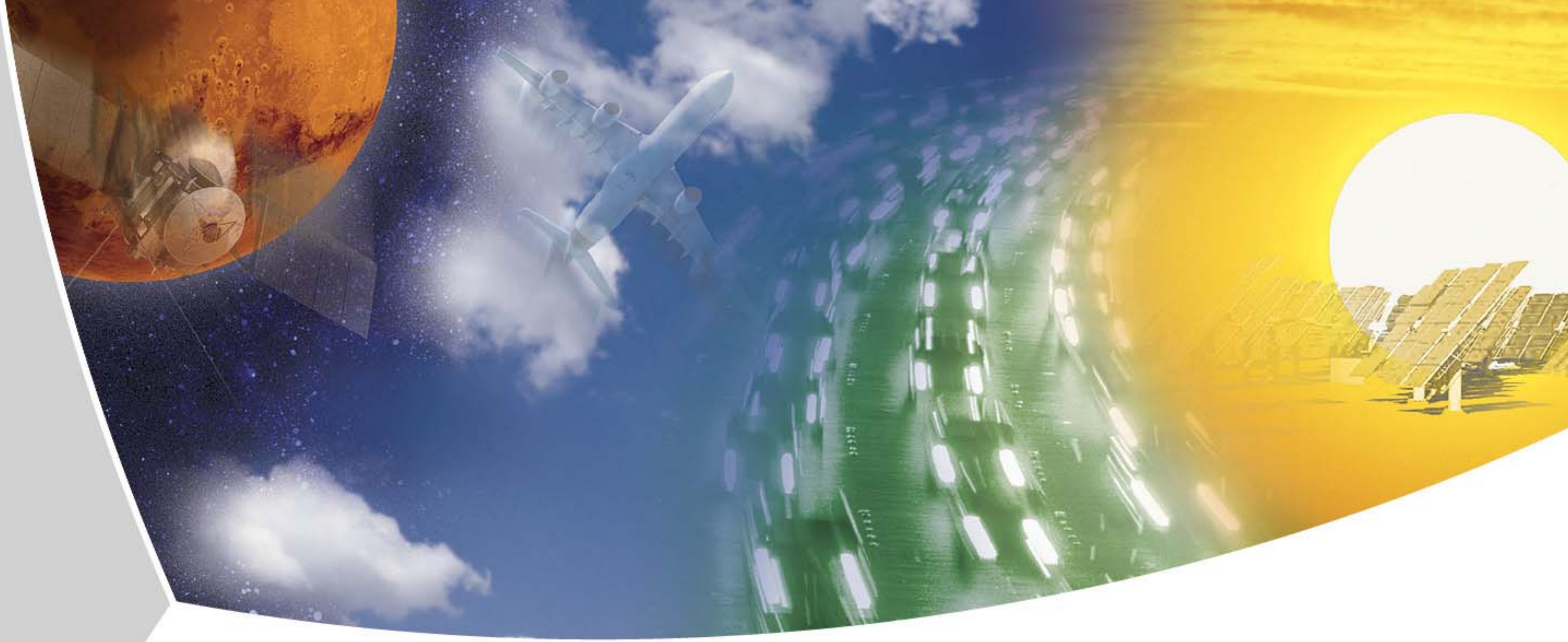

Sub-surface glacial structure over Nordaustlandet using multi-frequency Pol-InSAR

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11.06.2008

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Introduction: Pol-InSAR over Land Ice

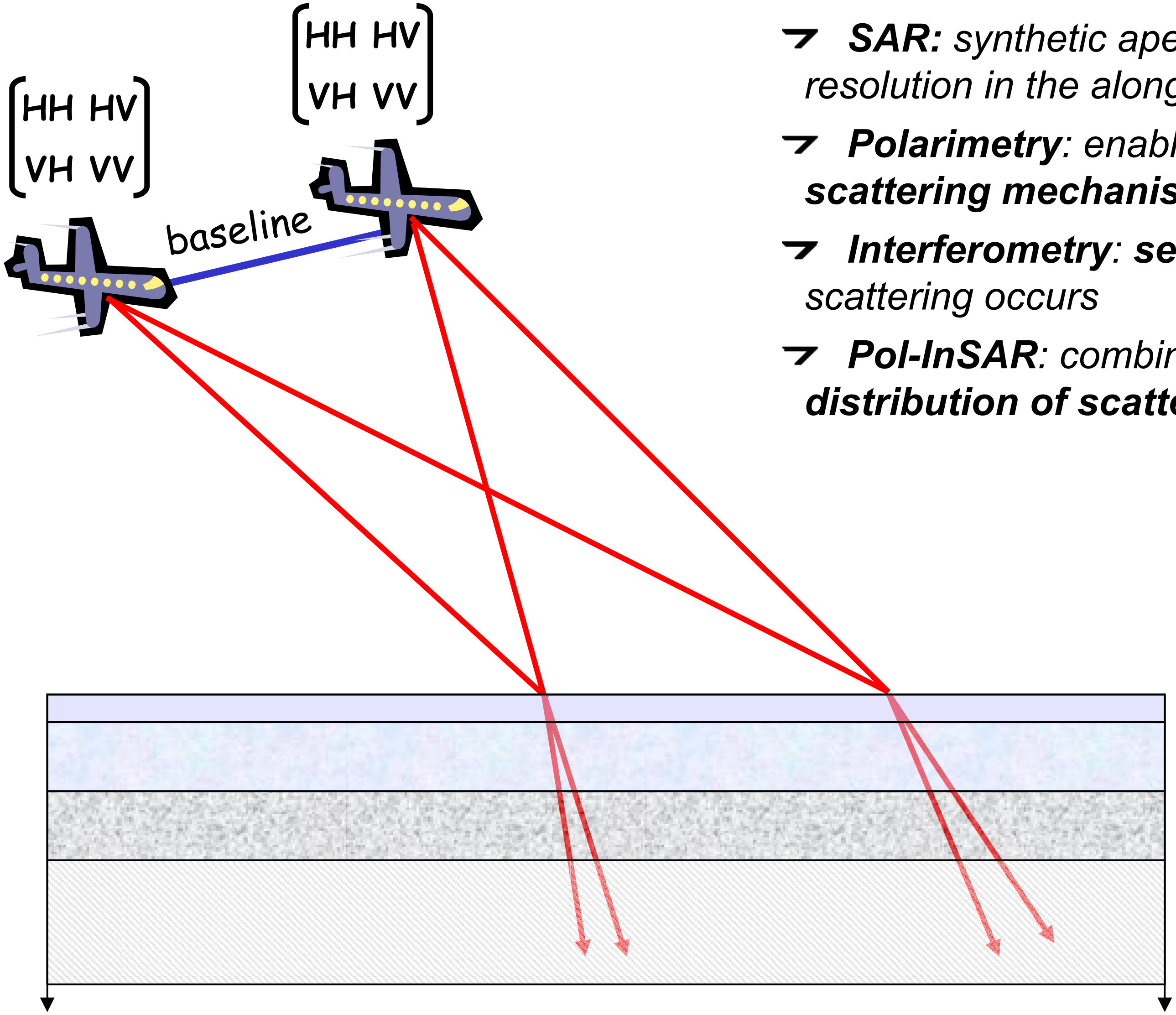
Motivation:

- *A greater understanding of the properties of glaciers/ice sheets including their topography, velocities, melting/accumulation rates, **densities and internal structure** (related to **rate of extinction**)*
- *SAR (**synthetic aperture radar**) sensors particularly well-suited for cryospheric measurements (polar areas dark for much of the year, high resolution & coverage)*
- ***polarimetry** yields information regarding scattering mechanisms (volume+surface scattering), **interferometry** regarding their distribution with height*

Goal:

- *For the first-time, **use Pol-InSAR observables to estimate land ice extinctions***

Airborne Polarimetric SAR Interferometry (Pol-InSAR)



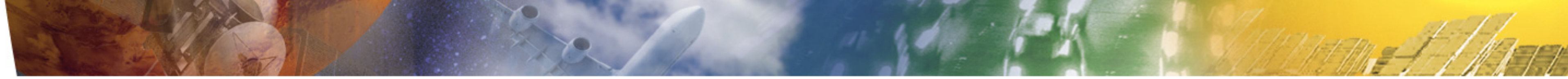
- **SAR:** *synthetic aperture radar enables high resolution in the along-track line-of-flight direction*
- ***Polarimetry**: enables the **separation of different scattering mechanisms** within a resolution cell*
- ***Interferometry**: **sensitive to the height** at which scattering occurs*
- ***Pol-InSAR**: combined, sensitive to the **vertical distribution of scattering mechanisms***

Data description

- ***ICESAR*** *data campaign*
- *conducted in Mar/Apr 2007 over Austfonna ice cap (Summit) and Etonbreen drainage basin, Svalbard, Norway (~ 80˚N, 24˚E)*
- *Joint project between*
    - ***DLR*** *(German Aerospace Center)*
    - ***ESA*** *(European Space Agency)*
    - ***AWI*** *(Alfred-Wegener Institute)*

Corner reflector at Summit

DLR’s E-SAR (left), AWI’s airborne platform

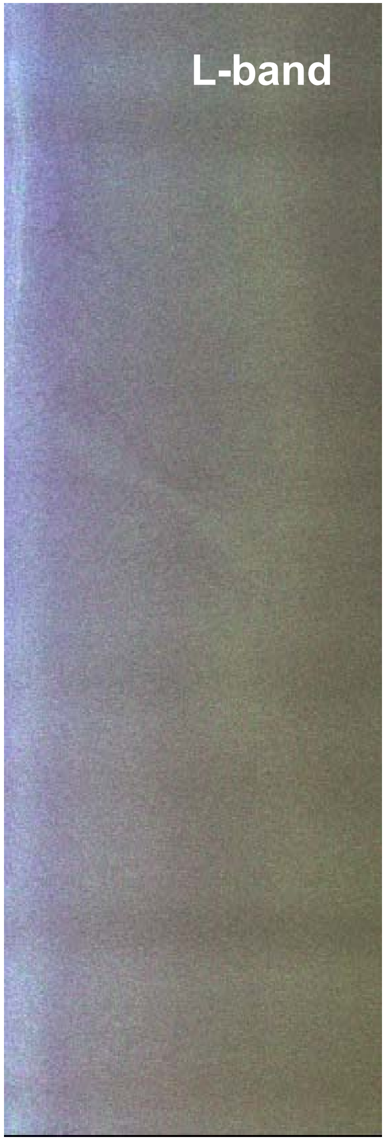


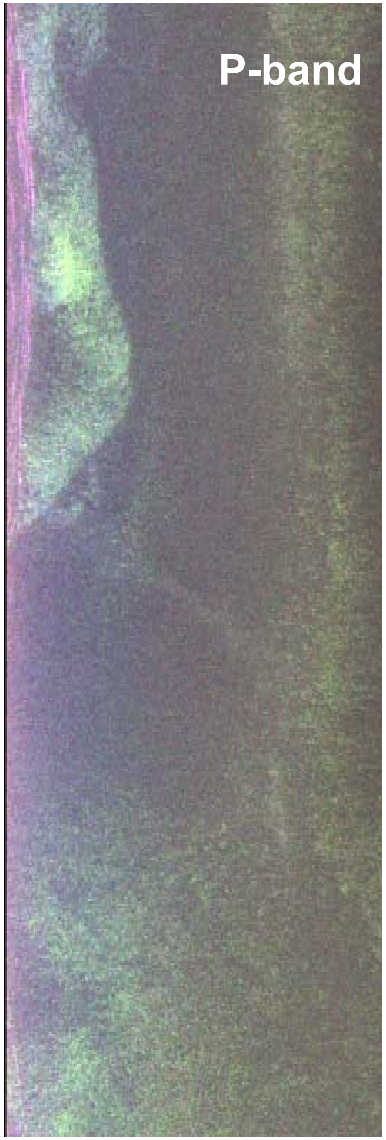
E-SAR parameters

	X	L	P
λ [m]	0.031	0.23	0.86
***f0* [GHz]**	9.60	1.30	0.35
PRF [Hz/chan]	1000	400	500
Chirp BW [MHz]	100		
Slant-rng res. Δrng [m]	1.5		
Slant-rng spac. δrng [m]	1.5		
Az res. SLC Δaz [m]	0.59	0.67	2.00
Az spac.SLC δaz [m]	0.33	0.45	0.72

