On the Interpretation of L- and P-band PolSAR Signatures of Polithermal Glaciers

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Motivation

- Interpretation of SAR backscatter to improve **delineation and classification of glaciers facies**

- Quantification of **internal refreezing of melt water** which significantly impacts mass balance

- Understanding and quantification of **glacier dynamics** occurring as consequence of climate changes

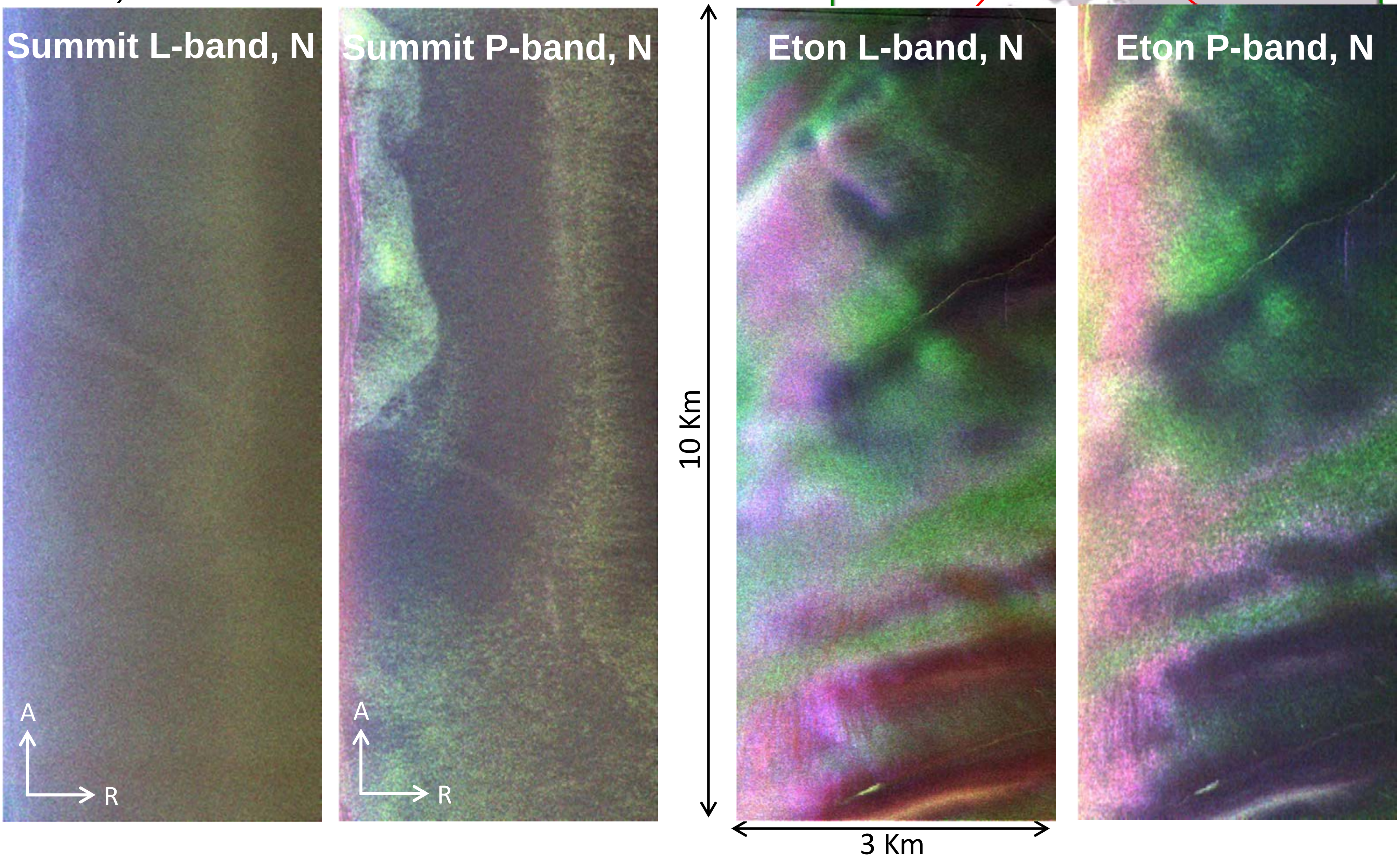
- Derive **penetration depth** to be used for correcting penetration bias in InSAR and radar altimeter products

- Long wavelength, in this case **L- and P-band**, SARs penetrate up to some tens of meters into the ice

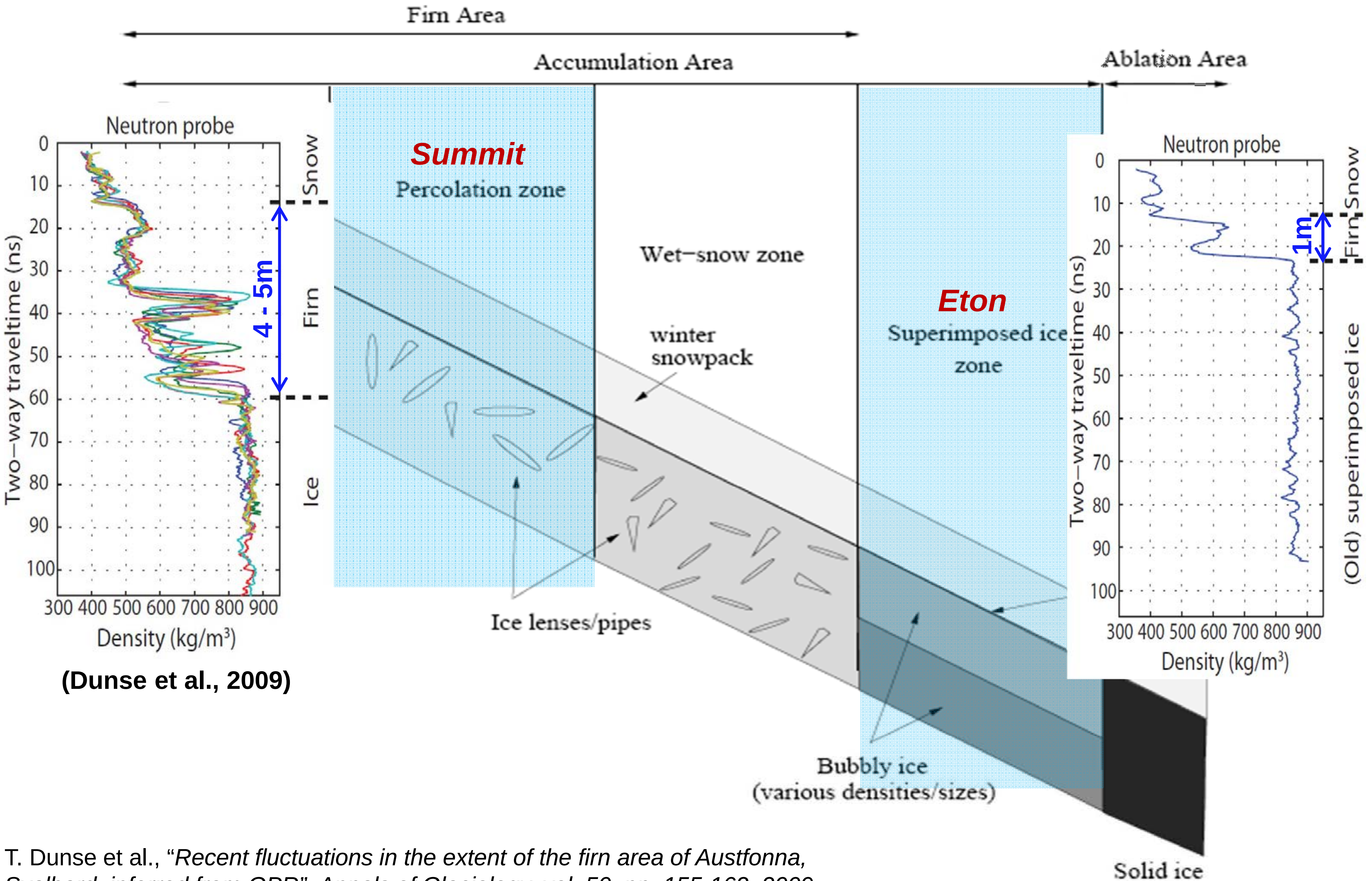
    - Suitable to investigate **subsurface structure** of glacier facies

Test Site: Nordaustlandet, Svalbard

- **Etonbreen and Summit of the Austfonna ice cap,** Svalbard Archipelago, Norway (~ 80˚N, 24˚E)



Glacier Facies

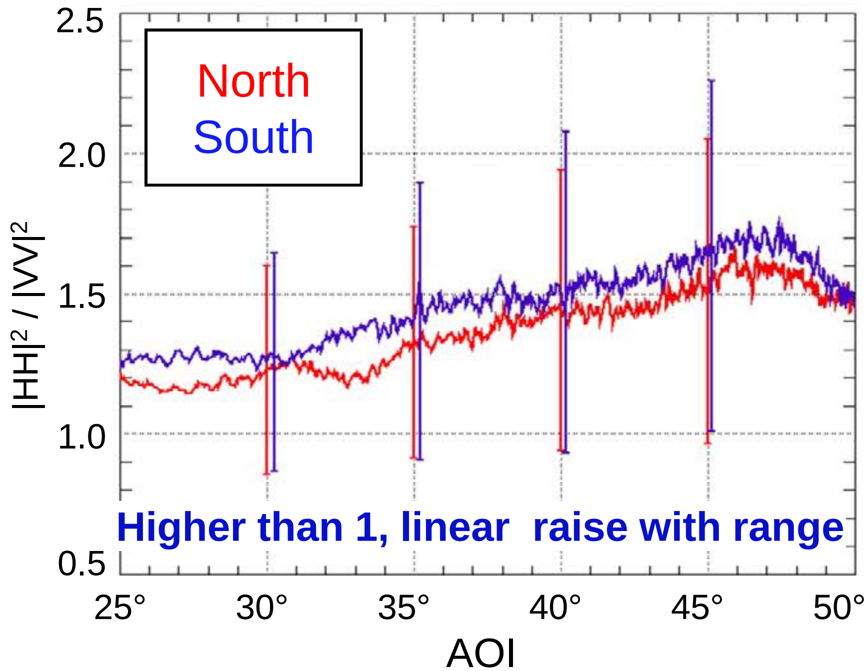


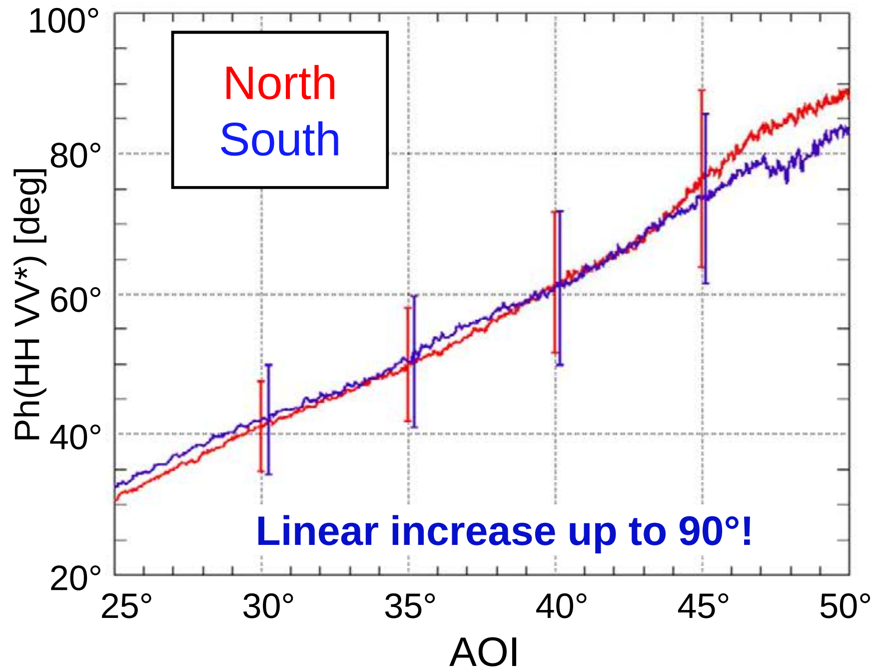
(Dunse et al., 2009)

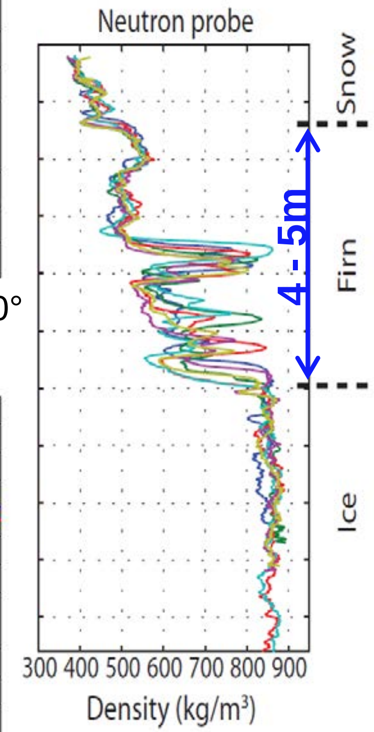
T. Dunse et al., “*Recent fluctuations in the extent of the firn area of Austfonna, Svalbard, inferred from GPR*”, *Annals of Glaciology, vol .50, pp. 155-162, 2009.*

