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High-resolution forest height mapping using Hongtu-1 multistatic X-band TomoSAR

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Motivation: accurate forest height is still spatially incomplete

Forest height is a core structural variable for biomass, carbon, and ecosystem monitoring. The gap is not accuracy alone — it is accuracy plus spatial completeness.

LiDAR

physically direct, but sparse measurement

Optical

wall-to-wall, but indirect measurement

TomoSAR

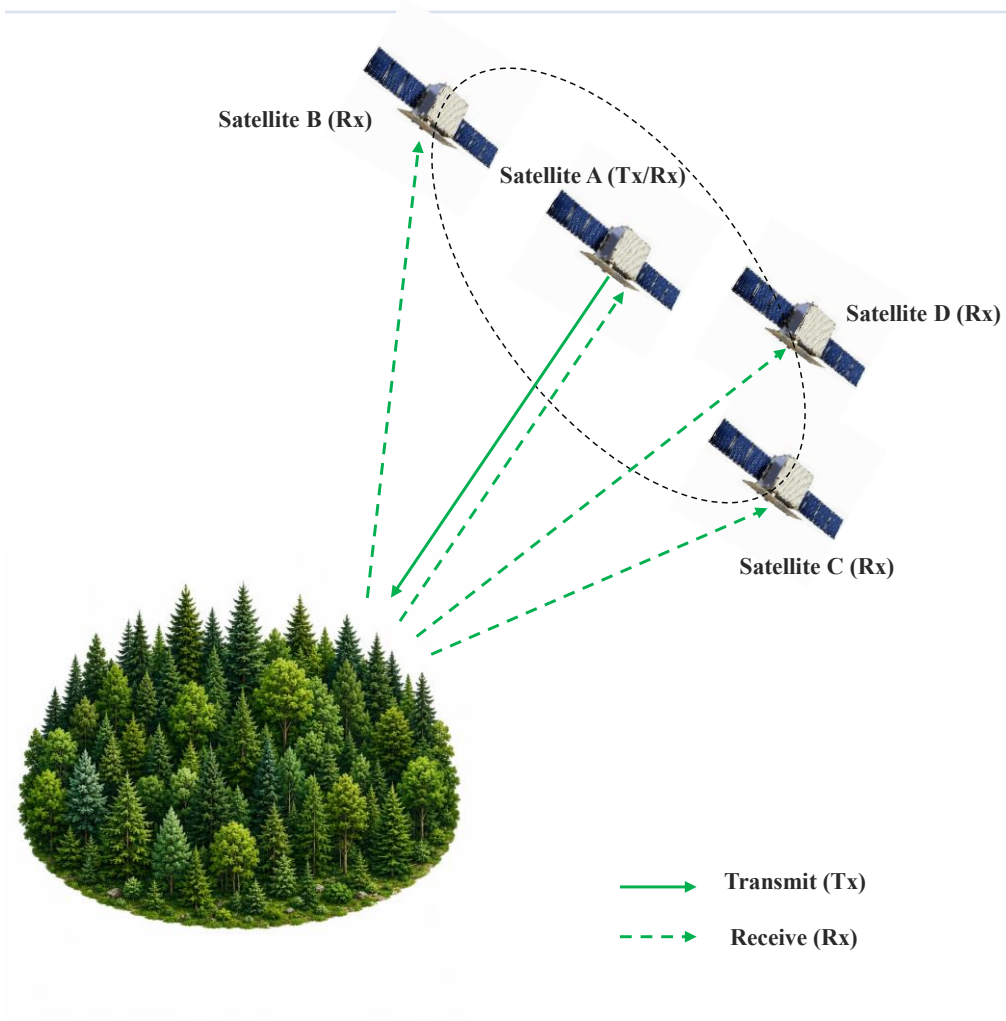
Continuous and direct 3D structural measurement

2 major obstacles for conventional repeat-pass TomoSAR

- Temporal decorrelation
- Atmospheric phase delay

Multistatic TomoSAR

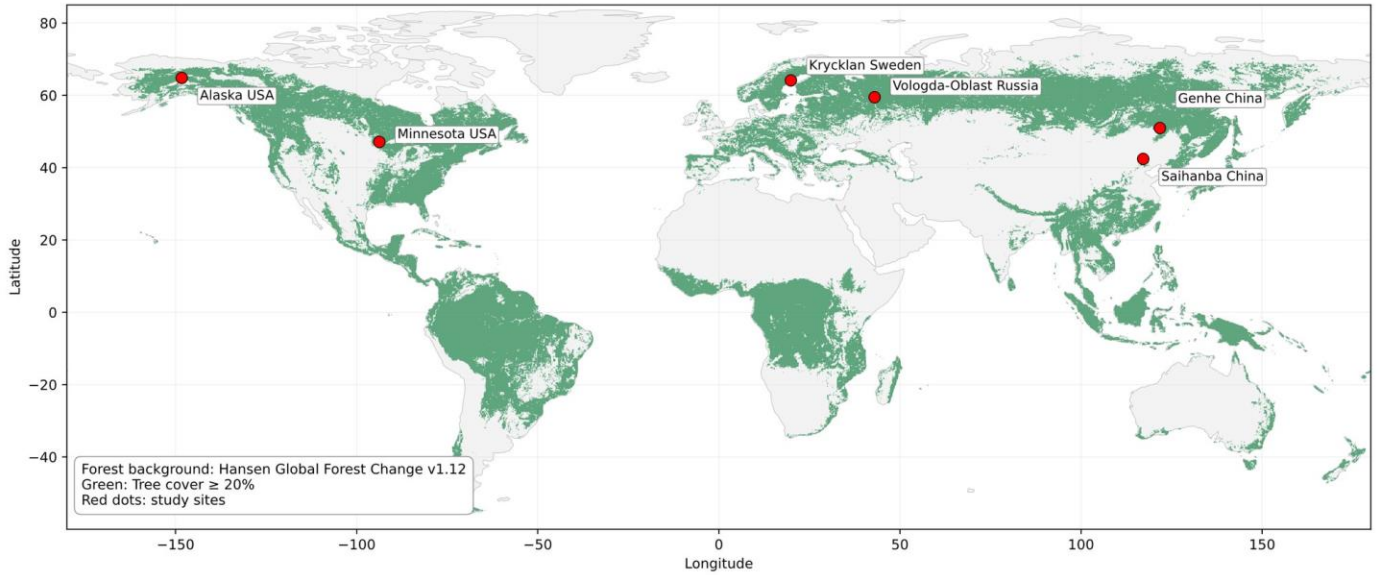
Why Hongtu-1 multistatic TomoSAR?



Simultaneous multi-baseline acquisition

- One transmitter with multiple receiving satellites observes the same area within one acquisition
- Temporal decorrelation and atmospheric phase delay are largely suppressed within each stack

Multi-site study design: six boreal and temperate forest sites



Site	Biome / type	Reference
Krycklan	Boreal mixed	airborne LiDAR + ICESat-2
Vologda	Boreal taiga	ICESat-2
Genhe	Cold-temp./southern boreal	airborne LiDAR + GEDI
Saihanba	Temperate plantation	airborne LiDAR + GEDI
Alaska	Interior boreal	ICESat-2
Minnesota	Boreal–temperate transition	ICESat-2 + GEDI

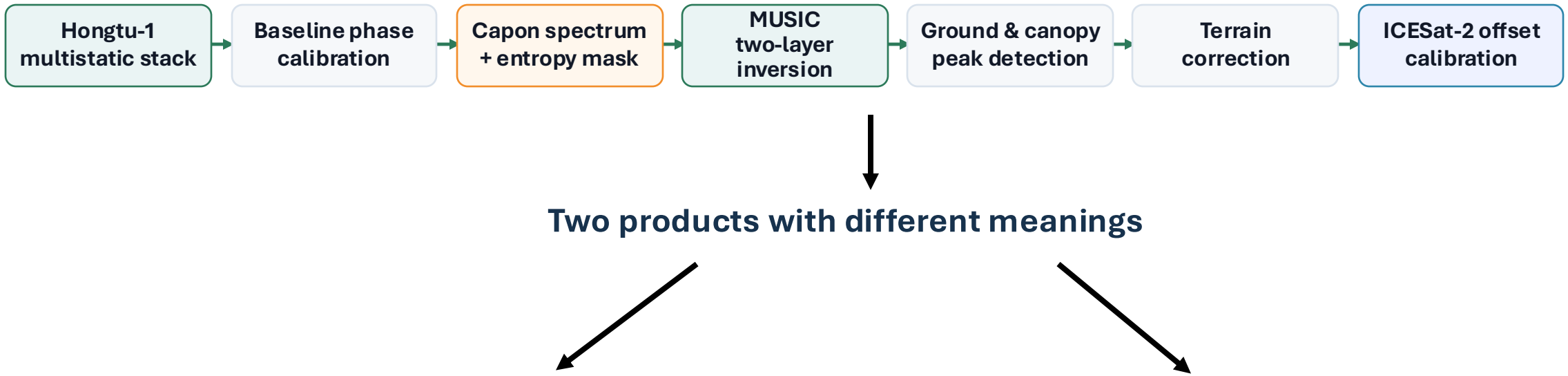
Acquisitions

- Single-date acquisitions: Sweden, Russia, China
- Repeated acquisitions: Alaska and Minnesota

Reference strategy

- ICESat-2 used for site-specific offset calibration
- Airborne LiDAR reserved for independent validation where available
- GEDI and Lang et al. product used as external benchmarks

Retrieval framework: from radar scattering center to canopy-top-equivalent height



Uncalibrated TomoSAR scattering center height

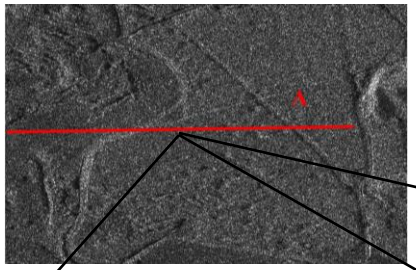
Which is an effective X-band canopy scattering center height product, used for physical interpretation and temporal analysis.