- *Focus on L-/P-band, Baselines of 5-20 m (L-band), 10-40 m (P-band)*

Experimental Data, Summit, Pauli images





surface
(HH+VV)
double bounce
(HH-VV)
volume
(2HV)

Modelling Ice Extinctions:

Volume/Surface separation with Polarimetric Decomposition

Isolation of the Ice Volume

Goal:

- *In order to estimate extinction of the ice volume, **necessary to separate ground and volume contributions***

Method:

- *Estimate ground-to-volume scattering ratios (**m**) through **decomposition of polarimetric covariance [C] matrix** (second-order statistics)*

$$S = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}$$

$$[C] = \begin{bmatrix} \langle |S_{HH}|^2 \rangle & \sqrt{2}\langle S_{HH} S_{HV}{}^* \rangle & \langle S_{HH} S_{VV}{}^* \rangle \\ \sqrt{2}\langle S_{HH}{}^* S_{HV} \rangle & 2\langle |S_{HV}|^2 \rangle & \sqrt{2}\langle S_{HV} S_{VV}{}^* \rangle \\ \langle S_{HH}{}^* S_{VV} \rangle & \sqrt{2}\langle S_{HV}{}^* S_{VV} \rangle & \langle |S_{VV}|^2 \rangle \end{bmatrix}$$

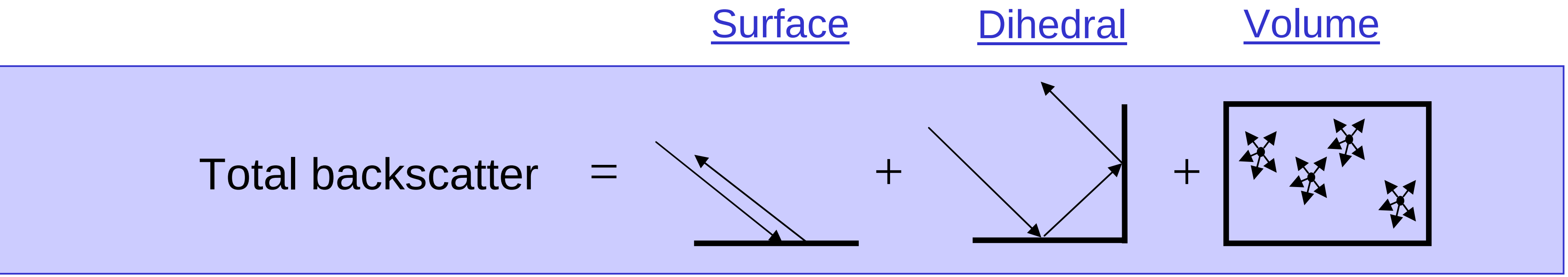
- ***Model elements of the [C] matrix using the Freeman 3-component decomposition** [1]*

[1] Freeman, 1998. *A three-component scattering model for polarimetric SAR*, TGARS, vol.36 no 3.

Polarimetric Decomposition

Freeman-3 Component Decomposition

- *Originally proposed for modelling forested regions with PolSAR*
- *Decomposes **[C]** into **surface**, **dihedral** and **volume** components*
- *Assume: **random volume of dipoles***
- *Adjust volume component for snow-firn transmissivities (T_s, T_P)*



