On the Correction of the Penetration-Related Elevation Bias in Harmony XTI Products of Ice Sheets and Glaciers

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DLR

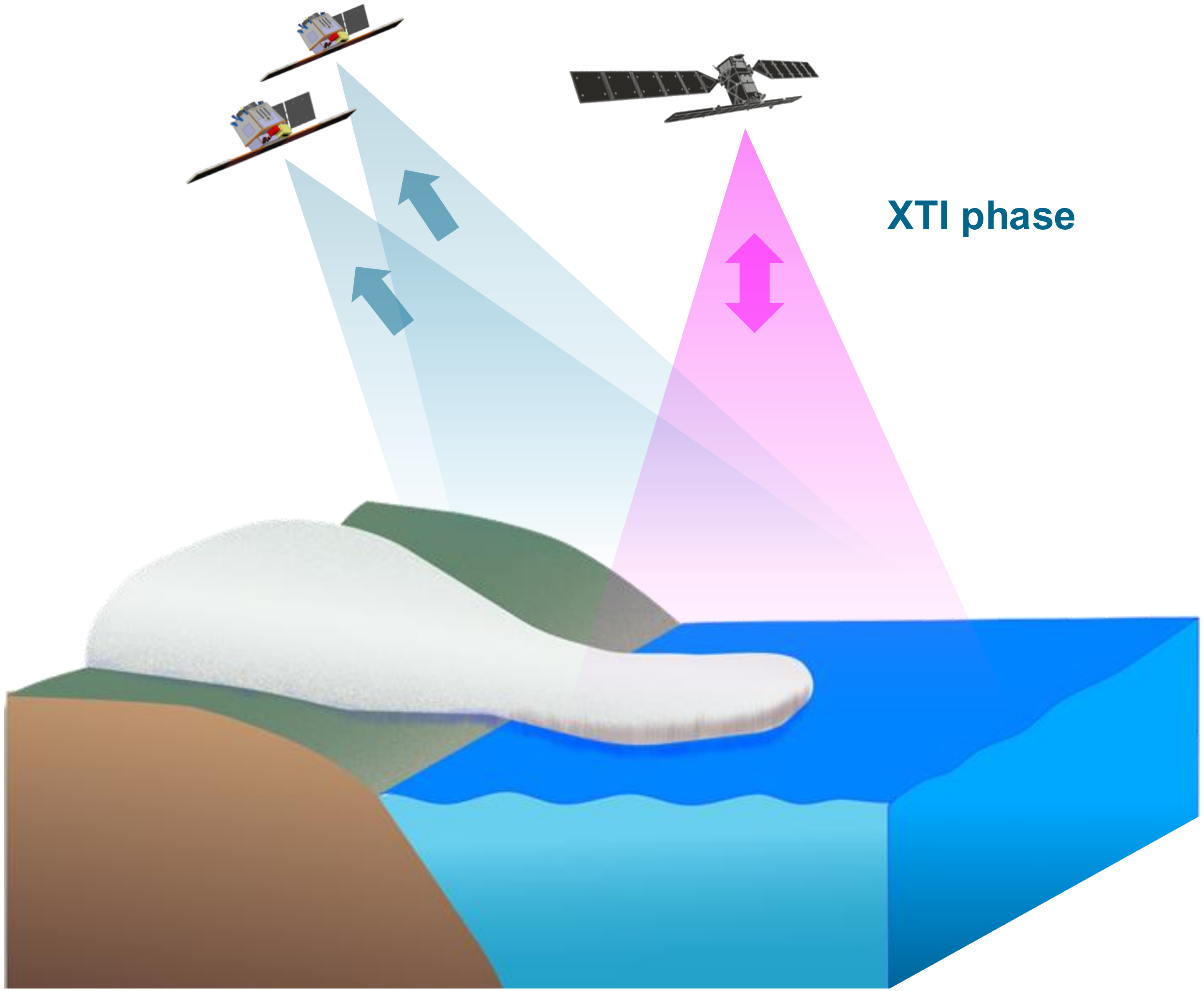
Harmony XTI Phase for Land Ice Applications

XTI phase
Single-pass cross-track interferometer

→ **Generation of single-pass InSAR Digital Surface Models (DSMs)**

→ **Topographic Change (TOC) products via DSM differencing**

→ **Glacier and ice sheet mass balance**



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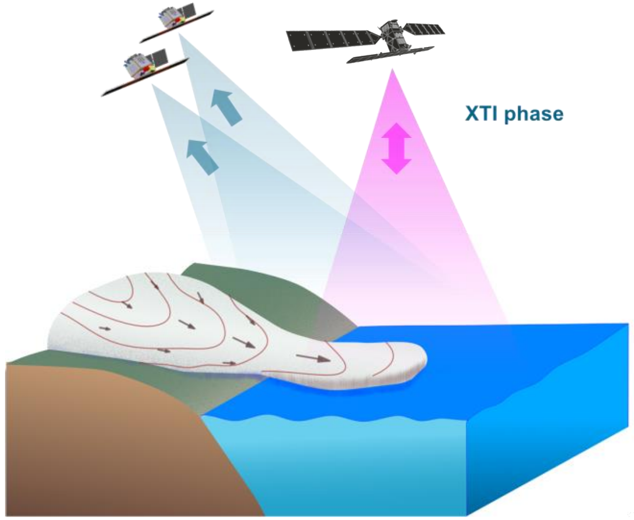
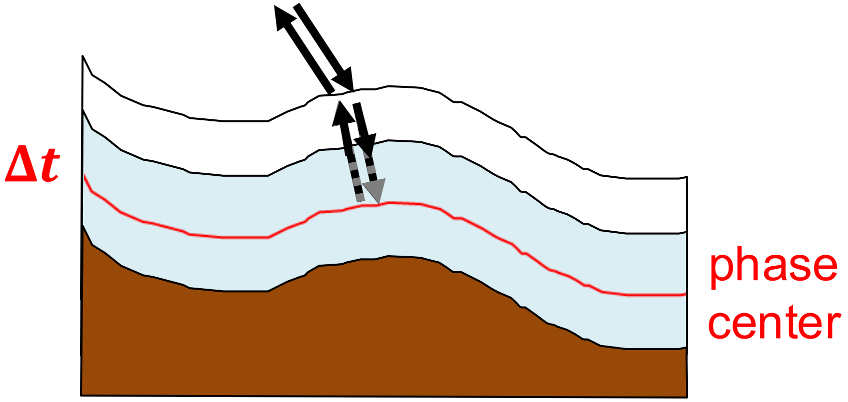


Challenge:
Signal penetration into snow, firn and ice
→ Systematic bias in InSAR DSMs

