SNOWWI:
A three frequency interferometric SAR for Snow Science applications

Paul Siqueira, Russel Tessier (UMass), Gordon Farquharson (Capella Space), Leung Tsang (Michigan), HP Marshall (Boise State), Elias Deeb (CRREL)

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Questions that we are trying to answer

- How much water is stored in seasonal snow and what are its spatial and temporal variations?
- Snow characteristics of importance
  - Snow Water Equivalent
  - Snow Depth
  - Snow grain size
- Develop an airborne instrument that will map snow characteristics over an extended region
- Create a theoretical backbone for the interpretation and inversion of satellite and airborne measurements
- Conduct ground campaign for calibration/validation validate measurements and concept
- Define a realizable satellite mission that can execute this vision on a global basis

SNOWWI: Snow Water-equivalent Wide Swath Interferometer and Scatterometer

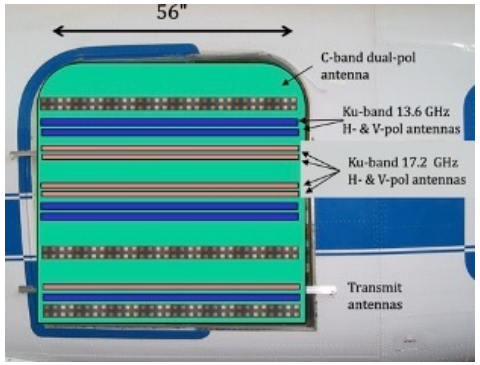
PI: Paul Siqueira, University of Massachusetts, Amherst

Objective

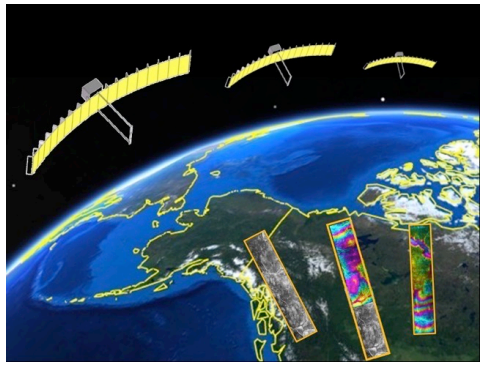
Create a two-frequency, dual-polarized (VV & HV) Ku-band InSAR and scatterometer for measuring snow properties of depth, density, height and Snow Water Equivalent. Specifications to have a 10 m resolution (80 looks), greater than -24 NESZ 3.5km swath, and interferometric height accuracy of 3 cm.

An airborne platform that combines the Ku-band systems with a C-band system will be constructed so that observations can leverage Sentinel-1 and RCM data to expand the coverage for airborne and spaceborne versions of the instrument.

Partnership with Capella Space will create realizable antenna designs, test the RF and telemetry interface to a spacecraft bus and explore constellation configurations



Ku- and C-band antennas fit to the left-rear door of a Twin Otter airborne platform



A constellation of dual-frequency dual-polarized Ku-band smallsats that can be configured to collect scatterometry and interferometric data

Approach

The SNOWWI development is centered around 4 basic activities:

1.) airborne instrument development,
2.) ground calibration and validation campaigns,
3.) theoretical and inversion algorithm development, and
4.) the transition of these activities into a realizable spaceborne constellation

the first three activities, together with modeling, will inform the constellation configuration of nominally 12 satellites

Co-Is/Partners: Elias Deeb (CRREL), Gordon Farquharson (Capella Space), HP Marshall (Boise State), Russel Tessier (UMass), Leung Tsang (Michigan)

Key Milestones

• Project start	03/22
• Bench verification of SNOWWI C & Ku-band RF up- & down-converters	09/22
• Bench test of SNOWWI interface to Ettus SDR, and Ku-high and C-band systems	03/23
• First Engineering flight of SNOWWI on Twin Otter First focused SAR image, begin snow season	09/23
• Verification of interferometric performance, Integration of Capella SDR	03/24
• Second snow season & Verify interfaces	09/24
• Final report and project end	03/25

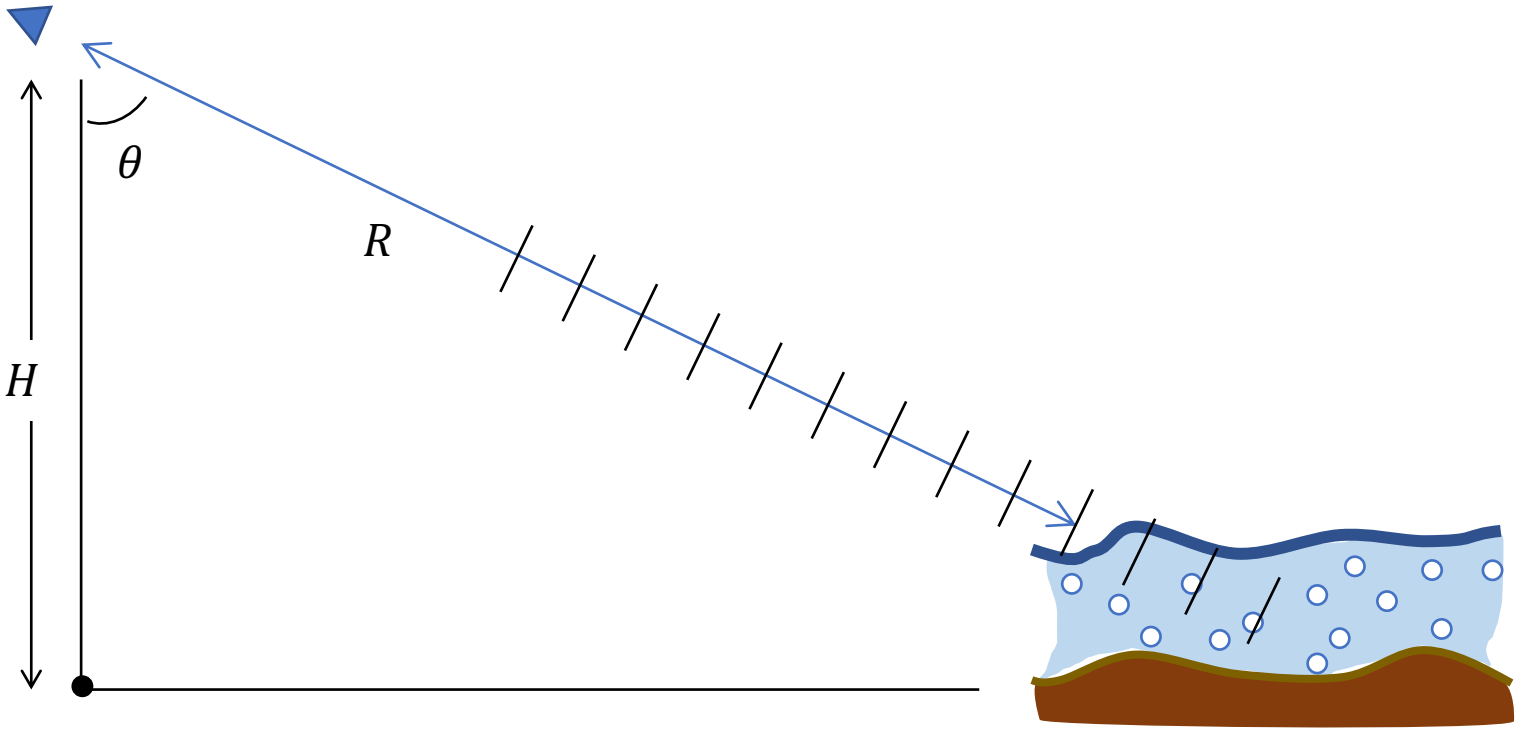
TRL_{in} = 3 $TRC_{current}$=4

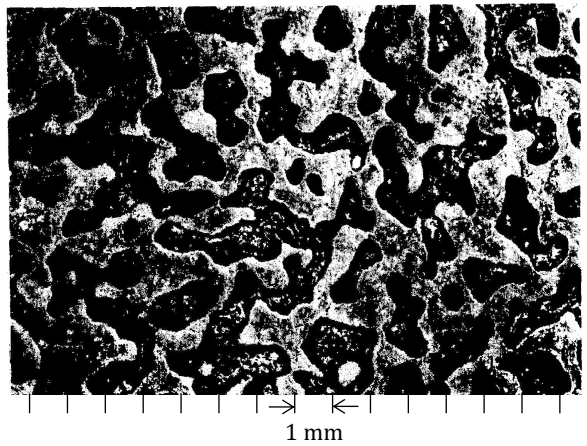
ESTO Earth Science Technology Office

Basic SAR measurements

- Radar Cross Section, RCS – σ°_{VV}
- Radar Cross Section, with polarization, σ°_{VV}, σ°_{HV}
- Radar Cross Section, frequency diversity, $\sigma^{\circ}_{VV}(f_1)/\sigma^{\circ}_{VV}(f_2)$

$$\sigma^{\circ}_{pq} = \langle E_{pq} E^{*}_{pq} \rangle = \left\langle \left| E_{pq} \right|^2 \right\rangle$$





	wavelength (λ)		
	free space	50 % vol. frac.	pure ice
Ku-band low (13.6 GHz)	2.2 cm	1.5 cm	1.2 cm
Ku-band high (17.2 GHz)	1.7 cm	1.4 cm	1.0 cm

