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Mangrove Canopy Height Retrieval from Multi-baseline TanDEM-X InSAR Observations using Volume Decorrelation

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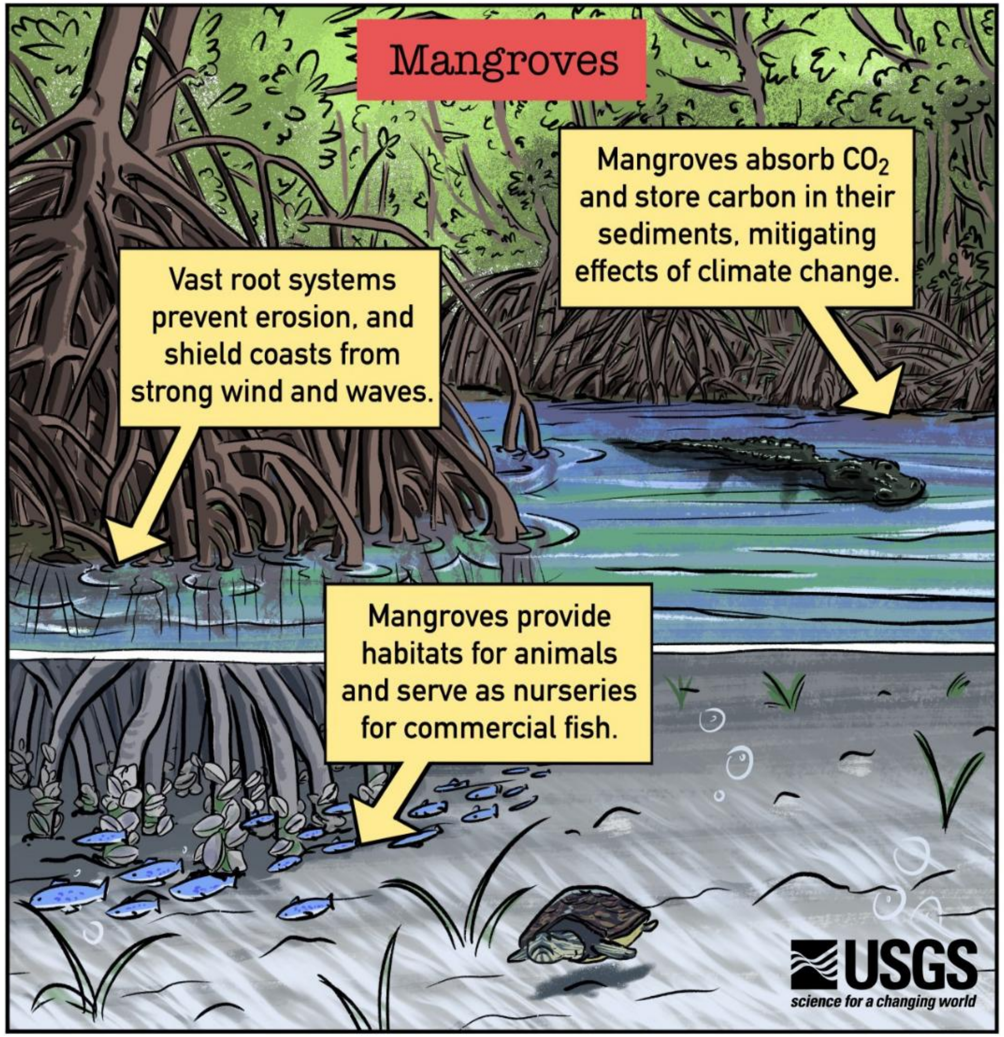
Importance of mangrove

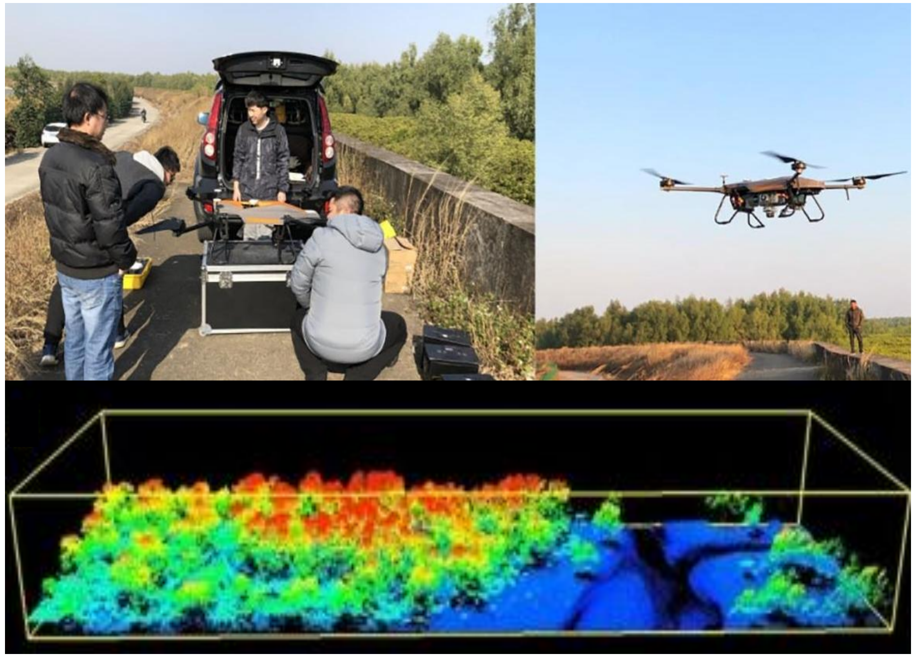
- Mangroves are representative blue carbon ecosystems and quantitative assessment of their biomass and carbon stocks is essential for climate change mitigation.
- Although most mangrove carbon is stored below ground, Above Ground Biomass (AGB) derived from canopy height is the best estimate for carbon stock assessment.

