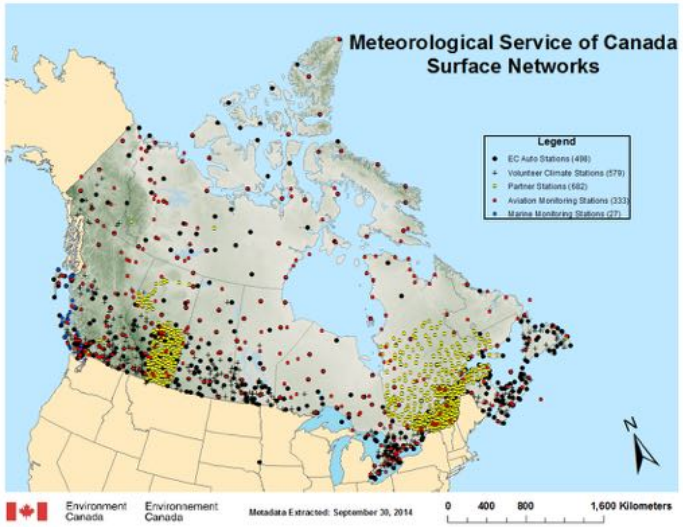
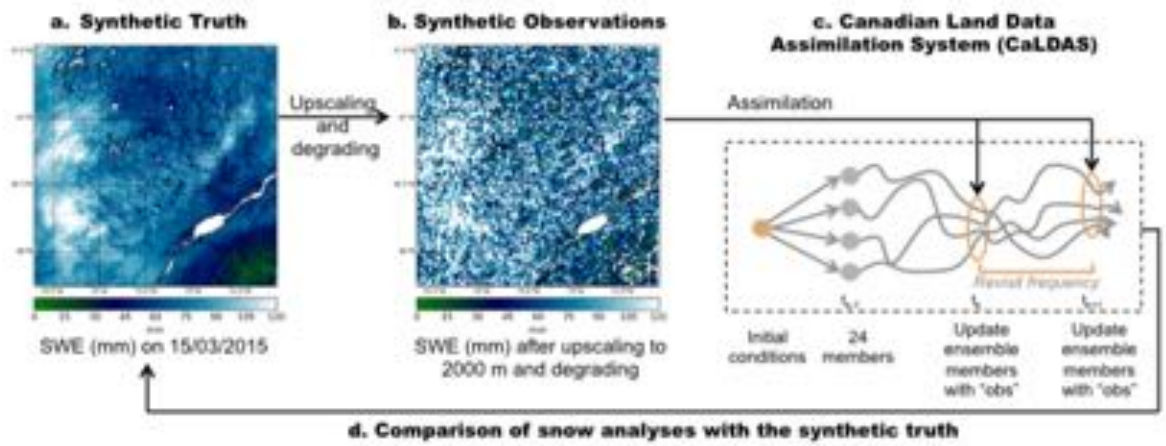
Canada

A Canadian Perspective on Capabilities in Observing and Modeling Snow





Garnaud, et al. (2018), JoH

Conventional observing networks don't provide the coverage or the type of measurements needed

Notable recent improvements in snow modeling at watershed and continental scales (SVS-2, CaLDAS)

Defining a Snow Mass Mission

Environment and Climate Change Canada (ECCC) identified high resolution information on seasonal terrestrial snow mass as a key observation gap (Client)

The most comprehensive snow information comes from coupling observations + modeling + <u>remote sensing</u>:

- ↑ snow extent or fractional cover (optical imagery)
- ↑ high resolution snow depth over limited regions (airborne LiDAR)
- ↔ coarse resolution hemispheric scale snow mass (passive microwave)
- ↓ moderate to high resolution snow mass (critical gap)

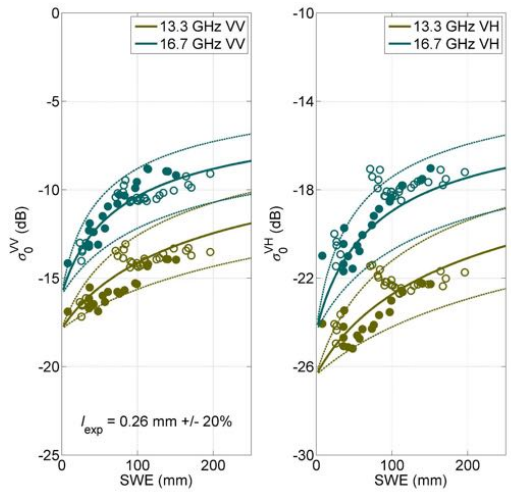
Canadian Space Agency (CSA) engaged to develop mission concept (Facilitator)

Client Side Perspective of ECCC

Improved remote sensing of snow mass is a priority at ECCC:

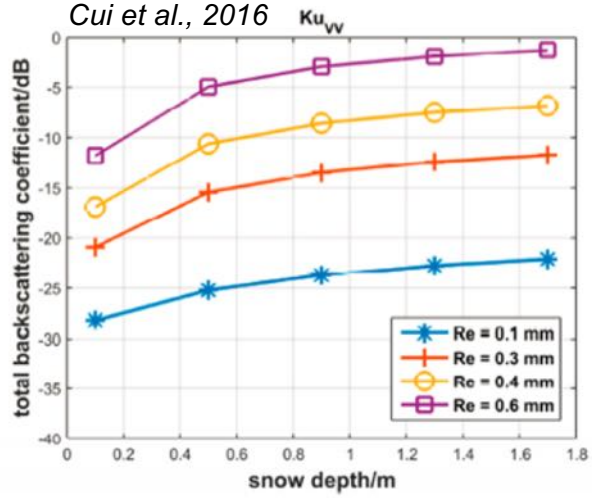
1. Climate services and water availability	⇨	How much water is stored as seasonal snow, how does it vary in space and time?	⇨	**Requires snow mass estimates**
2. Operational environmental prediction	⇨	What is the contribution of snow to the water cycle and how well can we predict it?	⇨	**Requires assimilation of remote sensing**

Dual-Frequency Ku-Band Radar for Snow Mass



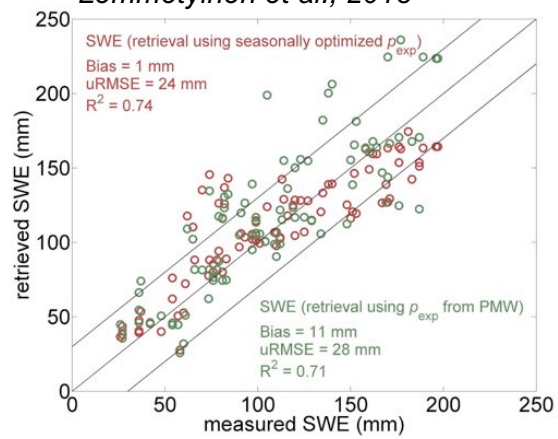
SnowScat backscatter at 13.3 and 16.7 GHz versus SWE, 2009/10 (open symbols) and 2010/11 (filled symbols). Lines show MEMLS simulations +/- 20% of measured microstructure.

