Experimental Results of Snow and Soil Moisture Measurement using P-Band Signals of Opportunity (SoOp)

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Outline

- Motivation
- Measurement Background
- Experiment Results
- UAV Experiments
- OSSE Capability
- Summary

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- **Summary**

Motivation

- Snow water equivalent (SWE) and root zone soil moisture (RZSM) in land are critical state variables in the terrestrial water cycle with impact on weather, climate, and ecosystems
- Knowledge of SWE and RZSM are also critical for water supply management
- P-band Signals of Opportunity has greater penetration than L-band Sensors, such as SMAP and GNSS-R

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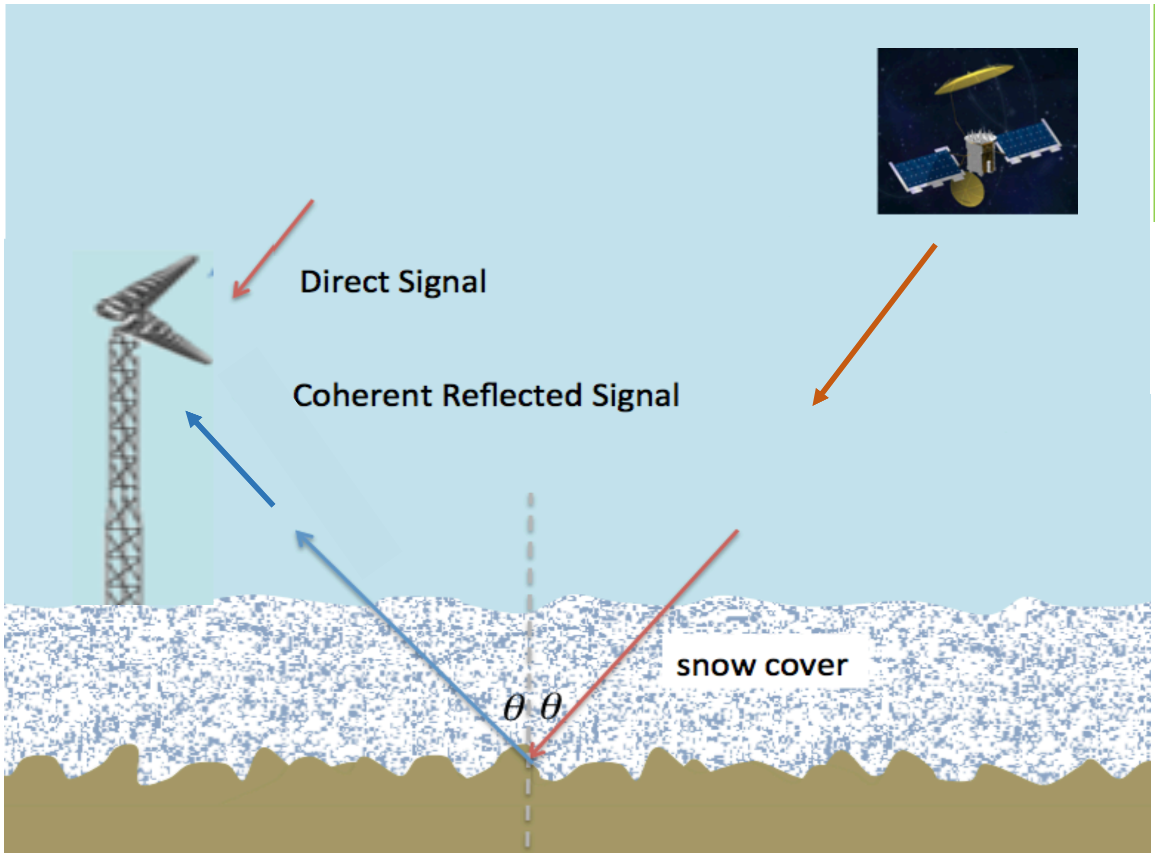
Measurement Principle



$$R \simeq R(f, \boldsymbol{Soil\ Moisture})$$

$$\phi_s \simeq \mathrm{a} \cdot f \cdot SWE$$

R = Reflectivity

ϕ_s = phase change

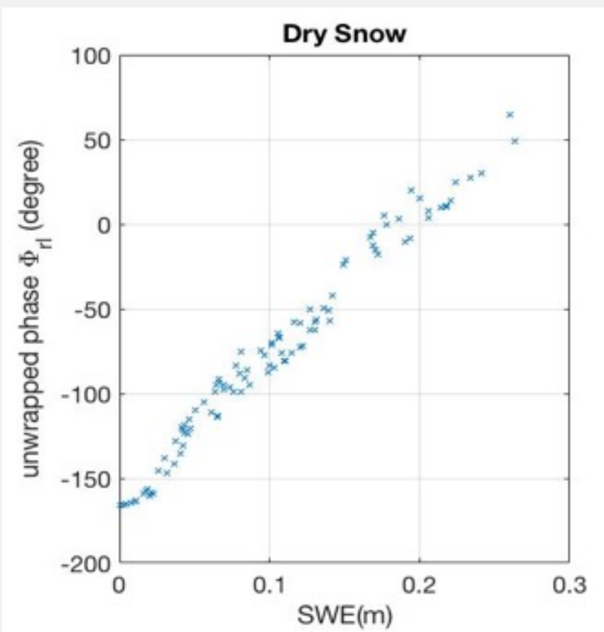
f = frequency

a : depends on incidence angle

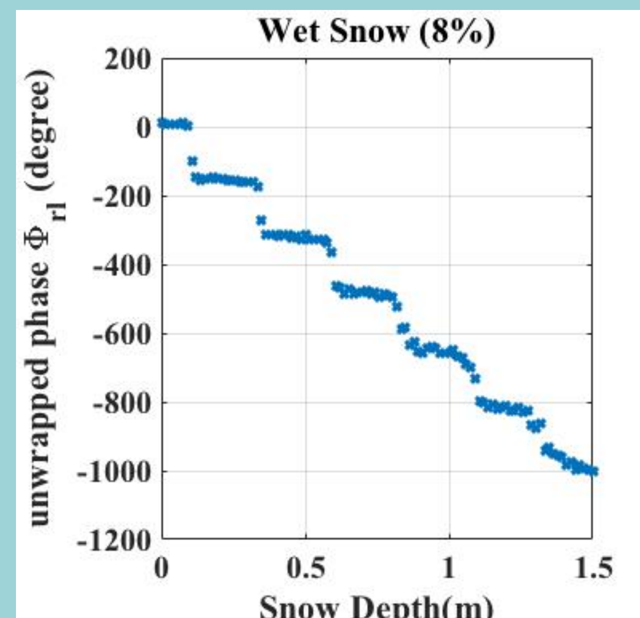
Yueh et al., 2017

Effect of Wet Snow

- Phase is related to SWE for dry snow
- Ground-snow interface dominates reflection



- Phase is related to snow depth for wet snow
- Air-snow interface dominates reflection



