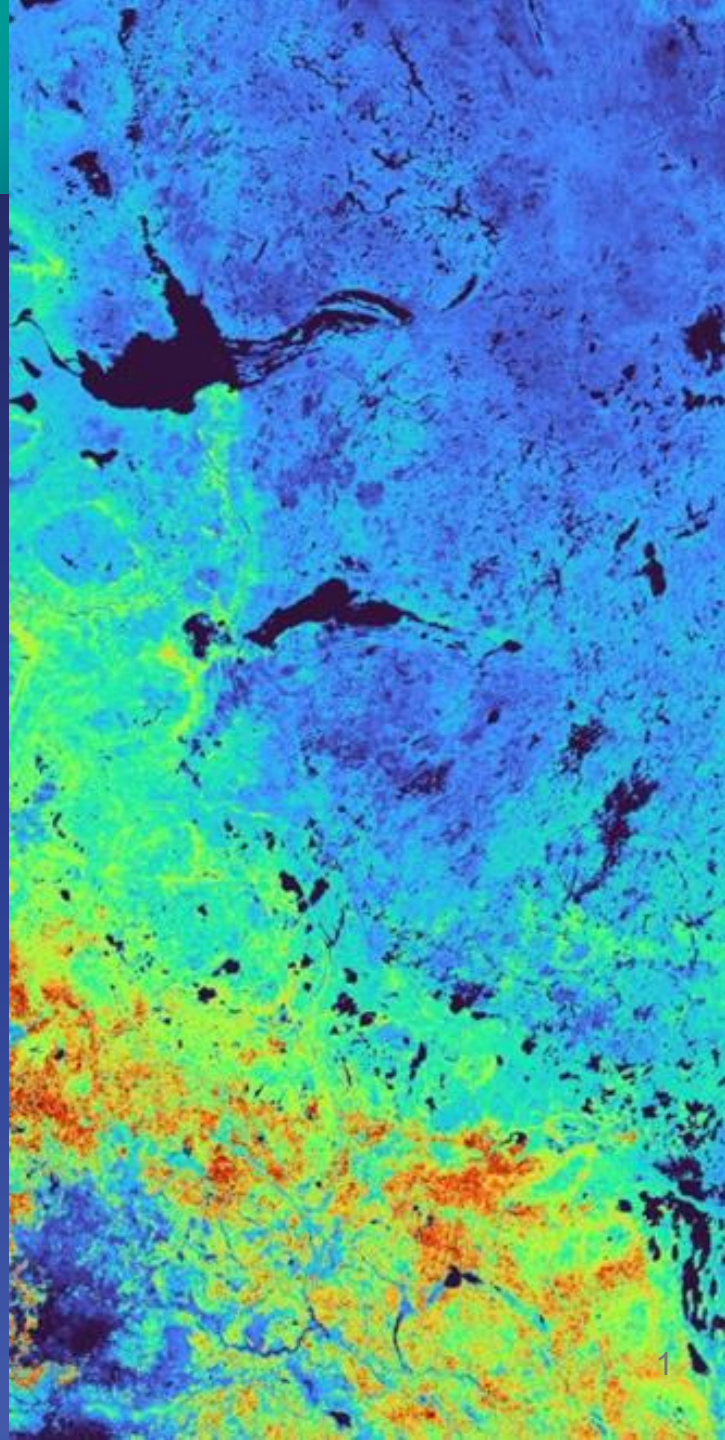
Natural Resources Canada | Ressources naturelles Canada

On the Characterization of Ice Cover Composition with Pol-InSAR and SAR Tomography: Preliminary Results of an Ice Road Case Study



F. Charbonneau and J.J. van der Sanden

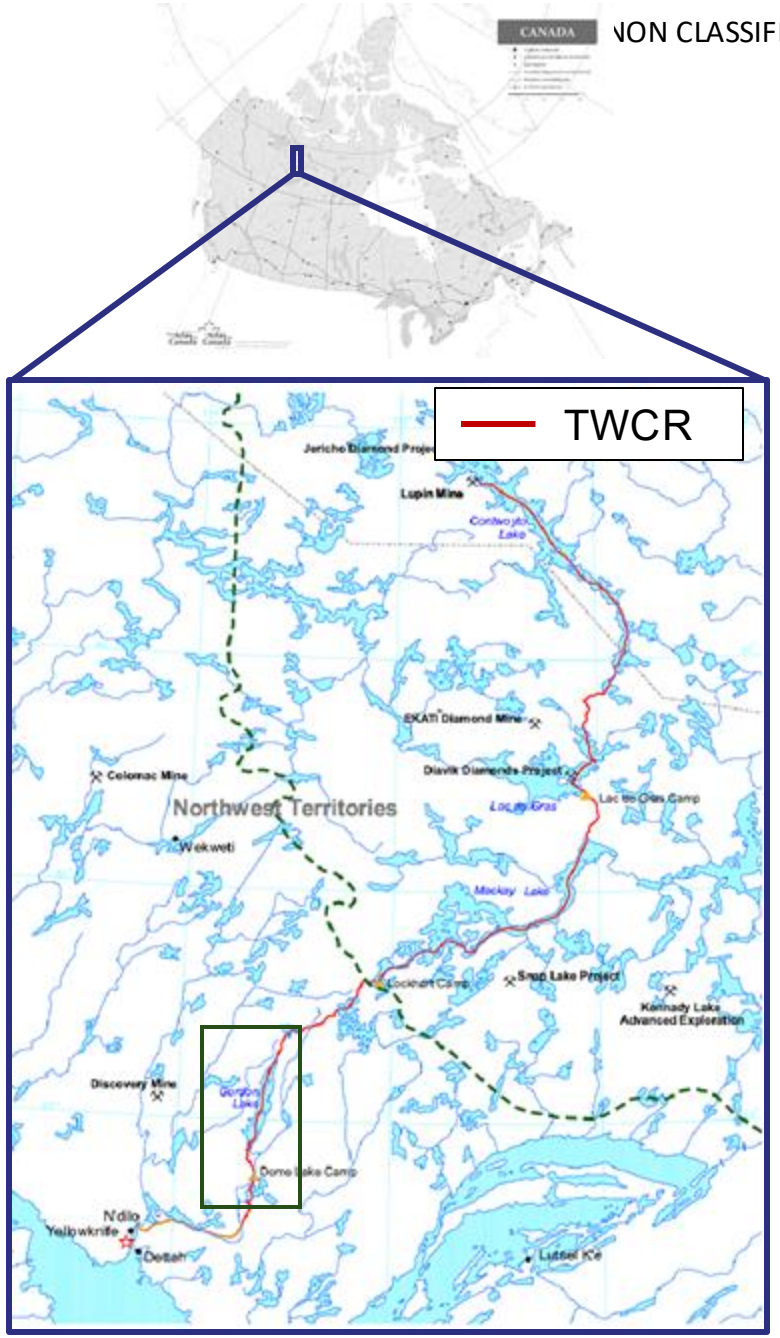
Natural Resources Canada
Geoscience and Earth Monitoring Sector
Canada Centre for Remote Sensing

FRINGE 2026 15 - 19 June 2026 Kraków, Poland

Canada

Introduction

- In countries such as Canada, ice roads facilitate crucial land transportation to isolated sites (e.g. communities, mining industries)
- Current methods to assess the trafficability of ice roads involve in situ measurements and are thus time-consuming, hazardous, and expensive
- In this presentation, we share preliminary results of a study into the utility of Pol-InSAR and SAR Tomography for assessing change in an ice cover's vertical composition due to e.g. differences in ice type, gas bubble inclusions
- Very few studies on "thin" ice with Pol-InSAR or Tomography
- Our study area is the Tibbitt-to-Contwoyto Winter Road (TCWR) in Canada's Northwest Territories



Objectives

Primary (project goal):

- From a trafficability point of view, estimate the **snow ice layer thickness** (structurally less resistant to overload) relative to the thermal/columnar ice layer.

Secondary:

- Answering (presentation objectives):
  1. Is there enough InSAR polarisation diversity in “thin” ice layer**(s)**?
  2. Can we distinguish volume scattering center from ice/water surface scattering position with tomography at sub-meter scale?

- Characterizing lake ice from Pol-InSAR analyses (by building an improved understanding of the radar wave interaction with the media)

- Characterizing lake ice from SAR tomographic analyses

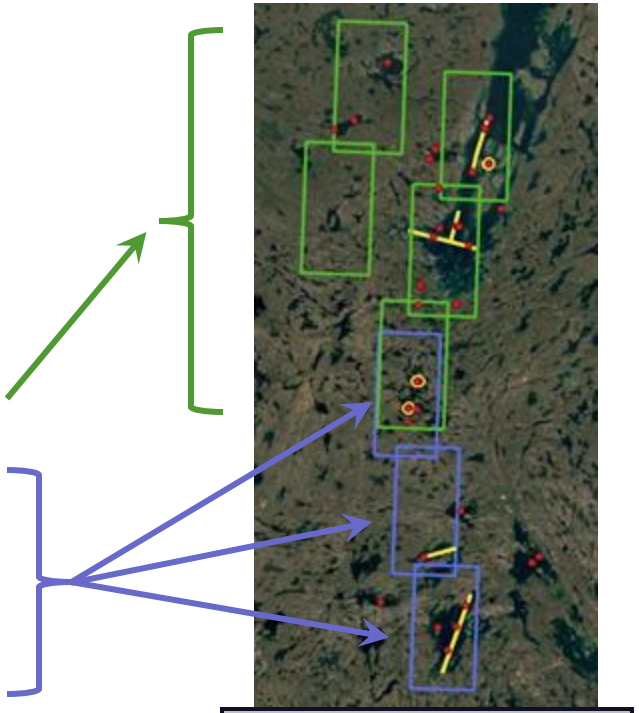
Fieldwork

- Research team members travelled to the study area to collect ground reference data from March 11 to 23, 2019
- Their field sites were pre-selected with the help of RADARSAT-2 polarimetric data that were acquired in February 2019
- The team collected data on selected ice cover and snow cover variables, including:
  - Ice cover: thickness, strata, ice type, impurities, substrate (water vs. lakebed)
  - Snow cover: thickness, strata, hand hardness, complex permittivity
- GPR measurement transects

DLR Airborne PermaSAR 2019 Campaign

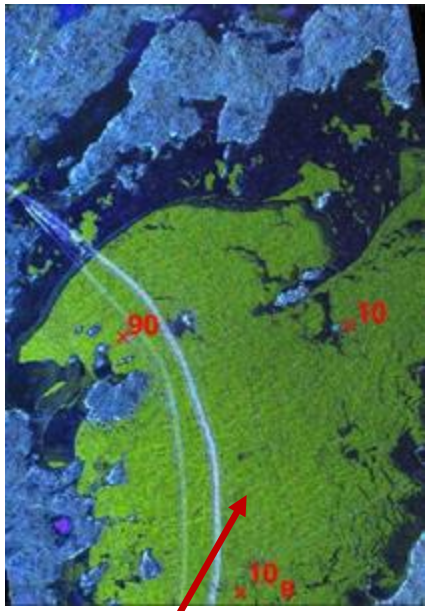
- F-SAR airborne SAR system
- SAR bands: X, C & L
- Polarization configuration: Fully polarimetric
- Pol-InSAR and Tomographic transects
- Altitude ≈ 4.2 km