Cui et al., 2016



Influence of microstructure related to wavelength, hence two Ku-band frequencies (comparable sensitivity to SWE; different sensitivity to microstructure) are necessary.

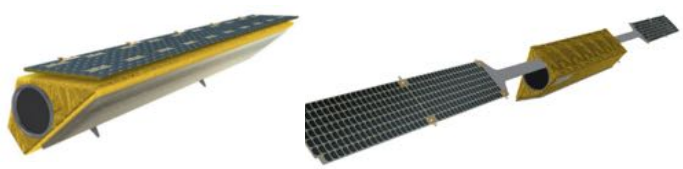
Lemmetyinen et al., 2018



SWE retrieved from dual-Ku band radar backscatter using seasonally optimized effective correlation length(red=radar derived; green=passive microwave derived).

Technical Concept

- Single-aperture **dual-frequency Ku-band** antenna (13.5/17.2 GHz); sequential frequency operation
- Complete coverage of **Canada every 3 days**
- **250 m resolution** (>4 looks), 10 m (single look) for targeted basins
- Canadian OSSE as proving ground (Garnaud et al. 2018)
- While standalone products are possible, focus will be on developing **integrated retrievals** that leverage observational and model-based outputs



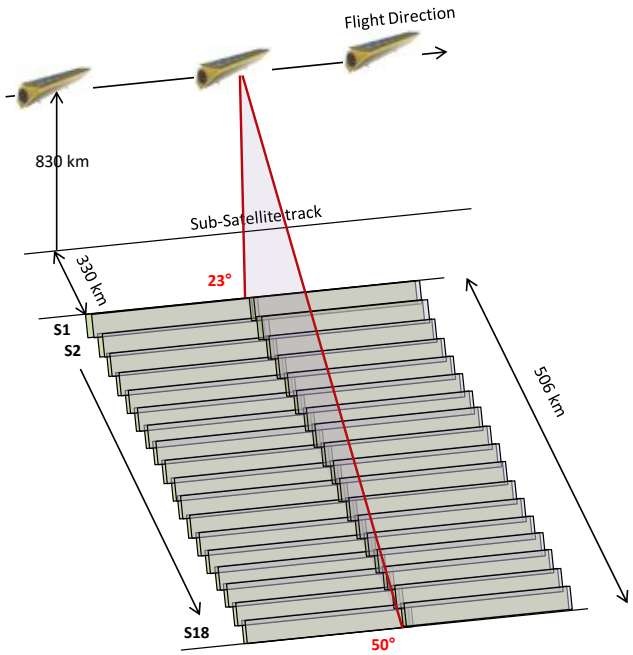
Characteristic	Threshold	Goal
Frequencies	Dual-band operation, 13.5 and 17.2 GHz	
Polarizations	VV; VH	
Ground Resolution	500 x 500m	250 x 250m
Number of Looks	>4	
Acceptable Incidence Angle Range	23° - 55°	23° - 50
NESZ – 13.5 GHz	<-26 dB (VV & VH)	
NESZ – 17.2 GHz	<-25 dB (VV & VH)	
Azimuth and Range DTAR	<-20 dB	
Radiometric stability	<0.5 dB	
Radiometric absolute accuracy	1 dB	0.5 dB

Revisit Period	Minimum Latitude
5 days	All latitudes
3 days	>43°
2 days	>61°
1 day	>65°

Ku-Band Radar Mission Status

- **Pre-phase 0** study to determine feasibility and identify technical concepts completed in 2018
- **Phase 0** contract awarded by CSA June 2019 to Airbus
  - **Pre-cursor mission options are a high priority**
  - **Targeted as a multi-application platform**
- Next step is **Phase A** at CSA, pending preparation of Business Case (spring 2020)

- **Science team** in place to strengthen underlying science case, identify secondary objectives and guide decision-making
- ECCC Airborne radar campaign during 2018/19 winter season at Trail Valley Creek (TVC)



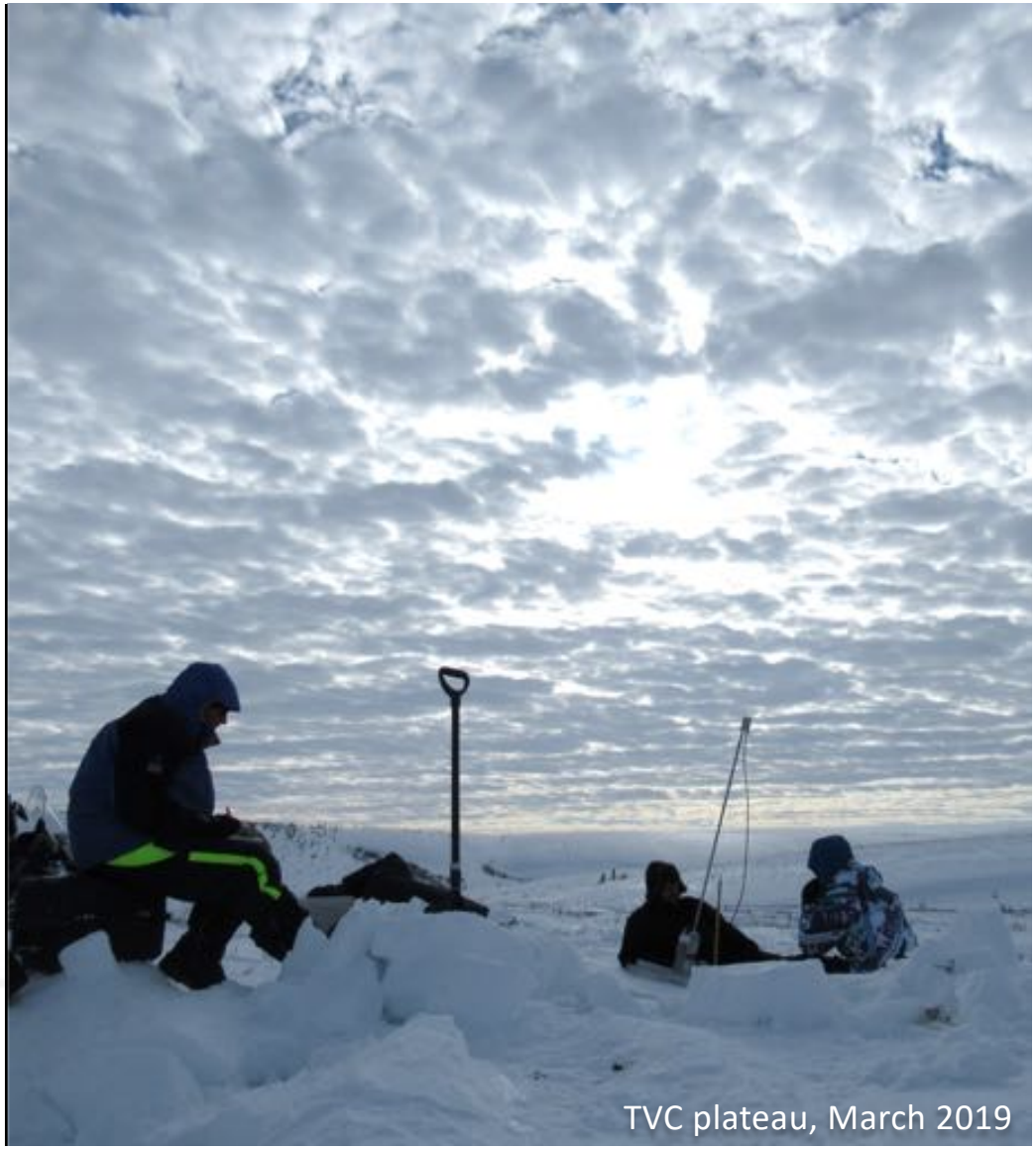
Mission Knowledge Gaps

- **Microstructure variability**
  - Over what scales do we expect variability?
  - Can models account this variability?

