Snow Depth Extraction based on Polarimetric Phase Differences

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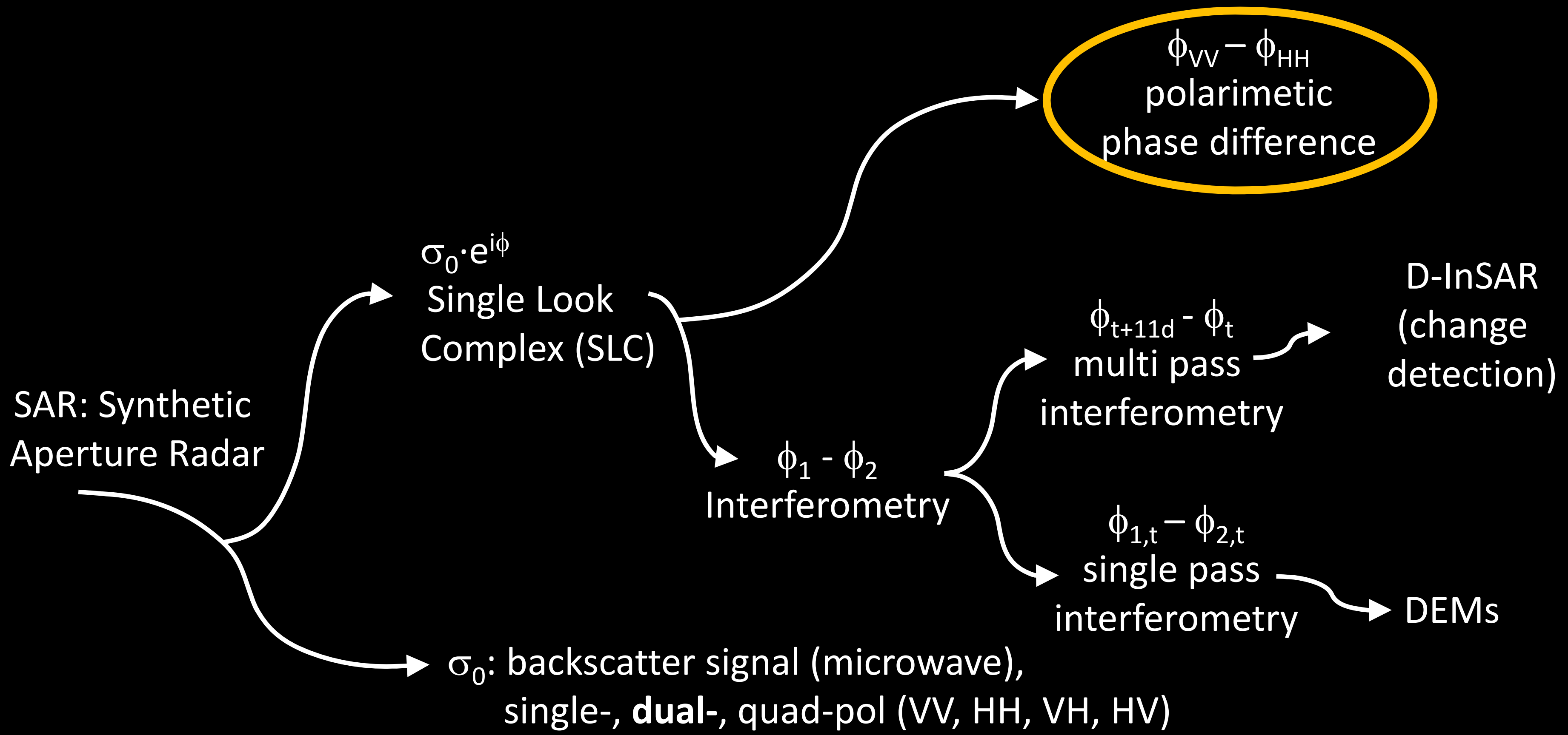
TerraSAR-X and TanDEM-X

A fantastic playground with many options.



- X-Band: ν = 9.65 GHz, λ = 3 cm, Resolution: 3 m, Repeat cycle: 11 days
- Monostatic **multi-pass** Interferometry: Δt = 11 days
- Bistatic **single-pass** Interferometry: Δt = 0

Why Radar techniques for Snow?

- Optical methods sample only the snow surface.
- Microwaves penetrate into the snow.
- High frequency are required to avoid total penetration : 5 - 50 GHz (limited by atmosphere).

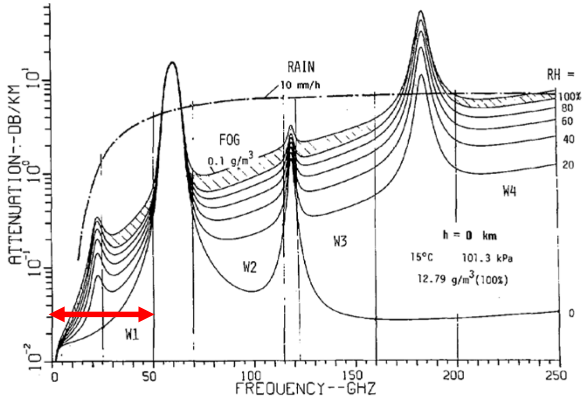
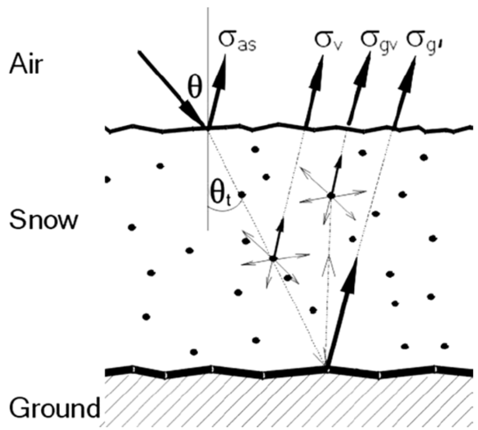


Fig. 1. Specific attenuation at sea level over the frequency range 1–250 GHz for various relative humidities (0 to 100 percent), including fog (0.1 g/m³) and rain (R = 10 mm/h).

Liebe 1983, *IEEE Trans. Antennas Propag.*

Typical interactions of microwave with snow :

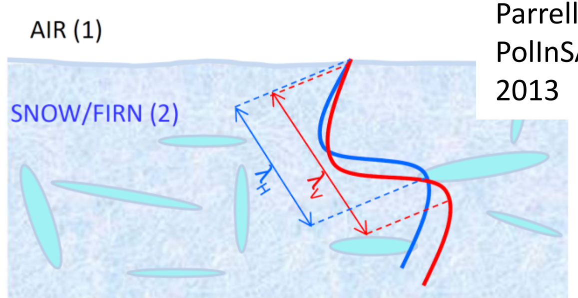
- Total penetration (T ≪ 0°C, ν ≪ 10 GHz).
- Total reflection at the surface (T ≥ 0°C).
- Volume scattering (T < 0°C, ν > 5 GHz, depth > 2 m).



Rott et al, 2010, *IEEE Proc.*

Interferometric applications for snow and ice:

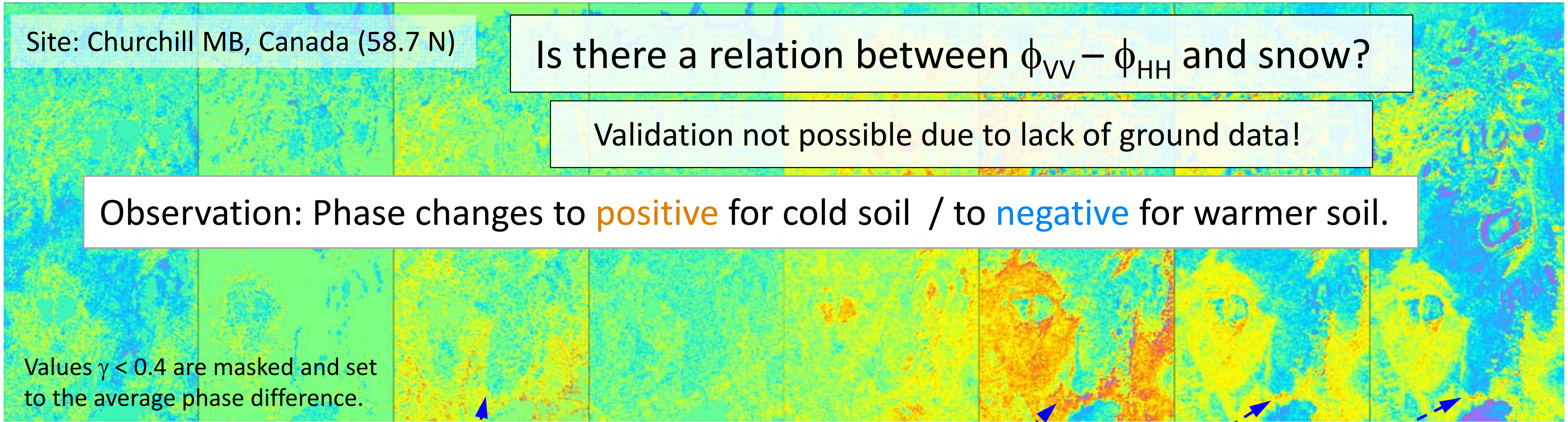
- Multipass coherence decay: Snowfall / Melting.
- Single pass: Comparing DEMs (deep firn, glacier mass balance).
- D-InSAR questionable: deformation of freezing ground, additional scatterers, atmosphere.
- Phase differences between different polarizations. *(this talk).*



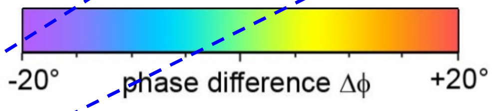
Parrella, PolInSAR 2013

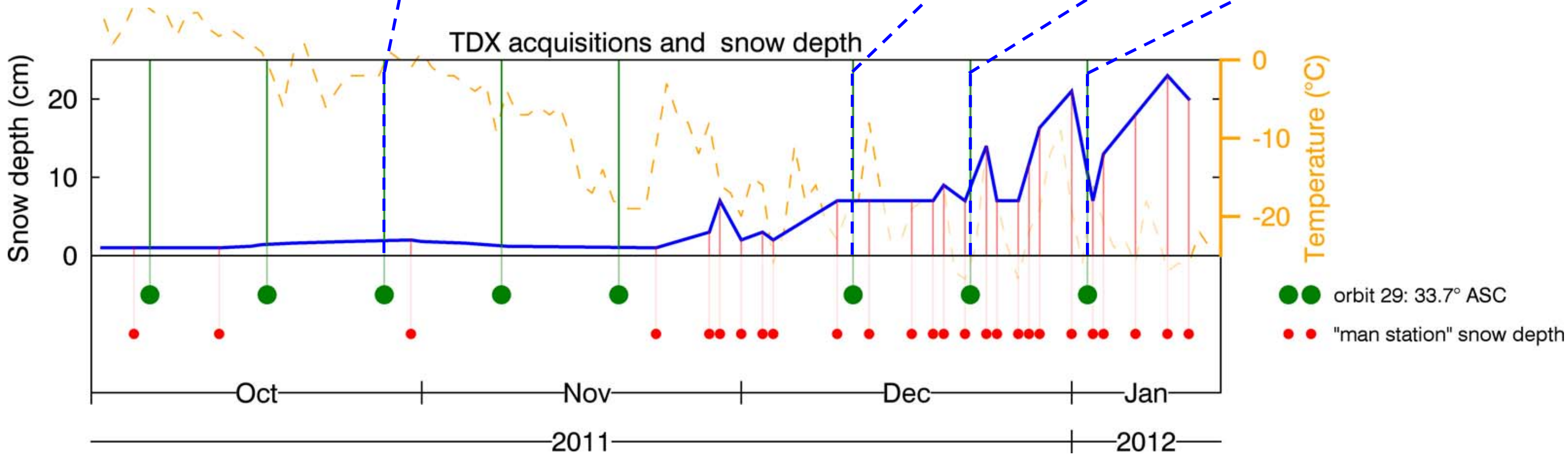
Time series of Polarimetric Phase differences $\phi_{VV}-\phi_{HH}$

06th Oct. 2011 | 17th Oct. | 28th Oct. | 08th Nov. | 19th, Nov. | 11th Dec. | 22nd Dec. | 02nd Jan. 2012