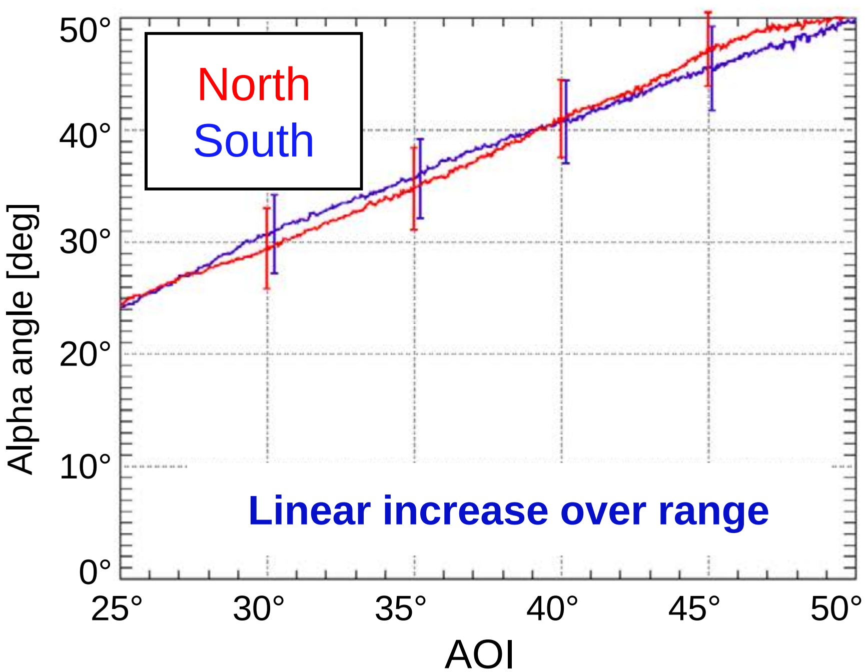
L-band Polarimetric Signatures - Summit

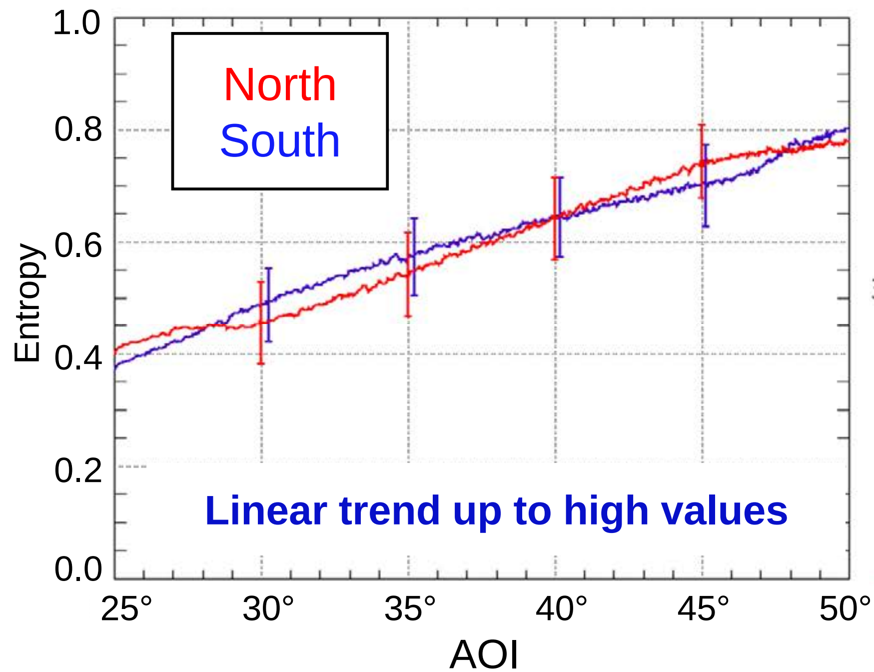
- Average along azimuth direction





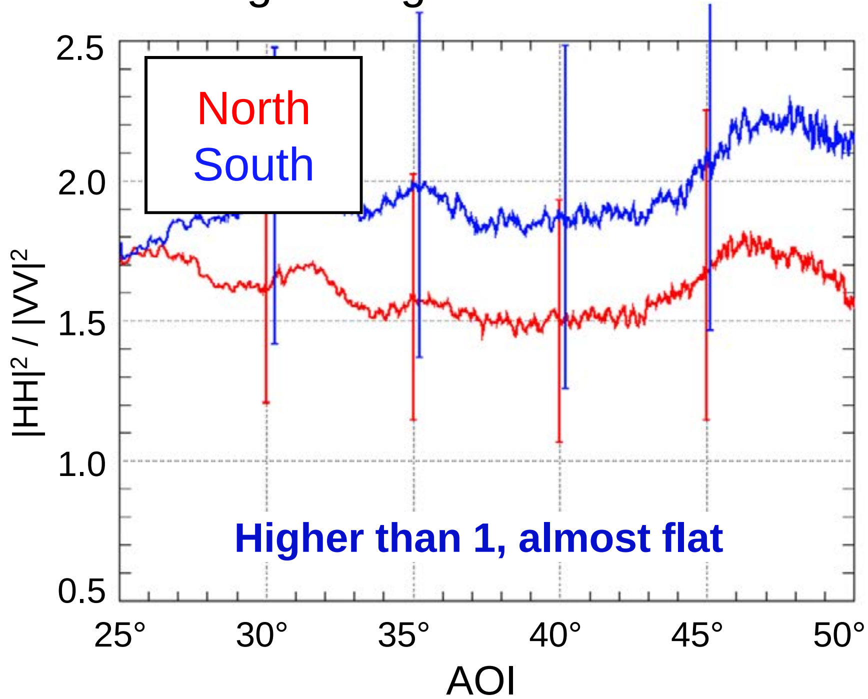


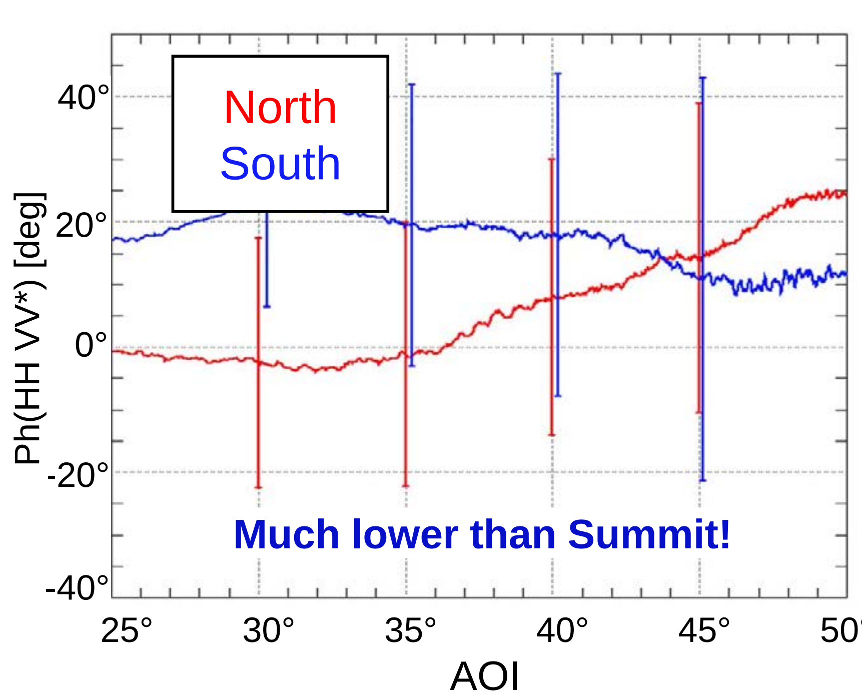


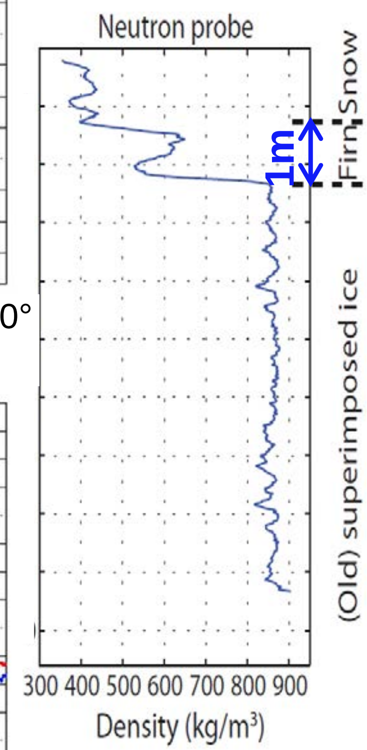


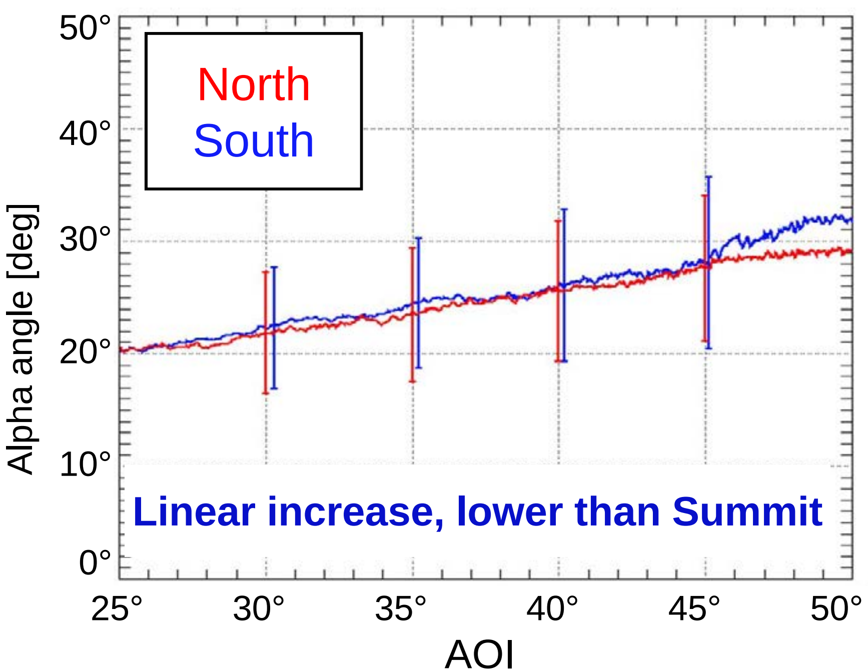
L-band Polarimetric Signatures - Eton

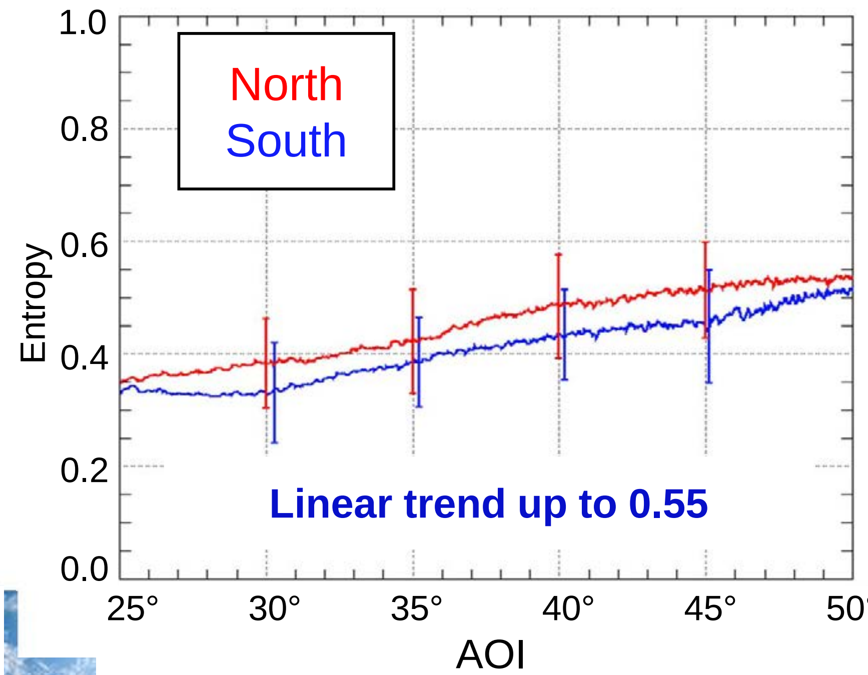
- Average along azimuth direction









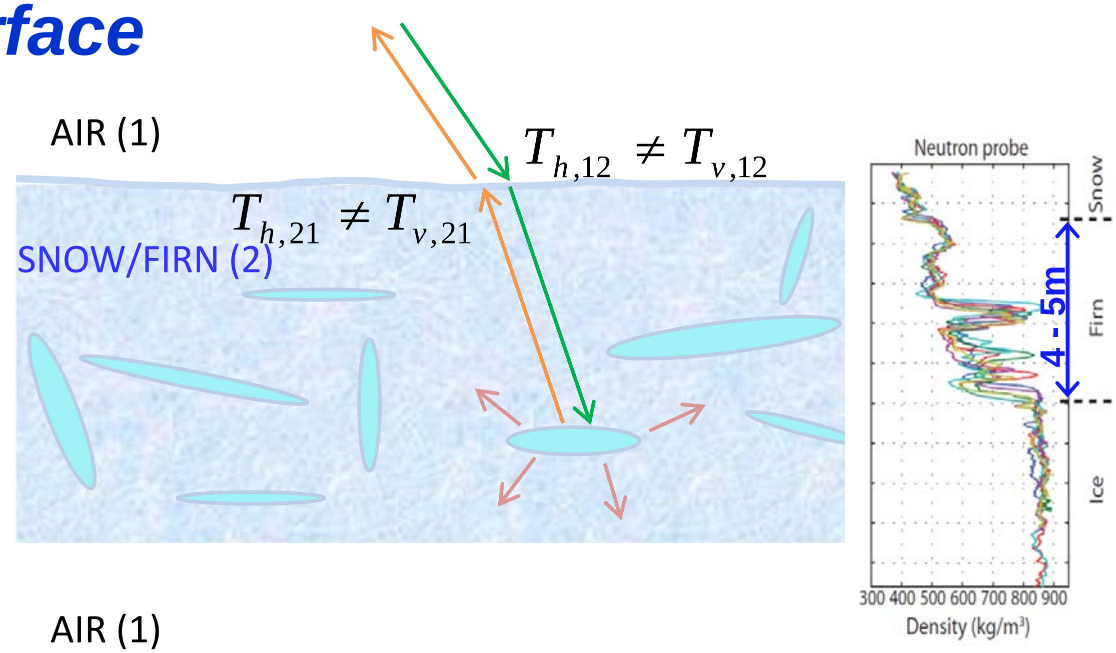


Modeling Polarimetric Signatures from Summit (Percolation Zone)

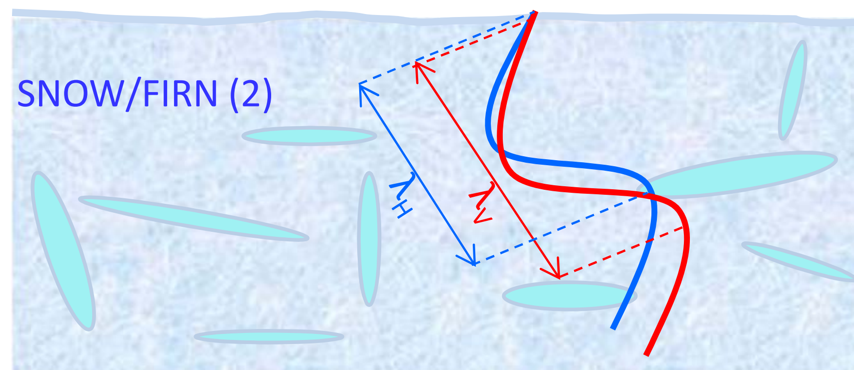
Modeling the Glacier Subsurface

Scattering from Percolation Zone

- Particle Scattering Model *(Cloude et al., 1999)* for ice pipes and lenses in firn
- Inclusion of **incidence angle** dependency
- **Transmission effects** at glacier surface (air/snow interface)



- **Differential propagation** effects *(Cloude et al., 2000)* due to dielectric anisotropy of polar firn ($n_{hh} \neq n_{vv}$) i.e. differential propagation phase and losses



$$[C_{tot}] = f_{lenses} \cdot [T][P][C_{lenses}][T]^t[P]^t + f_{pipes} \cdot [T][P][C_{pipes}][T]^t[P]^t + [N]$$

Transmission — Propagation effects

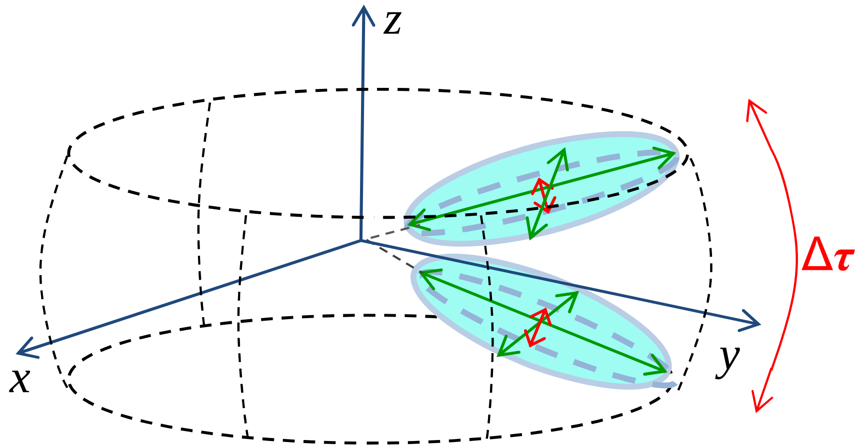
S.R. Cloude et al., *"Wide-band Polarimetric Radar Inversion Studies for Vegetation Layers"*, IEEE TGRS, vol. 37, n. 5, Sept. 1999.

S.R. Cloude et al., "*The Remote Sensing of Oriented Volume Scattering Using Polarimetric Radar Interferometry*", Proc. of ISAP2000, Fukuoka, Japan.

Modeling the Glacier Subsurface

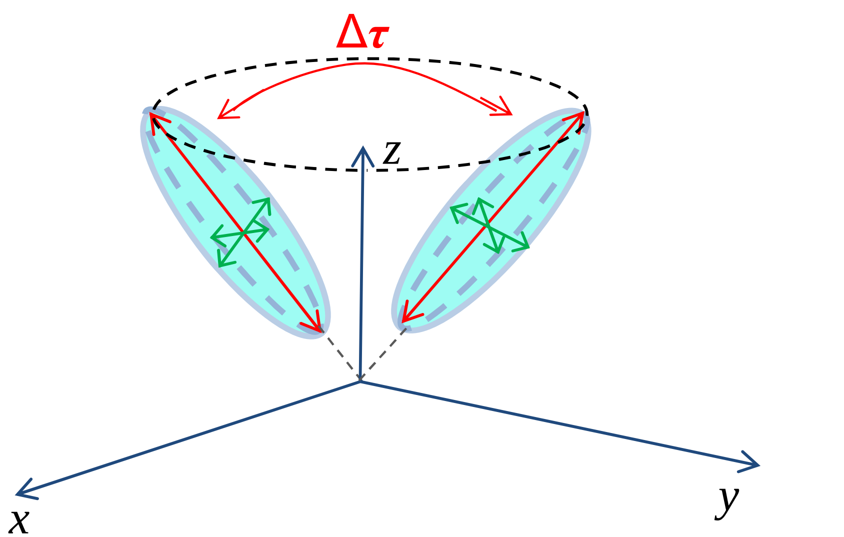
Ice Lenses

- Extent up to some tens of cm, few mm to some cm thick *(Jezek et al., 1994)*
- Typically oriented parallel to the firn surface (plane x-y)
- Modelled as (mainly) **horizontal oblates** (Ap << 1)



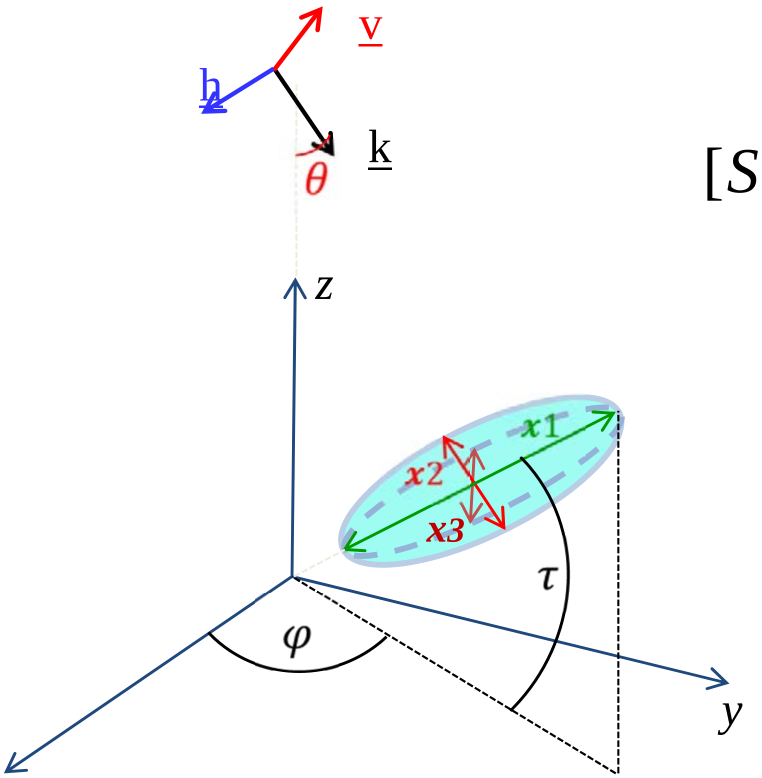
Ice Pipes

- Length up to some tens of cm , thickness of few cm
- Mainly vertically oriented *(Jezek et al., 1994)*
- Modelled as **vertical prolates** (Ap > 1)



K.C. Jezek, S.P. Gogineni, M Shanbleh, *"Radar Measurements of melt zones on the Greenland Ice Sheet"*, Geophys. Res. Letters, vol. 21, pp. 33-36, 1994.