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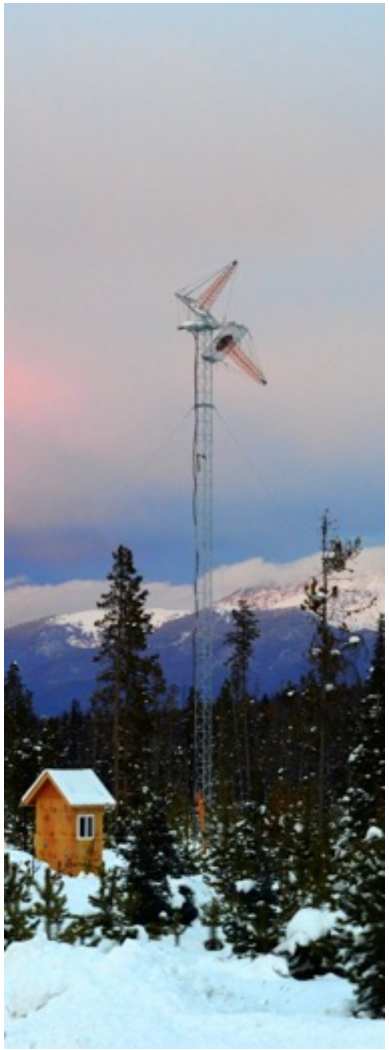
Experimental Setup



Site A

- Almost no vegetation
- Installed in Fall 2015
- Winter 2015-2016: 240-270 MHz
- Since 2016: 254-270 MHz, 360-376 MHz