- **Background and foreground interactions**
  - Can we separate soil and vegetation?
  - Do we need to see through the trees?

- **Scaling of backscatter retrievals**
  - Are convolution issues important at operational scales? (>250 m)

- **Temporal aspects of retrieval**
  - Can early season observations be used to decompose vegetation and soil?



Trail Valley Creek Snow Experiment

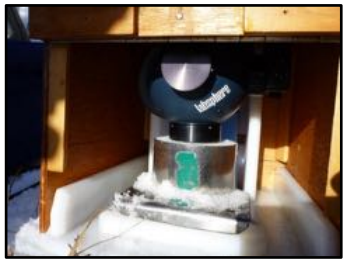
- November 9-23, 2018
  Early season snow; soil freeze-up
- January 7-23, 2019
  Accumulation period
- March 17-31, 2019
  End of season microstructure

Remote Sensing

- Airborne 13.5 GHz (Ku-band) radar
- Single-polarization (VV)
- 2 x 2 m, 100 m swath

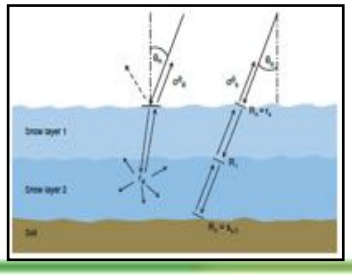
Surface Observations

- Snow distribution measurements (Magnaprobe)
- SnowMicroPen, IceCube microstructure measurements
- Background soil state measurements

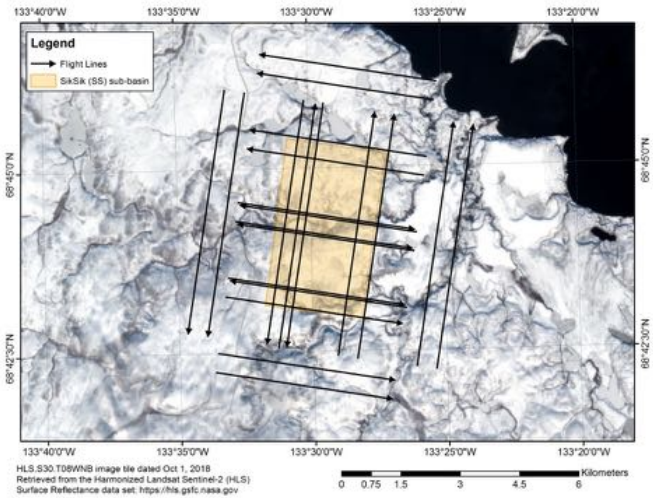


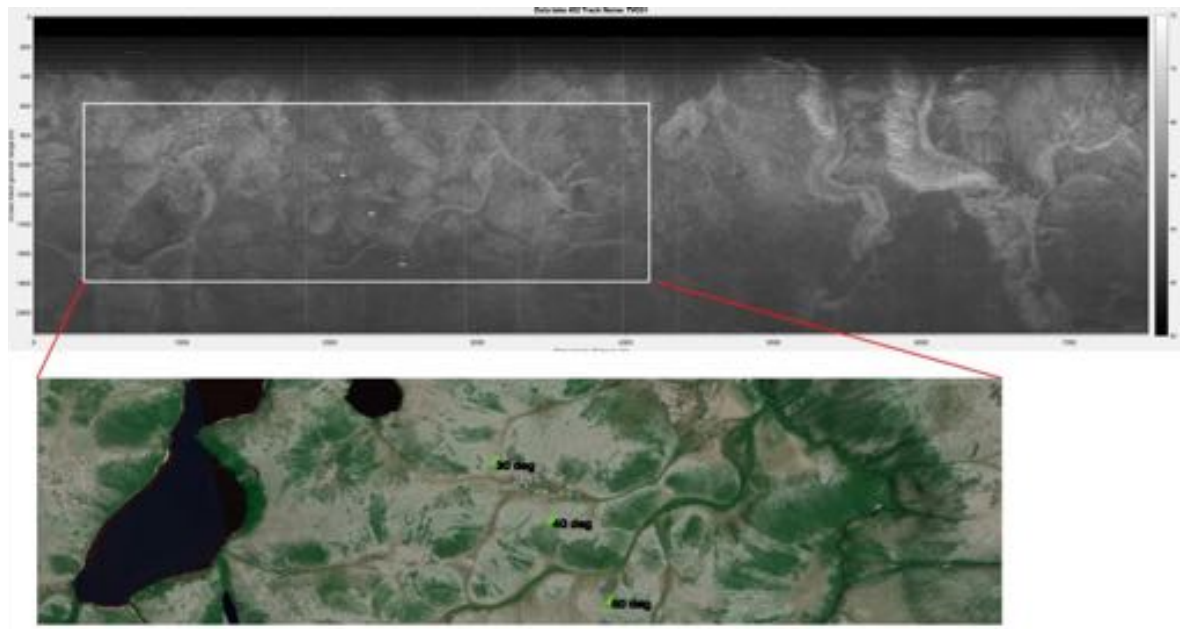
Radiometric Modeling

- SMRT (Picard et al, 2017) active-passive microwave radiative transfer model for snow
- Can use field estimated microstructure in the scattering coefficient