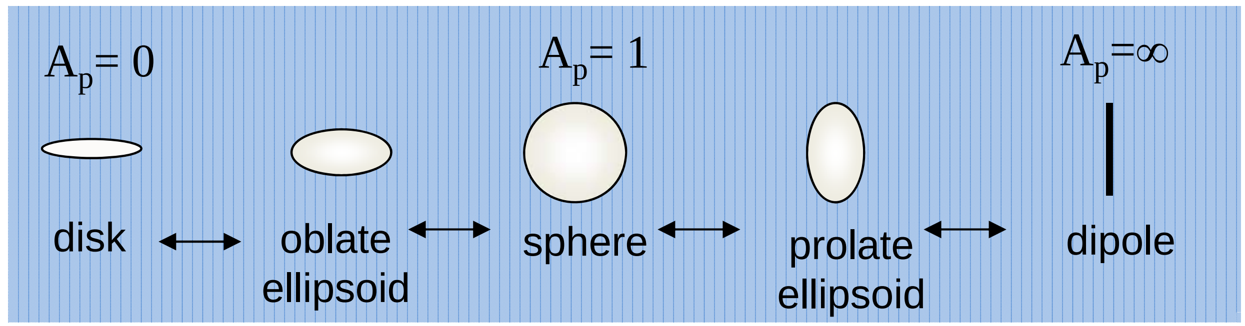
Particles Scattering Model



x_1, x_2, x_3 dipoles length

$$[S_p(A_p,\vartheta,\varphi,\tau)] = \begin{bmatrix} S_{hh}(A_p,\varphi,\tau) & S_{hv}(A_p,\vartheta,\varphi,\tau) \\ S_{vh}(A_p,\vartheta,\varphi,\tau) & S_{vv}(A_p,\vartheta,\varphi,\tau) \end{bmatrix}$$

$A_p = f(x_1,x_2,x_3)$ particle shape factor



$[C_p]$ → Average over orientation angles distributions → $[C_{vol}]$ ⇒

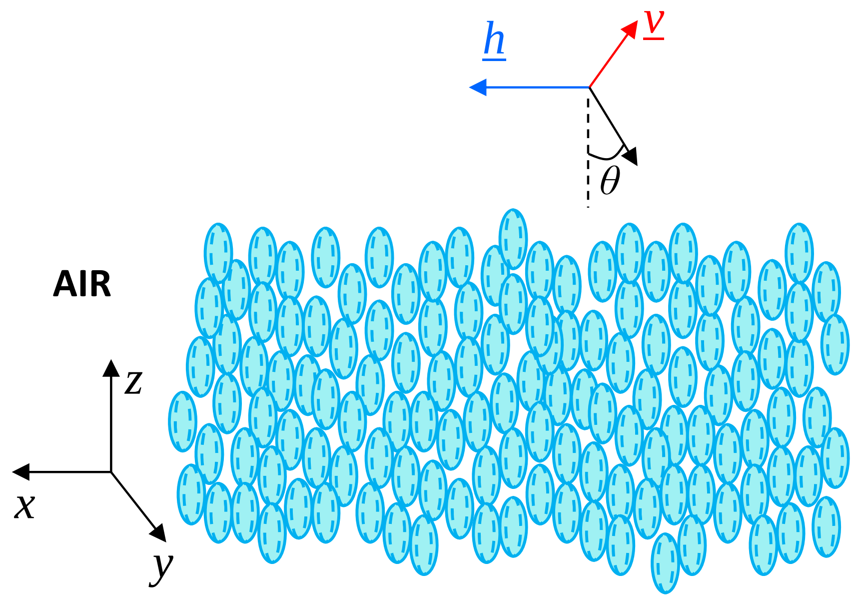
Single particle

Cloud of particles

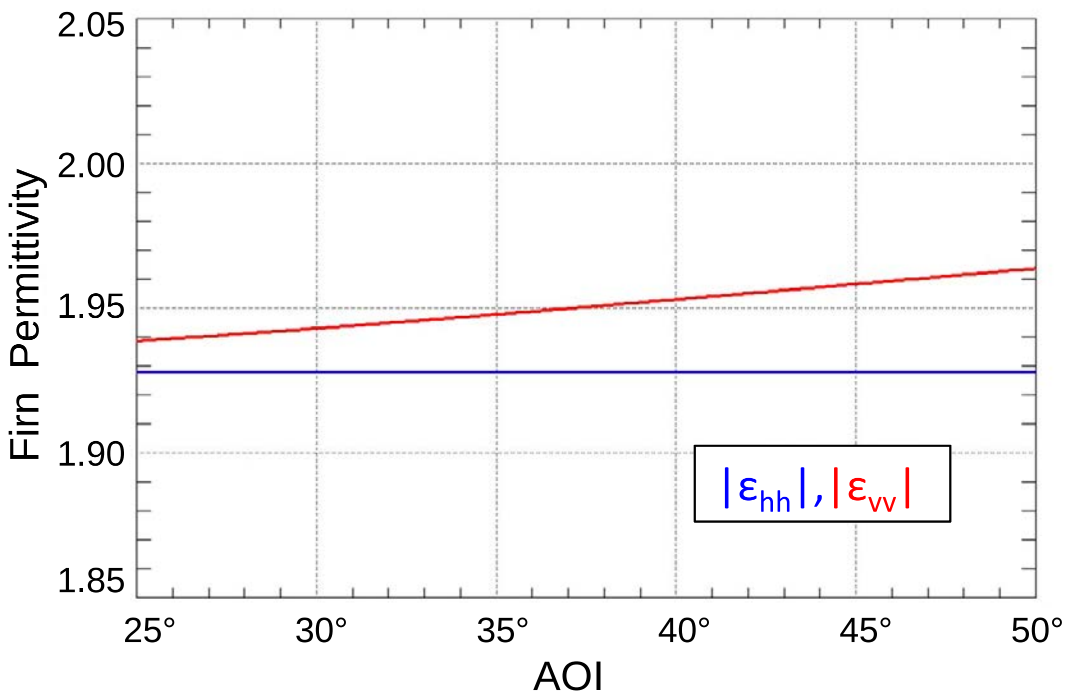
- Entropy (H)
- Alpha angle (α)
- Copolar ratio
- Copolar phase

Differential Propagation Effects

- Polar Firn is an ***anisotropic medium*** *(Alley 1987)*
  - Vertically oriented grains in air background
  - Prolate spheroidal shape (axis ratio ~1.2-1.4)
  - Size of few mm
  - Density of 0.4-0.7 Kg/m^3



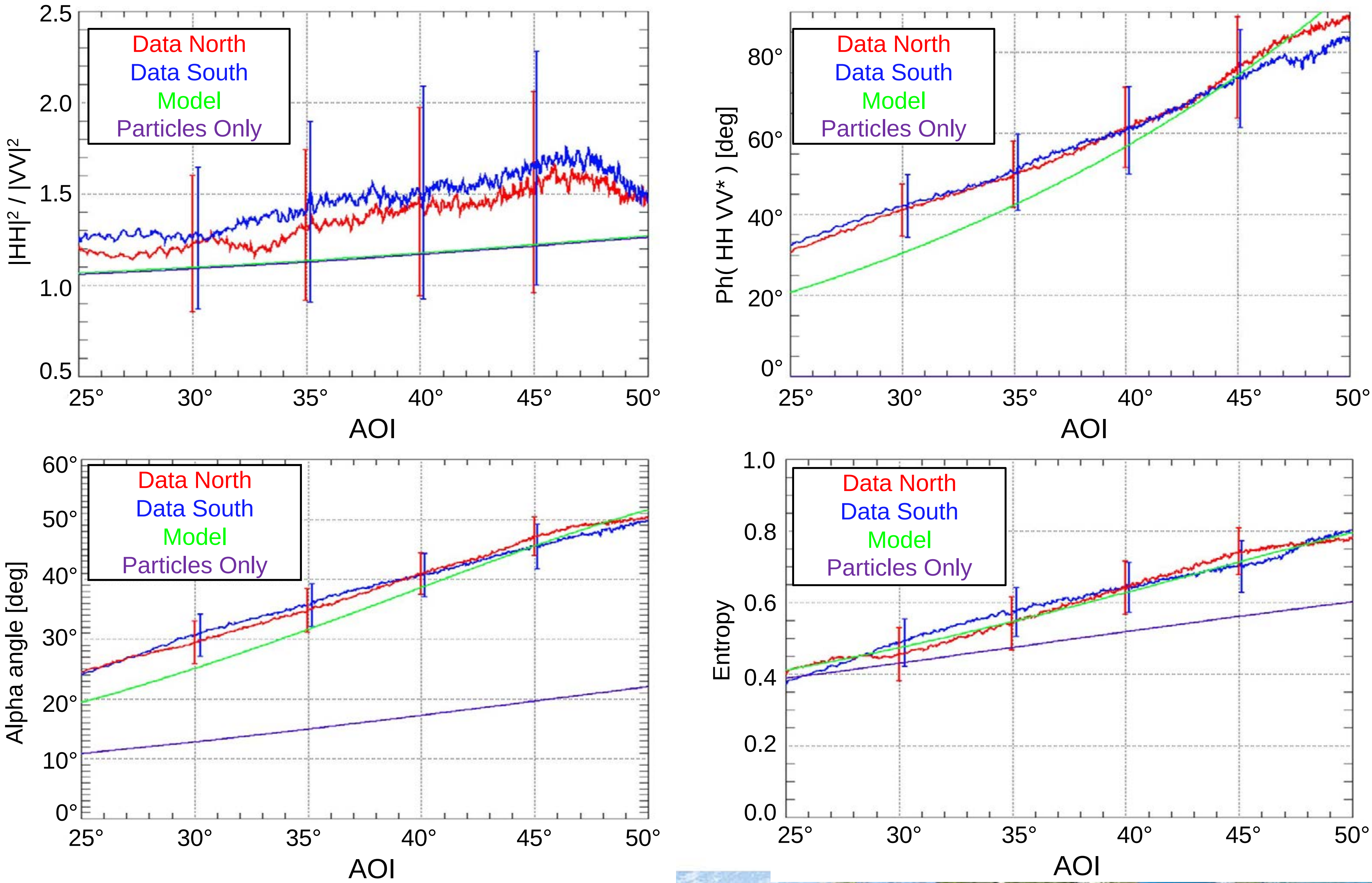
- ***Effective permittivity*** *for a two-phase mixture (Sihvola et al., 1988)*
  - *Ice grains in air background*
  - *60-70% volume fraction of grains*
  - *Prolate spheroids with Ap = 1.3*



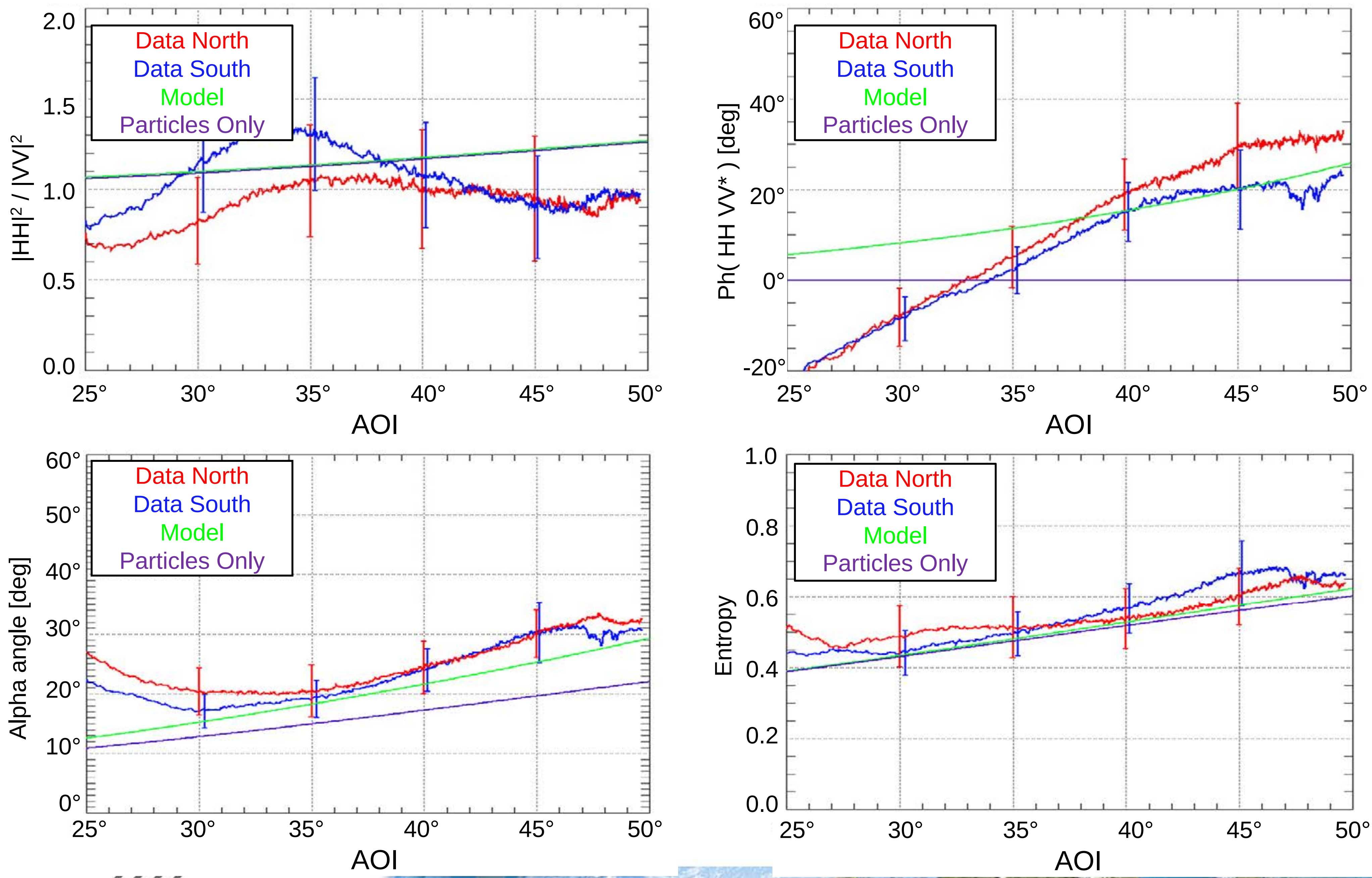
R.B. Alley, *"Texture of Polar Firn for Remote Sensing"*, Annals of Glaciology, vol. 9, 1987

A. Sihvola and Jin Au Kong, *"Effective Permittivity of Dielectric Mixtures"*, IEEE TGRS, vol. 9, n. 4, 1988

Model vs L-band Data, Summit



Model vs P-band Data, Summit



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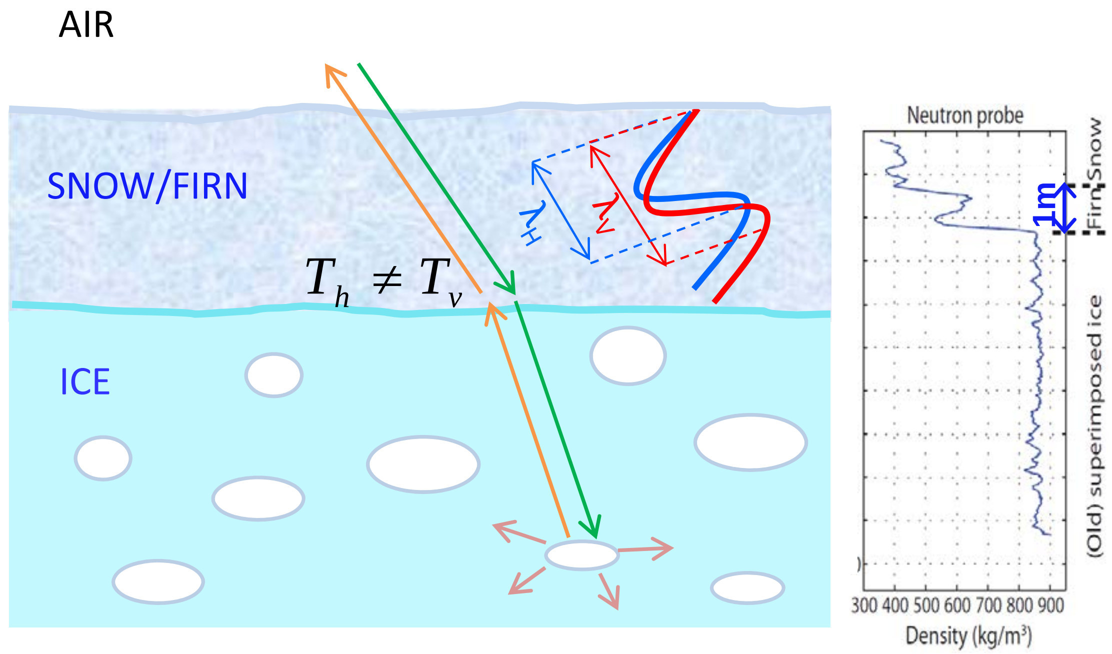
Modeling the Polarimetric Signatures from Etonbreen (SI zone)