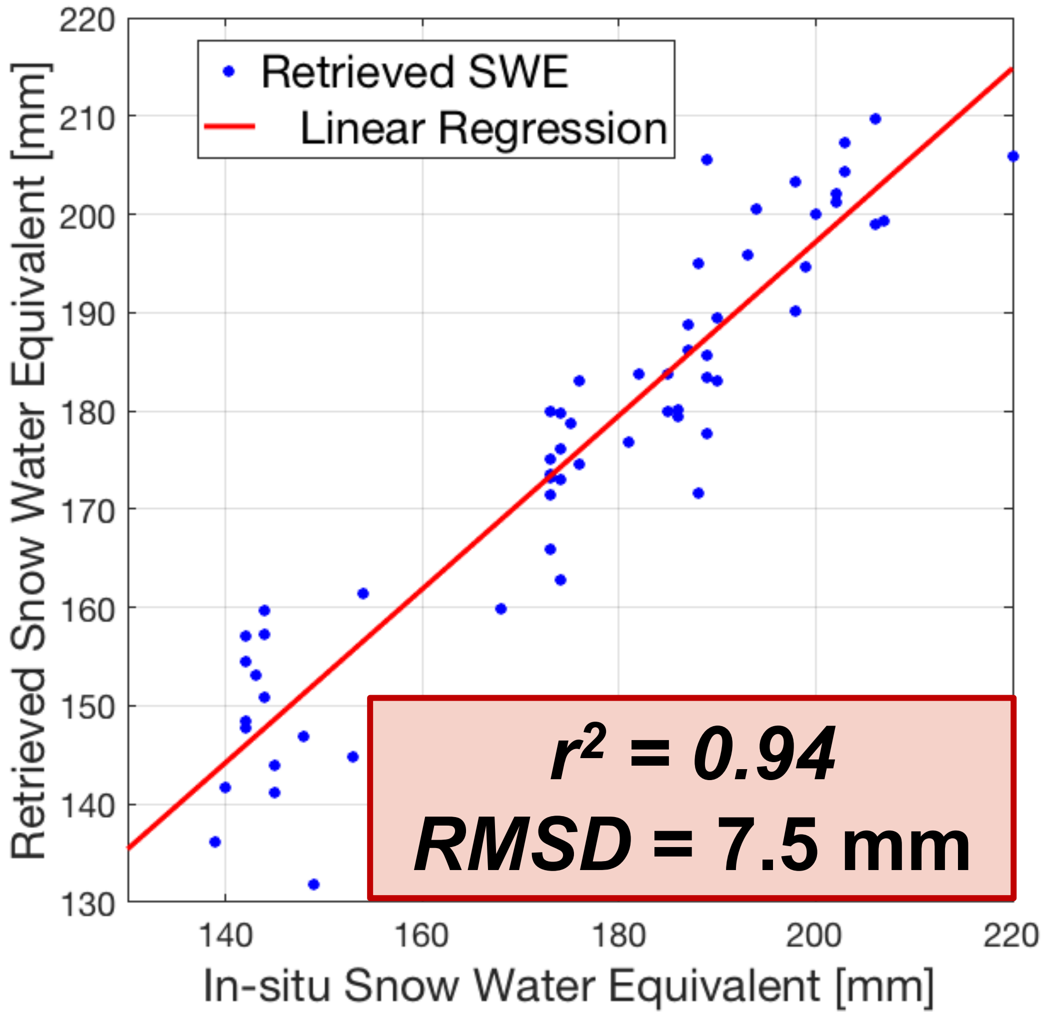
Effect of Vegetation

Site B

- Has small trees
- Installed in Fall 2016
- Recording 254-270 MHz, 360-376 MHz

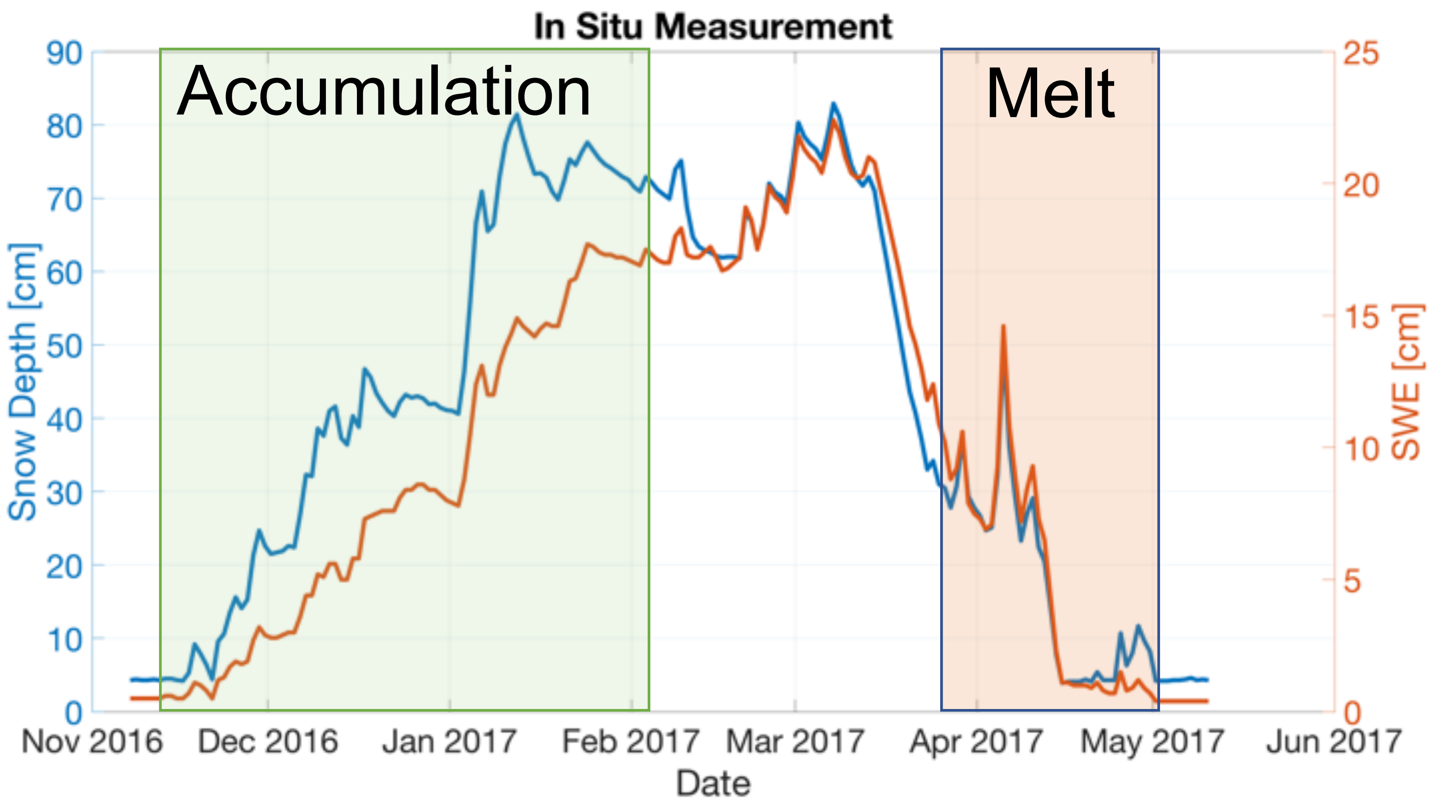
Fraser Experimental Forest

Winter 2015-2016: 260 MHz



Shah et al., 2017

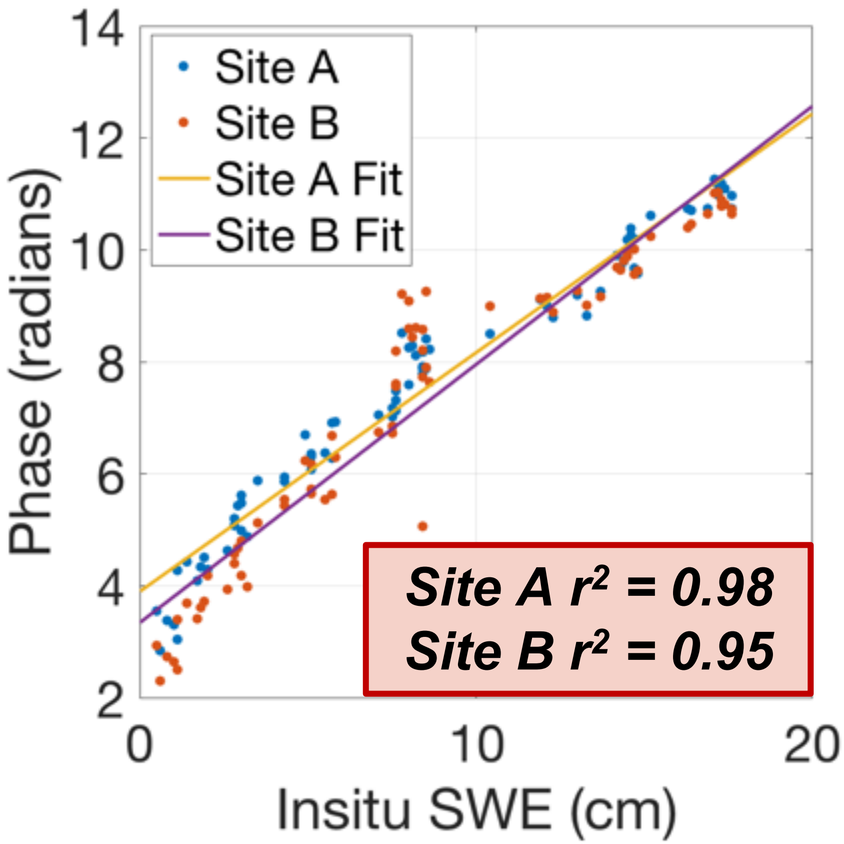
Winter 2016-2017: Insitu Data



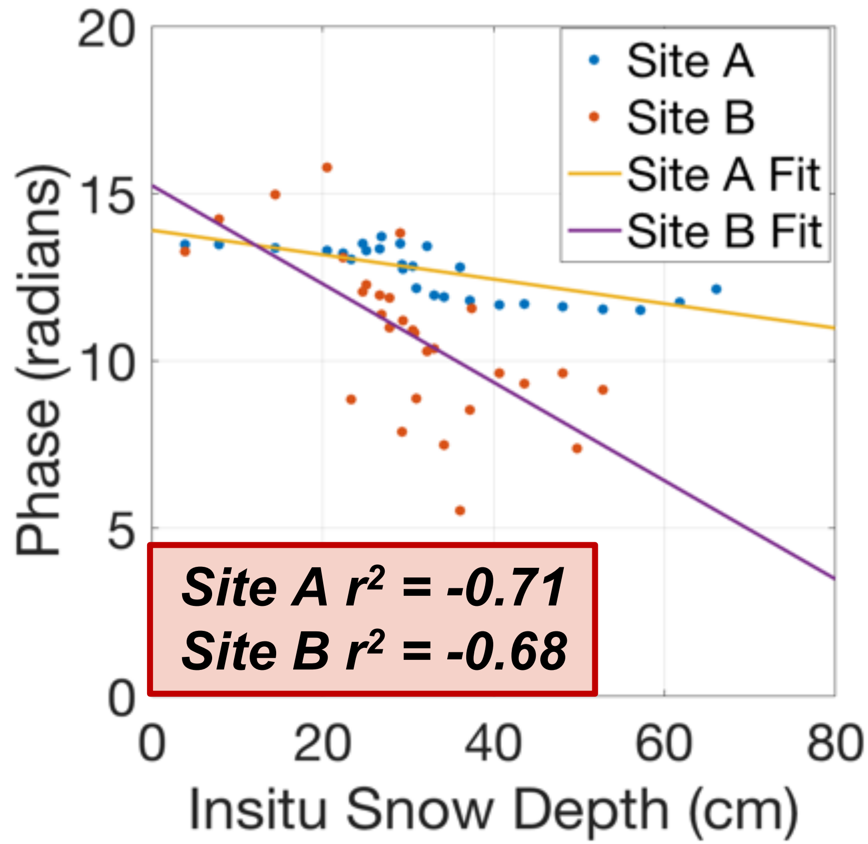
- Weekly snow pit measurements for snow depth, stratigraphy, and snow density
- Snow depth survey around the perimeter of the test site