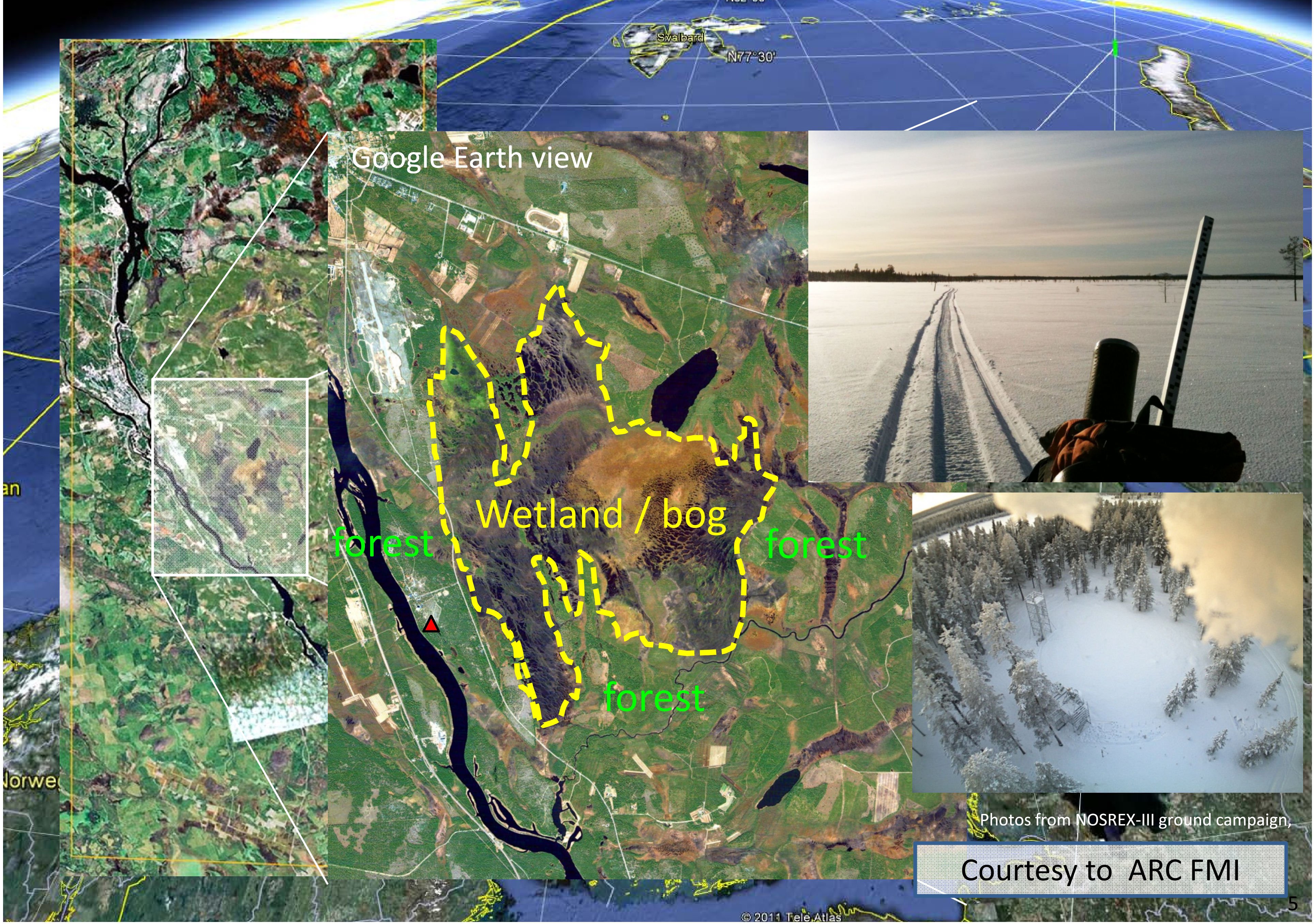


Color: Polarimetric phase differences between HH and VV (50 x 30 px smoothing window).

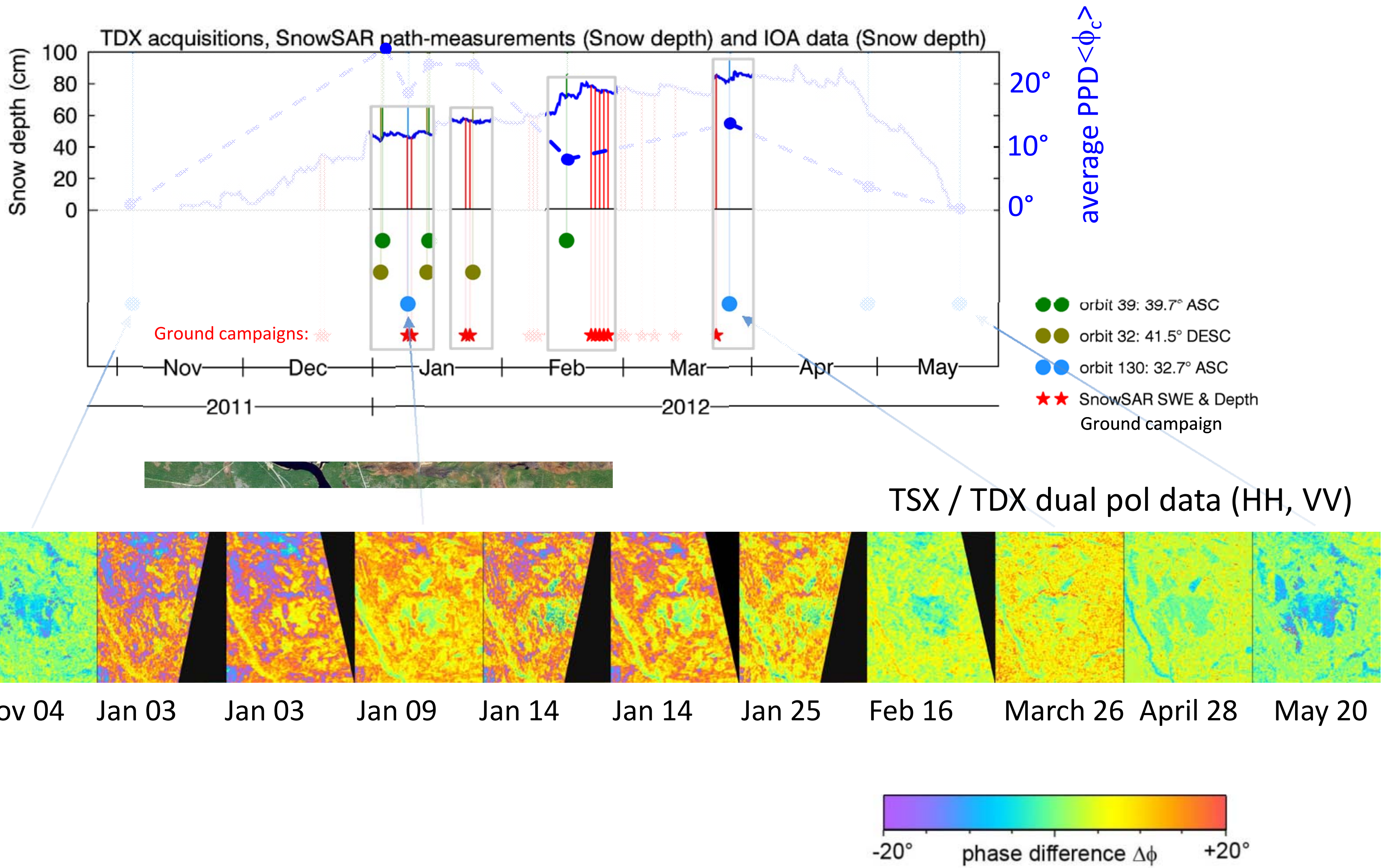




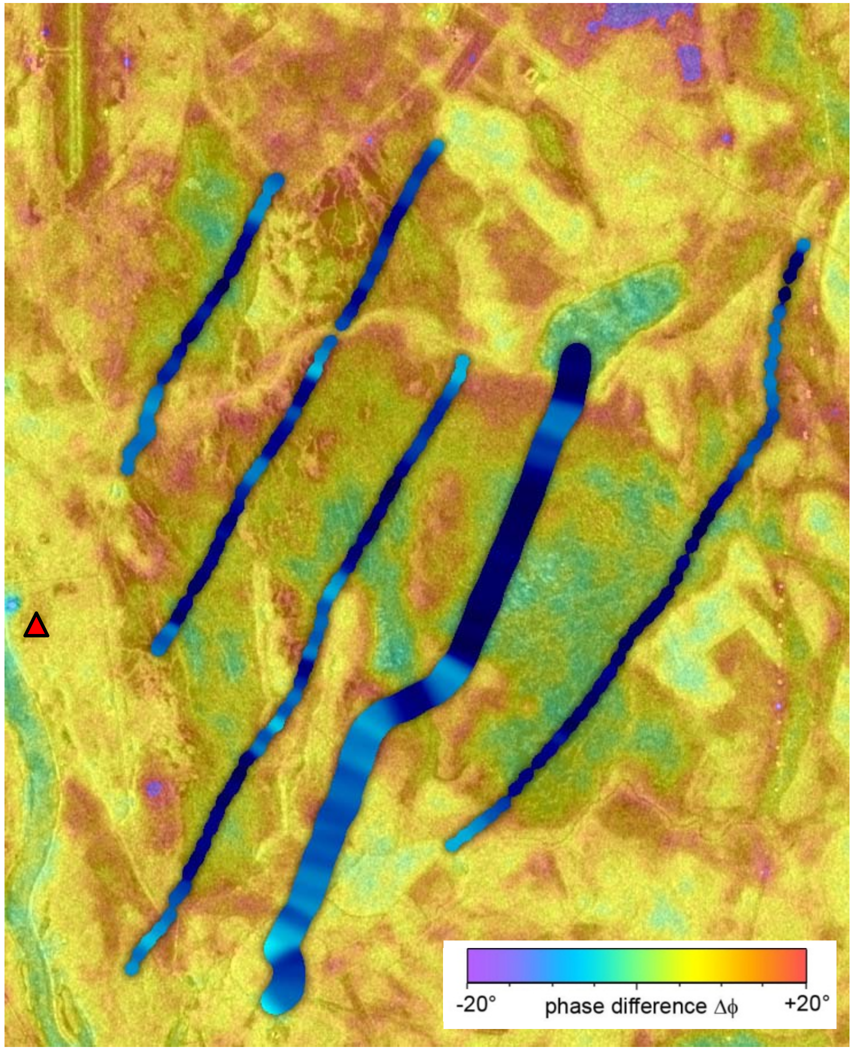
Sodankylae


N82°30'
Svalbard
N77°30'
Google Earth view
Wetland / bog
forest
forest
forest
Photos from NOSREX-III ground campaign,
Courtesy to ARC FMI
© 2011 Tele Atlas

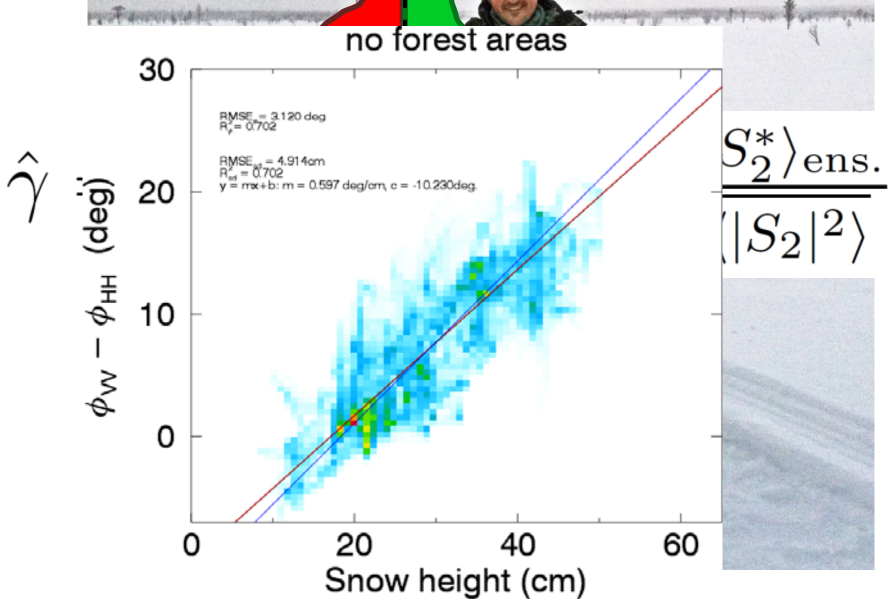
Co-polar PPD ($\phi_{VV} - \phi_{HH}$) over the winter