Modeling the Glacier Subsurface

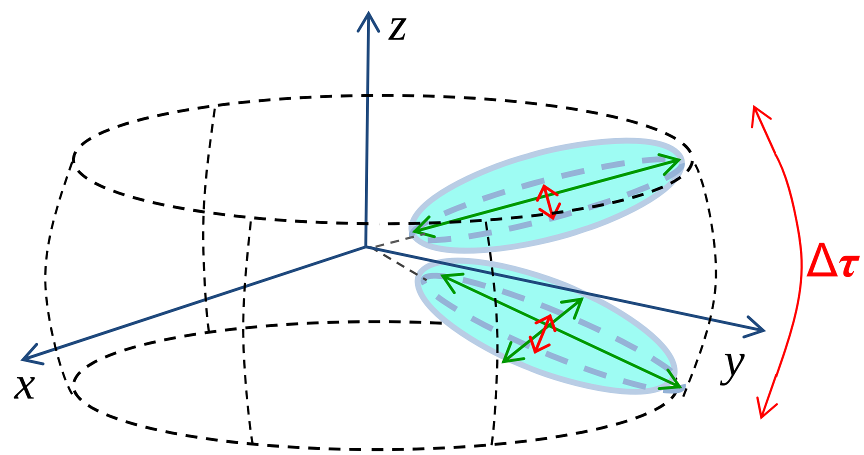
Scattering from SI Zone

- Particle Scattering Model *(Cloude et al., 1999)* for bubbly ice (air bubbles)
- Overlying snow/firn layer (1-2m) from previous winter

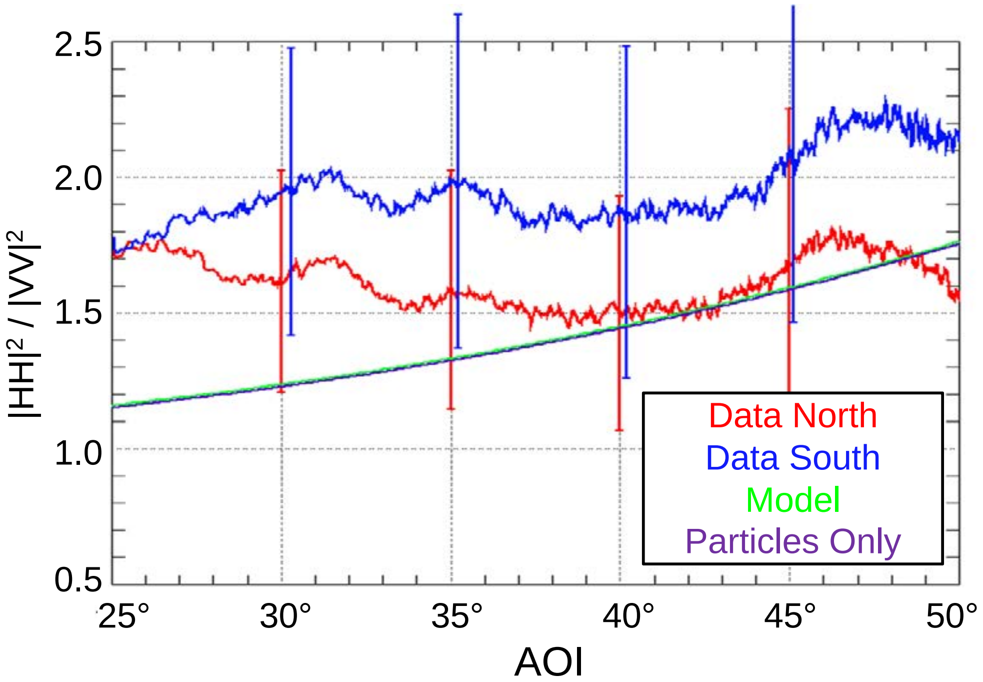


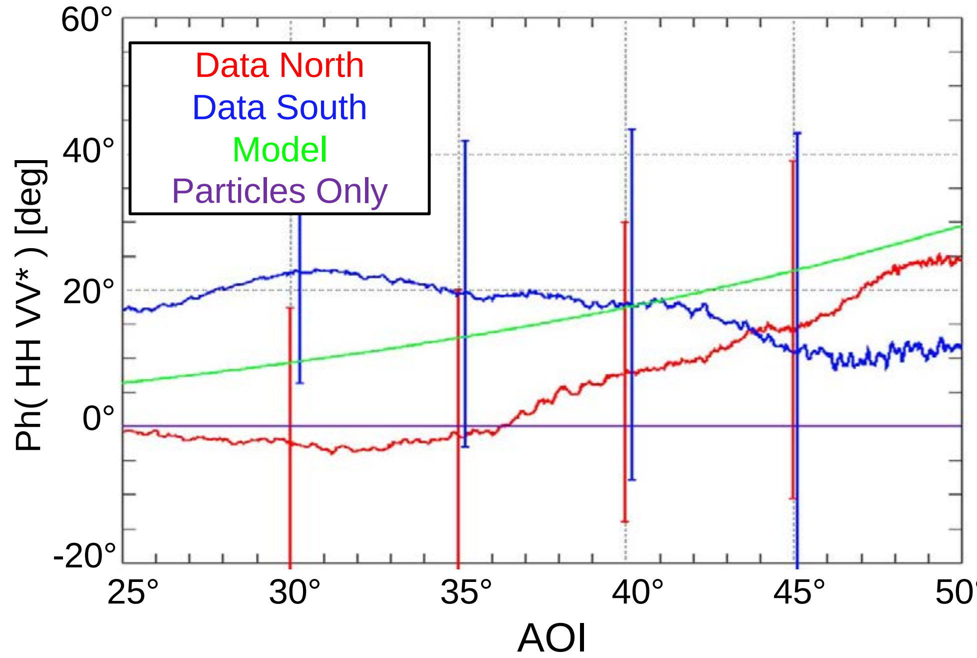
Air Bubbles

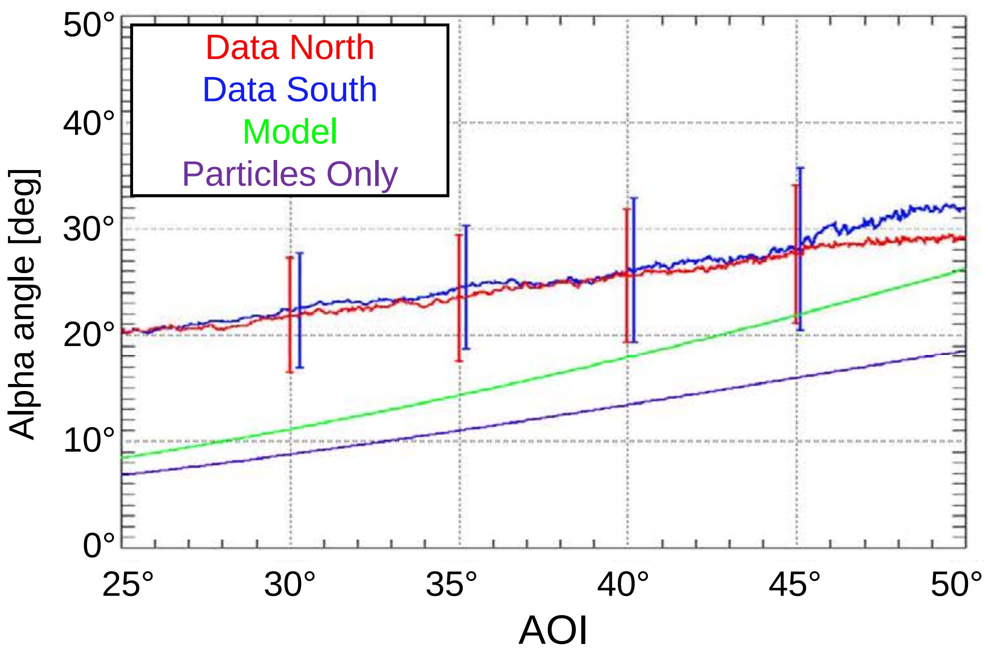
- Volume fraction depend on ice formation conditions
- Typical size are 1mm to 1cm
- Can have elongated shape due to pressure or temperature
- Modelled as (mainly) horizontal oblates (Ap < 1)

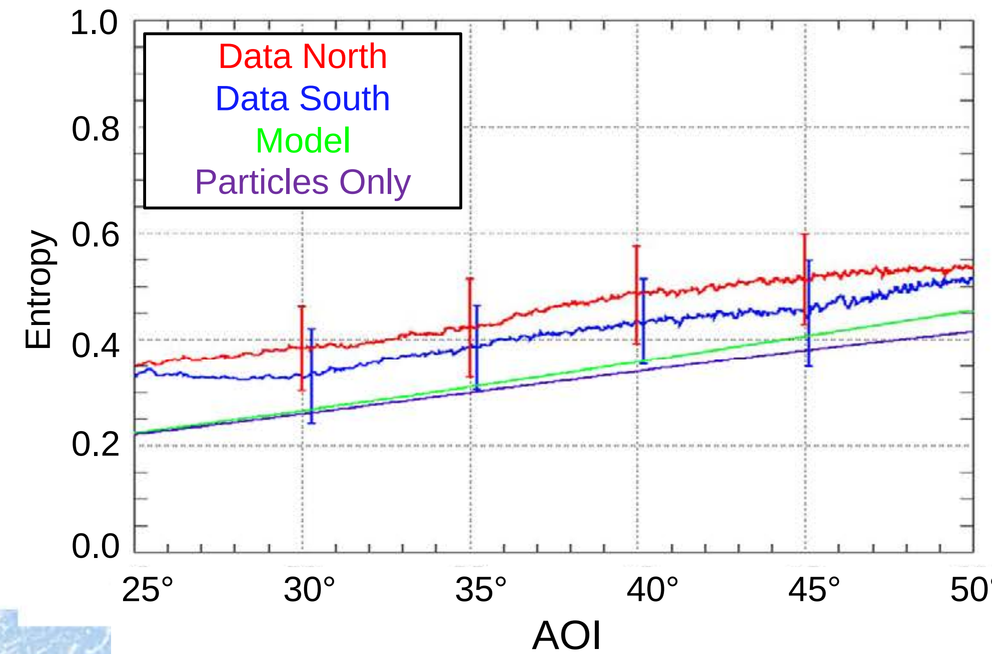


Model vs L-band Data, Eton

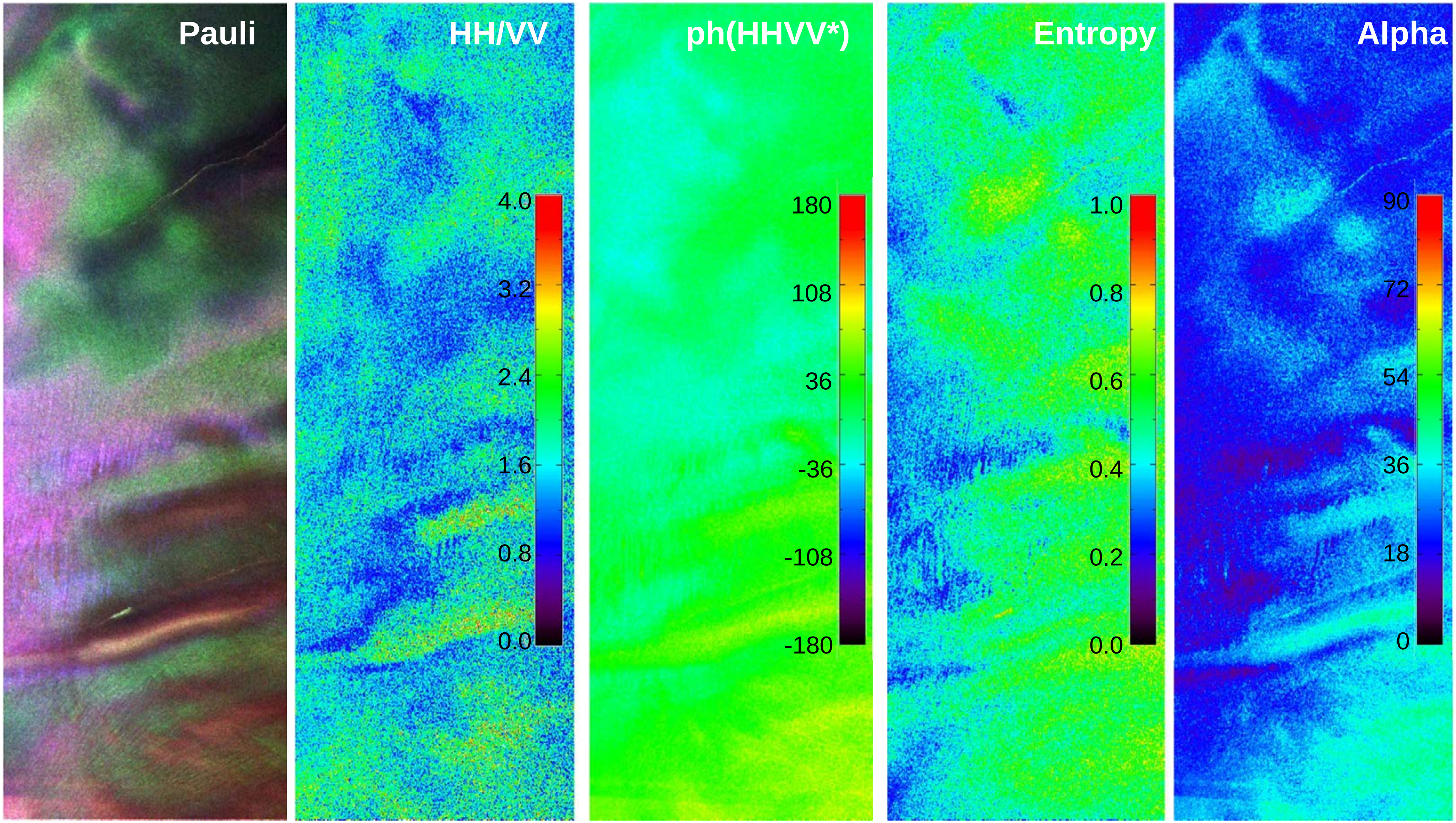




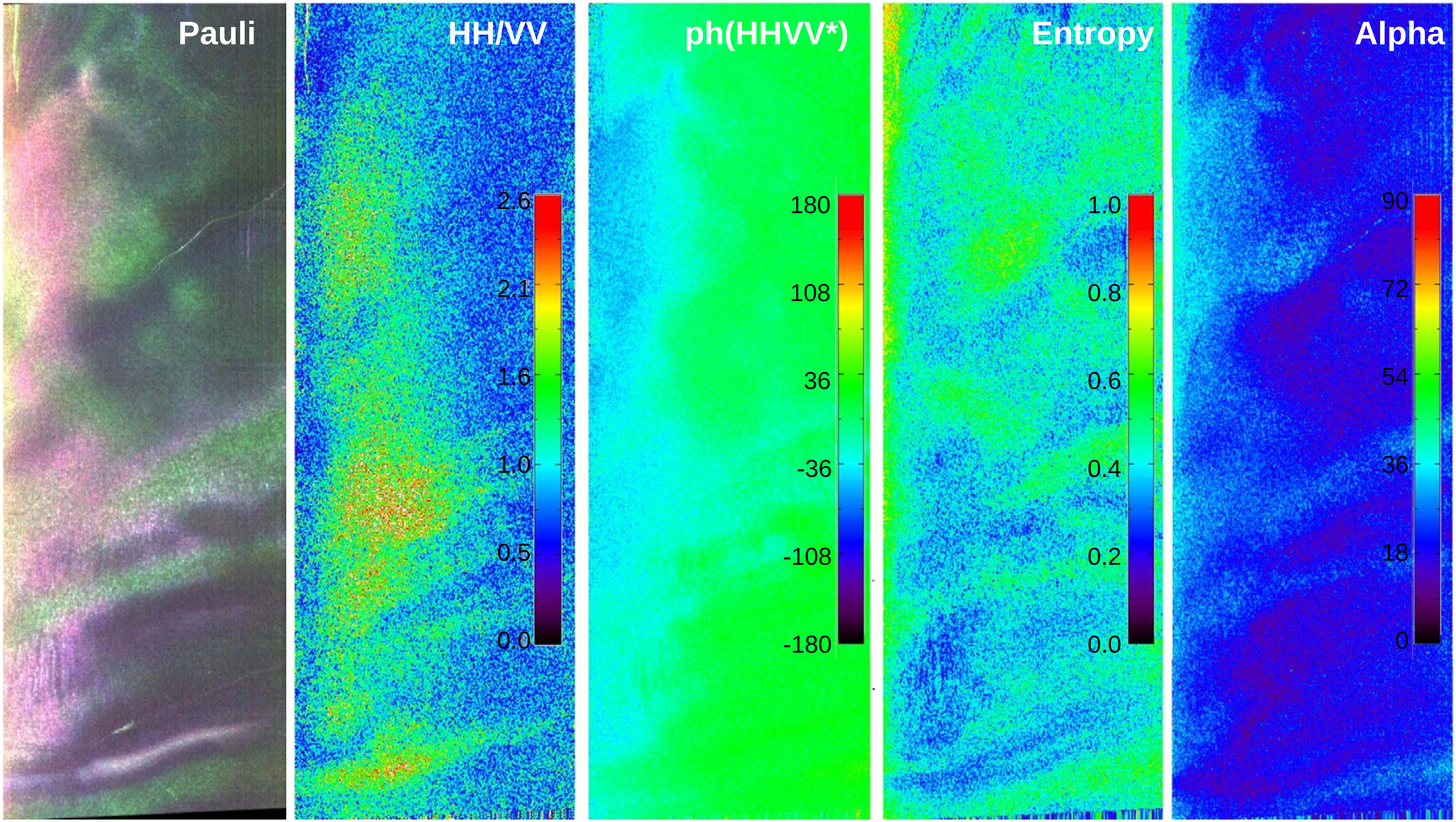




PolSAR Signatures Eton, L-band



PolSAR Signatures Eton, P-band



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Conclusions

- Modeling of backscatter contributions from subpolar glaciers
  - Adaptation of **Particle Scattering Model** for different glacier facies
- Inclusion of **incidence angle** to explain geometry dependency of polarimetric signatures
- **Particle shape** can explain **co-polar ratio** observed in the data
- **Firn anisotropy** might explain **co-polar phase** difference, **H** and **α**
  - Modeling of **differential propagation** effects
- **Percolation zone**
  - Particle Scattering Model for ice **pipes** and **lenses** (prolate/oblate spheroids) in firn background
  - Model prediction matches quite well the **L-band** data
  - **P-band** data reveals possible buried local structures → Not included in the modeling
- **Superimposed Ice zone**
  - Particle Scattering Model for **bubbly ice**
  - SI formation depends on local topography → Very irregular PolSAR signatures