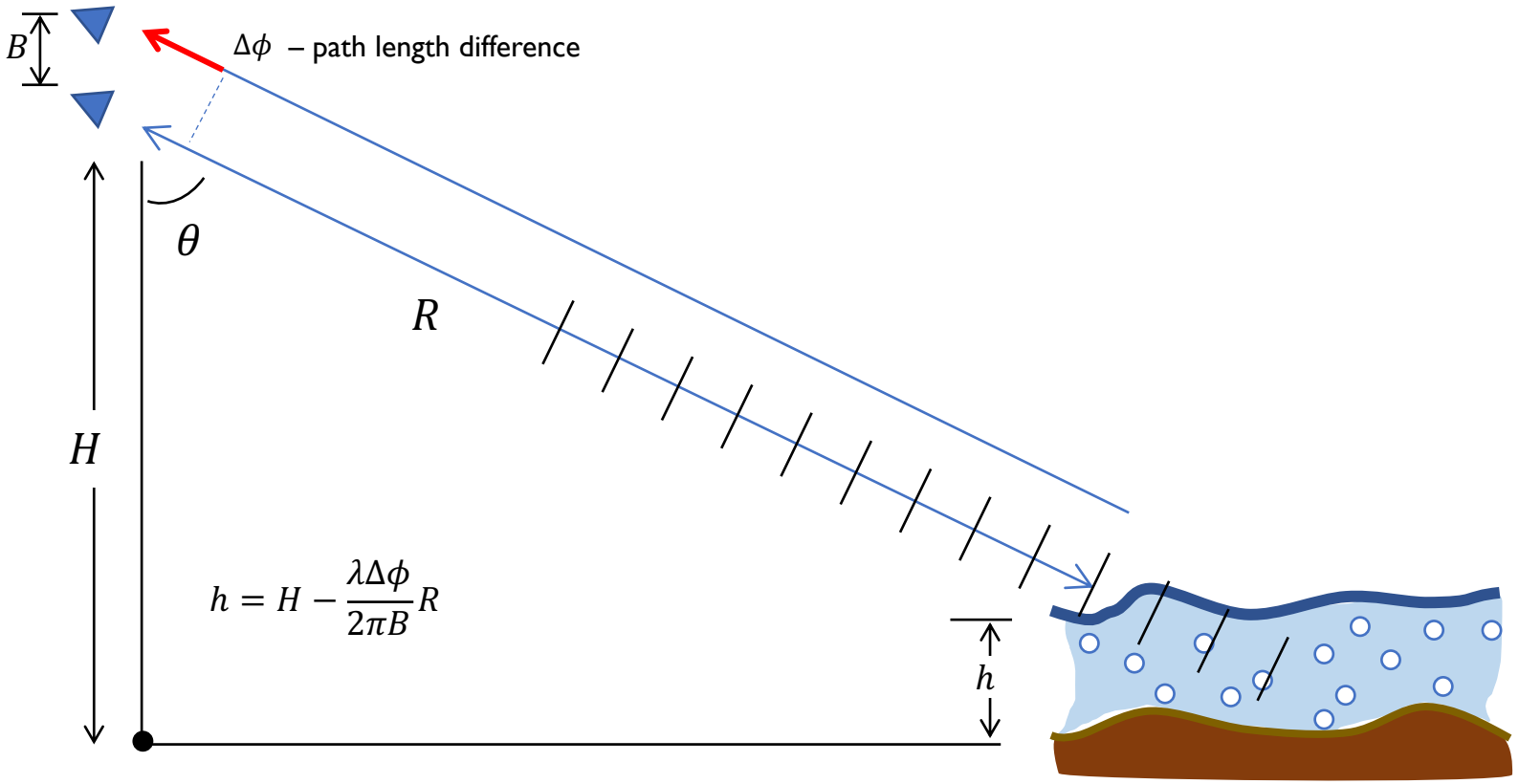
relative permittivity of ice, $\epsilon_r \approx 3.2$

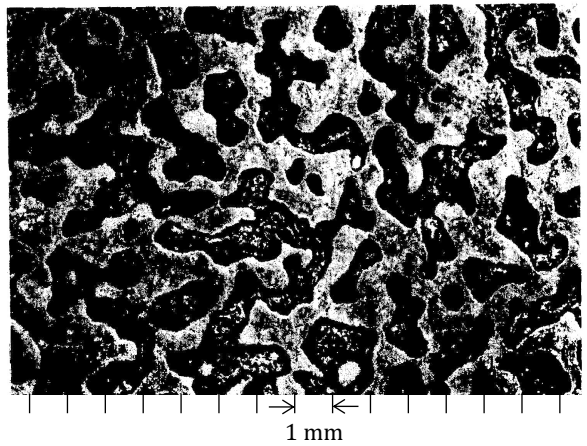
Basic SAR measurements

- Radar Cross Section, RCS – σ°_{VV}
- Radar Cross Section, with polarization, σ°_{VV}, σ°_{HV}
- Radar Cross Section, frequency diversity, $\sigma^{\circ}_{VV}(f_1)/\sigma^{\circ}_{VV}(f_2)$
- Interferometric Phase (& Differential height), $\Delta\phi \rightarrow h$
- Interferometric Correlation Magnitude, $|\gamma|$

$$\sigma^{\circ}_{pq} = \langle E_{pq} E^*_{pq} \rangle = \left\langle \left| E_{pq} \right|^2 \right\rangle$$

$$\gamma = |\gamma| e^{j\Delta\phi} = \frac{\langle E_1 E_2^* \rangle}{\sqrt{\langle |E_1|^2 \rangle \langle |E_2|^2 \rangle}}$$





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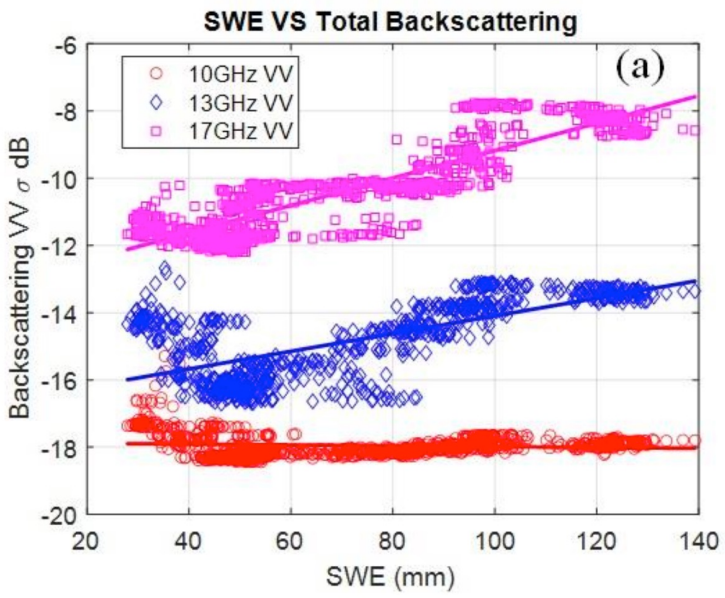
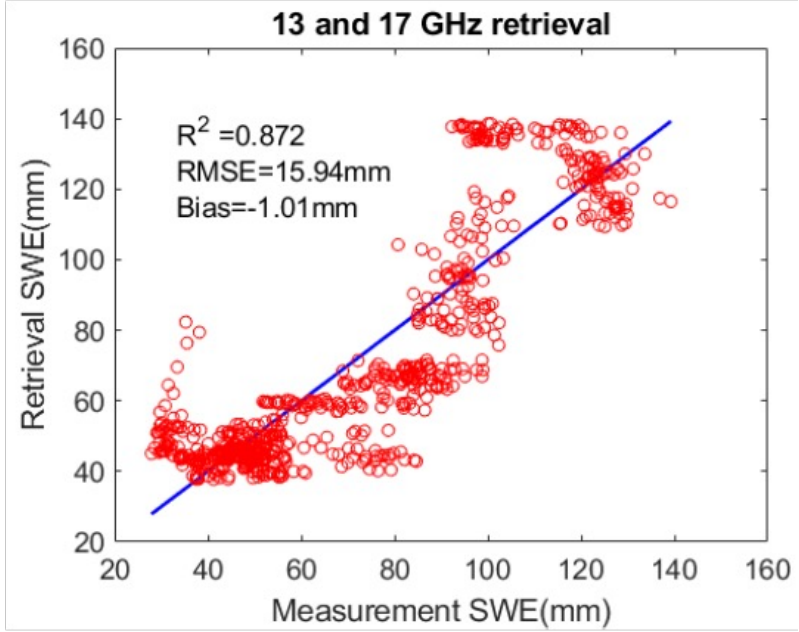
Snow behavior at microwave frequencies X & Ku-high versus Ku-low & Ku-high