Transects	Heading [º]	Horizontal Baselines [m] (relative to primary transect)	In Situ Sites
Pol-InSAR	13º (193º)	15	21 ISS + 6 GPR
Tomo & Pol-InSAR	349º	0, 10, 15, 20, 40, 60, 100	11 ISS + 4 GPR
Tomo & Pol-InSAR	169º	5, 10, 15, 35, 55	11 ISS + 4 GPR

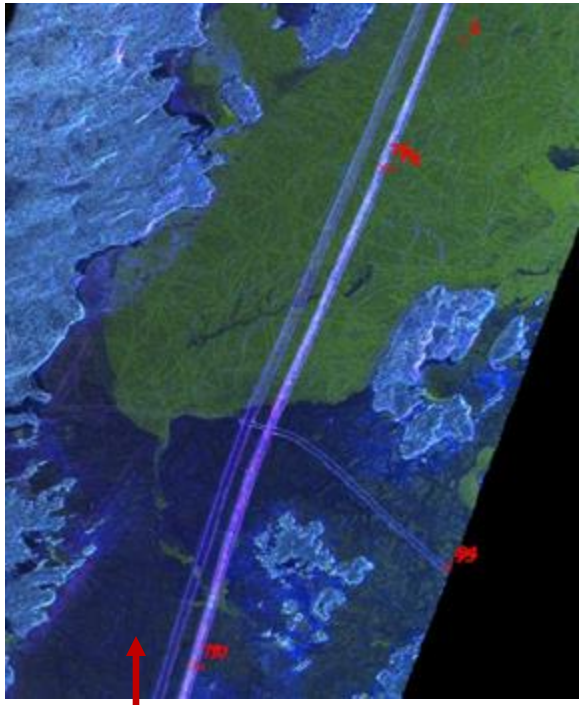


Some In Situ Sites on C-band Pauli Composite

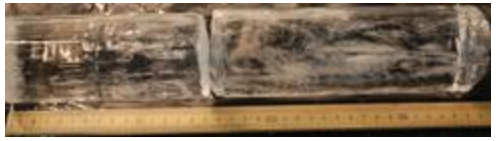
Scattering Mechanisms
Red: Even Bounce
Green: Depolarized
Blue: Odd Bounce

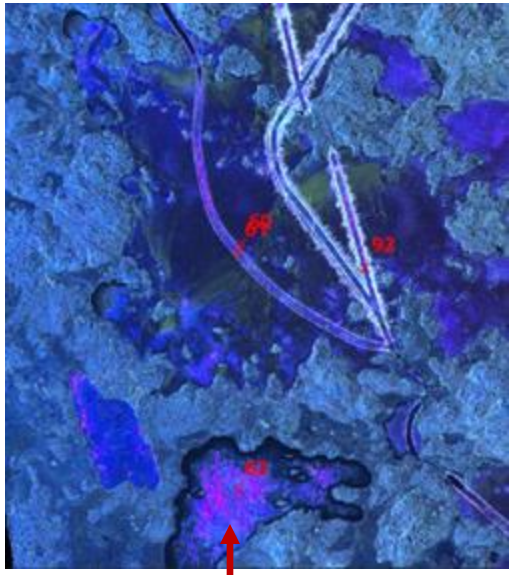


Snow (white) ice
Volume scattering due to spherical air bubbles (X, C-band)

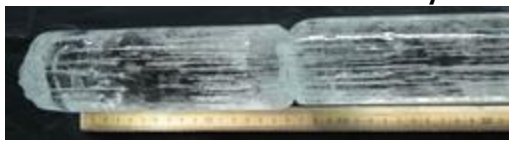


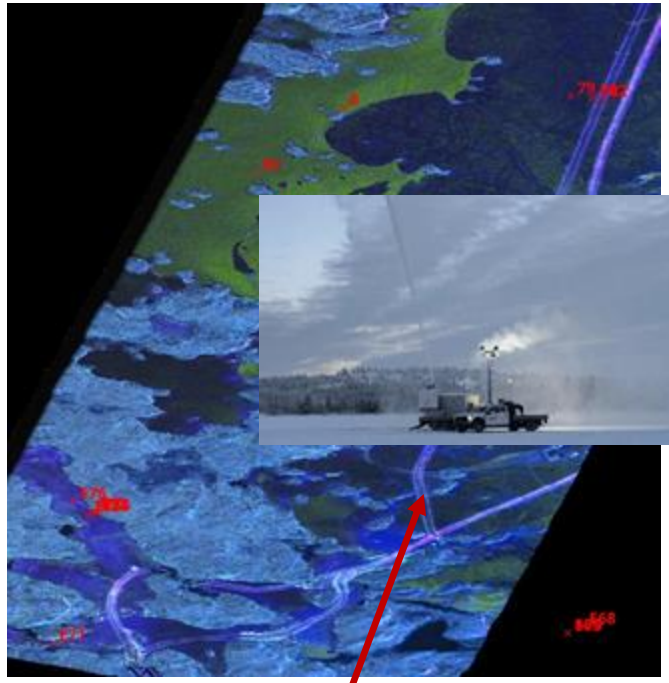
Columnar (black) ice
Surface scattering @ ice/water boundary





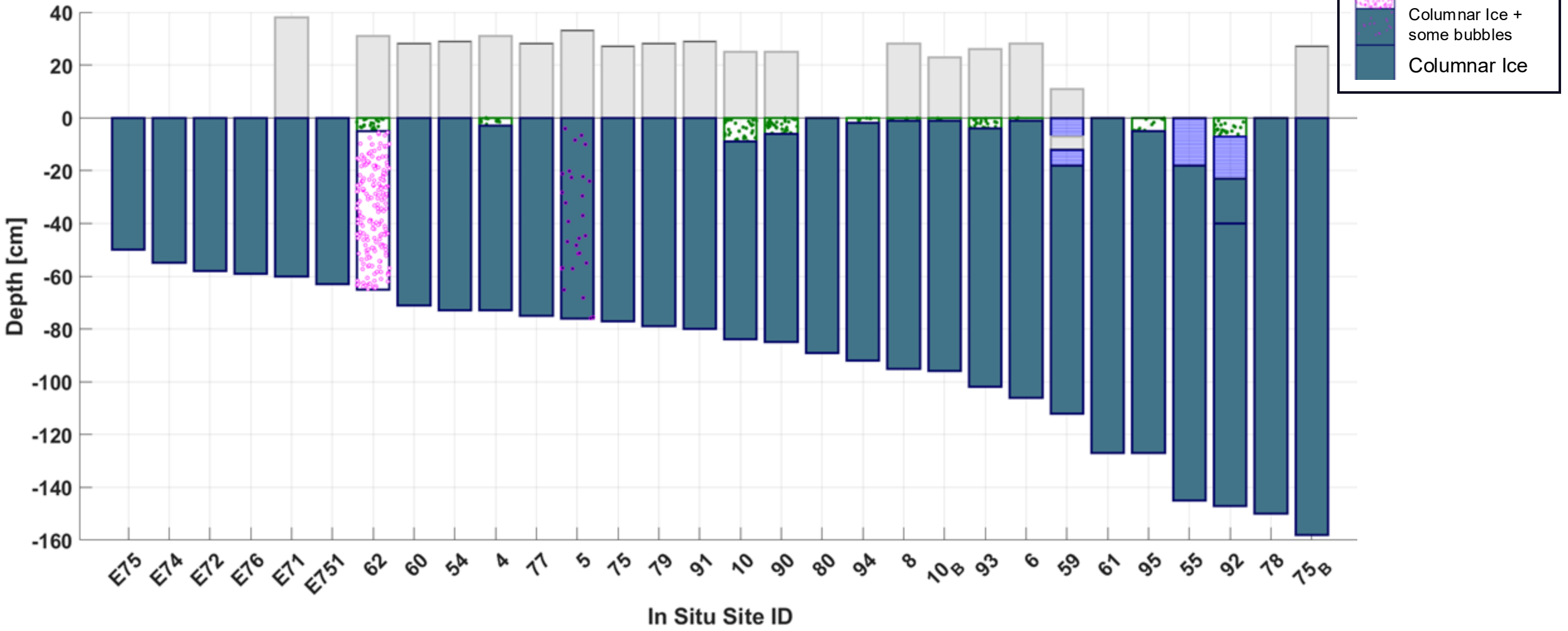
Columnar ice + elongated gas bubbles
Even bounce(?) and surface scattering @ ice/water boundary





Man-made (slush) ice
Surface scattering @ ice/water boundary

Snow and Ice Sample Profiles

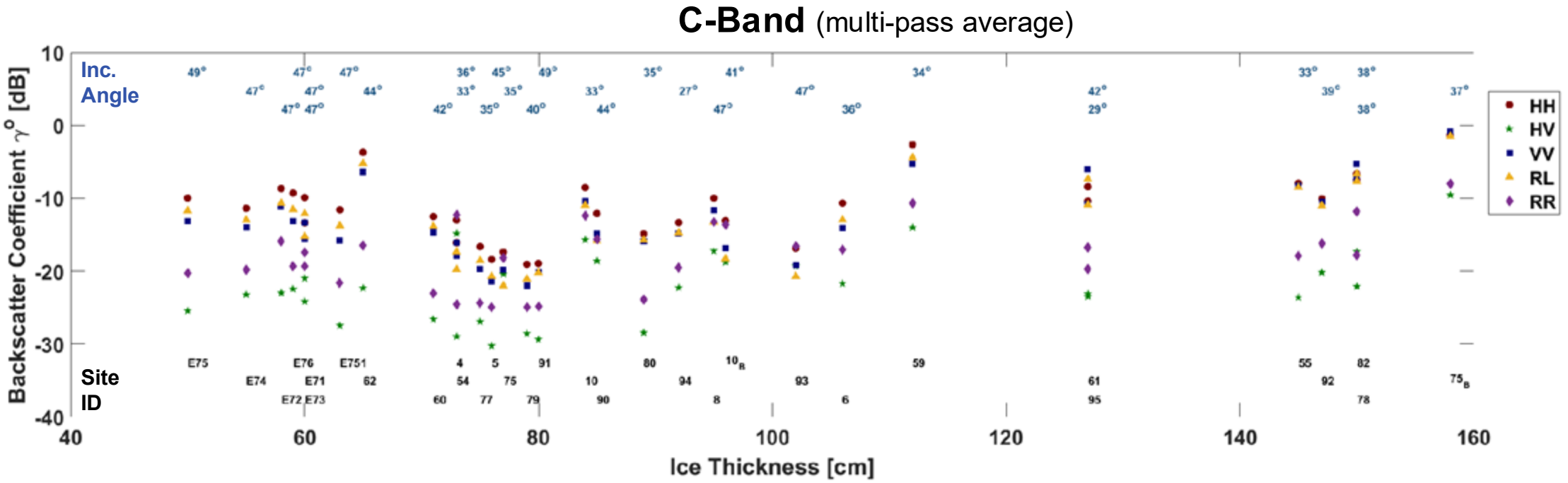


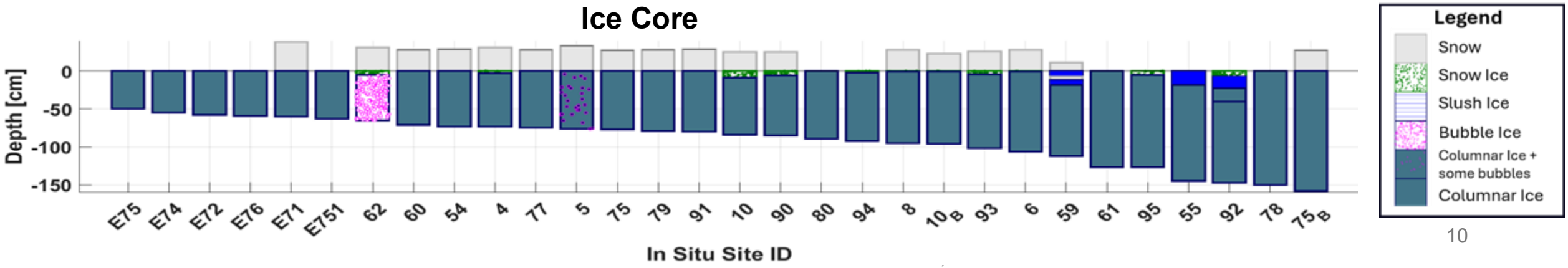
Why getting things complicated?