Airborne Radar System





16 flight lines samples 3 times during each campaign

Paul Siqueira's poster for more information

Snow Measurements

Static sites : Revisited each deployment

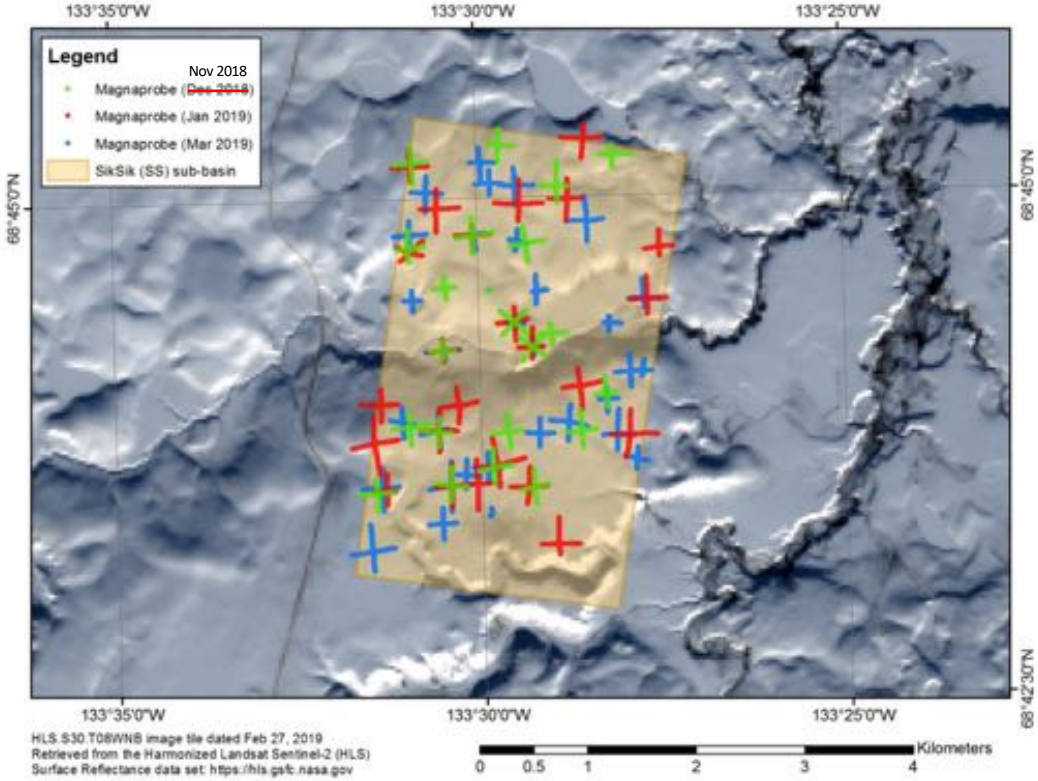
Roving sites: Stratified random selections

Campaign totals

Snow depths:	21946
SMP profiles:	1444
Snow pits:	76

Airborne snow products

Structure from motion (Depth; WLU)
Wide-band FMCW 2-18 GHz (Layering; AWI)
High-resolution LiDAR (Depth; AWI)



	Static	Roving	Total	$\overline{AT}$ [°C]	Crew [#]
November	6	16	22	-20.0	3
January	6	19	26	-28.4	4
March	6	26	32	-8.3	5

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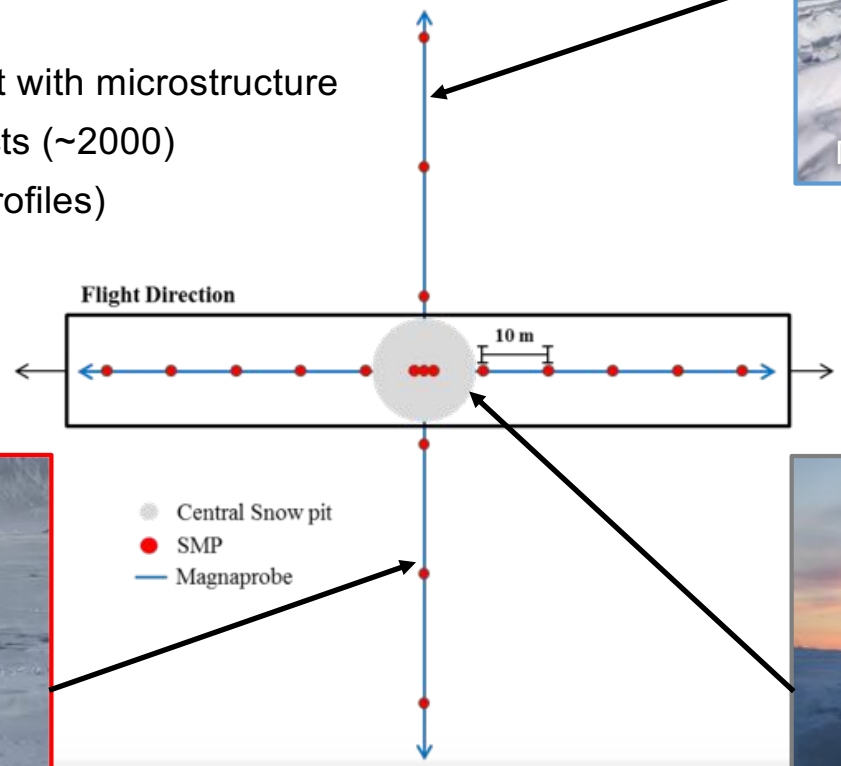
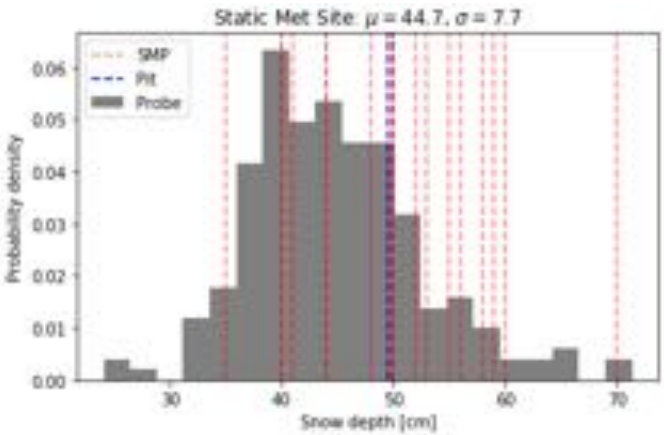
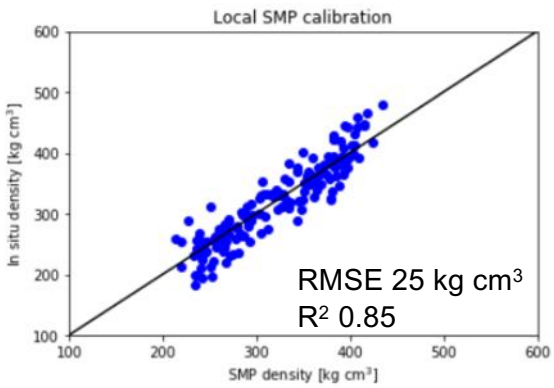
Sampling design

- Focused on characterizing **spatial variability** sub-scale to the radar footprint
- Central '**gold standard**' snow pit with microstructure
- Orthogonal **snow depth** transects (~2000)
- **SnowMicroPen** transects (19 profiles)



