Snow property extraction based on polarimetry and differential SAR interferometry

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TerraSAR-X and TanDEM-X
A fantastic playground with many options.

- X-Band: $\nu = 9.65$ GHz, $\lambda = 3$ cm, Resolution: 3 m, Repeat cycle: 11 days
- Monostatic **multi-pass** Interferometry: $\Delta t = 11$ days
- Bistatic **single-pass** Interferometry: $\Delta t = 0$
Why Radar techniques for Snow?

• Snow is a thin volume layer which is mostly transparent for microwave (T \ll 0°C).
• High frequency required to get interaction and to avoid total penetration: 5 - 20 GHz.

• How can we characterize snow by means of the complex interferometric coherence?

\[ \hat{\gamma} = \gamma \cdot e^{i\varphi} = \frac{\langle S_1 \cdot S_2^* \rangle_{\text{ens.}}}{\sqrt{\langle |S_1|^2 \rangle \langle |S_2|^2 \rangle}} \]

• What causes polarimetric phase differences and temporal decorrelation?

• Under which conditions can we characterize snow?

➢ Snow fall, melting, temperature change and wind drift cause high temporal variations!

• Which parameters do we get?
  – Snow / no snow?
  – Snow depth?
  – Snow water equivalent?
  – Water content?
  – Stratigraphy?
  – Soil information?
Photos from NOSREX-III ground campaign, Courtesy to ARC FMI
Sodankylæ 2012: Repeat pass coherence (Δt = 11 d)

Meadows and frozen wetland:
- low coherence $\rightarrow$ snowing or melting.
- Further interpretation (RVoG, etc.) difficult due to $\gamma_{\text{temp}}$.

Accumulating snow...

No snow left, +10°C
Polarimetric Phase Difference (PPD)

\[ \hat{\gamma} = \gamma \cdot e^{i\varphi} = \frac{\langle S_1 S_2^* \rangle_{\text{ens.}}}{\sqrt{\langle |S_1|^2 \rangle \langle |S_2|^2 \rangle}} \quad \rightarrow \quad \phi_c = \phi_{VV} - \phi_{HH} \quad \text{(co-polar)} \]

What about this: Is there any signature of snow? Snow as a layered structure?

\[ \phi_c = ??? \]
Snow is structures as layers. Microwaves reflections at layers are confirmed by the Swiss Institute for Snow and Avalanche Research (SLF).

\[ \phi_c = ??? \]

60 cm

Ice layers in a block of wind-compressed snow
co-polar PPD over the winter

TDX acquisitions, SnowSAR path-measurements (Snow depth) and IOA data (Snow depth)

Ground campaigns:

TSX / TDX dual pol data (HH, VV): $\phi_c = \phi_{VV} - \phi_{HH}$ (co-polar)
Ground truth vs. PPD $\phi_c$

1) Measure snow depth in the field.
2) Classification: no Forest / Forest.
3) Calculate PPD: $\phi_c = \phi_{VV} - \phi_{HH}$
4) Compare PPD with snow depth.
5) Plot correlations for acquisitions.
Acquisition date:
03 Jan 2012, orbit 32

Ground data takes:
9th + 10th Jan, 2012

Correlation between snow height and Polarimetric phase difference $\phi_{VV} - \phi_{HH}$ for forested and not forested areas.
Correlation between snow height and Polarimetric phase difference $\phi_{VV} - \phi_{HH}$ for forested and not forested areas.
Correlation between snow depth and PPD $\phi_{\text{VV}} - \phi_{\text{HH}}$.

Acquisition date:
09 Jan 2012, orbit 130

$\text{aoi} = 32.7^\circ$

Ground data takes:
9th + 10th Jan, 2012
Acquisition date:
14 Jan 2012, orbit 39

\( \text{aoi} = 39.7^\circ \)

Ground data takes:
9th + 10th Jan, 2012

Correlation between snow depth and PPD \( \phi_{VV} - \phi_{HH} \).
Correlation between snow depth and PPD $\phi_{VV} - \phi_{HH}$.

Acquisition date: **14 Jan 2012**, orbit 32

**aoi** = 41.5°

Ground data takes: 9th + 10th Jan, 2012
Correlation between snow depth and PPD $\phi_{VV} - \phi_{HH}$.

Acquisition date: 
**25 Jan 2012**, orbit 32

$aoi = 41.5^\circ$

Ground data takes: 
**23$^{th}$ + 24$^{th}$ Jan, 2012**
Acquisition date: 
**16 Feb 2012**, orbit 39

$\text{aoi} = 39.7^\circ$

Ground data takes: 
7th - 9th Feb, 2012 
22nd - 26th Feb, 2012 
(heavy snowfall between campaign and acquisition)

Correlation between snow depth and PPD $\phi_{VV} - \phi_{HH}$.

- Extrem increase of temperature.
- +20 cm of fresh humid snow.  
  -> no layers visible. (small penetration.)
Correlation between snow depth and PPD $\phi_{VV} - \phi_{HH}$.

- frequent humid snow fall, 0°C.
- only a few layers visible.
- penetration only in top layer.