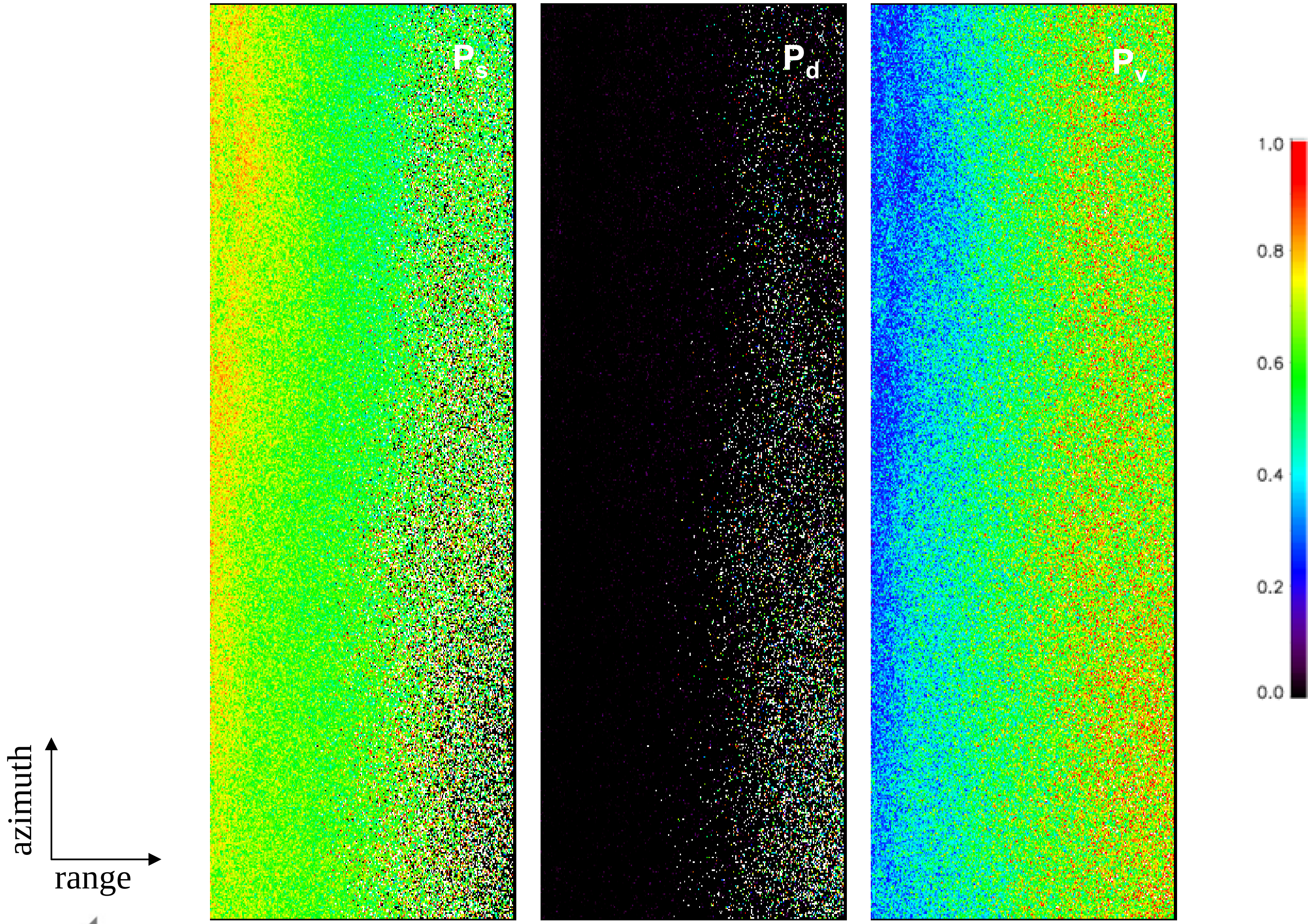
Surface Dihedral Volume

Total backscatter = + +

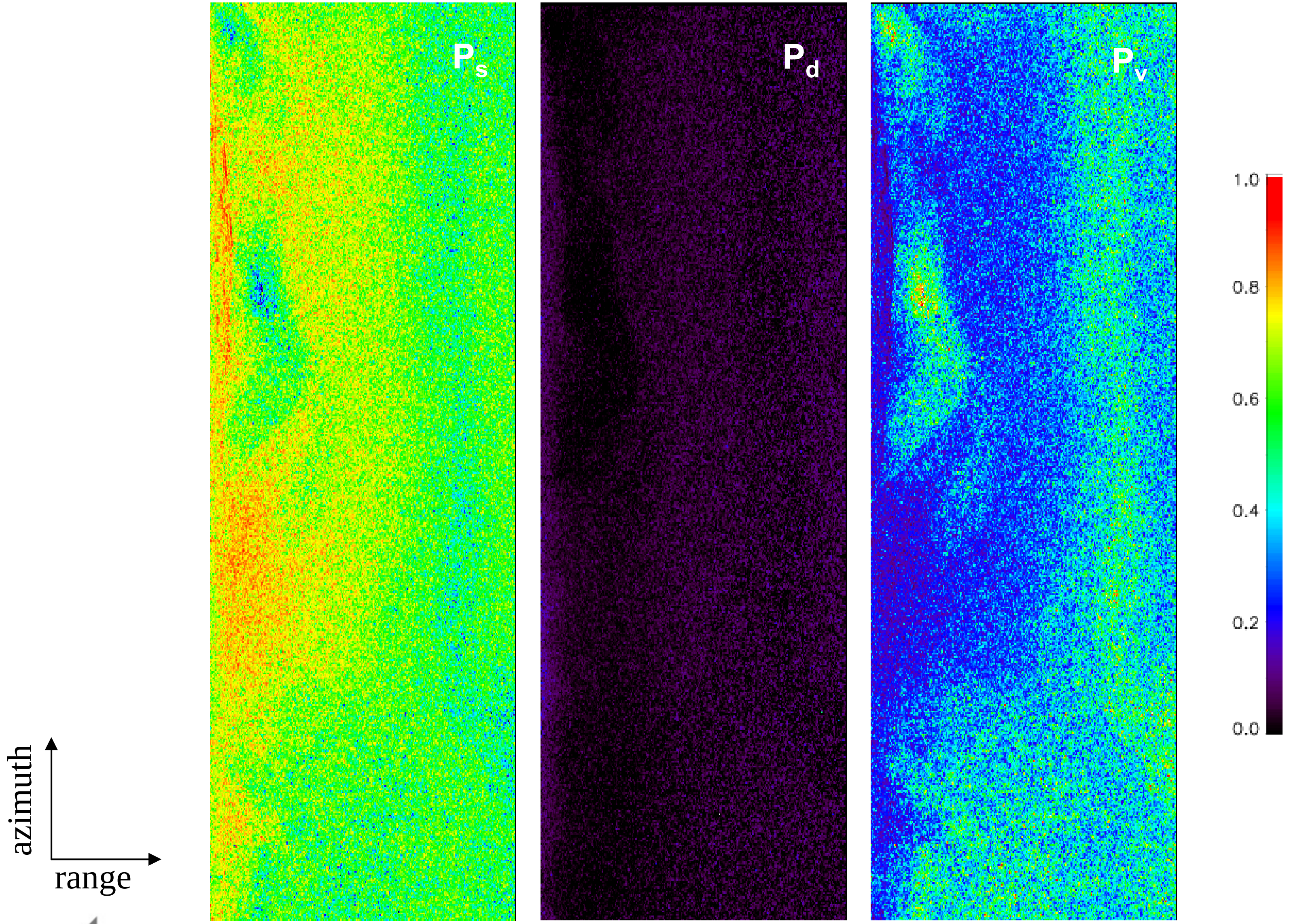
$$[C]=[C_s]+[C_d]+[C_v]$$

$$=f_s\begin{bmatrix}|\beta|^2 & 0 & \beta\\ 0 & 0 & 0\\ \beta^* & 0 & 1\end{bmatrix}+f_d\begin{bmatrix}|\alpha|^2 & 0 & \alpha\\ 0 & 0 & 0\\ \alpha^* & 0 & 1\end{bmatrix}+f_v\begin{bmatrix}T_s^4 & 0 & T_s^2T_P^2\,\frac{1}{3}\\ 0 & T_s^2T_P^2\,\frac{2}{3} & 0\\ T_s^2T_P^2\,\frac{1}{3} & 0 & T_P^4\end{bmatrix}$$