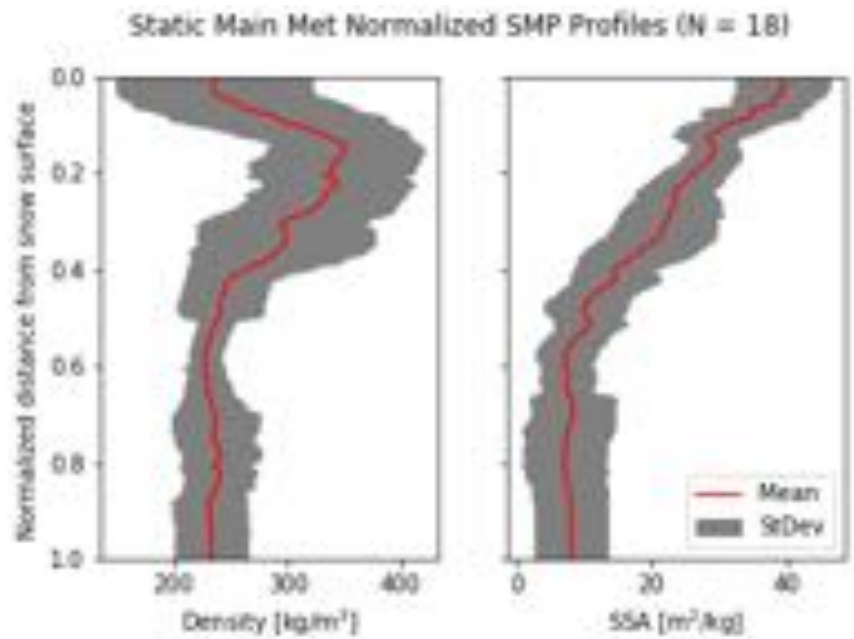


Snow depth distribution from magnaprobe surveys (gray); at snow pit location (blue line) and SMP profiles (red line)



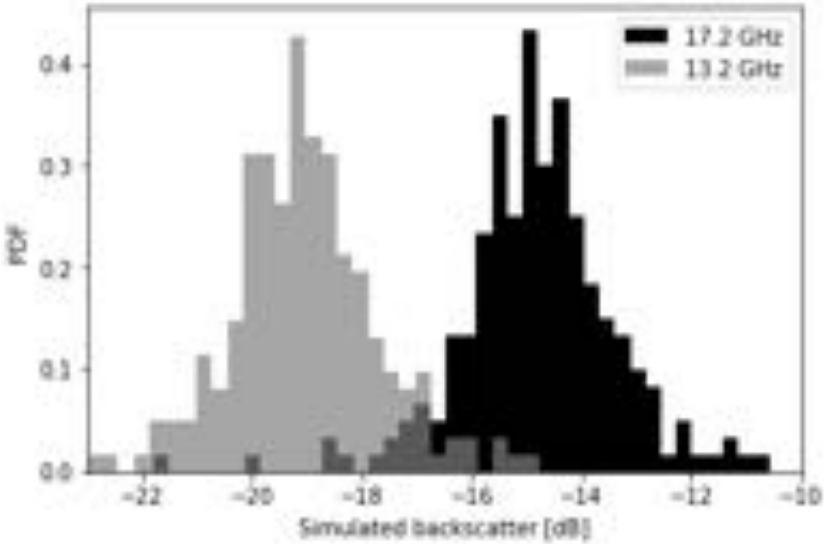
SMP derived snow density recalibrated from Proksch et. al. (2015)

- Central snow pit used to calibrate co-located SMP profile and derive high vertical resolution estimates of density and SSA
- Nearly impossible to characterize snow microstructure within a radar integrated area using a single snow pit so multiple SMP measurements improve this



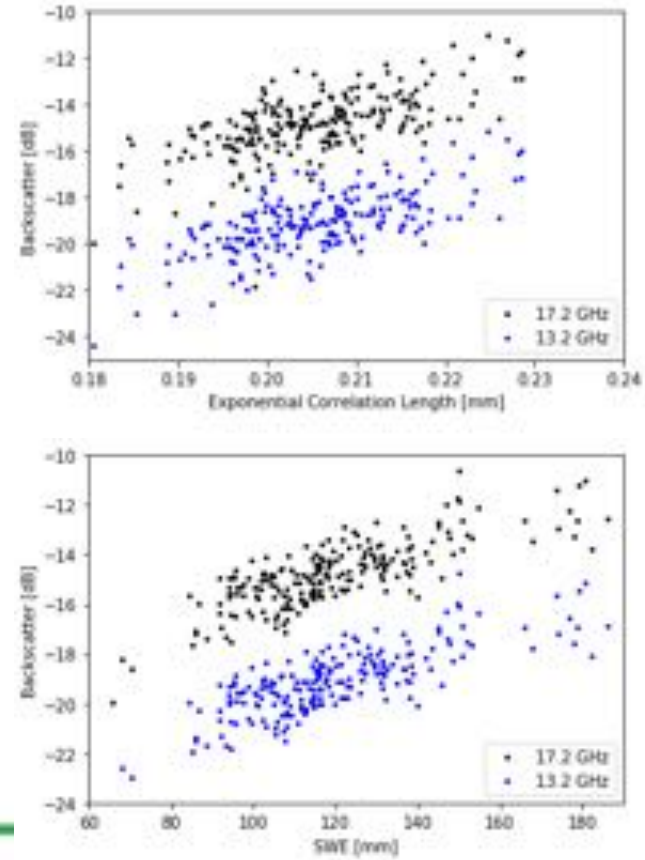
Parameterizing SMRT with SMP derived microstructure

SMRT forward backscatter (n=214)



- Output of backscatter distributions represent continuum of space observed by the radar
- Enhanced sensitivity testing possible to quantify and decompose SWE, microstructure, and background contributions