Winter 2016-2017: 260 MHz

Accumulation Period

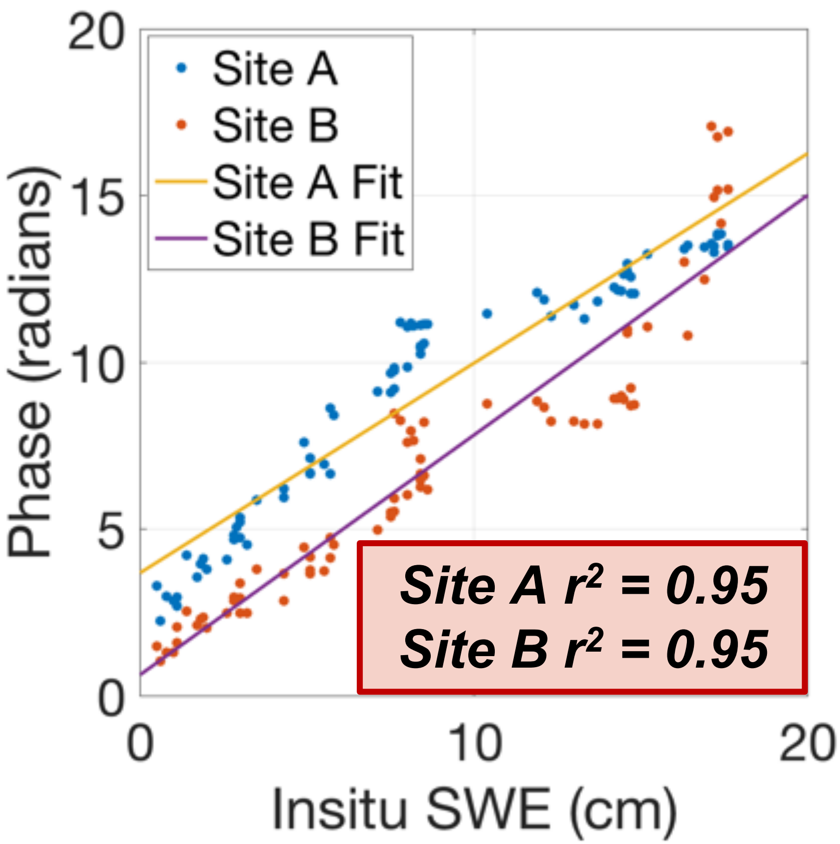


Melt Period

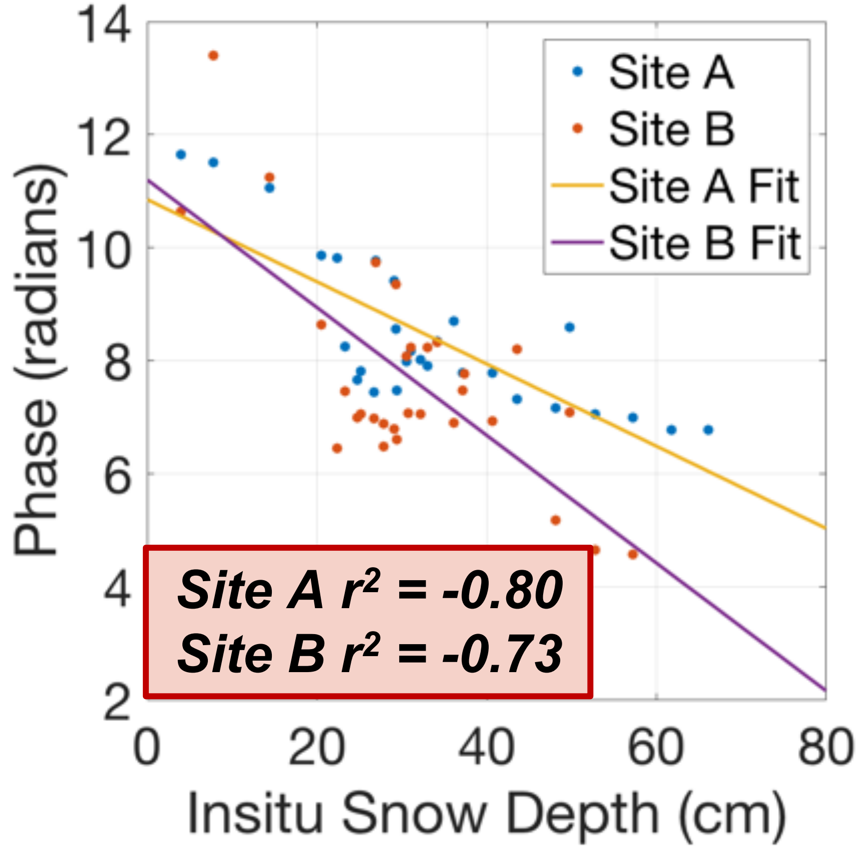


Winter 2016-2017: 367 MHz

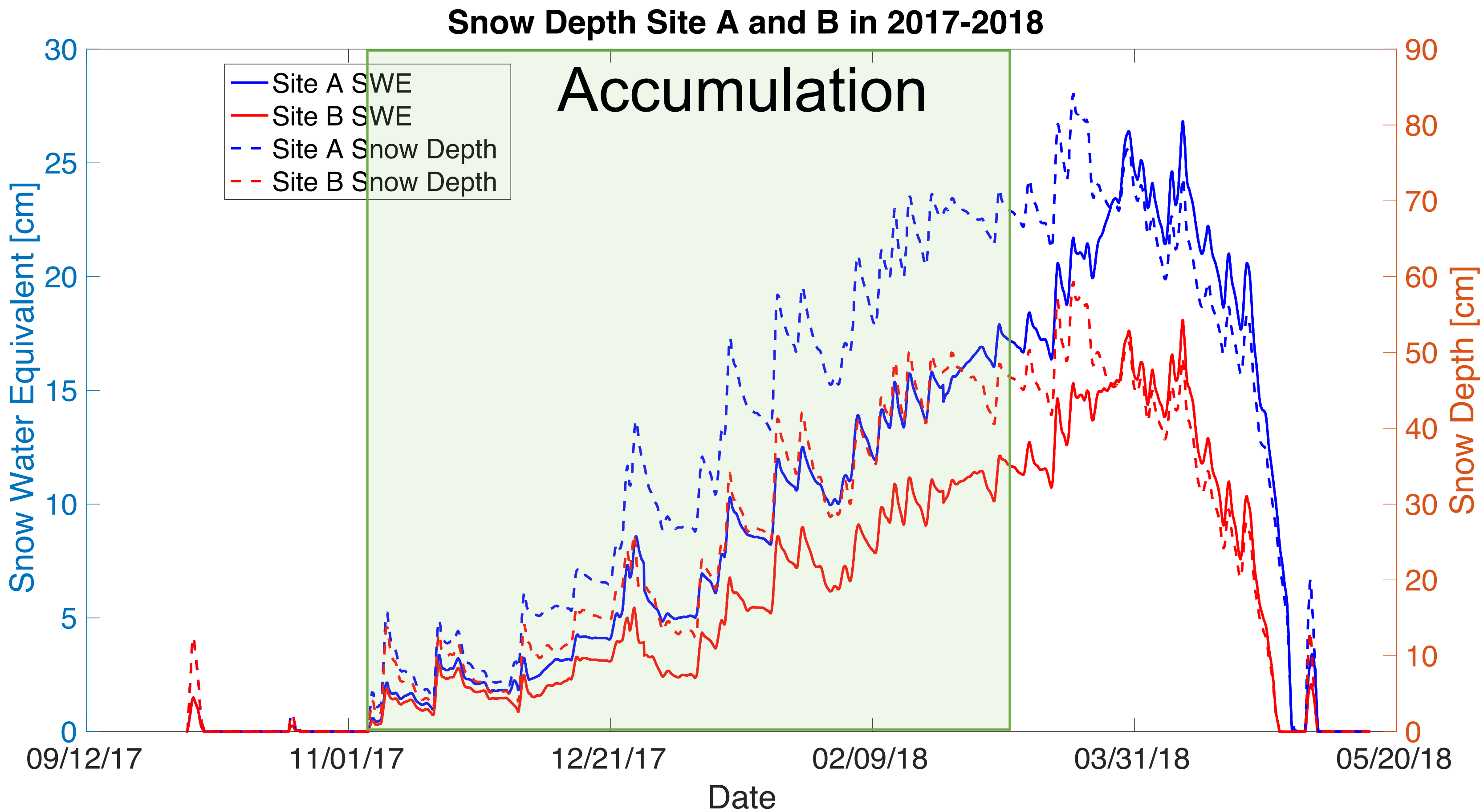
Accumulation Period



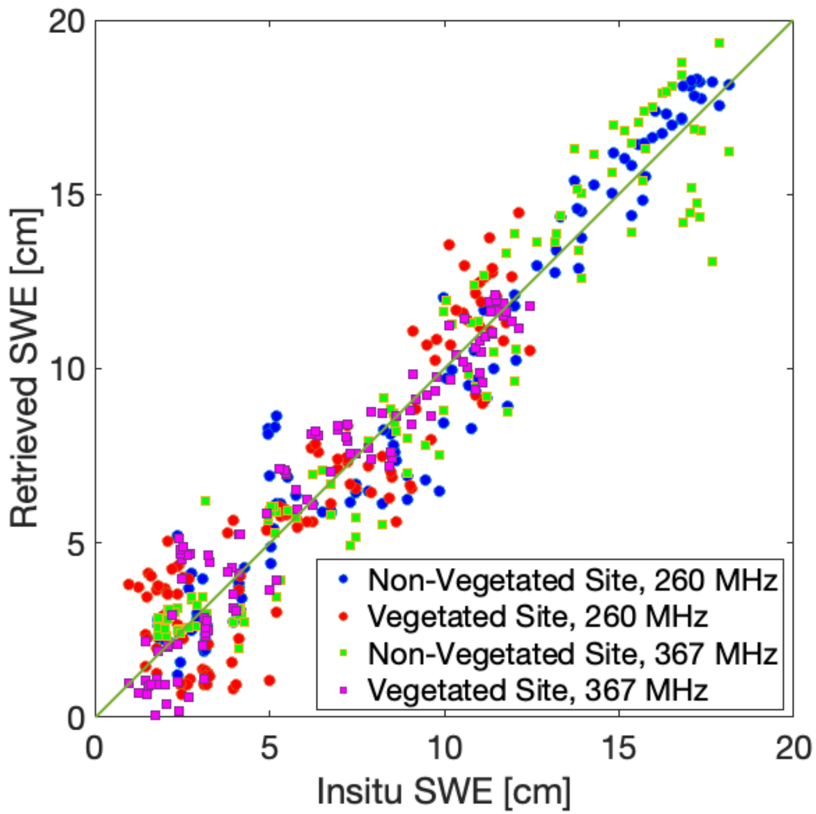
Melt Period



