Antarctic sea ice elevation and roughness retrieval using polarimetric SAR interferometry

Lanqing Huang[1] and Irena Hajnsek[1,2]

1 Institute of Environmental Engineering, ETH Zurich

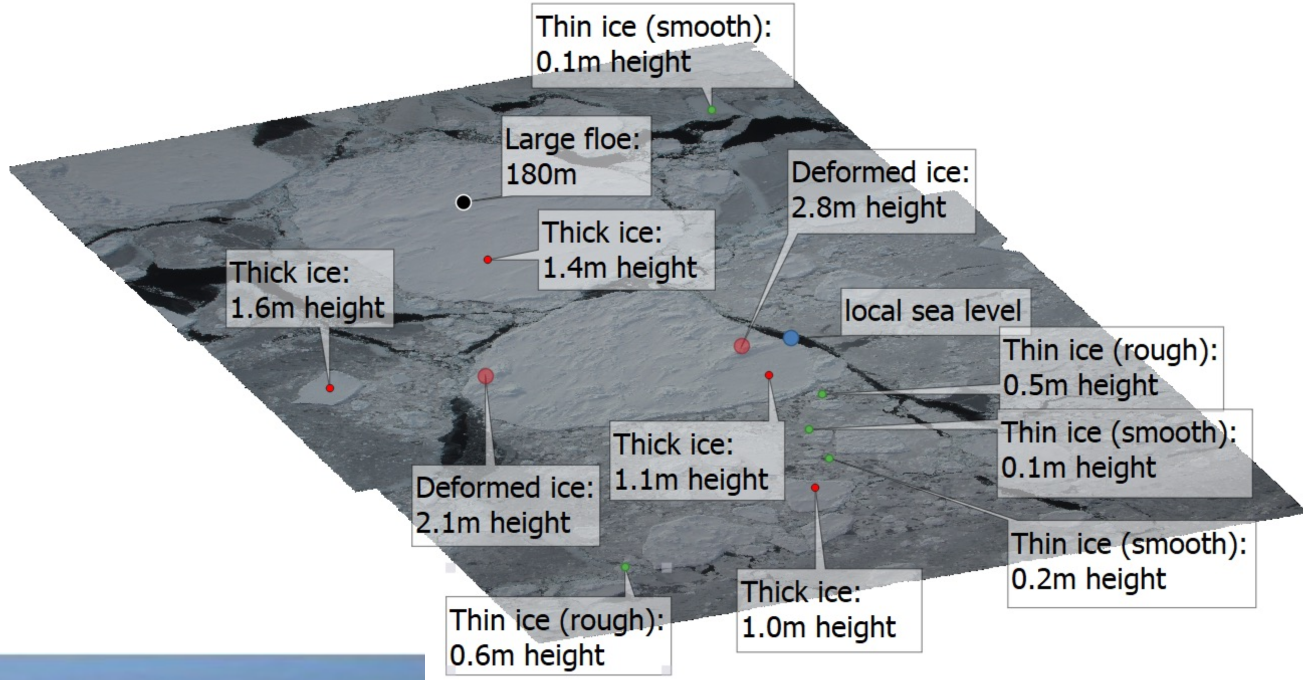
2 Microwaves and Radar Institute, DLR Oberpfaffenhofen

22/06/2022

0.Background

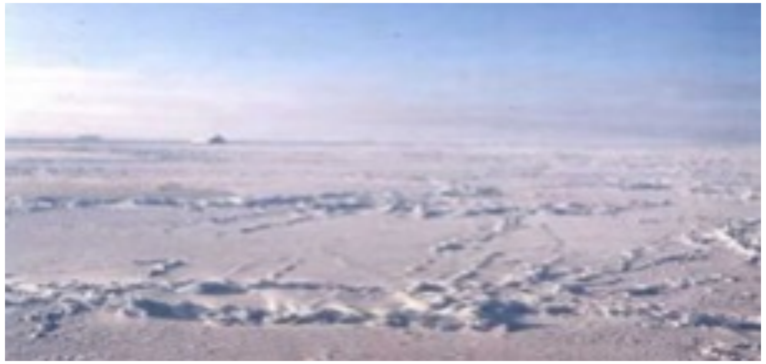
- **Sea ice** is frozen ocean water floating on the ocean surface.
- The topography of the sea ice is dominated by **ice ridges, shear zones, and hummocks,** leading to an intermittent change of the ice topography.

topography of the sea ice



Ridged sea ice [1]

Multi-year sea ice [1]



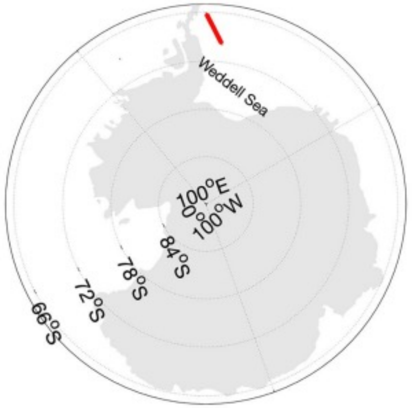
First-year sea ice [1]

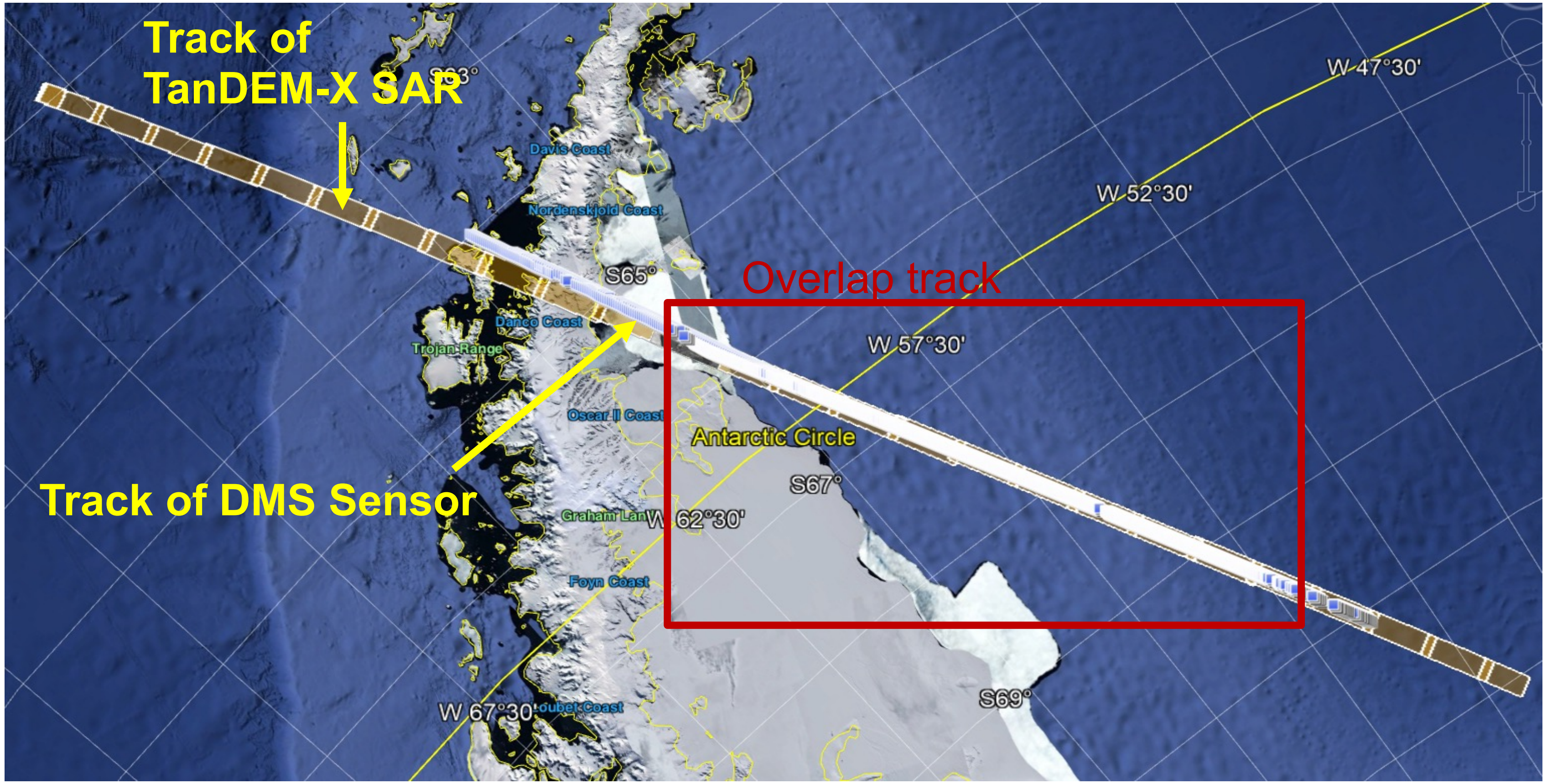
[1] All About Sea Ice., National Snow and Ice Data Center., https://nsidc.org/cryosphere/seaice/index.html.

1. OTASC Data Sets

- Coordinated campaign between spaceborne TanDEM-X from DLR and airborne Operation IceBridge (OIB) optical data from NASA [1];

- Western Weddell Sea on 29 October, 2017;
- **TanDEM-X SAR** from DLR: 9 spaceborne InSAR pairs;
- **Digital Mapping System (DMS)** sensor from NASA OIB aircraft.