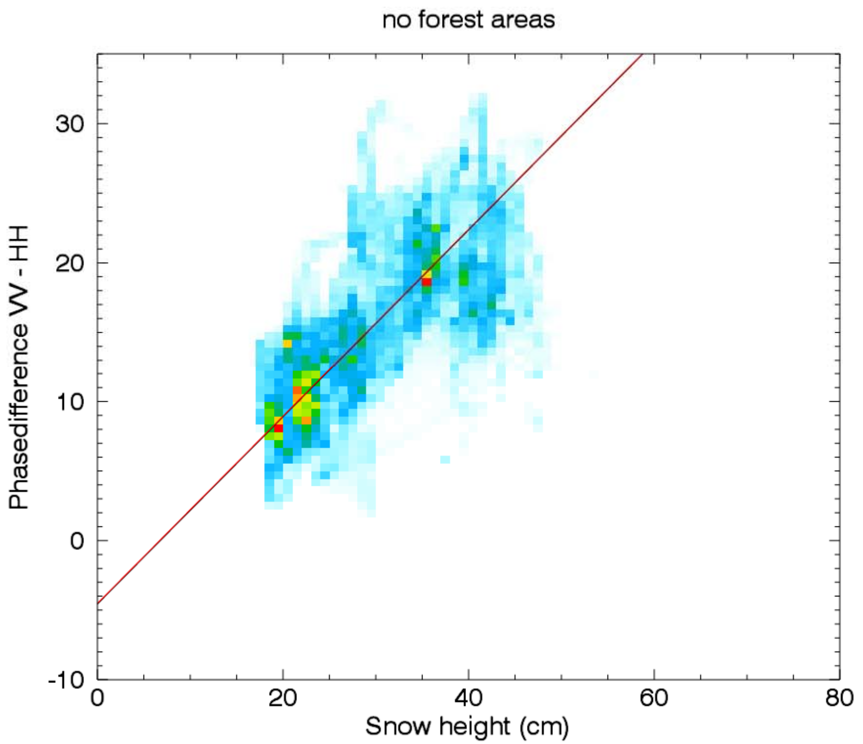


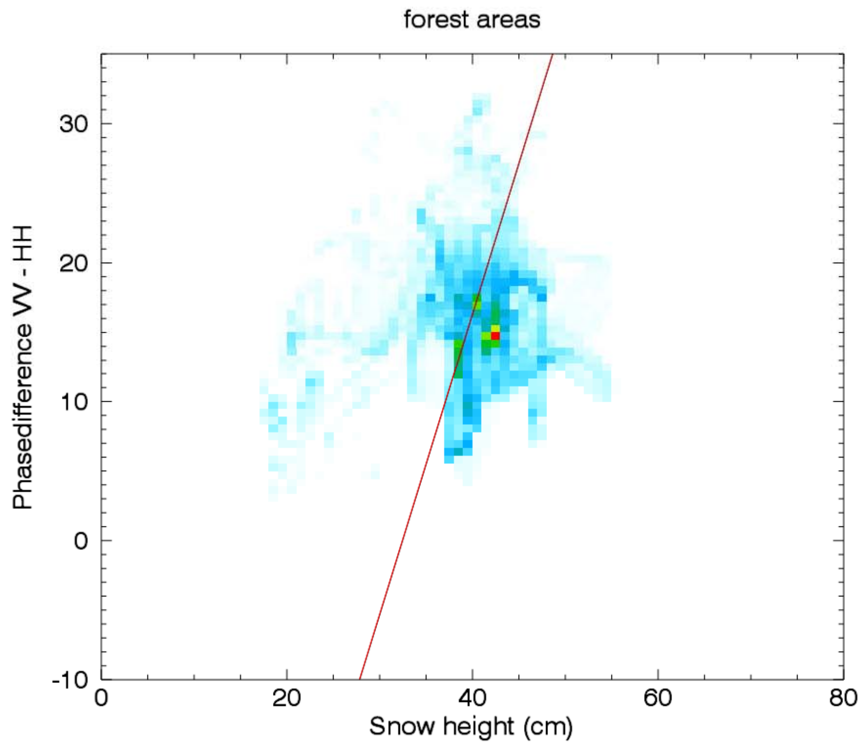
Ground measurement vs. PPD ϕ_c



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



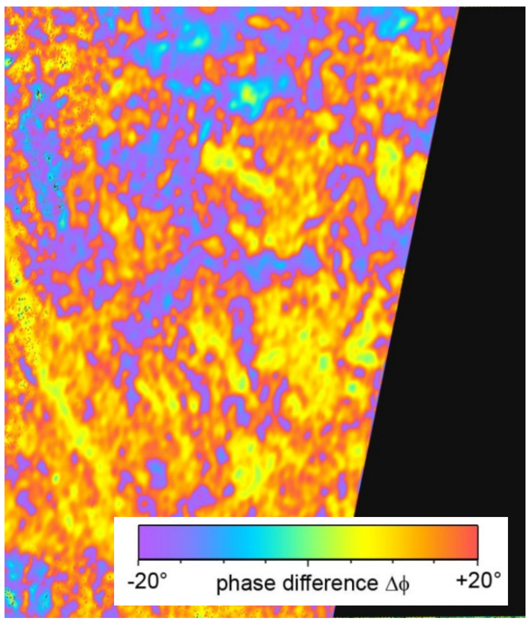


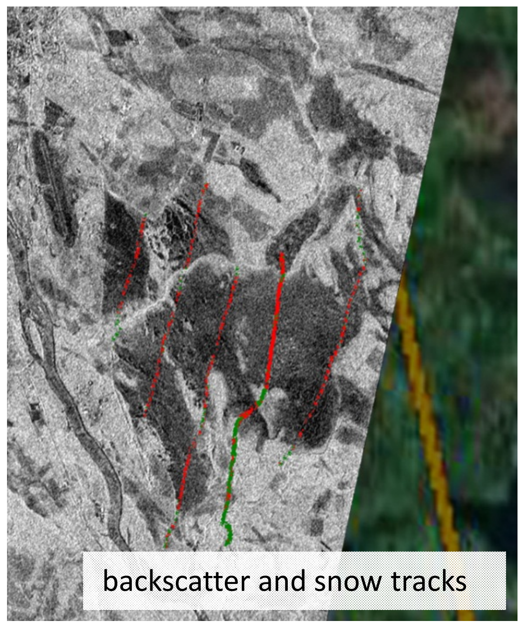


Acquisition date:
03 Jan 2012, orbit 32

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.



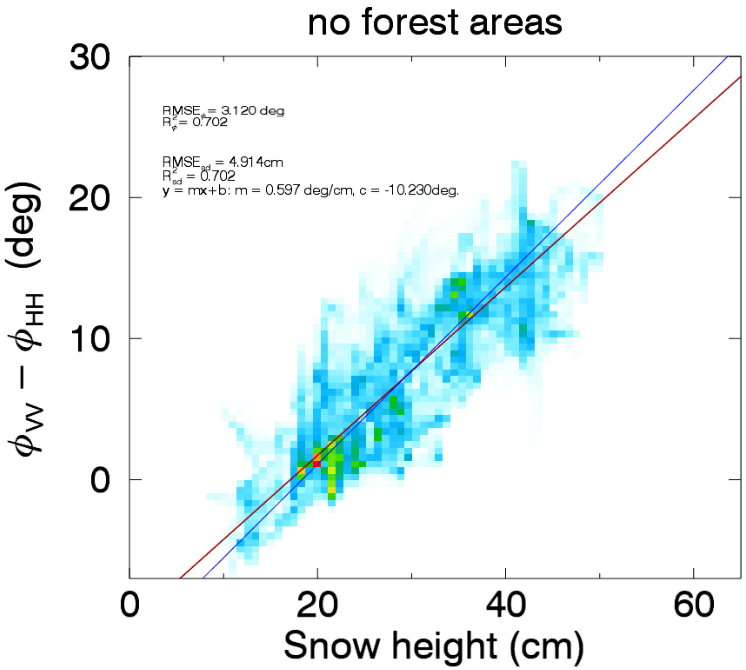


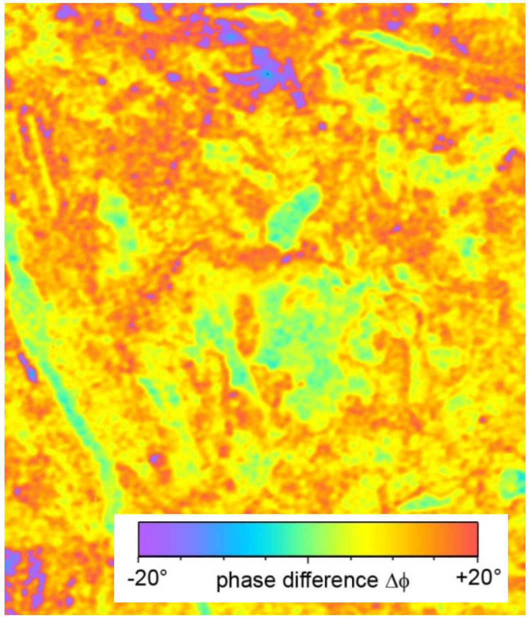
Evolution of ϕ_{VV} - ϕ_{HH}

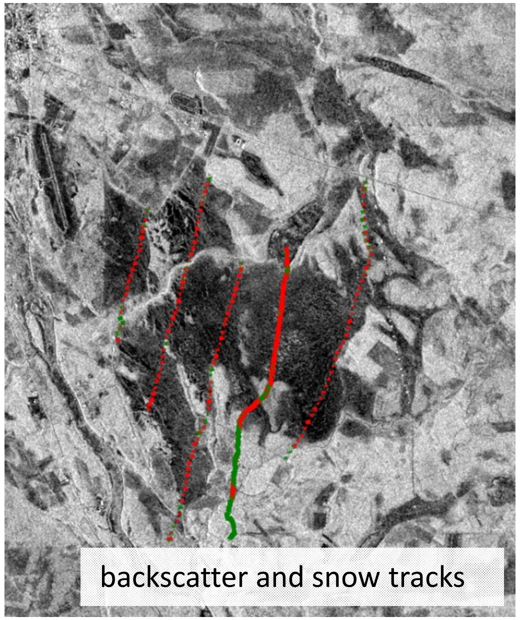
Acquisition date: **09 Jan 2012**
Ground data: **09 & 10 Jan, 2012**

Incidence angle: 32.7°
(orbit 130)

Slope: **6.0** deg / 10 cm
R-square: 0.70







Evolution of ϕ_{VV} - ϕ_{HH}

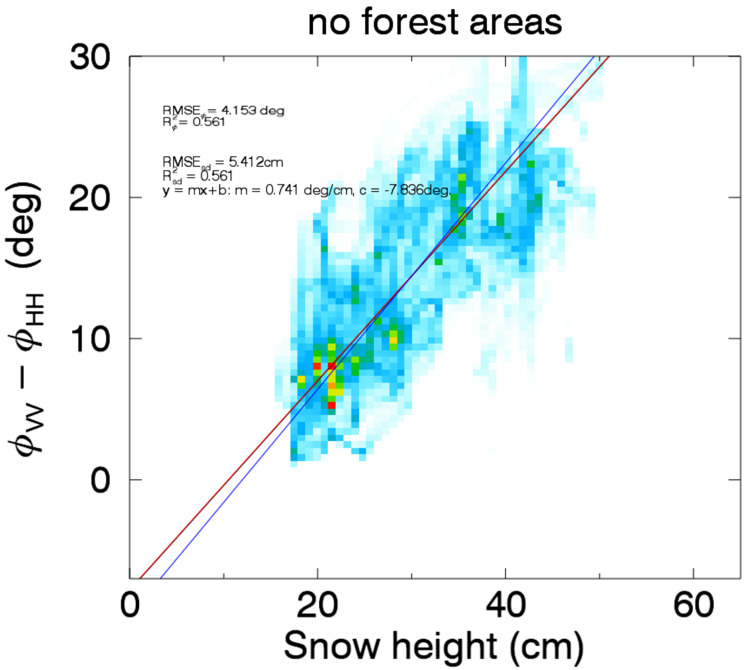
Acquisition date: **03 Jan 2012**
Ground data: **09 & 10 Jan, 2012**

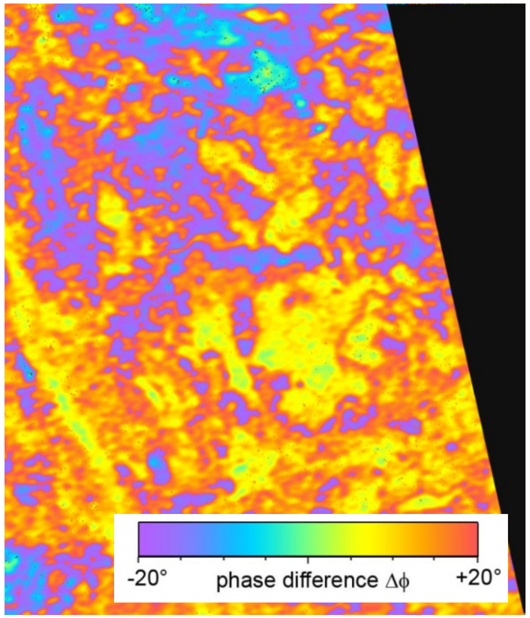
Incidence angle: 39.7°
(orbit 39)

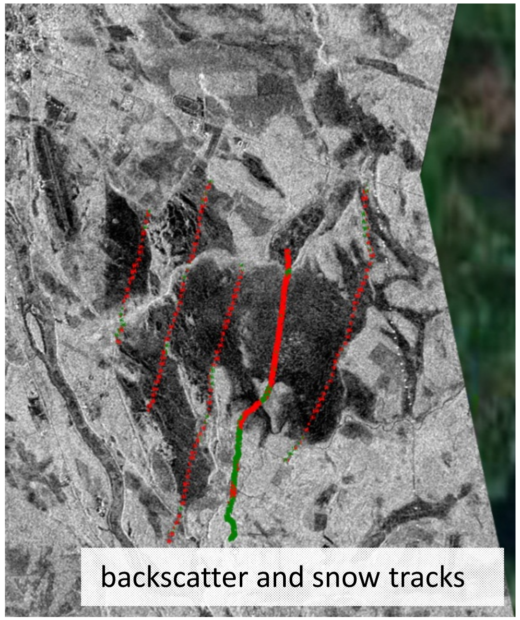
Slope: **7.4** deg / 10 cm
R-square: 0.56

- 6 days before
- higher incidence angle:

-> steeper slope







Evolution of ϕ_{VV} - ϕ_{HH}

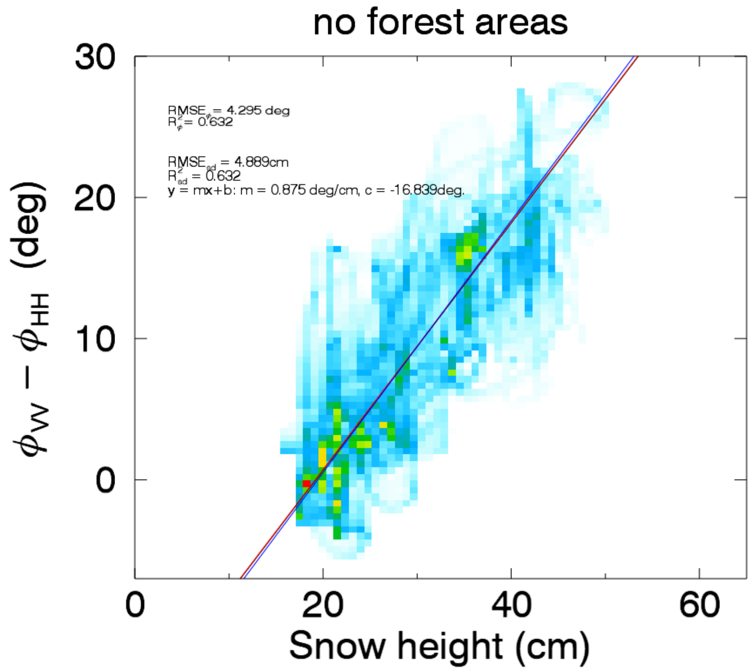
Acquisition date: **14 Jan 2012**
Ground data: **09 & 10 Jan, 2012**

