L-BAND INTERFEROMETRIC COHERENCE TIME-SERIES FOR FOREST PARAMETERS RETRIEVAL

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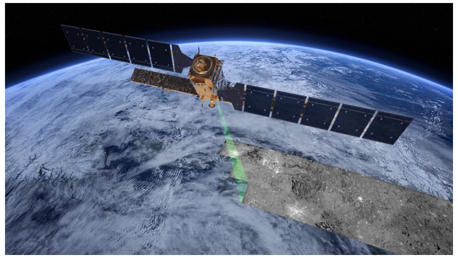
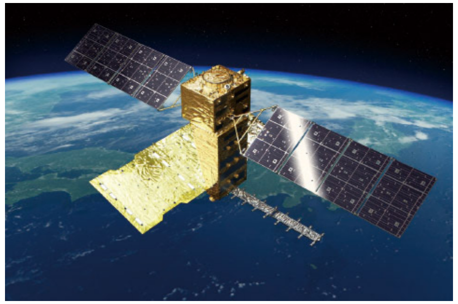
Background| Temporal Decorrelation in Vegetated Areas

- Several SAR missions are designed to acquire global **near zero baseline InSAR time-series**
- InSAR acquisitions over vegetated areas are affected by **temporal decorrelation** due to:
  - Vegetation Growth and Dynamics
  - Wind speed
  - Variation in Soil and Vegetation Water Content
- Using time-series of temporal coherence for land applications requires **models and retrieval algorithms**





Goal

Map forest properties from **time-series** of InSAR **temporal coherence** using a **model-based approach**

Physical Model of Temporal Polarimetric InSAR Coherence

Random Motion Over Ground Model (RMoG+)

- Model time-series of repeat-pass temporal coherence over land
- Scatterers' motion modeled with Gaussian + Brownian statistics

$$\gamma(t_1,t_2) = \frac{\sqrt{\mu_1\mu_2}\,\gamma_g + \gamma_v}{\sqrt{(\mu_1+1)(\mu_2+1)}}$$

Ground-level coherence

$$\gamma_g = \exp\left[-\frac{1}{2}\left(\frac{4\pi}{\lambda}\right)^2 \delta_g^2 T\right]$$