Track of TanDEM-X SAR

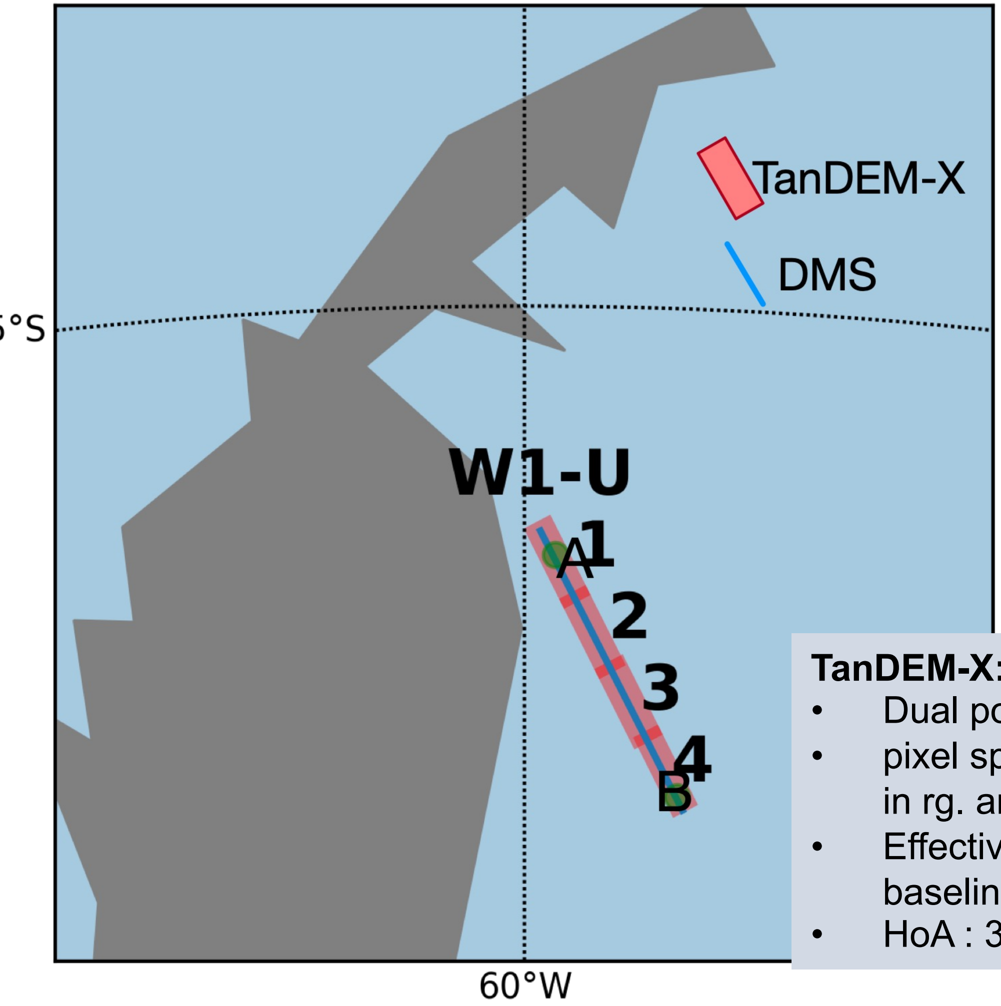
Track of DMS Sensor

Overlap track

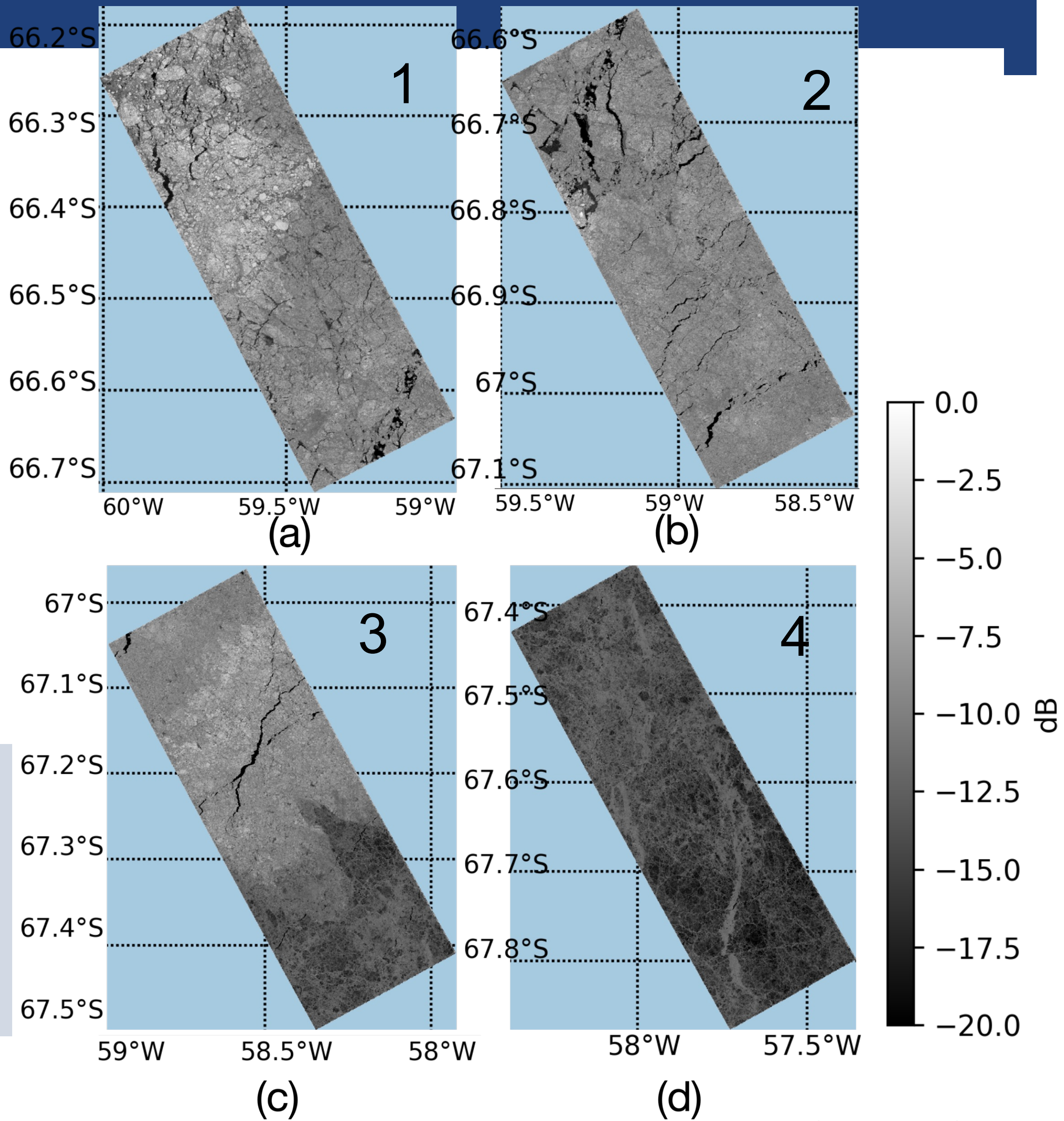
---

[1] Nghiem, Son, et al. "Remote sensing of antarctic sea ice with coordinated aircraft and satellite data acquisitions." *IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, 2018.

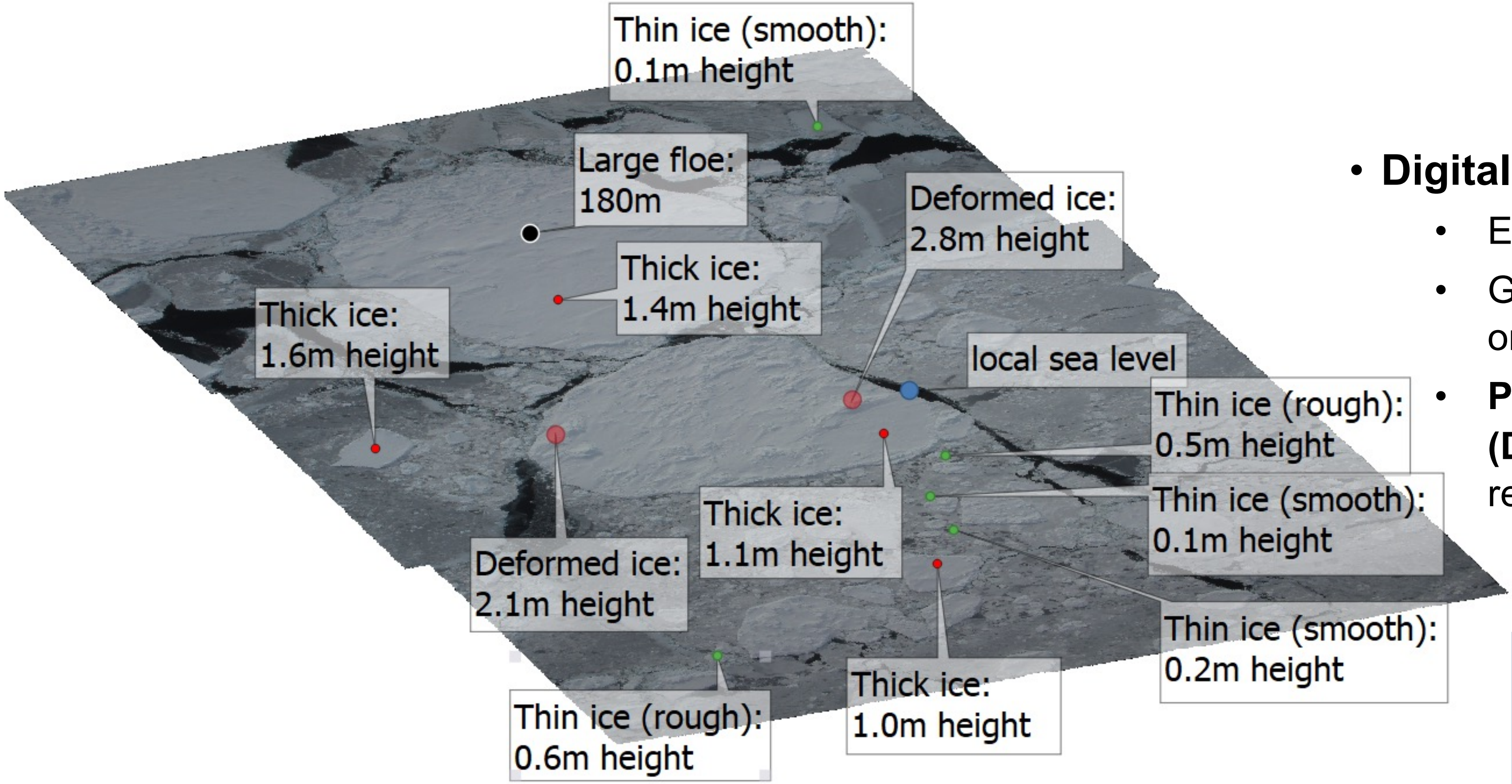
1. OTASC Data Sets - TanDEM-X



TanDEM-X:
- Dual pol (HH+VV)
- pixel spacing: 0.9m × 2.7m in rg. and az.
- Effective perpendicular baseline: 175.7m
- HoA : 32.5m.



1. OTASC Data Sets - DMS data



- **Digital Mapping System (DMS)**:
  - Equipped on the Operation IceBridge aircraft
  - Geolocated digital camera system with orthorectified images;
  - **Photogrammetric digital elevation model (DEM):** relative accuracy of ~0.2 m and a resolution of 40 cm by 40 cm.

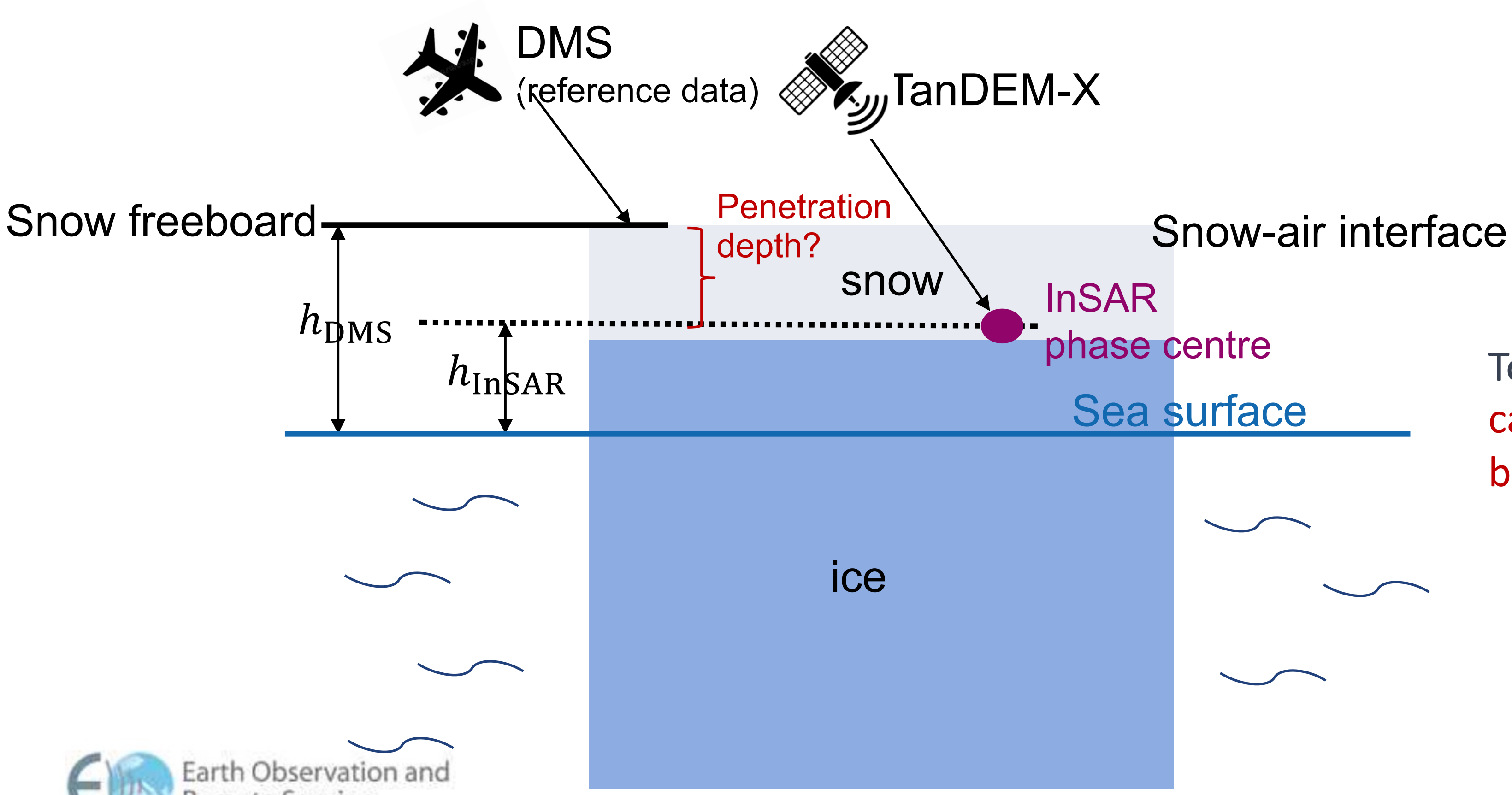
Co-registration was done manually as there are 6h temporal gap between TDM and DMS acquisition

DMS DEM is used as the reference data

2. Problem formulation

Objective: generate sea ice elevation (i.e., snow freeboard) from the single-pass InSAR data.