Winter 2017-2018



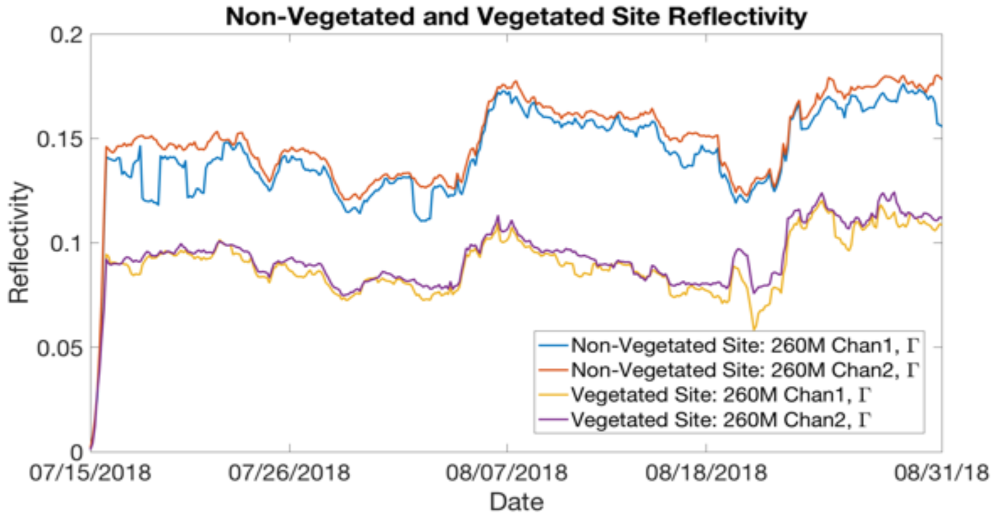
Winter 2017-2018

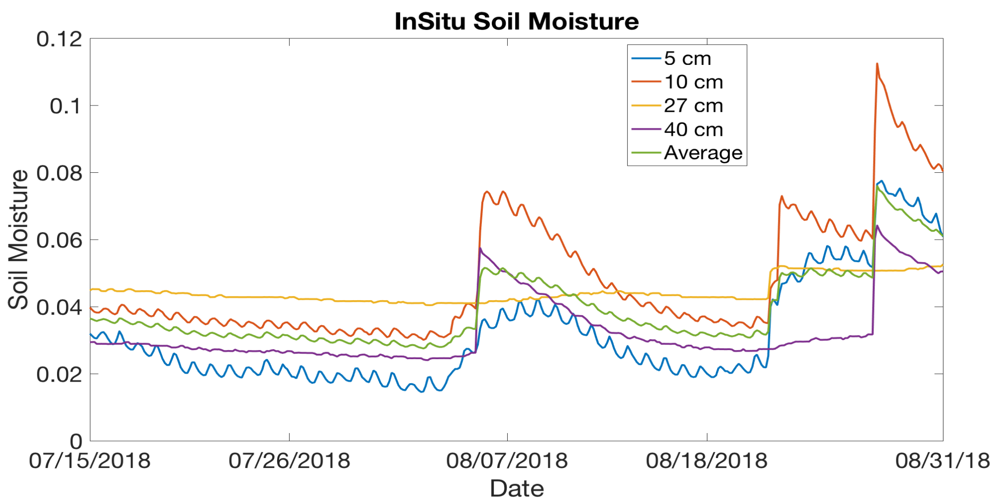


- Correlation were found to be more than 0.9 for all the frequencies.
- The RMSD between retrieved SWE and *in situ* SWE was found to be between 1.15-1.6 cm.