(With PoI-InSAR and/or Tomography)

Could we simply use polarimetric information?

Estimating Ice Thickness from Backscattering Coefficients Only?

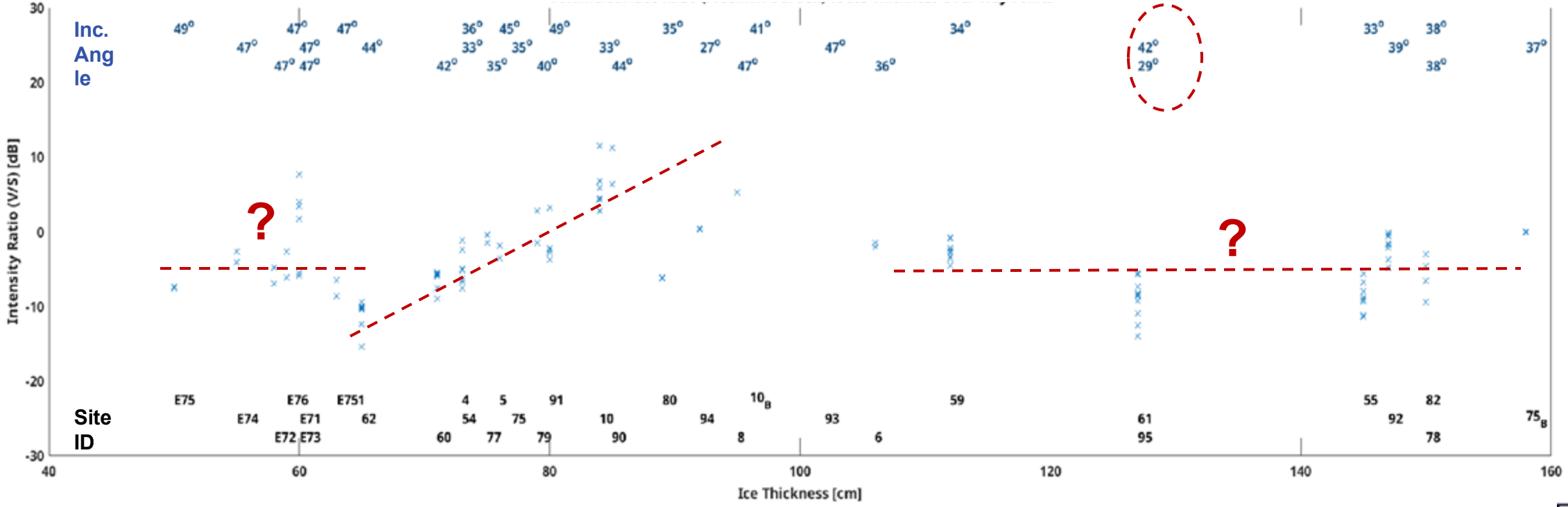


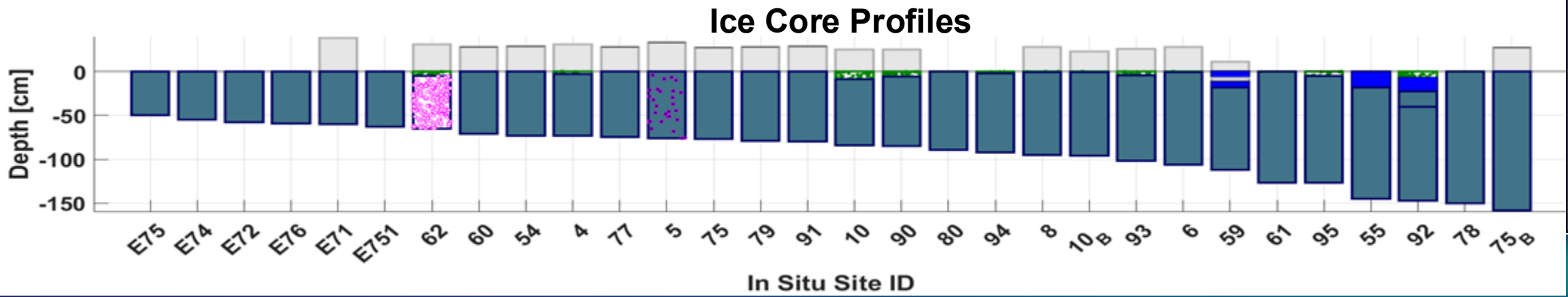


Volume/Surface Ratio

[Freeman-Durden Decomposition]

C-Band (FL02 individual passes)

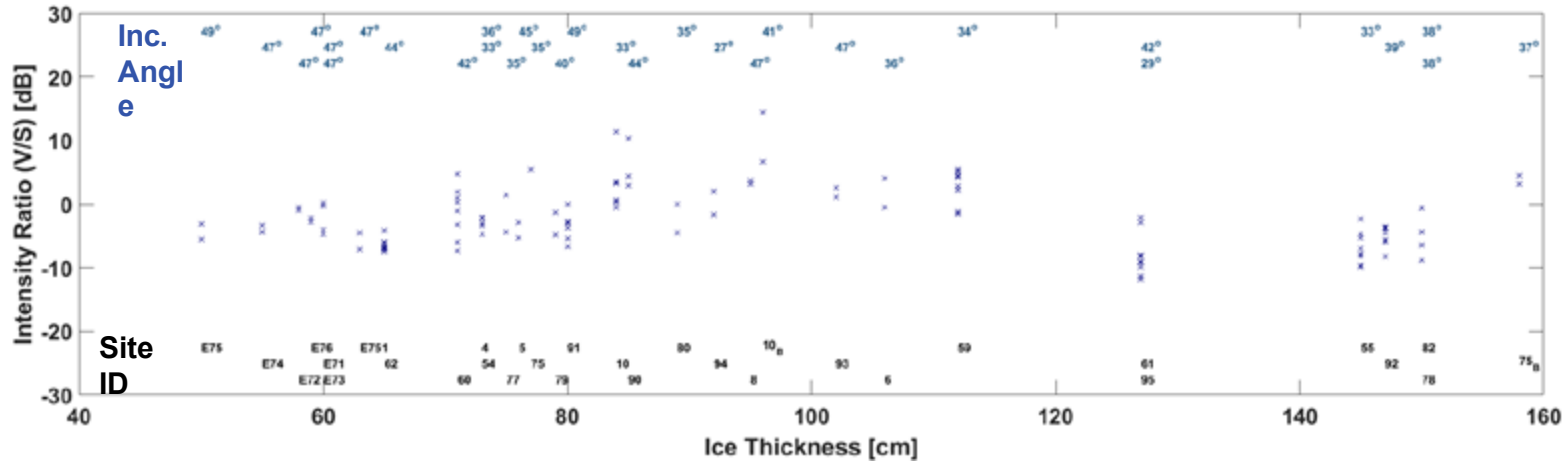




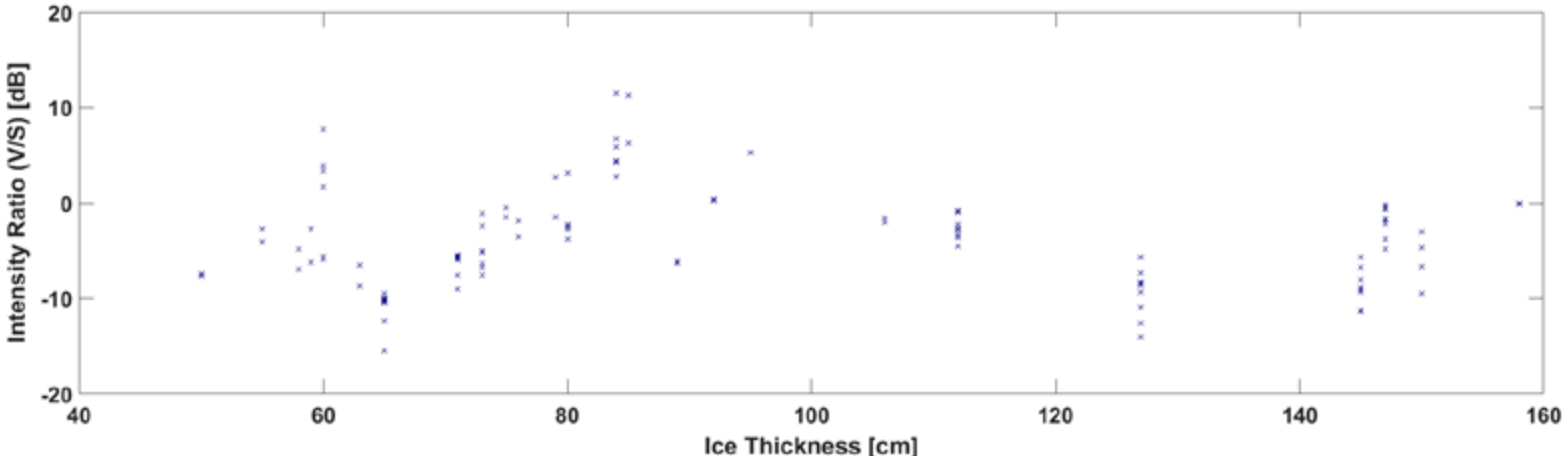
Volume/Surface Ratio
[Freeman-Durden Decomposition]

- Volume-Surface ratios, in function of ice layer thickness, behave similarly at the three bands
- Some correlation with ice core depths in the range of 60 to 90 cm, where rates differ between $\Delta\lambda$
- No clear relationship for ice layer > 1 m