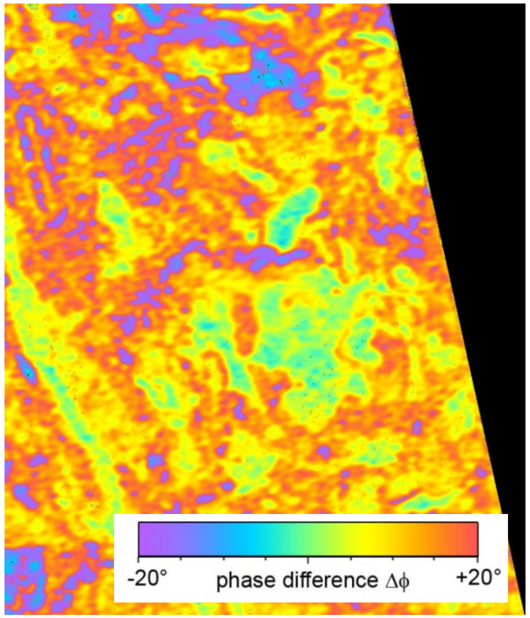
Incidence angle: 39.7°
(orbit 39)

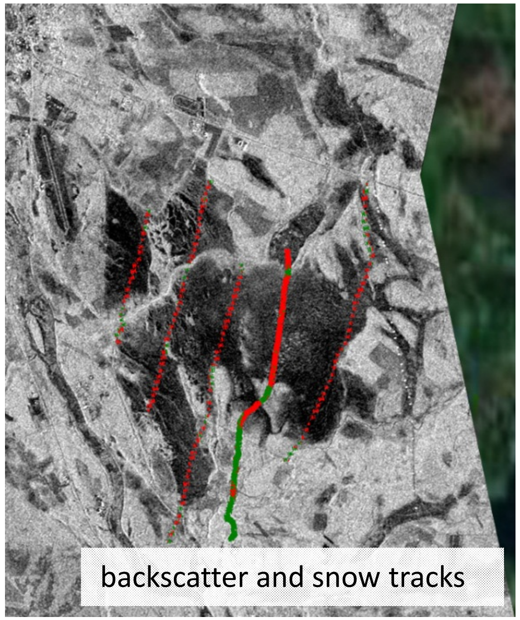
Slope: **8.6** deg / 10 cm
R-square: 0.63

- 11 days later
- same incidence angle

-> negative offest







Evolution of $\phi_{VV} - \phi_{HH}$

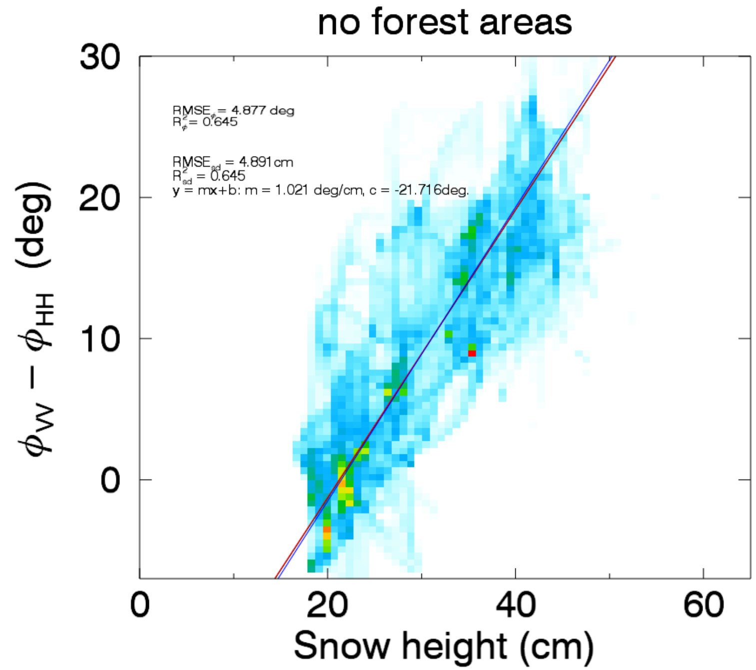
Acquisition date: **14 Jan 2012**
Ground data: **09 & 10 Jan, 2012**

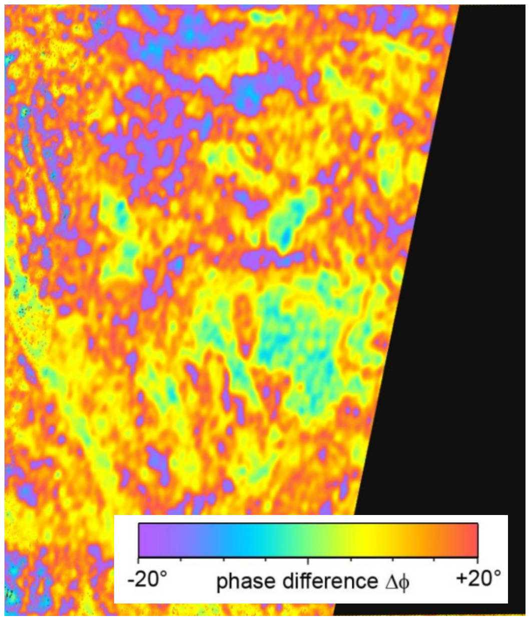
Incidence angle: 41.5°
(orbit 32)

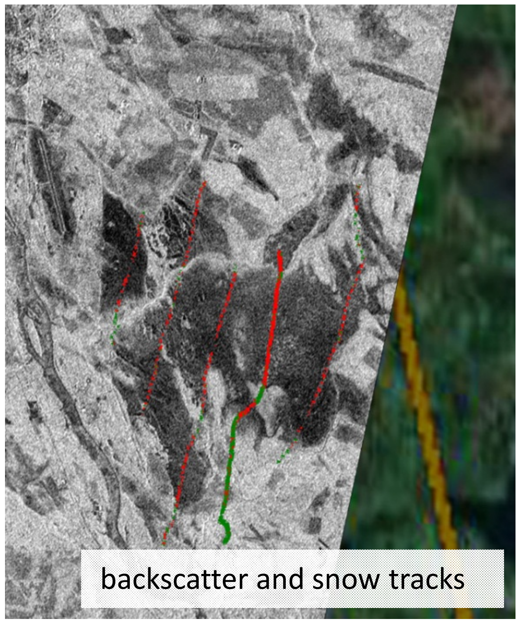
Slope: **10.2** deg / 10 cm
R-square: 0.65

- same date (11 hours before)
- higher incidence angle

-> steeper slope







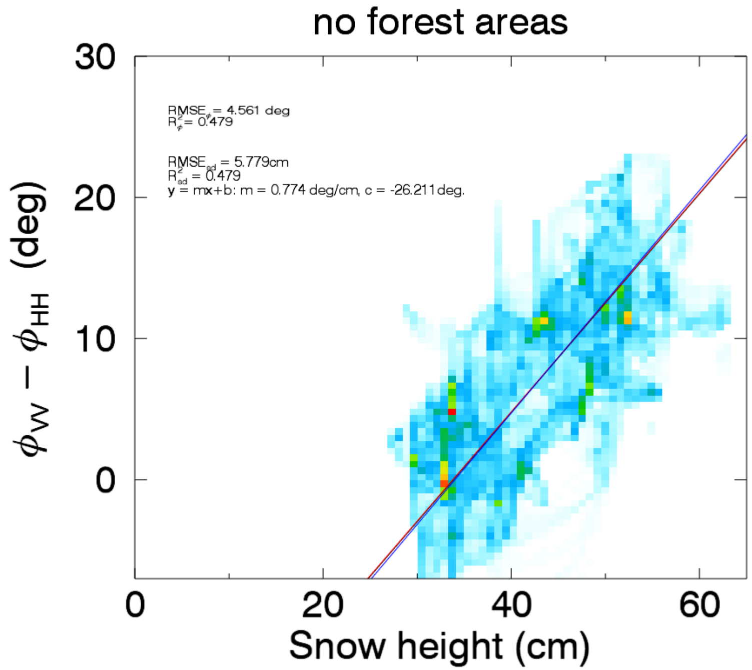
Evolution of ϕ_{VV} - ϕ_{HH}

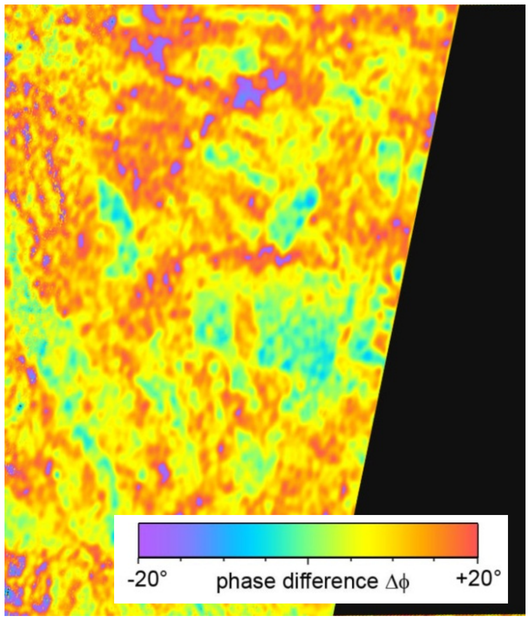
Acquisition date: **25 Jan 2012**
Ground data: **23 & 24 Jan, 2012**

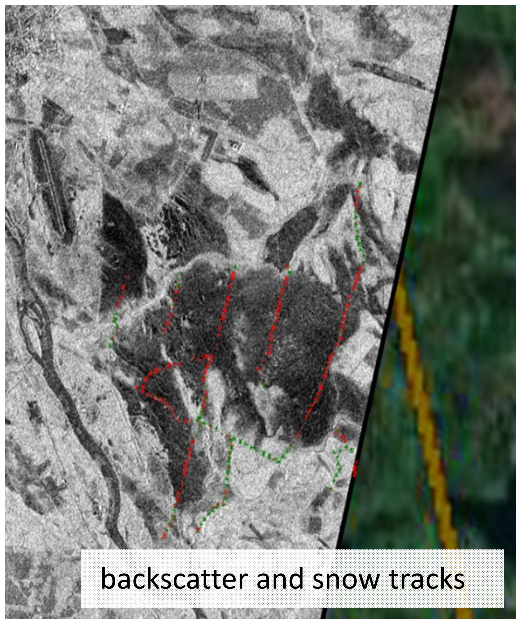
Incidence angle: 41.5°
(orbit 32)

Slope: **7.7** deg / 10 cm
R-square: 0.48

- 11 days later
- same incidence angle
-> less slope + negative offset







Evolution of $\phi_{VV} - \phi_{HH}$

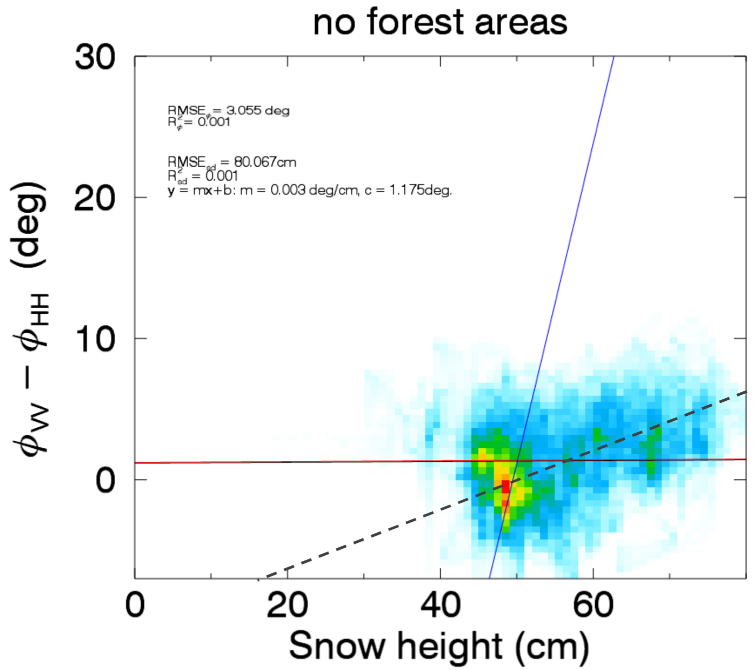
Acquisition date: **16 Feb 2012**
Ground data: **22 - 26 Feb, 2012**

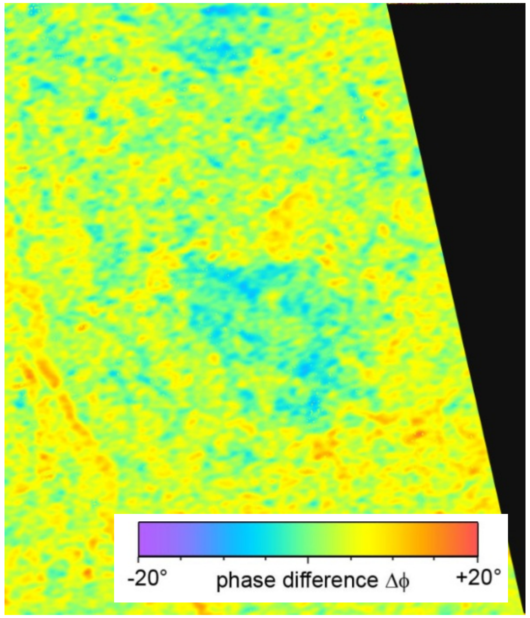
Incidence angle: 39.7°
(orbit 39)

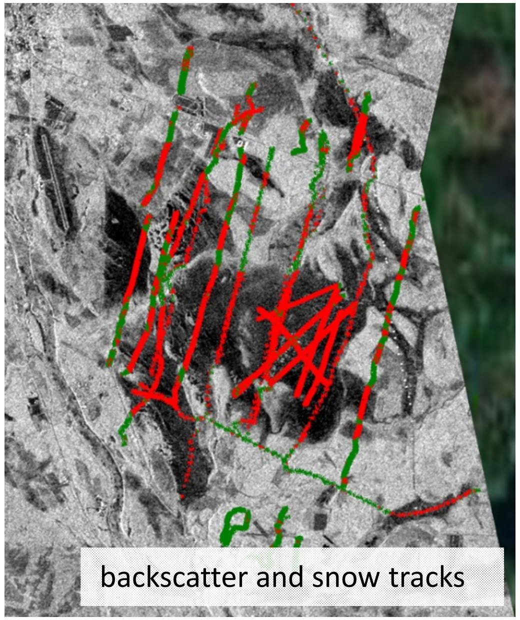
Slope: **2.1(?)** deg / 10 cm
R-square: 0.00?