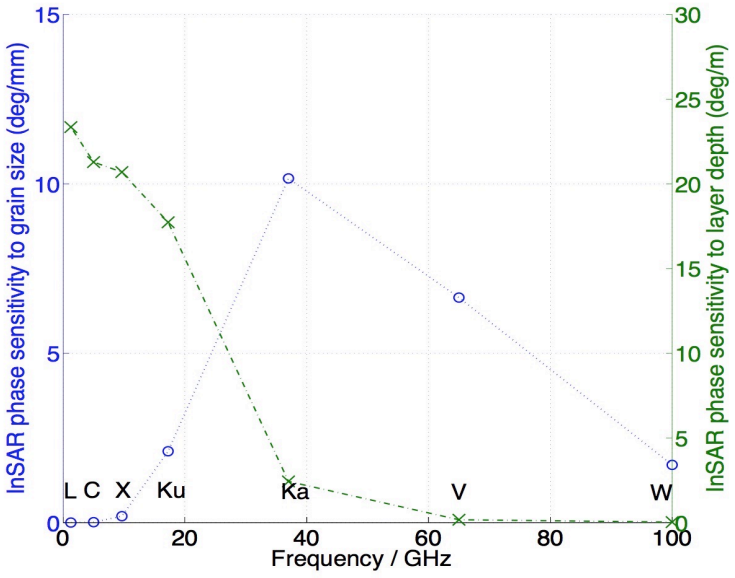
Zhu 2021



J. Zhu, Tsang, et al., 2021



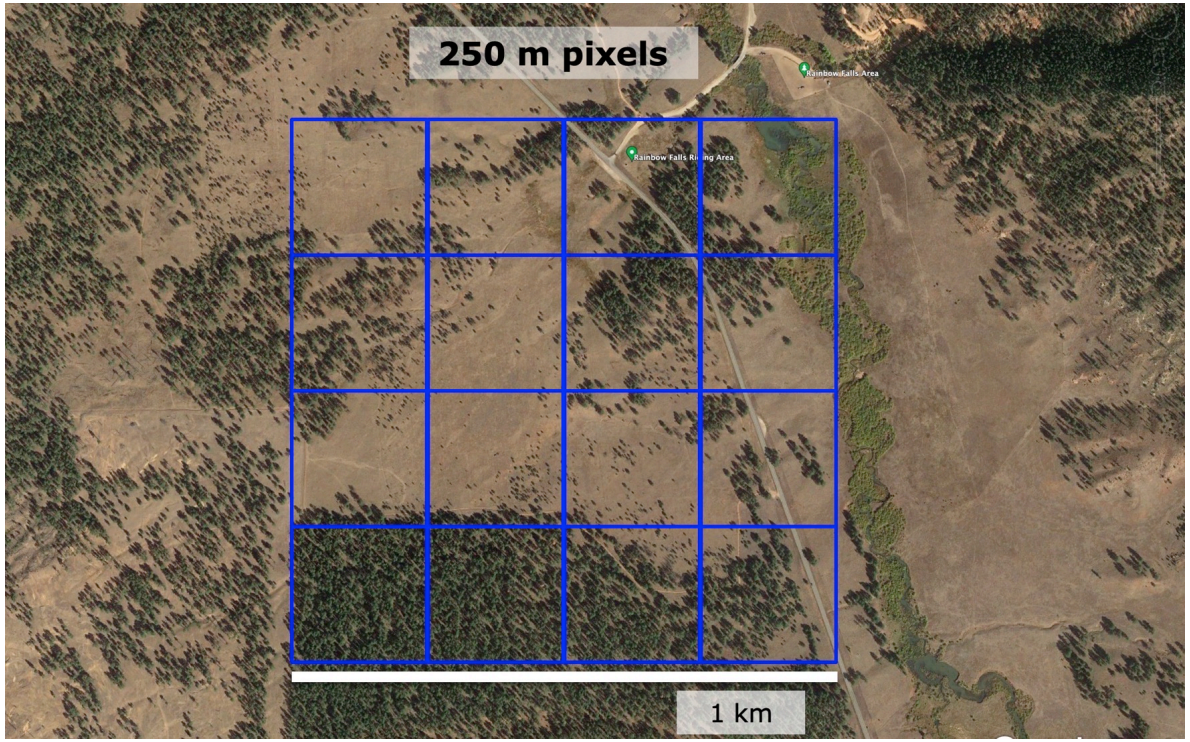
Lei et al., 2016

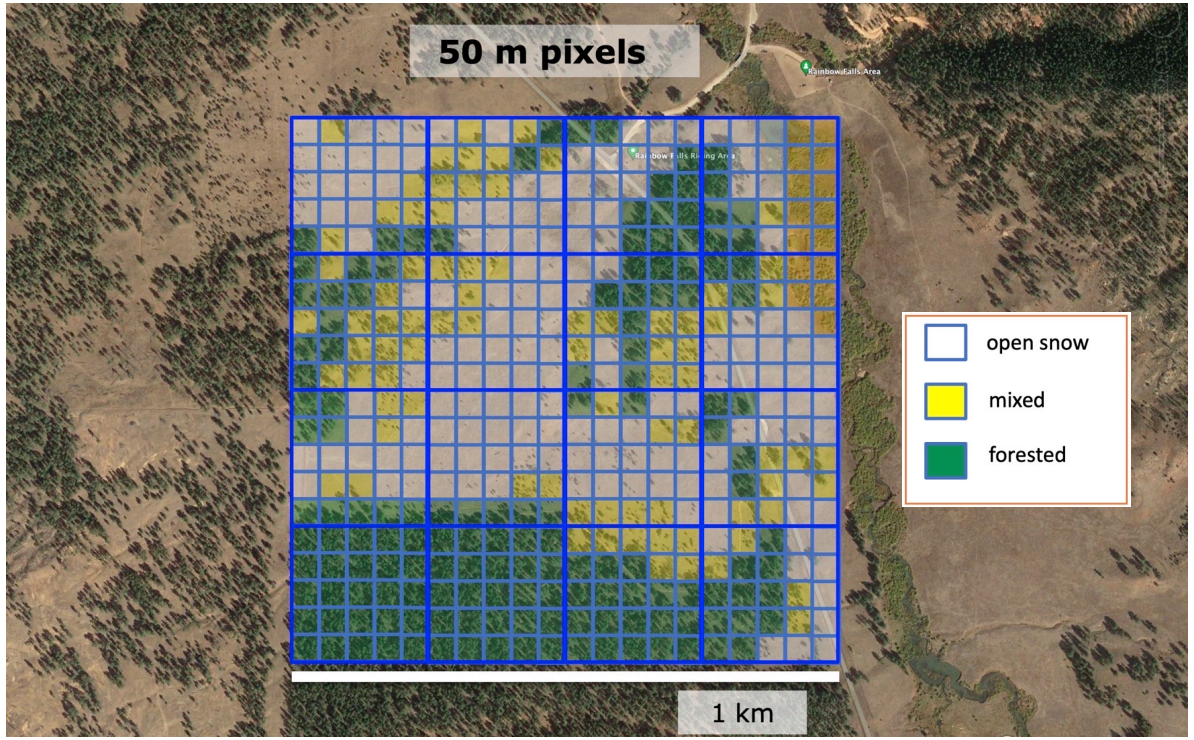


- Total backscatter and extracted volume contribution increases with increasing SWE
- Successful retrievals for combinations of 10 GHz & 17 GHz and 13 GHz & 17 GHz combinations
- With SNOWWI we will be able to collect more Ku-band data in order to improve models
- May add a 10 GHz channel to SNOWWI and/or utilize commercial systems to collect the data

High resolution

- High Resolution Systems like Synthetic Aperture Radar (SAR) resolution allows discrimination between landcover types
- Example: a 50 m nominal resolution will allow discrimination between different landcover types
- Non-stationarities at the sub-pixel can follow different algorithmic pathways in order to solve for the net snow characteristics



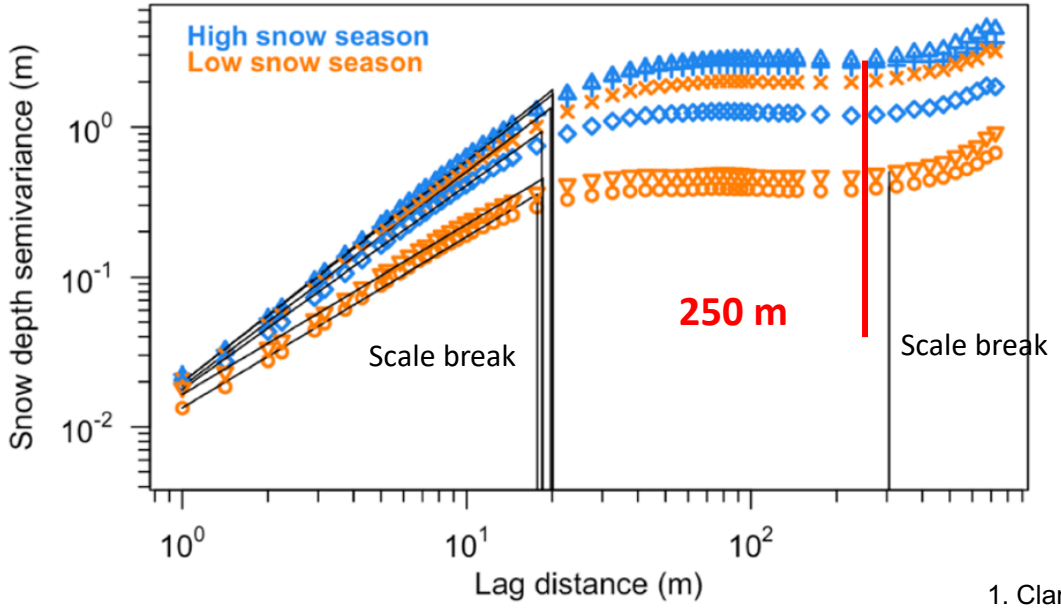


[1]Kuuluvainen, T., E. Jiirvinen, T.J. Hokkanen, S. Rouvinen and K. Heikkinen, "Structural heterogeneity and spatial autocorrelation in a natural mature Pinus sylvestris dominated forest," Ecography, 21(2), 1998, https://www.jstor.org/stable/3682794