L-band, Freeman-3 decomposition: relative powers



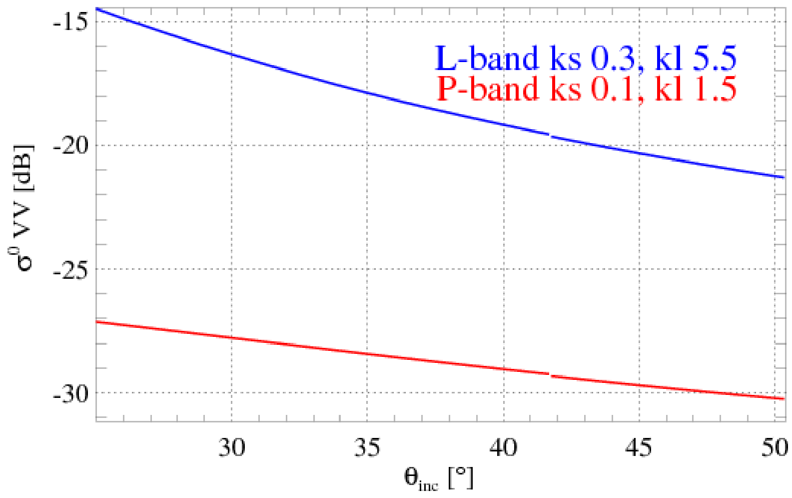
P-band, Freeman-3 decomposition: relative powers



Volume/Surface Separation: Experimental data vs. theory

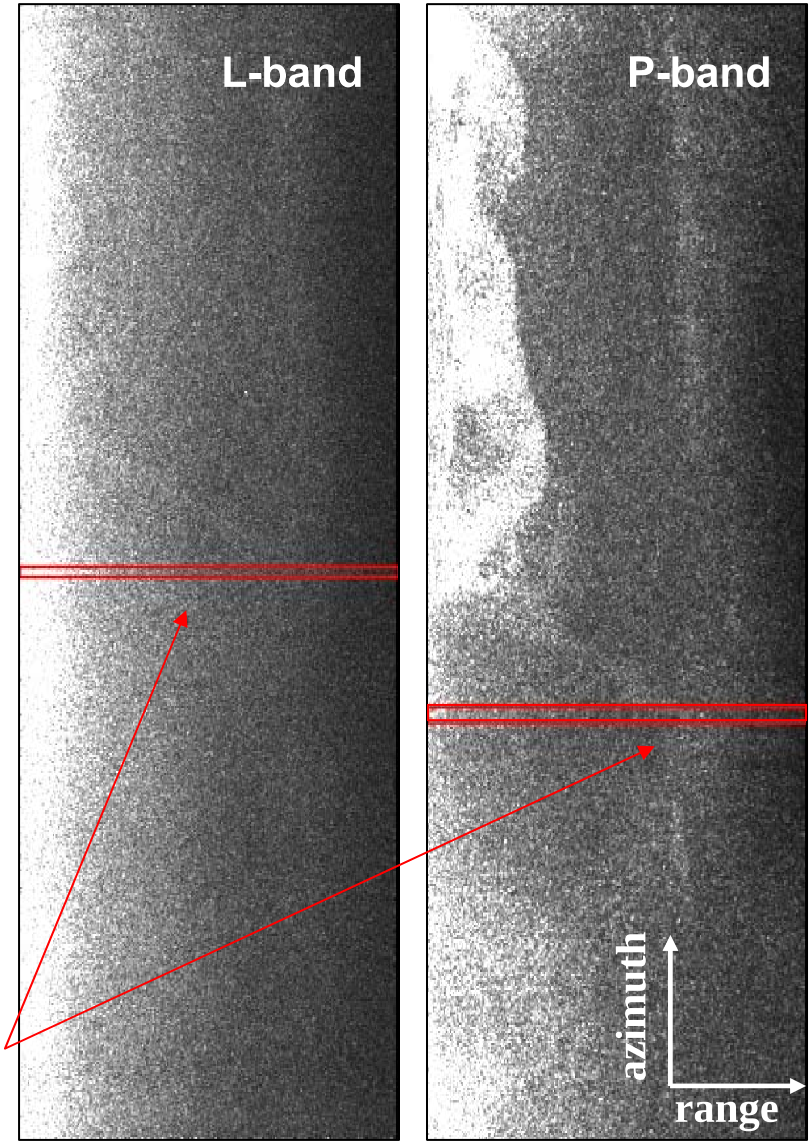
Theory:

- *Expected Bragg surface σ^0 as a function of λ with incidence angle θ*[1] *(s=1cm, ℓ=20 cm)*



- *Assuming a homogeneous volume, expect same trend for ground-to-volume scattering ratios **m***

$$m = \frac{P_S}{P_V} \propto \sigma^{0}{}_{Bragg}$$



Homogeneous subset

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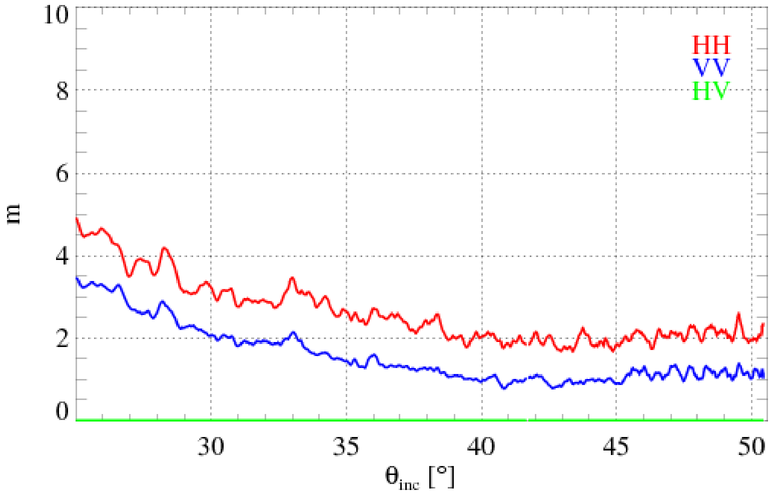
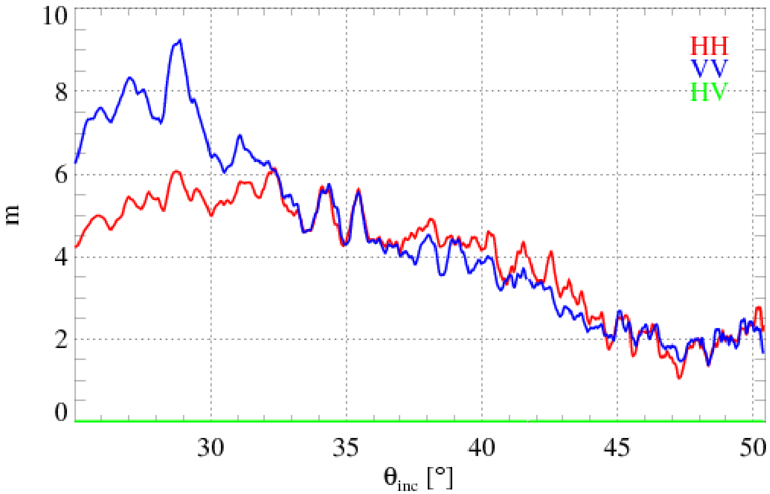
[1] Ulaby, 1982. Microwave Remote Sensing, Active and Passive, Vol. II