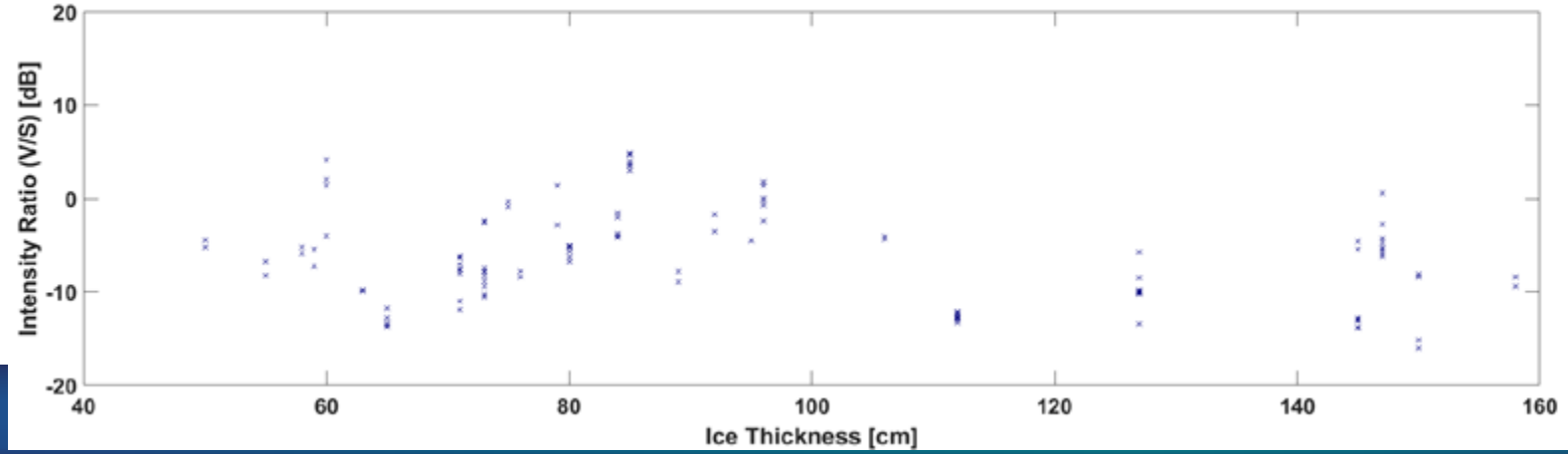
X-Band



C-Band



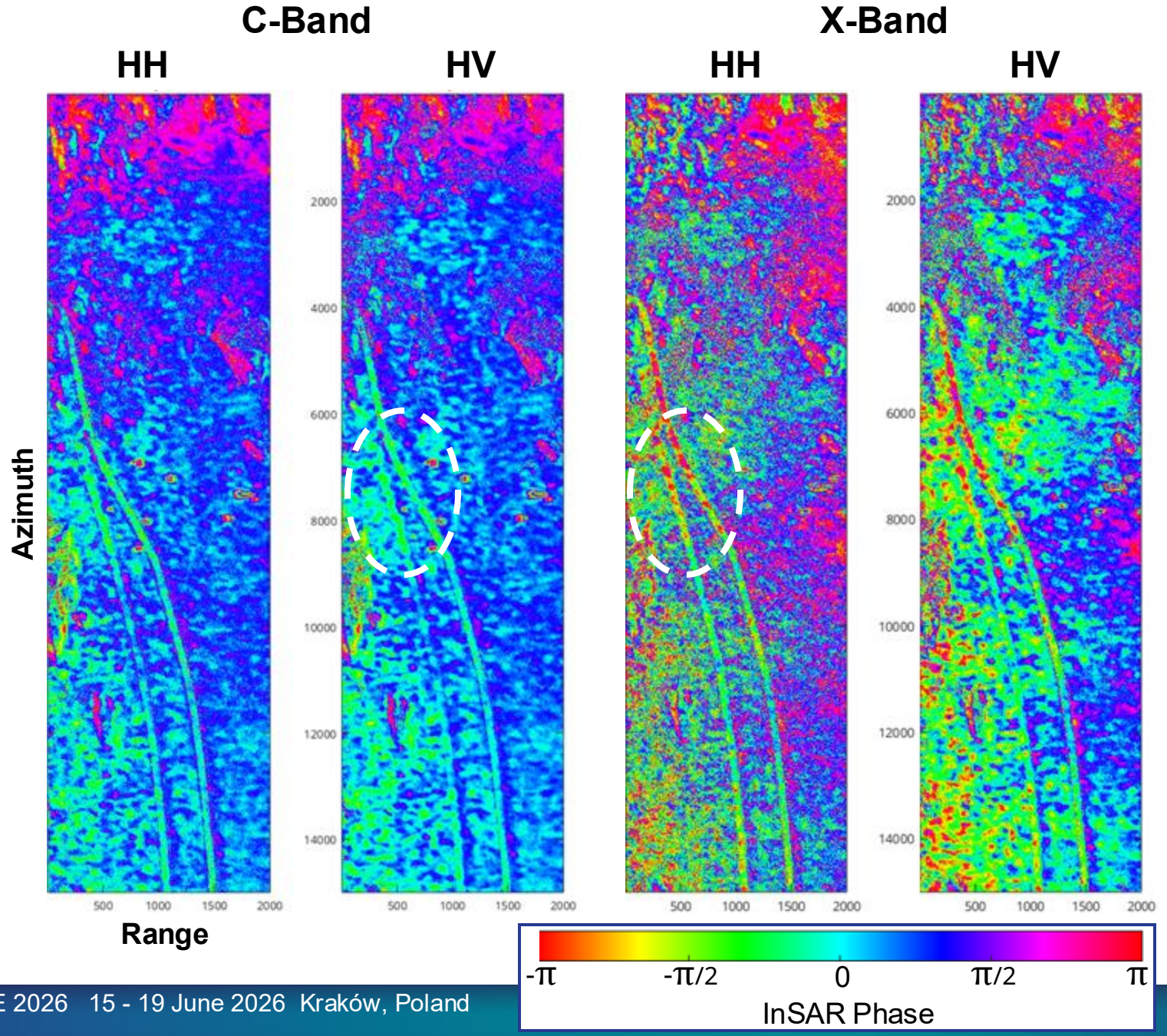
L-Band



Single Pol InSAR Phase

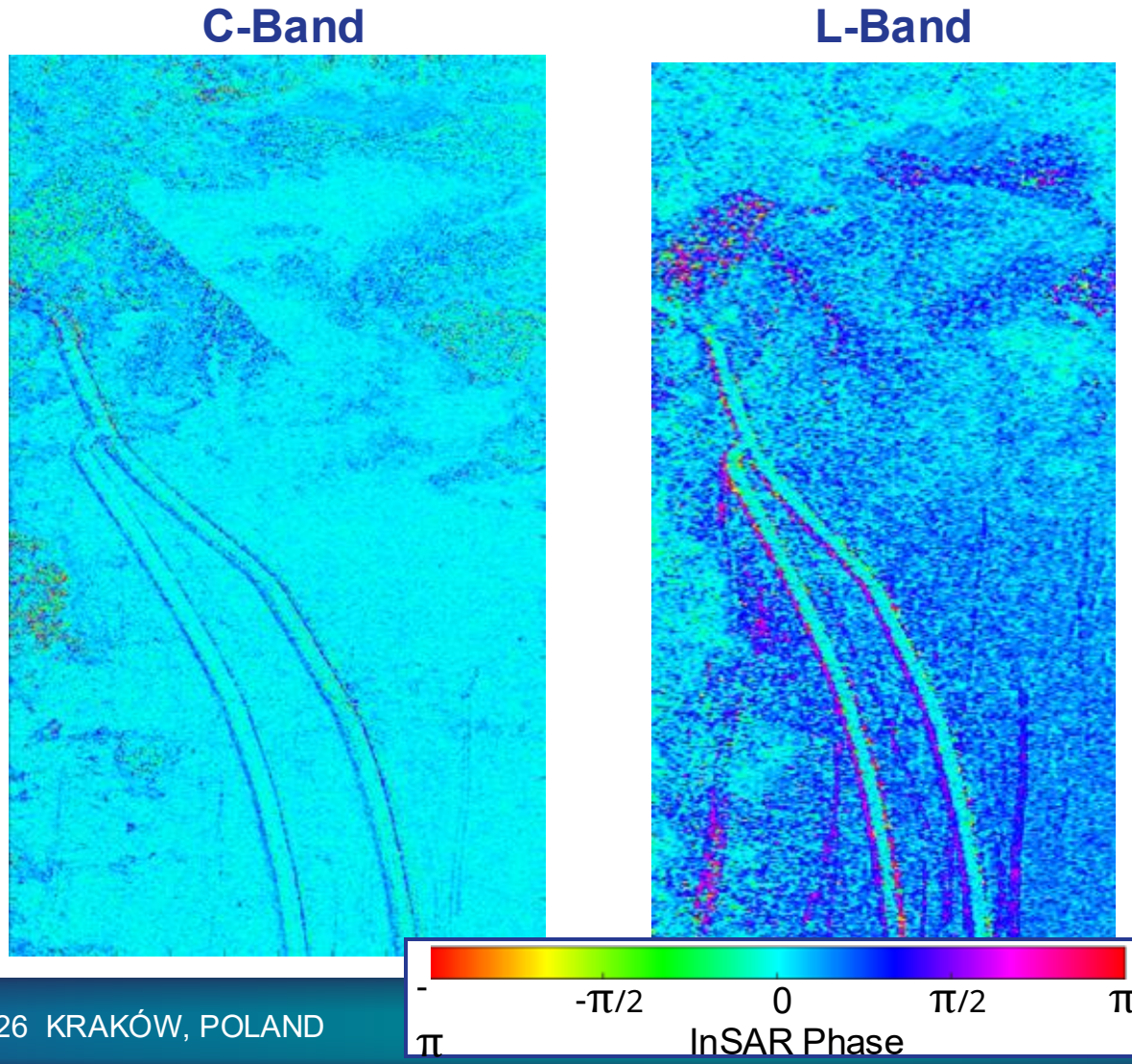
[15 m baseline]

- From a single InSAR baseline:
  - ✓ Some slight spatial variations
  - ✓ Cross-Pol phases better defined than Col-Pol phases
  - ✓ No clear “visual” difference between “two” polarizations @ C-band
  - ✓ The InSAR phase varies spatially, depending on the wavelength



Polarization Differential Phase $\Delta\varphi_{HH} - \Delta\varphi_{HV}$

- A simple comparison HH InSAR phase against the HV InSAR reveals some nice features
- Even features that are not visible in the single polarization interferogram



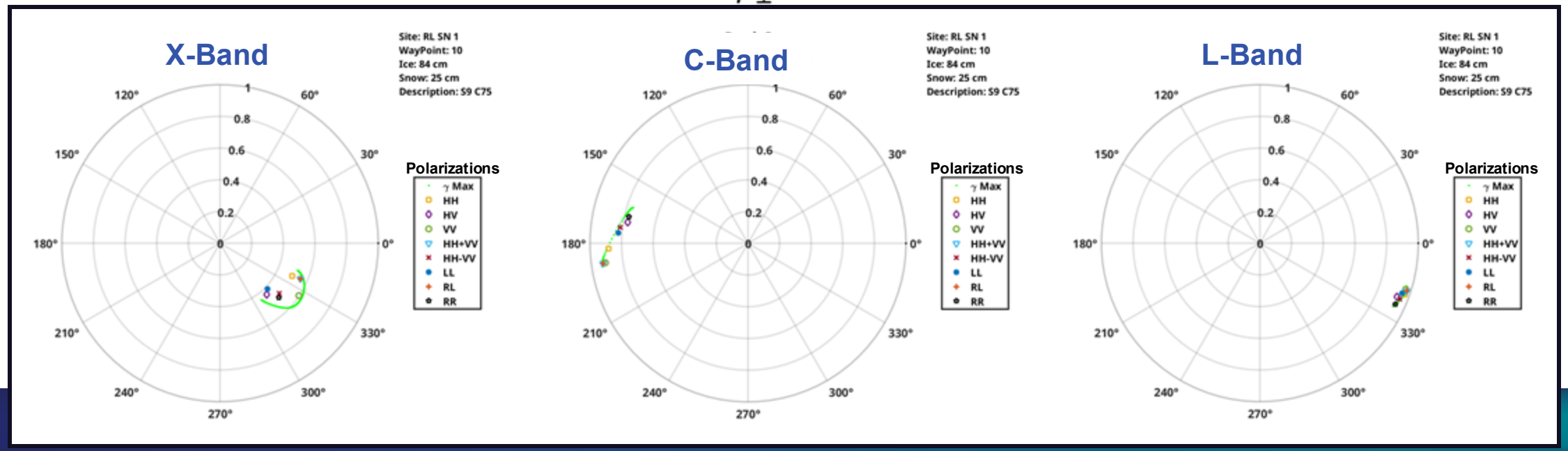
What can we get from Pol-InSAR?