Calibrated canopy-top-equivalent height

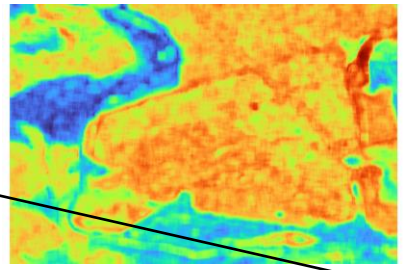
Which is a LiDAR-like height product after site-specific offset calibration for forest height mapping.

Entropy masking and MUSIC improve vertical peak separation

Optical context



SAR amplitude



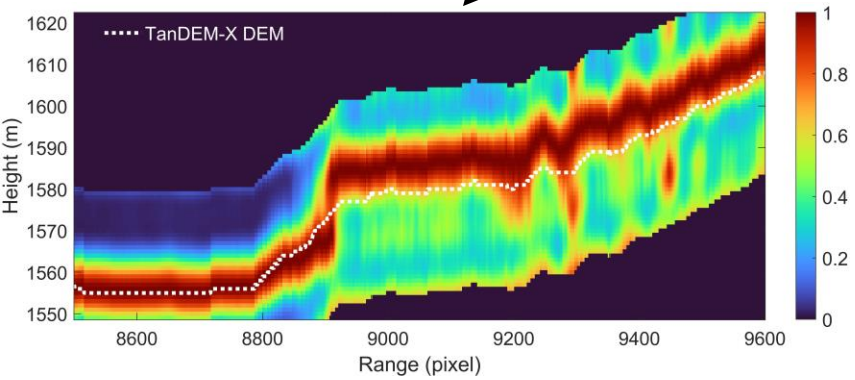
Entropy map

Forest mask

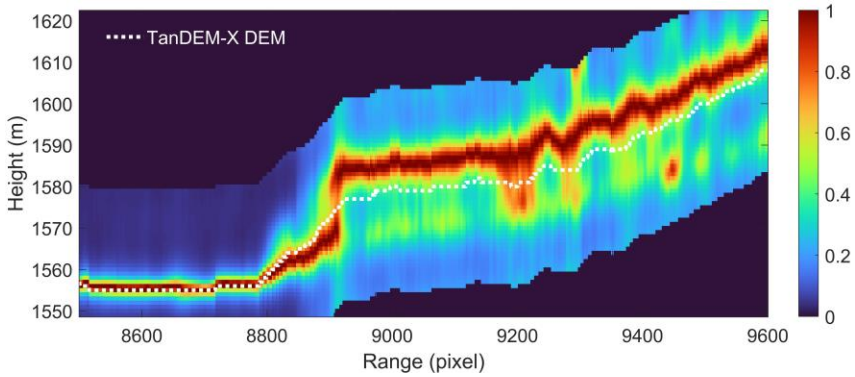
Saihanba example

Entropy threshold removes obvious non-forest targets before height retrieval;

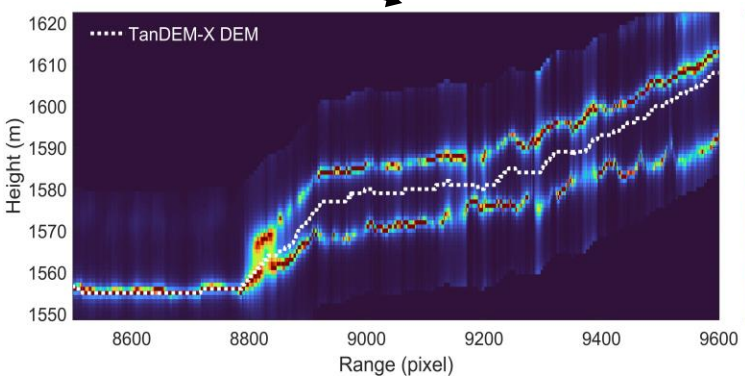
MUSIC sharpens the ground and canopy peaks under a two-layer constraint.



Fourier: diffuse response



Capon: improved focusing



MUSIC: clearer two-layer peaks

At the expense of radiometric accuracy

Some representative tomograms over other test sites also Reveals better resolution of the two-layer MUSIC

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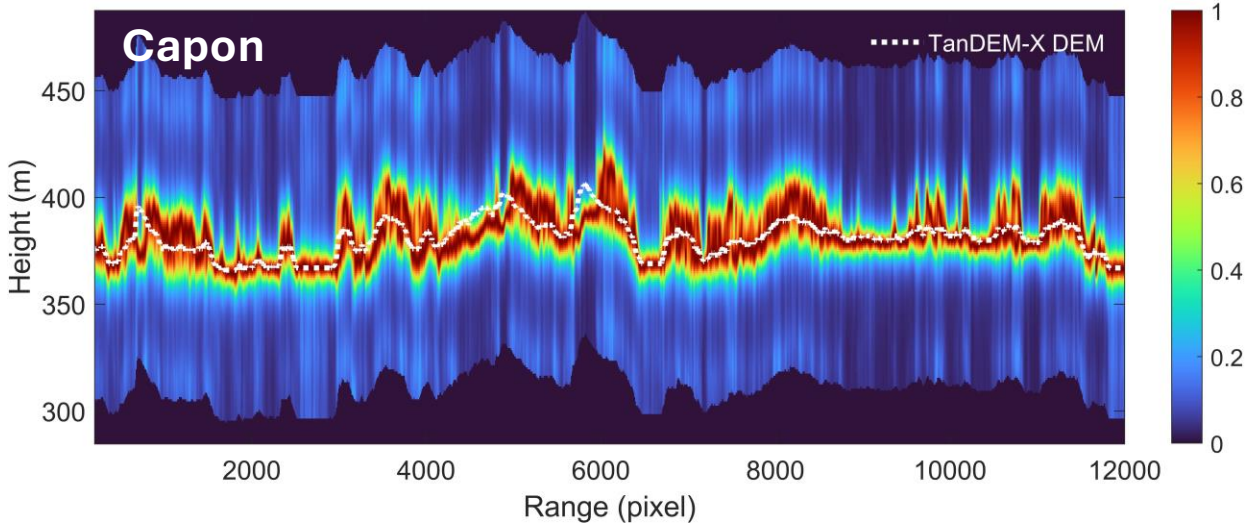
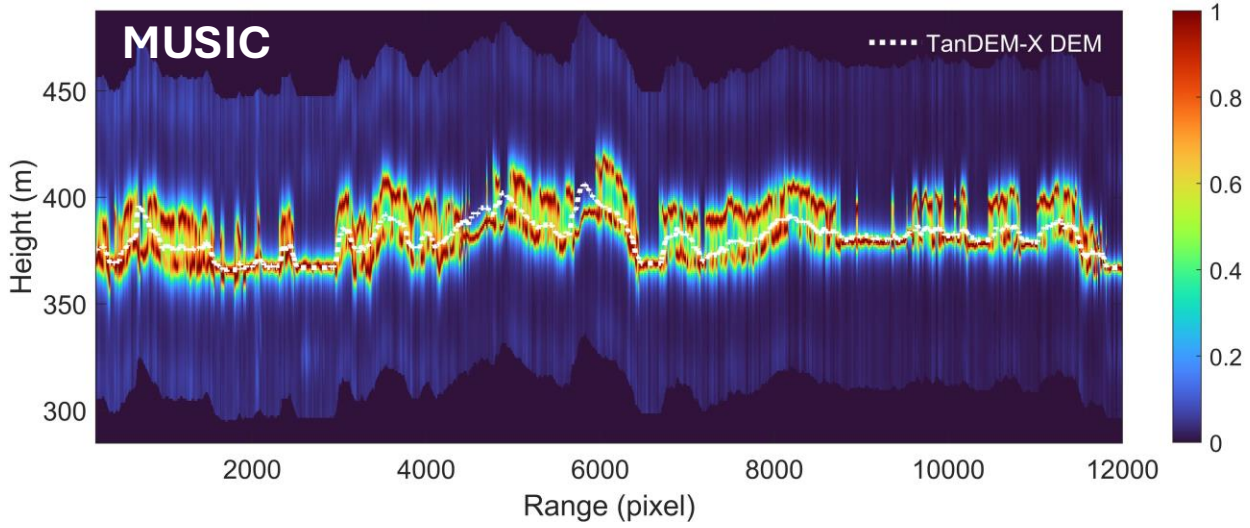
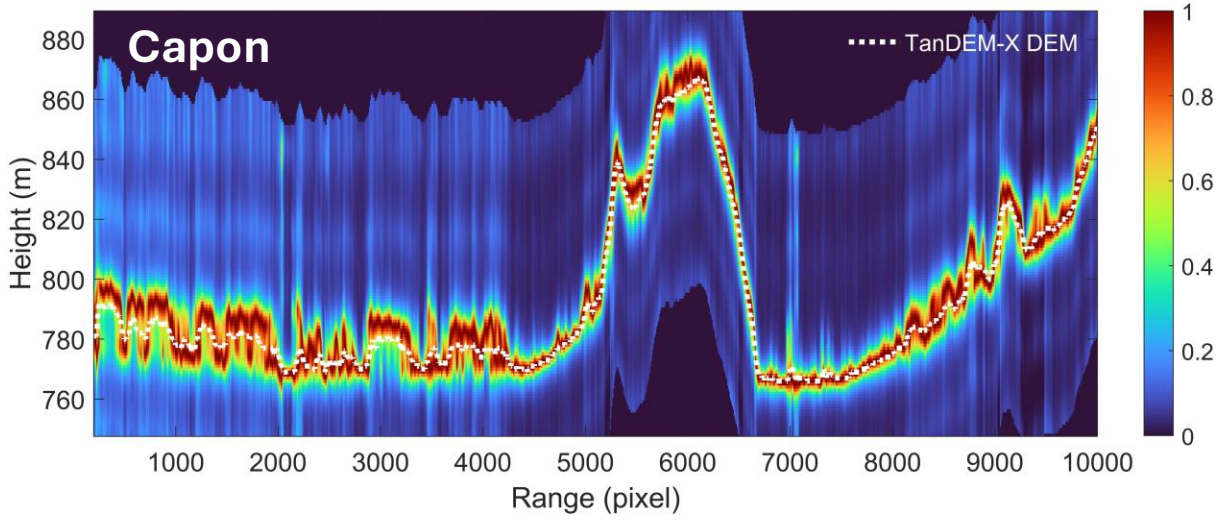
EARTH OBSERVATORY OF SINGAPORE