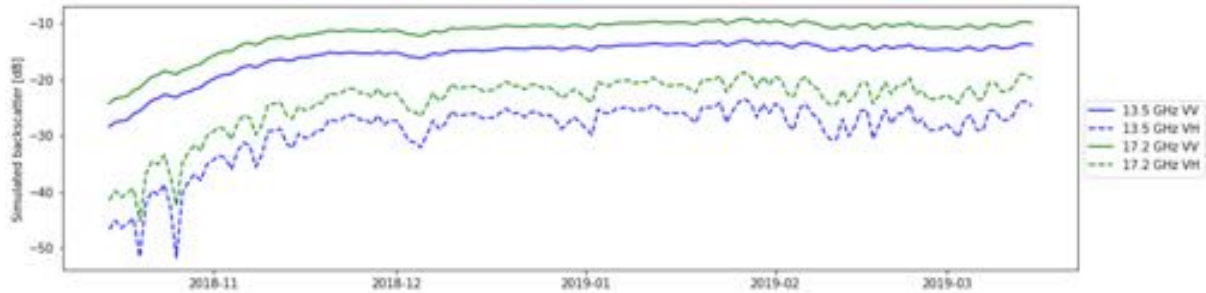
Sensitivity analysis

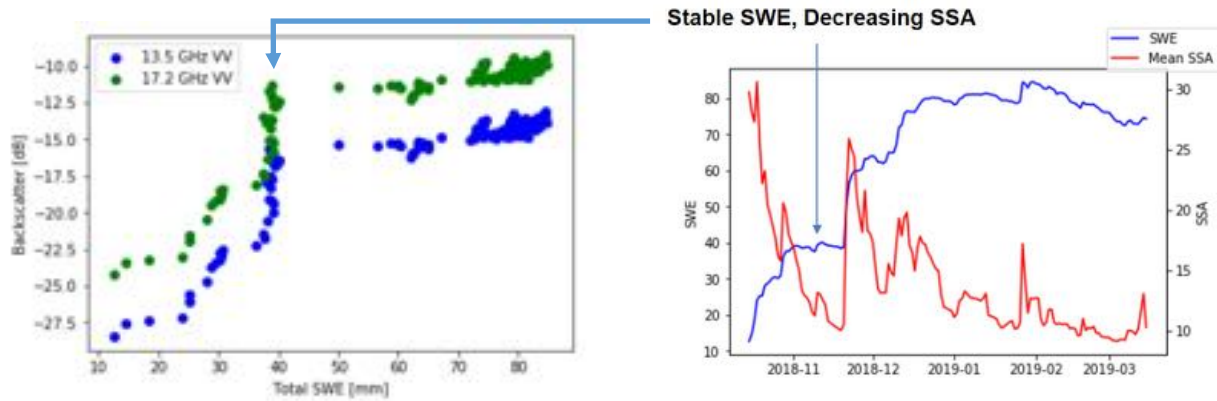


Ku-band Radar Assimilation

- Retrievals require a coupled physical model to separate microstructural influence
- Snow simulated with SVS-2 (driven by HRDPS at 2.5-km grid spacing): Explicit Snow (ES) scheme (Decharme et al, 2016) + snow metamorphism scheme from Crocus (Brun et al., 1992)
- Represents the effects of blowing snow on the properties of surface snow (compaction & fragmentation) but depth hoar underestimated
- SVS-2 outputs drive the Snow Microwave Radiative Transfer (SMRT) backscatter model; 'optimistic' snow only simulation (assumes we're able to decouple unwanted vegetation and background signals)

SMRT Simulated Backscatter for TVC





Areas of Synergy with SnowEx

- Recognition that providing enhanced information on seasonal snow is of significant economic, political, and cultural value
- Field sites for potential campaigns
  - Development across multiple snow environments
- Capacity to pursue new opportunities with new datasets
  - SnowEx airborne and ground-based radar assets
- Development of retrieval and assimilation framework; support for secondary objectives
- Students looking for data, we're open by default
- **Community support required to advance to Phase A**

TVC Black Spruce Forest, January 2019

Study Team

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Geoff Burbidge, Jose Marquez

Airbus Defense and Space

Philip Marsh, Branden Walker

Wilfrid Laurier University

Paul Siqueira

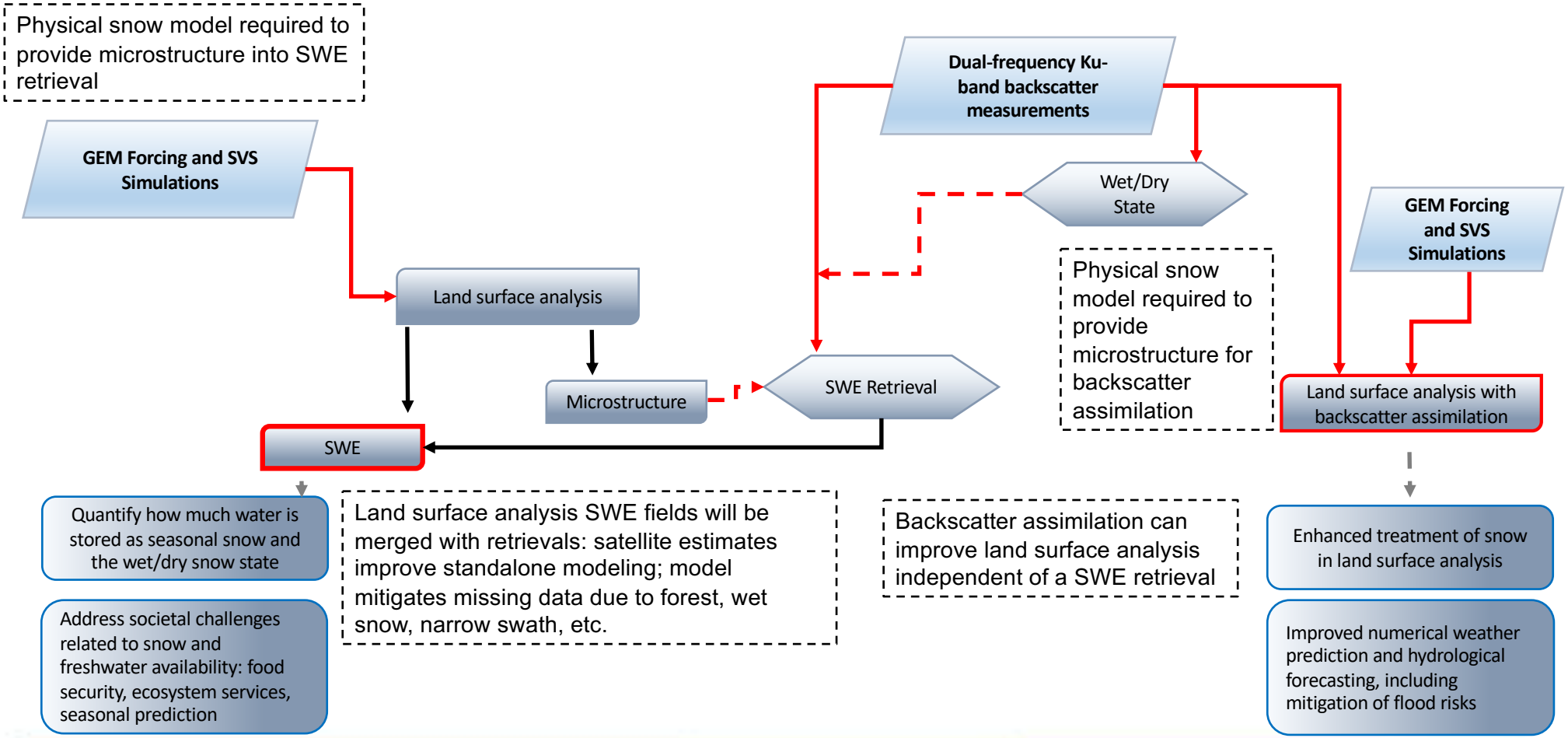
UMass

Juha Lemmetyinen

Finnish Meteorological Institute

Science Team to steer Phase 0 activities

User/Stakeholder team under consideration


Physical snow model required to provide microstructure into SWE retrieval
GEM Forcing and SVS Simulations
Land surface analysis
Microstructure
SWE
Dual-frequency Ku-band backscatter measurements
Wet/Dry State
SWE Retrieval
Physical snow model required to provide microstructure for backscatter assimilation
GEM Forcing and SVS Simulations
Land surface analysis with backscatter assimilation
Quantify how much water is stored as seasonal snow and the wet/dry snow state
Address societal challenges related to snow and freshwater availability: food security, ecosystem services, seasonal prediction
Land surface analysis SWE fields will be merged with retrievals: satellite estimates improve standalone modeling; model mitigates missing data due to forest, wet snow, narrow swath, etc.
Backscatter assimilation can improve land surface analysis independent of a SWE retrieval
Enhanced treatment of snow in land surface analysis
Improved numerical weather prediction and hydrological forecasting, including mitigation of flood risks