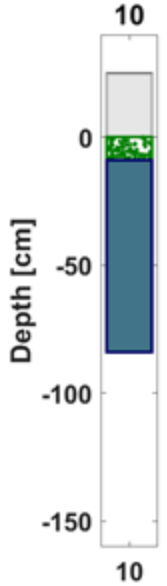
Pol-InSAR λ's Dependency

$$\gamma(\varpi) = \frac{\varpi^{*T}\,\Omega_{12}\,\varpi}{\varpi^{*T}\,T\,\varpi}$$

- Expressing the InSAR coherence, for all polarimetric configurations, helps in characterizing the volumetric media
- Thicker ice layer reduces the coherence amplitude and increase the Pol-InSAR phase diversity
- **X-Band** is too sensitive (low coherence) to ice cover layer
- **L-Band** mostly keeps high coherence amplitude and valuable phase diversities, which increase with layer thickness and longer baseline
- **C-Band** shows stronger coherence amplitude and phase variation with ice cover thickness
- **C- and L-Band** have good modelling potential for this application (interacting media)

$$\beta_{\perp} = 15m$$





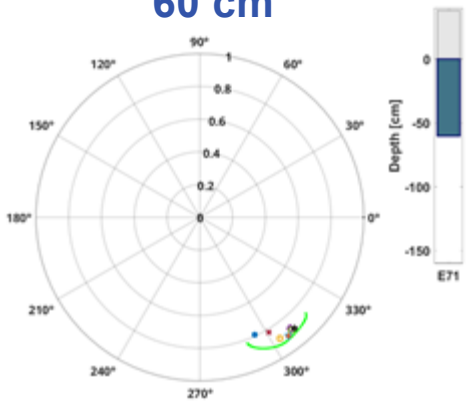
Pol-InSAR Function of Ice Layer Thickness: C-Band [15 m baseline]

$$\gamma(w) = e^{i\phi} \frac{\gamma_v + \mu(w)}{1 + \mu(w)}$$

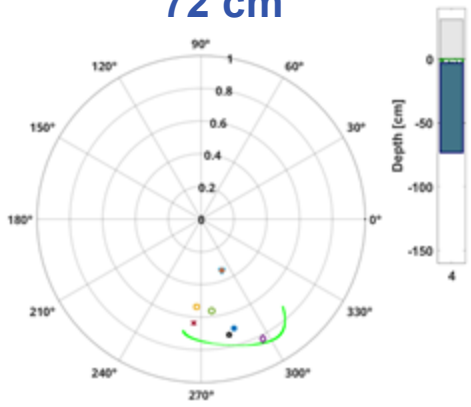
- Volumetric interactions of the radar wave with the ice layer(s) influence the Pol-InSAR coherence amplitude and phase diversity
- Presence of air bubbles and thin snow ice layer impacts the “traditional” volumetric mode
- Multi-layer models will need to be implemented

Total Ice Thickness

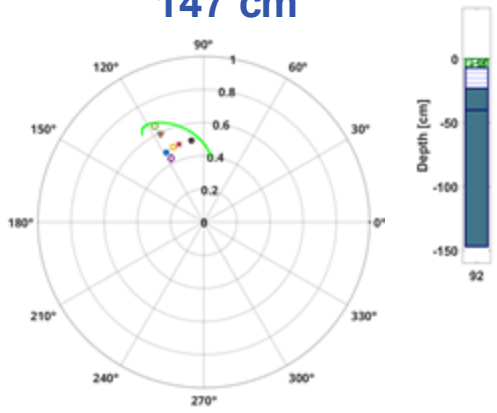
60 cm



72 cm



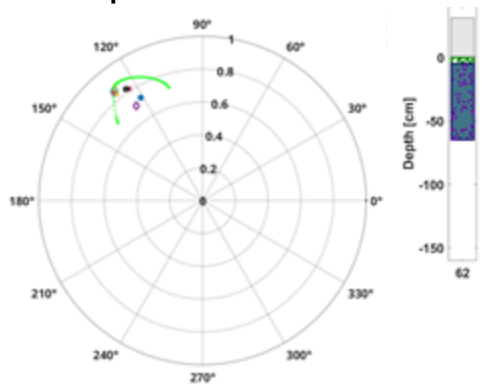
147 cm



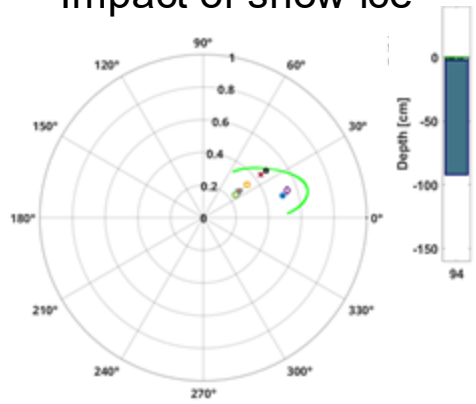
Polarizations

- γ Max
- HH
- HV
- VV
- HH+VV
- HH-VV
- LL
- RL
- RR

Impact of bubble ice

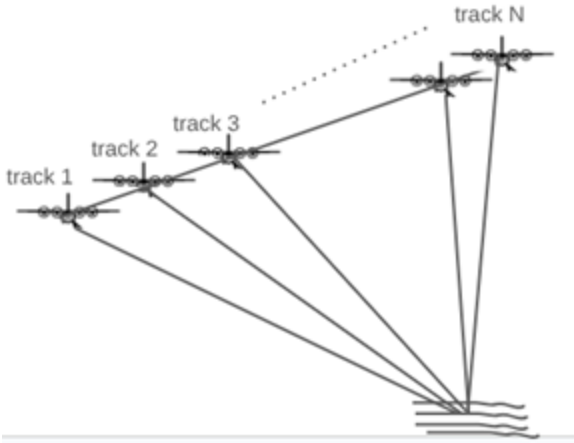


Impact of snow ice

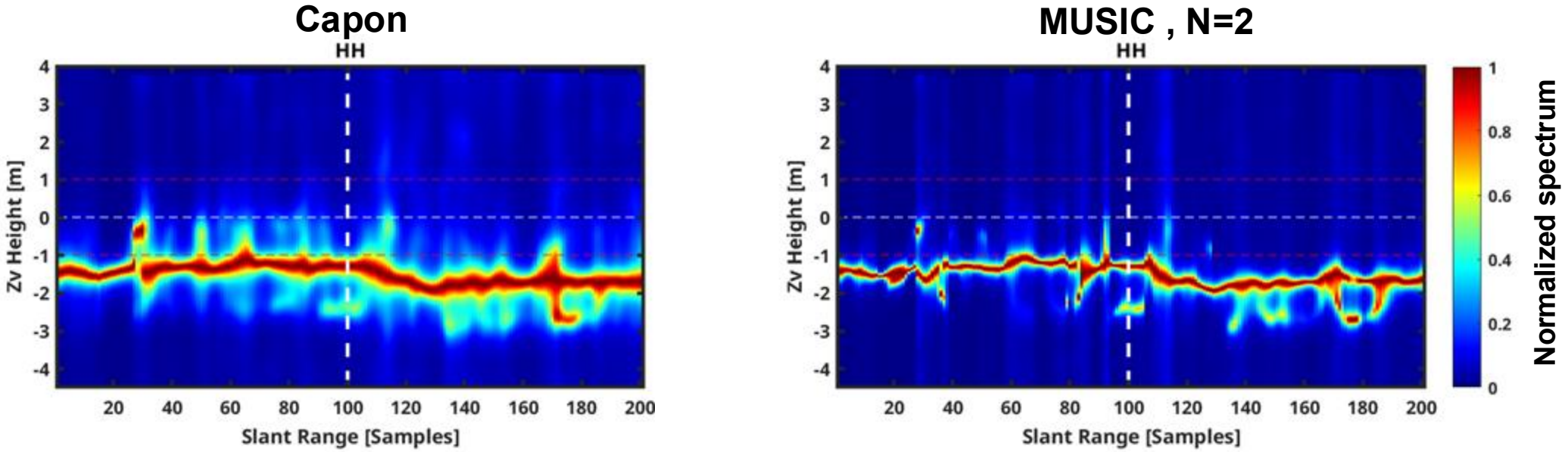


What can we get from TomoSAR?

Capon and MUSIC approaches



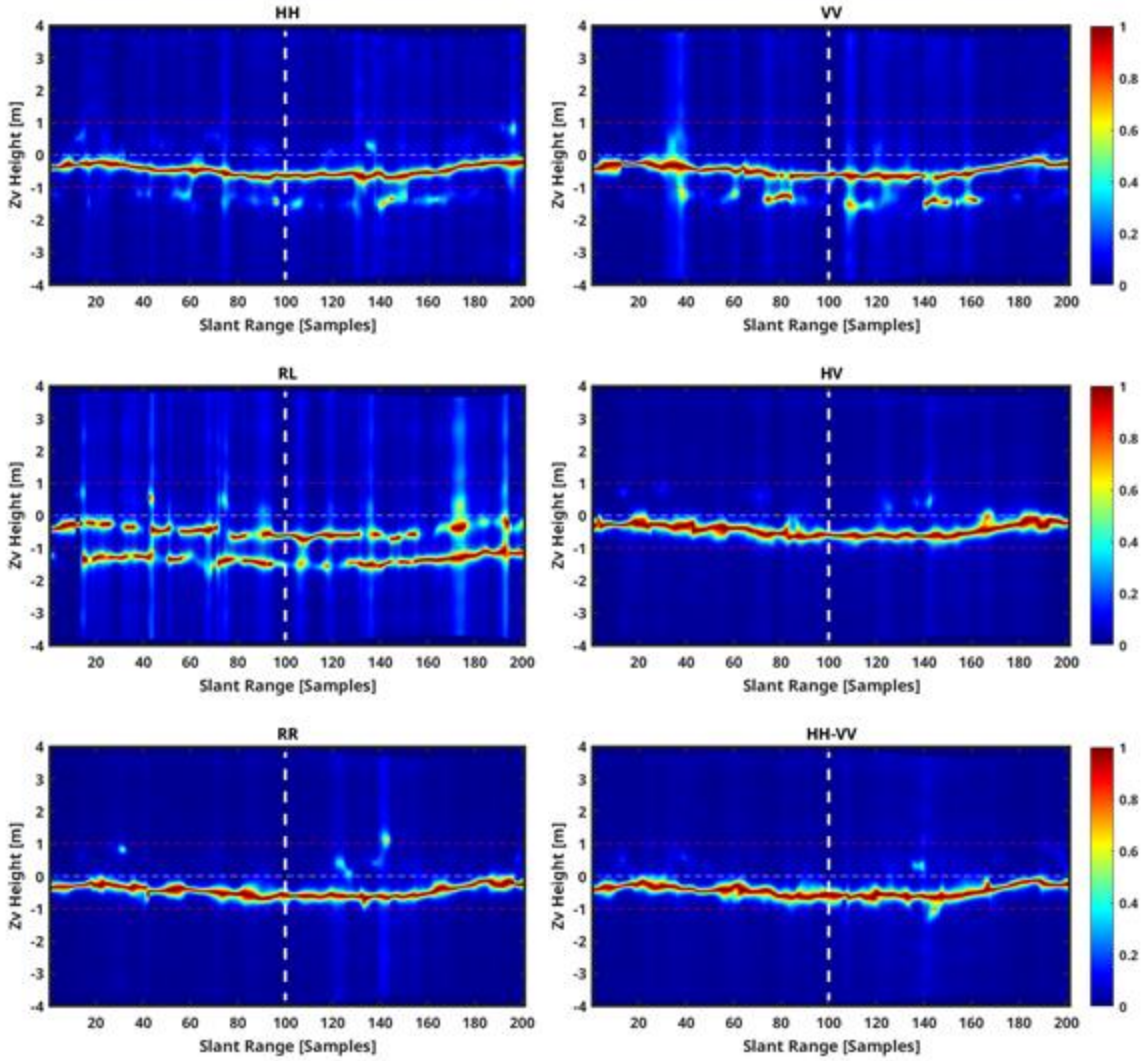
- Capon: High resolution beamforming
- MUSIC: Multiple Signal Classification based on N «source emitters»