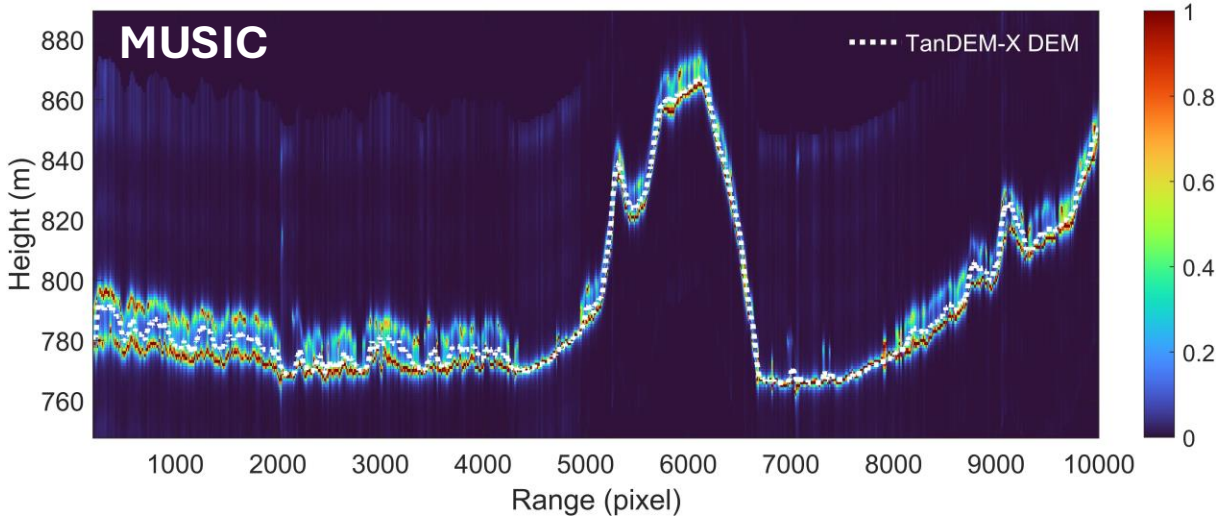
Minnesota





Genhe





Some representative tomograms over other test sites also Reveals better resolution of the two-layer MUSIC

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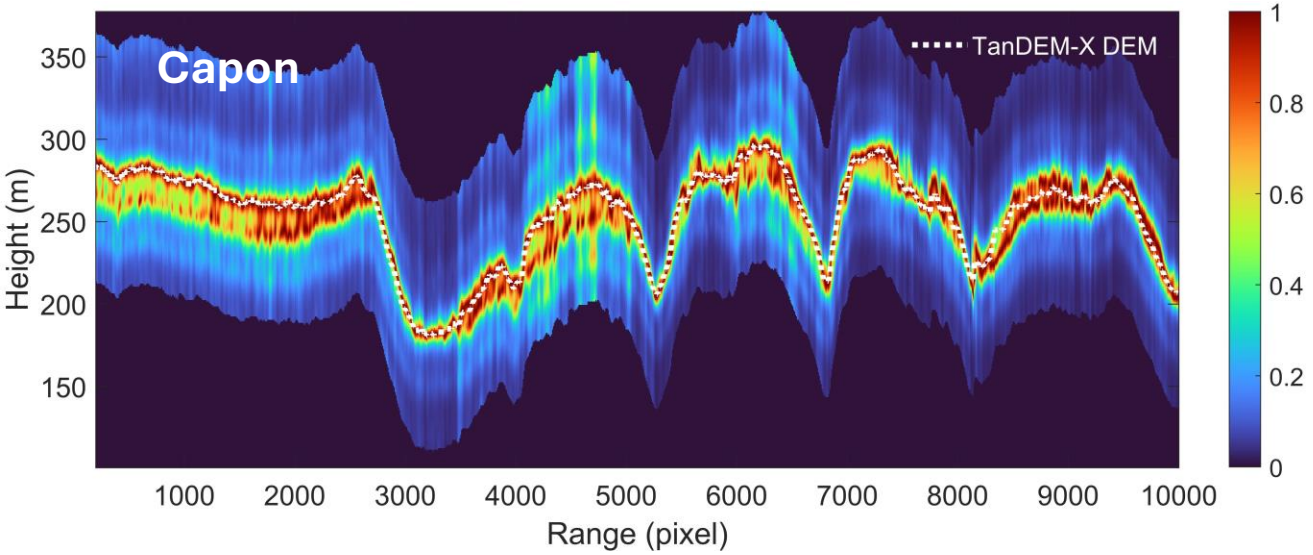
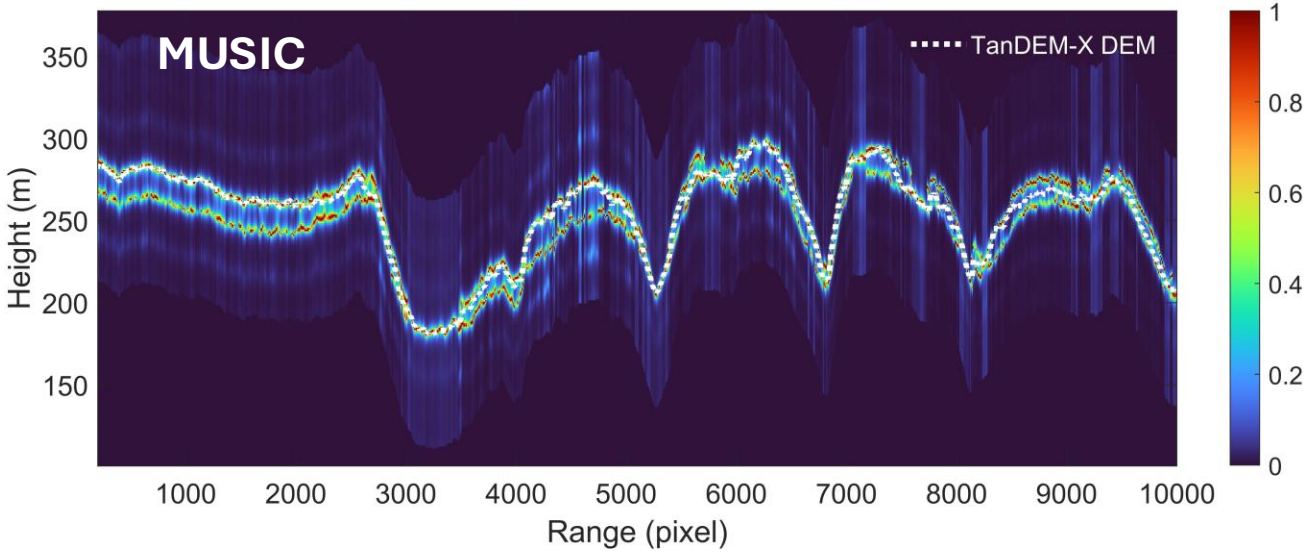
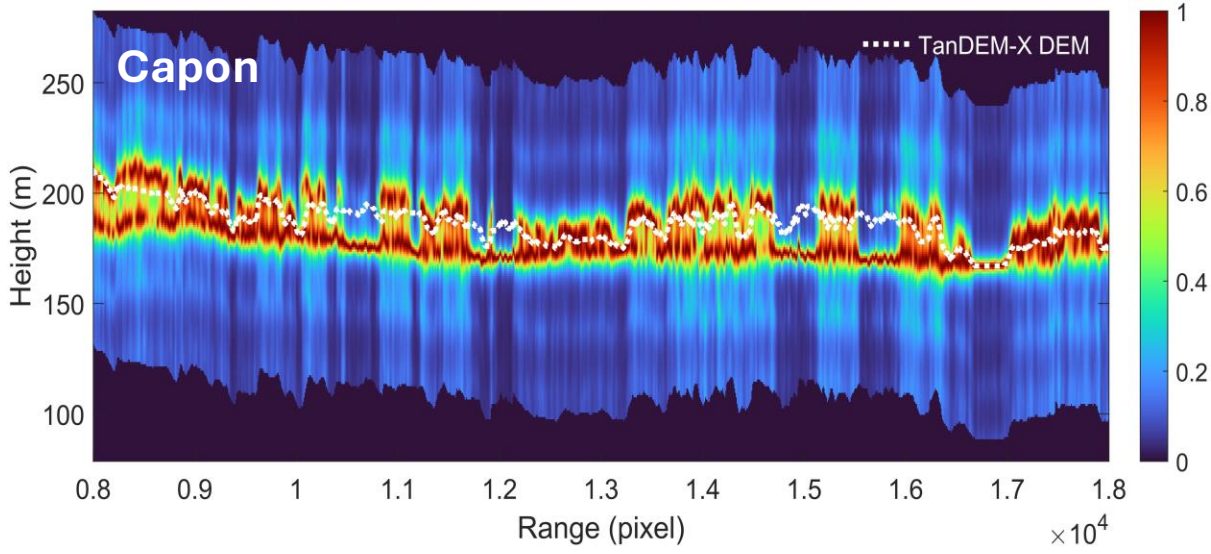
EARTH OBSERVATORY OF SINGAPORE