Mangrove ecosystems ▶
(Image courtesy of United States Geological Survey, USGS)



Mangrove monitoring

▲ Mangrove field survey (Maung *et al.*, 2025)



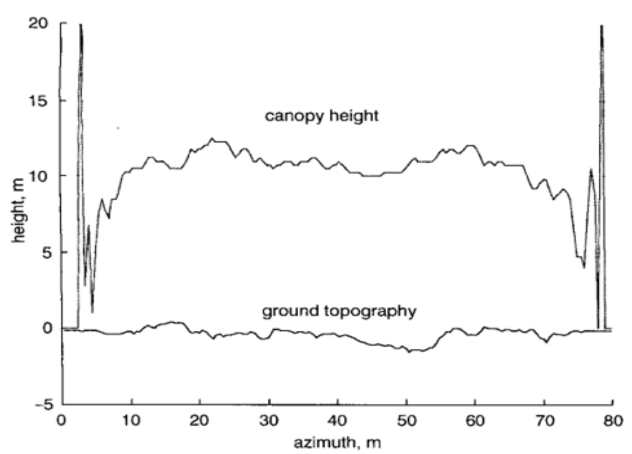
▲ Mangrove UAV-LiDAR survey (Tian *et al.*, 2022)

- Mangrove forests change over time, making ongoing monitoring essential.
- Field surveys and UAV-LiDAR provide accurate and detailed measurements, while continuous monitoring over large areas remains a challenge.

Previous studies

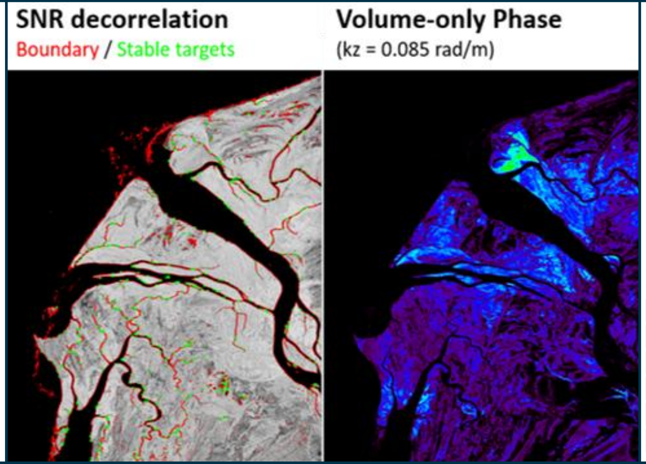
- Previous studies have investigated canopy height retrieval using SAR observations.

Cloude & Papathanassiou (2003)



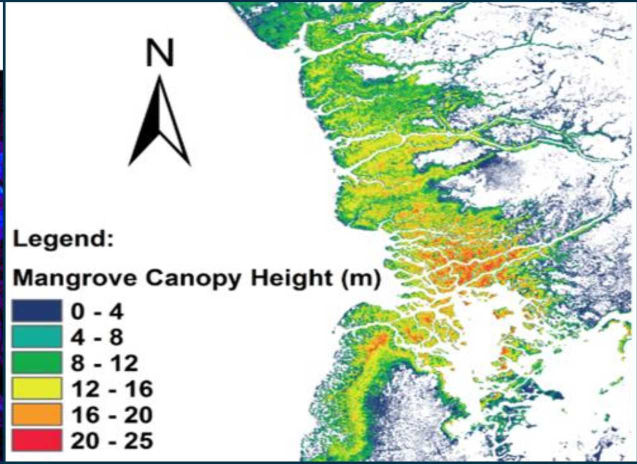
- Three-stage Random Volume over Ground (RVoG) inversion
- PolInSAR based ground–volume separation

Lee & Fatoyinbo (2015)



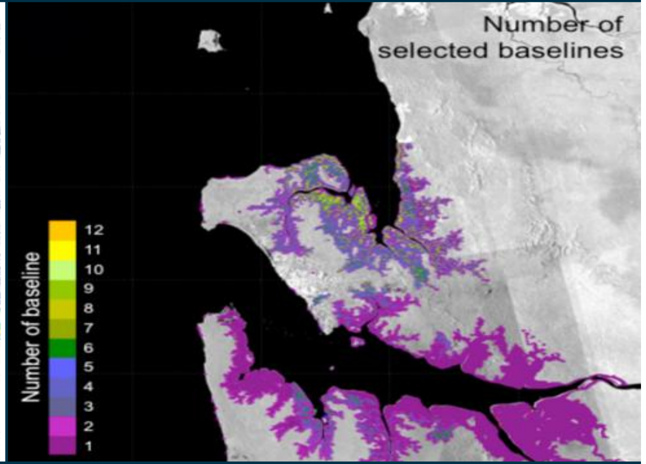
- Single-/dual-pol TanDEM-X inversion
- Ground phase estimation without external DEM

Feliciano *et al.*, (2017)



- Multiple TanDEM-X acquisitions
- Regional-scale canopy height mapping

Lee *et al.*, (2018)



- Multi-baseline TanDEM-X height estimation
- External Digtal Elevation Model (DEM) assisted baseline selection