- Penetration of microwaves into old, thick, and deformed ice can be 0.3-1m [1]
- Dry snow is transparent to X-band radar

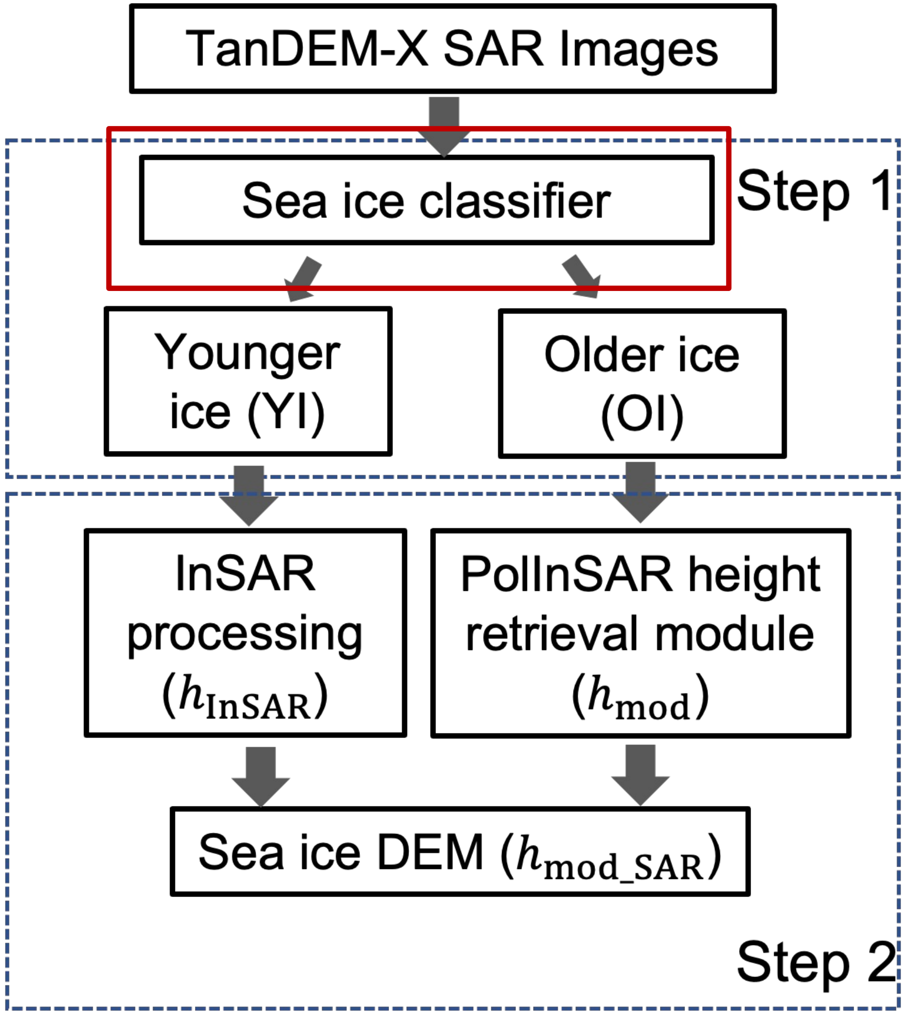


- Radar penetration into snow and ice is negligible for younger sea ice (due to the higher salinity)[1]

↓

To accurately retrieve sea ice elevation, categorizing sea ice based on penetration bias variation is essential.

3. Method



TanDEM-X SAR Images

Sea ice classifier

Step 1

Younger ice (YI)

Older ice (OI)

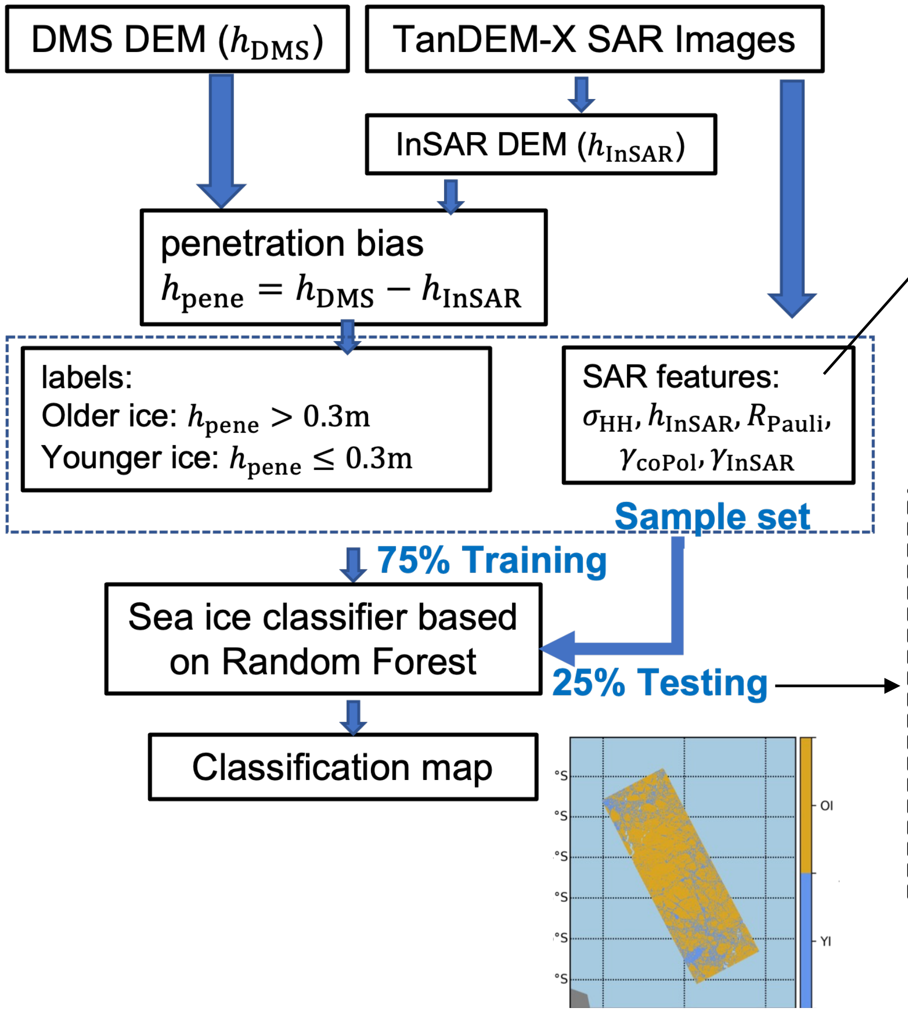
InSAR processing (h_{InSAR})

PolInSAR height retrieval module (h_{mod})

Sea ice DEM ($h_{\mathrm{mod\_SAR}}$)

Step 2

Sea ice classification according to radar penetration depth



DMS DEM (h_{DMS})

TanDEM-X SAR Images

InSAR DEM (h_{InSAR})

penetration bias
$h_{\mathrm{pene}} = h_{\mathrm{DMS}} - h_{\mathrm{InSAR}}$

labels:
Older ice: $h_{\mathrm{pene}} > 0.3\mathrm{m}$
Younger ice: $h_{\mathrm{pene}} \leq 0.3\mathrm{m}$

SAR features:
$\sigma_{\mathrm{HH}}, h_{\mathrm{InSAR}}, R_{\mathrm{Pauli}}, \gamma_{\mathrm{coPol}}, \gamma_{\mathrm{InSAR}}$

Sample set

75% Training

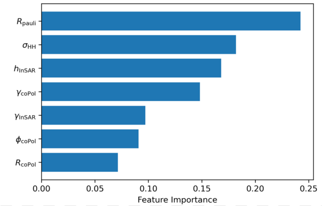
25% Testing

Sea ice classifier based on Random Forest

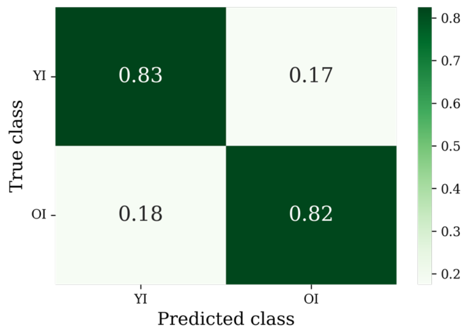
Classification map

SAR features:

- Backscattering intensity in HH
- InSAR phase center
- InSAR coherence
- Pauli ratio
- Co-pol coherence

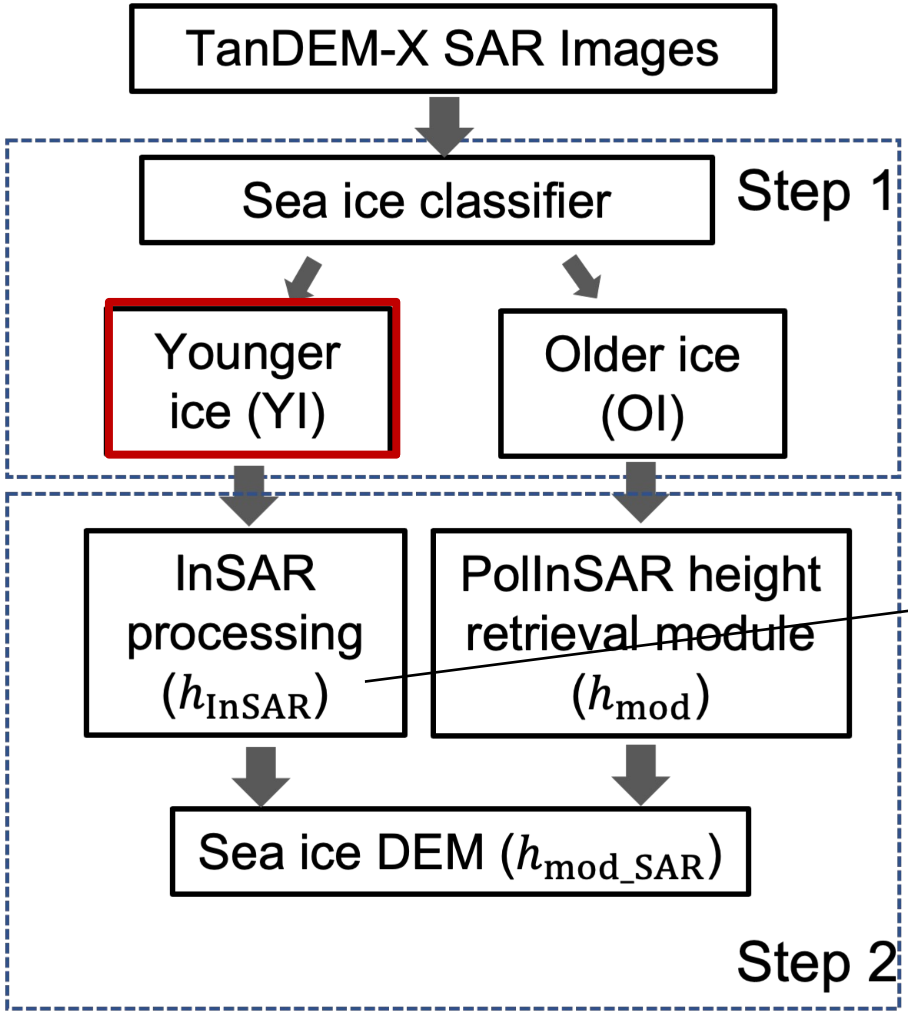


Accuracy = 0.84



3. Method

YI: radar penetration into snow and ice is negligible[1]



TanDEM-X SAR Images

Step 1

Sea ice classifier

Younger ice (YI)

Older ice (OI)

