Characterisation of oriented volumes in glacier ice and extinction inversion with Pol-InSAR

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**Pol-InSAR for ice characterisation/extinction estimation**

**Motivation:**
- Monitor the cryosphere, greater understanding of the properties of glaciers/ice sheets including their densities and internal structure (related to rate of extinction)

**Extinction:**
- Extinction ($\kappa_e$) accounts for the combined effect of absorption and scattering in the medium
- may be expressed in terms of the penetration depth ($d_{pen}$) at which the 1-way backscattered power falls to $e^{-1}$ ($\sim 37\%$)

$$\kappa_e = \kappa_a + \kappa_s = \frac{-\cos \theta_r}{d_{pen}}$$

- Conventionally expressed as a 2-way coefficient in units of dB/m

**Goal:**
- use Pol-InSAR observables (combining polarimetric decomposition and interferometric coherences) to estimate glacier ice extinctions for oriented volumes
Data description

- ICESAR data campaign (joint project between DLR, ESA, AWI)
- conducted in Mar/Apr 2007 over Austfonna ice cap (Summit) and Etonbreen drainage basin, Svalbard, Norway (~ 80°N, 24°E)
- Multibaseline fully-polarimetric L-band (1.3 GHz) and P-band (0.35 GHz) data

Corner reflector at Summit

DLR’s E-SAR (left), AWI’s airborne platform
Experimental Data, Summit, Pauli images

L-band

P-band

surface

(double bounce (HH-VV))

volume

(2HV)

Rng. Swath
~3.5 km,
Az. Swath
~10 km
Modelling Oriented Volumes

& Ice Extinctions
Oriented Volumes

**Background:**

- Comparatively little research has been done to date on characterisation of orientation of distributed volumetric targets using polarimetry.
- Typically, oriented volumes modelled only for particles lying on the plane perpendicular to the radar LOS (line-of-sight).

**Advantages/Limitations:**

- Computation of the modelled covariance \([C]\) matrix relatively straightforward.
- However, following issues should be considered:
  - Modelling is confined to a 2-D plane, whereas scatterers are distributed in 3-D.
  - Results referenced to the plane \(\perp\) to LOS are difficult to relate to physical orientations of scatterers.
  - The reference plane (\(\perp\) to LOS) changes with \(\theta_{inc}\), further complicating interpretation.
Oriented Volume

Line of flight
Simulations: $\omega_0=0^\circ$, fix $\psi=0^\circ$

- Results at $\theta=0^\circ$ equivalent to results from 2-D (plane $\perp$ to LOS) model
- As $\theta_{inc}$ increases, VV and HV differ significantly from values assuming scatterers lie in the plane $\perp$ to LOS
Simulations: $\omega_0 = 0^\circ$, $-90^\circ \leq \psi \leq 90^\circ$

- Can model a wide range of $|HH|^2/|VV|^2$ polarisation ratios, required to reproduce the diversity seen in experimental data
- At $\Delta\omega = 90^\circ$ (random volume), $HH=VV$
**Polarimetric Decomposition**

**Surface and Oriented Volume**
- Assume surface described by Small Perturbation Model (SPM)
- Model oriented volume
  \[
  [C_v](\tau_0, \omega_0, \Delta\omega)
  \]
- Adjust volume component for snow-ice transmissivities (\(Y_s, Y_P\))
- Fix \(\omega_0\) based on observed HH/VV
- Invert observed \([C]\) for \(f_s, f_v, \Delta\omega\)

**Ground-to-volume scattering ratio**
- Define vector \(m\):
  \[
  m_{HH} = \frac{P_{S\ HH}}{P_{V\ HH}} \quad m_{VV} = \frac{P_{S\ VV}}{P_{V\ VV}} \quad m_{HV} = 0
  \]

\[
[C_{total}] = [C_s] + [C_v]
\]

\[
\begin{bmatrix}
1 & 0 & \beta \\
0 & 0 & 0 \\
\beta^* & 0 & |\beta|^2 \\
\end{bmatrix}
= f_s
\begin{bmatrix}
Y_s^2 C_{v11} & 0 & Y_s Y_P C_{v13} \\
0 & Y_s Y_P C_{v22} & 0 \\
Y_s Y_P C_{v13} & 0 & Y_P^2 C_{v33} \\
\end{bmatrix}
\]

\[
C_{v11} = 12\Delta\omega + 8\cos(2\omega_0)\sin(2\Delta\omega) + \cos(4\omega_0)\sin(4\Delta\omega)
\]

\[
C_{v13} = 4\Delta\omega + 2\cos^2(\tau_0)\cos(2\omega_0)\sin(2\Delta\omega) - \cos(4\omega_0)\sin(4\Delta\omega)\sin^2(\tau_0)
\]

\[
C_{v22} = 2C_{v13}
\]

\[
C_{v33} = 12\Delta\omega + 2(5 + \cos(2\tau_0)\cos(2\omega_0)\sin(2\Delta\omega)\sin^2(\tau_0) + \cos(4\omega_0)\sin(4\Delta\omega)\sin^4(\tau_0))
\]
**Coherence modelling**

- Fundamental InSAR observable **coherence**: $\gamma$
- Assuming scattering medium is $^1$:
  - *infinite*, homogeneously lossy (**constant extinction** $\kappa_e [1/m]$)
  - consists of uniformly distributed and uncorrelated scattering centres

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

$k_{\text{zvol}} = \text{vert. wave number in the volume}$

- Combine with a ground contribution from snow-firn interface ($m = \text{ground-to-volume scattering ratio}$):

\[
|\gamma| = \left| \frac{\gamma_{\text{vol}}(\kappa_e) + m}{1 + m} \right|
\]

Results with
Experimental Data
L-band, Oriented Volume Decomposition

Ps

Pv

ω0

Δω

ω0=0° (along)

ω0=90° (across)
**P-band, Oriented Volume Decomposition**

- $P_s$
- $P_v$
- $m_e$
- $\Delta \omega$

$\omega_0 = 0^\circ$ (along)
$\omega_0 = 90^\circ$ (across)
$\kappa_{e\,HH}$, Multibaseline ($\text{mask } 0.01 < k_z < 0.1$)

L-band Subset

P-band Subset

$\kappa_e$ dB/m

$\kappa_e$ dB/m
Summary

Extinction model

- Separated ground and volume contributions using novel polarimetric decomposition for oriented volumes
  - Model has the advantage of a direct relation to the physical orientations of scatterers in an Earth-based reference system
  - Allows for a 3-D distribution of volume particles
- Estimated extinctions using a Pol-InSAR coherence model, combining baselines for a more robust solution
- 2-D images of extinctions at L- and P-band, useful in identifying regions of internal ice structure, not visible with optical systems nor 1-D GPR profiles

Recommendations

- Cross-track passes perpendicular to the glacier centre line should be flown for additional insight into possible orientation effects of the ice scattering bodies
- GPR data collected nearly simultaneously to the SAR data and at the same centre frequencies recommended for a meaningful comparison with inverted extinctions
- Time series of P-band data to track changes in ice structure, which could reveal changes in long-term accumulation, wind, and melt patterns
Thank you