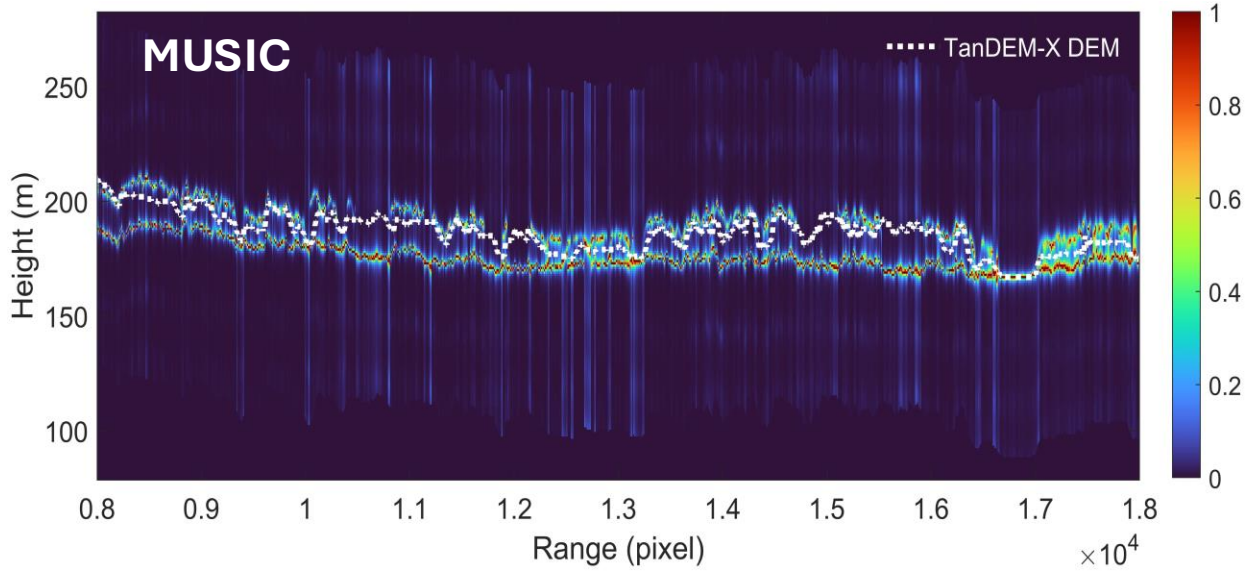
Alaska





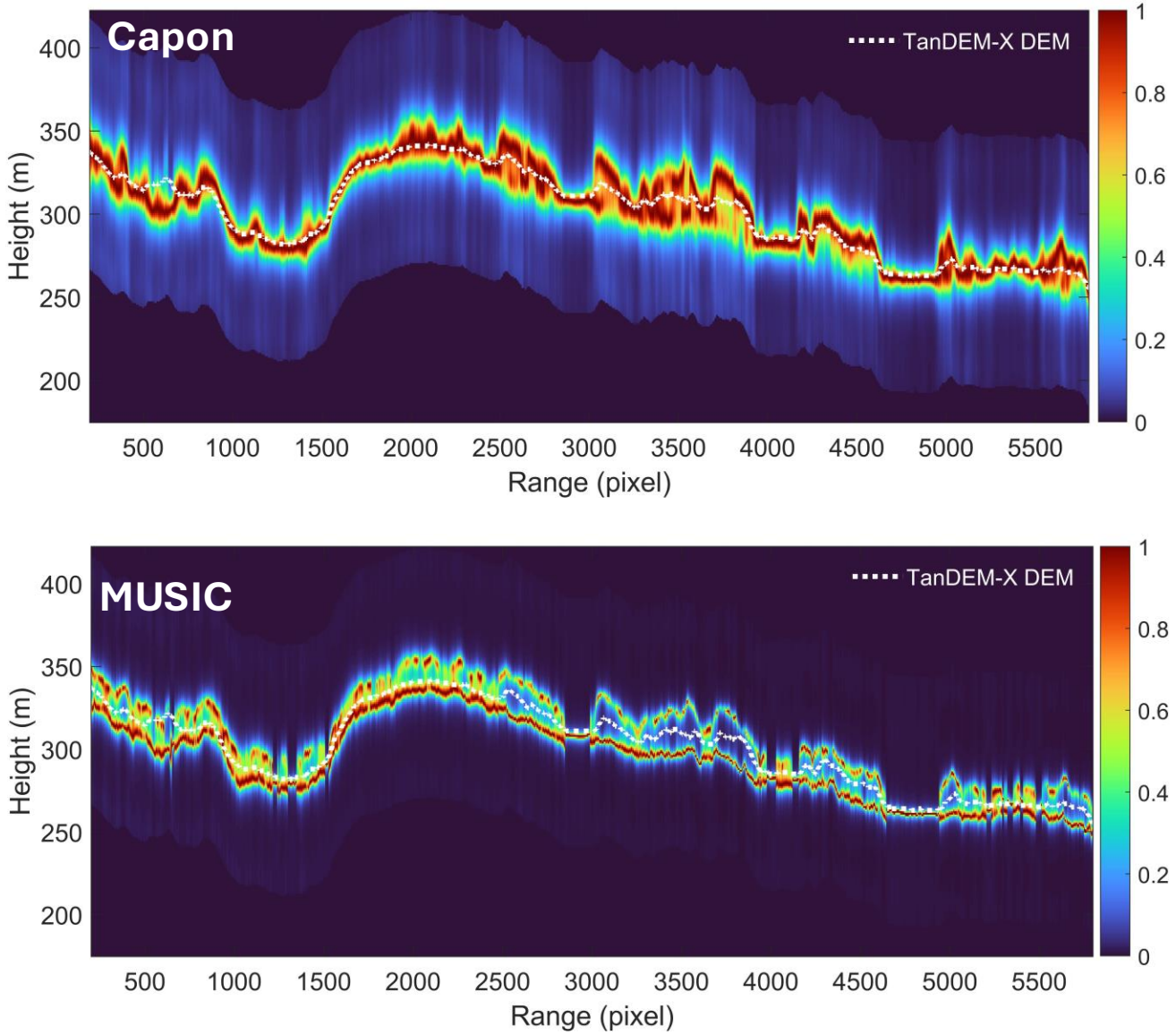
Vologda



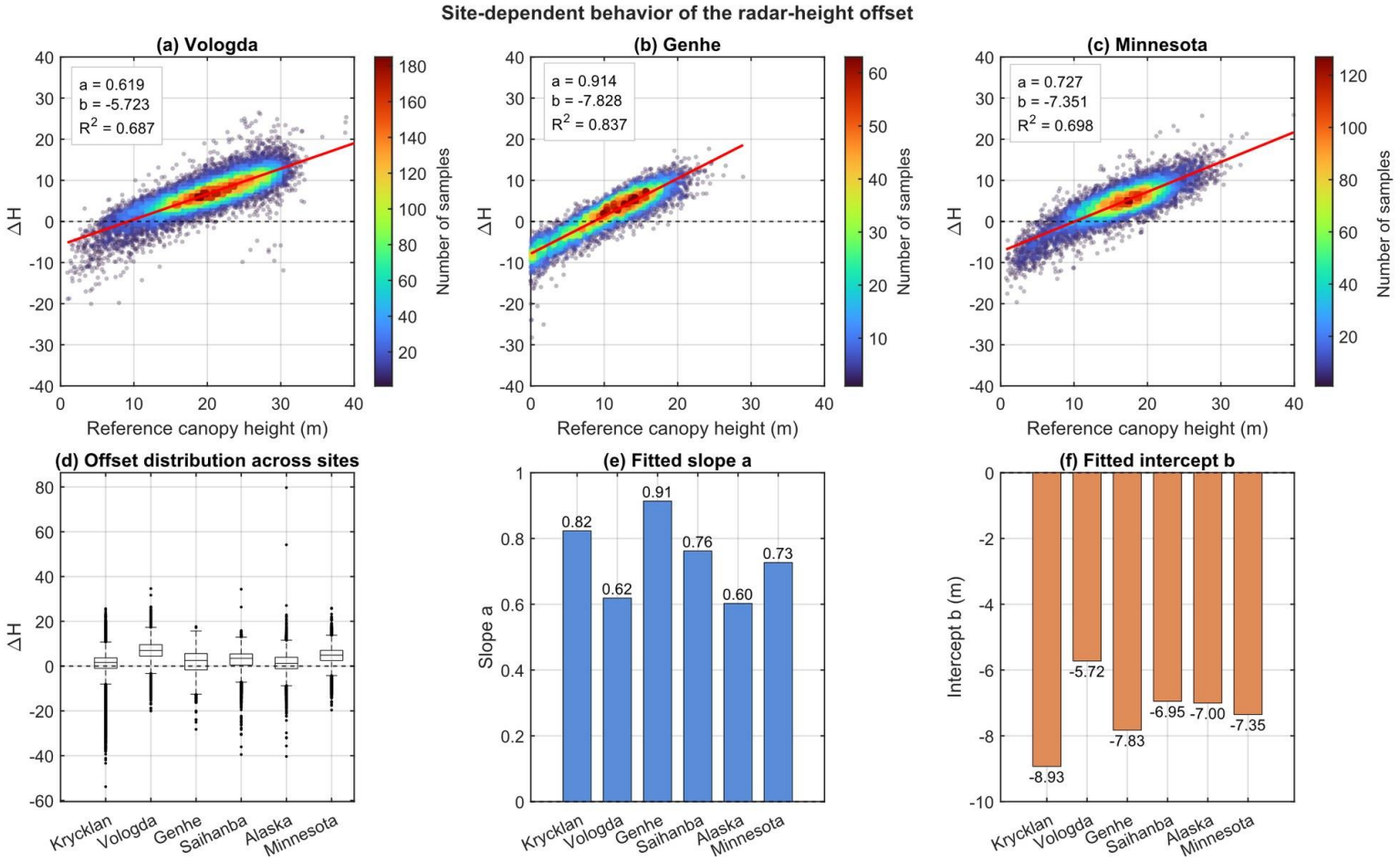


Some representative tomograms over other test sites also Reveals better resolution of the two-layer MUSIC

Krycklan



Result 1: behavior of offset between TomoSAR canopy scattering center height and LiDAR canopy top height



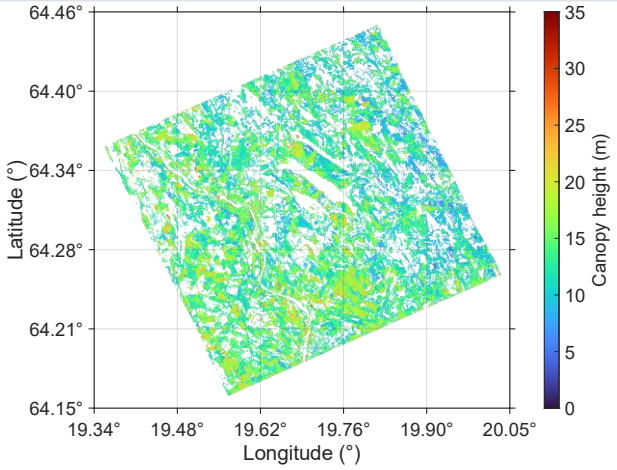
Observed behavior