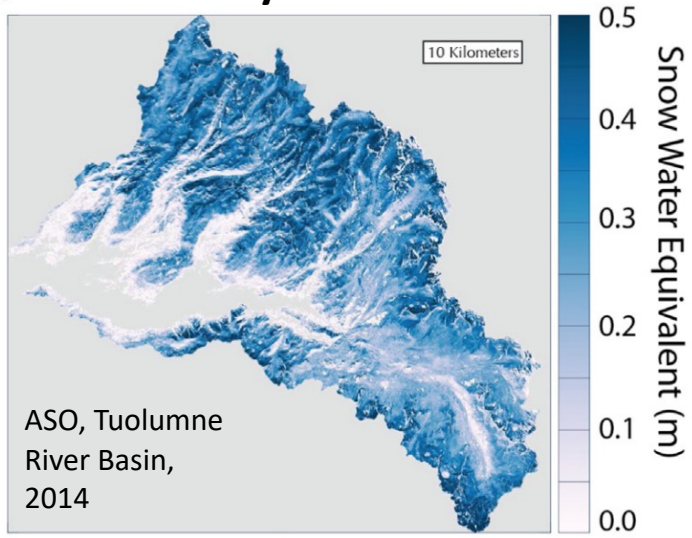
Spatial Variability of SWE

- SWE variability is important for water supply needs is associated with topography, stand-scale vegetation, and climate[1,2]
- Observations at a 250 m spatial resolution are appropriate for capturing SWE variability, as there is self-similar spatial variations at the 100 to 300 m scale[3,4]
- Finer scale variability (1 to 10 m) due to wind and local vegetation processes[1,5] are less important for mapping SWE at watershed to regional scales

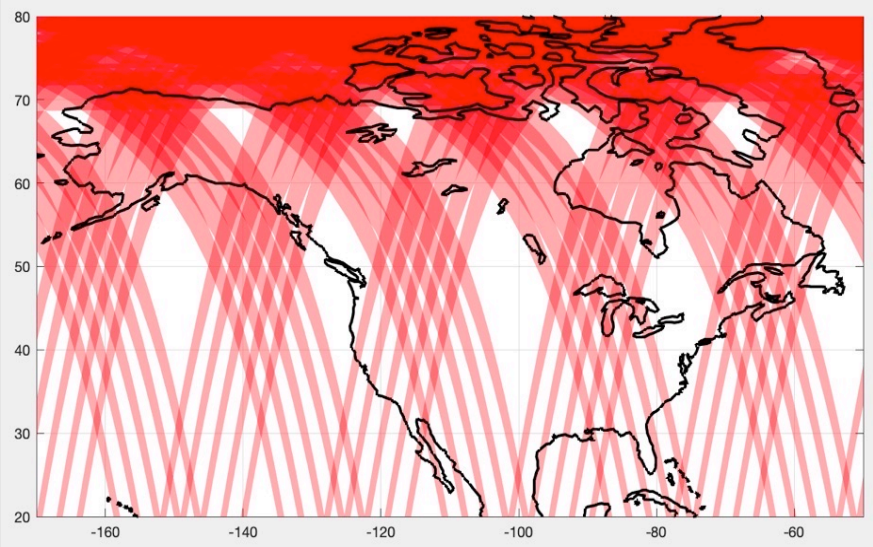
Spatial scales of snow variability[4]



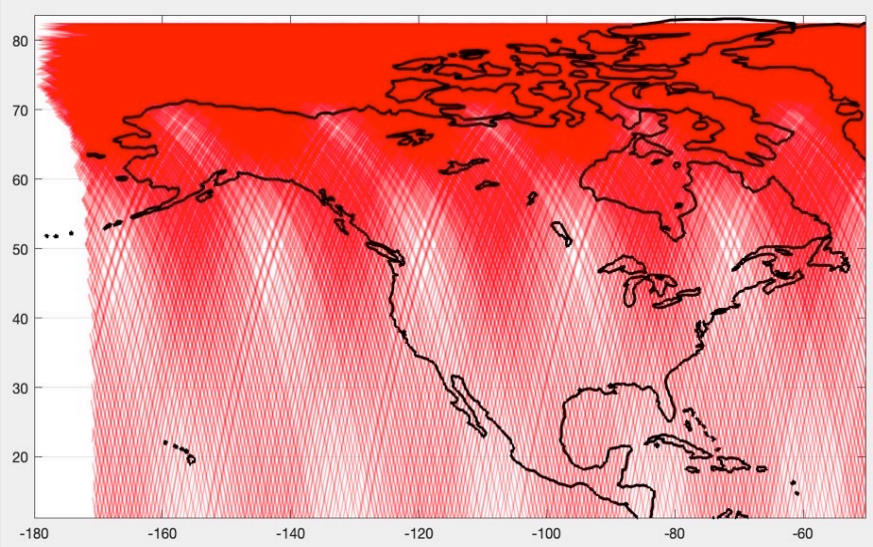
SWE Variability across a watershed[2]



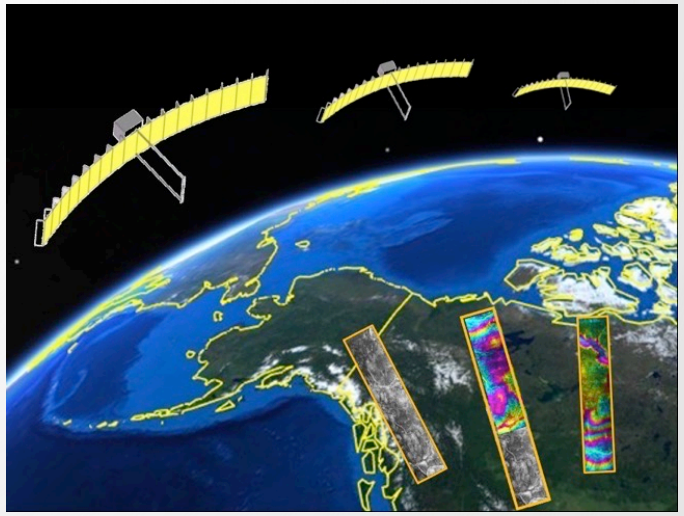
1. Clark et al. (2011), 2. Painter et al. (2016), 3. Scipión et al. (2013), 4. Mendoza et al. (2020), 5. Deems et al., (2008)

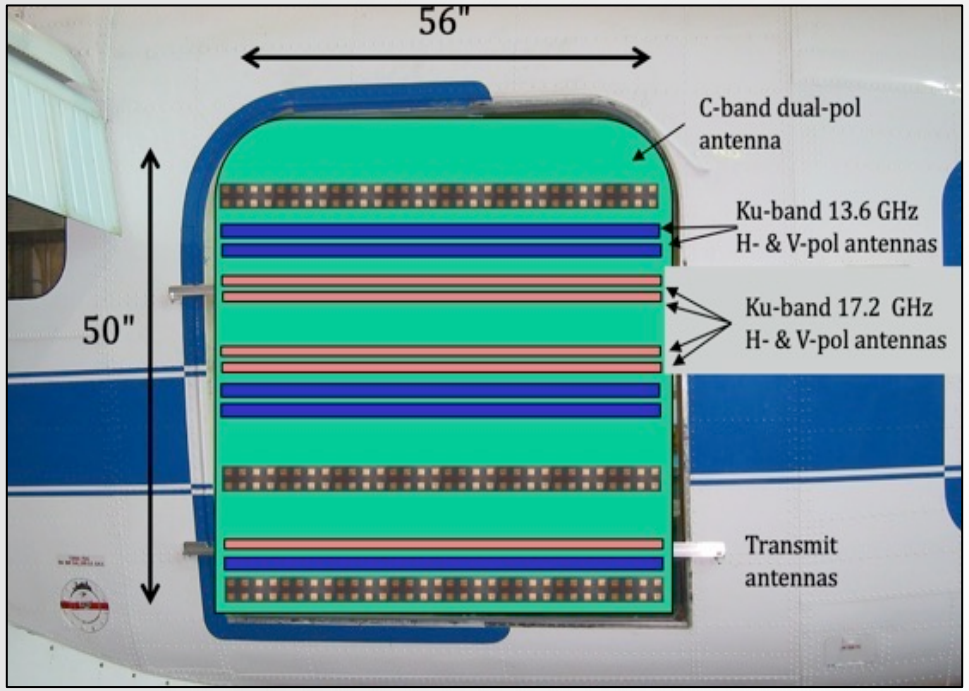


NISAR Configuration
240 km swath



12-satellite constellation
660 km swath
(50 km each)