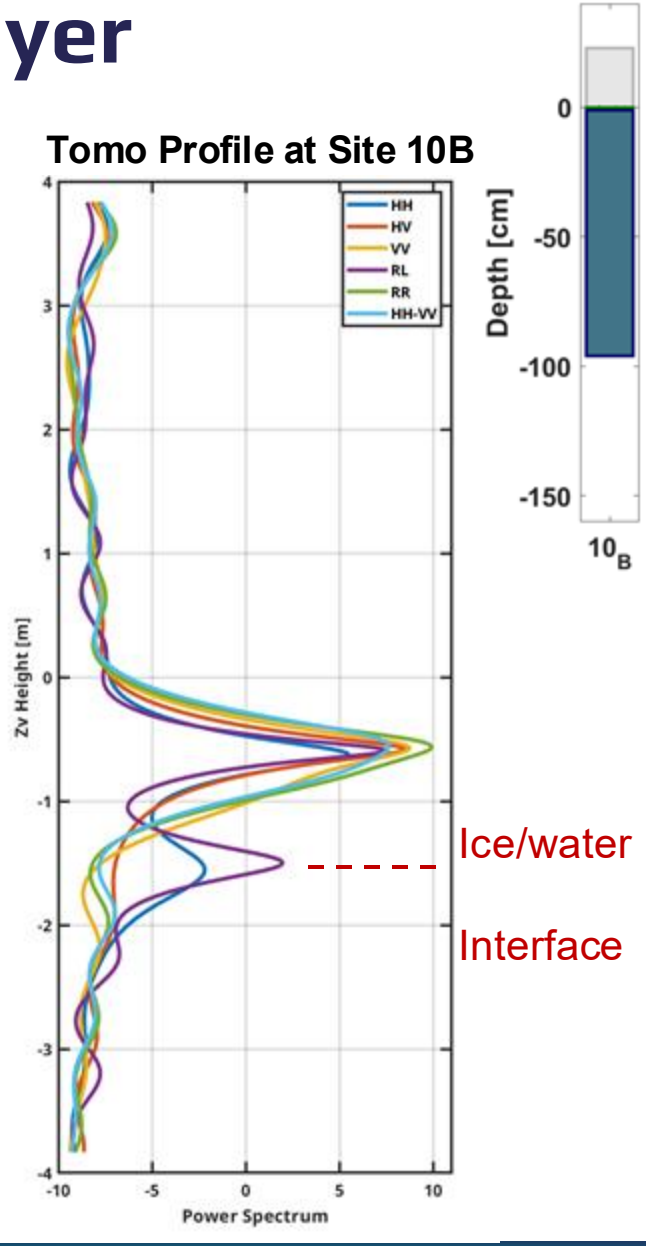


Following results were generated with the MUSIC approach

Slant Range SAR Tomography: Snow + Ice Layer

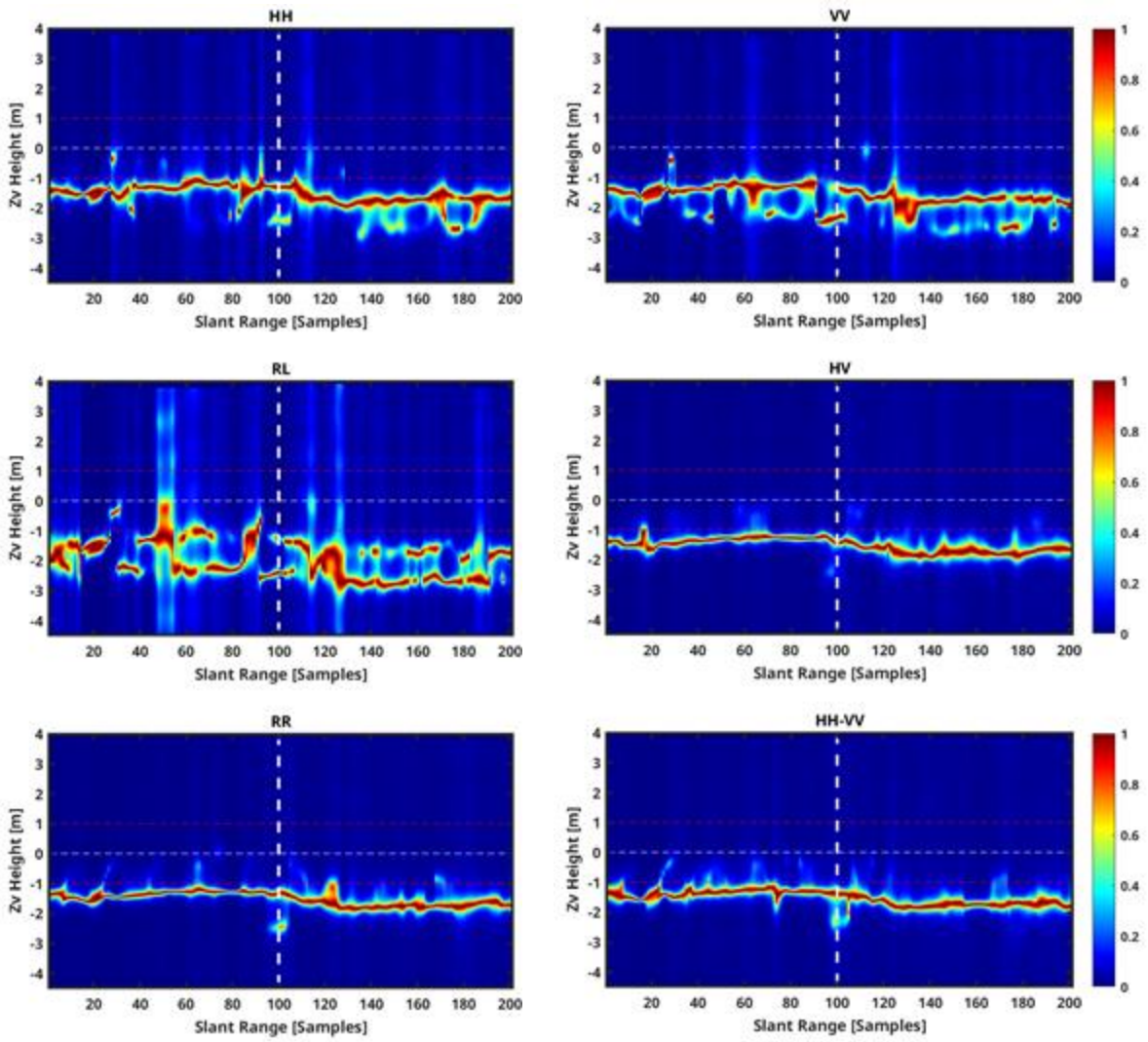
- TomoSARs over “thin” ice shows polarization dependency
- RL (surface scattering like) and co-pol (HH & VV) seem to highlight surface scattering at the ice/water interface
- Depolarization depth is stable at all polarizations

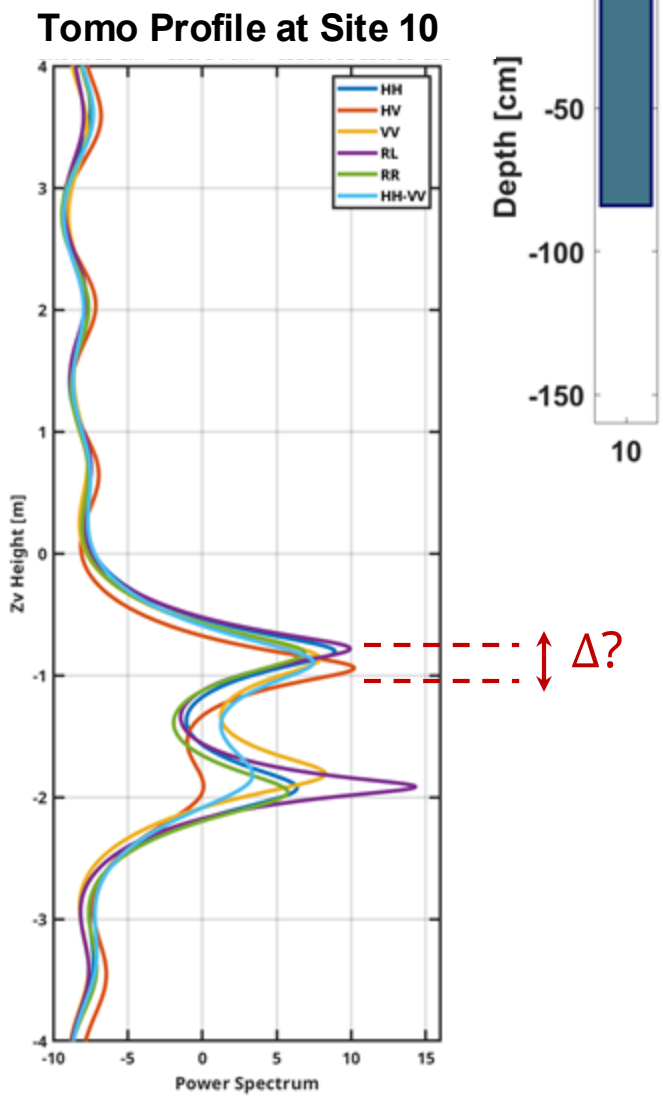




TomoSAR: Impact of Snow Ice Layer

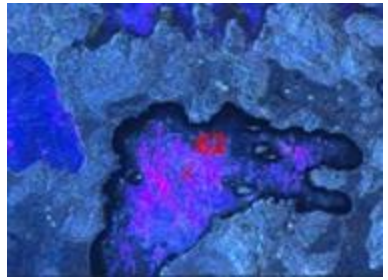
- Compared to previous site, snow ice layer induces a shift of the volumetric scattering center (HV) position
- Some physical modeling potential