- 22 days later
- similar incidence angle

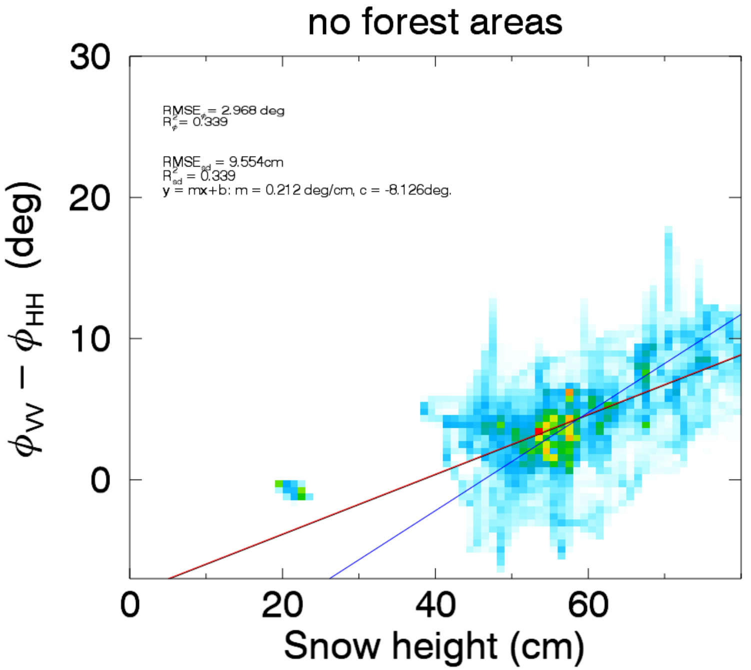
-> almost no slope







Evolution of ϕ_{VV} - ϕ_{HH}

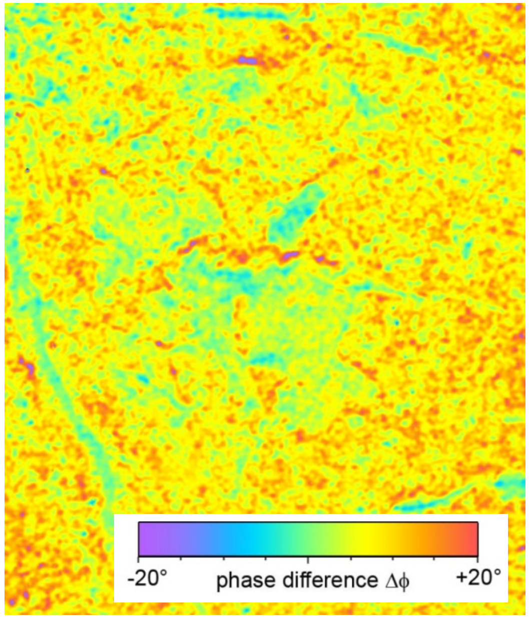


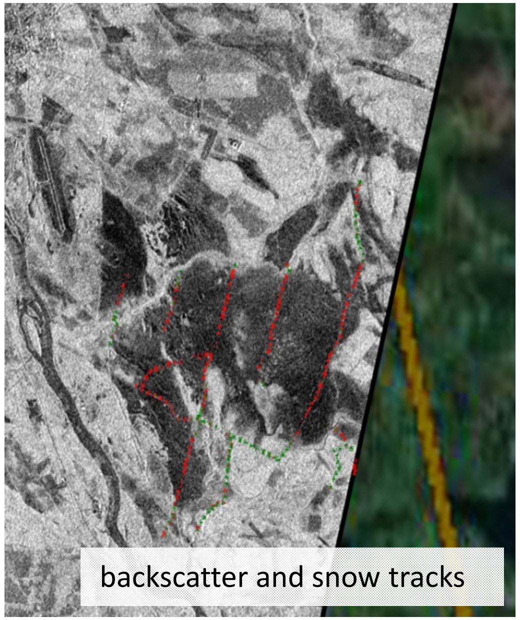
Acquisition date: **26 March 2012**
Ground data: **23 March, 2012**

Incidence angle: 32.7°
(orbit 130)

Slope: **2.1** deg / 10 cm
R-square: 0.34

- 40 days later
-> still quite flat





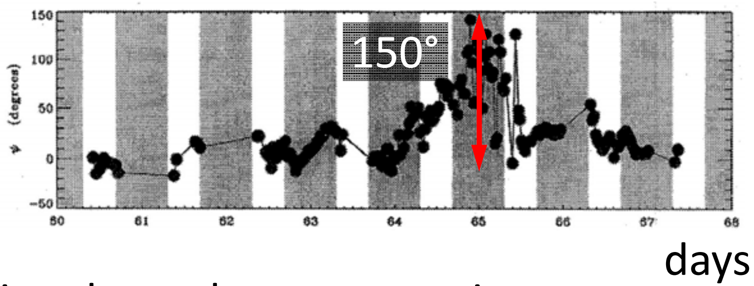
How is snow depth proportional to (ϕ_{VV} - ϕ_{HH})?

Summarize observations:

- Steeper slope/higher phase diff. in early winter
- Steeper slope for higher incidence angle
- Slope decreases with time

- Fresh snow causes very high phase differences. -> Also observed by [Chang, 1993] at 95 GHz.

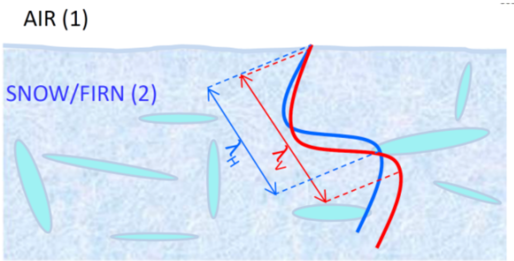
  Chang, P. et al. «Polarimetric backscatter from fresh and metamorphic snowcover at millimeter wavelengths», *IEEE Transactions on Antennas and Propagation, ,* **1996**, *44*



- Oriented particles within a volume cause polarization dependent propagation speeds [Cloude, 2000] & [Parrella, 2013].

  Cloude et al. «The Remote Sensing of Oriented Volume Scattering Using Polarimetric Radar Interferometry.», *Proceedings of ISAP,* Fukuoka, Japan, **2000**.

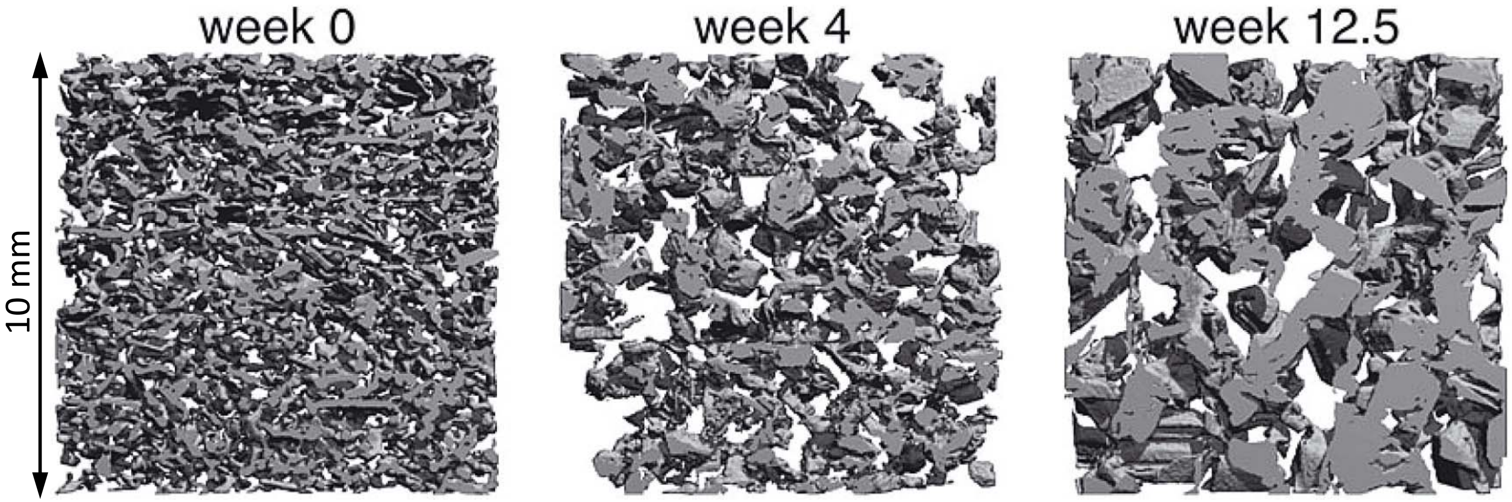
  Parrella, G. "On the Interpretation of L- and P-band PolSAR Signatures of Polithermal Glaciers", *POLInSAR,* ***2013***



- Recrystallization of snow changes the shape and orientation of ice grains in a snow cover driven by a vertical temperature gradient. [Riche, 2013]

  Riche, F. et al. "Evolution of crystal orientation in snow during temperature gradient metamorphism", *Journal of Glaciology,* **2013**, *59*, 47-55

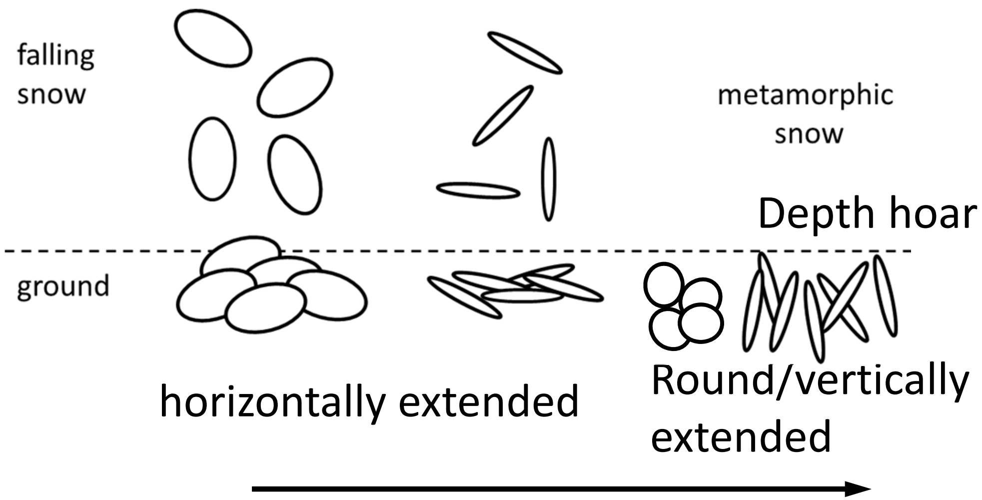
Why is snow depth proportional to ($\phi_{VV} - \phi_{HH}$)?



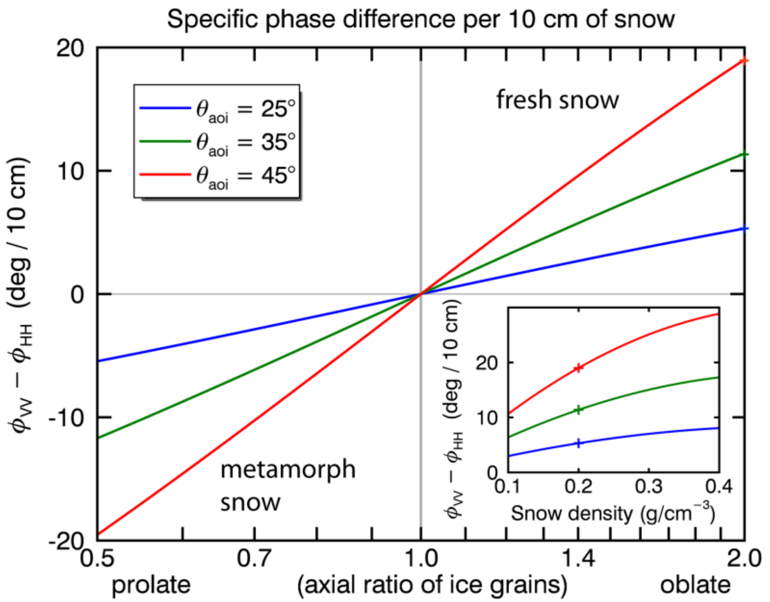
Riche, F. et al. "Evolution of crystal orientation in snow during temperature gradient metamorphism", *Journal of Glaciology,* **2013**, *59*, 47-55

> 11 recrystallization cycles after 12 weeks.