Goal

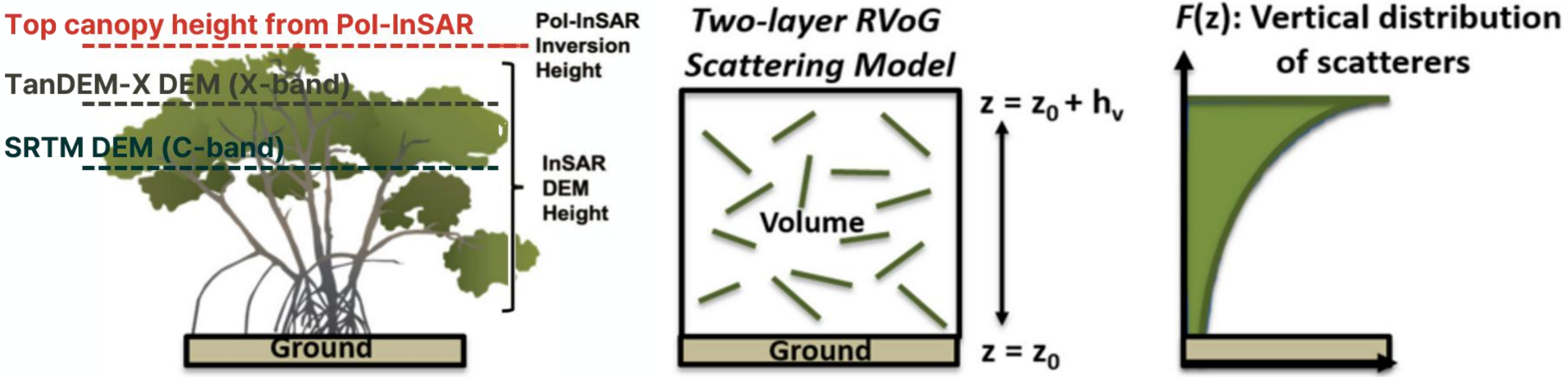
- Main Goal

  Retrieve mangrove canopy height in the southern Everglades using TanDEM-X interferometric SAR (InSAR) observations

- Specific Objectives
  - Canopy height retrieval without DEM
  - RVoG inversion using volume decorrelation
  - Multi baseline analysis for reduction of vertical ambiguity

Volume decorrelation and canopy height

- Radar signals penetrate into the vegetation layer, causing the observed phase to represent a scattering phase center rather than the true top canopy height.
- The vertical distribution of scatterers produces volume decorrelation, which can be modeled using the Random Volume over Ground (RVoG) framework.



▲ Schematic illustration of the RVoG model modified after Cloude & Papathanassiou (2003)

Study area - Everglades

▲ Landsat optical image of mangrove forest in southern Everglades and the study area (yellow box)

◀ 2017 Hurricane Irma damage to Everglades (Lagomasino *et al.*, 2021)

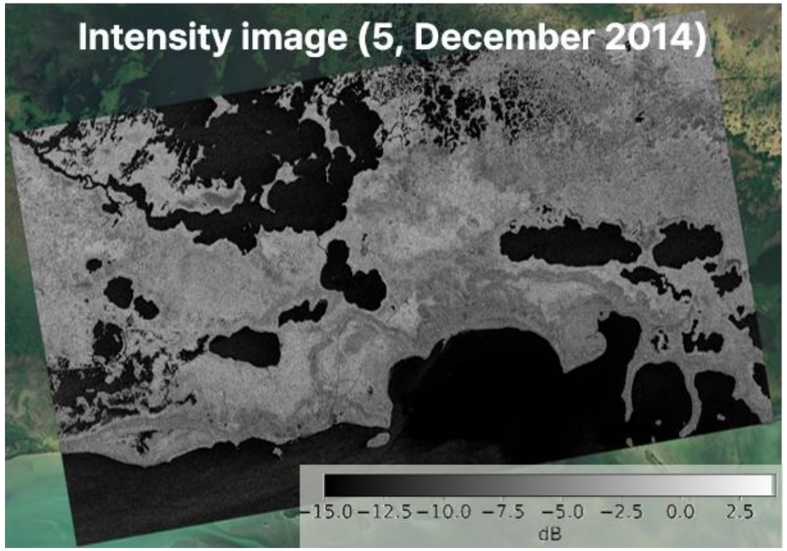
2026 wildland fire damage to Everglades (Image courtesy of NASA) ▶

TanDEM-X InSAR observations

- TanDEM-X pursuit monostatic data (~9.6 GHz) are well suited for canopy height retrieval because temporal decorrelation is minimized (~10 seconds).
- The use of multiple baselines enables the evaluation of height sensitivity under different observation geometries.

▼ List of TanDEM-X single polarized (HH) datasets

No.	Date	Acquisition time	Perpendicular baseline [m]	Height of ambiguity (HoA) [m]	Vertical wavenumber (Kz) [rad/m]
1	2014.12.05.	23:22:15.05	174.15	29.39	0.214
2		23:22:24.94			
3	2014.12.27.	23:22:13.72	257.18	20.95	0.299
4		23:22:23.48			
5	2015.02.20.	23:22:11.72	343.98	14.40	0.408
6		23:22:21.93			