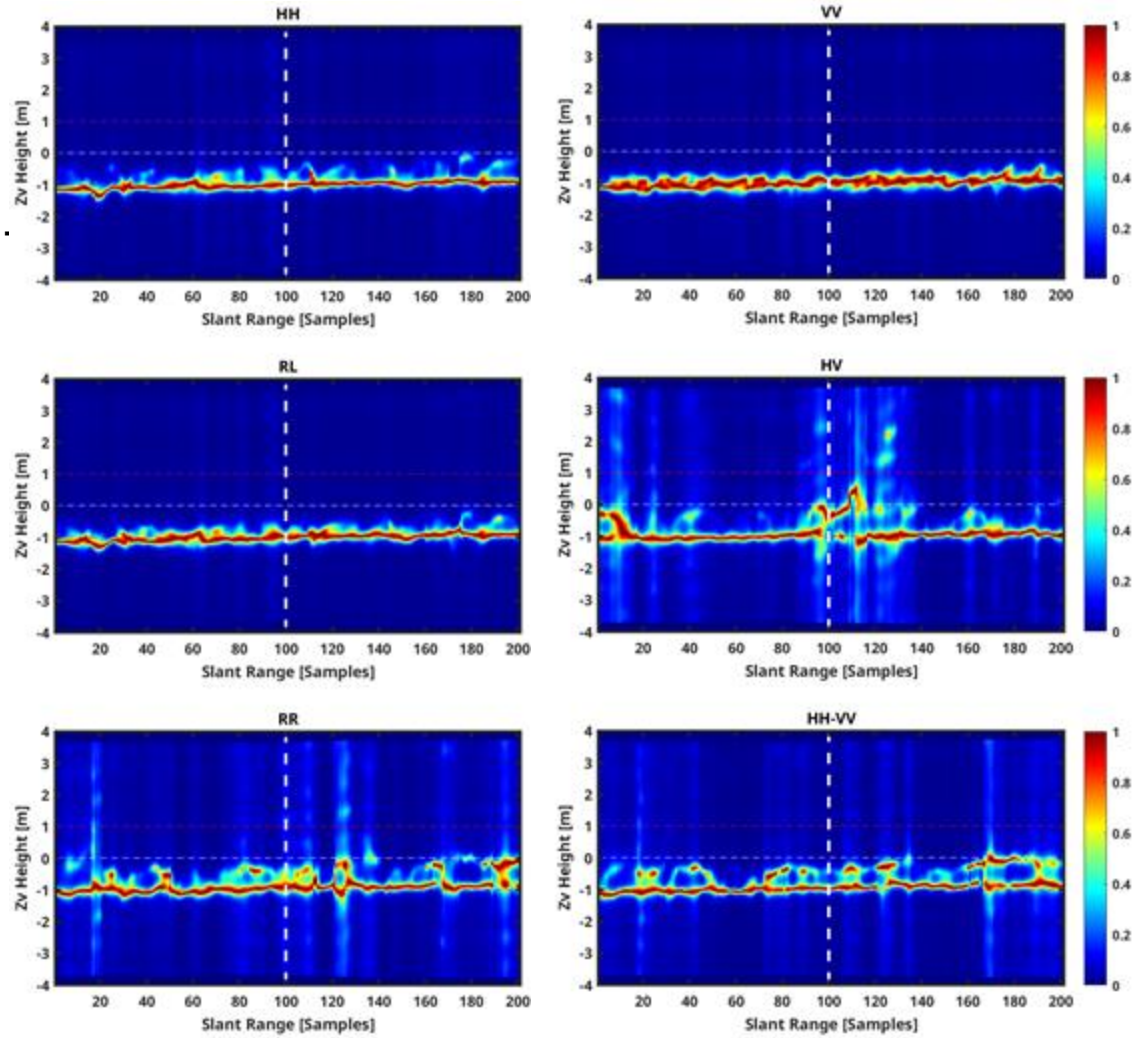


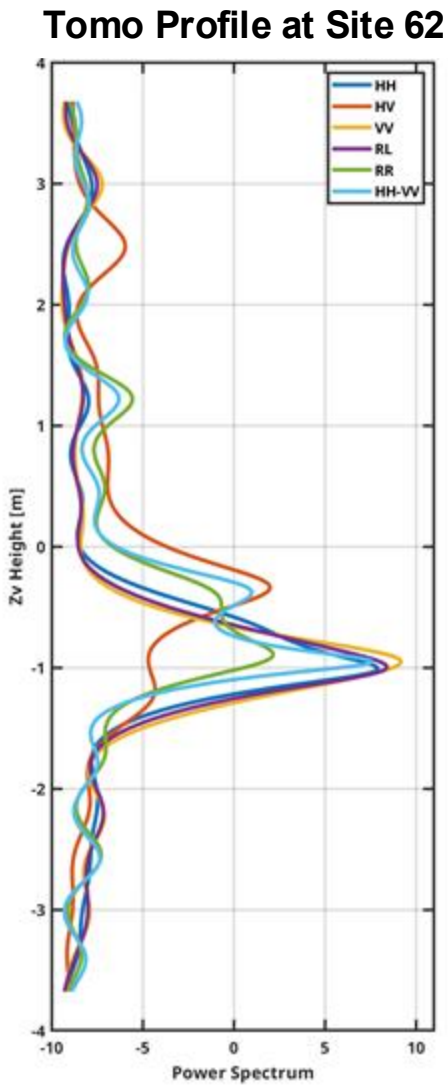


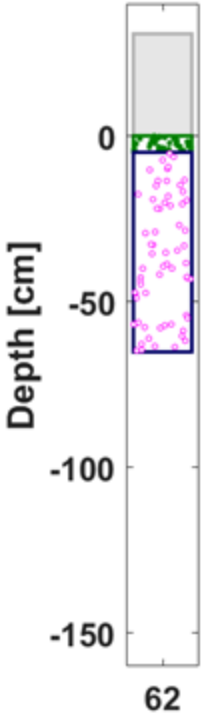
TomoSAR: Impact of Bubble Ice Layer

- Dubble layer spreads the tomogram distribution at RR,(HH-VV) & HV polarizations
- Less surface contribution
- Stimulate debate about bubble layer: Even bounce or not?