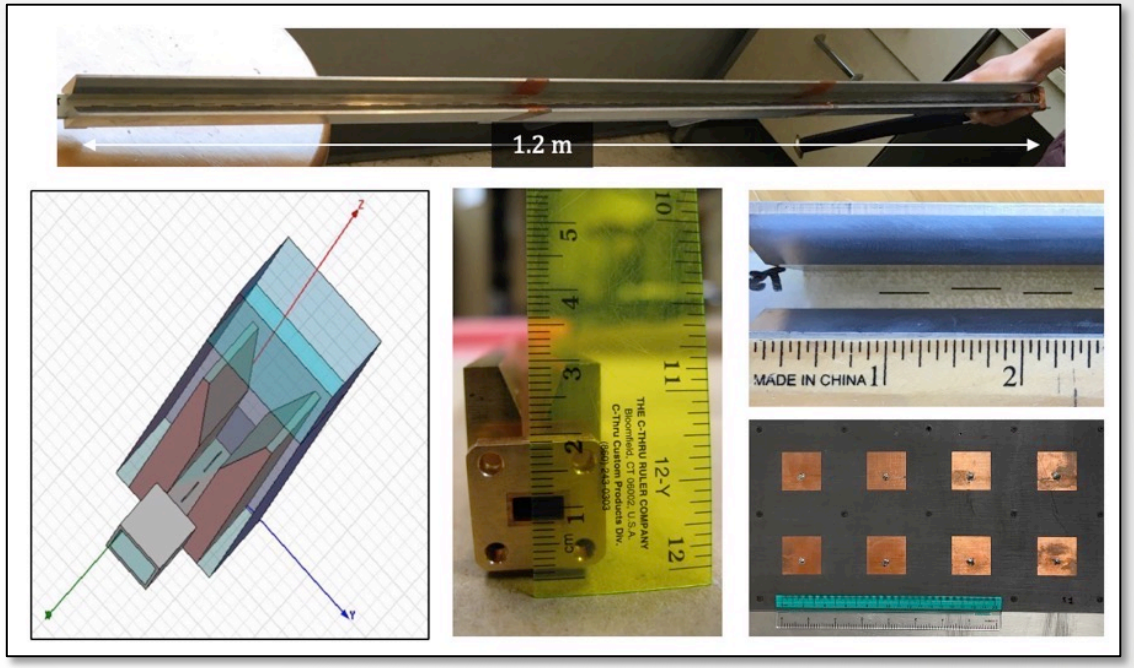
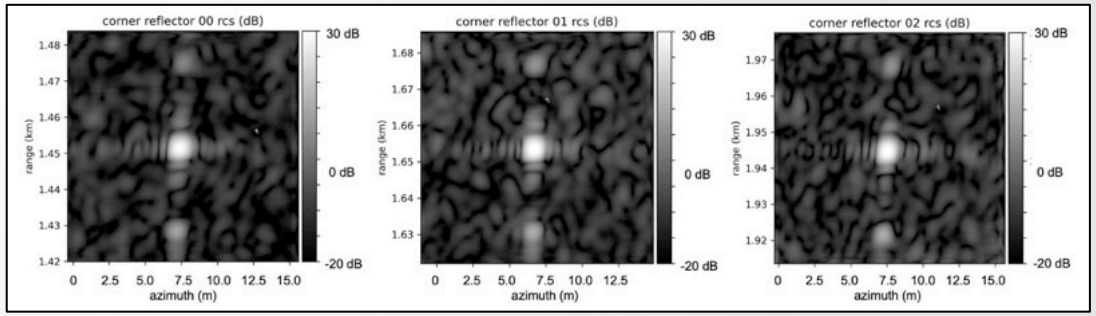


Table 1. *Table of SNOWWI system performance. All systems are dual-polarized (nominally VV & VH)*

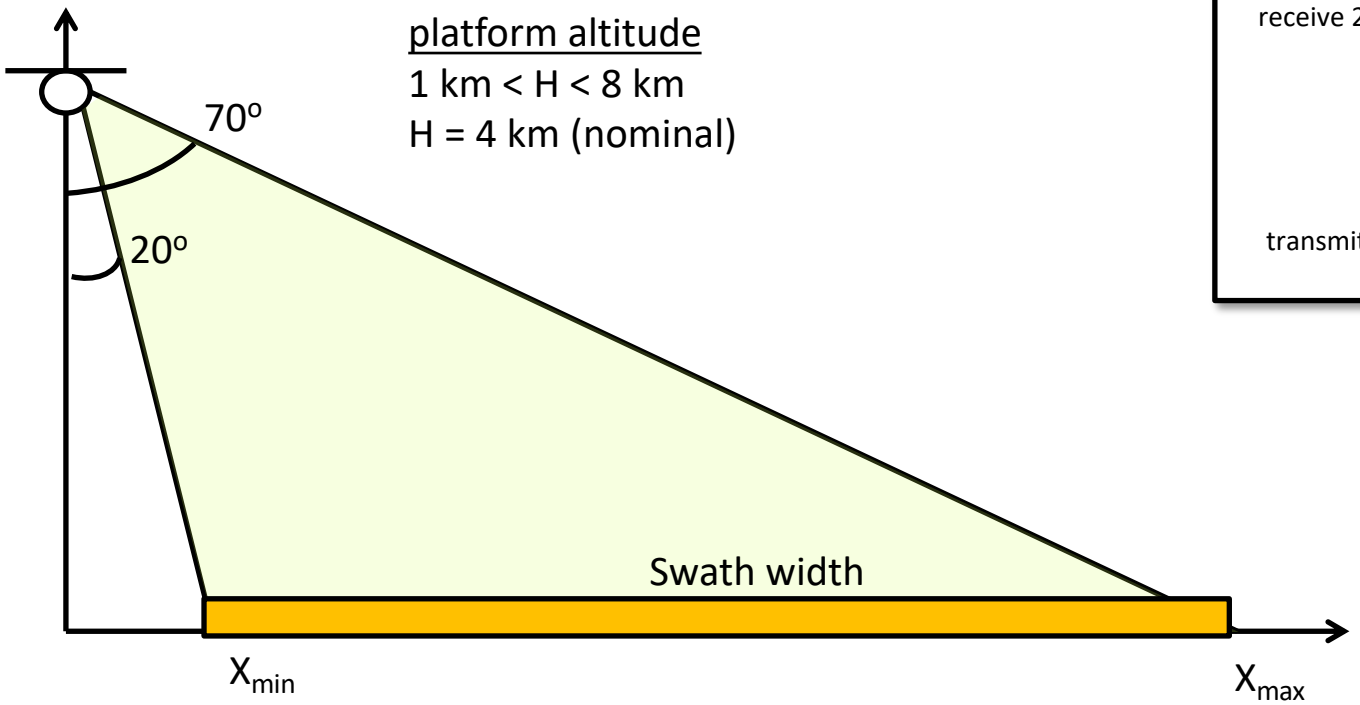
Frequency band	wavelength	Antenna size (Intf. baseline)	Transmit power	Swath width*	Height accuracy†
C: 5.35 – 5.43 GHz	5.6 cm	8 cm x 1 m (100 cm)	120 W	5.1 km	50 cm
Ku-low: 13.60 – 13.68 GHz	2.2 cm	2.2 cm x 1m (88 cm)	150 W	3.5 km	3 cm
Ku-high: 17.20 – 17.28 GHz	1.74 cm	1.7 cm x 1m (70 cm)	150 W	3.5 km	3 cm

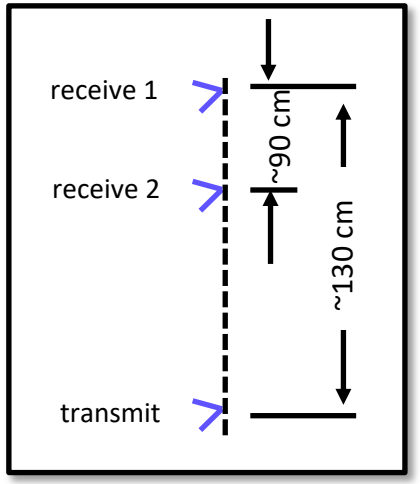
** assuming 4 km a.g.l. and better than -24 dB NESZ performance, †Height accuracy is computed for 4 km a.g.l., 45 degree incidence, -15 dB σ^o, and 10m x 10m resolution with 80 looks.*

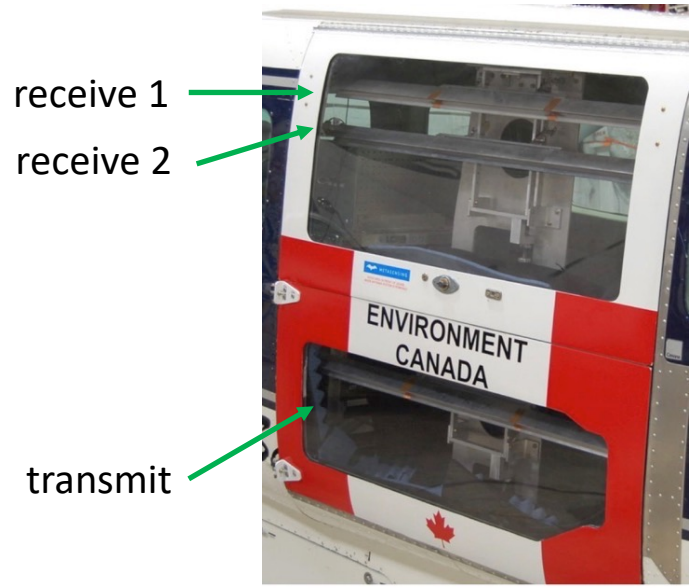


Airborne analysis

- Design of airborne system needs to make trades between antenna geometry, transmit power, platform altitude