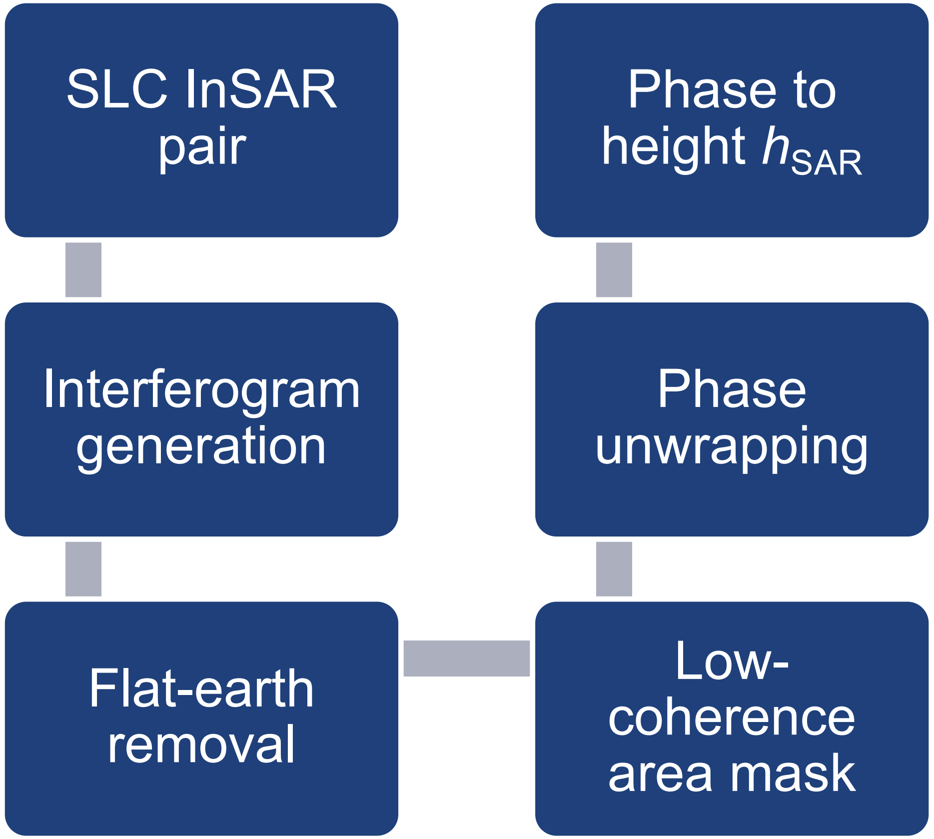
Step 2

InSAR processing (h_{InSAR})

PolInSAR height retrieval module (h_{mod})

Sea ice DEM ($h_{\mathrm{mod\_SAR}}$)

InSAR processing



SLC InSAR pair

Interferogram generation

Flat-earth removal

Low-coherence area mask

Phase unwrapping

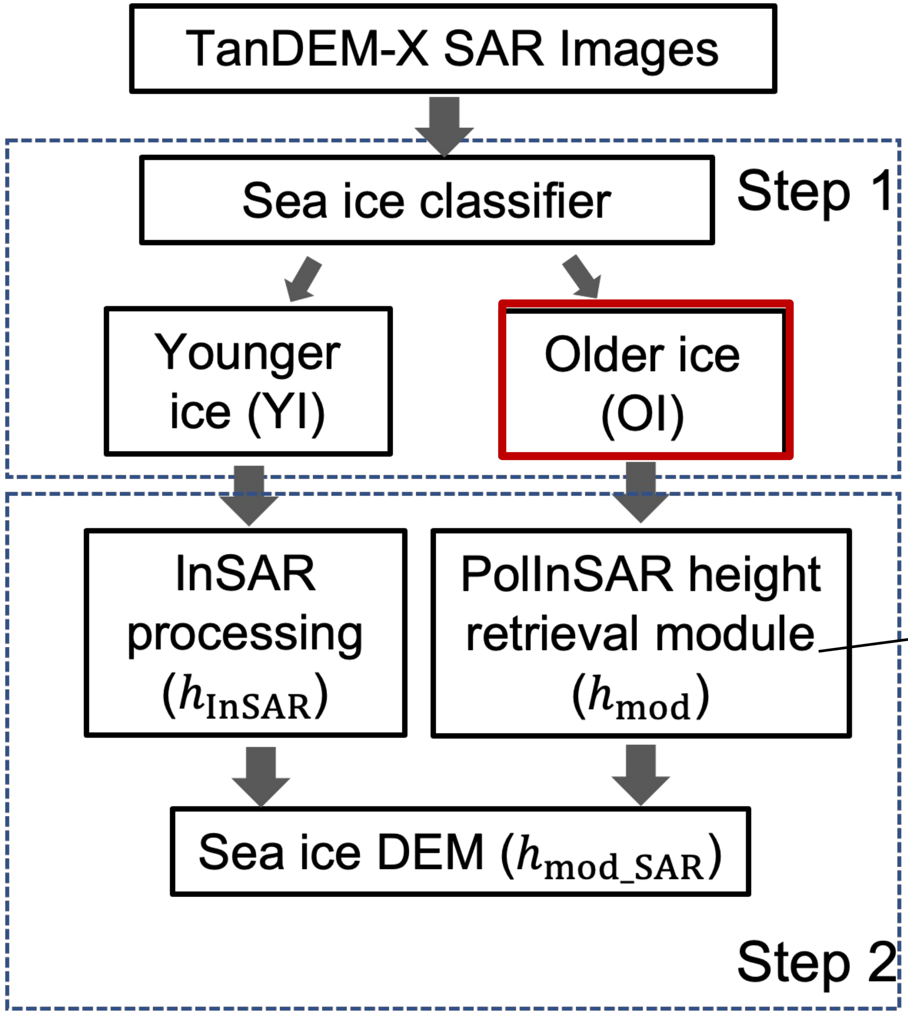
Phase to height h_{SAR}

---

[1] Martti Hallikainen and Dale P Winebrenner, “The physical basis for sea ice remote sensing,” Microwave remote sensing of sea ice, vol. 68, pp. 29–46 1992.

Earth Observation and Remote Sensing

3. Method



TanDEM-X SAR Images

Step 1

Sea ice classifier

Younger ice (YI)

Older ice (OI)

OI: radar penetration into snow and ice need to be corrected

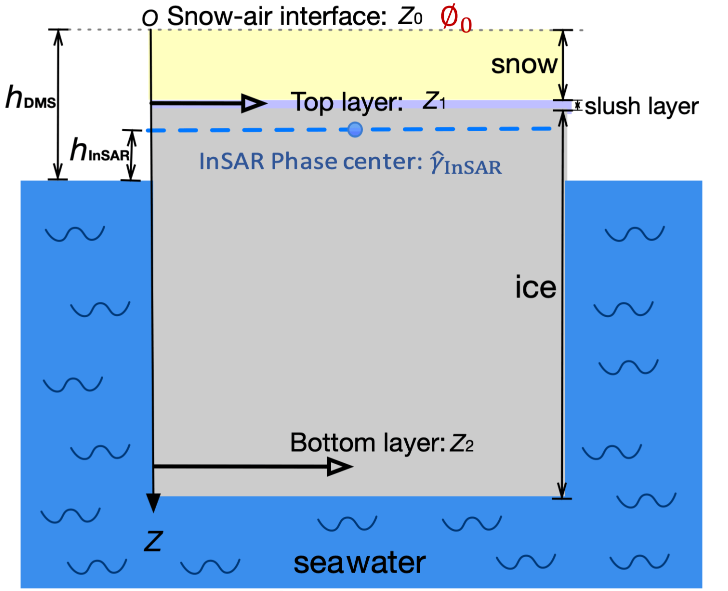
InSAR processing (h_{InSAR})

PolInSAR height retrieval module (h_{mod})

Sea ice DEM ($h_{\text{mod\_SAR}}$)

Step 2

Two-layer plus volume model [1]



$$\gamma_{InSAR} = e^{i\phi_0}\frac{1\cdot e^{i\phi_1}+me^{i\phi_2}}{1+m} = e^{i\phi_0}\gamma_{mod\_S}(m,z_1,z_2)$$

Complex InSAR coherence

Model inversion [1]

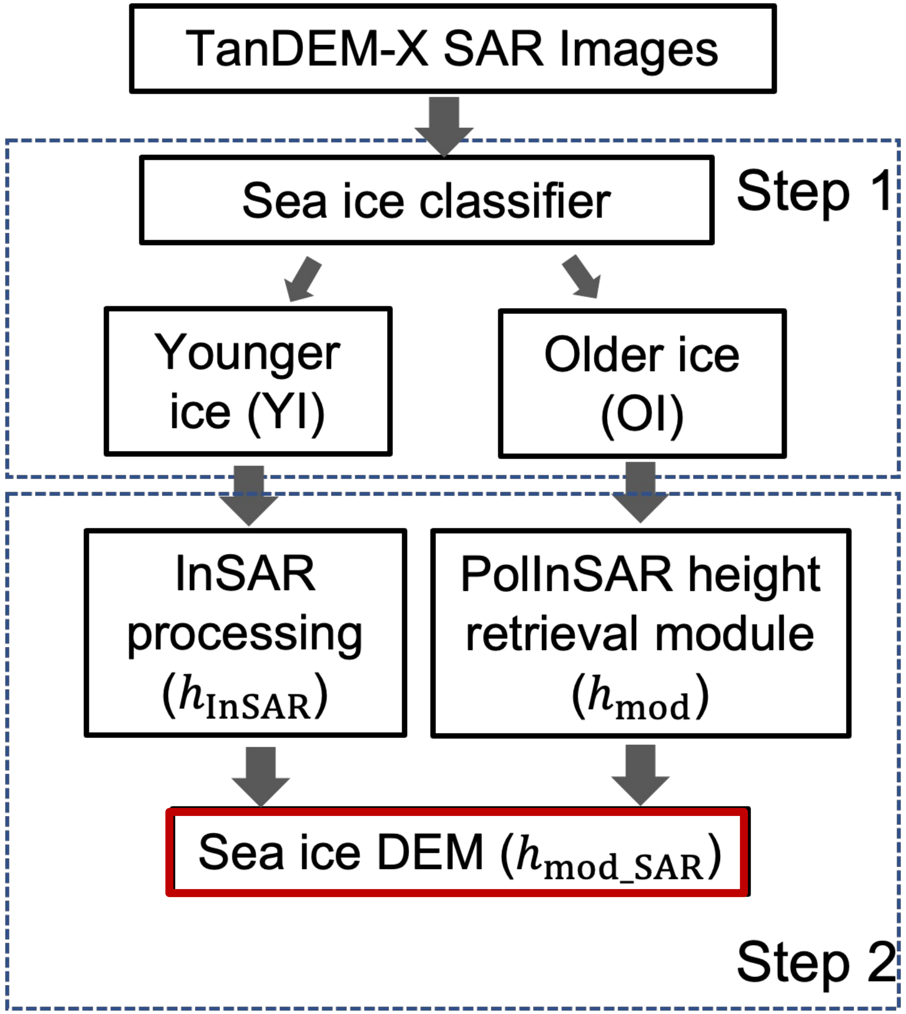
Z_1: snow depth
m: layer-to-layer ratio

➡

$\emptyset_0$: topography phase (our aim)
Z_2: position the bottom layer

[1] Huang, Lanqing, Georg Fischer, and Irena Hajnsek. "Antarctic snow-covered sea ice topography derivation from TanDEM-X using polarimetric SAR interferometry." *The Cryosphere* 15.12 (2021): 5323-5344.