Ground-to-volume ratios, Subset

L-band



P-band



$$m_{HH} = \frac{P_{S\ HH}}{P_{V\ HH}} \quad m_{VV} = \frac{P_{S\ VV}}{P_{V\ VV}} \quad m_{HV} = 0$$

- *As expected, general trend of* ***decreasing m with*** *θ at both freqs*
- ***m values higher for P-band than for L-band****: perhaps related to significantly less volume backscatter (relative size scatterers with respect to wavelength)*

Modelling Ice Extinctions:

InSAR Coherence Model

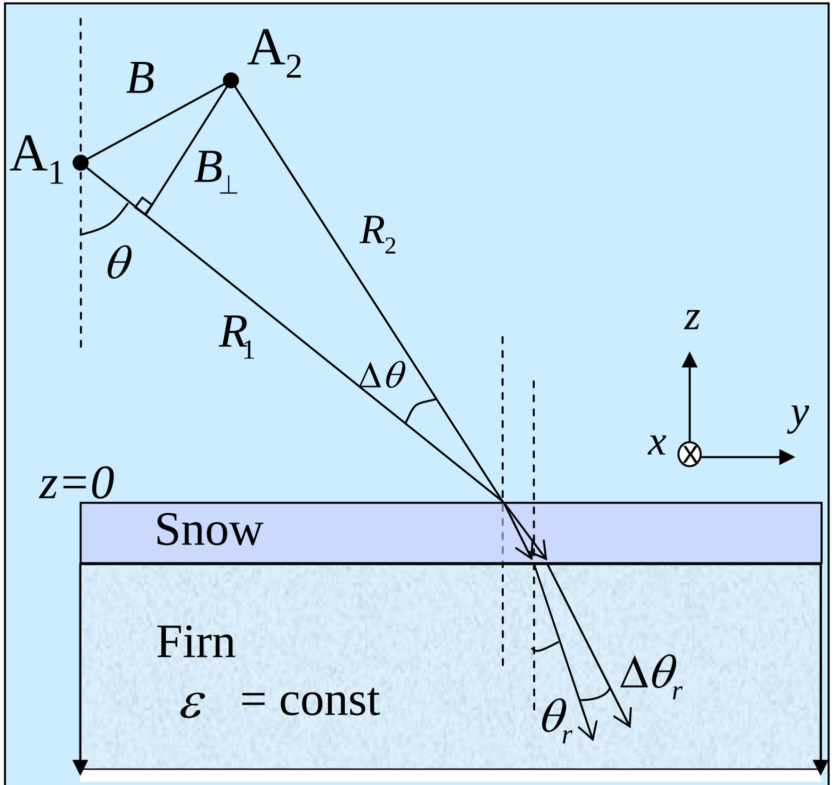
Coherence modelling

- Fundamental InSAR observable **coherence:** γ

$$\gamma = \frac{\langle S_1 S_2^* \rangle}{\sqrt{\langle S_1 S_1^* \rangle \langle S_2 S_2^* \rangle}}$$

- Assuming scattering medium is [1]:
  - ***infinite***, *homogeneously lossy (**constant extinction κ$_e$** [1/m])*
  - *consists of uniformly distributed and uncorrelated scattering centres*

$$\gamma_{vol} = \frac{1}{1 + \dfrac{j \cos\theta_r k_{zvol}}{2\,\boxed{\kappa_e}}} \qquad k_{zvol} = \frac{4\pi\sqrt{\varepsilon}}{\lambda}\,\frac{\Delta\theta_r}{\sin\theta_r}$$



- *ε = dielectric permittivity*

- *Combine with a ground contribution from snow-firn interface **(m = ground-to-volume scattering ratio)** and take absolute value:*