Long-Term Coherence

$$\delta_g = 0 \text{ m}/\sqrt{\text{day}},\, T \to \infty$$

$$\gamma_\infty = \frac{\sqrt{\mu_1\mu_2}}{\sqrt{(\mu_1+1)(\mu_2+1)}}$$

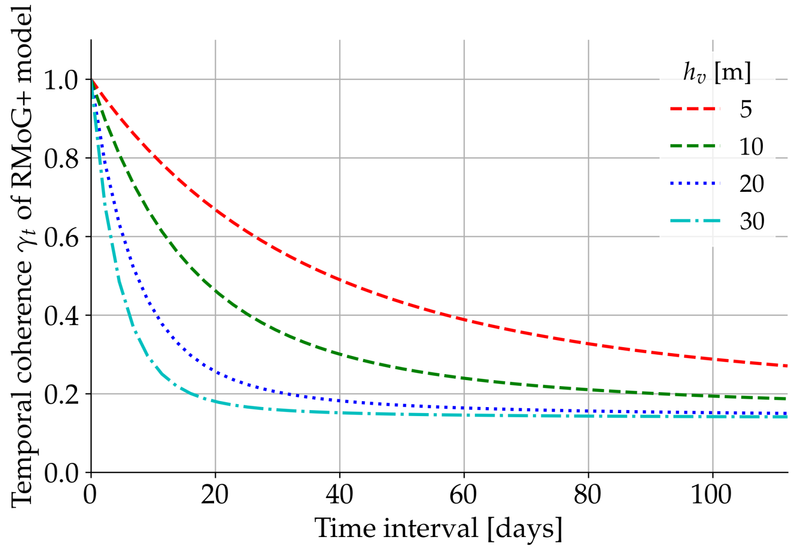
Vegetation-layer coherence

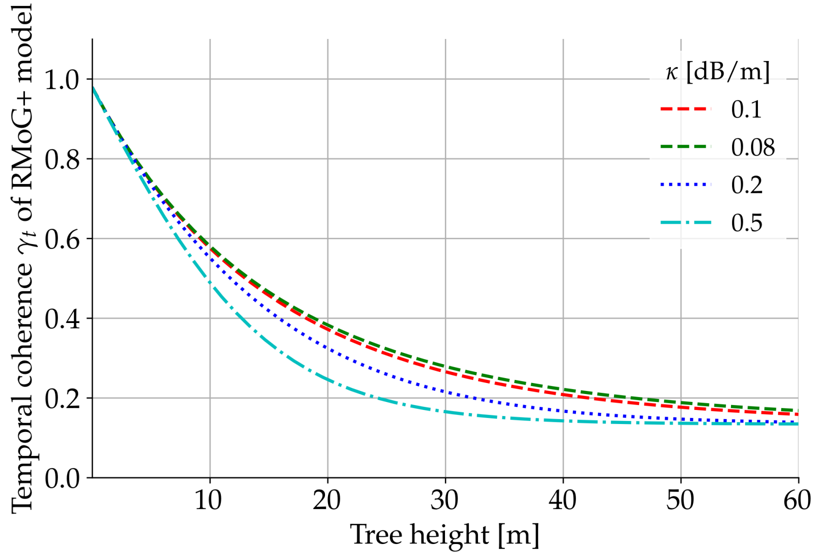
$$\gamma_v = \gamma_g \frac{p(e^{qh}-1)}{q(e^{ph}-1)}$$

$$q = p - \frac{1}{2}\left(\frac{4\pi}{\lambda}\right)^2 \frac{\delta_v^2 - \delta_g^2}{h_r} T$$

$$p = \frac{2\kappa}{\cos\theta}$$

(Lavalle, M. et al., 2012; 2023)





Forest Parameters Retrieval Algorithm Development

Forest parameters estimation is attained through a 3-step procedure which involves the inversion of RMoG model and Water Cloud Model (WCM) over the LiDAR GEDI samples of vegetation height

RMoG+ unknown parameters

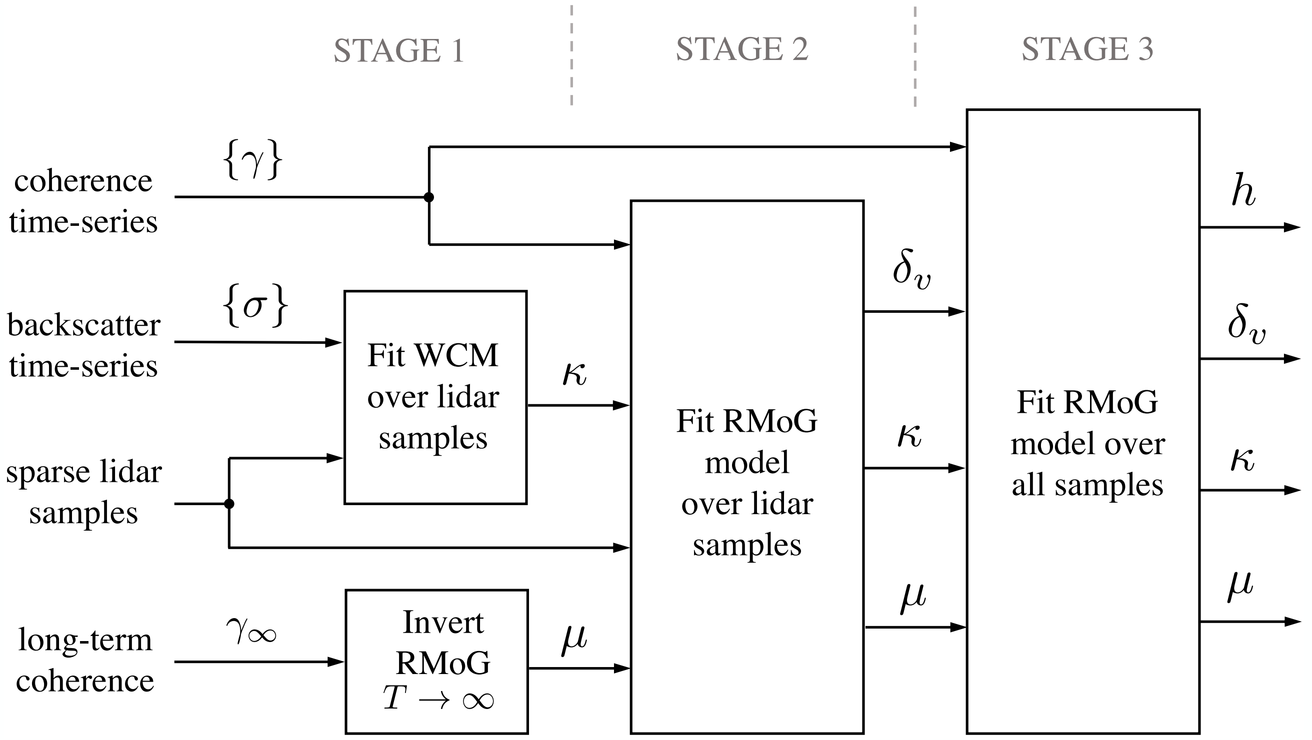
Structural parameters

- μ_1 Ground-to-volume ratio at $t = t_1$
- κ Vegetation extinction coefficient
- h Vegetation height