Simplification for model:

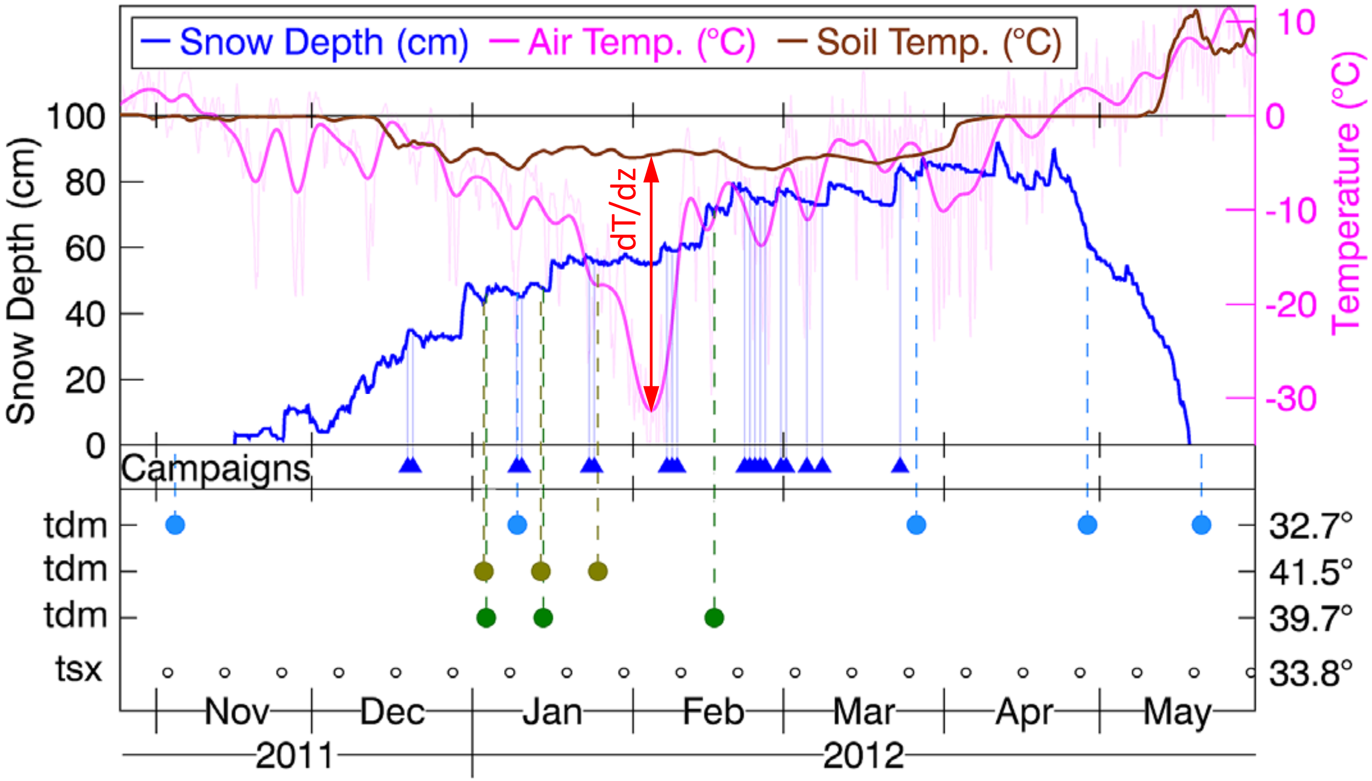


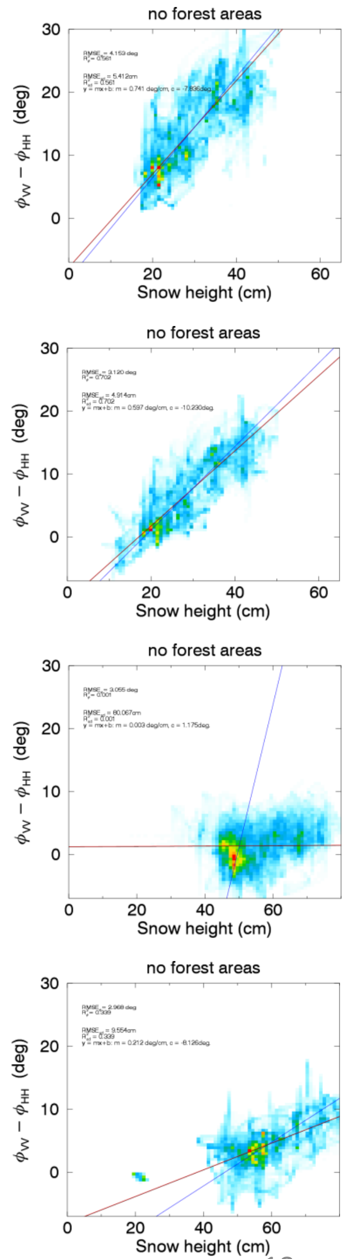
Recrystallization speed depends on temp. gradient dT/dz



Parrella, G. "On the Interpretation of L- and P-band PolSAR Signatures of Polithermal Glaciers", *POLinSAR* ***2013***

Interpretation of results:



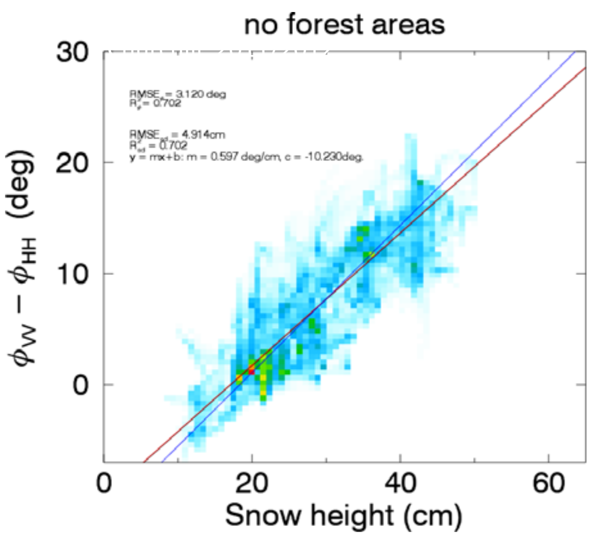


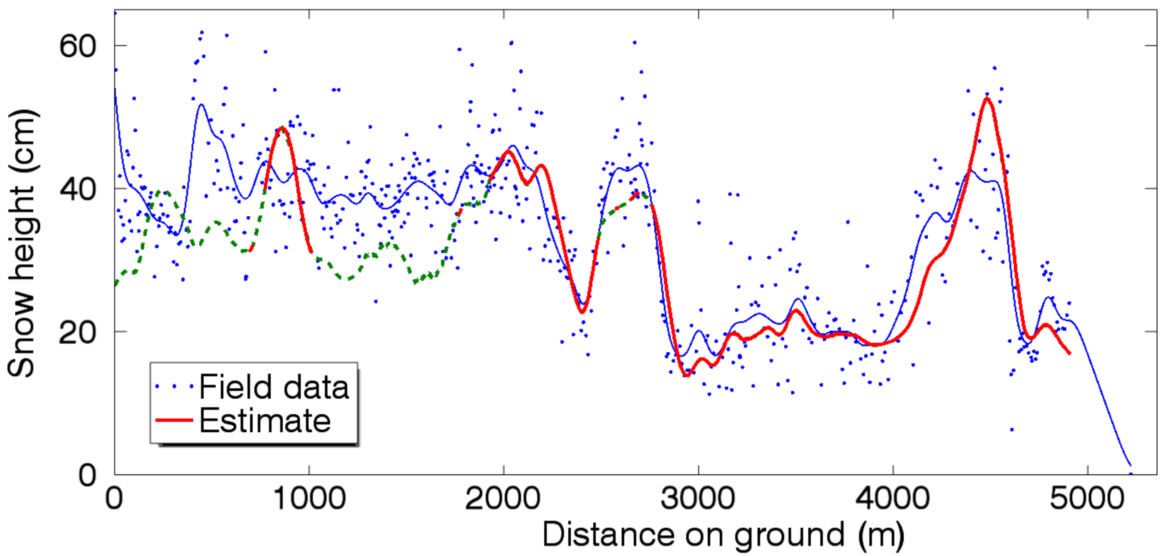
- The high vertical temperature gradient between Jan. and Feb. causes a fast recrystallization and the phase difference dissappears.

- Fresh fallen snow in december causes the phase difference which can be modeled for a horizontal-to-vertical grain size ratio of 1.3.

Summary

- Correlation has been found between phase difference $\phi_{VV} - \phi_{HH}$ and snow depth over open area.
- [Parrella13] provided a model based on oriented particles which can explain the observed phase differences.
- Recrystallization of ice grains (oblate -> spherical) causes the phase difference to decay.
- Detection of fresh fallen dry snow is possible and depth can be determined.





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.

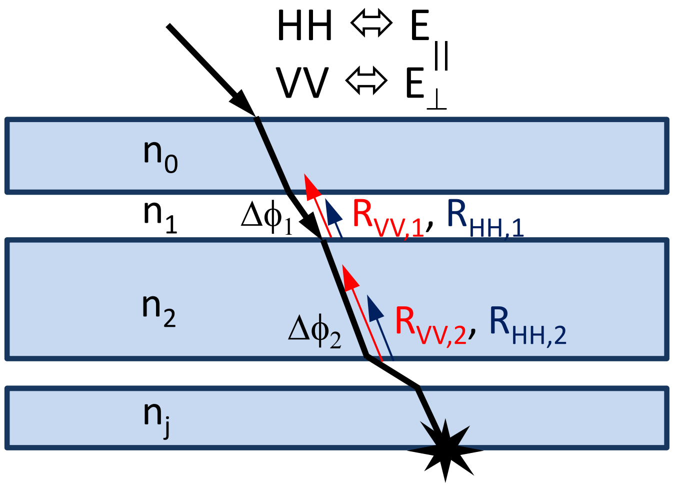

Thanks,
any questions?
Earth Observation and Remote Sensing of Snow
Silvan Leinss, ETH Zürich

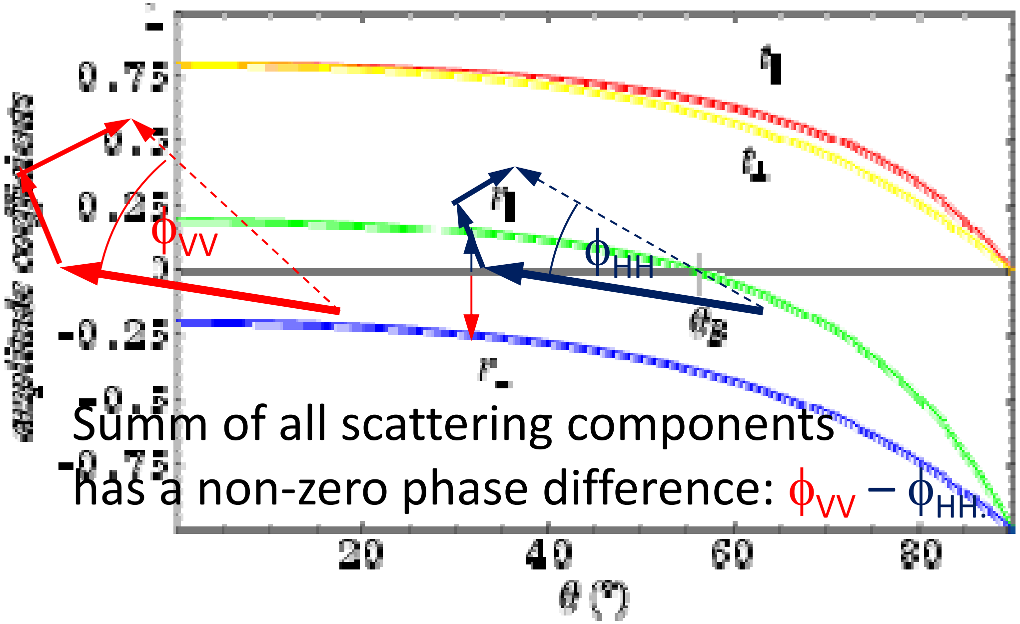
Why is Snow depth proportional to (ϕ_{VV} - ϕ_{HH})?