Next Steps

- Further modeling for SI zone → Account for heterogeneity of the test site
  - Possible internal interactions between layers with different bubble content

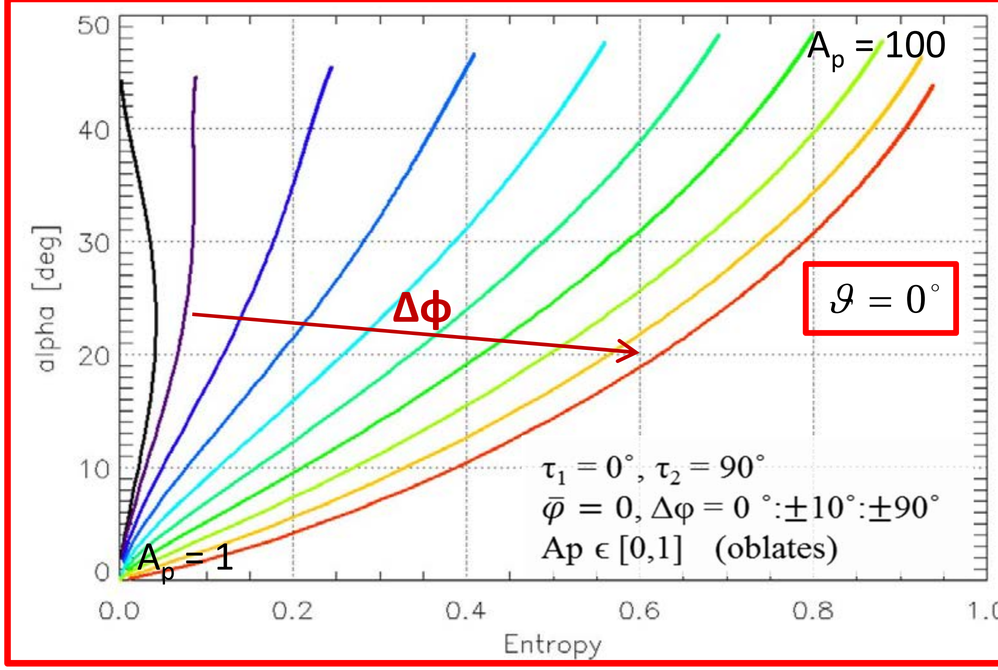
Thanks for your attention!

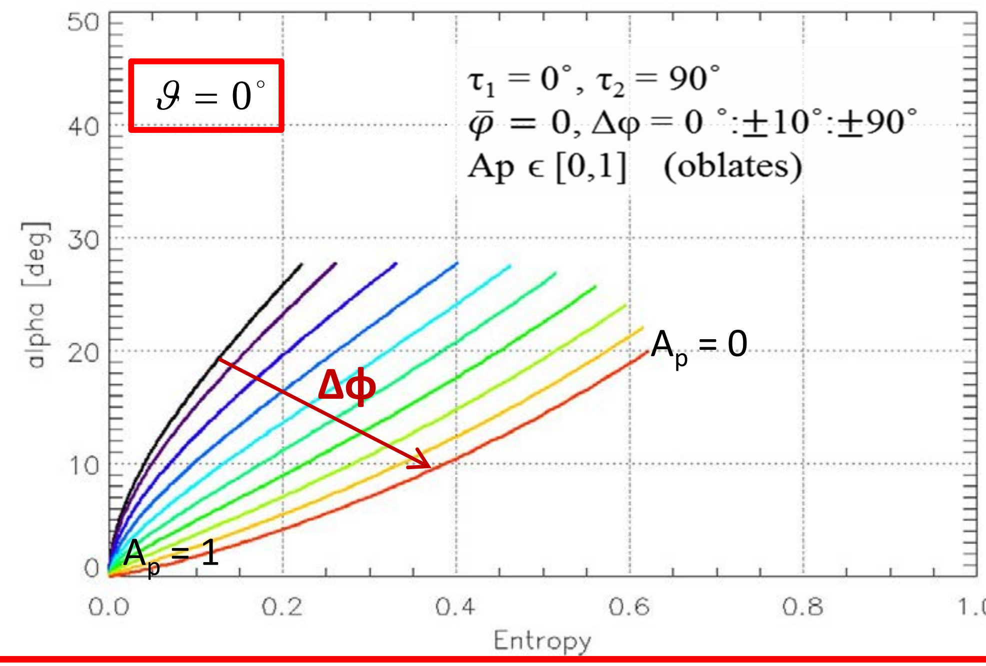
… Questions ?

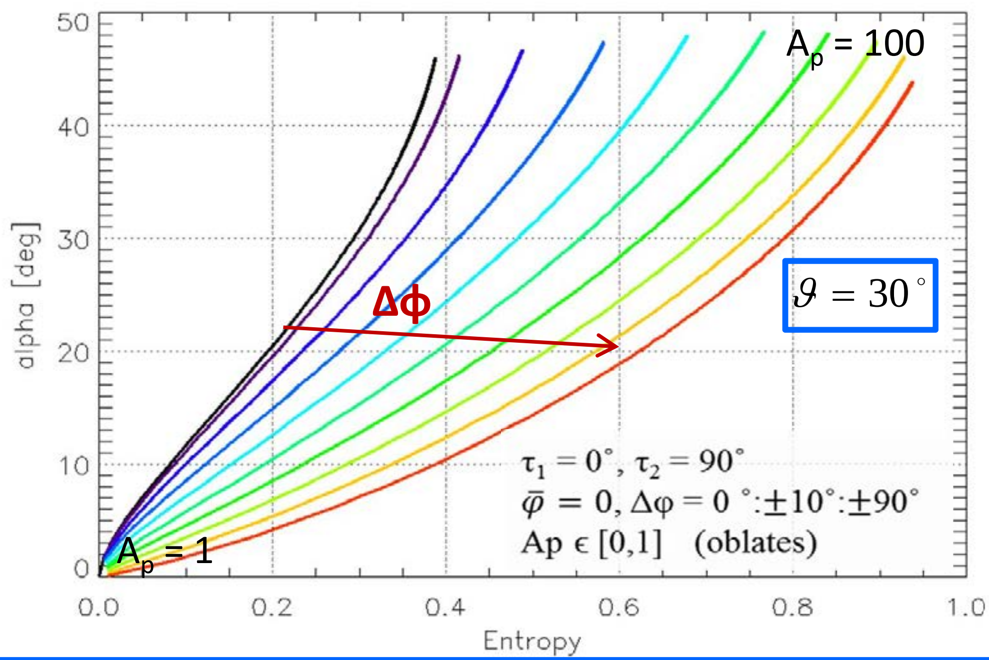
BACKUP

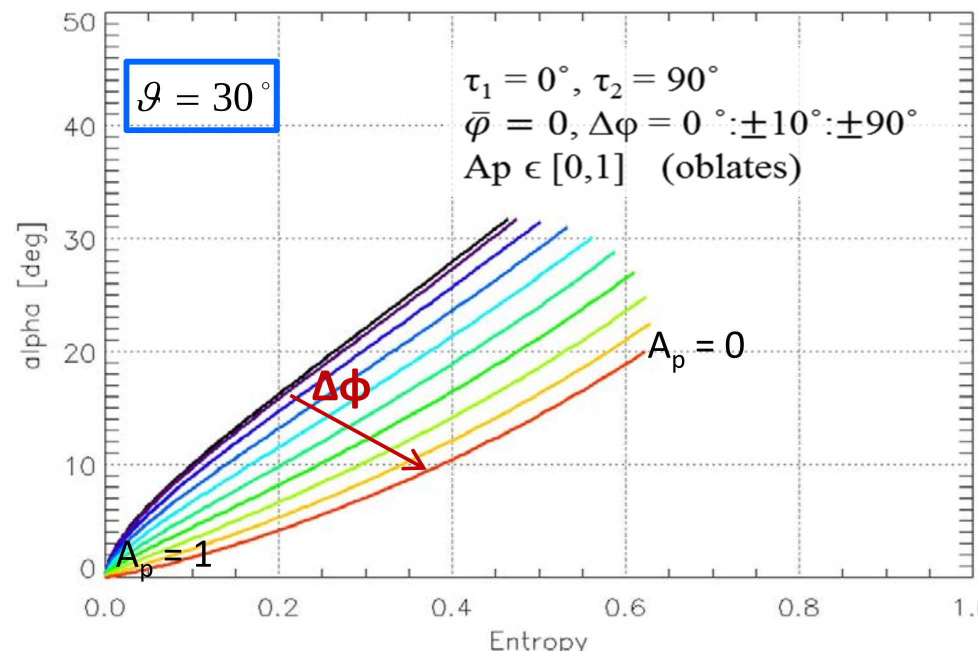
Scattering from a Cloud of Particles: AOI Dependency

Prolates | Oblates





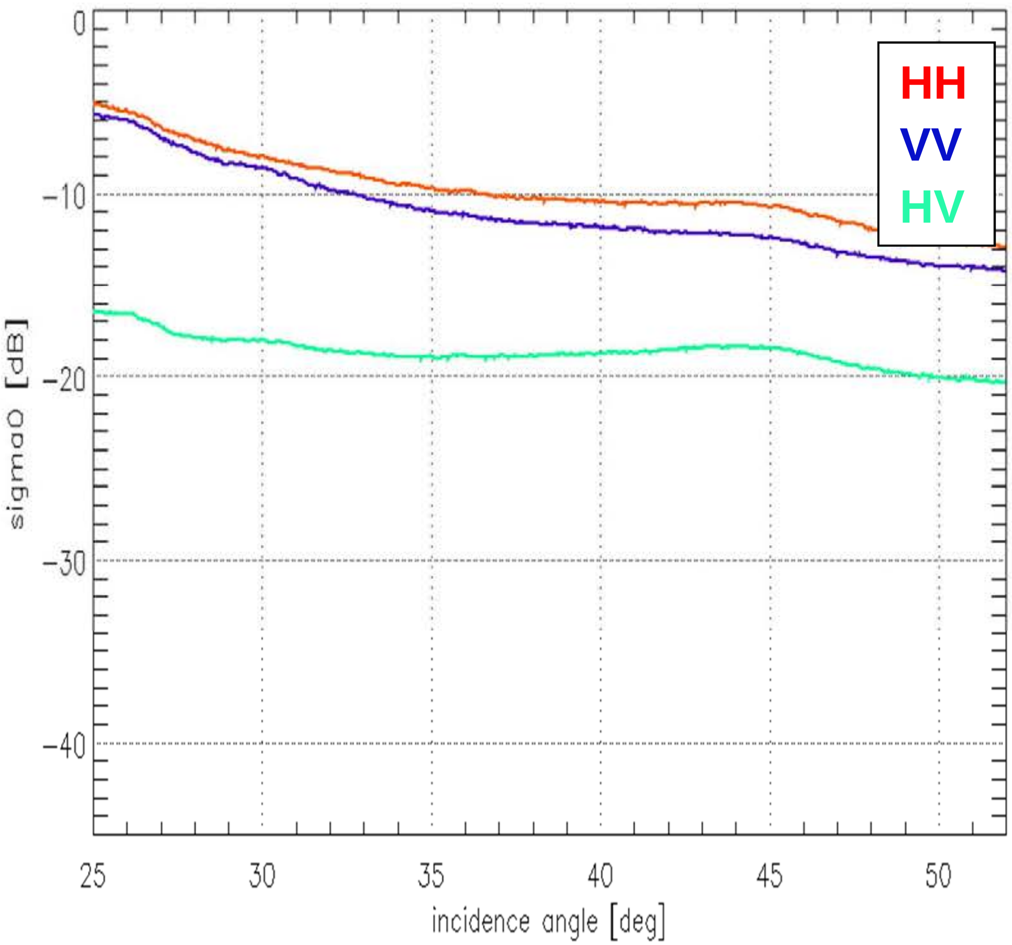




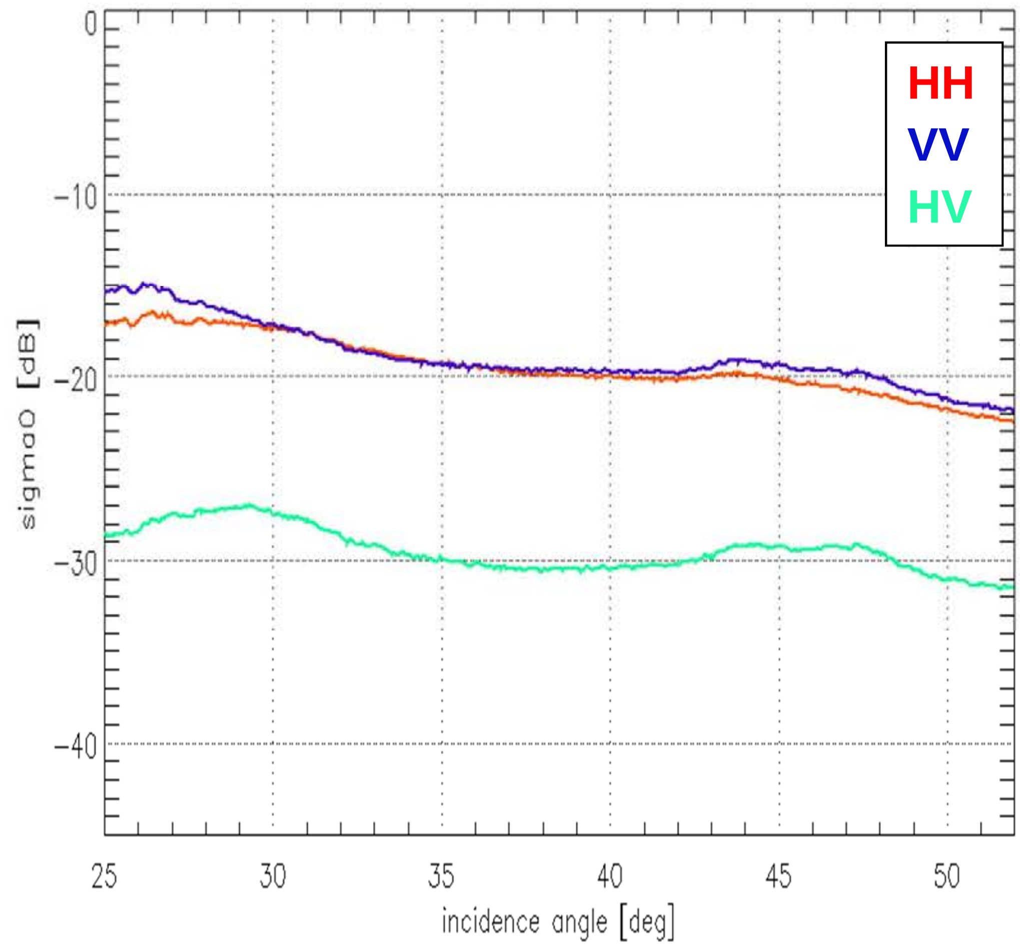
Summit, N, March

Backscattering vs AOI

L-band

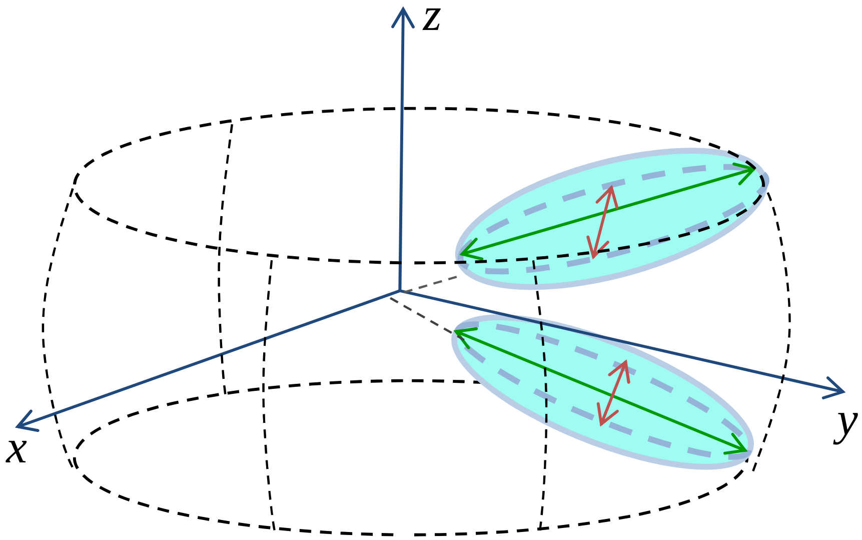


P-band



Simulated Scenario

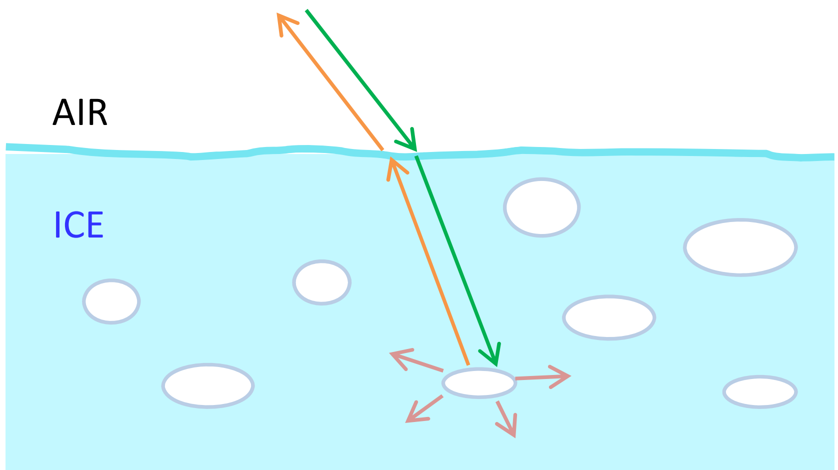
- **Horizontal** oblate air bubbles
- Limited tilt angle distribution (rotation around x-axis)
- Random canting angle (rotation around z-axis)
- **Penetration depth** of 15 m at L- and 35 m at P-band
- AOI from 25° to 50° (E-SAR)