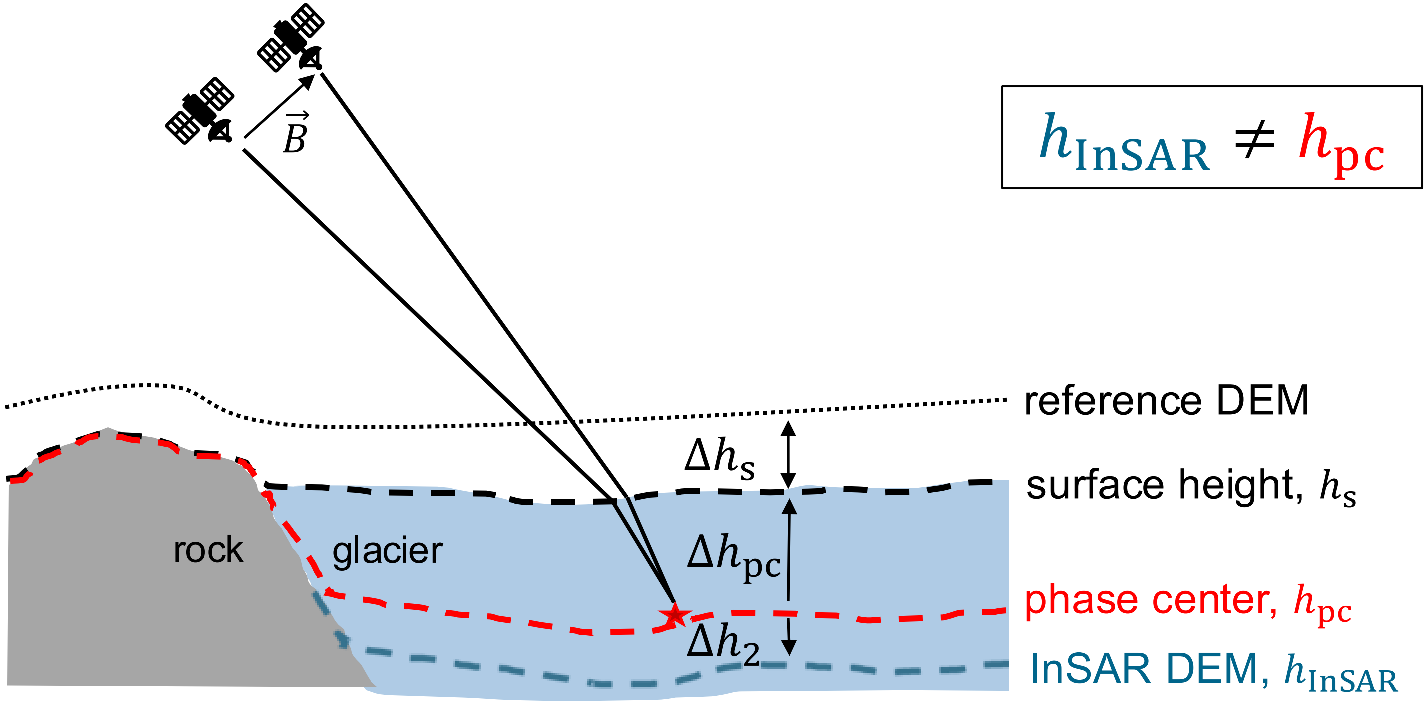


Penetration Bias Change
≠
Mass Change

InSAR Elevation Bias — Geometric Interpretation

- Radar signals partially penetrate snow/firn/ice
  - → Phase center may lie underneath the surface (Δh_{pc})
  - → Δh_{pc} can be estimated via the InSAR coherence [1,2]
- Surface height retrieval:

$$h_{\mathrm{s}} \approx h_{\mathrm{pc}} + \Delta h_{\mathrm{pc}}$$



Signal Propagation Effect [3]:

- The InSAR DEM (h_{InSAR}) is generated assuming free space propagation
- In reality, the propagation through the volume introduces a reduced propagation velocity and refraction effects on the surface
- h_{InSAR} does not replicate the **physical** phase center height
- Surface height retrieval:

$$\boldsymbol{h_s \approx h_{\mathrm{InSAR}} + \Delta h_{\mathrm{pc}} - \Delta h_2}$$

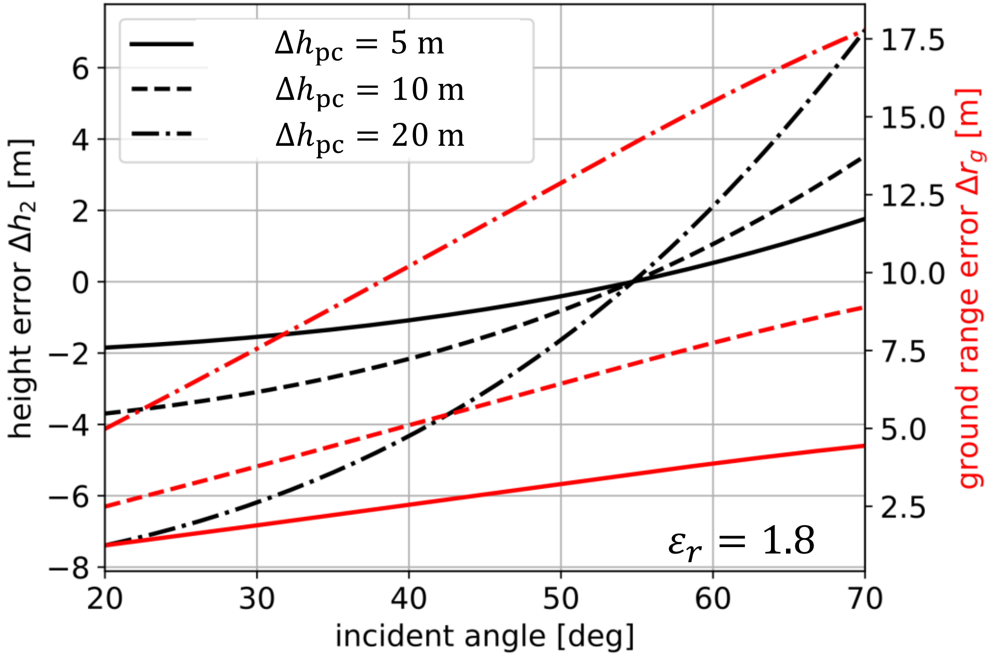
[1] E. W. Hoen and H. A. Zebker, "Penetration depths inferred from interferometric volume decorrelation observed over the Greenland Ice Sheet," in IEEE TGRS, vol. 38, Nov. 2000
[2] J. Dall, "InSAR Elevation Bias Caused by Penetration Into Uniform Volumes," in IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 7, pp. 2319-2324
[3] A. Benedikter, M. Rodriguez-Cassola, P. Prats-Iraola, G. Krieger and G. Fischer, "On the Processing of Single-Pass InSAR Data for Accurate Elevation Measurements of Ice Sheets and Glaciers," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 62, pp. 1-10, 2024

Propagation-Related Bias, Δh_2

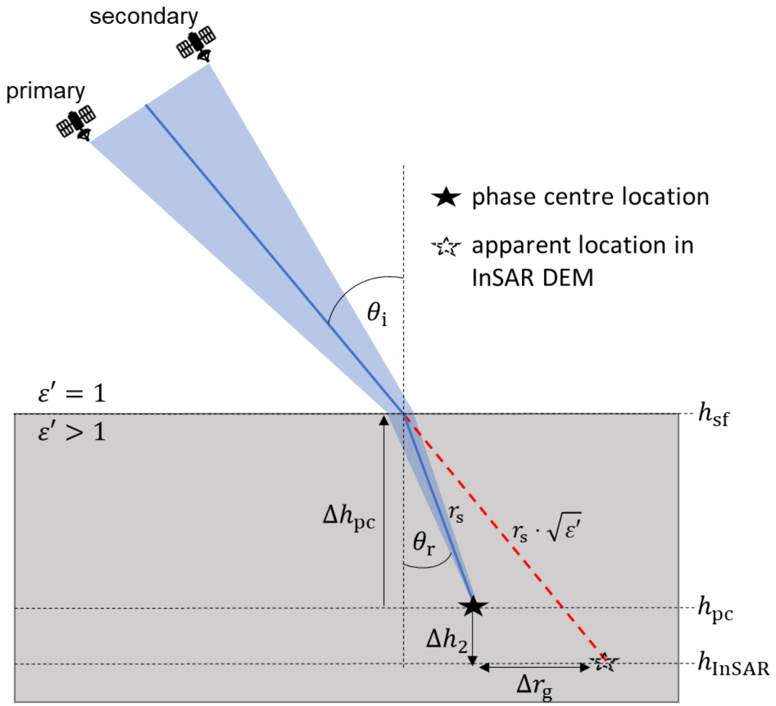
k_z: vertical wavenumber
θ_i: local incident angle
θ_r: refraction angle
ε_r': relative permittivity of the firn
Δh_{pc}: penetration bias

Interpretation 1: stretch of the vertical wavenumber

- Vertical wavenumber in the volume: $k_{z,vol} = k_z \cdot \sqrt{\varepsilon_r'} \cdot \frac{\cos\theta_i}{\cos\theta_r}$
- Propagation bias: $\Delta h_2 = \frac{\Delta h_{pc} \cdot k_{z,vol}}{k_{z,vol}} - \frac{\Delta h_{pc} \cdot k_{z,vol}}{k_z} = \Delta h_{pc} \cdot \left(1 - \sqrt{\varepsilon_r'} \cdot \frac{\cos\theta_i}{\cos\theta_r}\right)$



Interpretation 2: delayed and refracted beam



$$\Delta h_2 = \Delta h_{pc} \cdot \left(1 - \sqrt{\varepsilon_r'} \cdot \frac{\cos\theta_i}{\cos\theta_r}\right)$$