RVoG inversion using single polarimetric data

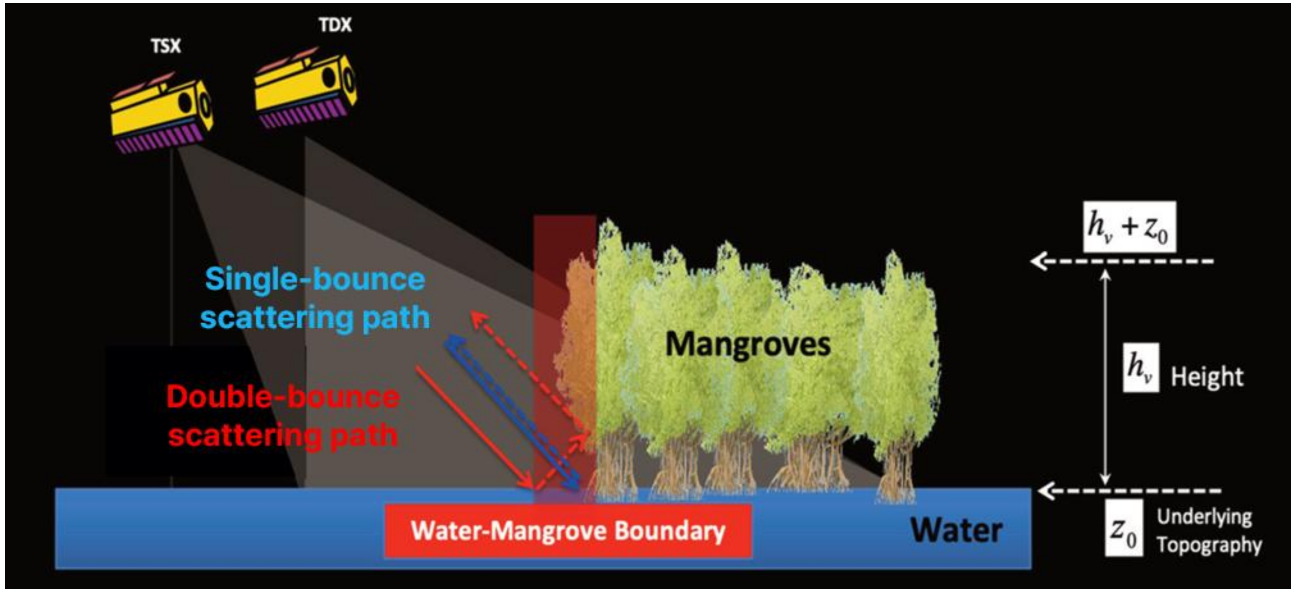
- The observed interferometric coherence can be decomposed as Hajnsek *et al.*, 2009

$$\tilde{r} = e^{i\emptyset_0}\boldsymbol{\tilde{\gamma}_{vol}}\gamma_{rg}\gamma_{SNR}\tilde{\gamma}_{Temp}$$

γ_{rg} → Applying common-band filtering (< 3% bandwidth loss)

γ_{SNR} → Estimating γ_{SNR} using noise information

$\tilde{\gamma}_{Temp}$ → Assuming negligible temporal decorrelation (≈0)



Water–Non water boundary derived from SNR
&
Double bounce coherent scatterers between water surface and mangrove trunks

Phase of intersection pixels
= Underlying topographic phase ($e^{i\emptyset_0}$)

◀ Schematic diagram of topographic phase estimation (Lee & Fatoyinbo, 2015)

RVoG inversion using single polarimetric data

- This study follows the RVoG inversion approach proposed by Feliciano *et al.*, 2017.

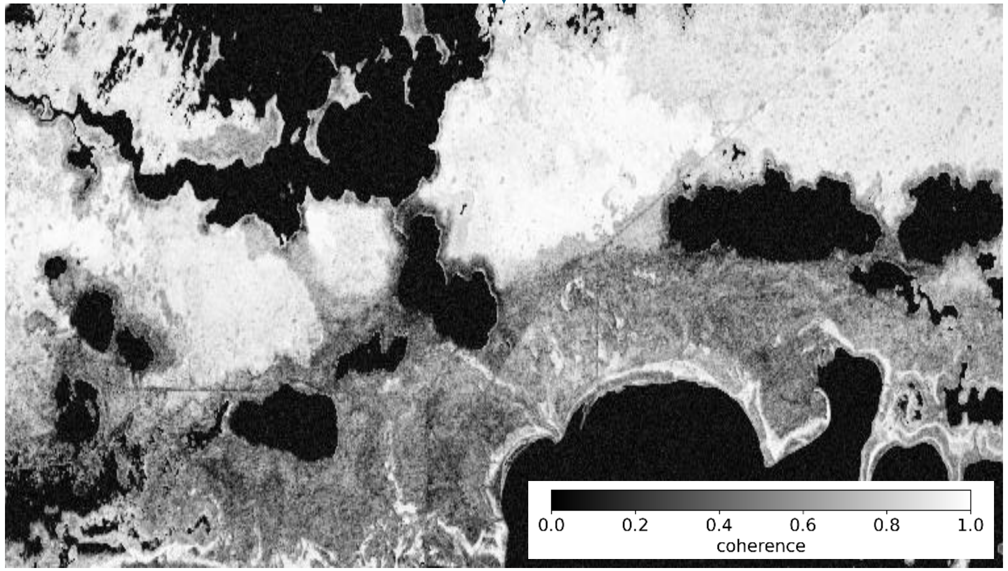
(0 - 2 dB/m)

$$\tilde{r}(h_v) = \cancel{e^{i\phi_0}}\,\tilde{\gamma}_{vol}\,\cancel{\gamma_g}\,\cancel{\gamma_{SNR}}\,\cancel{\tilde{\gamma}_{Temp}} \longrightarrow \text{Applying RVoG model } \boxed{\tilde{r}(h_v)} = \frac{\int_0^{h_v} e^{\frac{2\sigma}{\cos\theta_0}z'}\, e^{ik_z z'}\, dz'}{\int_0^{h_v} e^{\frac{2\sigma}{\cos\theta_0}z'}\, dz'}$$