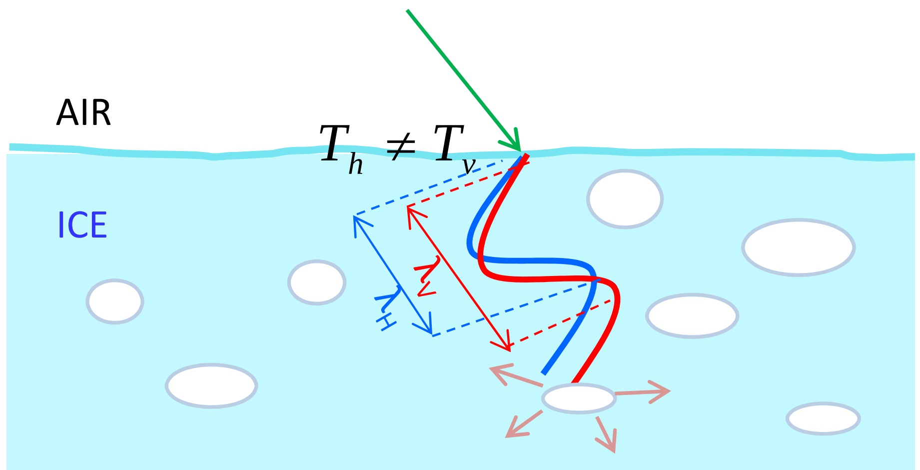


- Simulated cases:

1) Particles cloud only

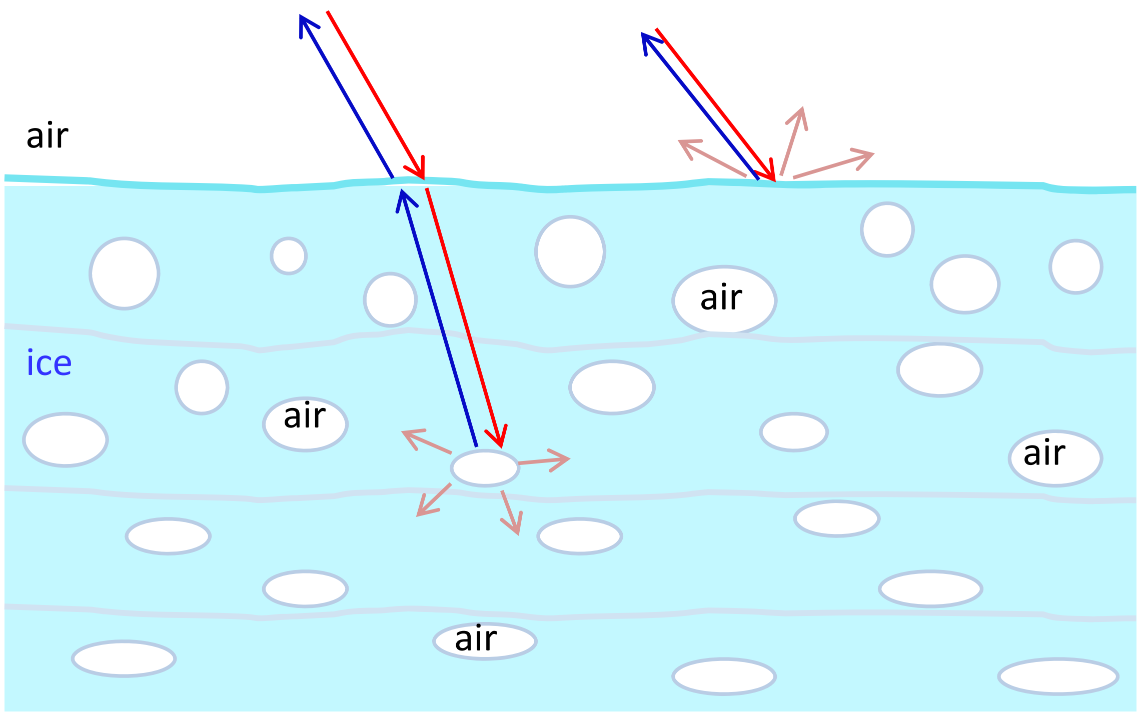
2) Particles cloud + **transmission** + **differential propag.** effects





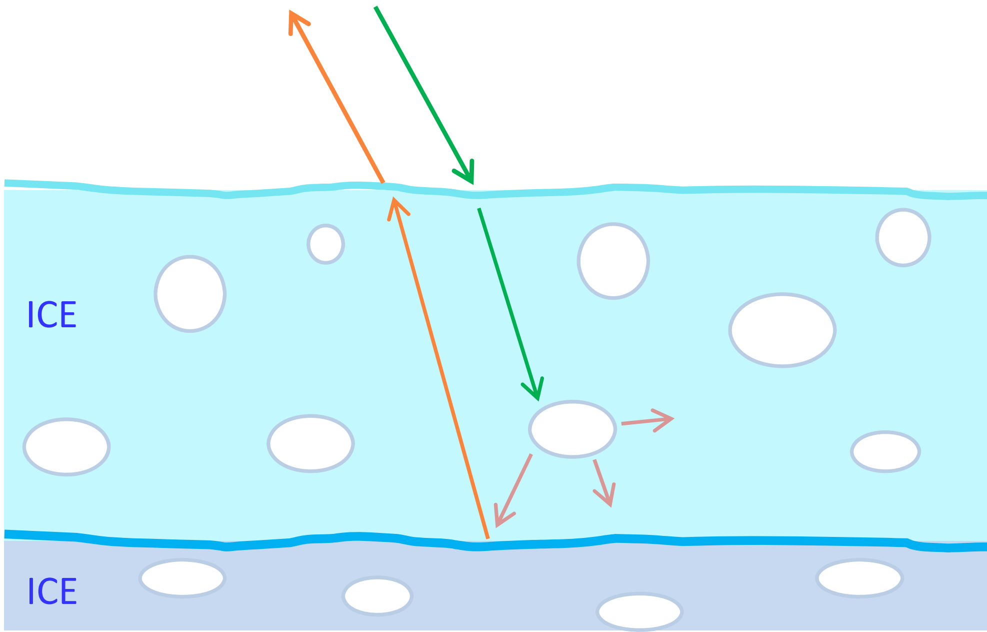
Air Bubbles in Glacier Ice

- **Air bubbles** get trapped when snow accumulates and becomes firn
- **Firn is richer** of bubbles than ice
- Bubbles occupy up to **10% of the ice volume** in the upper layers (several tens of m)
- Tendency to **disappear with depth** (bubble-free ice around 100-150m)
- Typical size range from **few mm to some cm**
- Generally are sphere-like, and **get flattened with depth/pressure**



Dihedral Component

- Scattering from **particles-subsurface** interaction
  - **Firn-Ice interface**
  - Presence of layered dielectric contrast
- **Weak component** compared to volume and surface
- Significant contribution to **copolar phase**

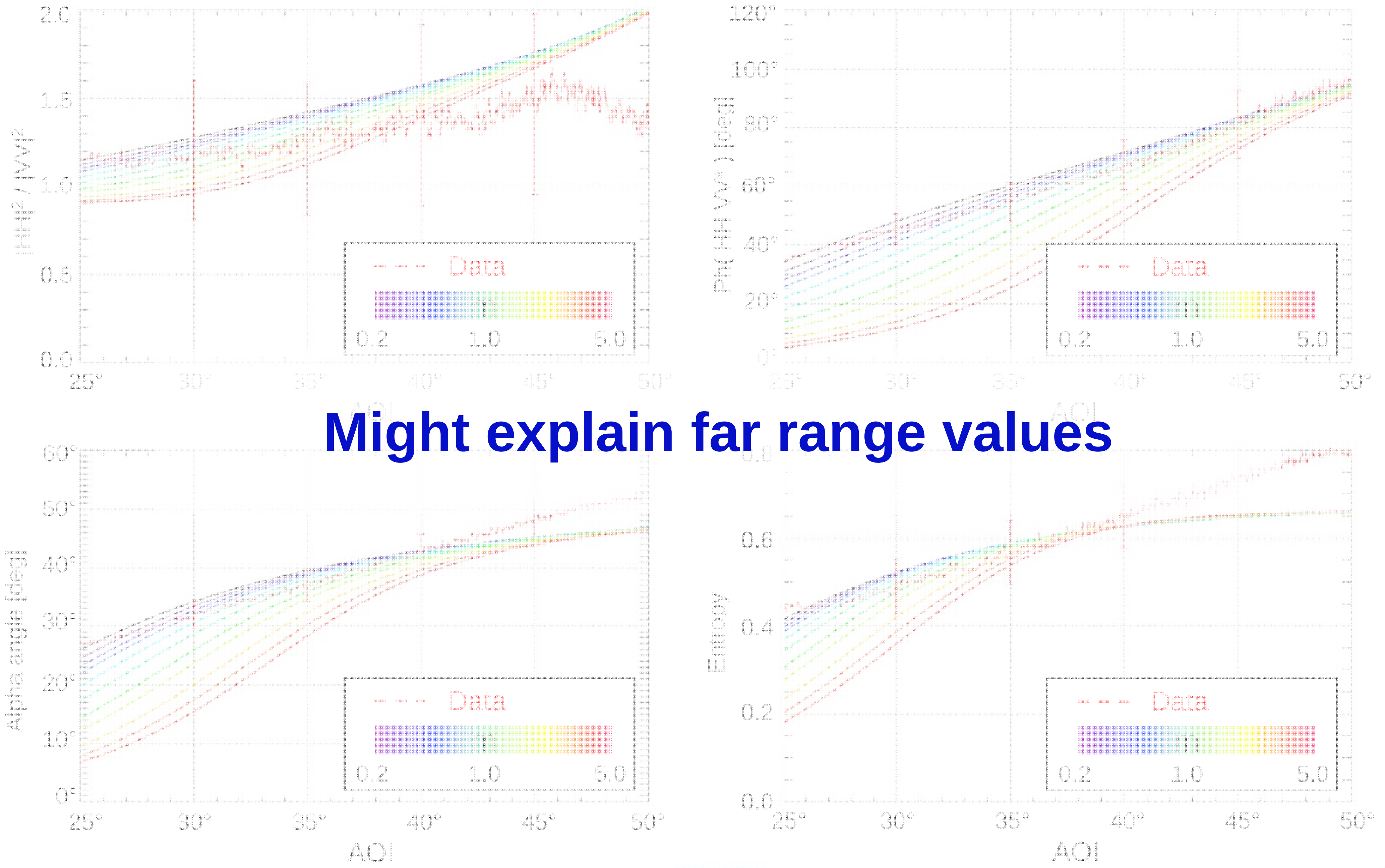


$$[C_{tot}] = f_s \cdot [C_{surf}] + f_v \cdot [T][P][C_{vol}][T]^t[P]^t + f_d \cdot [C_{dih}] + [N]$$

Outlook

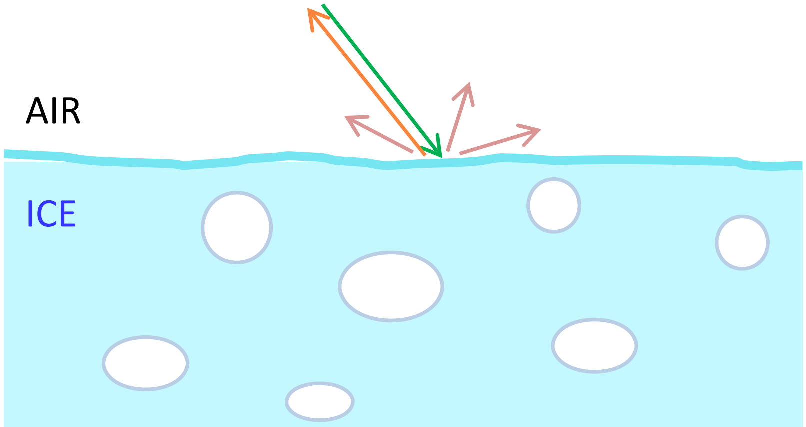
- Include propagation and transmission effects

3 Components (Vol+Surf+Dihedral) vs L-band Data



Might explain far range values

Modeling the Ice Surface – Bragg Scattering

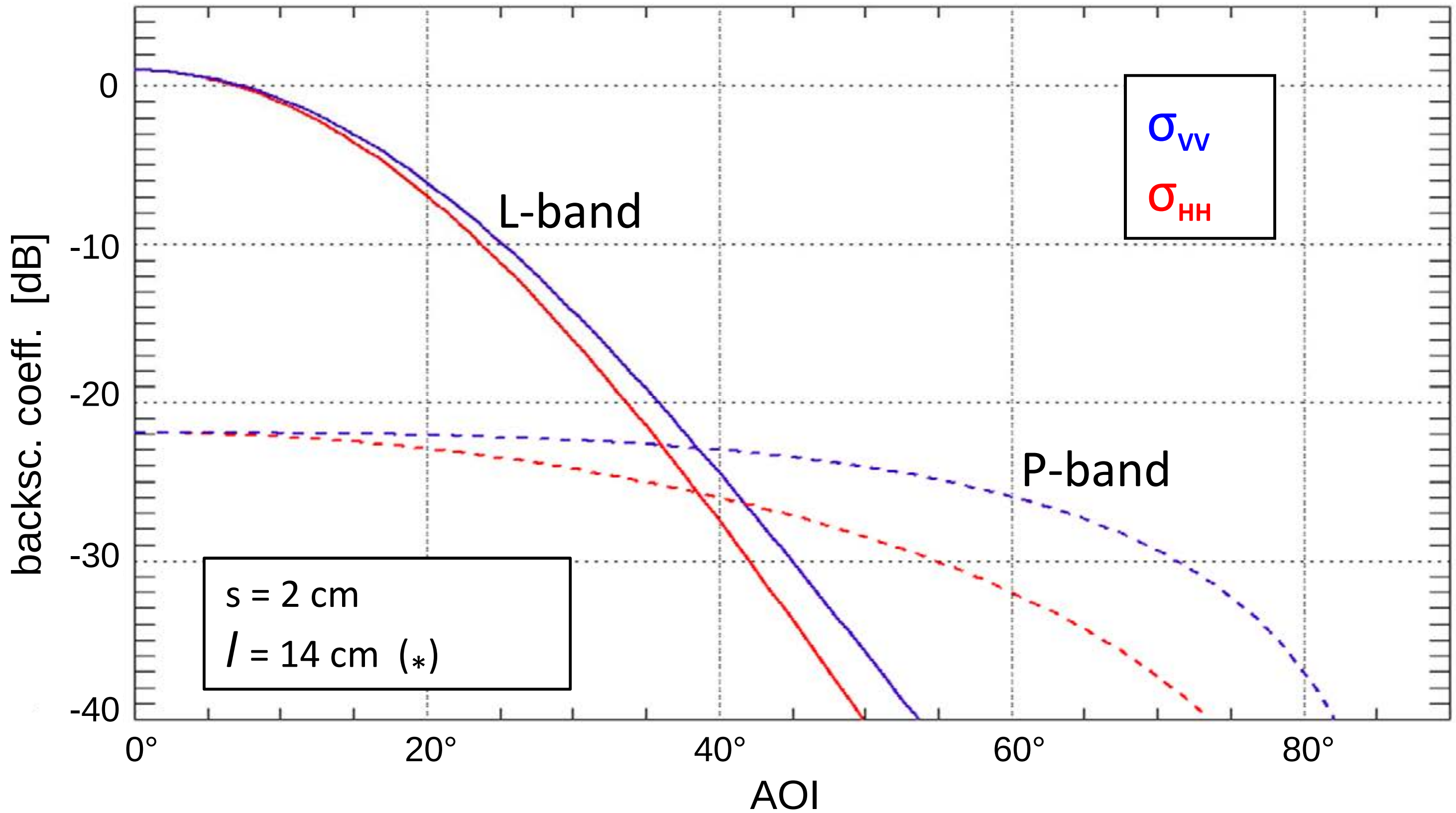


Small Perturbations Model

s = standard deviation of vertical surface roughness

l = surface correlation length

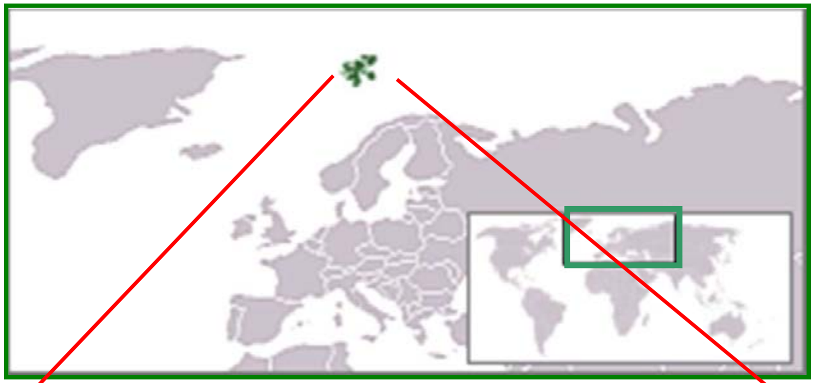
$$W_{surf}(l, \vartheta) = \frac{1}{2} l^2 e^{-(kl \sin \vartheta)^2}$$ roughness spectrum