Suggestions:

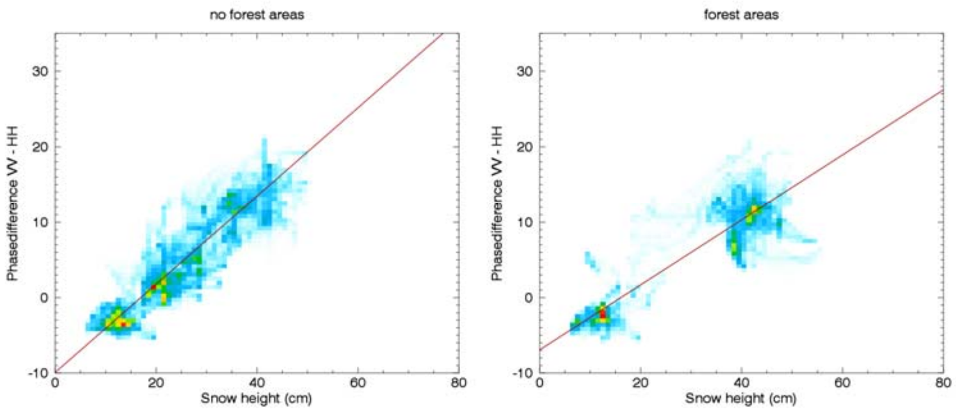
1. Propagation speed differs for HH and VV.
2. Different penetration depth for HH and VV.
3. Linear combination of phase-jumps at different layers.

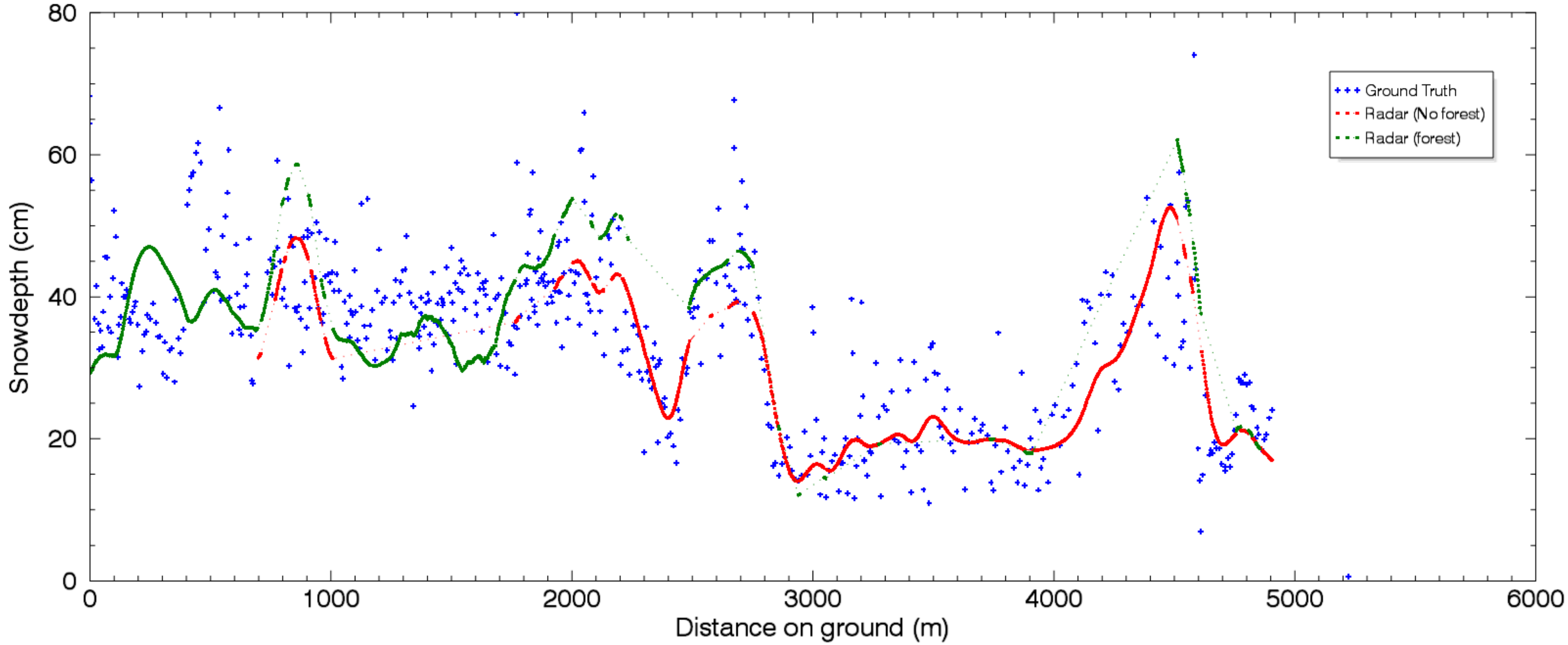
#2 is supported by different Fresnel-coefficients at snow layers for polarizations.





Spatial comparison of snow depth along transect with PPD.





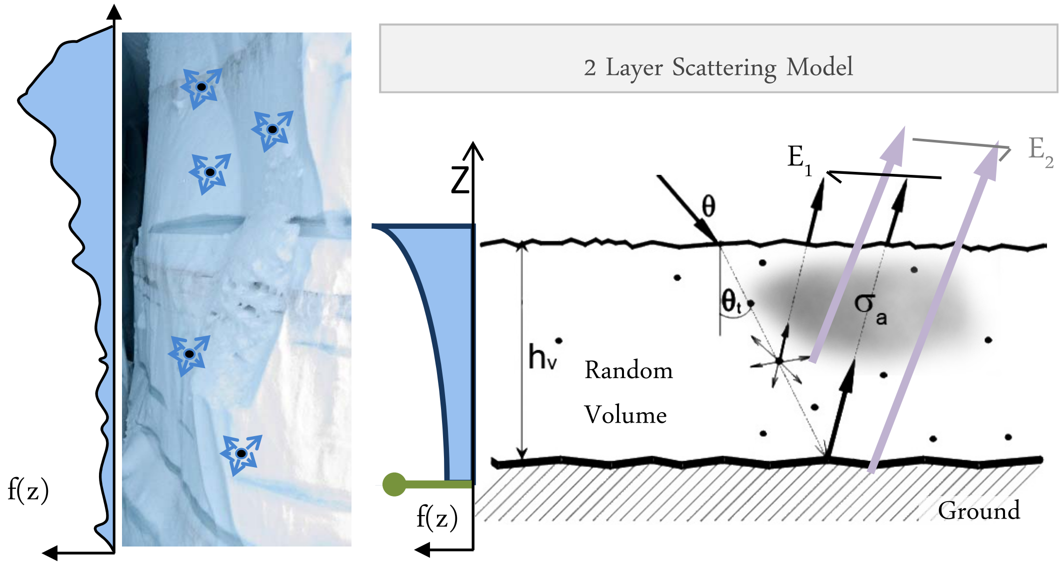
Co-polar phase difference ϕ_c follows the snow depth along the transect.

InSAR: Random Volume over Ground Model

$$\tilde{\gamma}_{Vol}(f(z)) = e^{i\kappa_z z_o} \frac{\int_o^{h_v} f(z)\cdot e^{i\kappa_z z}dz}{\int_o^{h_v} f(z)dz}$$

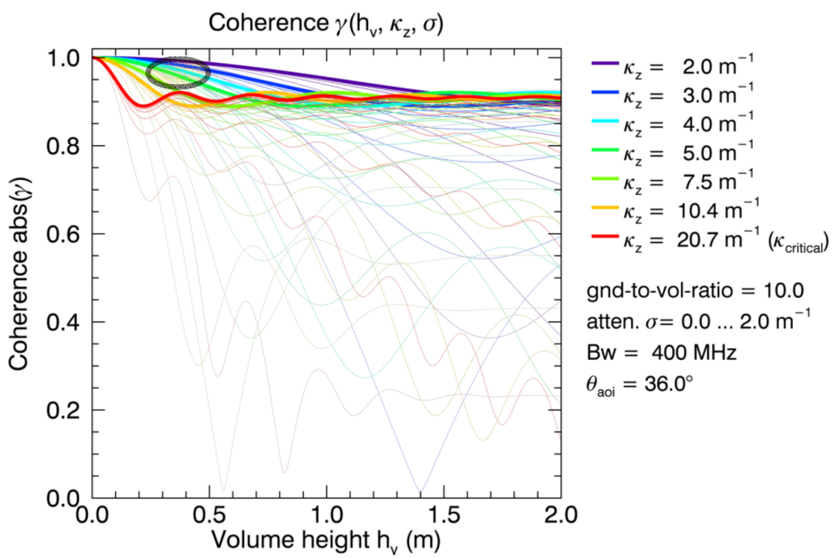
Expected volume coherence.

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



Realistic reflectivity function / modelled reflectivity function for a snow pack.

Expected coherence for homogeneous snow layer over ground:



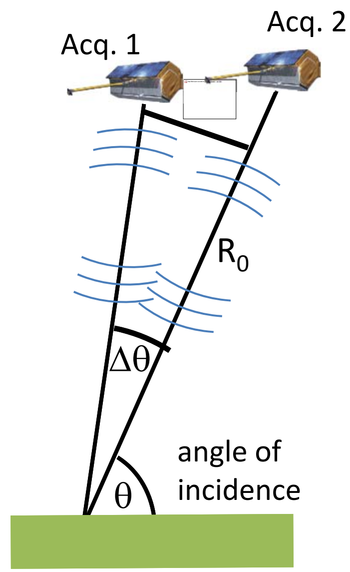
Good sensitivity to snow volume can be archived for κ_z = ~2...7 m^{-1} corresponding to baselines of

$b_\perp$ = 5... 8 km -> terraSAR-X (h = 514 km)

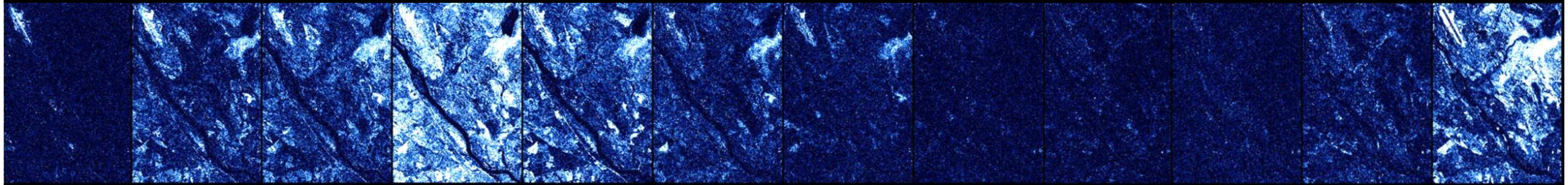
$b_\perp$ = 10...30 m -> airplane (h_{AGL}=2.5 km)

$b_\perp$ = 15...25 m -> airplane (h_{AGL}=1.5 km)

$$B_\perp = \Delta\theta \cdot R_0 = \sin\theta \cdot \frac{\kappa_z \lambda}{4\pi} \cdot R_0$$



Sodankylae 2012: Repeat pass coherence (Δt = 11 d)

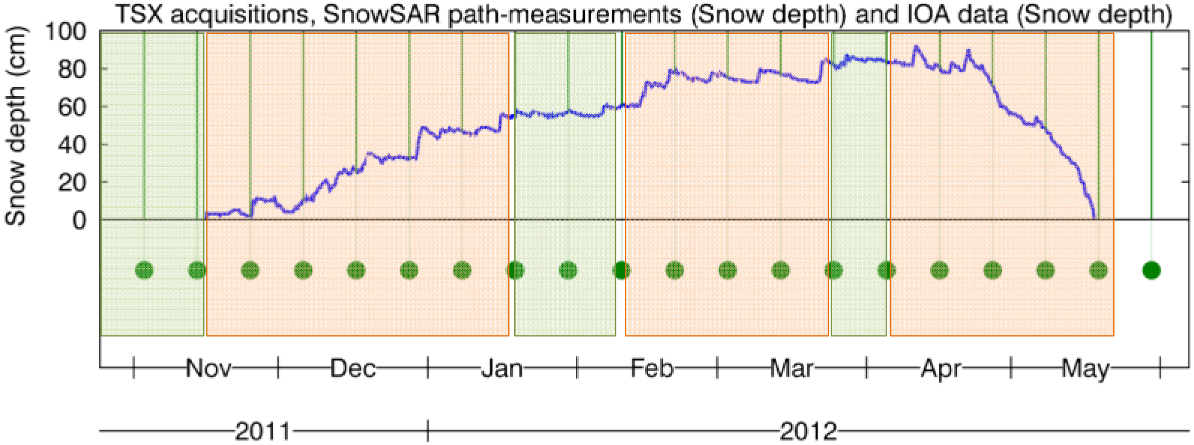


May | Oct. 01 | Oct. 12 | Oct. 23 | Nov. 03 | Nov. 14 | Nov. 25 | Dec. 06 | Dec 17 | Dec. 28 | Jan. 08 | Jan. 19 | 30th

+3°C, no snow

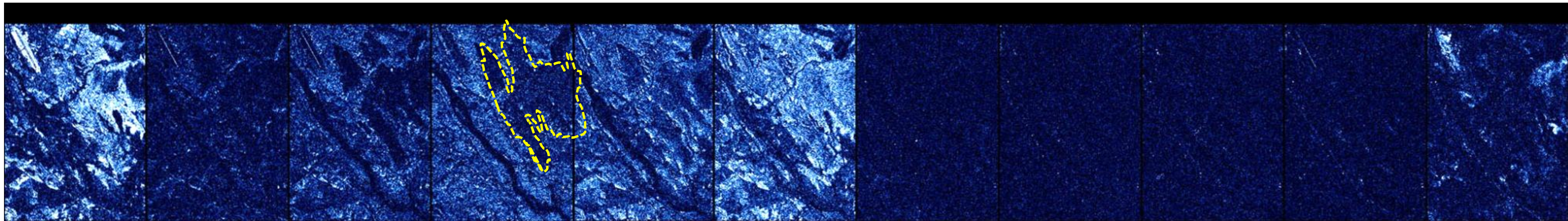
Accumulating snow … . . . .