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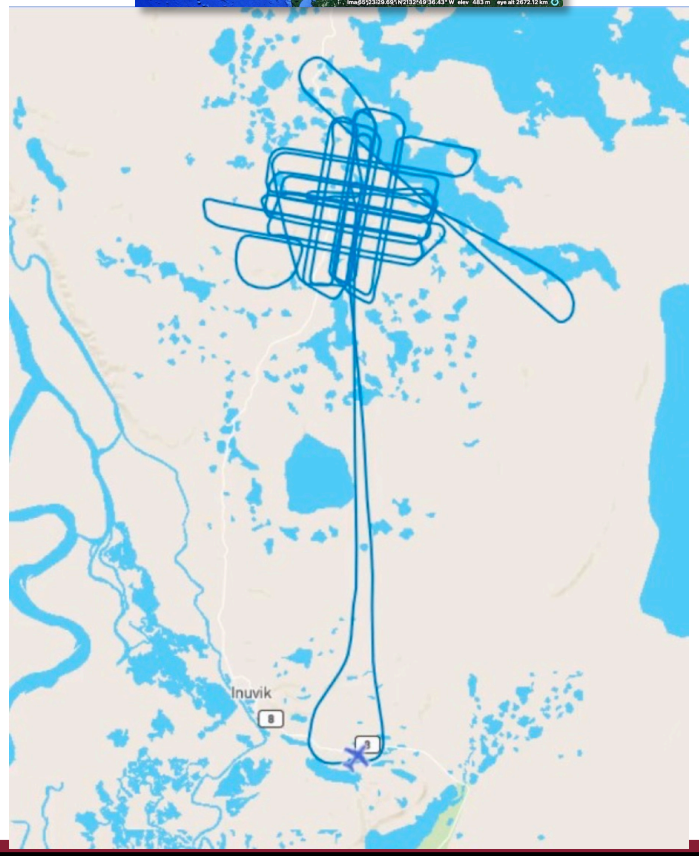
Pre-cursor observatoins
Trail Valley Creek deployment (ECCC & UMass)

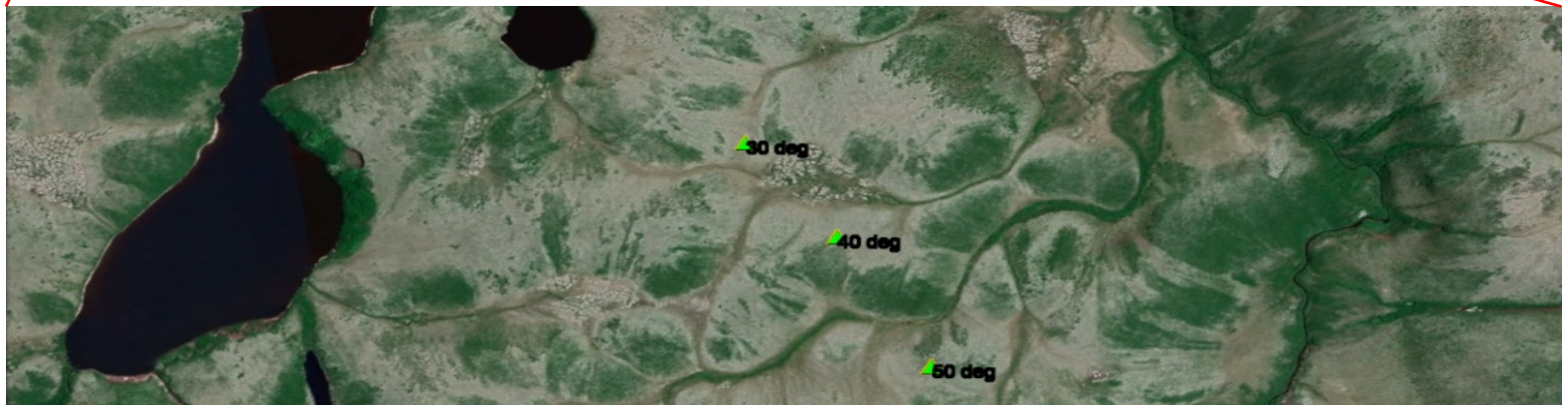
- Objective: Characterize snow volume-scattering using Ku-band SAR & InSAR over a broad diversity of look angles (25° – 65°) throughout the 2018-19 winter season
- 3-observing periods (Nov, Jan & Mar)
- Provide base-set of measurements for TSMM & other satellite missions

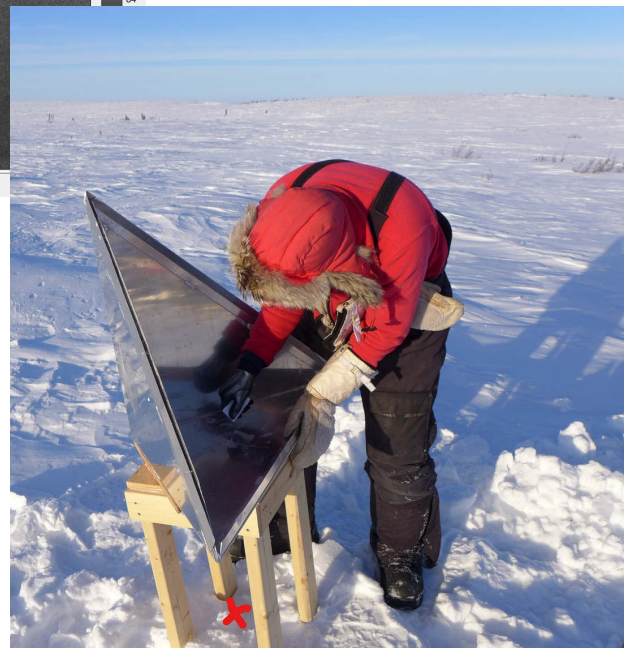
Date (2018 – 2019)	# Flt lines
13 Nov	24
14 Nov	23
15 Nov	25
12 Jan	24
13 Jan	24
15 Jan	26
17 Mar	25
20 Mar	~25
22 Mar	28
23 Mar	26



Trail Valley Creek Studies

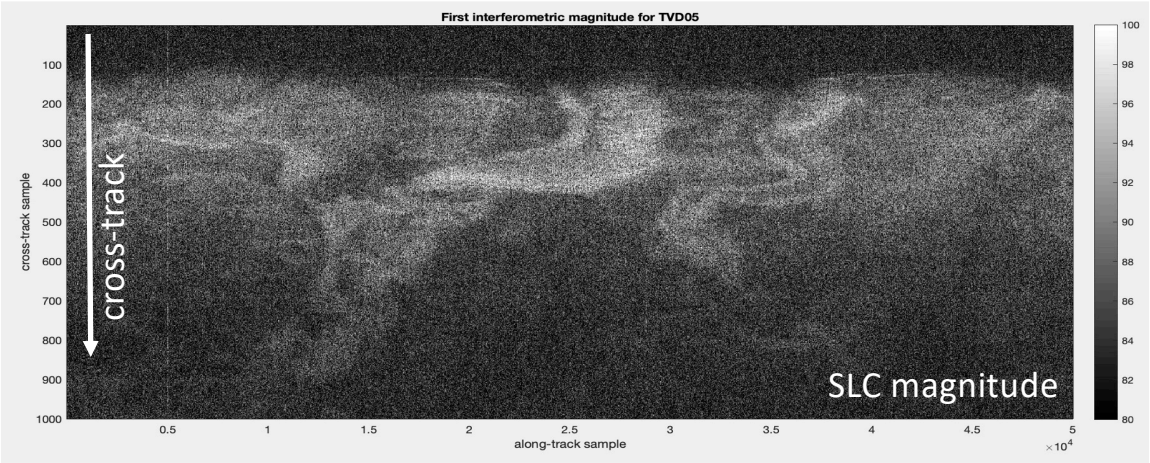
Early results

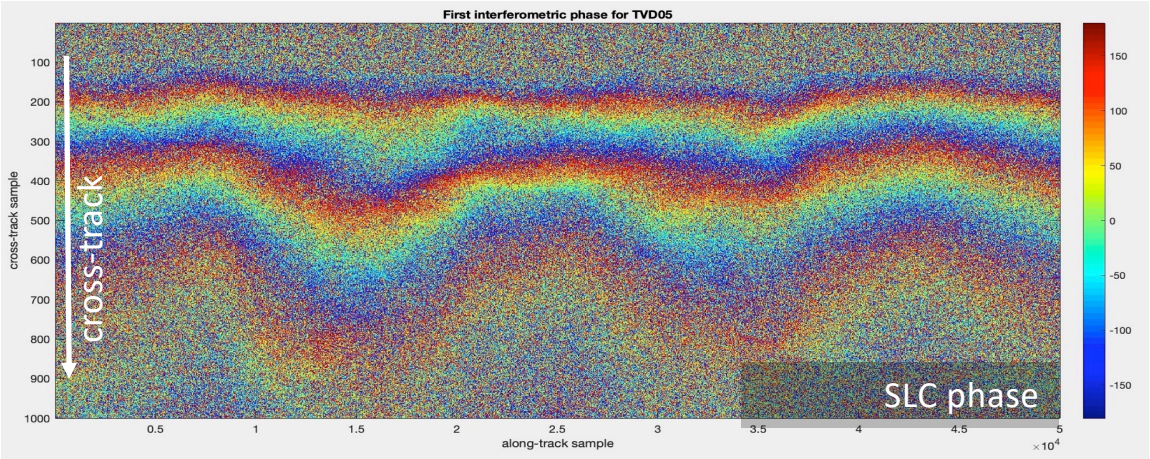


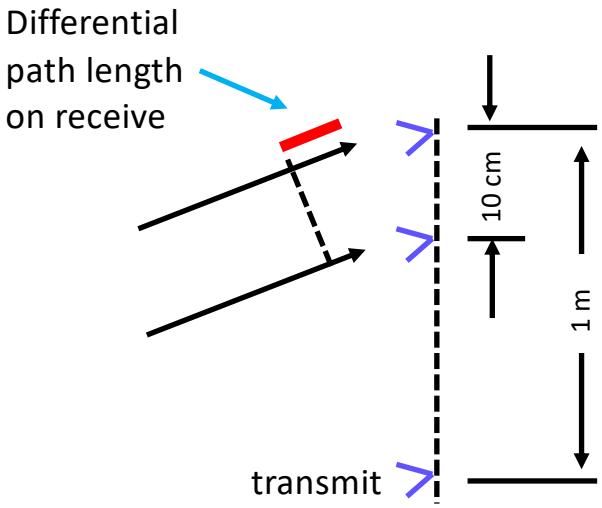


Interferometric data

Flight path (along-track)