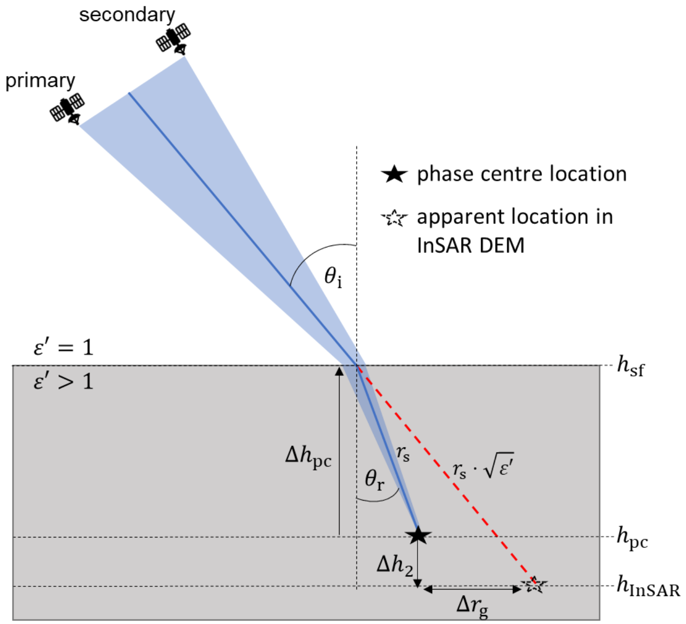
$$\Delta r_g = \Delta h_{pc} \cdot \tan\theta_r \cdot \left(\sqrt{\varepsilon_r'} \cdot \frac{\sin\theta_i}{\sin\theta_r} - 1\right)$$

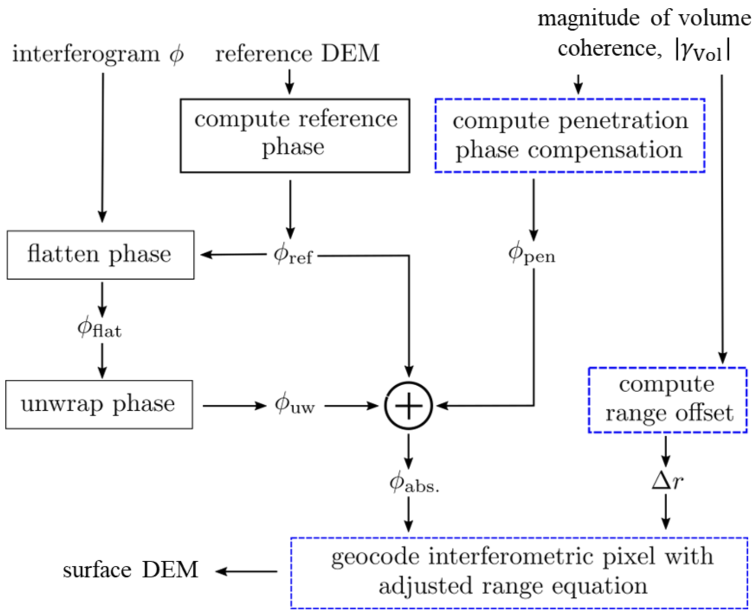
Elevation Bias Correction

Penetration results in a 3-D geolocation error

→ should not be treated as a 1-D height correction

→ Accommodation within the InSAR DEM generation





1) Estimate volume coherence

$$|\gamma_{vol}| = \left| \frac{\gamma_{tot}}{\gamma_{therm} \cdot \gamma_{quant} \cdot \gamma_{amb} \cdot \gamma_{rg} \cdot \gamma_{az}} \right|$$

2) Estimate penetration phase ϕ_{pen} and slant range offset Δr

$$\phi_{pen} = \arctan\left(\sqrt{|\gamma_{vol}|^{-2} - 1}\right)$$

$$\Delta r = \sqrt{\varepsilon} \cdot \frac{\Delta h_{pc}}{\cos\theta_r} = \frac{\phi_{pen}}{k_z \cdot \cos\theta_i}$$

3) Interferometric geocoding with adapted range and phase

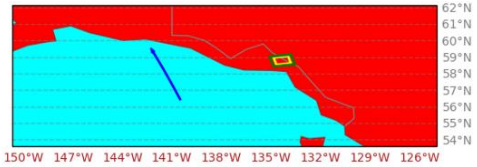
$$\begin{cases} \phi_{abs.} = \dfrac{4\pi}{\lambda} \cdot \left(|\mathbf{p} - \mathbf{s}_p| - |\mathbf{p} - \mathbf{s}_s|\right) + \phi_{pen} \\ r_p = |\mathbf{p} - \mathbf{s}_p| + \Delta r \\ f_{DC,p} = \dfrac{2}{\lambda \cdot r_p} \cdot \mathbf{v}_p \cdot (\mathbf{p} - \mathbf{s}_p) \end{cases}$$

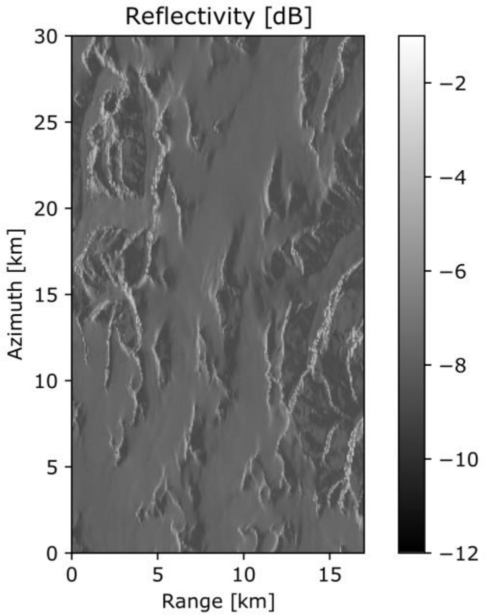
Elevation bias correction does not require firn permittivity (density) knowledge!

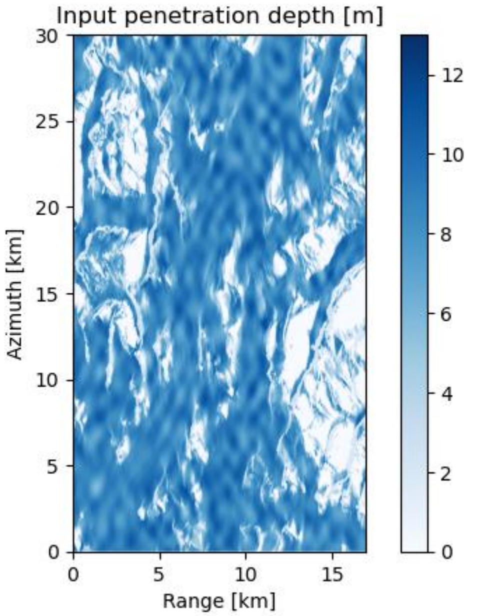
Tests Using the Harmony End-to-End Simulator

Parameter	Description / Value
frequency	5.405 GHz
SLC resolution (az x rg)	20 m x 5 m
interferogram resolution (az x rg)	100 m x 100 m
incident angle (mean)	30°
height of ambiguity (mean)	60 m
NESZ (mean)	−20 dB
penetration depth	0 m to 12 m
firn permittivity ε_r	1.8, constant
reflectivity	−12 dB to −1 dB

Raw data are simulated with injection of volume penetration and processed until DSM products

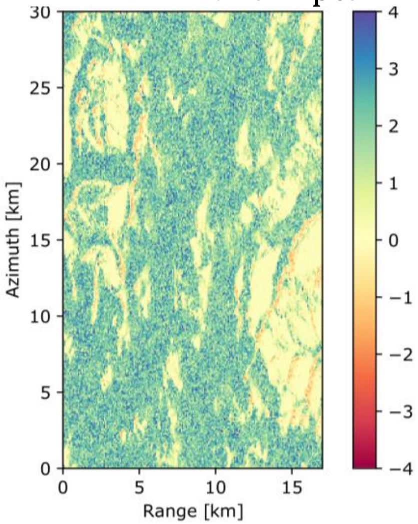




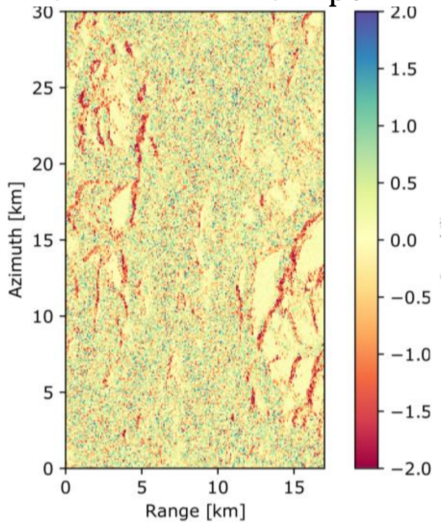


Surface elevation (DSM) retrieval error evaluation

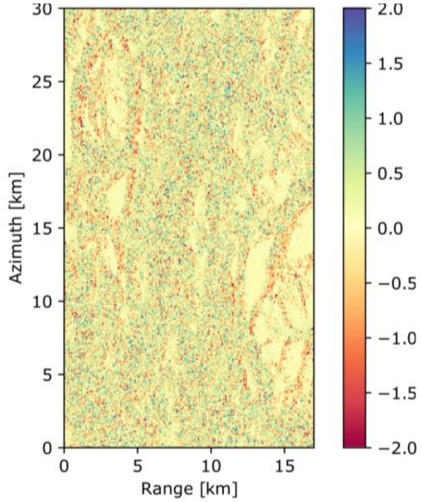
Compensate penetration bias only (Δh_{pc})