-10°.. -30°C



Meadows and frozen wetland:

- low coherence → snowing or melting.
- Further interpretation (RVoG, etc.) difficult due to γ_{temp}.



30th | Feb. 10 | Feb. 21 | Mar. 03 | Mar. 14 | Mar. 25 | Apr. 05 | Apr. 16 | Apr. 27 | May 08 | May 19 | 30th

stable weather

+20 cm snow

+10 cm snow

+10 cm snow

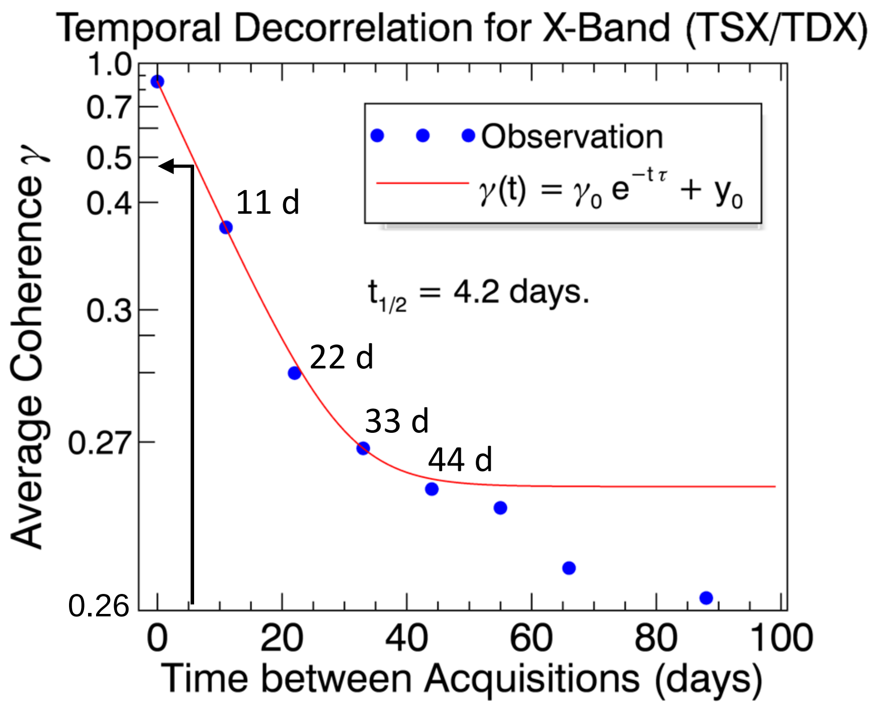
cold stable weather, snow depth: 80 cm

Setting …

. . . . Melting… . . . .

No snow left, +10°C

Change detection by coherence decay:

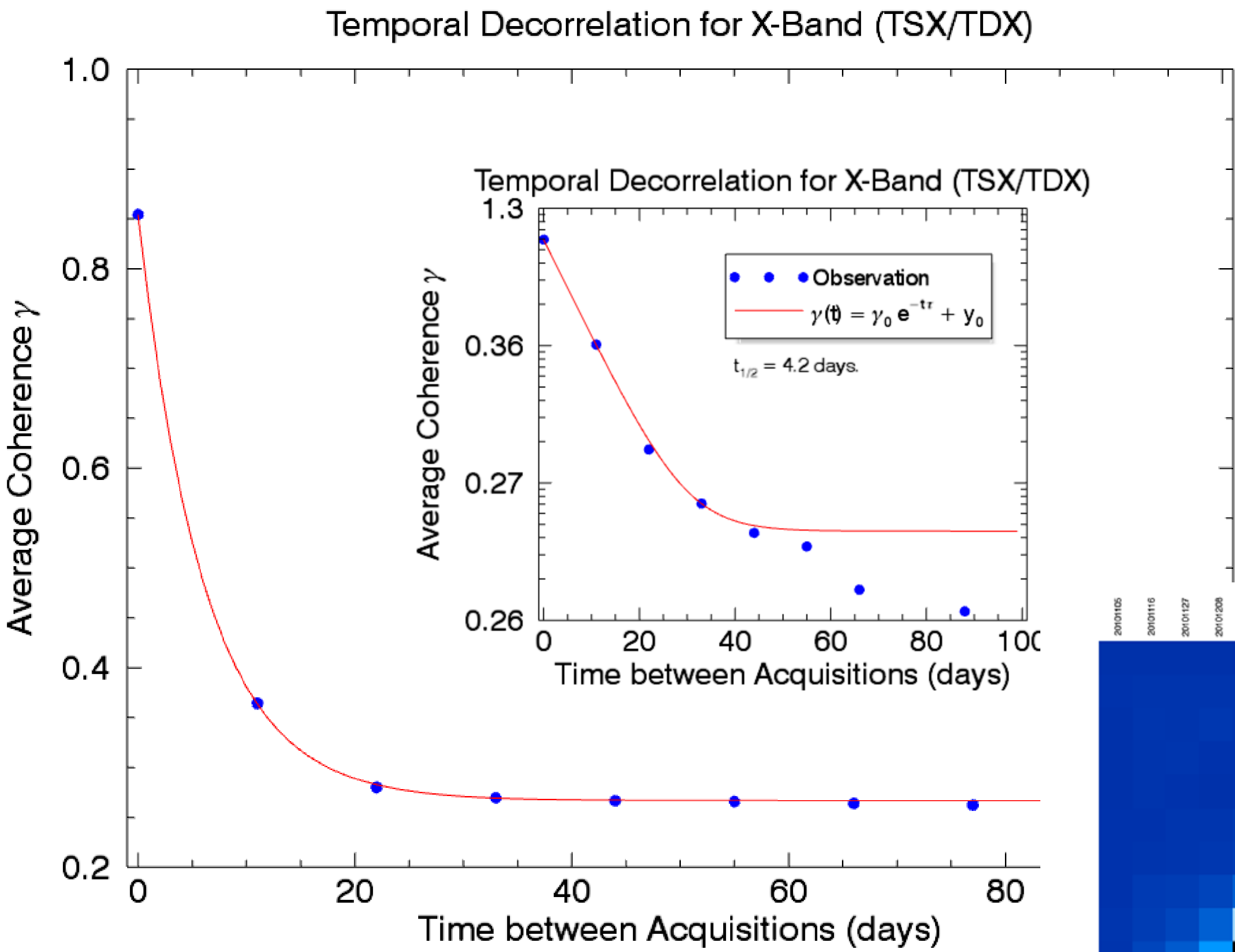


Strong temporal decorrelation in X-band caused by Snowfall, melting or strong wind drift.

For each point the coherences of at least 8 scenes of the same testsite were averaged.

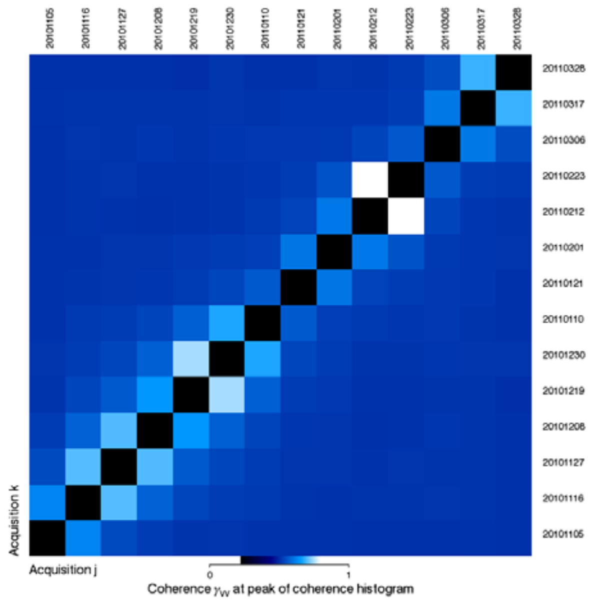
- Decay time of coherence: $t_{1/2}$ = 4.2 days.
- Repeat-times of *a few days* are favourable.

Decay of coherence for X-band TSX data



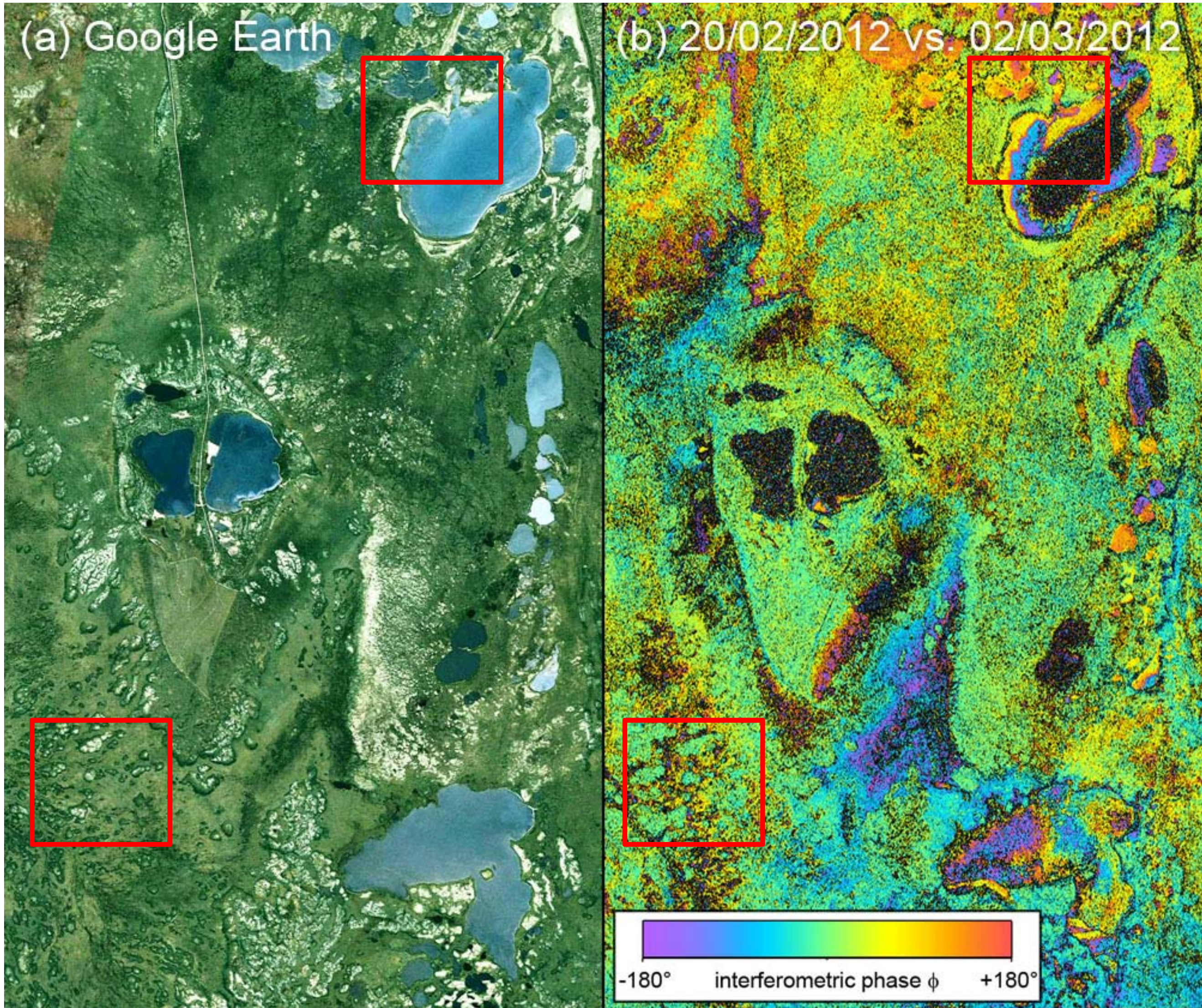
Decay time of Coherence:
$t_{1/2}$ = 4.2 days

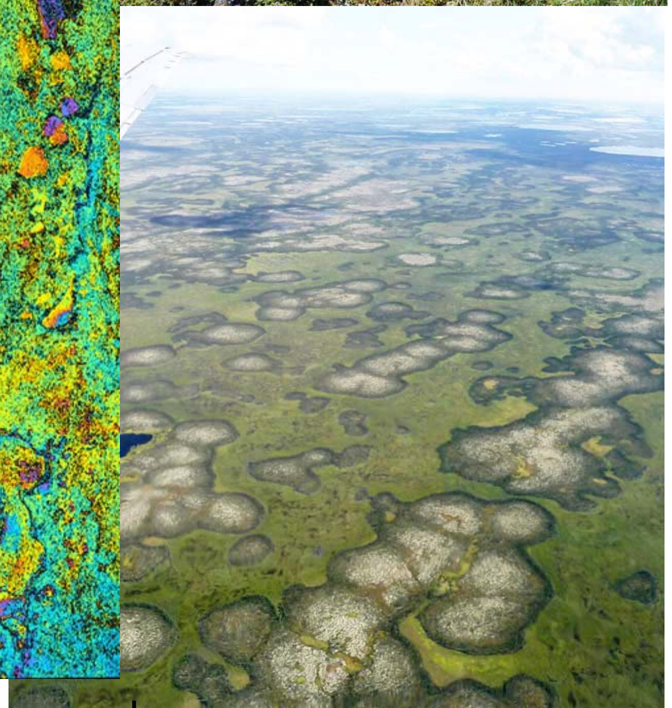
-> Very valuable if repeat-times of a few days are possible.



For each point 8 or more scenes of the same testsite were u
calculated from each scene were averaged. The red line is a

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?