	260 MHz	370 MHz
Non-Vegetated Site	1.26 cm	1.50 cm
Vegetated Site	1.60 cm	1.15 cm

Summer 2018: Soil Moisture





- Both sites showed sensitivity to the changes in soil moisture
- Correlation between reflectivity and soil moisture was between 0.6-0.7
- Attenuation due to vegetation is also observed as the reflectivity

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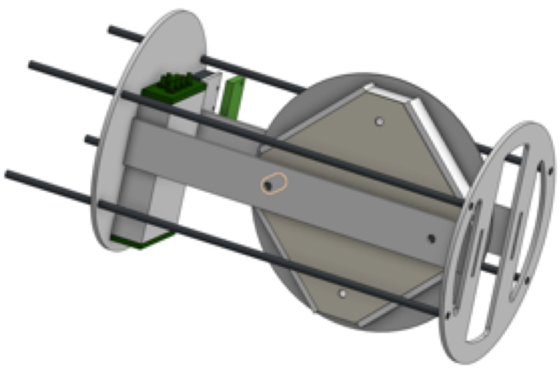
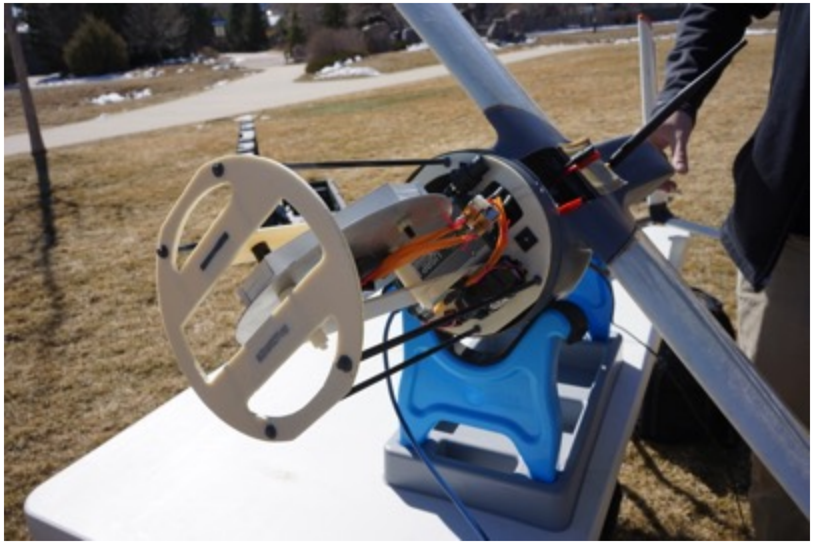
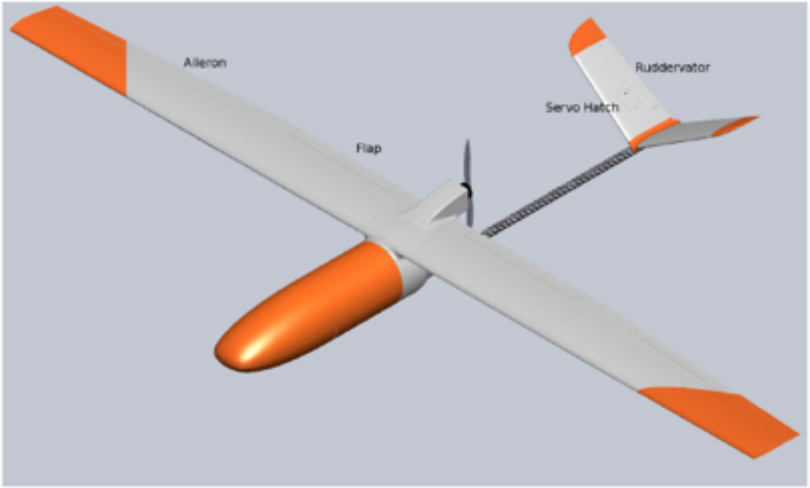
UAV SoOp Experiments