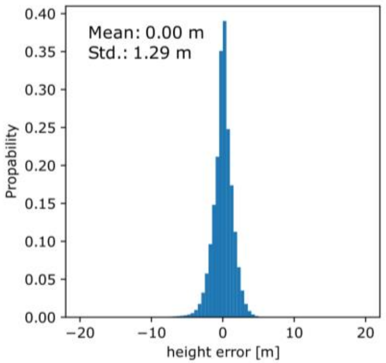


Compensate penetration + propagation bias ($\Delta h_{\mathrm{pc}} + \Delta h_2$)

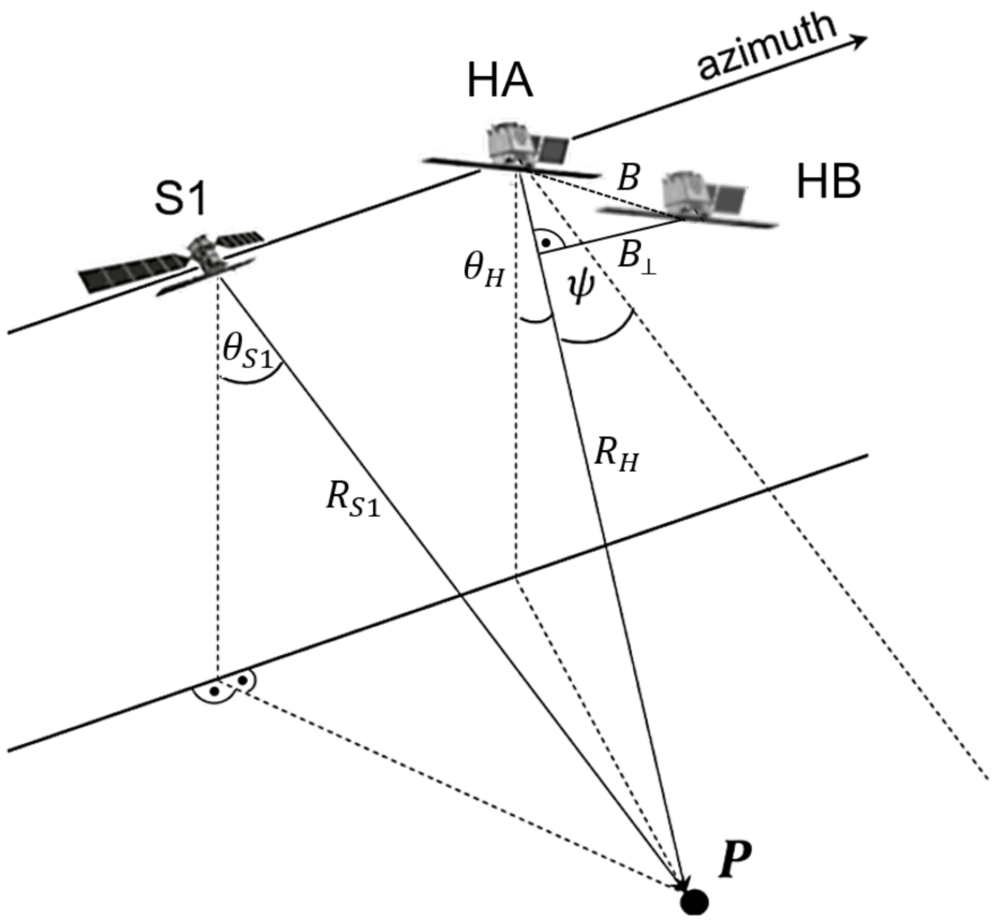


Accommodation of penetration phase and range in DEM generation





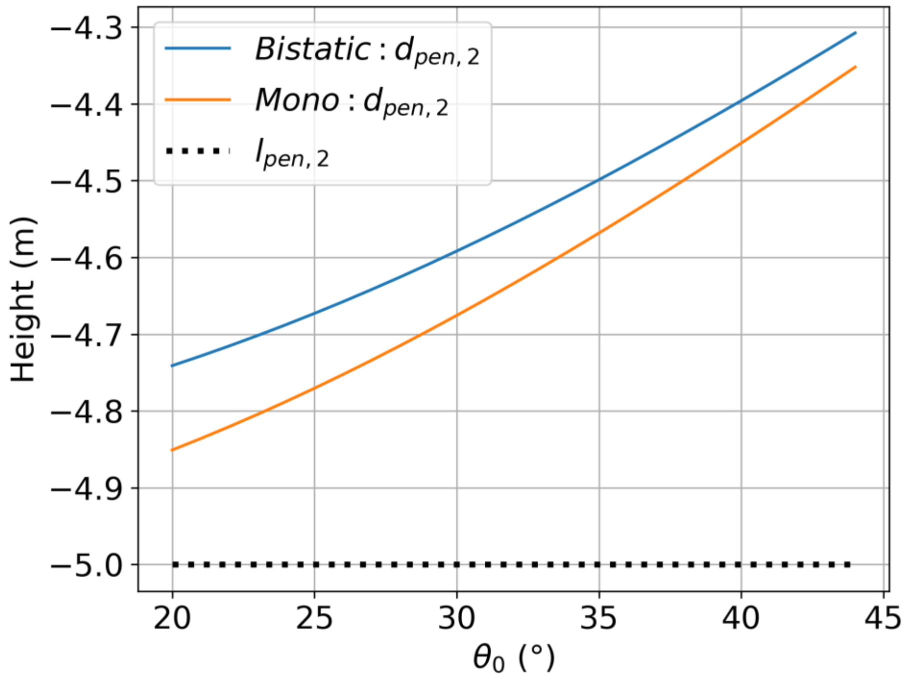
Effects of Squinted, Bistatic Observation



Squint angle: $\psi = 20° - 26°$

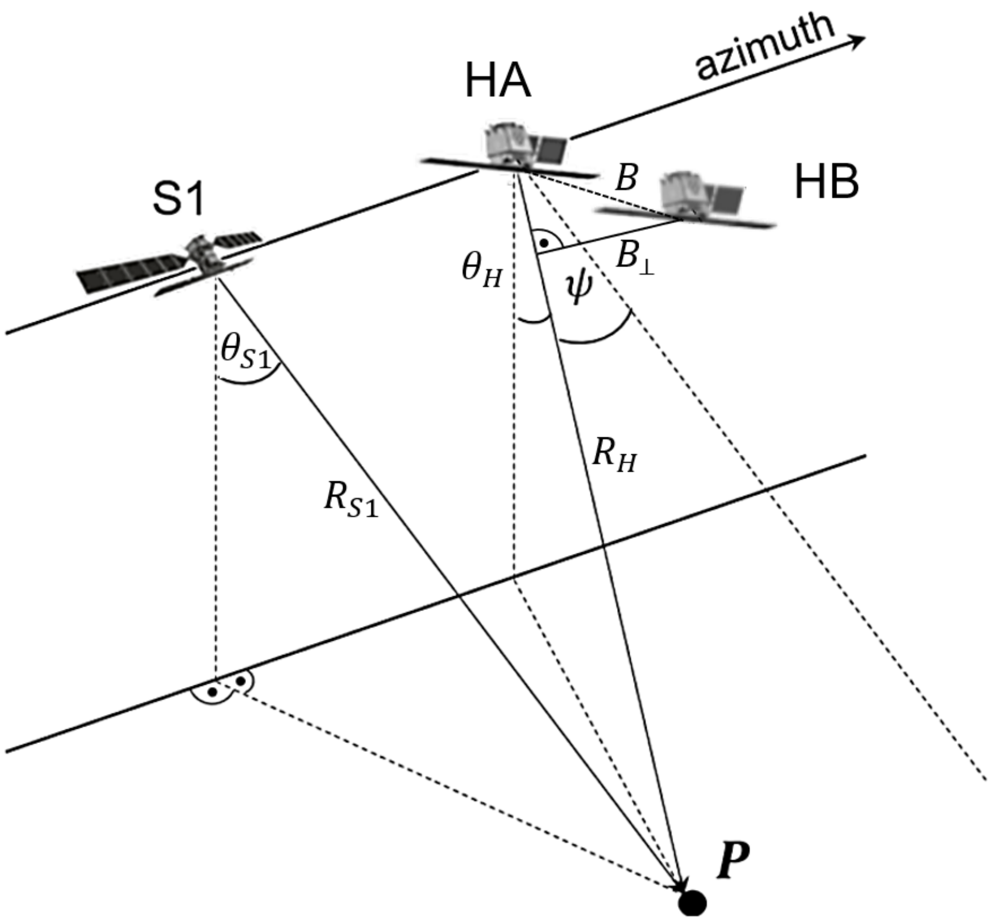
1. Slight change in 2-way penetration depth