3. Method



TanDEM-X SAR Images

Step 1

Sea ice classifier

Younger ice (YI)

Older ice (OI)

Step 2

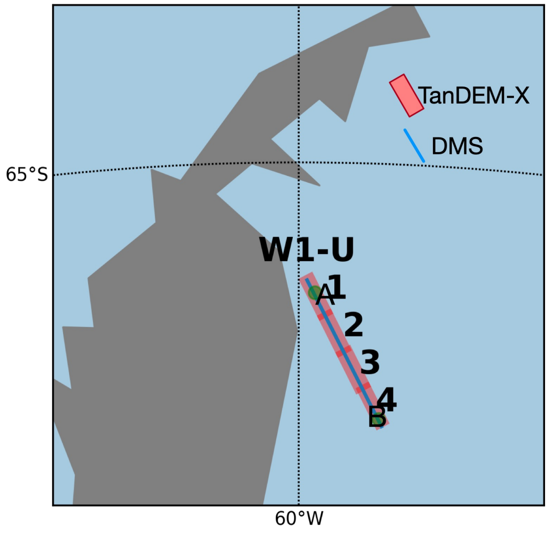
InSAR processing (h_{InSAR})

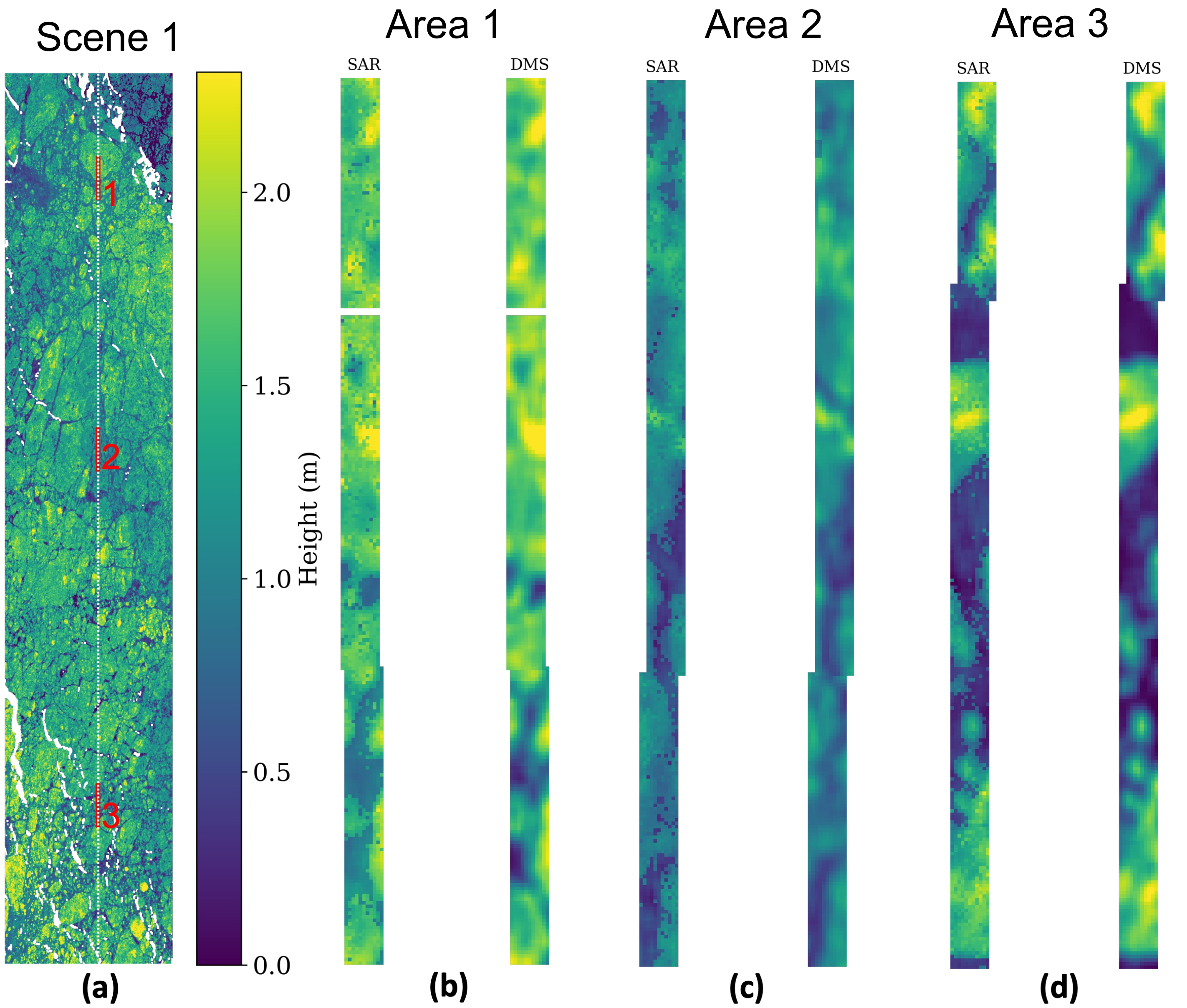
PolInSAR height retrieval module (h_{mod})

Sea ice DEM ($h_{\mathrm{mod\_SAR}}$)

4. Result

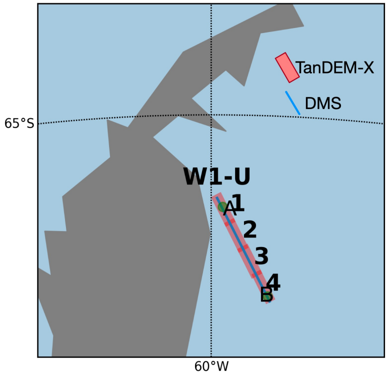
- Sea ice elevation (i.e., snow freeboard) derived using the proposed method
- Visual validation: SAR DEM vs DMS DEM