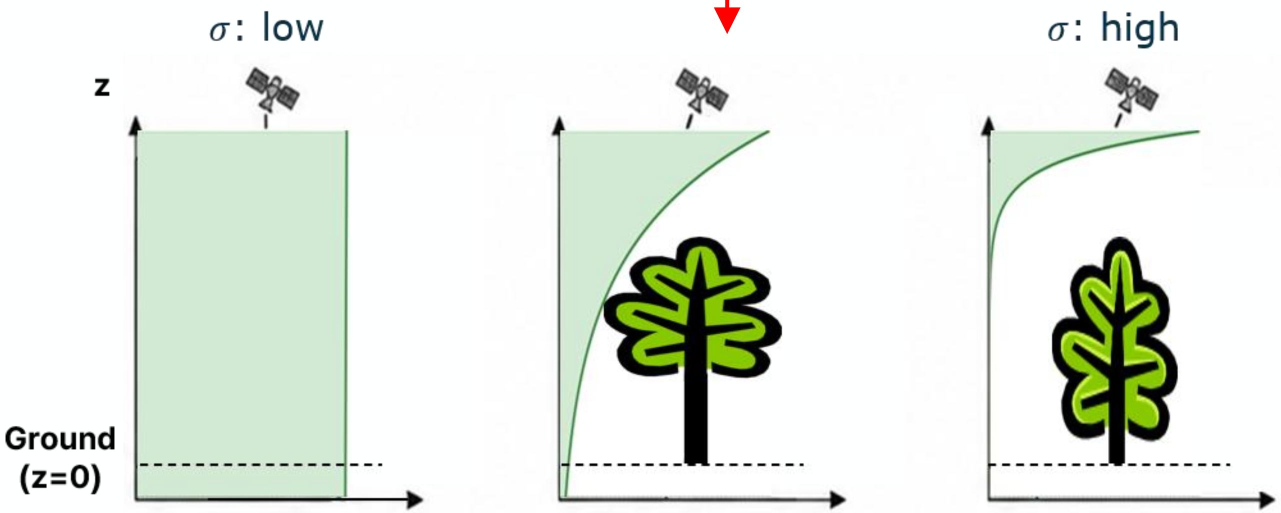
▭: Known values
⬭: Unknown values

Observed volume-only coherence

Vertical distribution (F(z))



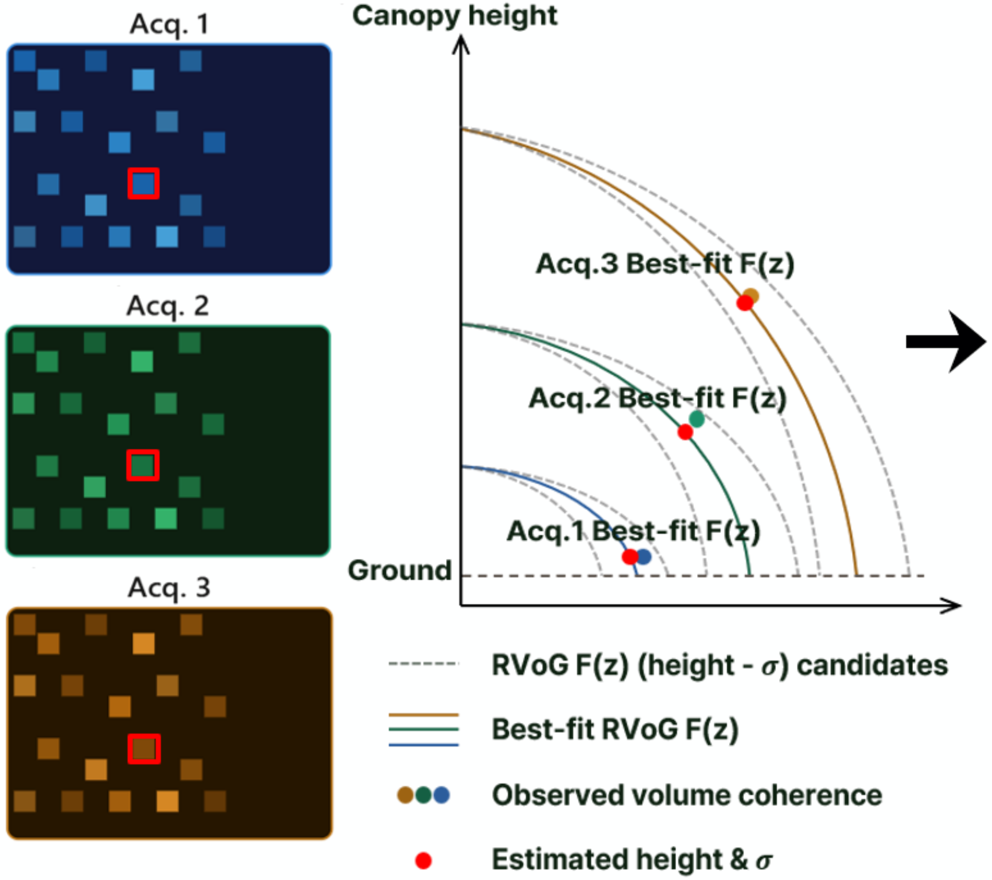
▲ Volume only coherence map



▲ Schematic illustration of RVoG F(z) profiles for varying extinction coefficient (σ)

Proposed multi baseline RVoG inversion

Each acquisitions search over all (height, σ) pairs
→ Select best fit F(z) with minimum residual



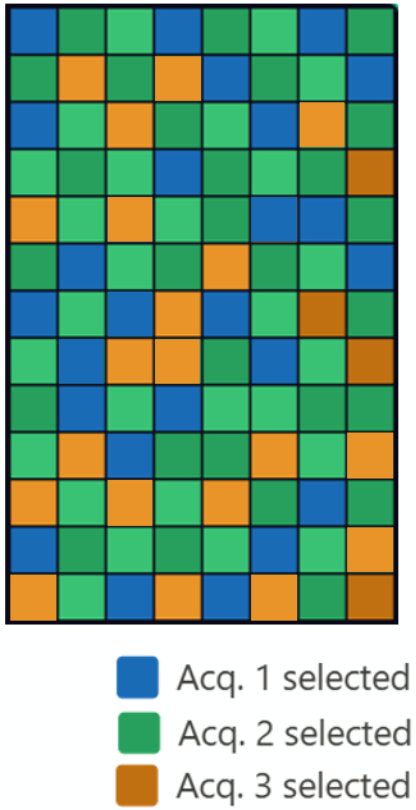
Per-pixel selection
with minimum RVoG residual