2-way penetration *depth*
for a 2-way penetration *length* of 5 m
(density $\rho = 0.5 g/cm^3$)



Harmony 2-way penetration depth only <5% smaller

Effects of Squinted, Bistatic Observation



Squint angle: $\psi = 20° - 26°$

Detailed analysis:

G. Fischer, A. Benedikter, K. Belinska, K. Papathanassiou, I. Hajnsek, H. Rott, T. Nagler, P. Prats-Iraola, *Bistatic Signal Penetration Geometry over Land Ice for the Harmony Mission,* EUSAR 2026

- **Only marginal changes in the complex volume coherence expected for Harmony**
- **Squinted, bistatic characteristic can be fully accommodated in the DSM generation process**

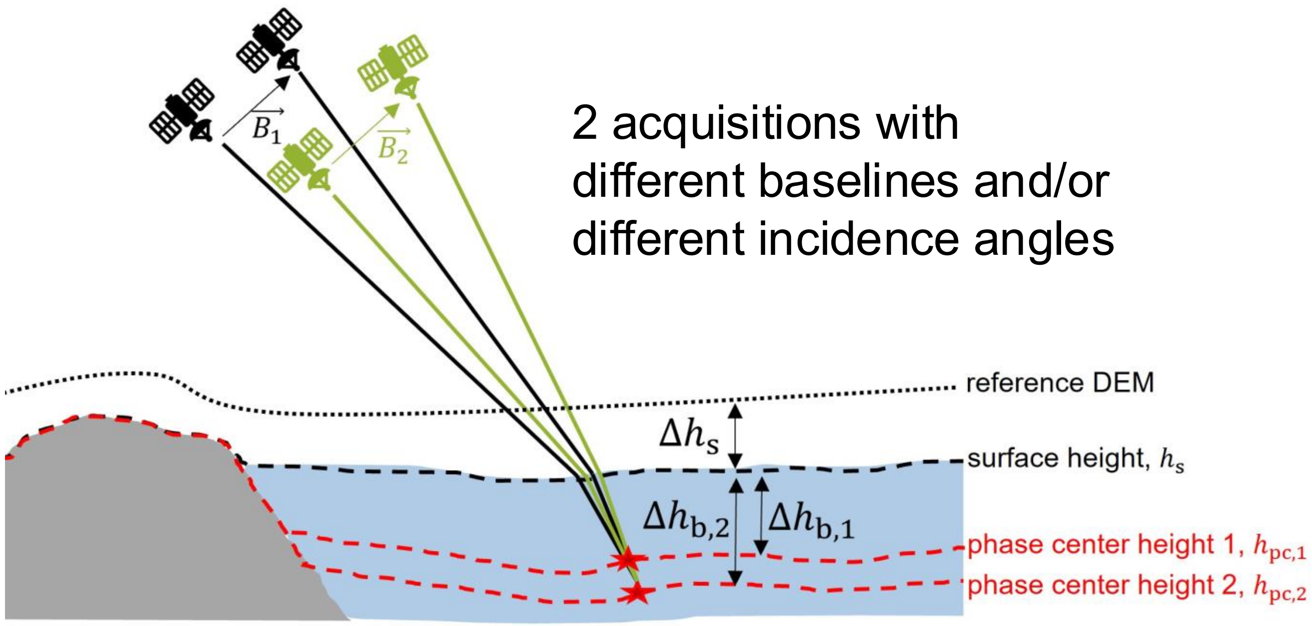
Exploit Multiple Interferograms with Geometric Diversity

Motivation

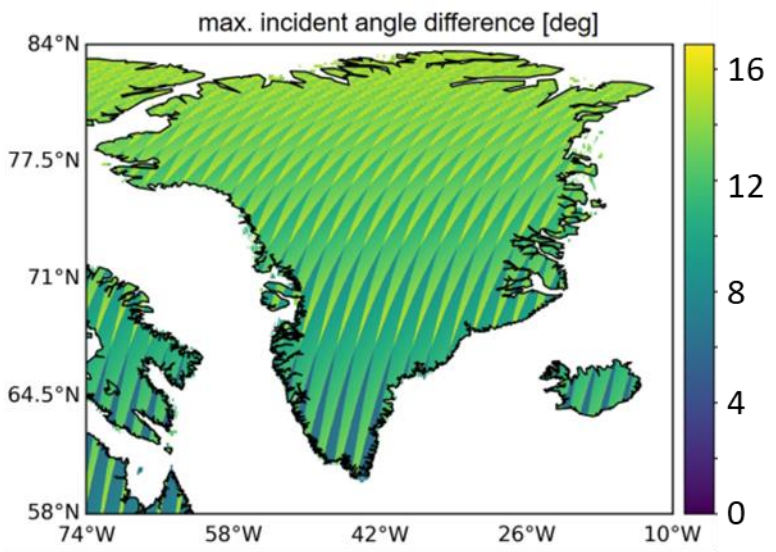
Limitations of penetration correction based on the estimated volume coherence magnitude ($|\gamma_{\mathrm{vol}}|$) and a Uniform Volume Model

- Deviations from the Uniform Volume assumption result in biased estimates
- Coherence estimation introduces noise and potentially biases (heterogeneous areas)

Can we exploit multiple interferograms with different observation geometries?

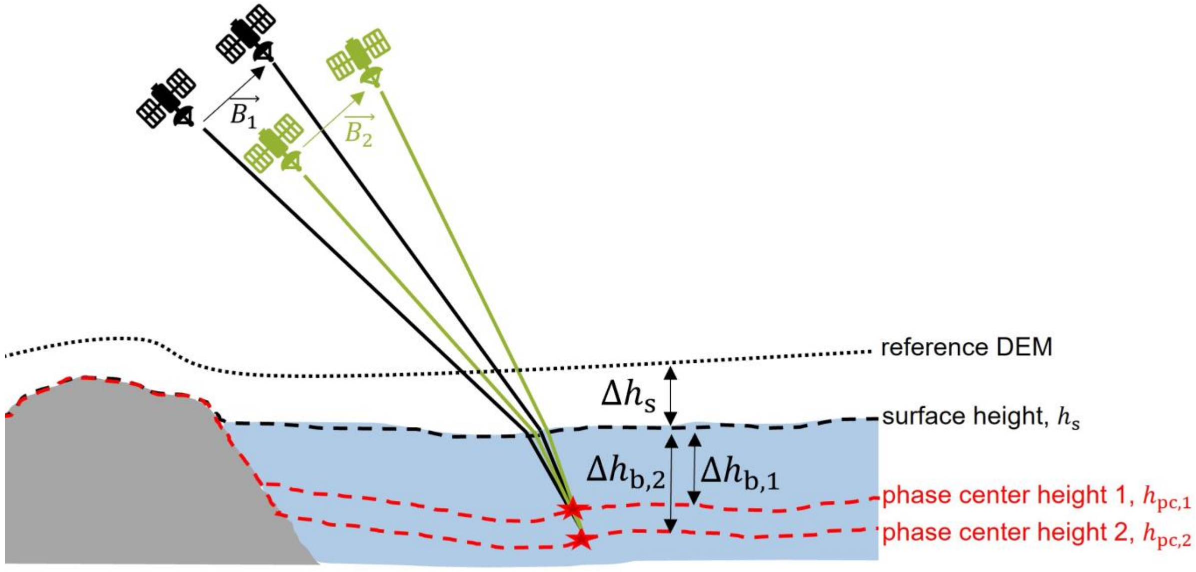


2 acquisitions with different baselines and/or different incidence angles



Considering:
- Sentinel-1 incident angle range
- Only descending passes

Exploit Multiple Interferograms with Geometric Diversity



Interferometric phase (after flattening):

$$\phi_1 \approx k_{z,1} \cdot \Delta h_s + k_{z,1,vol} \cdot \Delta h_{b,1}$$

$$\phi_2 \approx k_{z,2} \cdot \Delta h_s + k_{z,2,vol} \cdot \Delta h_{b,2}$$

3 unknowns and 2 equations

Uniform Volume Assumption

We can restrict the system to 2 variables, the surface height Δh_s and the penetration length l

$$\phi_1 = k_{z,1} \cdot \Delta h_s + \tan^{-1}\left(k_{z,1,vol} \cdot \cos(\theta_{r,1}) \cdot \frac{l}{2}\right)$$