- ΔH = reference LiDAR canopy top – TomoSAR scattering center height
- Offset **increases linearly** with canopy height
- Fitted slope and intercept are site-dependent

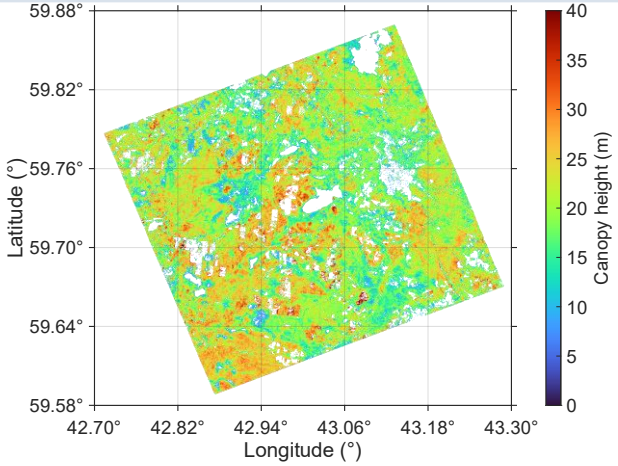
Implication

A single global bias correction is not justified. Site-specific offset calibration is needed when a canopy-top-equivalent product is required.

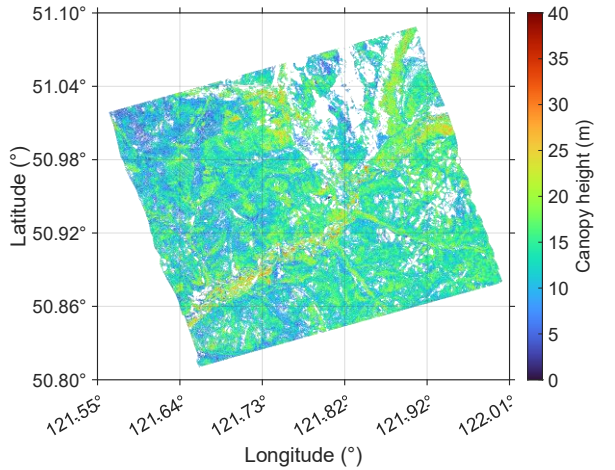
Result 2: reveals Hongtu-1 TomoSAR better accuracy and spatial completeness