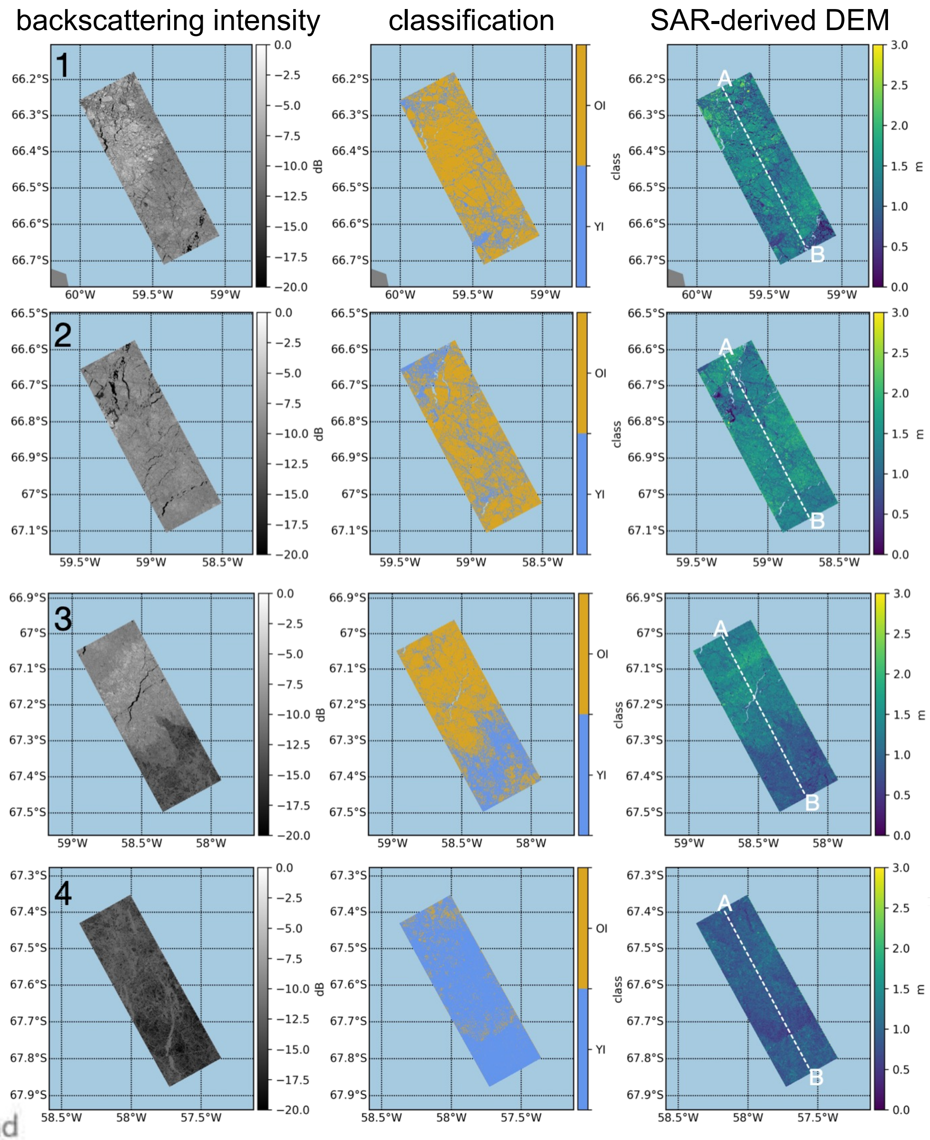


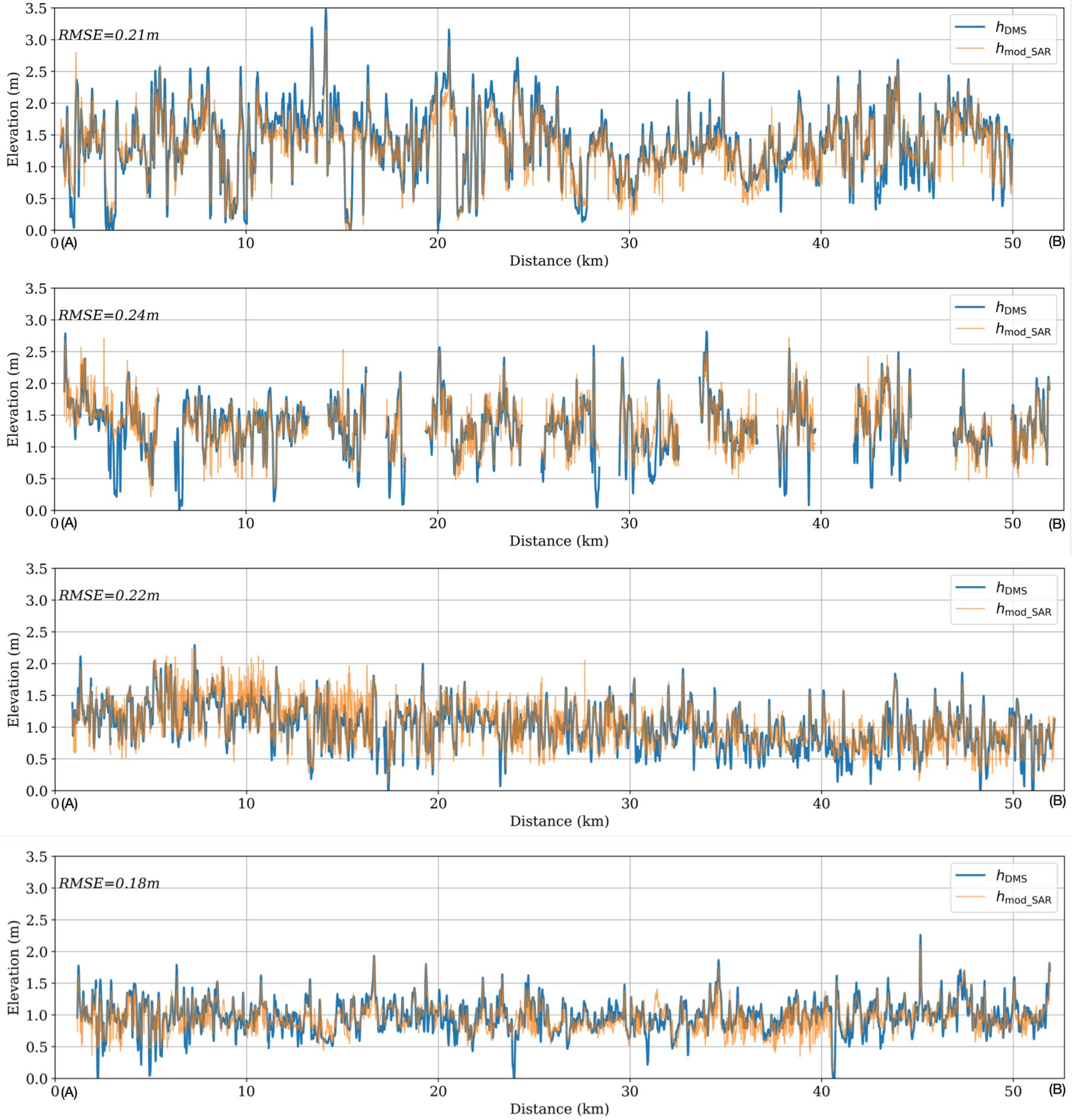


4. Result

- Quantitative validation







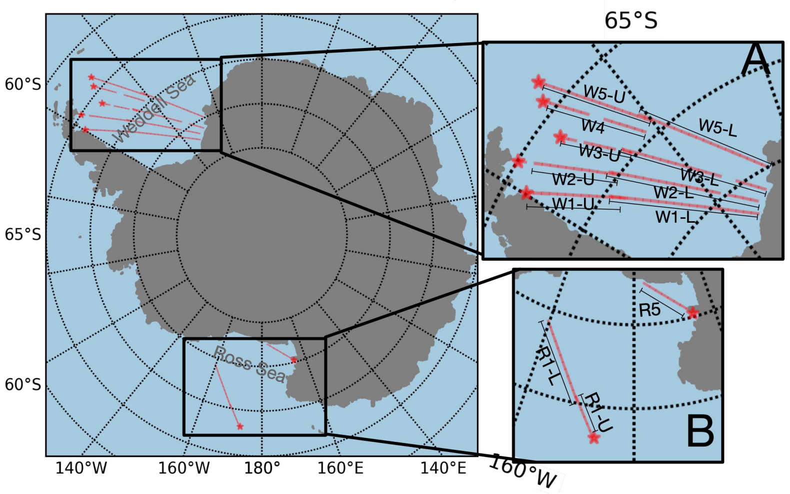
Earth Observation and Remote Sensing

4. Result

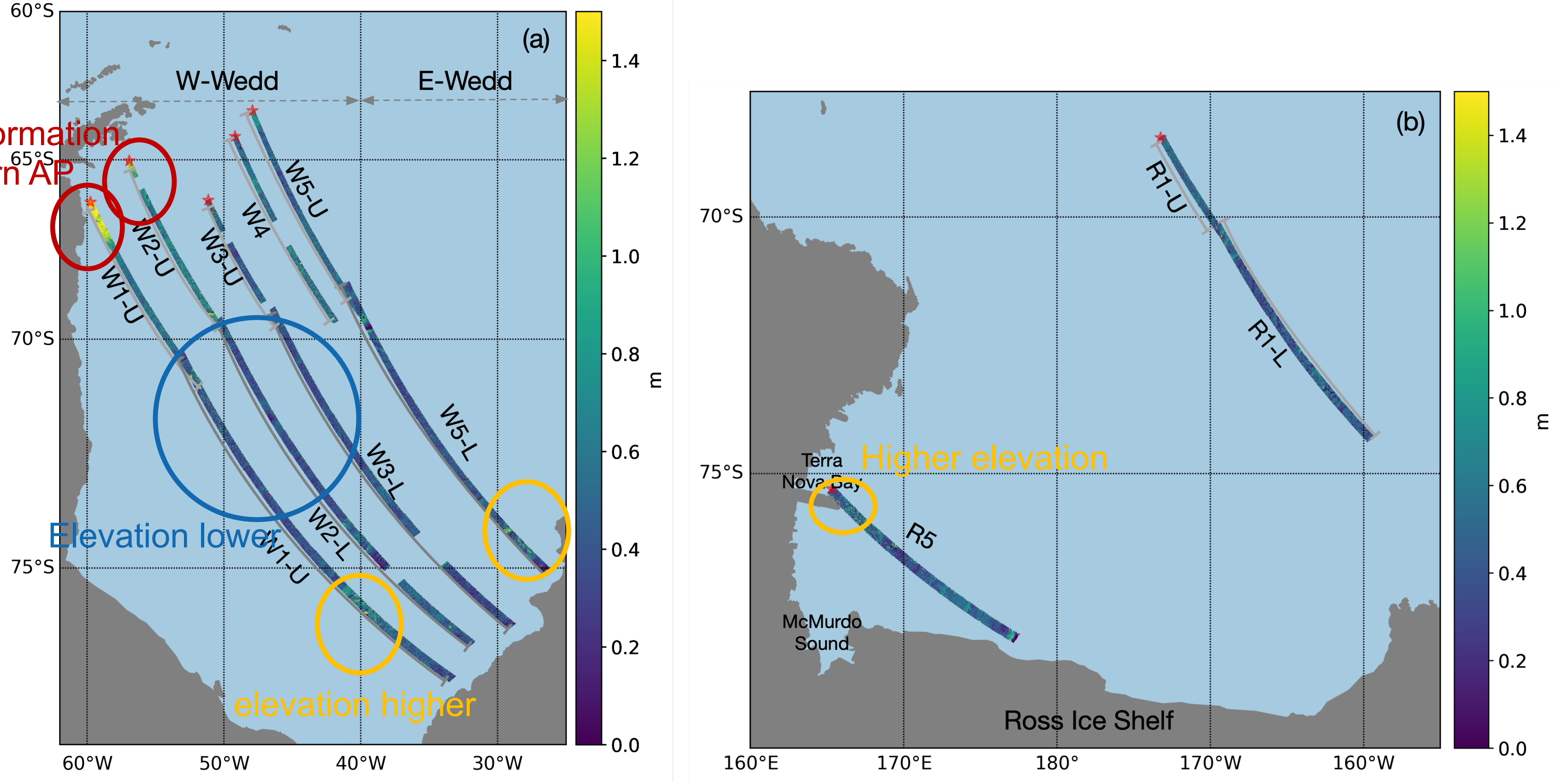
Applying the proposed into over an extended region in Weddell and Ross Sea

- 162 TanDEM-X images
- October-November in 2017
- Stripmap dual-polarization (HH+VV)

Extended region



SAR-derived DEM



Significant deformation near the eastern AP

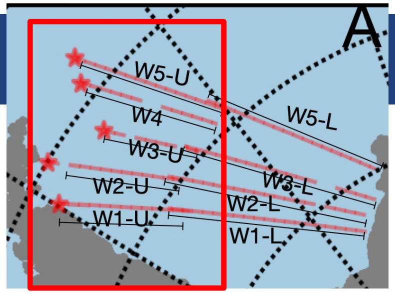
Elevation lower

elevation higher

Higher elevation

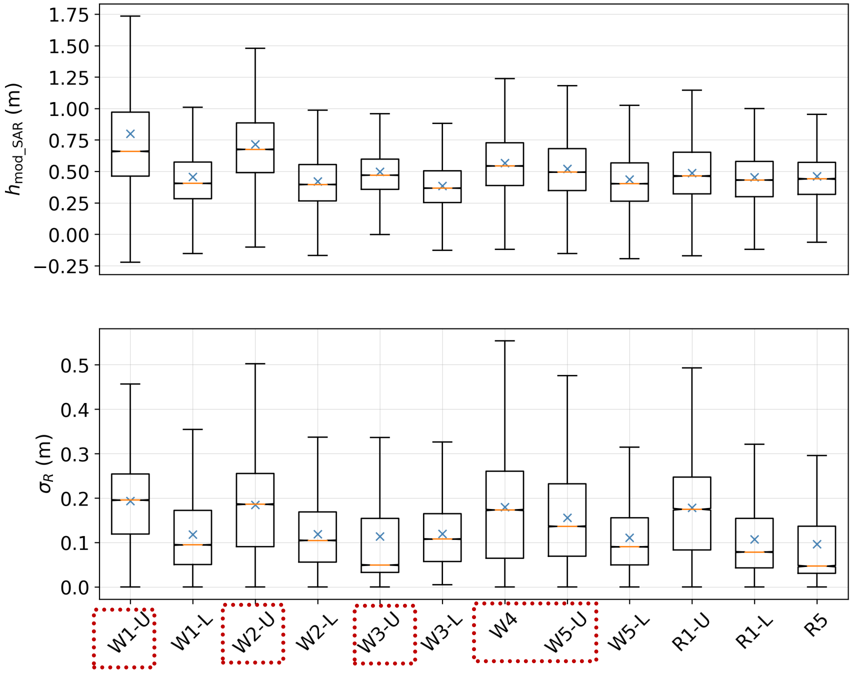
4. Result

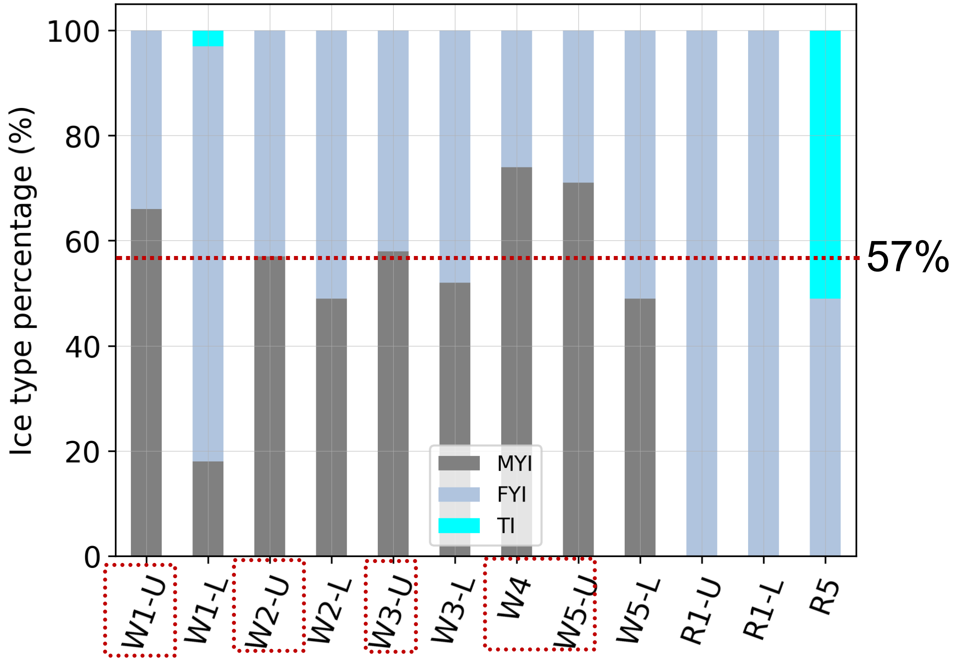
Northwestern
Weddell sea



Regional variation of sea ice topography

- Roughness: the standard deviation of the elevation within a 50×50m area
- Ice chart: US. National Ice Center





Sector	Mean elevation (m)	Mean roughness (m)
W1-U	0.80	0.19
W1-L	0.46	0.12
W2-U	0.72	0.19
W2-L	0.42	0.12
W3-U	0.50	0.11
W3-L	0.39	0.12
W4	0.57	0.18
W5-U	0.52	0.16
W5-L	0.44	0.11
R1-U	0.49	0.18
R1-L	0.45	0.11
R5	0.46	0.10

- Sea ice in the northwestern Weddell Sea exhibits higher averaged elevations (>0.5m) than the southeastern region and Ross Sea.
- Topographic values (i.e., elevation and roughness) are consistent with the ice types, where exhibit a substantial proportion (>57%) of MYI.

5. Recap

- Proposed **a method to retrieve sea ice elevation** (i.e., snow freeboard) from dual-polarization interferometric SAR images, taking into account the significant variation in penetration bias across different ice types.
- The proposed method was applied to a broad area spanning the Weddell Sea and the Ross Sea
    - Sea ice undergoes **significant deformation nearby the eastern AP**.
    - Sea ice in the **northwestern** Weddell Sea exhibits **higher** averaged elevations than the southeastern region
    - Sea ice topography provide additional information to sea ice classification mapping

Thank you !

0.Background

Why needs SAR?