A Ku-band Radar Mission for Seasonal Snow Mass

Current TRL between 5 and 9 for all sub-systems:

-Technical concepts under development as part of Phase 0 industrial contract funded by CSA

-Technology development roadmap under separate CSA funding line

Current SRL between 3 and 4:

-SWE retrieval frameworks under development at ECCC, U. Michigan, and the Finnish Meteorological Institute

-improvement of radar modeling of vegetation and soil

-assessment of snow microstructure estimates provided by SVS

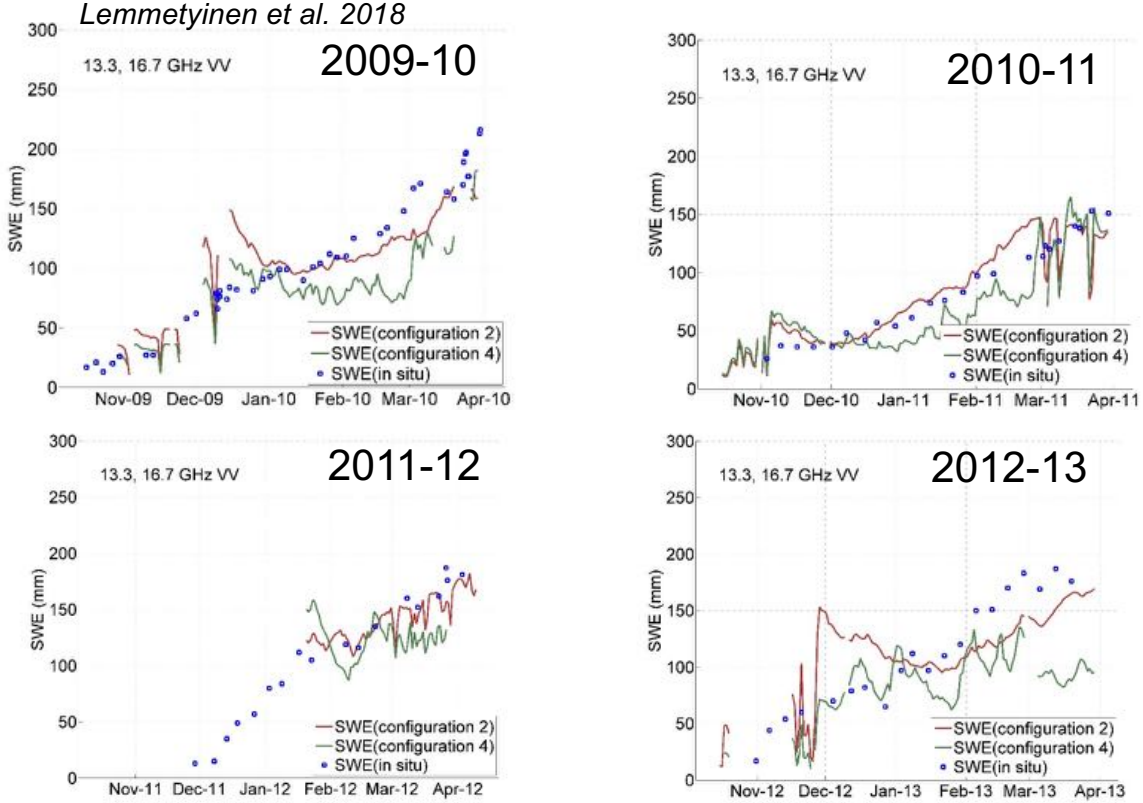
-preparation of CaLDAS for assimilation of Ku-band radar backscatter (Stephane.Belair@canada.ca)

-Future field campaign options not finalized (Joshua.King@canada.ca)

Secondary mission objectives identified (e.g. sea ice); further experimental work is required to develop these further

SWE Retrieval Demonstration

Lemmetyinen et al. 2018



- Retrievals over four winter seasons using tower-based SnowScat backscatter data
- Inversion of semi-empirical MEMLS model
- Optimal snow microstructure retrieved from both radar and passive microwave data

SWE retrievals:

Configuration 2: optimized average microstructure for each *winter season*

Configuration 4: prior microstructure retrieved from passive microwave (synergistic retrieval)

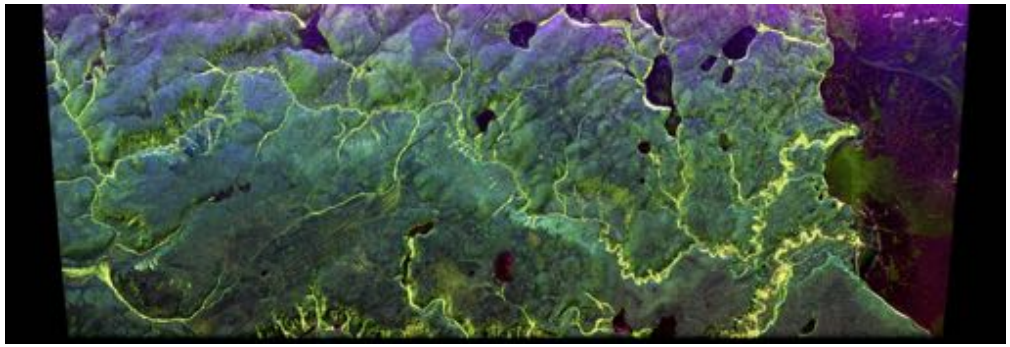
Supporting Measurements

AWI Polar 6 (Airborne)
- High resolution lidar
- Wideband FMCW 2-18 GHz SnowRadar

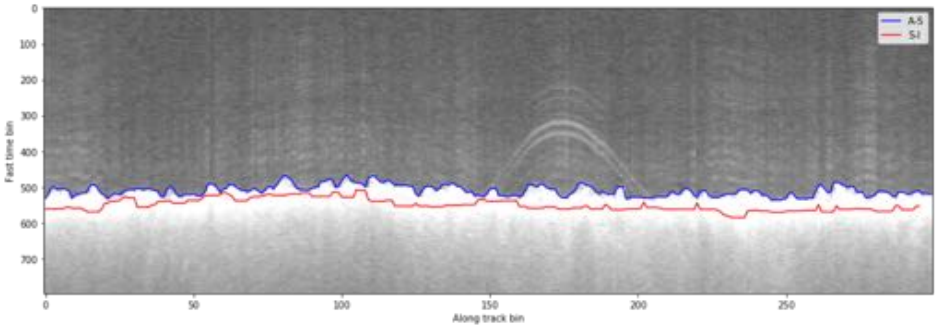
DLR F-SAR (Airborne)
- Multi-frequency InSAR