Acq.1 HoA = 10 m	**Estimated height = 8.5 m** Model residual = 0.12
Acq.2 HoA = 20 m	**Estimated height = 7.0 m** Model residual = 0.04
Acq.3 HoA = 30 m	**Estimated height = 9.5 m** Model residual = 0.2

$r_2 < r_1 < r_3$

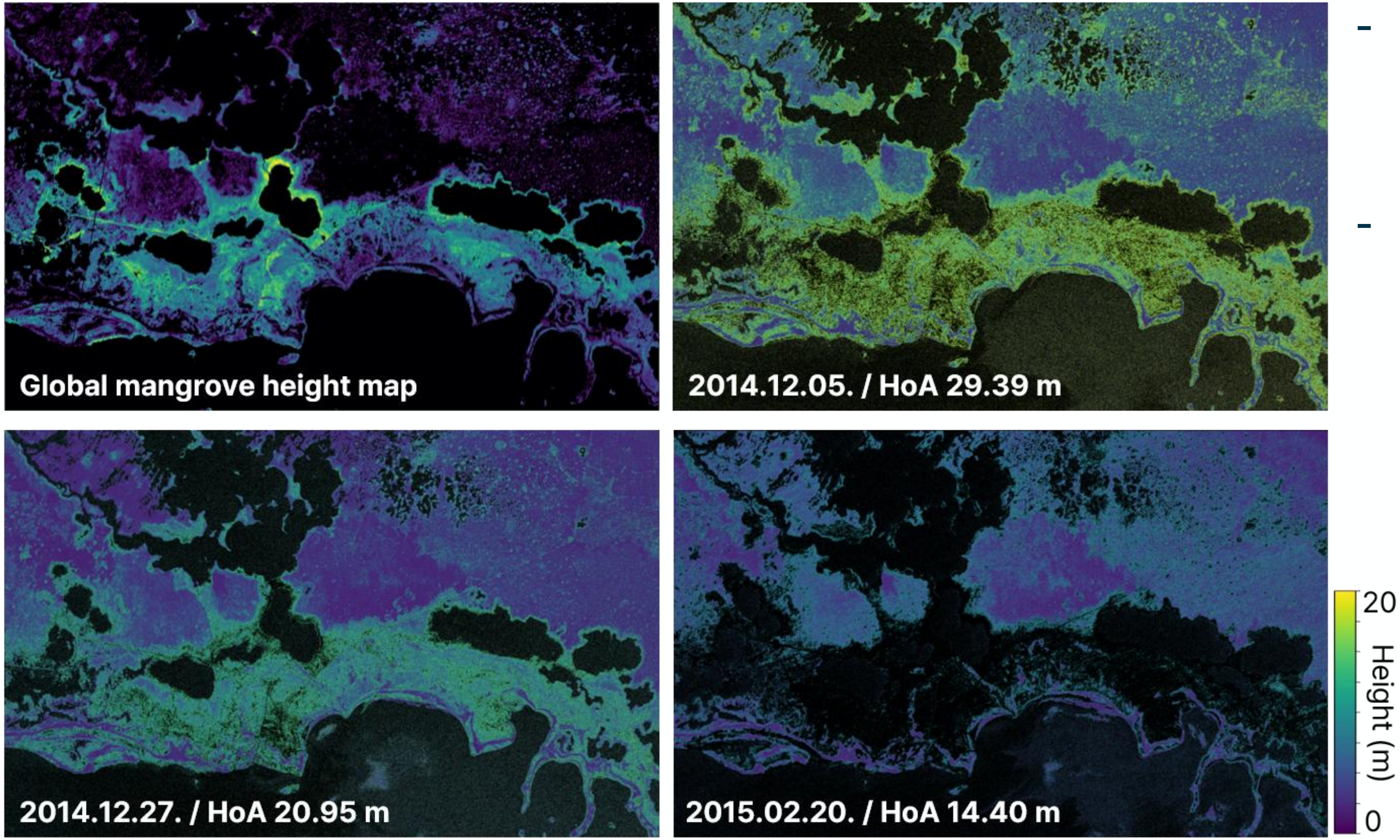
Final estimate:
Acquisition 2 selected
height = 7.0 m / σ = 0.5 dB/m