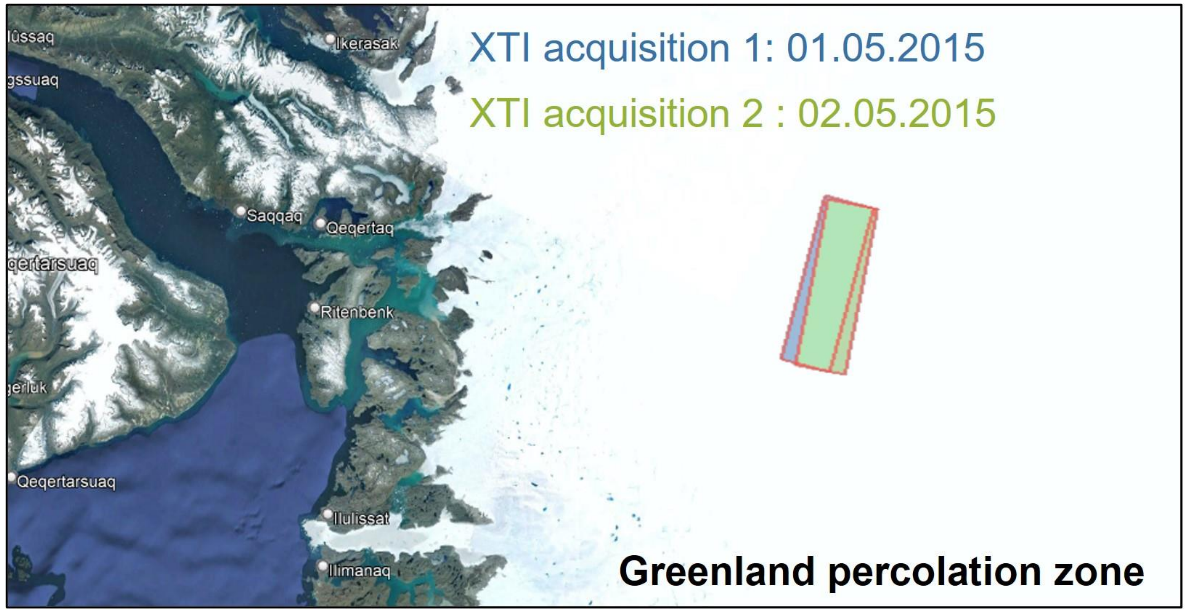
$$\phi_2 = k_{z,2} \cdot \Delta h_s + \tan^{-1}\left(k_{z,2,vol} \cdot \cos(\theta_{r,2}) \cdot \frac{l}{2}\right)$$

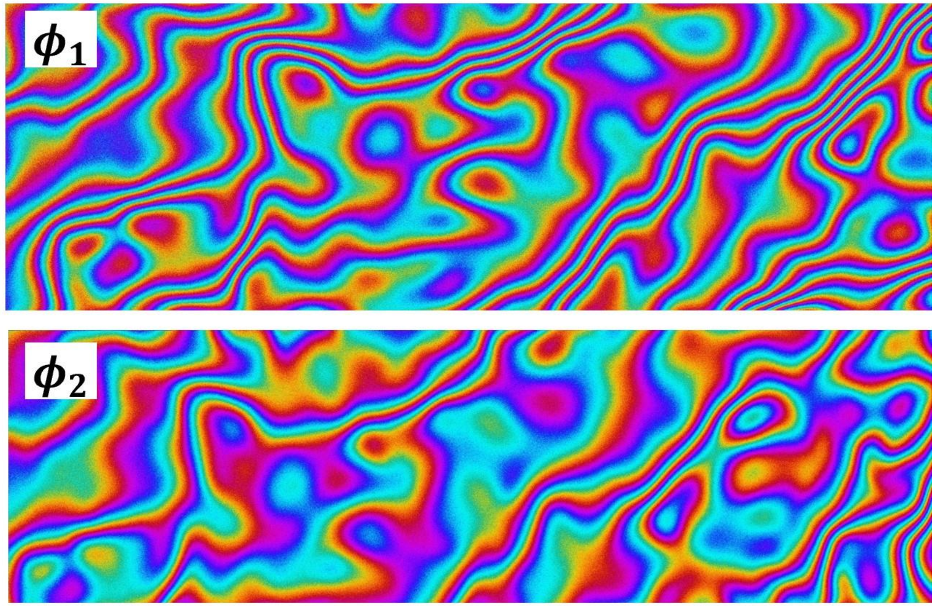
- Can be solved numerically
- Again, surface height retrieval does not require permittivity knowledge

Exploit Multiple Interferograms with Geometric Diversity

TanDEM-X Experiment

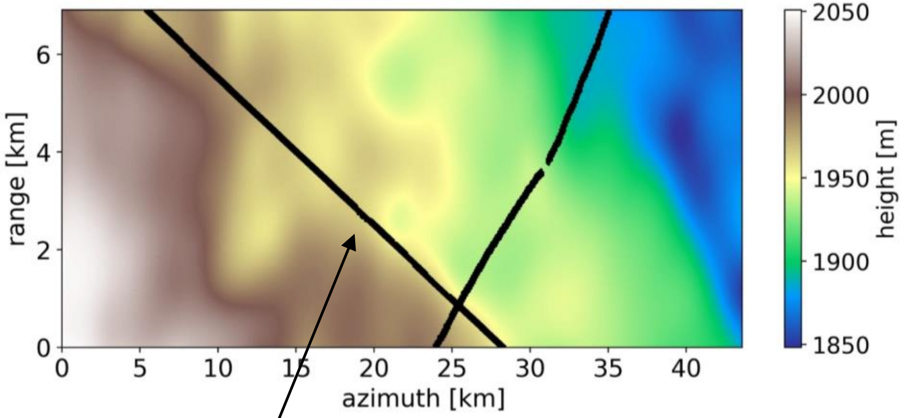
Parameter	Acquisition 1	Acquisition 2
Date	01.05.2015	02.05.2015
Mean incidence angle	35°	46°
Perpendicular baseline	455	383
Mean HoA	12 m	21.5 m