$$\boxed{|\gamma| = \left| \frac{\gamma_{vol} + m}{1 + m} \right|}$$

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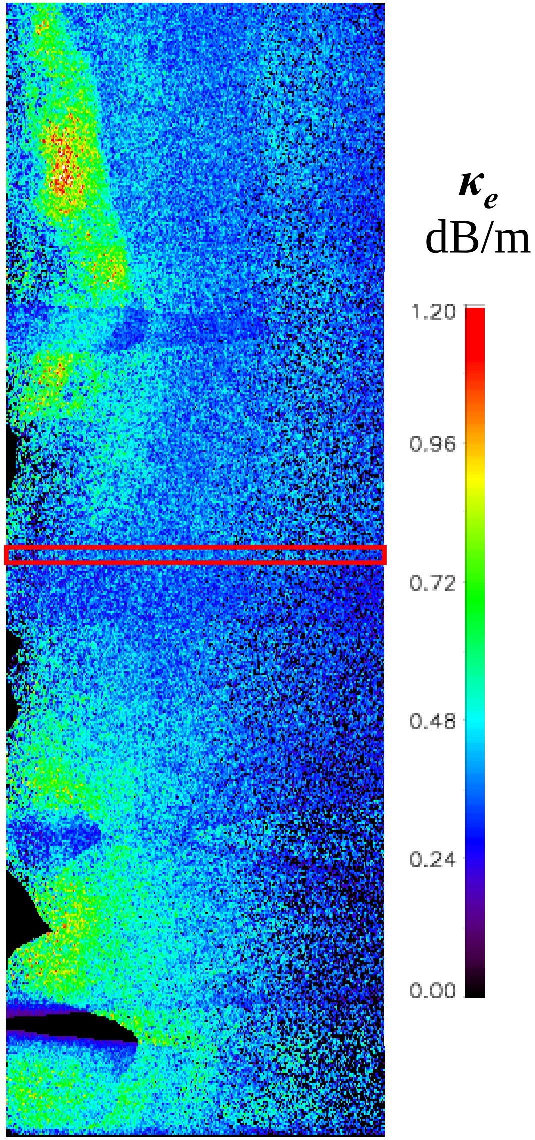
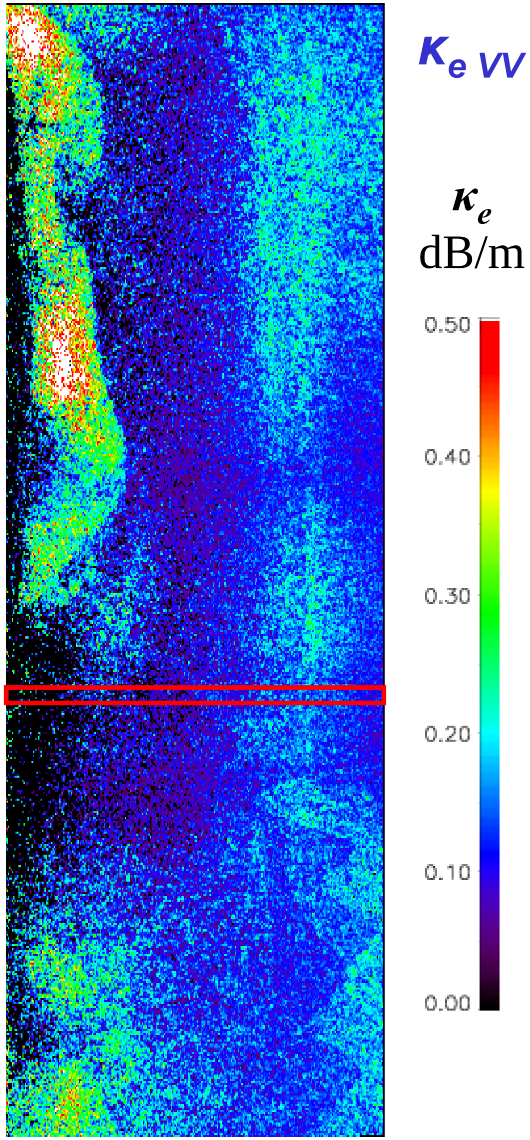
[1] Sharma,2007. *Multi-frequency Pol-InSAR signatures of a subpolar glacier*. Pol-InSAR, 22-26 Jan., Frascati.

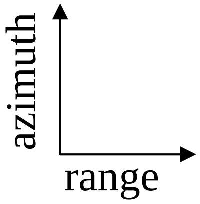
Expt Data, All B, *mask* $(0.01 < k_z < 0.1)$

$\kappa_{e\ VV}$ L-band



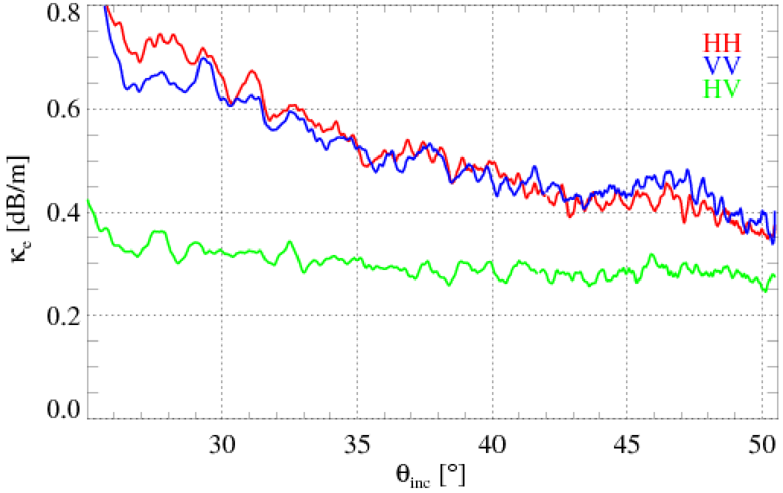
$\kappa_{e\ VV}$ P-band



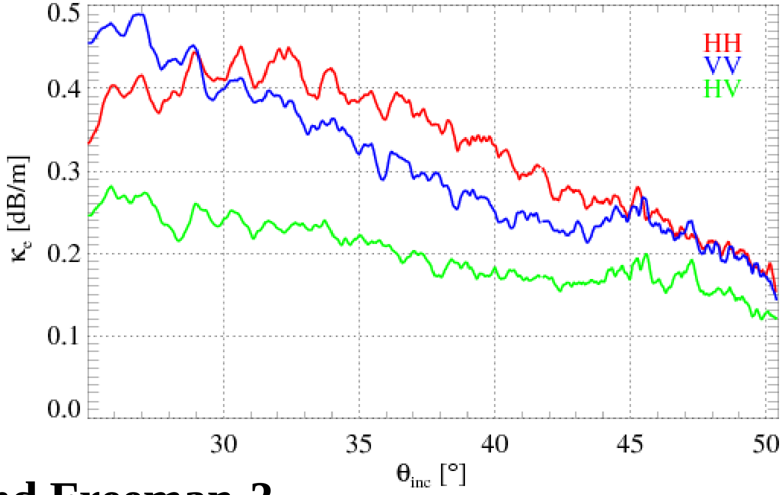


Expt Data: Extinction Inv. Subset, All B

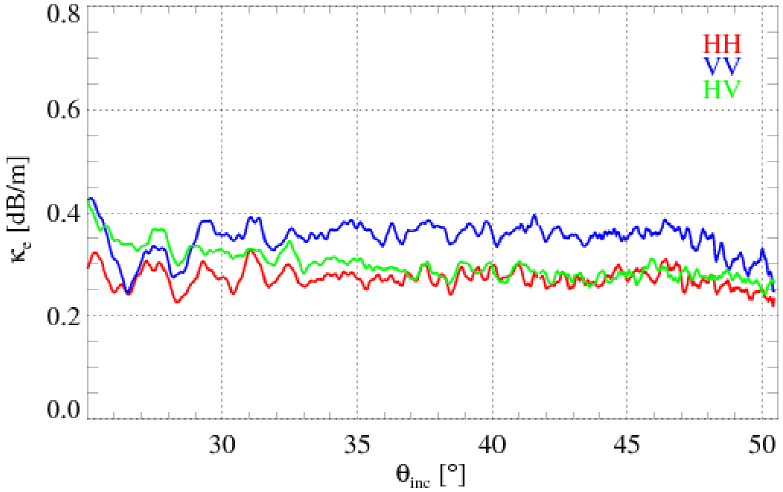
L-band, Volume only (m=0)