Canopy height map using multi baseline observations



▲ Example processing scheme for the proposed multi-baseline RVoG inversion

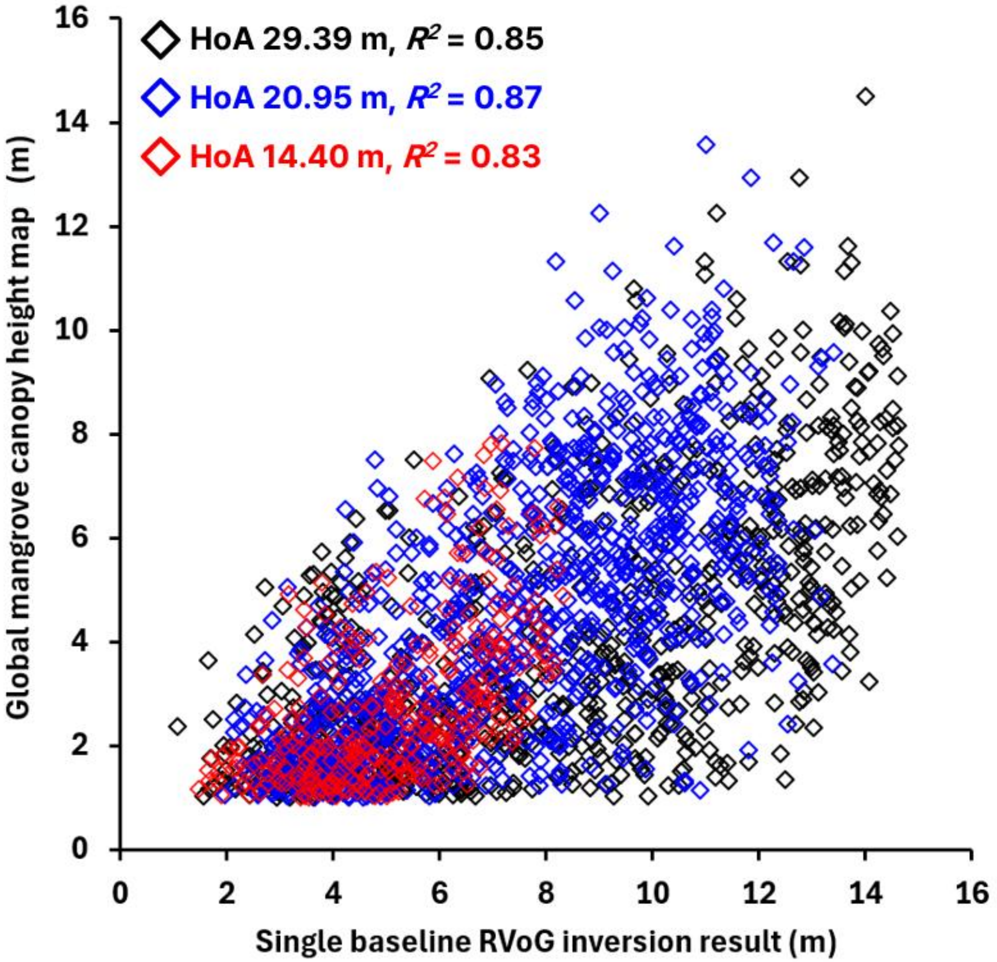
Results - Single baseline RVoG inversion



- Perpendicular baselines: 174.15, 257.18, and 343.98 m.
- Validated against the global mangrove canopy height map derived from TanDEM-X (Simard *et al.*, 2025).

◀ Reference mangrove height map and single baseline inversion results

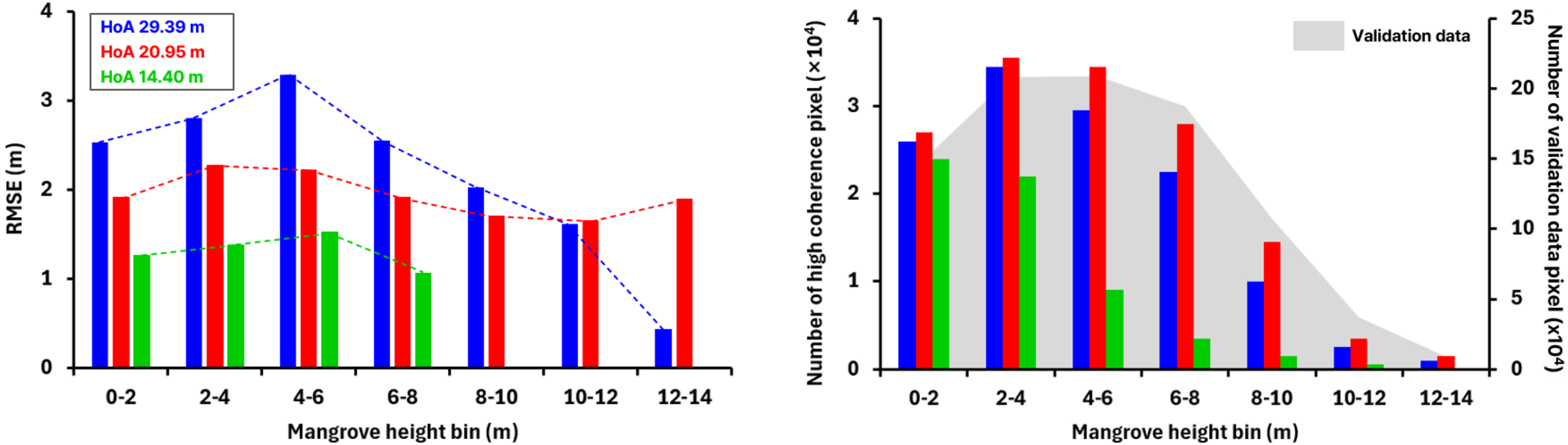
Results - Single baseline RVoG inversion



- All single baseline inversions showed strong agreement with the reference canopy height map (R^2 = 0.83–0.87).
- Different scatter distributions among baselines indicate that canopy height retrieval performance is highly dependent on HoA.
- These results highlight the influence of observation geometry on vegetation height sensitivity.

◀ Scatter plot showing the correlation between estimated and reference canopy heights

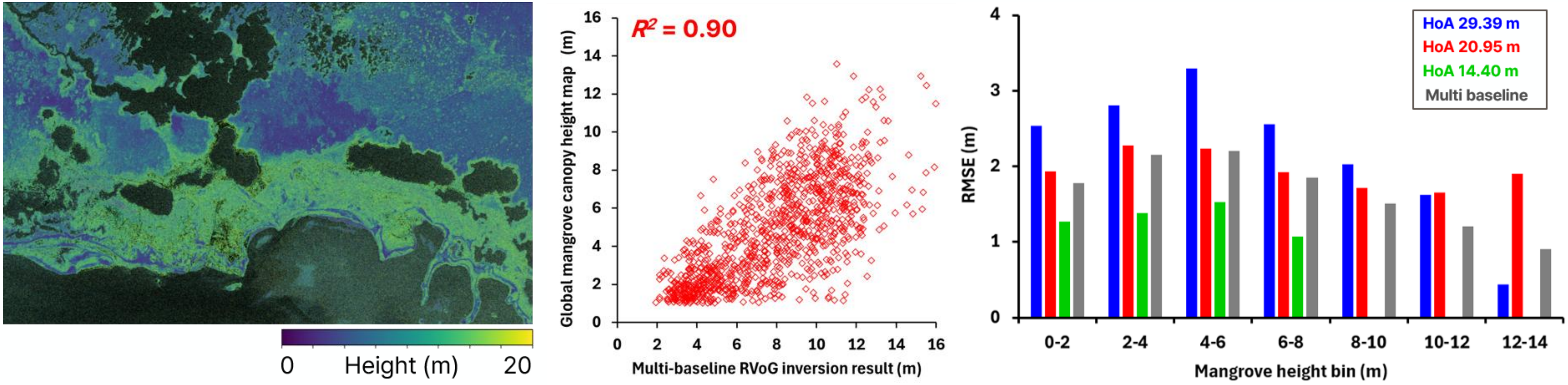
Limitations of single baseline



▲ RMSE by height bin (left) and number of high-coherence pixels per height bin (right) for each HoA dataset