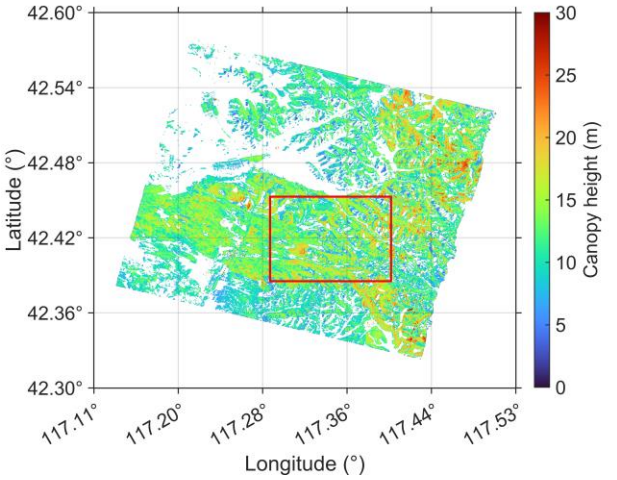
Krycklan



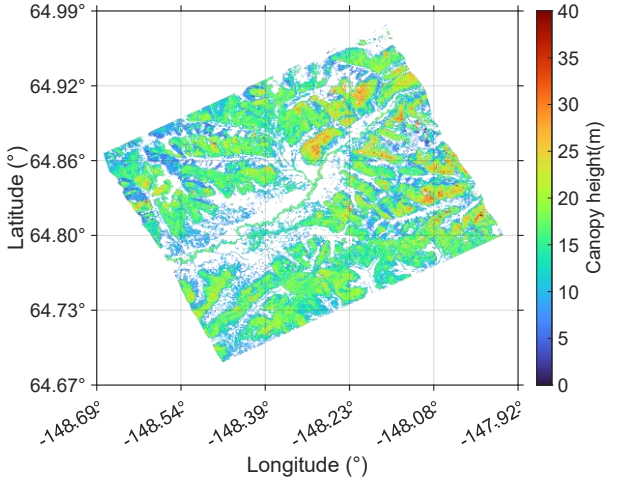
Vologda



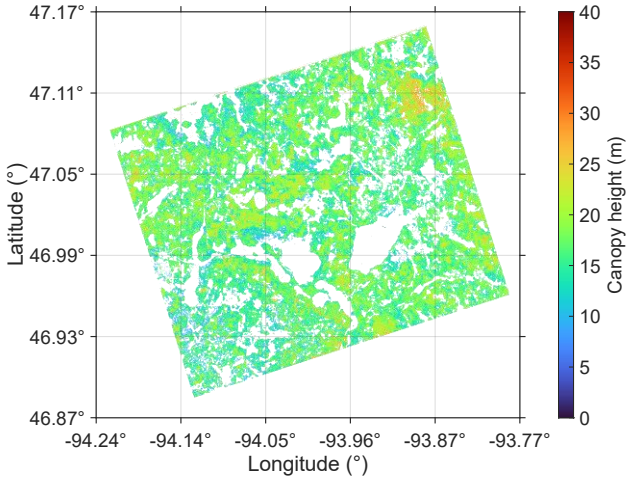
Genhe



Saihanba



Alaska



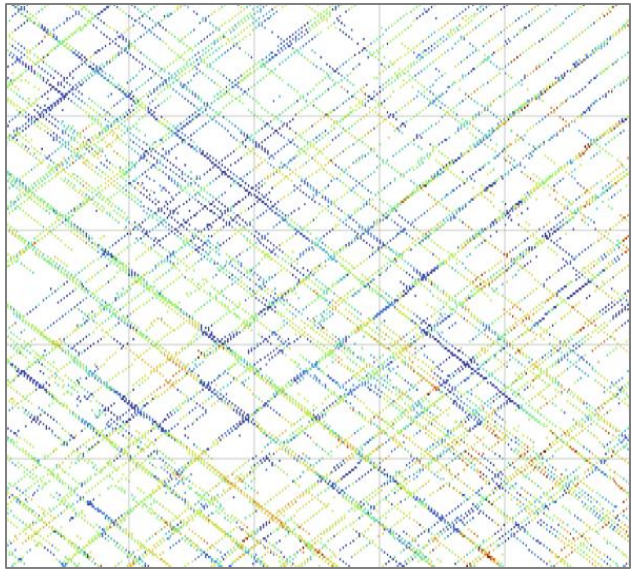
Minnesota

Wall-to-wall structure, not just sparse samples

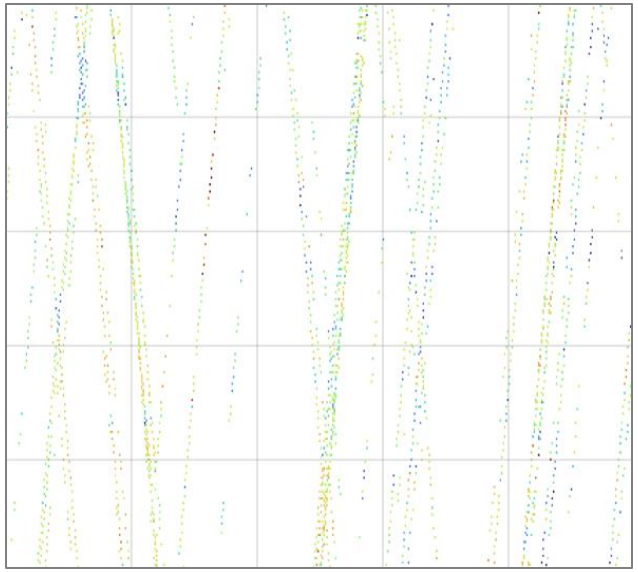
Preserves stand-scale heterogeneity and broader landscape gradients across boreal, boreal-transition, and temperate plantation forests.

Result 2: reveals Hongtu-1 TomoSAR better accuracy and spatial completeness

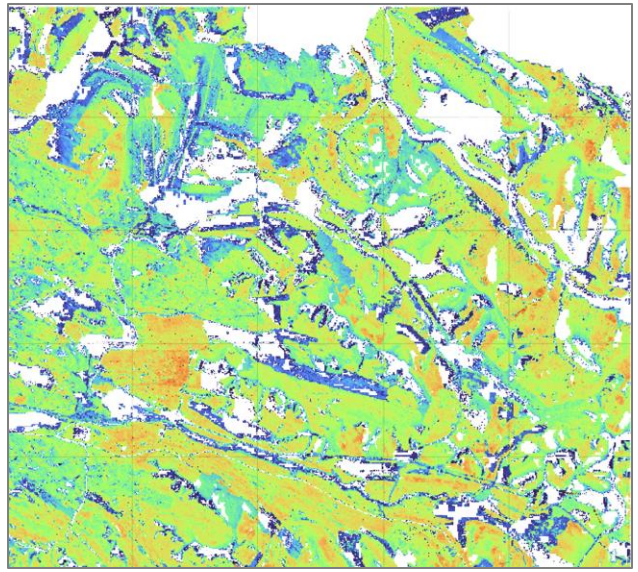
GEDI



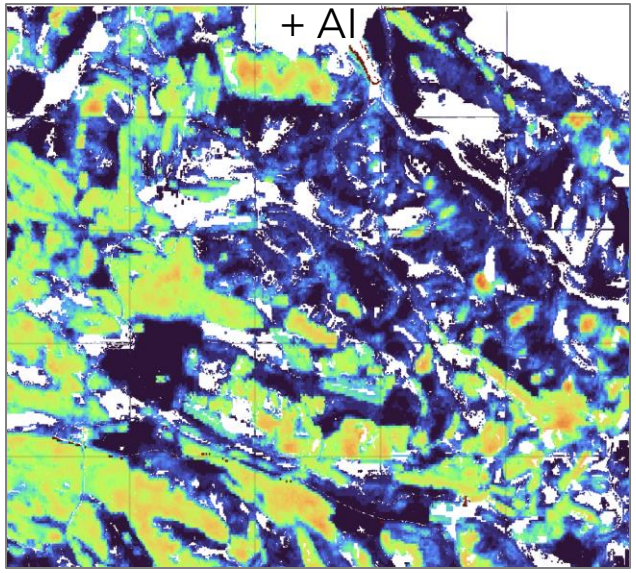
ICESat-2



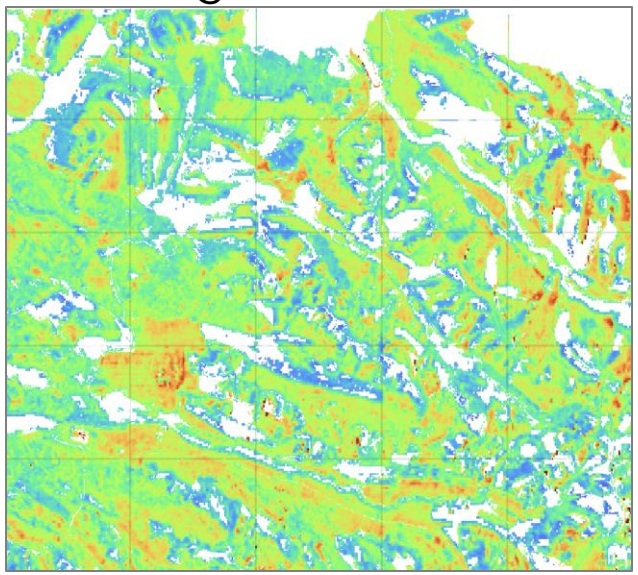
Ground truth



A State-of-the-art GEDI + Sentinel-2 + AI



Hongtu-1 TomoSAR

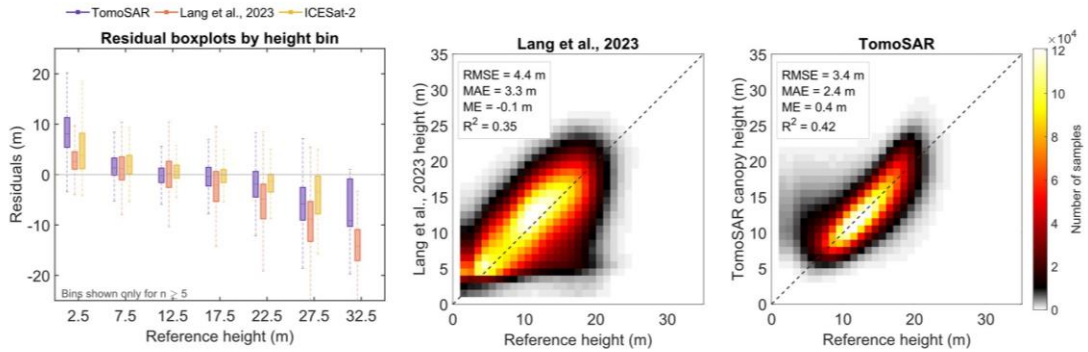


TomoSAR tracks local stand-scale patterns more continuously than sparse LiDAR samples, and with more site-specific detail than the global optical benchmark.