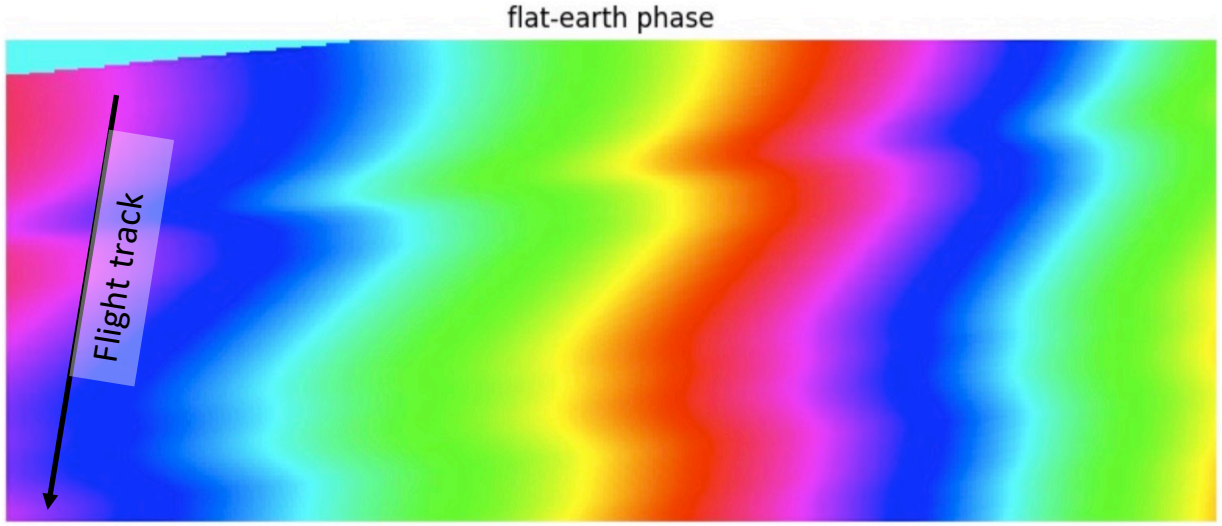




Differential path length, as a function of the look angle, leads to interferometric fringes in the cross-track direction.

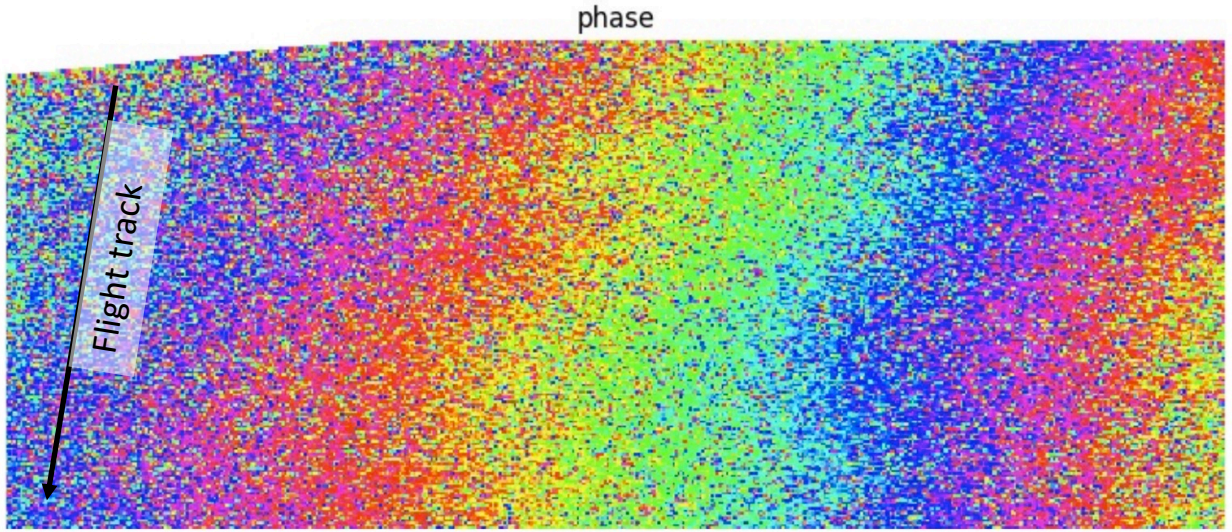
Changing phase as a function of the flight path, can be converted into topography and estimates of the snow depth

Interferometric fringes



Differences between interferograms lead to residual topography (from snow and other ground cover)

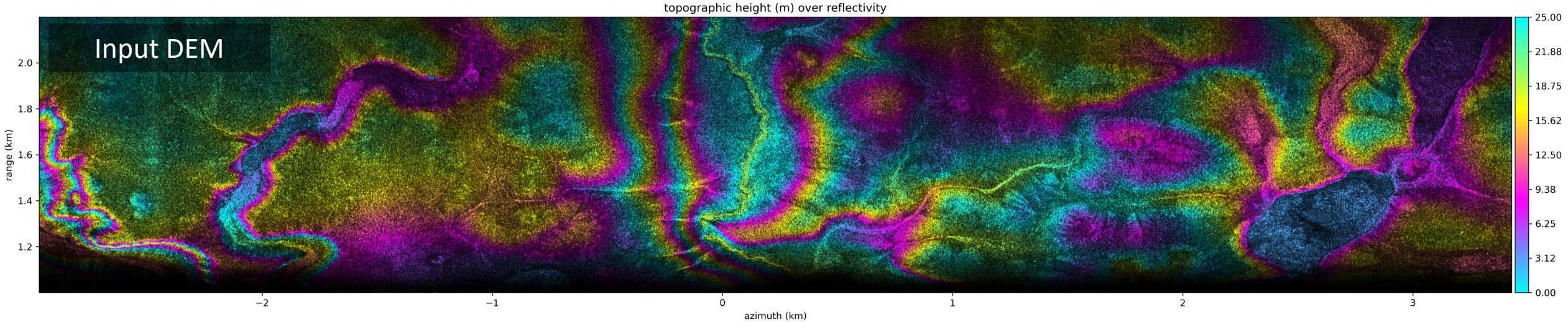
Fringes calculated from motion data and known DEM

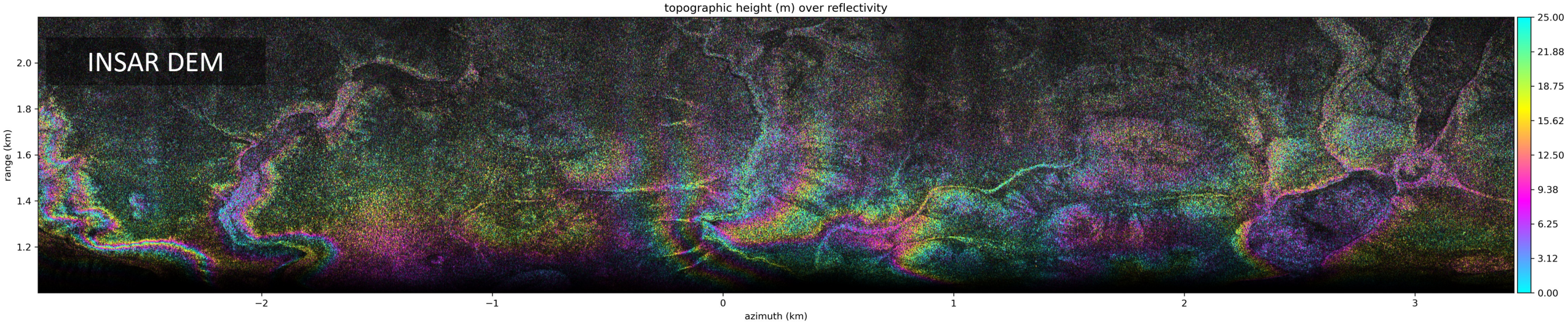


Fringes calculated SLC interferograms

Trail Valley Creek Studies

Digital Elevation Models





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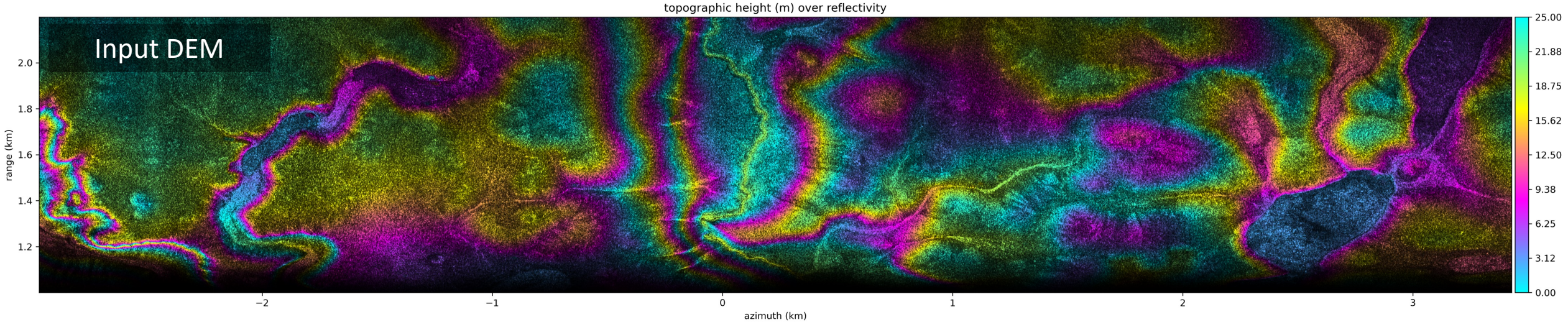