Acquisition date: 
**26 March 2012**, orbit 130

aoi = 32.7°

Ground data takes: 
**23rd March, 2012**
TDX acquisitions, SnowSAR path-measurements (Snow depth) and IOA data (Snow depth)

Snow depth (cm)

Temperature (°C)

- orbit 39: 39.7° ASC
- orbit 32: 41.5° DESC
- orbit 130: 32.7° ASC
- SnowSAR SWE & Depth

Nov | Dec | Jan | Feb | Mar | Apr | May

2011 | 2012

18
Why is Snow depth proportional to $(\phi_{VV} - \phi_{HH})$?

Suggestions:
1. Propagation speed differs for HH and VV.
2. Different penetration depth for HH and VV.
3. Linear combination of phase-jumps at different layers.

#2 is supported by different Fresnel-coefficients at snow layers for polarizations.

Summ of all scattering components has a non-zero phase difference: $\phi_{VV} - \phi_{HH}$. 
Conclusion

Repeat pass InSAR:

Snowfall and melting events cause strong decorrelation of repeat pass Interferometric coherence.

Polarimetry:

• Clear evidence for correlation between PPD $\phi_{VV} - \phi_{HH}$ and snow over open area. (Volume scattering in forests destroys a clear phase signal).

• Model is under development and ideas area welcome!

Special thanks to FMI, Enveo, Gamma Remote Sensing, EC, NASA JPL, WSL-SLF for ground campaigns. **Distributed measurements** make incomparably better validations possible than fixed stations.
Spatial comparison of snow depth along transect with PPD.

Co-polar phase difference $\phi_c$ follows the snow depth along the transect.
Change detection by coherence decay:

- Decay time of coherence: $t_{1/2} = 4.2$ days.
- Repeat-times of *a few days* are favourable.

Strong temporal decorrelation in X-band caused by Snowfall, melting or strong wind drift.

For each point the coherences of at least 8 scenes of the same testsite were averaged.
Decay of coherence for X-band TSX data

For each point 8 or more scenes of the same testsite were used and the coherences values calculated from each scene were averaged. The red line is a fitted exponential.

Decay time of Coherence: $t_{1/2} = 4.2$ days

-> Very valuable if repeat-times of a few days are possible.
Differential-InSAR: Local phase patterns due to freezing?

Local phase pattern correlate with freezing structures on the ground.
Up/down lift by freezing/thawing cycles?
InSAR: Random Volume over Ground Model

\[ \tilde{\gamma}_{\text{Vol}}(f(z)) = e^{i\kappa z_0} \frac{\int_0^{h_i} f(z) \cdot e^{i\kappa z} dz}{\int_0^{h_o} f(z) dz} \]

Expected volume coherence.

\( f(z) \): Vertical reflectivity function = “backscattered radiation per depth volume”.

Expected coherence for homogeneous snow layer over ground:

- Good sensitivity to snow volume can be archived for \( \kappa_z = 2...7 \text{ m}^{-1} \)
- corresponding to baselines of

  \[ b_{\perp} = 5...8 \text{ km} \rightarrow \text{terraSAR-X (h = 514 km)} \]
  \[ b_{\perp} = 10...30 \text{ m} \rightarrow \text{airplane (h}_{\text{AGL}}=2.5 \text{ km}) \]
  \[ b_{\perp} = 15...25 \text{ m} \rightarrow \text{airplane (h}_{\text{AGL}}=1.5 \text{ km}) \]

\[ B_{\perp} = \Delta \theta \cdot R_0 = \sin \theta \cdot \frac{\kappa_z \lambda}{4\pi} \cdot R_0 \]
Baseline overview for TanDEM-X

Perpendicular baselines (m) between TanDEM-X and TerraSAR-X for Churchill datasets.

Date of acquisition (dd/mm/yyyy).
DEM generation with TDX

-> gap filling algorithm
Generation of a DEM
TanDEM-X Pol-InSAR: DEM(VV) vs. DEM(HH)

Interferometric phase difference (HH)-(VV)
Polarimetry: Phase differences VV-HH

Values $\gamma < 0.4$ are masked and set to the average phase difference.

Is there a relation between $\phi_{VV} - \phi_{HH}$ and snow?

Validation not possible due to lack of ground data!

Polarization: Phase differences (50x30 px smoothing window).
Brightness: Absolute value of coherence (7x9 px window).

TDX acquisitions and snow depth

Oct  | Nov  | Dec  | Jan
--- | --- | --- | ---
2011 | 2012

0  | 5  | 10  | 15  | 20  | 25  | 30  | 35  | 40  | 45  | 50  | 55  | 60  | 65  | 70  | 75  | 80  | 85  | 90  | 95  | 100

orb 29: 33.7° ASC
"man station" snow depth

Temperature ($^\circ$C)

-20  | -15  | -10  | -5  | 0  | 5  | 10  | 15  | 20
TanDEM-X: Double D-InSAR

Phase difference $HH(t+11) - HH(t)$

Differential complex coherence $\gamma_{MM}(t+11) \ast \bar{\gamma}_{VH}(tt)$
- Abs_coherence
- complex interferogram.

( - interferogram)