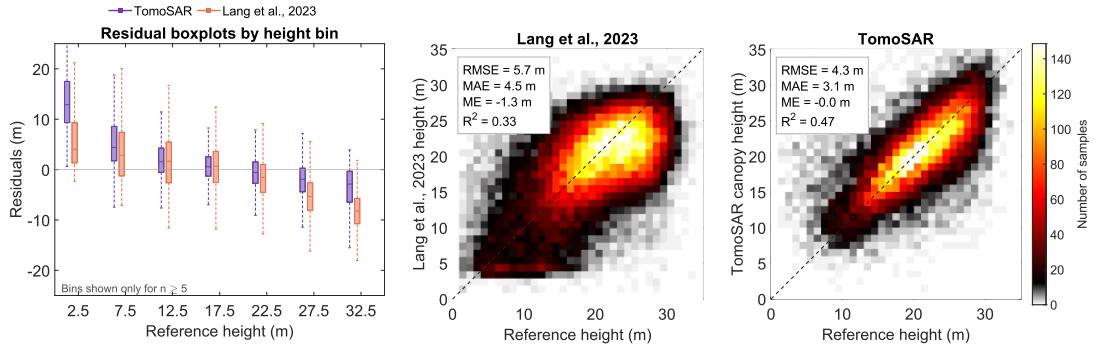
Saihanba zoom-in

Result 3: quantitatively evaluation

Calibrated canopy-top-equivalent height achieves RMSE of 3.4–5.6 m at a 10-m grid across six sites.



Krycklan



Vologda

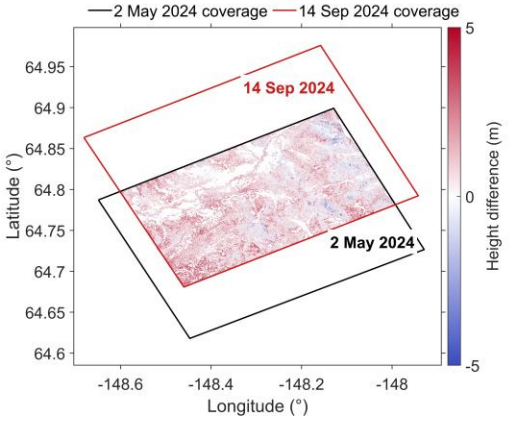
Site	Reference	RMSE	Note
Krycklan	airborne LiDAR	3.4 m	better than Lang/ICESat-2
Vologda	ICESat-2	4.3 m	better than Lang
Genhe	airborne LiDAR	5.6 m	GEDI slightly lower
Saihanba	airborne LiDAR	3.4 m	best/tied best
Alaska	ICESat-2	4.9 m	better than Lang
Minnesota	ICESat-2	4.4 m	better than Lang/GEDI

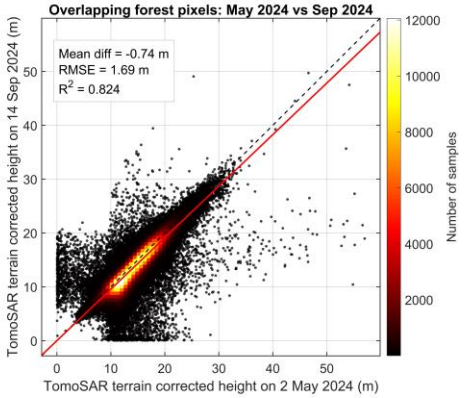
What matters

- TomoSAR is not always the best point-wise dataset, but is **consistently among the top performers**
- The main added value is competitive accuracy with **far greater spatial completeness**

Result 4: temporal shifts in the X-band scattering center

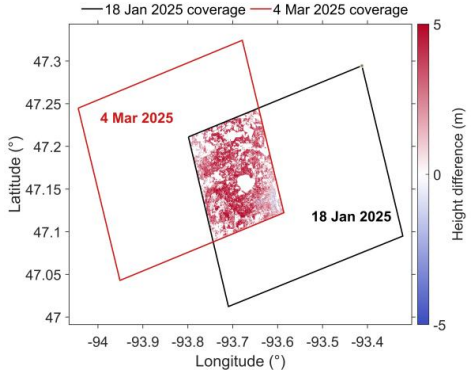
Alaska: low-variability reference

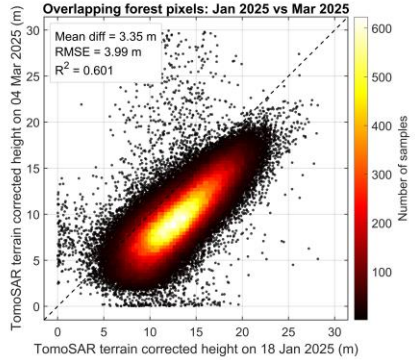


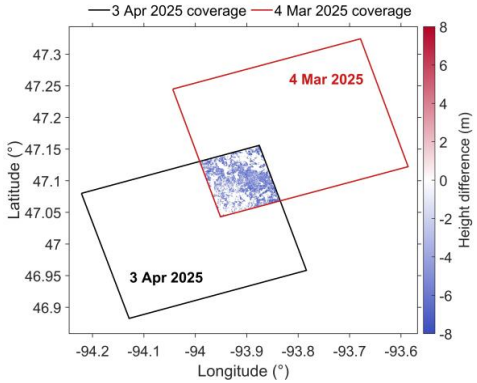


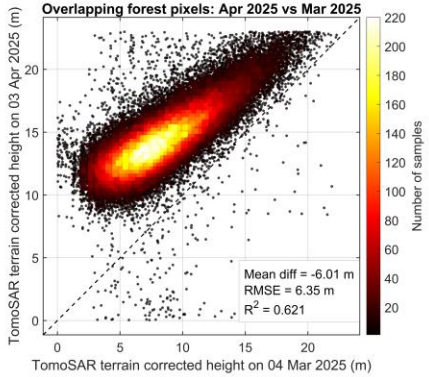
May–Sep mean diff: −0.74 m
RMSE: 1.69 m | R^2: 0.824

Minnesota: pronounced V-shaped shift







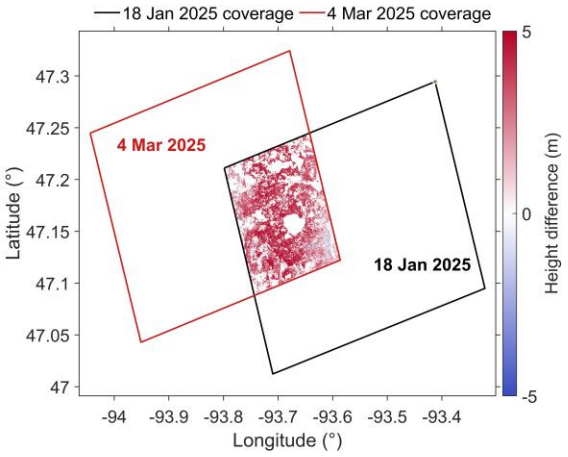


canopy scattering-center difference (Jan – Mar): +3.35 m
canopy scattering-center difference (Mar – Apr): −6.01 m

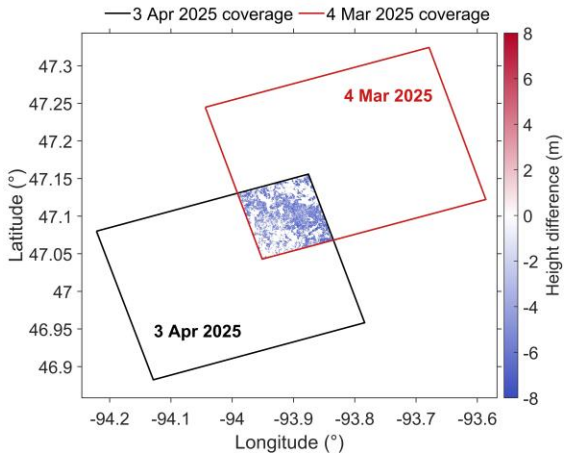
Interpretation: the uncalibrated height is a time-varying radar canopy scattering-center metric, not a fixed-biased canopy-top estimate.