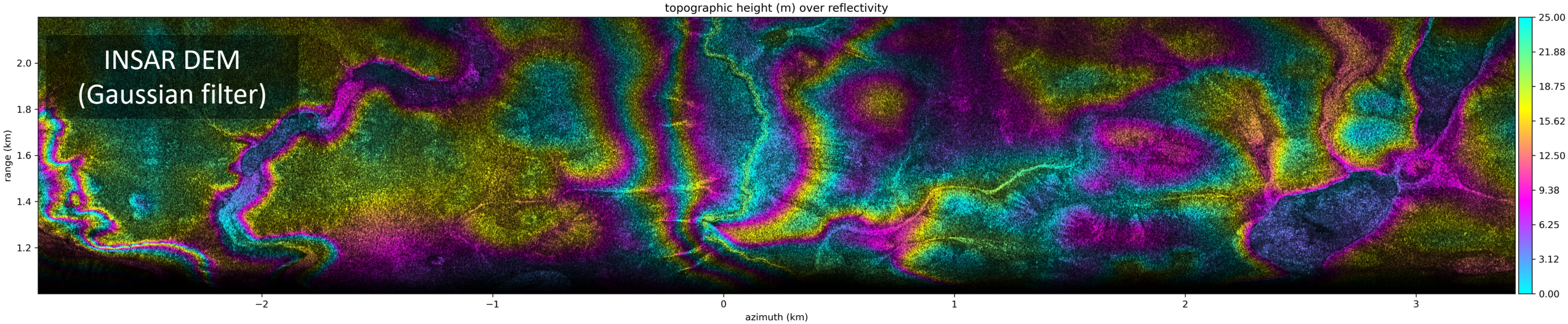

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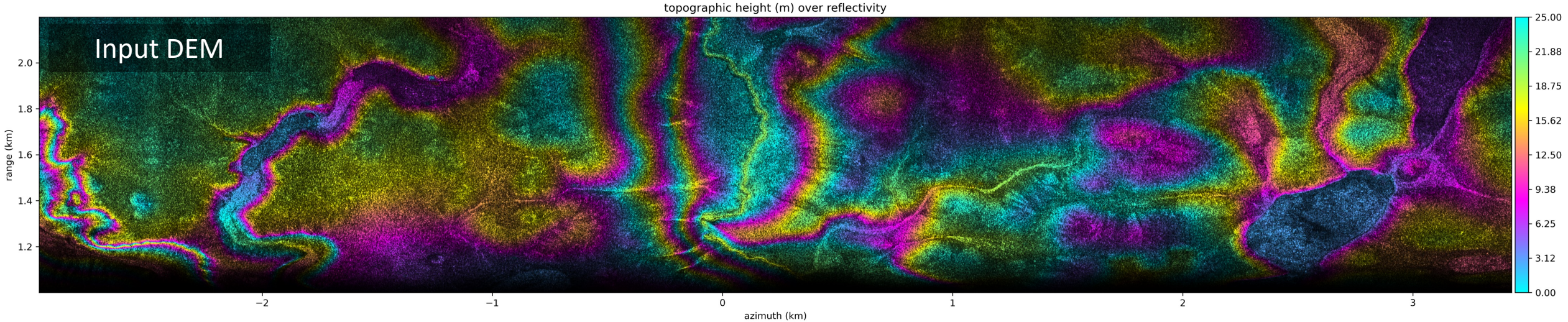
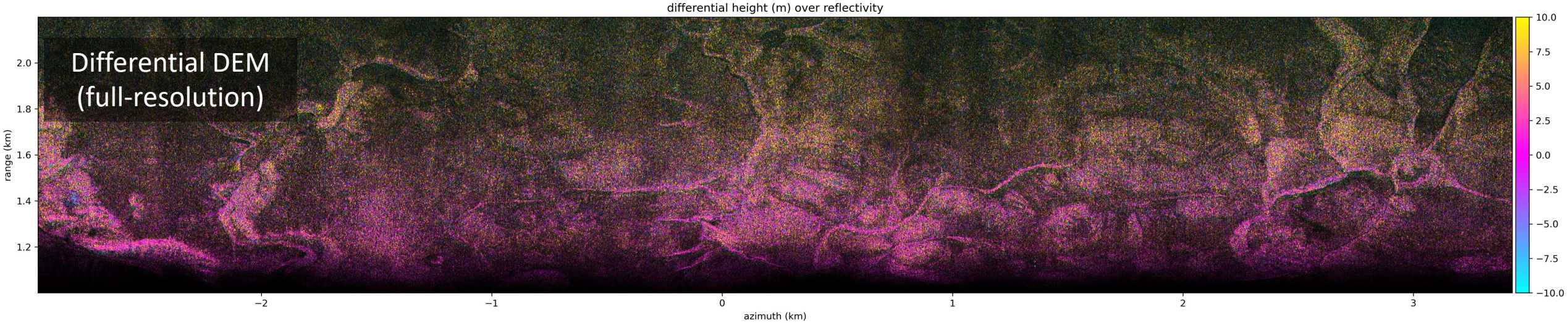
Differential DEM





Trail Valley Creek Studies

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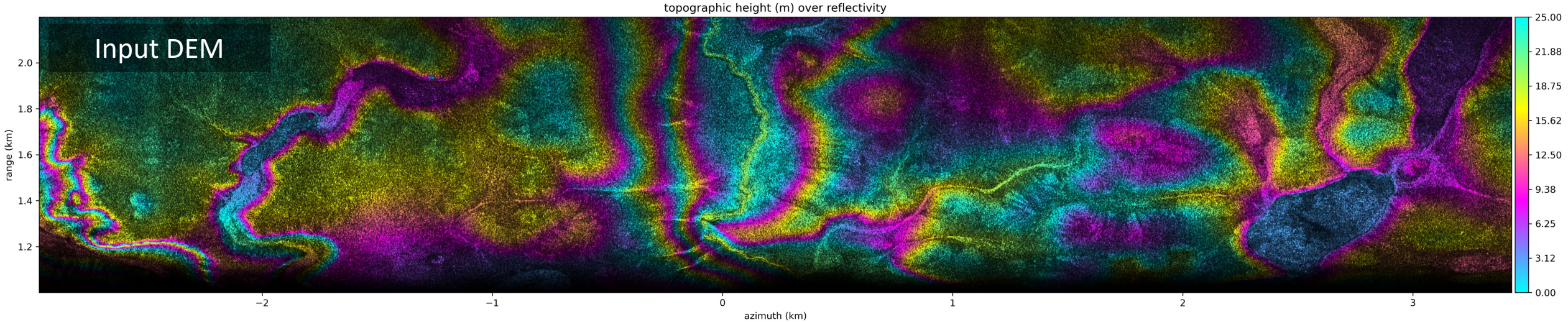

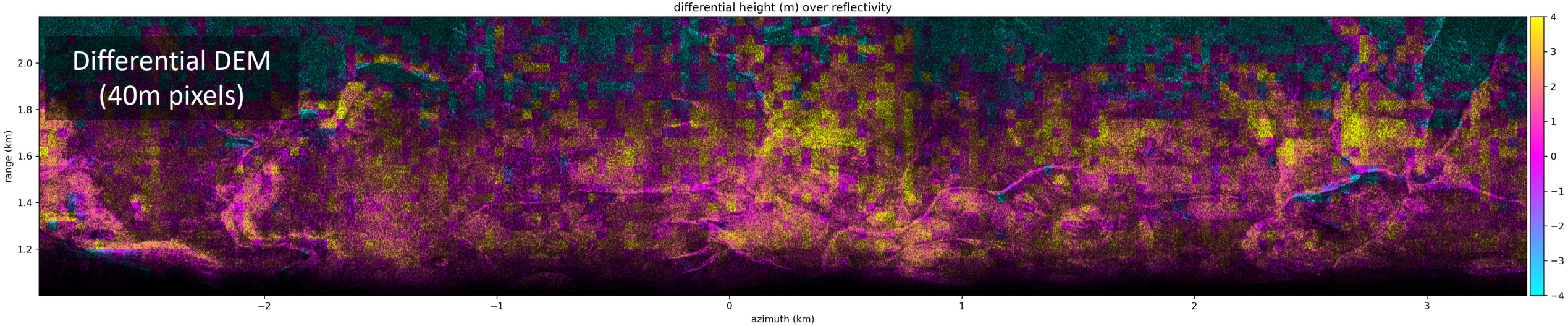

QUESTIONS ?

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