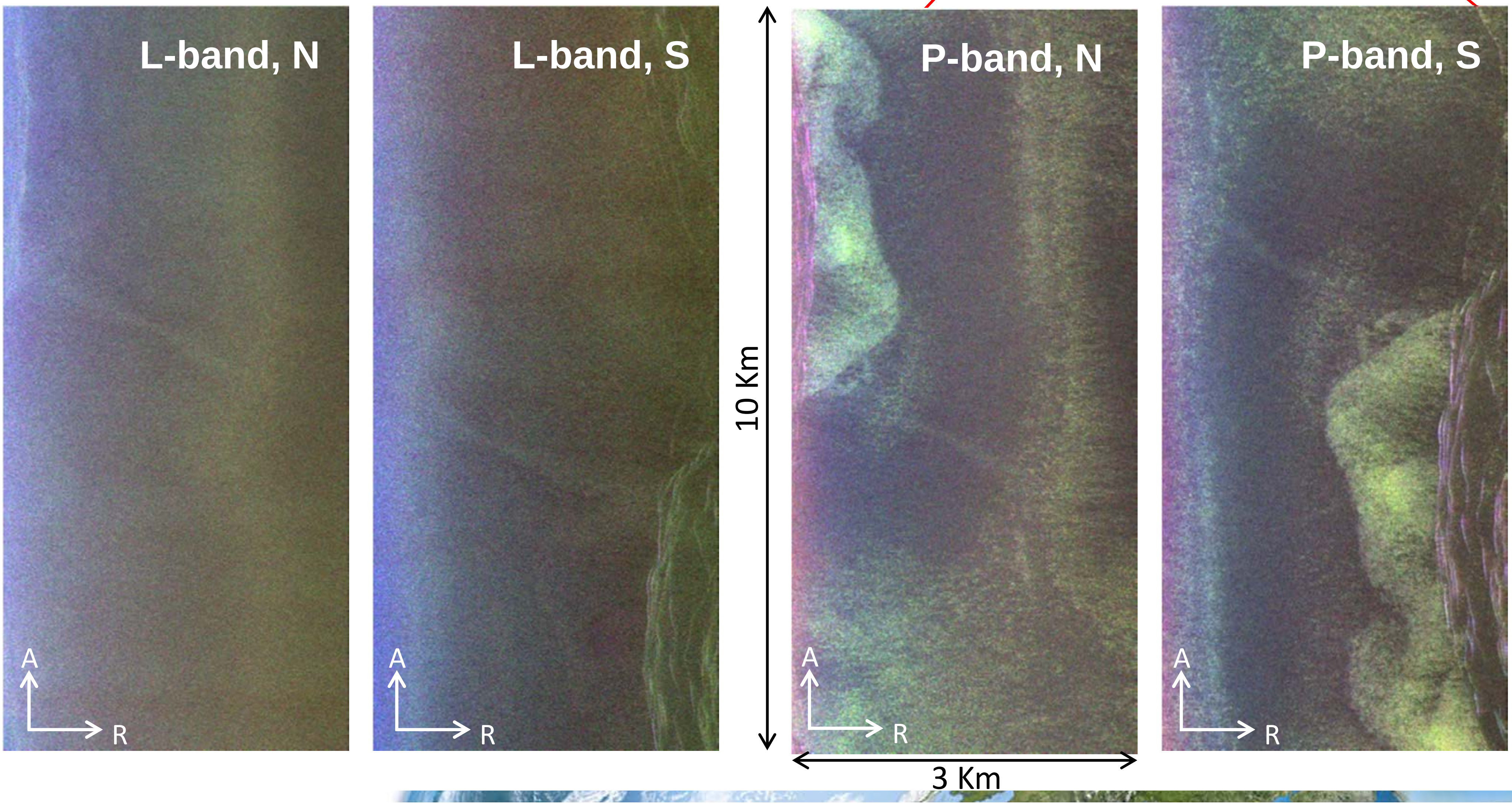


(*) H. Rott, and R.E. Davis "Multifrequency and Polarization SAR Observation on Alpine Glaciers", *Annals of Glaciology,* vol.17, pp. 98-104, 1993.

Test Site: Nordaustlandet, Svalbard

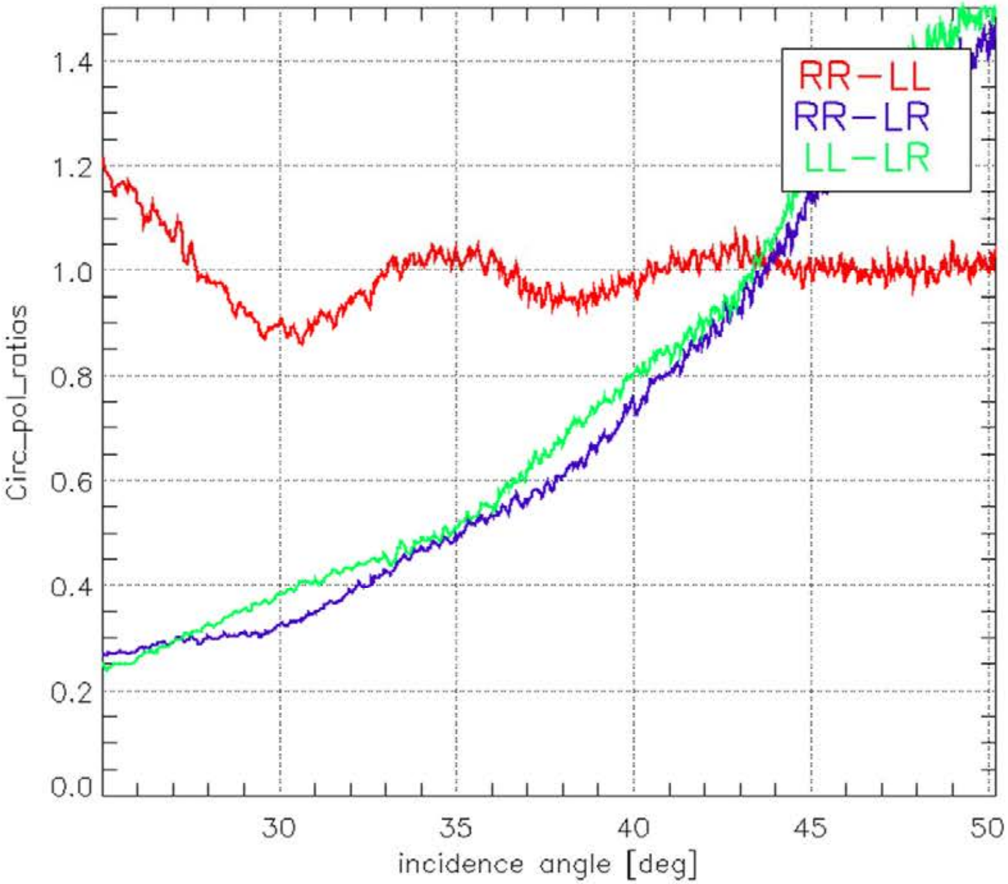
- **Summit of the Austfonna ice cap**, Svalbard Archipelago, Norway (~ 80˚N, 24˚E)
- **Flat topography**, max **ice thickness** ~560m
- **IceSAR 2007** data, fully polarimetric, L- and P-band, South and North flights, **AOI** 25°-50°