Payload Design and Integration



Receiving frequency:
360-365 MHz
Power: 7 Watts
Weight: 2.3 kg



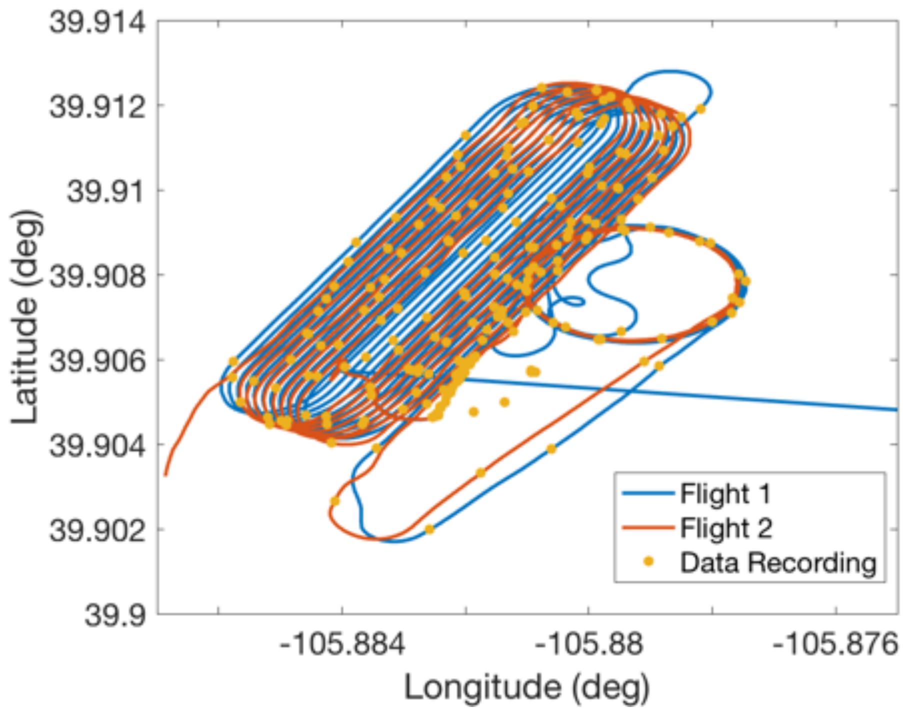


UAV SoOp Experiments

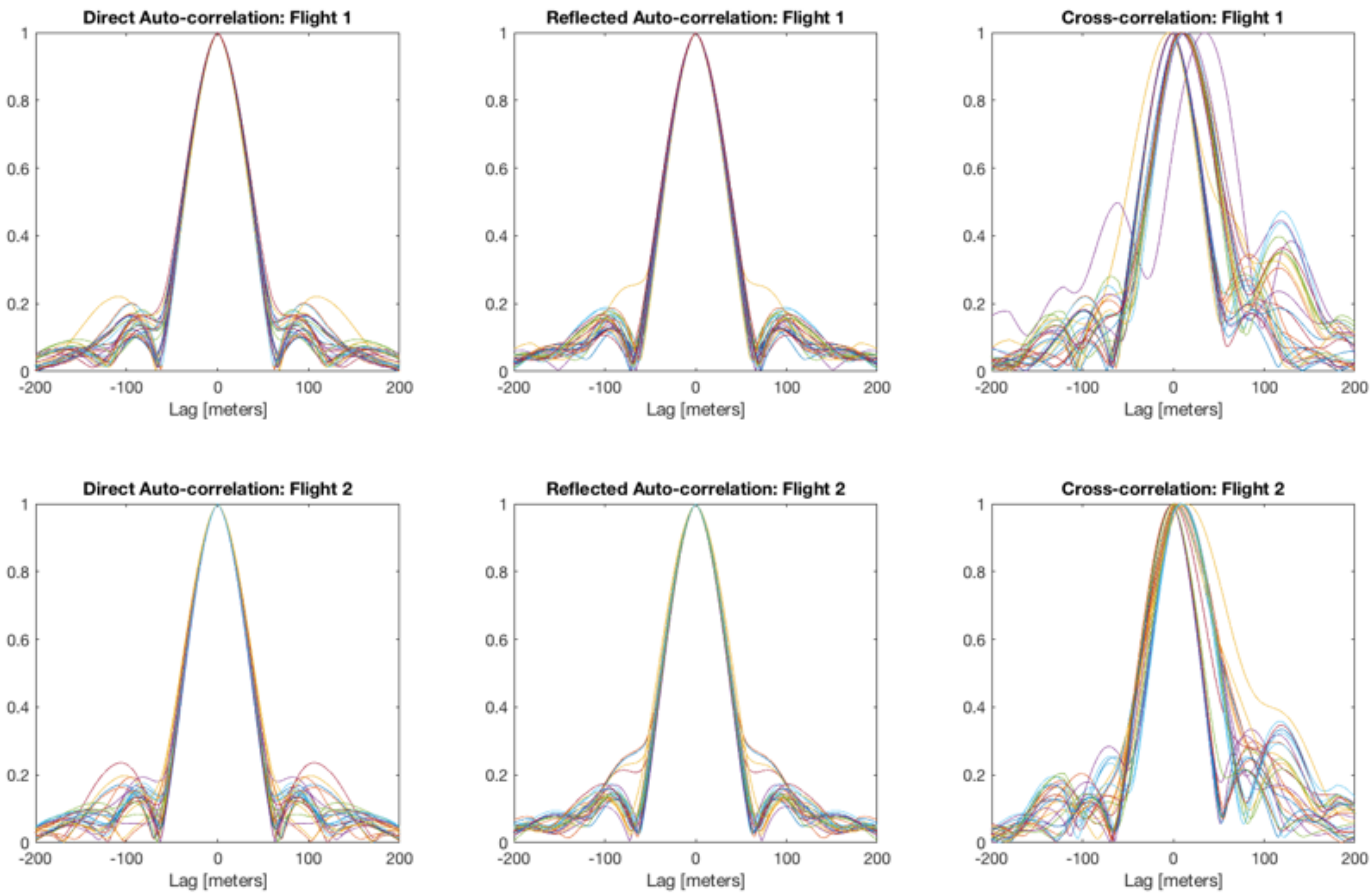
Payload Design and Integration

Receiving frequency:
360-365 MHz
Power: 7 Watts
Weight: 2.3 kg

Flights Conducted on April 27, 2018



UAV SoOp Data: First Look



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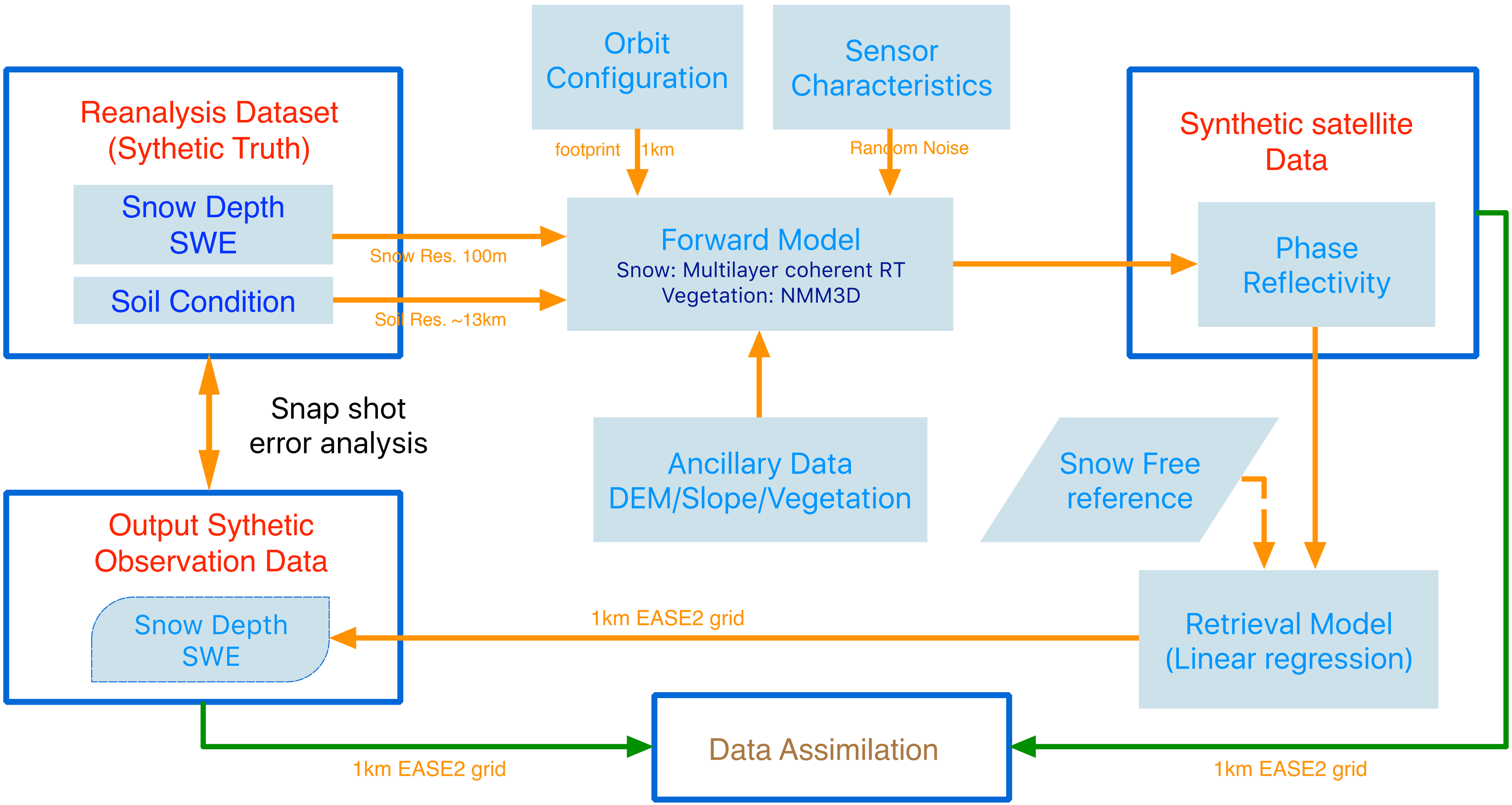
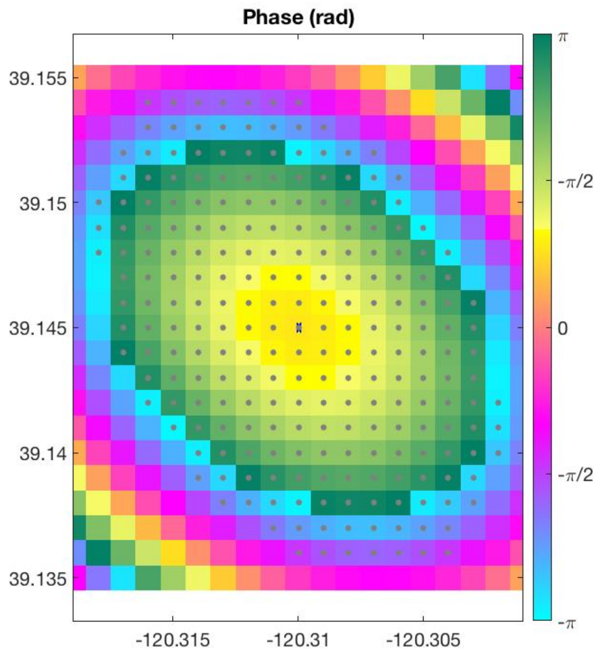
OSSEs Capability Development