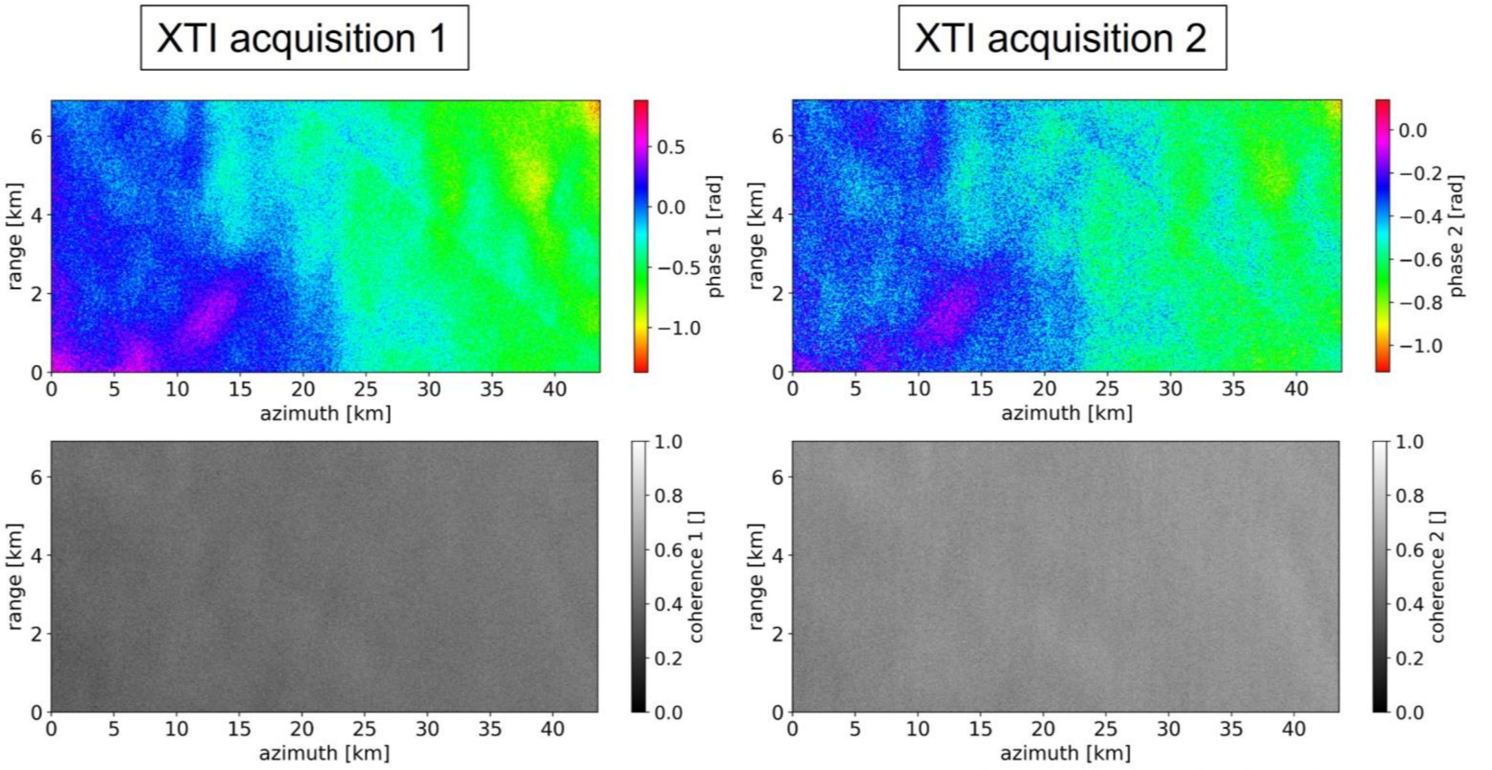


Exploit Multiple Interferograms with Geometric Diversity

Copernicus 30 m DEM in radar coordinates



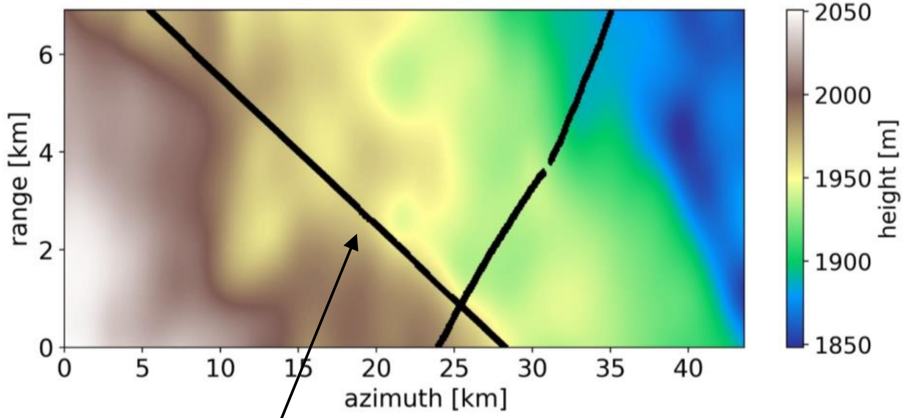
LIDAR tracks (Operation IceBridge)



Acquisition 2 is mapped to acquisition 1

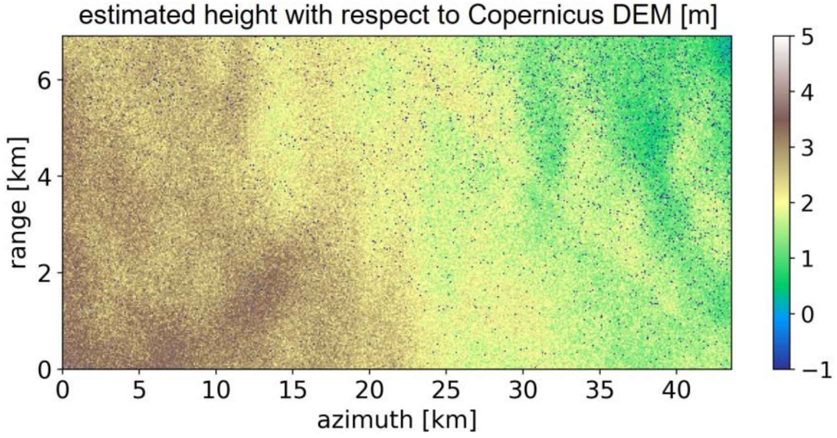
Exploit Multiple Interferograms with Geometric Diversity

Copernicus 30 m DEM in radar coordinates

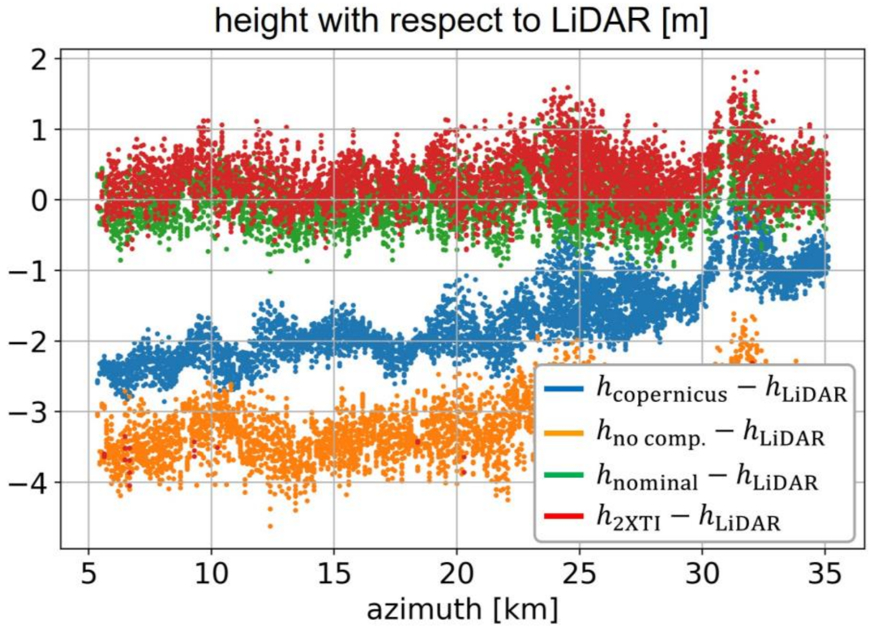


LIDAR tracks (Operation IceBridge)