- HoA of 20.9 m provided the most stable canopy height estimations.
- The other configurations showed varying sensitivity depending on the height range.
- Valid pixel with high coherence (>0.6) counts decreased with canopy height, with HoA 14.4 m showing the most rapid decline above 8–10 m.

Results - Multi baseline RVoG inversion



▲ Multi baseline RVoG inversion result (left), scatter plot against global mangrove canopy height map (middle), and RMSE by height bin for each HoA configuration (right)

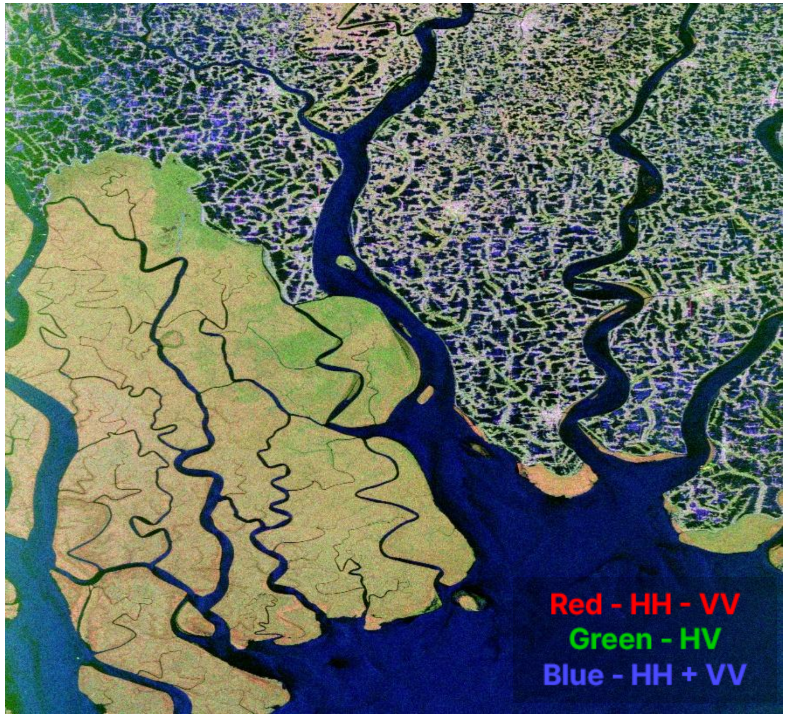
- Multi baseline RVoG inversion result showed strong correspondence with the global mangrove canopy height map (R^2 = 0.90).
- The multi baseline approach showed relatively stable performance across a wider height range compared to individual acquisitions.

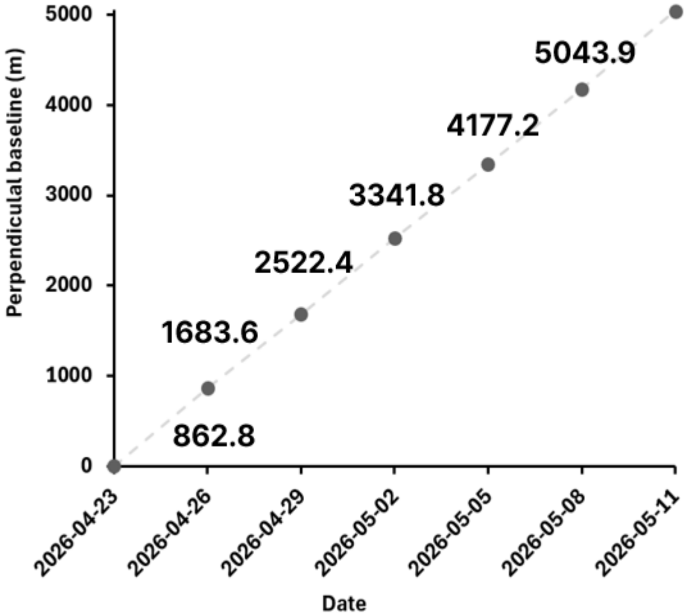
Summary

- This study estimated mangrove canopy height by applying multi baseline RVoG inversion without an external DEM, extending previous single baseline and DEM dependent studies.
- Single baseline results showed that estimation performance varied depending on HoA, with each baseline exhibiting limited sensitivity within a specific height range.
- By integrating multiple baselines with different HoA and kz configurations, vertical ambiguity and observation-dependent bias were reduced, achieving R^2 above 0.9.
- These findings suggest that multi baseline integration can enhance robustness of canopy structure estimation across a wider height range.
- This approach demonstrates the potential of InSAR application for mangrove monitoring.

Future work

- Combining P-band BIOMASS full polarimetric data with the multi baseline RVoG approach is expected to enable more accurate canopy height retrieval.





Perp. baseline - Min.: 862.8 Max.: 5043.9
Temp. baseline - 3 days

▲ Pauli decomposition from BIOMASS full polarimetric data (left), volume coherence and baseline configuration of BIOMASS InSAR observations (right) over Sundarbans

Thank you

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