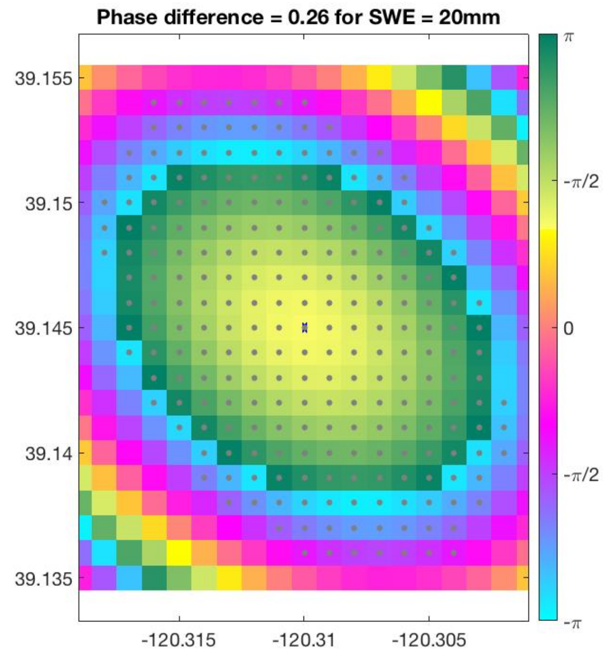


Case 1: Homogeneous SWE distribution on flat surface

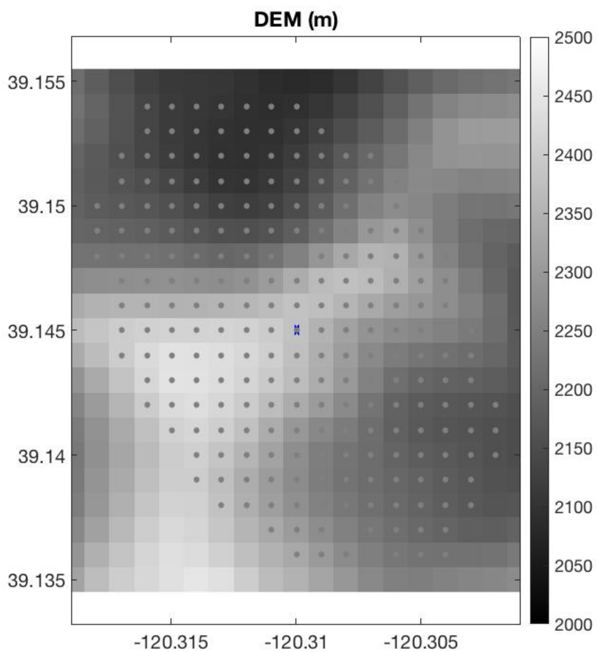
Bare Surface

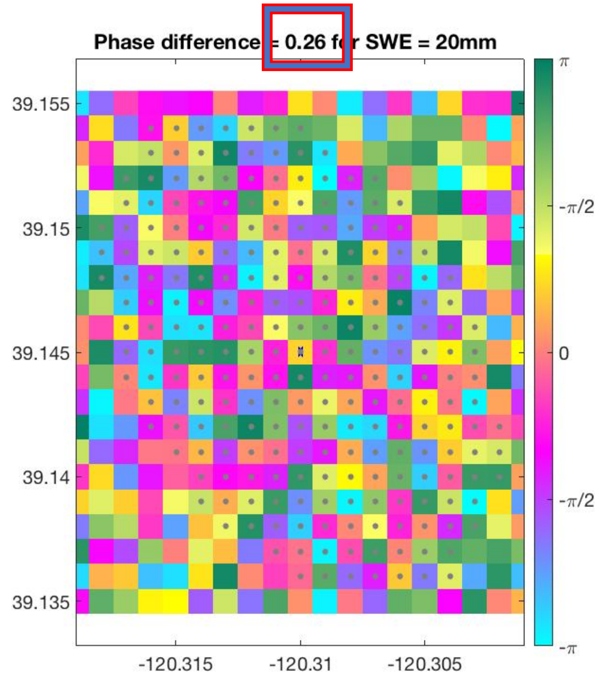


Phase Difference for 20 mm SWE = 0.26



Case 2 : Homogeneous SWE distribution with DEM





Phase Difference for 20 mm SWE = 0.26

This footprint is from a mountain range with mean elevation of 2259 m and standard deviation of 95 m

Phase distribution is random due to DEM, however, the phase difference between snow on and off stays the same

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Summary

- SoOp technique can provide accurate sampling of SWE
- Phase directly proportional
  - SWE for dry snow
  - Snow Depth for wet snow
- Measurement principle demonstrated with field campaign
- Minimal effect of vegetation noticed for short trees
  - Measurement under canopy possible
- UAV Experiment will be done in future
- OSSE capability being built for end-to-end simulations
  - If the snow distribution over the first Fresnel zone is homogeneous, the DEM will destruct the phase distribution, but will not change the phase difference between the snow on and off scene. The SWE can be retrieved directly.
- SNOOPI will validate this measurement from space

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BACKUP

OSSEs study (End-to-End Simulation)

- Orbit sampling options and trade space
  - Number of receivers, launched altitude, repeat frequency, error budget
- Forward modeling
  - Phase and amplitude of reflected signals at 170, 260, 360 and 1557 MHz frequencies
- Retrieval simulation
  - SWE (dry or wet for a range of vegetation biomass over CONUS)
  - RZSM
- Data assimilation assessment
  - Determine the impact of orbit sampling options on hydrologic forecasting

Inhomogeneity study: Numerical calculation using Kirchhoff integral

- Input data: DEM and SWE is in 100m.
- The scattered field is calculated using Kirchhoff integral ‘

$$\bar{E}_s(\bar{r}) = \frac{ik}{4\pi}\sqrt{\frac{P_t\eta_0}{2\pi}}\iint_{S'} d\bar{r}' \frac{e^{ik(R_{pt}+R_{pr})}}{R_{pt}R_{pr}} \left(\bar{\bar{I}} - \hat{k}_s\hat{k}_s\right)\cdot \bar{F}(\alpha,\beta)$$

$$\bar{F}(\alpha,\beta) = \sqrt{1+\alpha^2+\beta^2}\begin{bmatrix} (-1+R_h)\left(\hat{e}_i\cdot\hat{k}_i\right)\hat{q}_i + (1+R_v)(\hat{e}_i\cdot\hat{p}_i)\,\hat{n}\times\hat{q}_i \\ +\hat{k}_s\times\left[(1+R_h)(\hat{e}_i\cdot\hat{q}_i)\right]\hat{n}\times\hat{q}_i + (1-R_v)(\hat{e}_i\cdot\hat{p}_i)\left(\hat{n}_i\cdot\hat{k}_i\right)\hat{q}_i \end{bmatrix}$$

Where, the local orthonormal system is defined as followed,

$$\hat{q}_i = \frac{\hat{k}_i\times\hat{n}'}{\left|\hat{k}_i\times\hat{n}'\right|}$$

$$\hat{p}_i = \hat{q}_i\times\hat{k}_i$$

Alpha and beta are the local slopes of the horizontal direction (x,y)

W. Gu, H. Xu, and L. Tsang, "A Numerical Kirchhoff Simulator for GNSS-R Land Applications," *Progress In Electromagnetics Research*, Vol. 164, 119-133, 2019.

Dielectric Constant of Wet Snow