Retrieved surface height from 2 InSAR phases with respect to Copernicus DEM



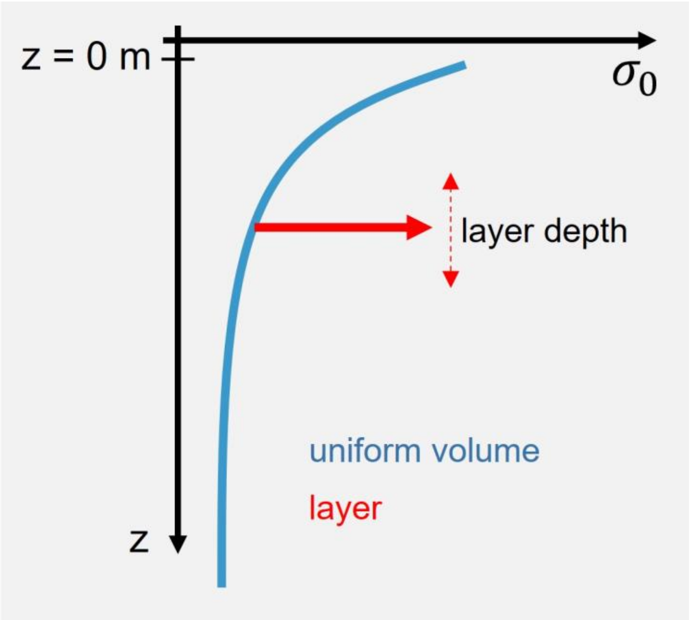
Comparison to LIDAR

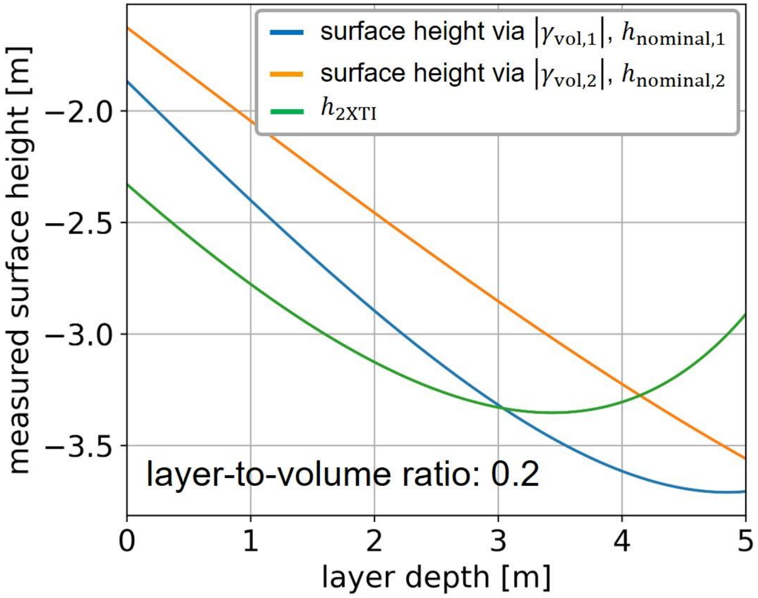


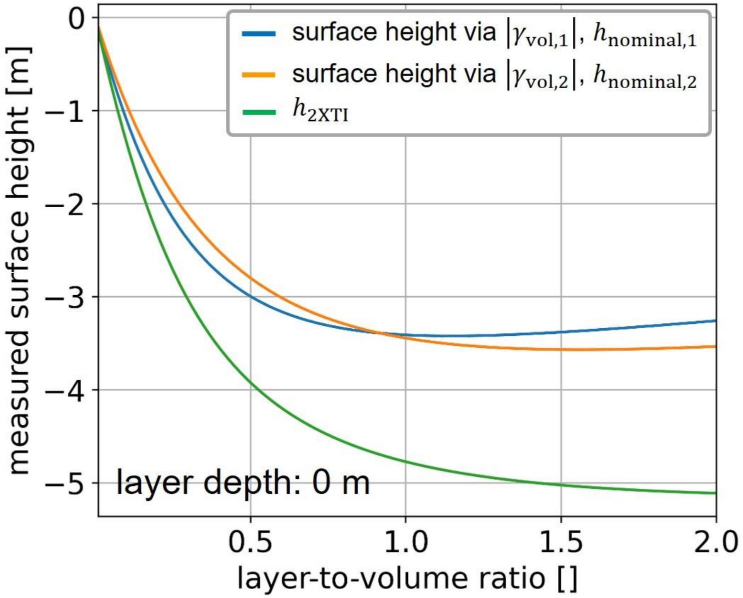
Exploit Multiple Interferograms with Geometric Diversity

Potential for identifying deviations from the Uniform Volume Model assumption

Example: UV model + layer





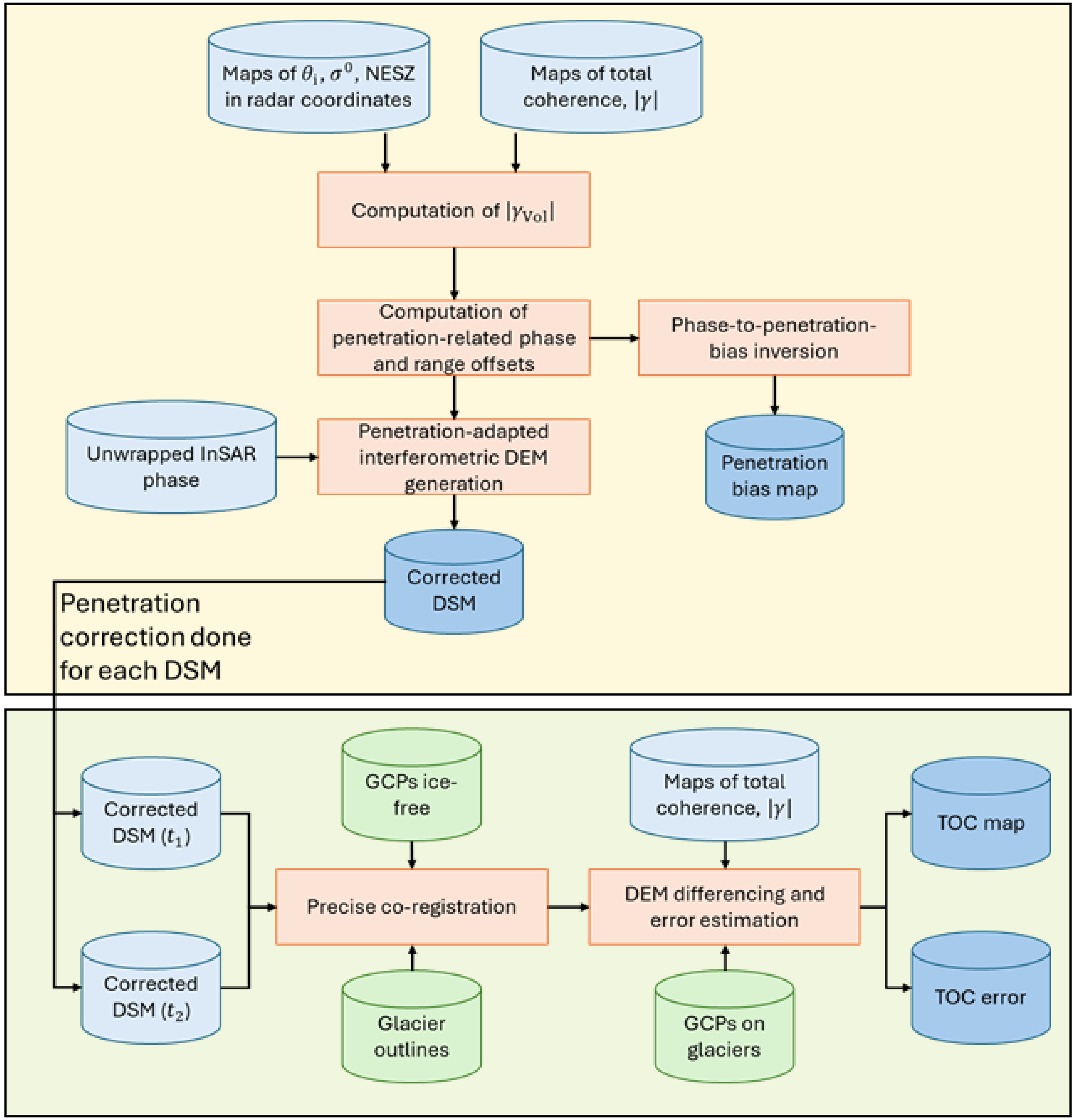


Summary

- Elevation bias correction is a fundamental aspect for the Harmony XTI products over ice sheets and glaciers
- Conventionally processed DEMs over dielectric dense volumes show a biased representation of the phase center height
- Surface height retrieval does not require permittivity knowledge
- Penetration correction should accommodate the full 3-D geolocation problem
- Squinted and bistatic Harmony geometry has only a mild impact on volume coherence and can be naturally accommodated
- Multiple interferograms with geometric diversity provide an interesting option for phase-only surface retrieval and potentially offer improved robustness to more complex volume distributions

Backup

Processing Flow for the TOC Product



Generation of penetration-corrected **Digital Surface Models (DSMs)**

Generation of **Topographic Change (TOC)** product

Elevation Bias Correction

Assuming a Uniform Volume Model with constant, isotropic extinction

Geometric Interpretation

$$h_s \approx h_{\mathrm{InSAR}} + \Delta h_{\mathrm{pc}} - \Delta h_2$$

Penetration bias retrieval via volume coherence (Uniform Volume Model):

$$\Delta h_{\mathrm{pc}} = \frac{1}{k_{z,\mathrm{Vol}}(\varepsilon_r')} \arctan\left(\sqrt{|\gamma_{\mathrm{Vol}}|^{-2} - 1}\right)$$

Propagation bias:

$$\Delta h_2 = \Delta h_{\mathrm{pc}} \cdot \left(1 - \sqrt{\varepsilon_r'} \cdot \frac{\cos\theta_i}{\cos\theta_r}\right)$$

$$h_s \approx h_{\mathrm{InSAR}} + \frac{1}{k_z} \arctan\left(\sqrt{|\gamma_{\mathrm{Vol}}|^{-2} - 1}\right) = h_{\mathrm{InSAR}} - \frac{\angle\gamma_{\mathrm{Vol}}}{k_z}$$

Elevation bias correction does not require firn permittivity (density) knowledge!