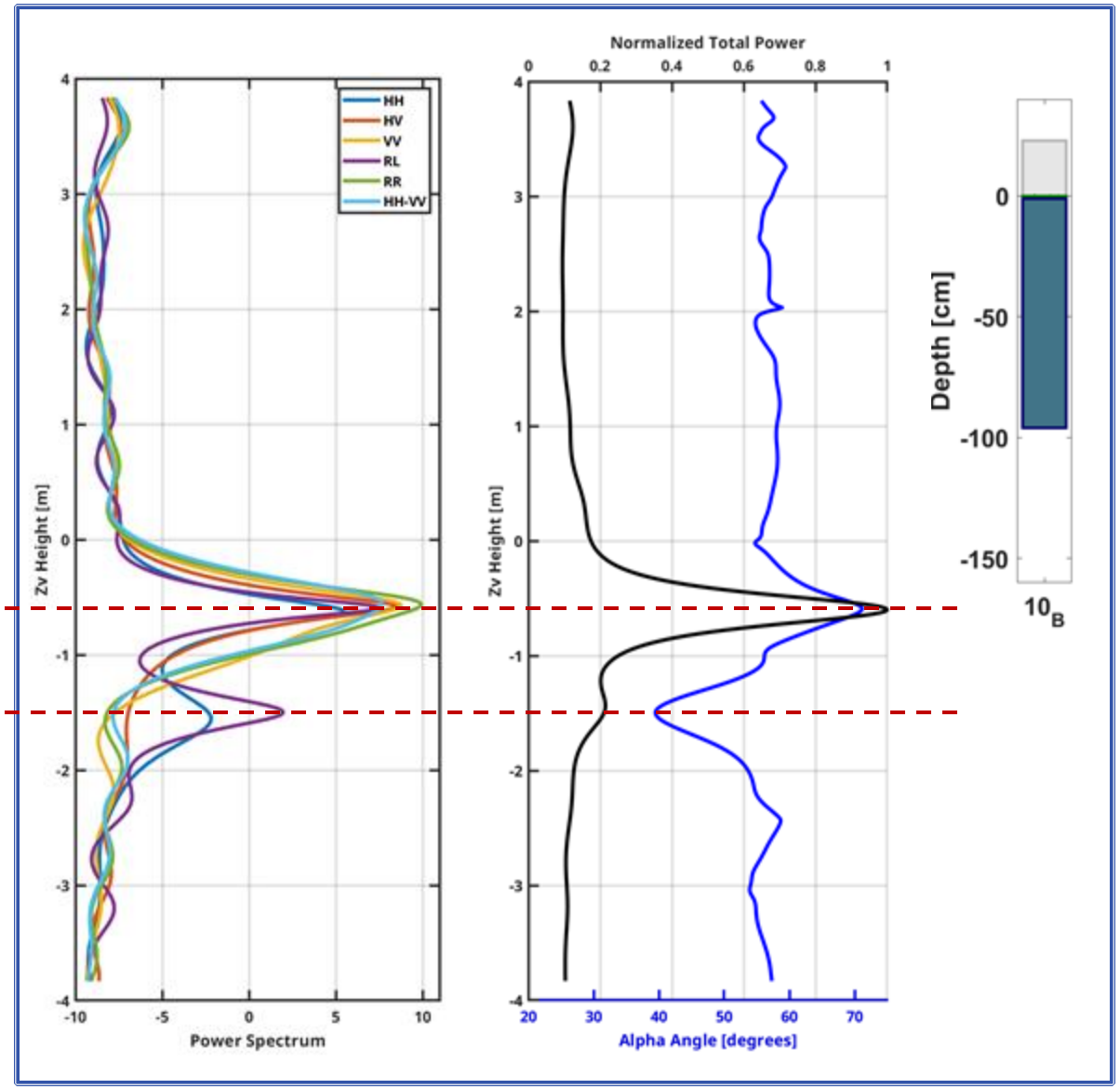


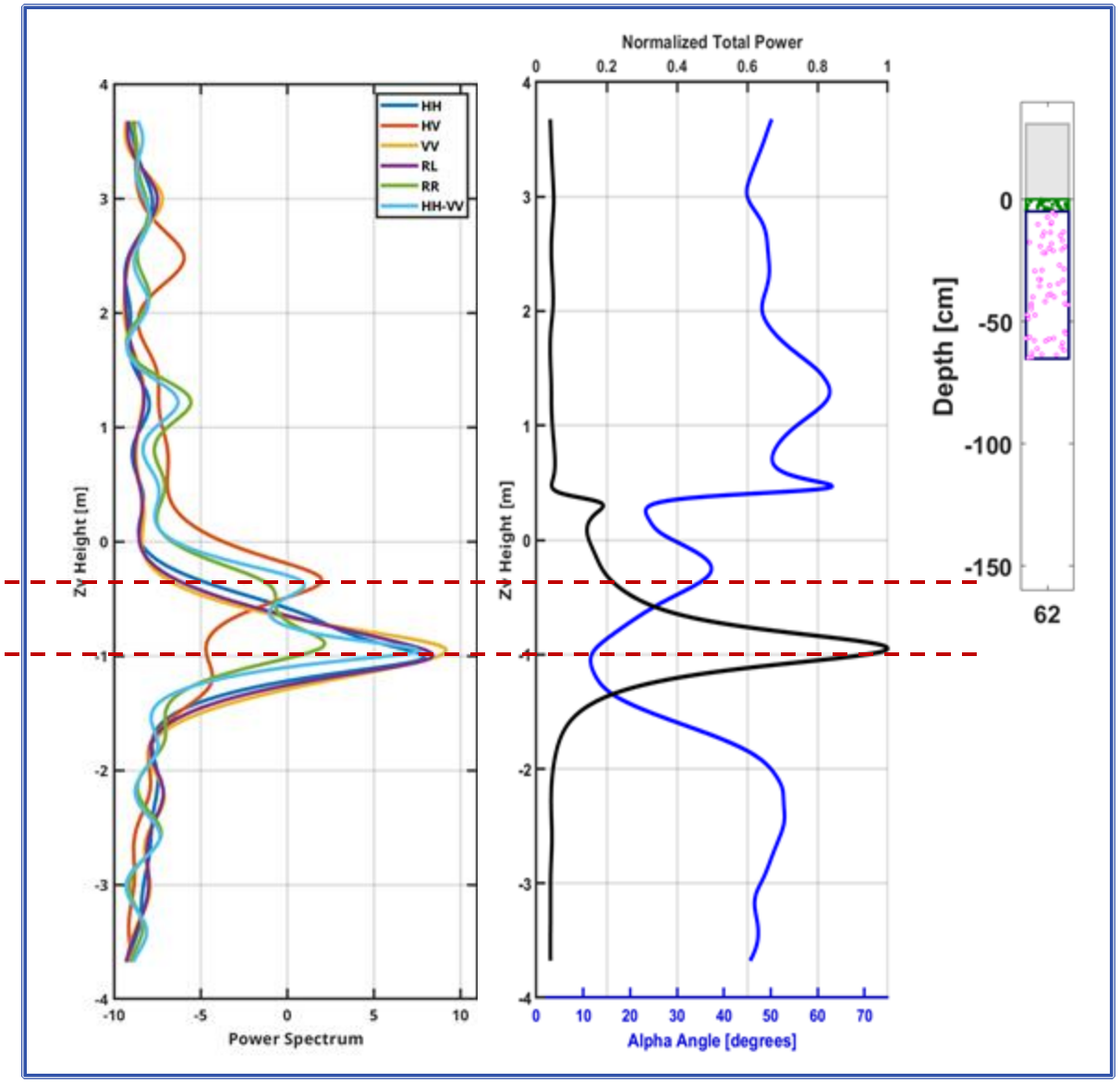






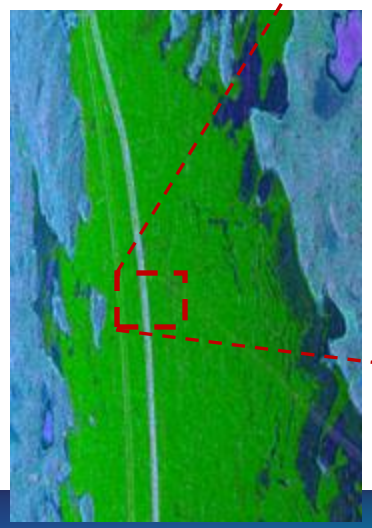
Compared to Alpha Angle (from H-α Decomposition)

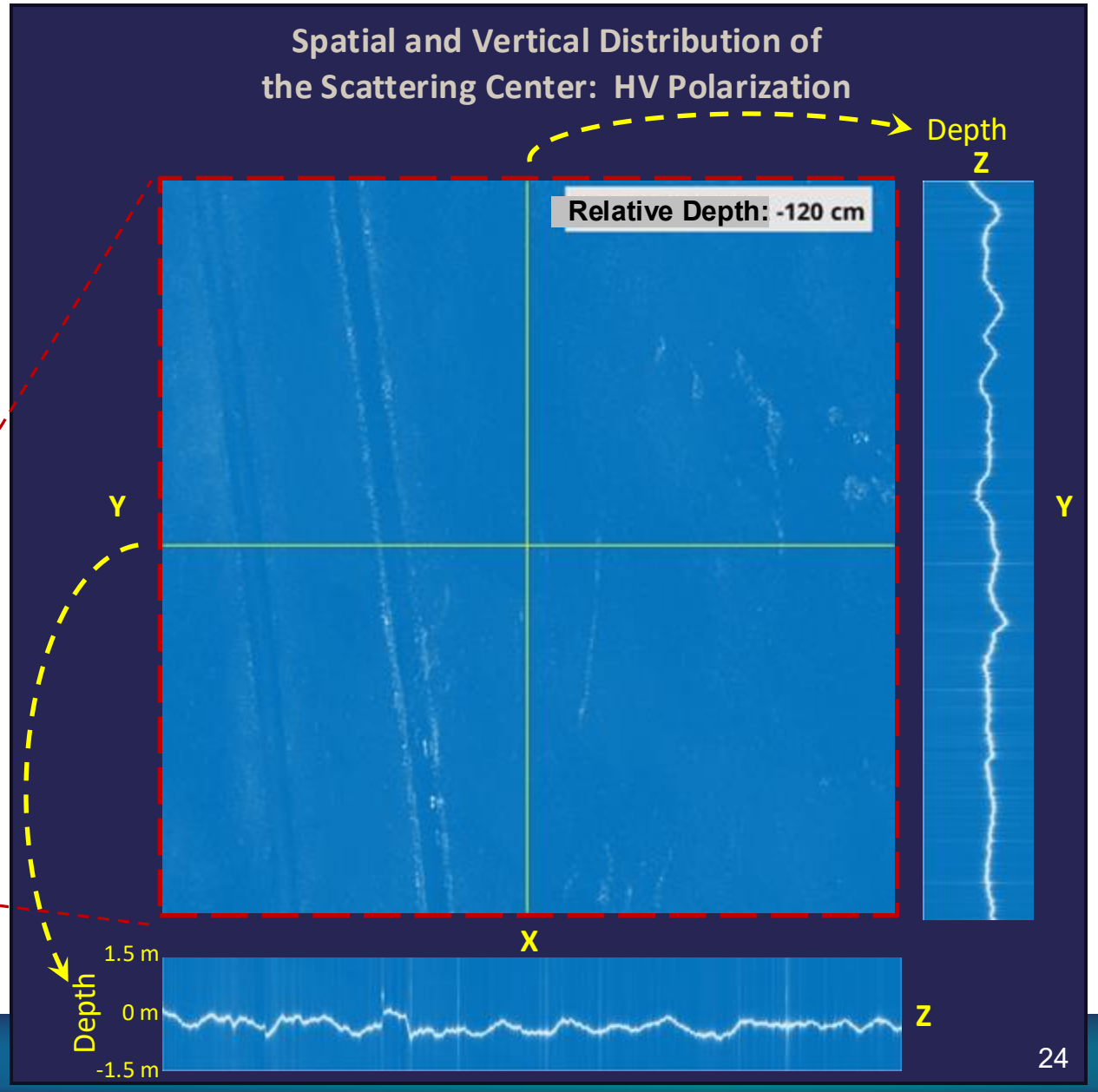




3D Tomogram: HV Polarization

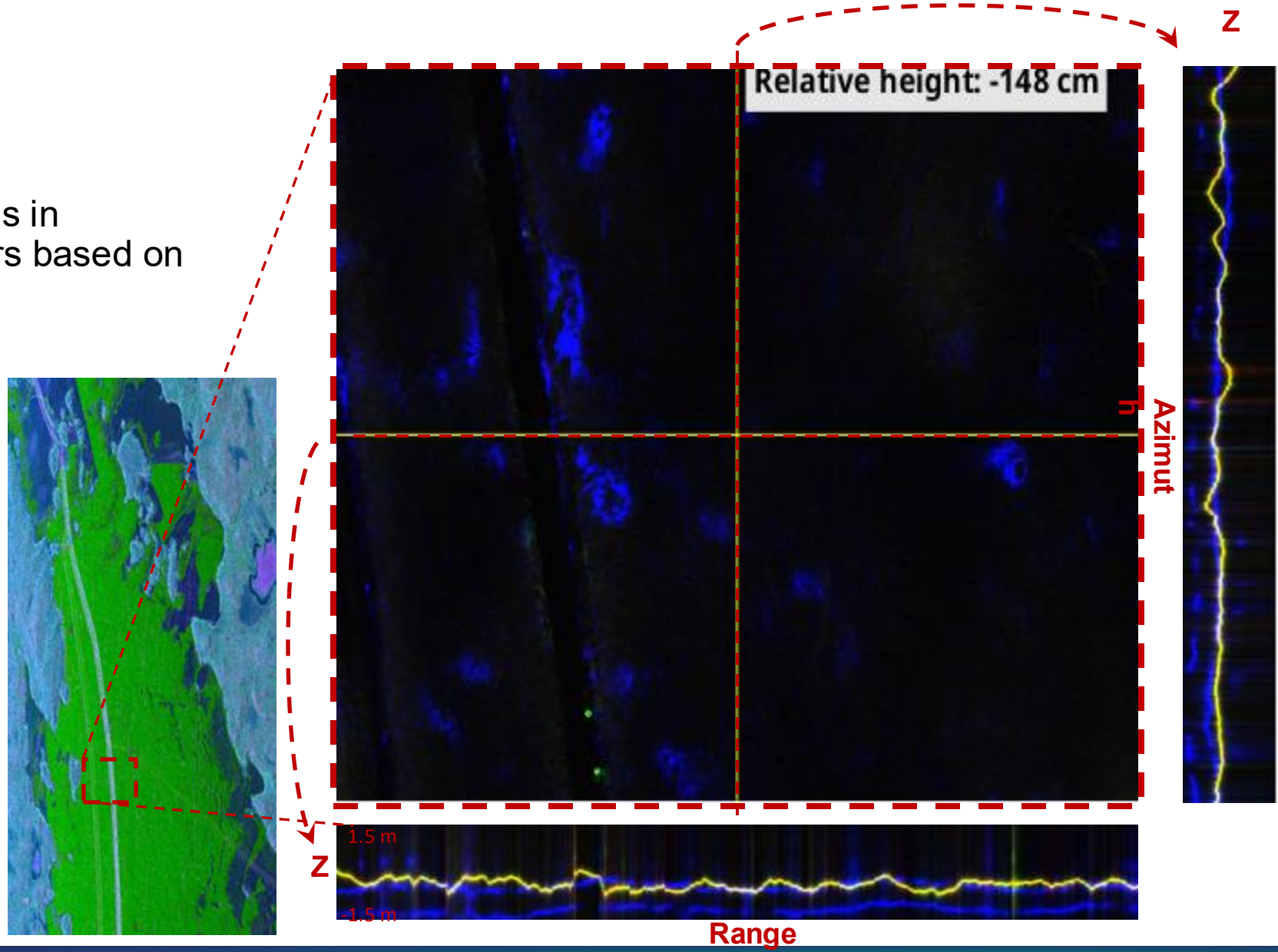
- Range (azimuthal) tomograms show interesting trend, but dough persist
- Expressing X-Y tomograms helps in getting confidence with results
- 3D tomogram clearly shows spatial distribution of the scattering centers





3D Composite Tomogram: HH-VV, HV & RL Polarizations

- Combining polarization diversity helps in identifying different scattering centers based on main scattering mechanisms.



Conclusion & Next Steps

- **Pol-InSAR** polarization diversity:
  - Even if lake ice media are “thin” layers with low dielectric constant, radar wave interactions induce significant phase shift and coherence amplitude change for characterization
  - C- and L-Bands sound to be adequate wavelength for lake ice, while X-band is too sensitive to perpendicular baseline and ice core profile.

- **Tomography:** Surprisingly (to some point) and gladly, SAR tomography shows some modeling potential of thin ice layers.
  - Nonetheless, tomograms aren’t always clear depending on incident angle and ice core profiles
  - C-Band sounds to be the adequate wavelength for lake ice

- **Next steps:**
  - Closer look to multi-layer physical model(s) and Capon distribution profiles
  - Explore advanced TomoSAR models (i.e.: SKP)

Acknowledgements

- German Aerospace Centre (DLR), FSAR Team for these **outstanding airborne SAR data!**
- Hugo Drouin and George Choma, **NRCan\CCRS** for fieldwork and radio license paperwork support
- Polar Continental Shelf Program of Natural Resources Canada
- Tibbitt-to-Contwoyto Winter Road Joint Venture Ltd.
- Northwest Territories Geoscience Office
- Great Slave Helicopters

Questions?

Source: https://jvtcwinterroad.ca/gallery/

Canada