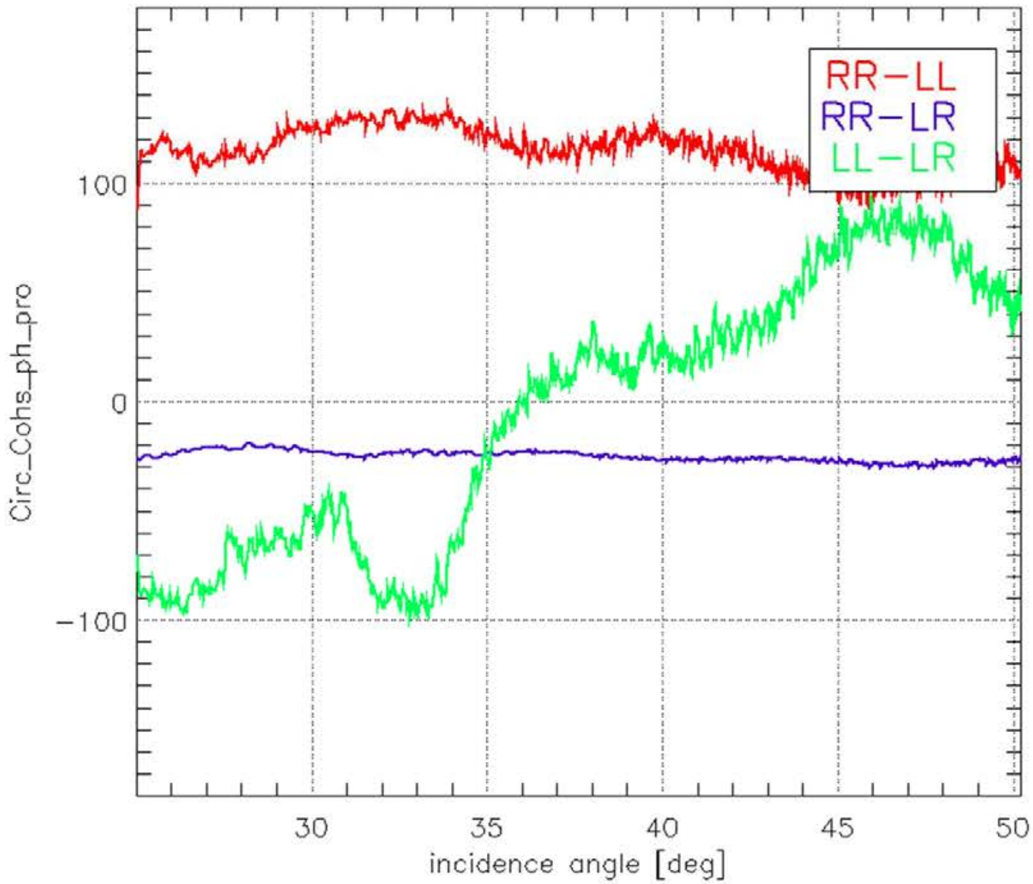


Summit, March, North, L-band – Circular Pol

Ratios

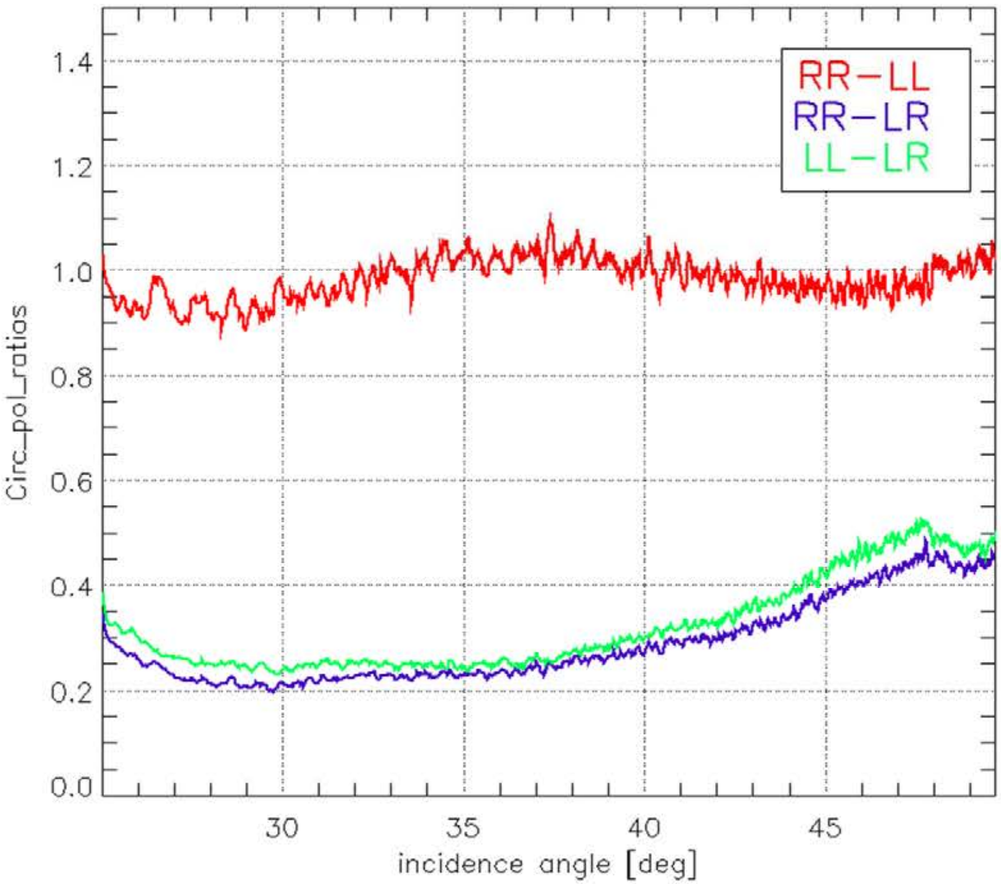


Phases

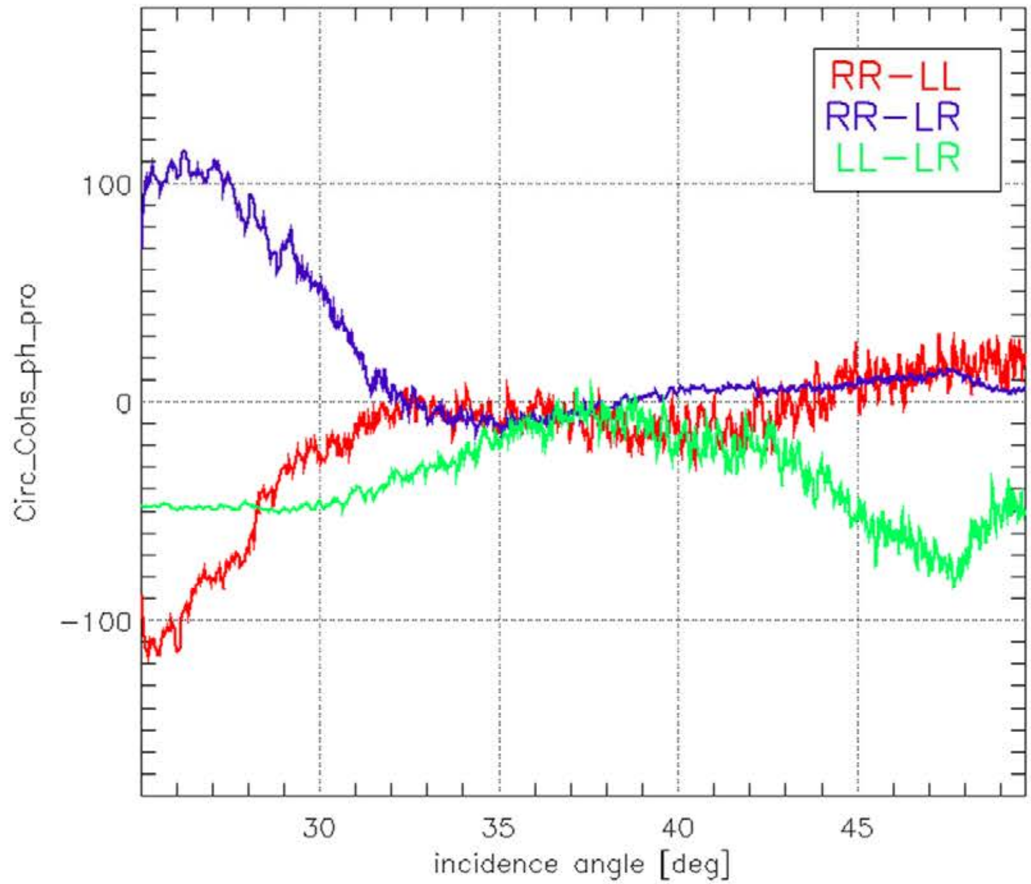


Summit, March, North, P-band – Circular Pol

Ratios



Phases



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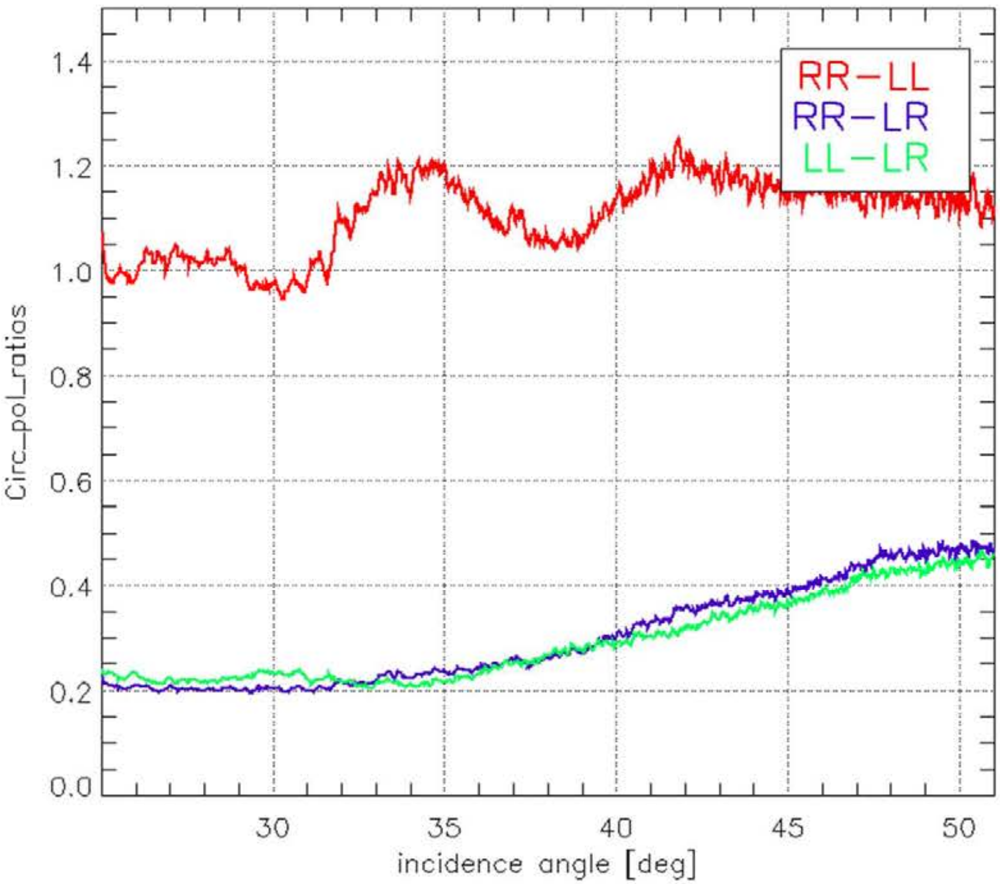
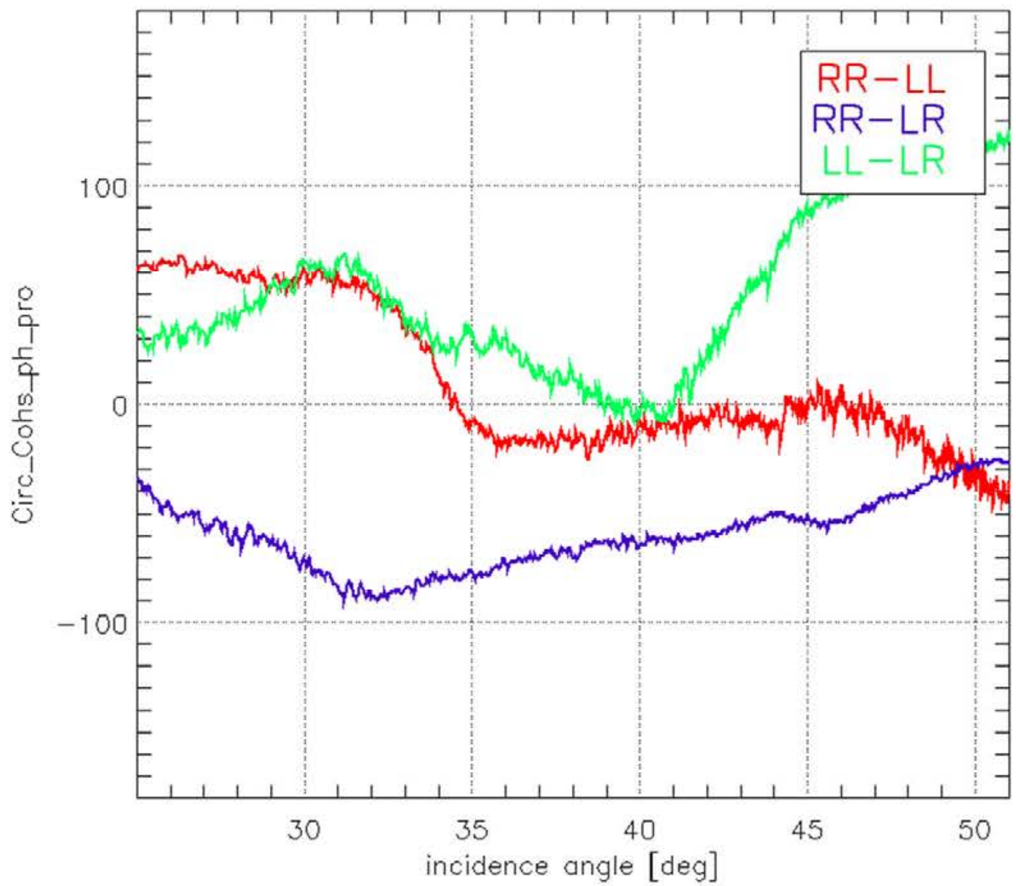
Eton, March, North, L-band – Circular Pol

Ratios

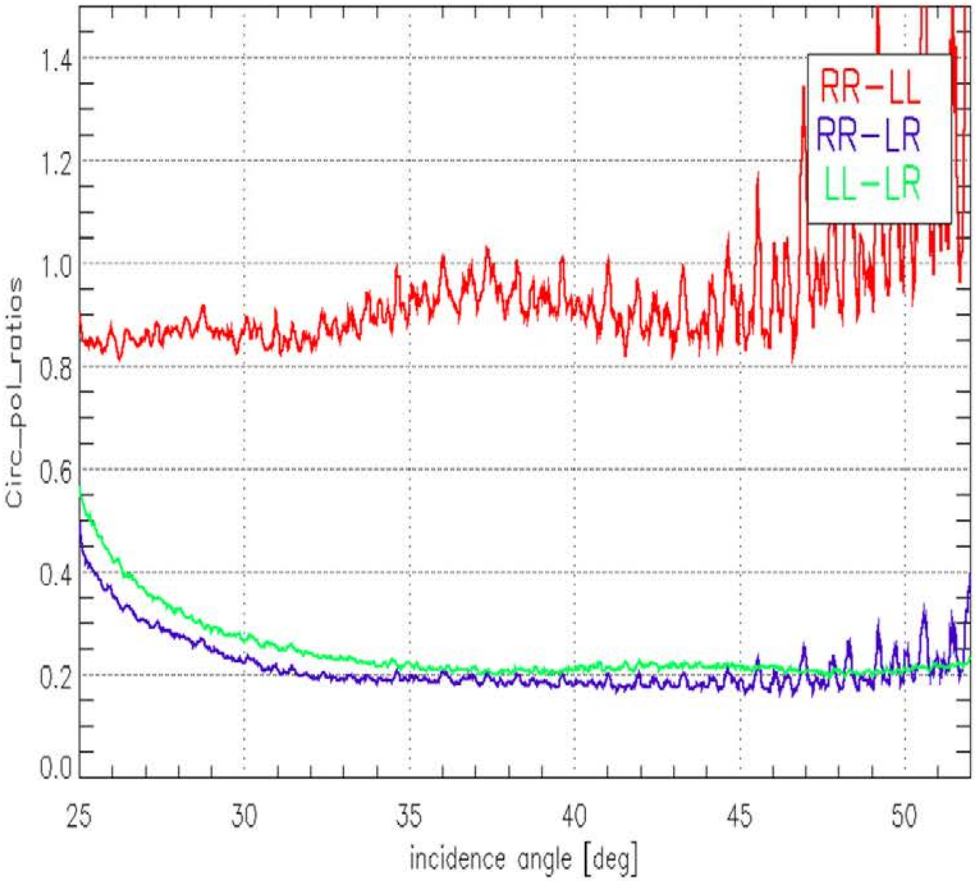


Phases

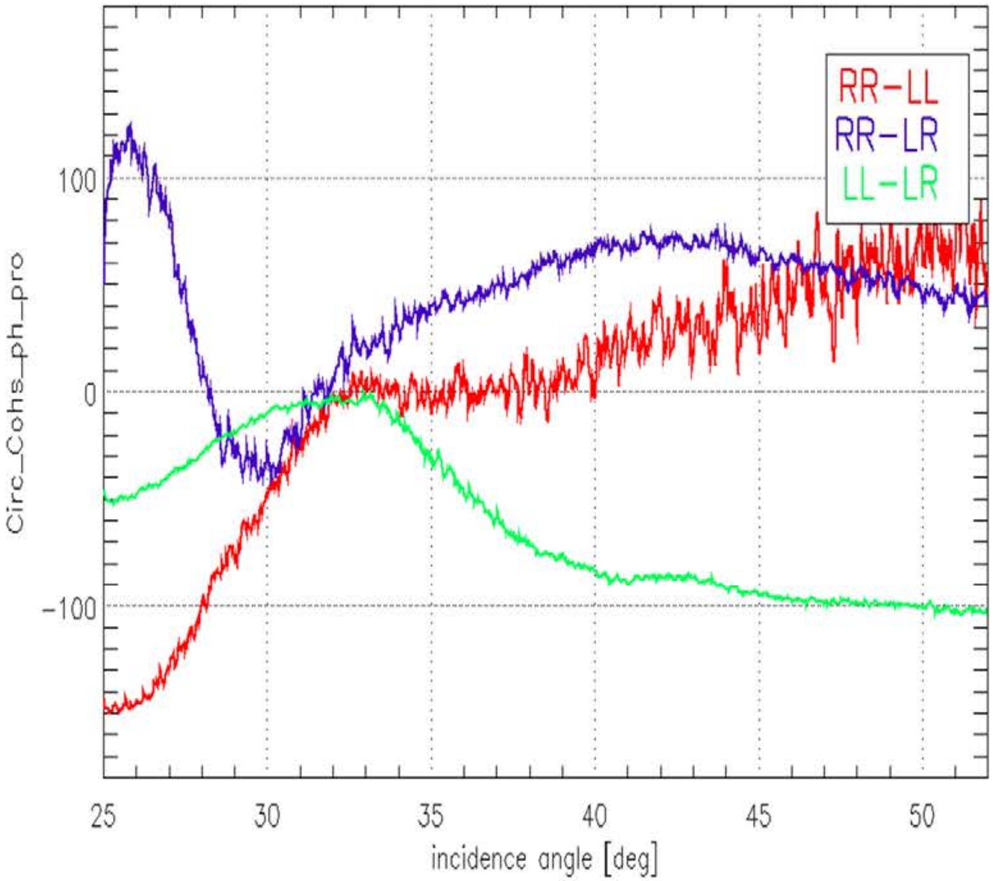


Eton, March, North, P-band – Circular Pol

Ratios

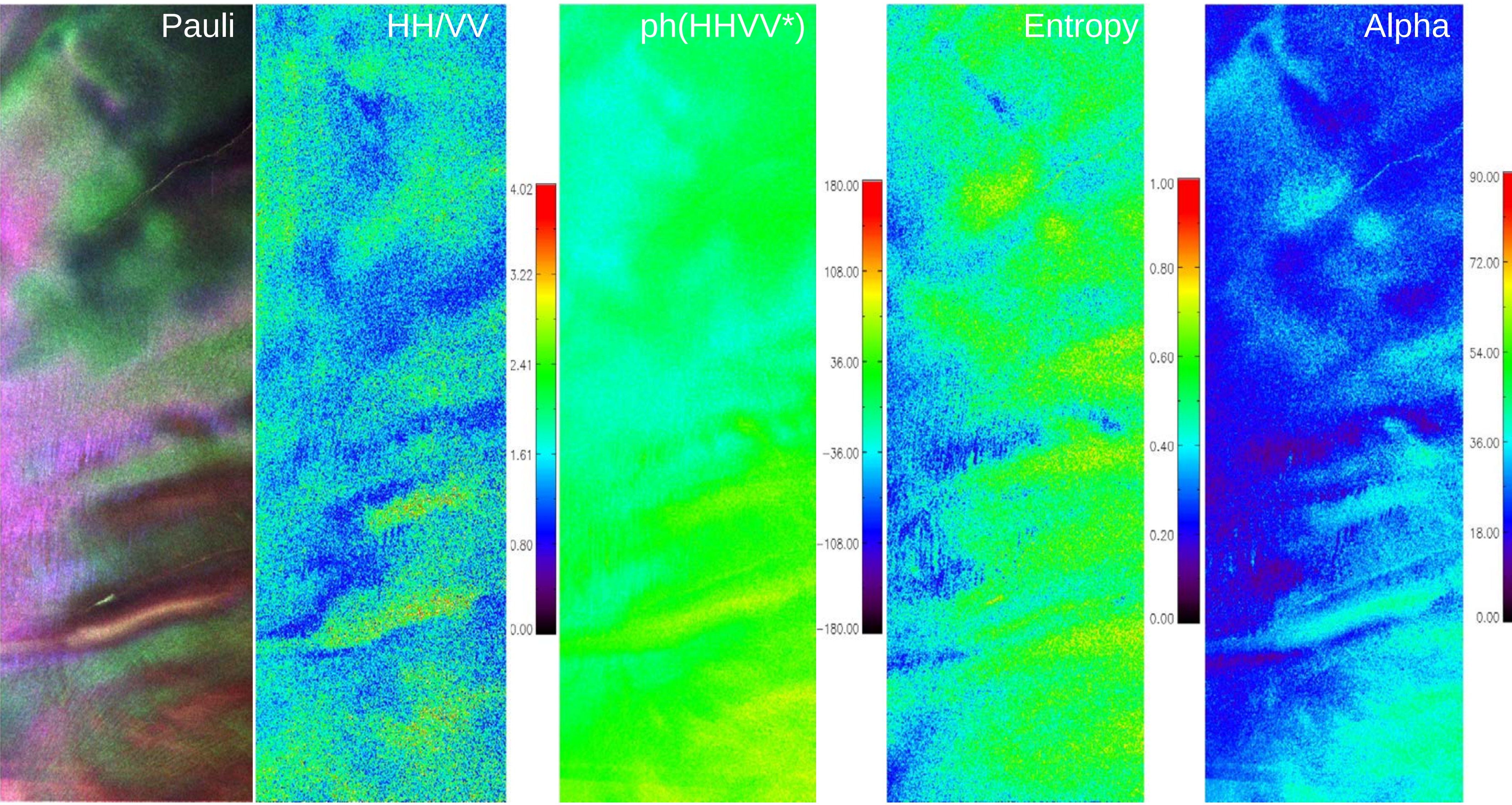


Phases

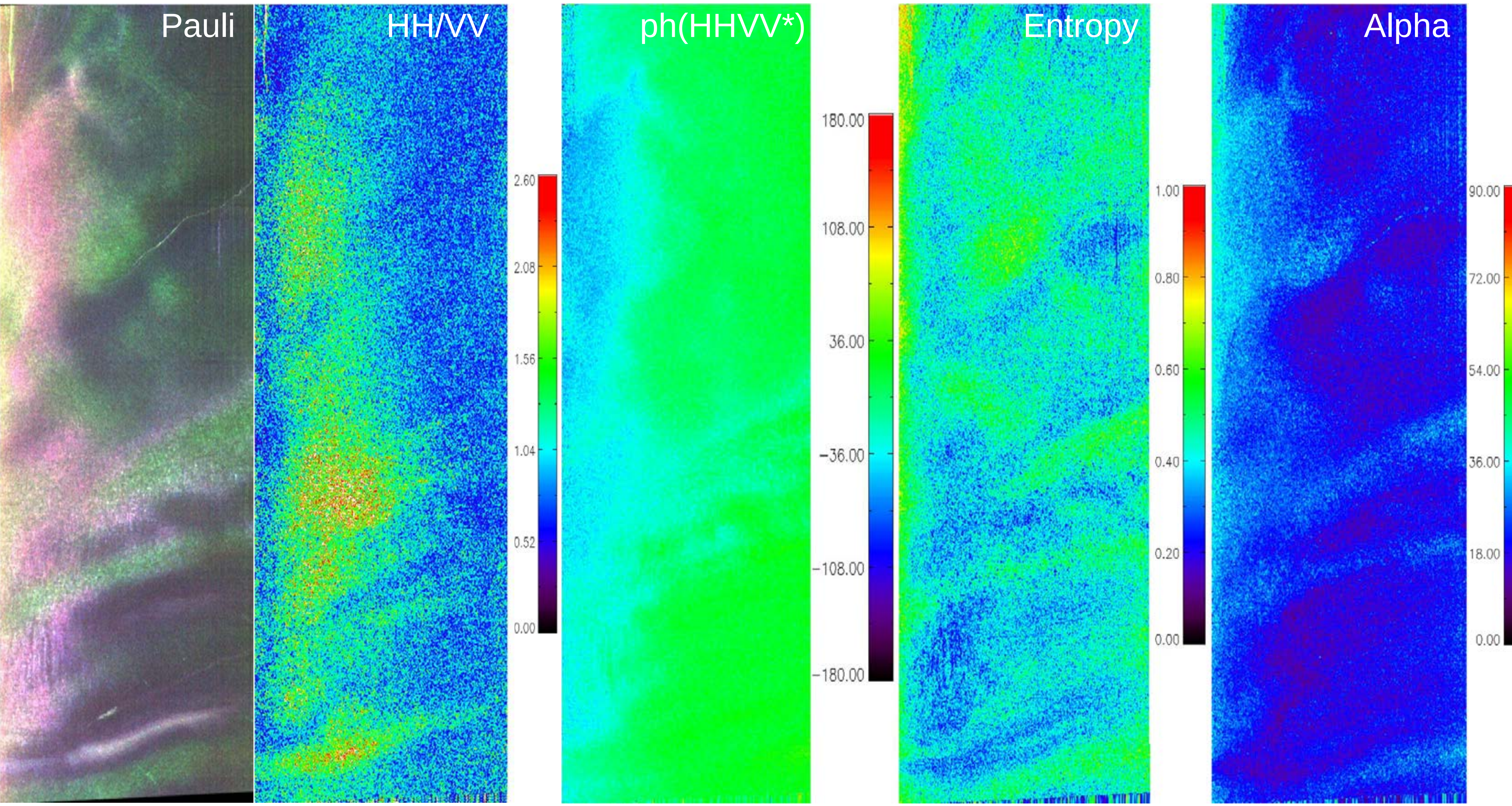


DLR

Eton, N, April, L-band



Eton, N, April, P-band



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