- High spatial resolution at meter scales
- Regardless of cloud cover, darkness, and weather conditions
- Invaluable for monitoring ocean and remote areas, particular for polar regions

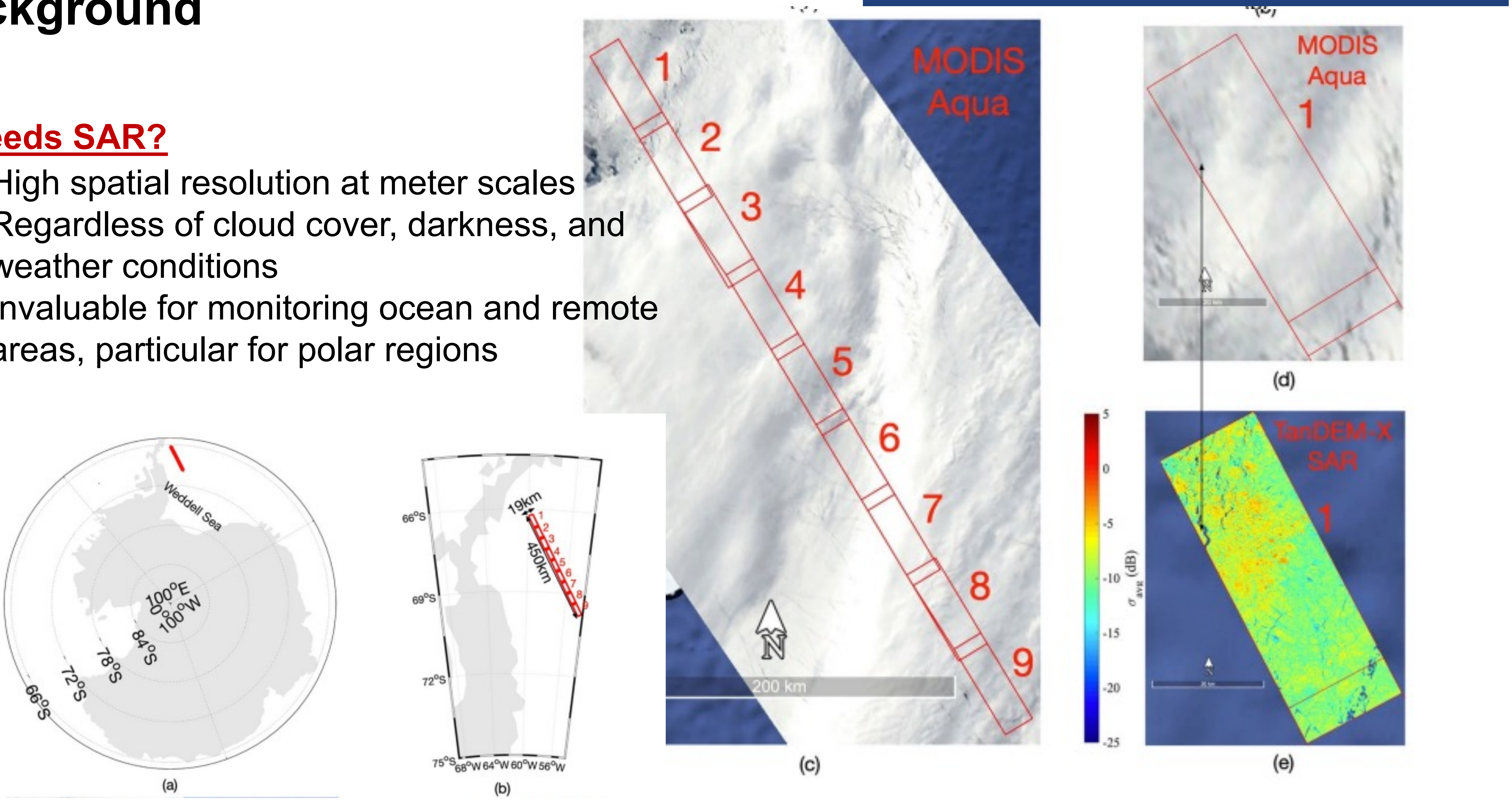
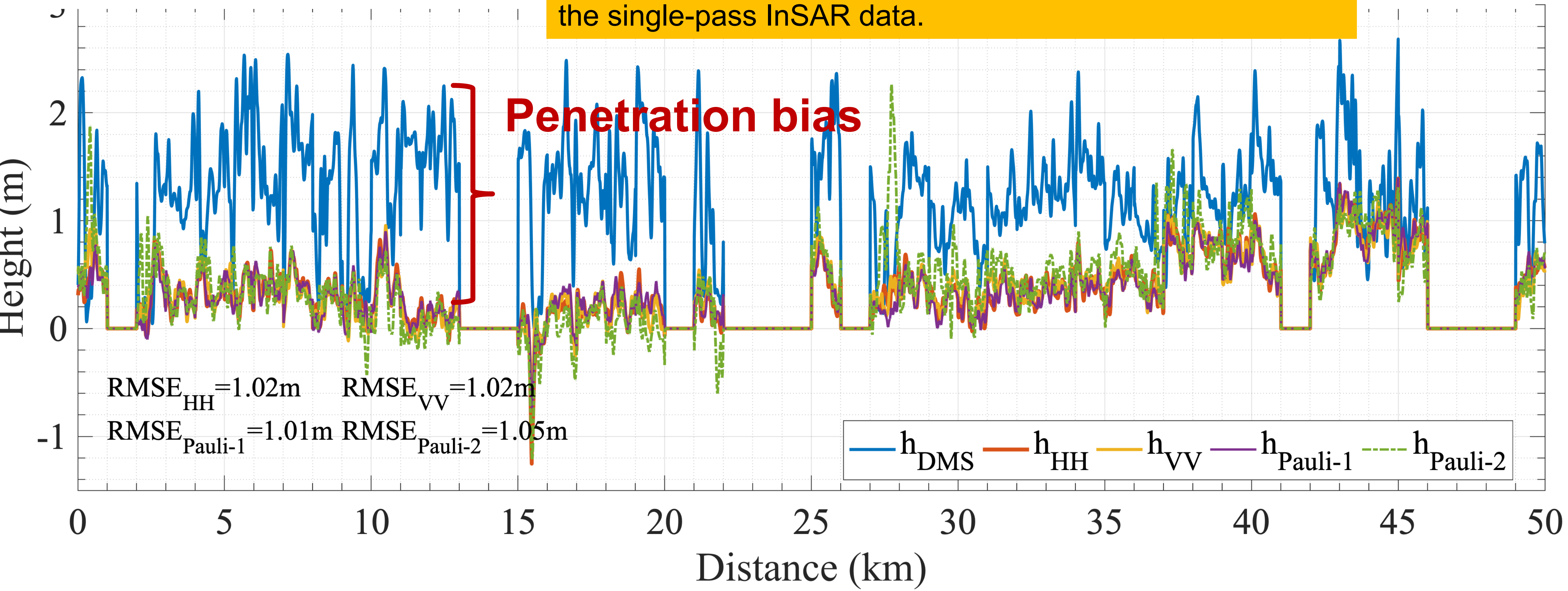


Figure 1. Demonstration of the study area (Scenes 1–9). (a) and (b) Geo-location of the study area. (c) Optical MODIS Aqua images over the study area. (d) Optical MODIS Aqua image over Scene 1. (e) TanDEM-X SAR image over Scene 1; the pseudo color represents the averaged noise-subtracted backscattering intensity of HH and VV polarizations.

2. Problem formulation

Objective: correct the penetration bias of InSAR method and generate sea ice elevation (including snow cover) from the single-pass InSAR data.



Penetration bias

$RMSE_{HH}$=1.02m $RMSE_{VV}$=1.02m

$RMSE_{Pauli-1}$=1.01m $RMSE_{Pauli-2}$=1.05m

3.2. Pol-InSAR model

Interferometric coherence decomposition

$$\boxed{\tilde{\gamma}_{\mathrm{InSAR}}} = e^{i\overset{1}{\boxed{\phi_0}}}\,\overset{2}{\cancel{\boxed{\gamma_s}}}\,\overset{3}{\cancel{\boxed{\gamma_{\mathrm{SNR}}}}}\,\overset{4}{\boxed{\tilde{\gamma}_v}}$$

Measured from data

1: topographic phase. The objective of this study.

2: baseline or surface decorrelation which depends on the nature of the surface scattering; it can always be removed by employing range spectral filtering and thus is set equal to 1 in this study.

3: decorrelation due to additive noise in the signals, only contribute to the magnitude, can be corrected using NESZ values.

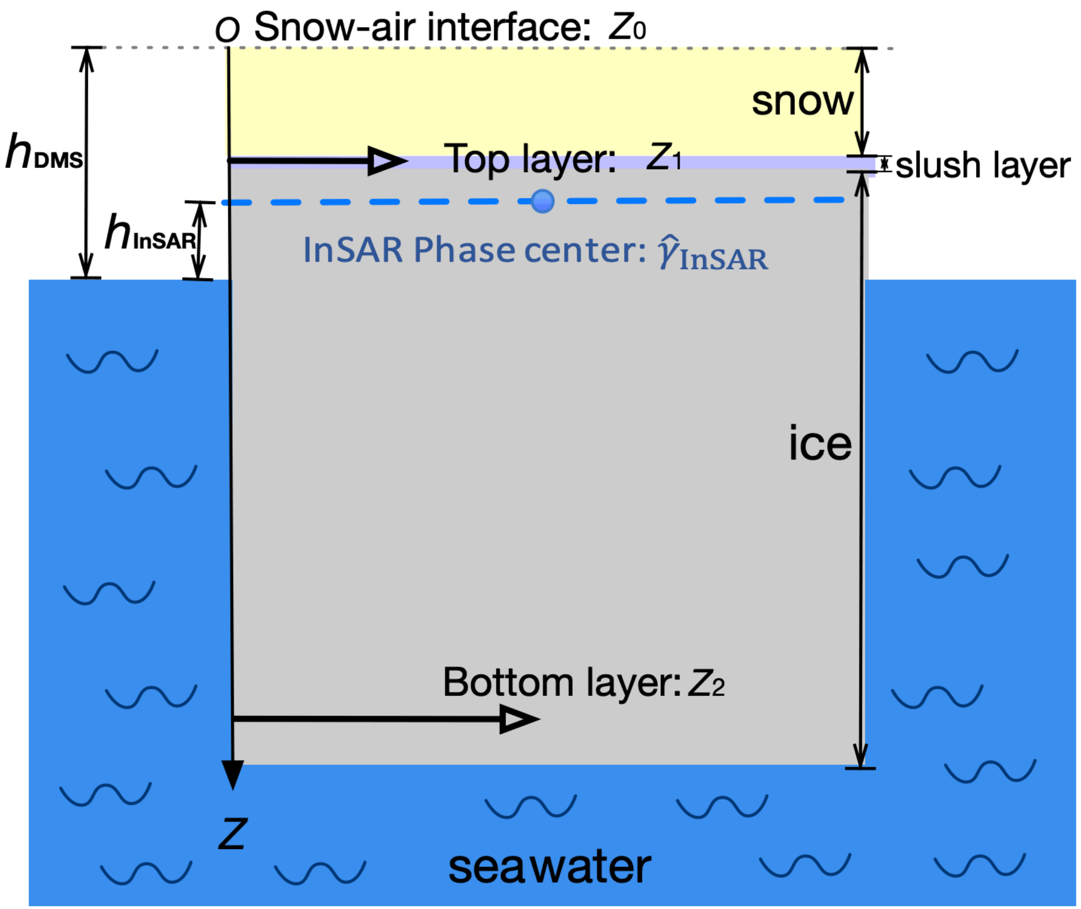
4: complex volume decorrelation. This study develops a model to estimate it.

$$\tilde{\gamma}_v = \frac{\int_0^D \boxed{\sigma_v(z)}\, e^{i\boxed{\kappa_{z\_\mathrm{vol}}}z}\, dz}{\int_0^D \sigma_v(z)\, dz}$$

Complex volume decorrelation can be estimated by choosing an appropriate **vertical structural function** and a suitable **InSAR baseline** configuration

4. Method

Proposed model: 2-Layer Plus Volume Model



Two Surface scattering: top layer and bottom layer
Two Volume scattering: snow volume and ice volume

Assumed to be uniform volume

Snow volume · ice volume · Top layer · Bottom layer

$$\gamma_{InSAR} = e^{i\phi_0}\frac{\alpha\boxed{\gamma_v(\sigma_1, z_{01})} + e^{i\phi_1}(1-\alpha)\boxed{\gamma_v(\sigma_2, z_{12})} + m_1 e^{i\phi_1} + m_2 e^{i\phi_2}}{1 + m_1 + m_2}$$

$$= e^{i\phi_0}\gamma_{mod\_T}(\sigma_1, \sigma_2, \alpha, m_1, m_2, z_1, z_2)$$

7 parameters! ➡ Model simplicity required

σ_1 snow extinction coefficient
σ_2 ice extinction coefficient
α weight parameter between snow and ice volume
m_1 is layer-to-volume scattering ratio of top layer
m_2 is layer-to-volume scattering ratio of bottome layer
z_{01}= z_0-z_1 snow volume
z_{12}= z_1-z_2 ice volume
z_0 is set to 0 z_1 and z_2 are the positions of the two layers with negative values

4. Method

Simplification of the model

Merge the contributions of the **snow volume**, the **ice volume**, and **the top layer** into one Dirac delta

$$\gamma_{InSAR} = e^{i\phi_0}\frac{\boxed{\alpha\gamma_v(\sigma_1, z_{01})} + \boxed{e^{i\phi_1}(1-\alpha)\gamma_v(\sigma_2, z_{02})} + \boxed{m_1 e^{i\phi_1}} + m_2 e^{i\phi_2}}{1 + m_1 + m_2}$$

$$= e^{i\phi_0}\gamma_{mod\_T}(\cancel{\sigma_1}, \cancel{\sigma_2}, \cancel{\alpha}, \cancel{m_1}, m_2, z_1, z_2)$$

7 parameters!