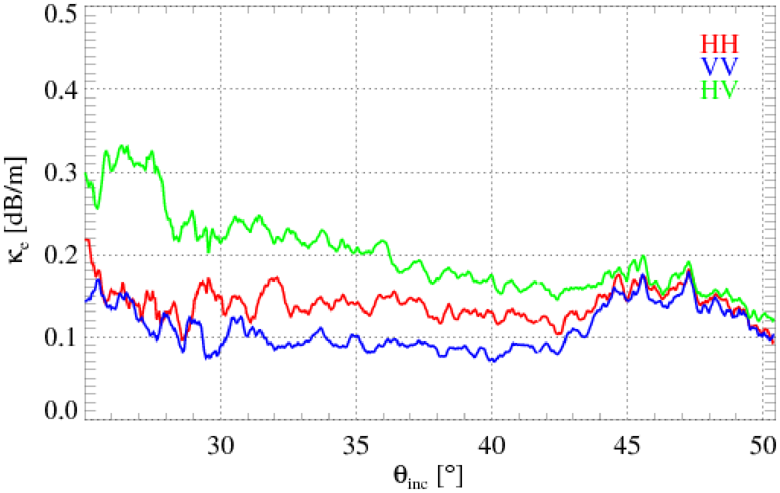
P-band, Volume only (m=0)



L-band, Freeman-3



P-band Freeman-3



Summary

Extinction model

- *Adapted existing PolSAR decomposition/Pol-InSAR coherence model created for vegetation scenarios to a glacier geometry*
- ***Separated ground and volume contributions** using Freeman-3 component decomposition*
- ***Estimated extinctions** using InSAR, combining baselines for a more robust solution*
- ***2-D images of extinctions at L- and P-band**, useful in identifying areal extents of internal ice structure, not visible with optical systems nor 1-D GPR profiles*

Future Work

- *Extend method to polarimetric decompositions modelling an **oriented volume** instead of a random volume*
- *Relate extinctions to geophysical parameters (grain size/density, presence of percolation features such as ice lenses/pipes,etc.)*

Questions ?

Volumetric decorrelation

$$\gamma_{vol} = \frac{\int \sigma_v(z) e^{-jk_{zvol} z} dz}{\int \sigma_v(z) dz}$$

- Assuming scattering medium is:
  - homogeneously lossy (i.e. constant extinction)
  - consists of uniformly distributed and uncorrelated scattering centres

$$\sigma_v(z) = \sigma_v^0 e^{\frac{2z\kappa_e}{\cos\theta_r}}$$

- Where:
  - σ_v^0 = averaged normalized RCS per unit vol. $[m^2/m^3]$
  - κ_e = extinction coeff. [1/m]

    = $\cos(\theta_r) / d_{pen}$
  - $z/\cos(\theta_r)$ = penetration length in the vol. [m]

- Evaluate γ_{vol} for $-\infty < z < 0$

$$\gamma_{vol} = \frac{1}{1 + \frac{j \cos\theta_r k_{zvol}}{2\kappa_e}}$$

Extinction:

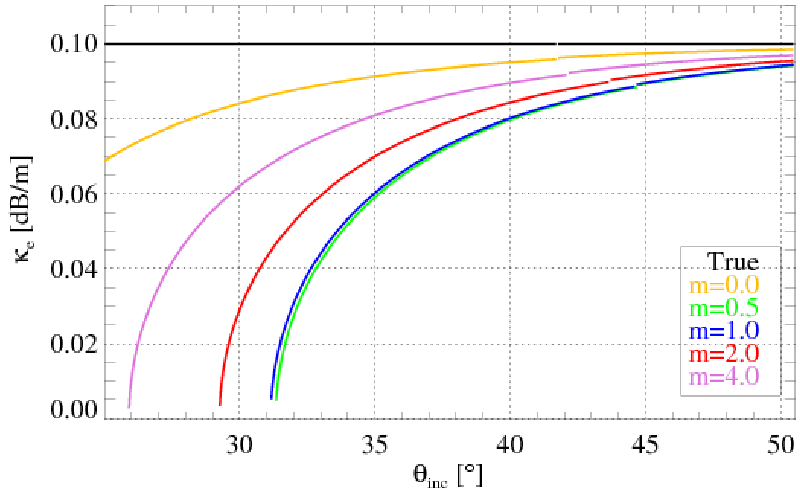
- *Non-linear solution for extinction κ_e*

$$\kappa_e = \frac{\cos\theta_r \left|k_{zvol}\right|}{2(1+m)} \sqrt{\frac{\left|\gamma\right|^2 (1+m)^2 - m^2}{1-\left|\gamma\right|^2}}$$

$$\kappa_e = \underset{\substack{\uparrow \\ \text{Absorption} \\ \text{coeff}}}{\kappa_a} + \underset{\substack{\uparrow \\ \text{Scattering} \\ \text{coeff}}}{\kappa_s}$$

Extinction Inversion: Sensitivity analysis

P-band, B=20 m, κ_e true = 0.1 dB/m, δm=0.1



$$\kappa_e = \frac{\cos\theta_r \left|k_{zvol}\right|}{2(1+m)} \sqrt{\frac{\left|\gamma\right|^2 (1+m)^2 - m^2}{1-\left|\gamma\right|^2}}$$

- ***Plot bias in inverted extinctions due to an error in m*** *(ground-to-vol scattering ratio)*
- *constant m assumed; decreasing m with θ will exaggerate trend even further*
- *non-linear soln for κ_e creates large jumps in soln for*

  $0 < m < 1$

P-band, m=1, κ_e true = 0.1 dB/m, δm=0.1