RADARSAT-2 (ECCC) and TerraSAR-X (DLR)
- Bi-monthly dual-pol acquisitions

Structure from Motion (WLU)
- Drone flight each deployment
- Snow depth maps at 2 cm resolution

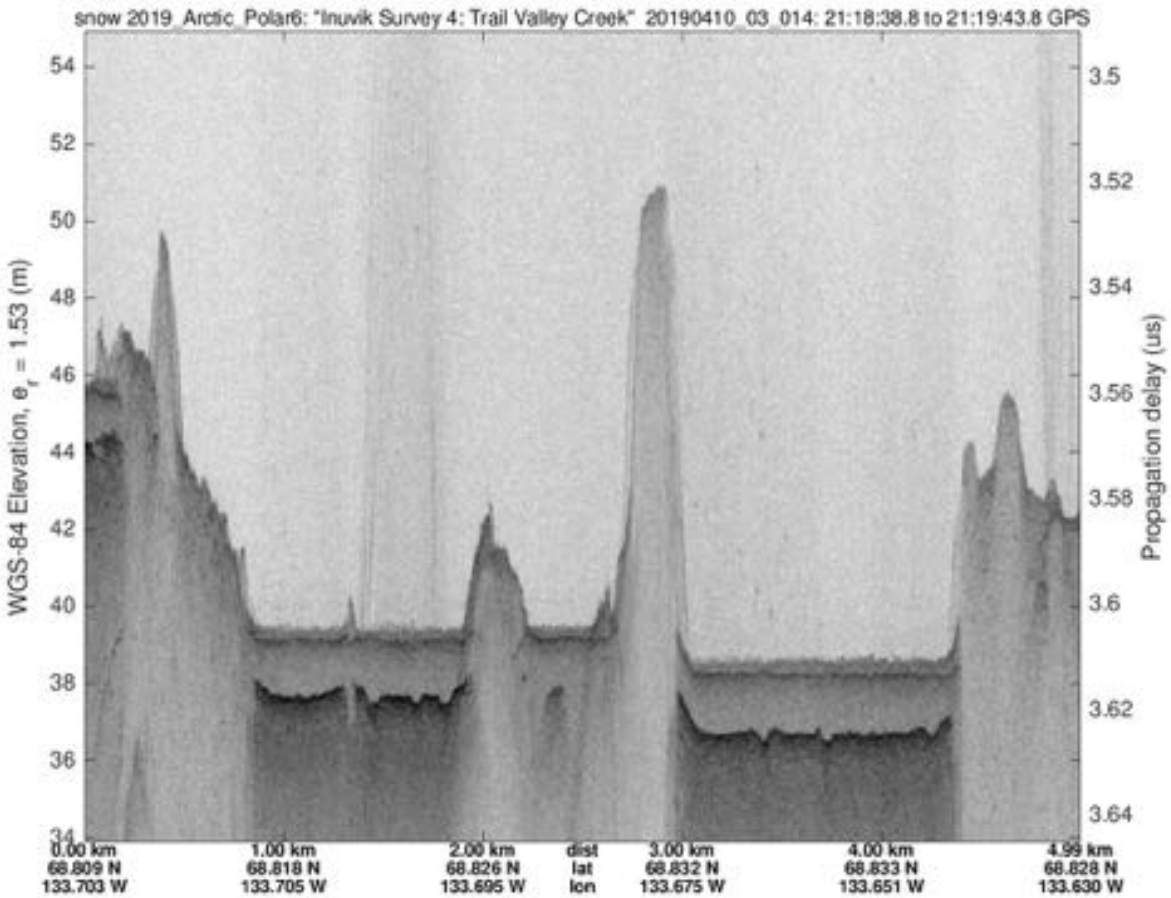


L-band backscatter from DLR F-SAR



Snow depth from AWI SnowRadar

Supporting Measurements



AWI UWB 2-18 GHz Radar

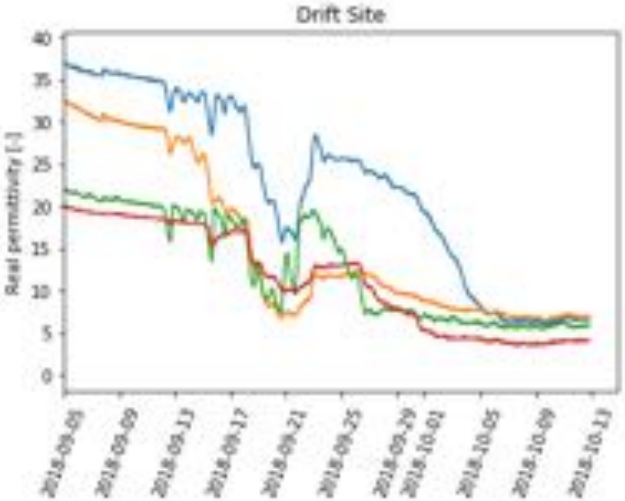
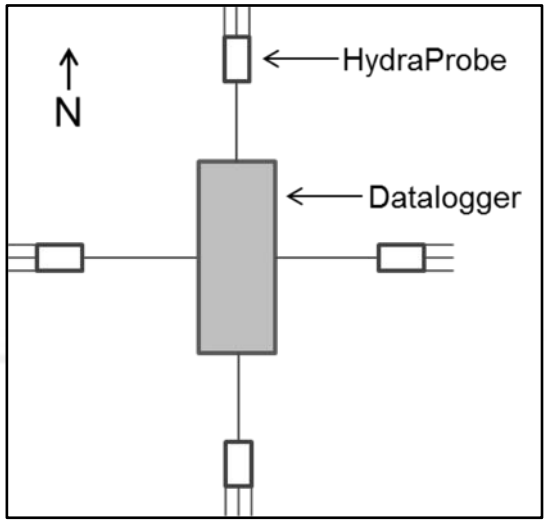
Pre-Cursor Concepts

Aim for ~20% of full mission cost (reduced technical and scientific risk) achieved via:

- Simplified antenna design
  - narrow imaging swath but maintain temporal revisit of 3-5 days
- Reduced power requirements
  - reduce duty cycle to 5-10% of orbit
- Short life span
  - <3 year mission duration
- Reduced number of frequencies (reduce to single frequency Ku-band)
  - Last resort option

❖ The key is to get repeat measurements in the right locations
❖ The ECCC assimilation (and SWE retrieval) framework can work with narrow swath observations

Sampling design - static sites

- Focused on **characterizing temporal variability**
  - Permittivity ← Stevens HydraProbe
  - Surface Roughness ← AWI Airborne lidar

- 6 sites selected with unique coverage (Drifts, plateaus, valleys)
  - Sites visited during each field deployment