Result 4: temporal shifts in the X-band scattering center

Minnesota: pronounced V-shaped shift (MUSIC)



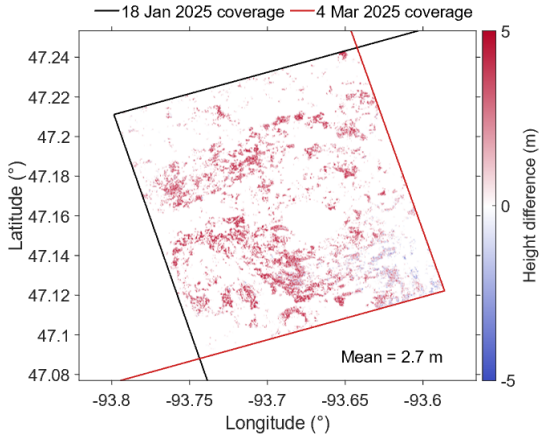
Jan – Mar



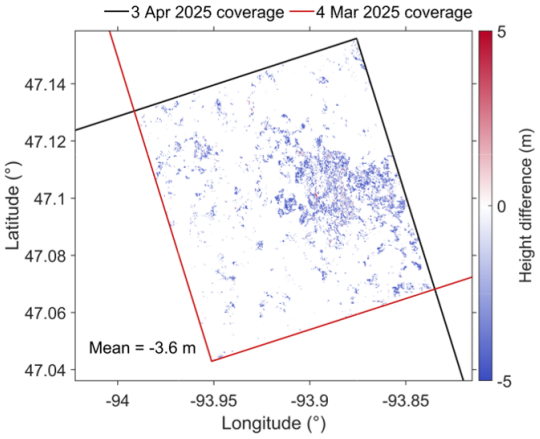
Mar – Apr

canopy scattering-center difference (Jan – Mar): **+3.35 m**
canopy scattering-center difference (Mar – Apr): **–6.01 m**

Minnesota: pronounced V-shaped shift (Capon)



Jan – Mar



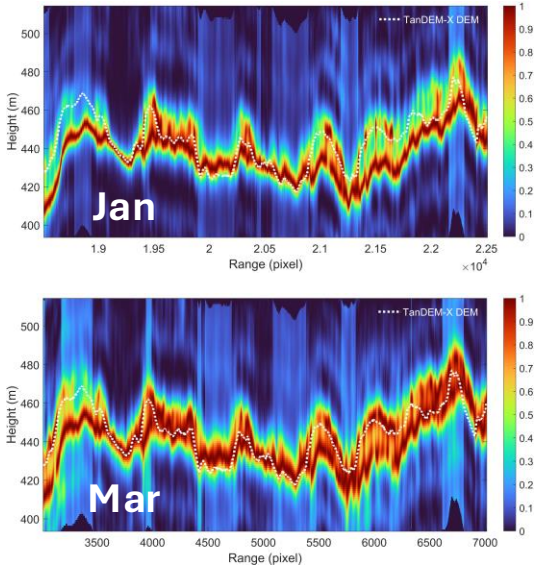
Mar – Apr

canopy scattering-center difference (Jan – Mar): **+2.7 m**
canopy scattering-center difference (Mar – Apr): **–3.6 m**

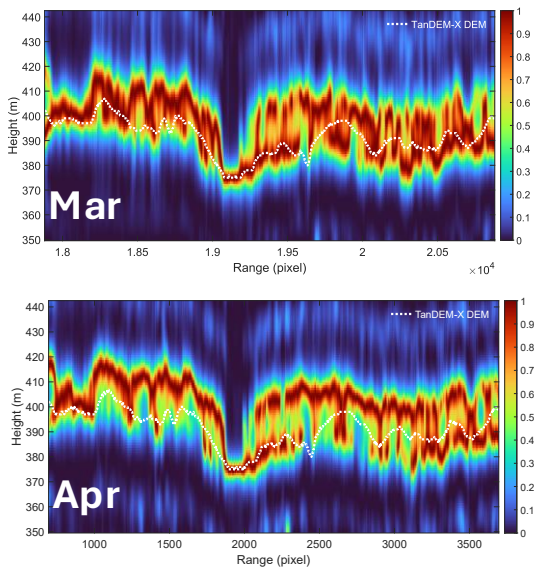
Capon reproduces this V-shape shift of canopy scattering center !

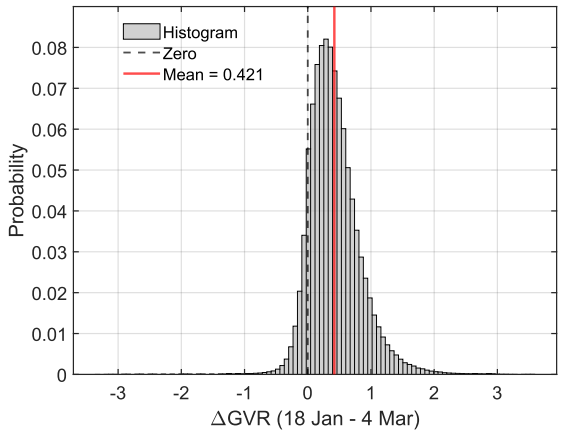
Physical context: snow–canopy state modulates the scattering center shift

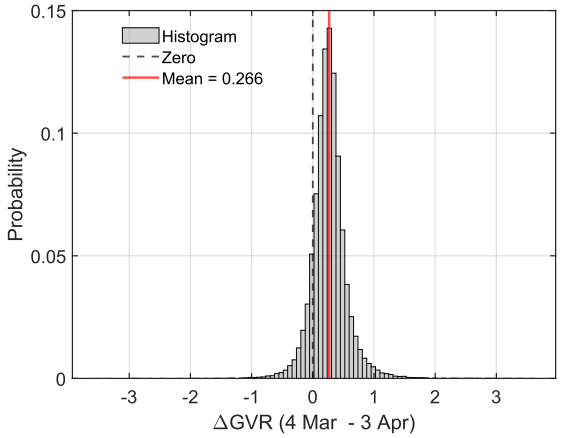
Capon transect A: Jan vs Mar

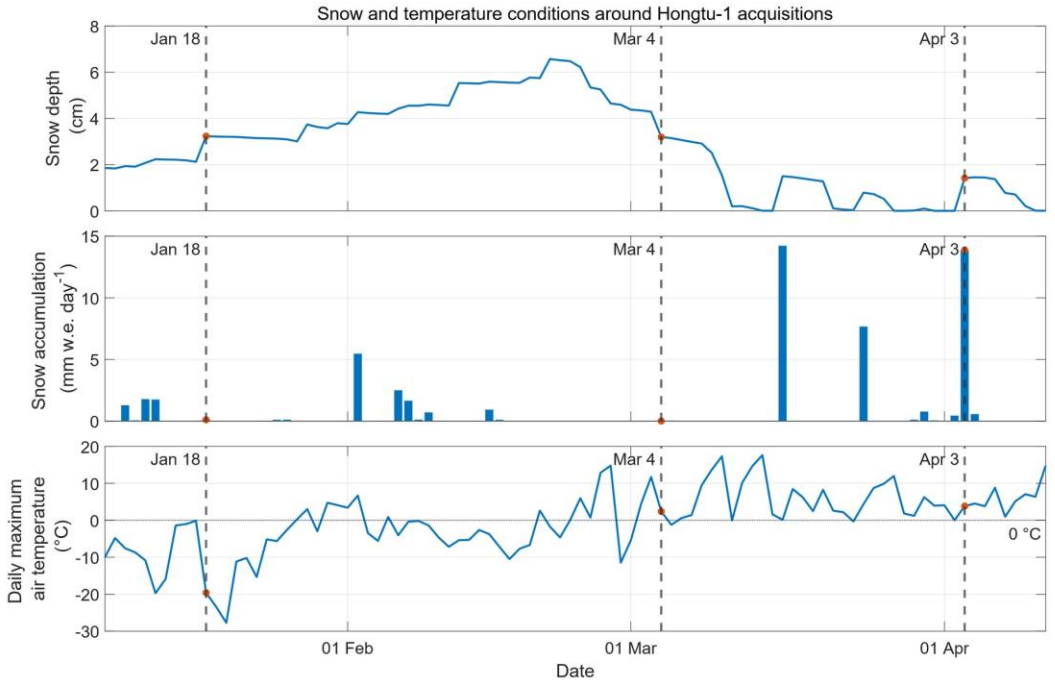


Capon transect B: Mar vs Apr









Snow-state interpretation

- January: -20°, cold, frozen canopy results in a near transparent canopy volume scattering
- March: above 0°, results in warming and ablation of canopy ice and snow; canopy scattering shifts
- April: there was a fresh snow event before image acquisition; canopy contribution shifts upward while ground contribution remains weak

Implications for forest structure mapping

What multistatic X-band TomoSAR adds

- Wall-to-wall, high-resolution forest height maps with competitive accuracy
- A radar-derived canopy scattering-center is sensitive to short-term canopy–snow scattering-state changes

Where caution is needed

- The two-layer model is a retrieval constraint, not a full forest physics model
- Site-specific LiDAR calibration remains necessary for canopy-top-equivalent products
- Tropical or very complex canopies require separate testing

Take-home messages

- Hongtu-1 multistatic X-band TomoSAR produces spatially continuous higher resolution forest height maps across six boreal and temperate sites, with competitive accuracy ranging from **3.4** to **5.6** m.
- Before calibration, TomoSAR height should be interpreted as an **X-band canopy scattering center**, not a direct canopy top.
- Repeated acquisitions show that this scattering center can **shift by several meters under snow-affected seasonal conditions**.

Thank you

Questions

Acknowledgment: PIESAT / Hongtu-1 data provider, NASA GEDI and ICESat-2 mission teams, NSIDC DAAC, Swedish Forest Agency, and collaborators.