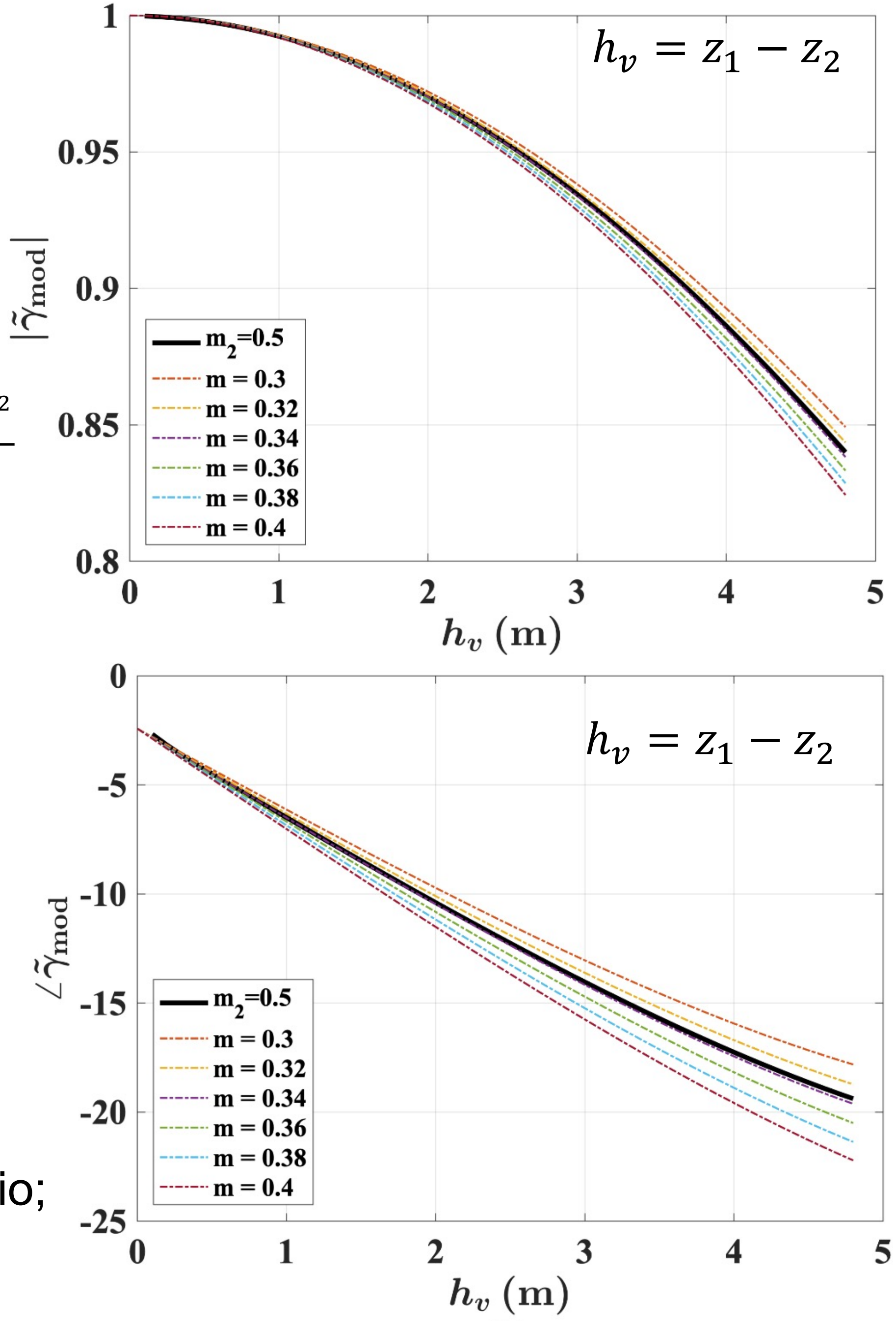
The approximated by merging the contributions of the snow volume, the ice volume, and the top layer into one Dirac delta:

$$\gamma_{InSAR} = e^{i\phi_0}\frac{1 \cdot e^{i\phi_1} + m e^{i\phi_2}}{1 + m}$$

$$= e^{i\phi_0}\gamma_{mod\_S}(m, z_1, z_2)$$

3 parameters!

z_1 and z_2 position of the top and bottom layer, m is the layer-to-layer ratio;



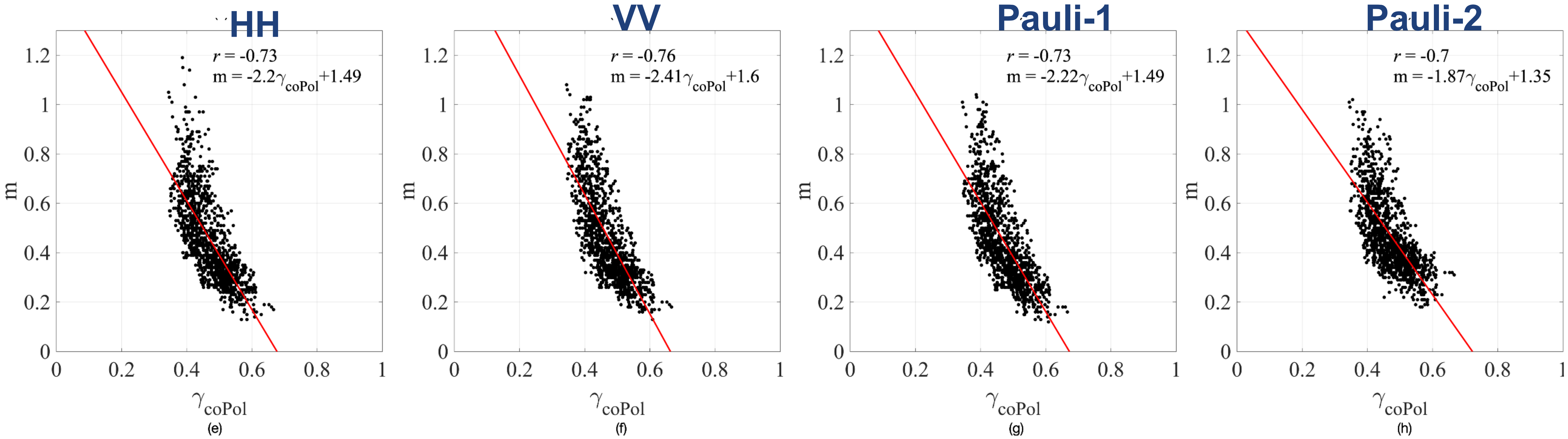
(b)

Simplified model:

$$\gamma_{InSAR} = e^{i\phi_0}\frac{1\cdot e^{i\phi_1}+me^{i\phi_2}}{1+m} = e^{i\phi_0}\gamma_{mod\_S}(m,z_1,z_2)$$

z_1 and z_2 position of the top and bottom layer, m is the layer-to-layer ratio;

Relation between the layer-to-layer ratio *m* and the coPol coherence



(e) (f) (g) (h)

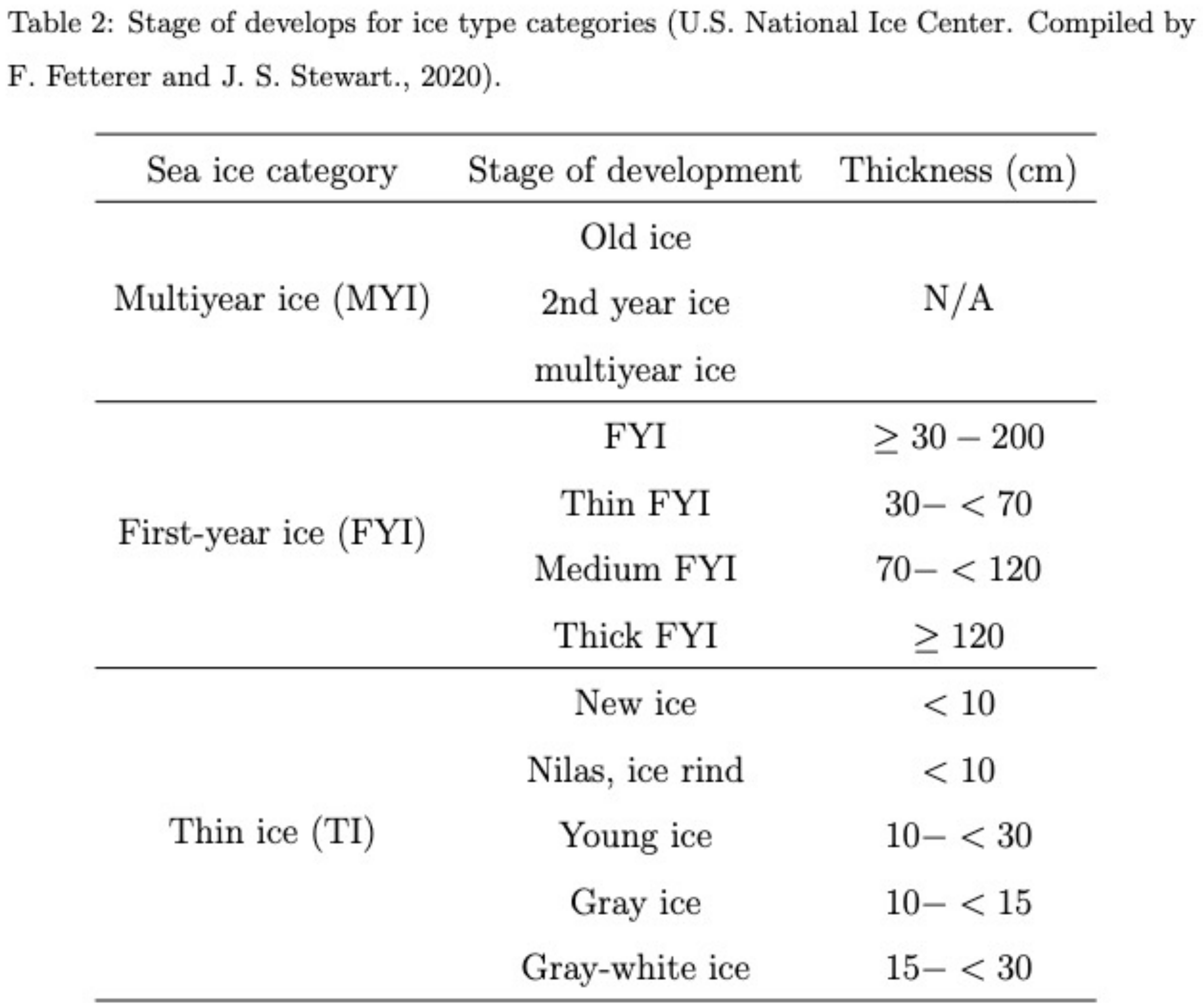


Table 2: Stage of develops for ice type categories (U.S. National Ice Center. Compiled by F. Fetterer and J. S. Stewart., 2020).

Sea ice category	Stage of development	Thickness (cm)
Multiyear ice (MYI)	Old ice 2nd year ice multiyear ice	N/A
First-year ice (FYI)	FYI	$\geq 30 - 200$
	Thin FYI	$30- < 70$
	Medium FYI	$70- < 120$
	Thick FYI	≥ 120
Thin ice (TI)	New ice	< 10
	Nilas, ice rind	< 10
	Young ice	$10- < 30$
	Gray ice	$10- < 15$
	Gray-white ice	$15- < 30$