Dynamic parameters

- μ_2 Ground-to-volume ratio at $t = t_2$
- δ_g Ground-scatterers motion rate std
- δ_v Canopy-scatterers motion rate std

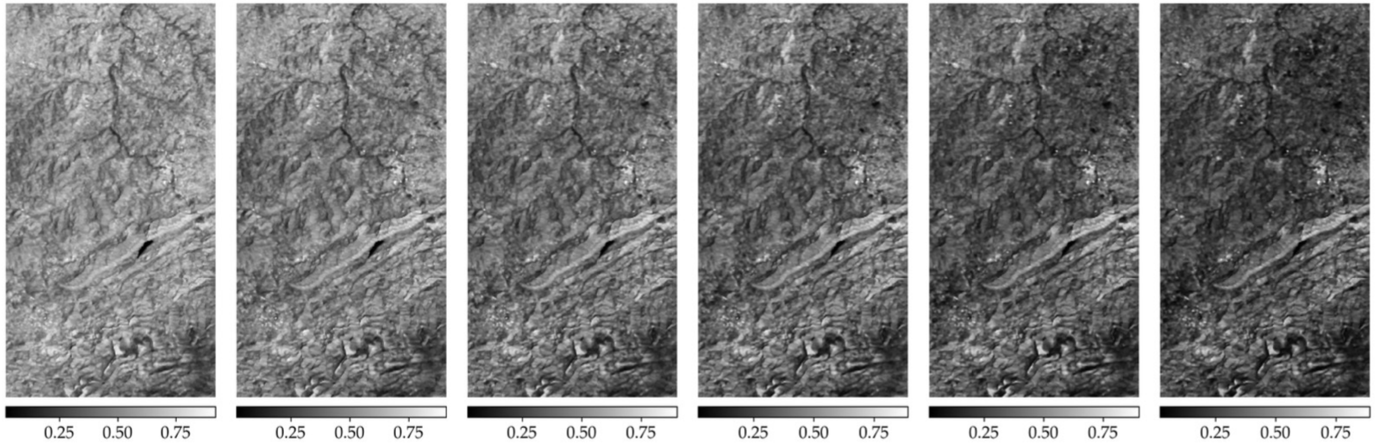
3-Stage Forest Parameter Estimation from Time-Series of InSAR Coherence

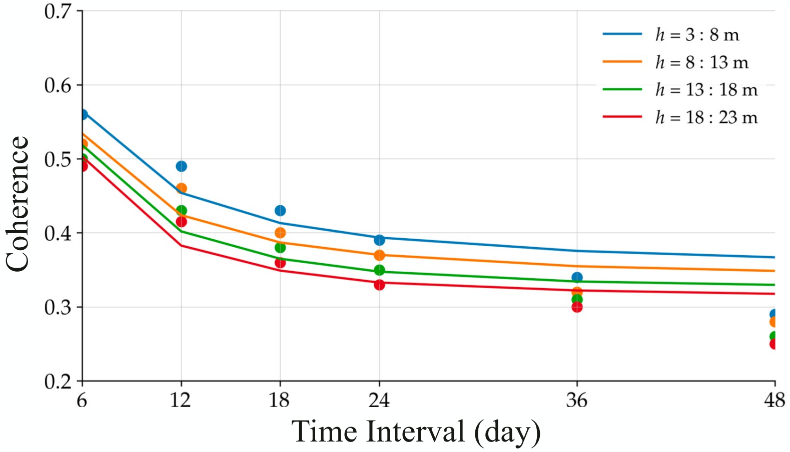


Tree Height Retrieval from Sentinel-1 InSAR Coherence Time-Series

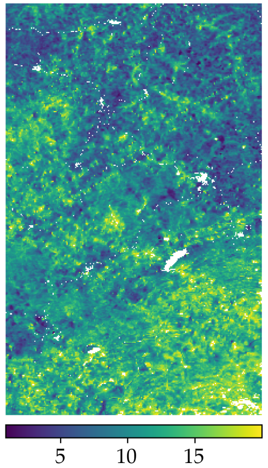
<u>**Input dataset**</u> **:**

Global 3-arcsec **C-band Sentinel-1 data set** (Kellndorfer et al., *Nature Sci. Data* 2022)





Estimated Tree Height – 90 m resolution map



M. Lavalle, et al., "Model-Based Retrieval of Forest Parameters From Sentinel-1 Coherence and Backscatter Time Series," in *IEEE Geos. and Rem. Sens. Lett.* vol. 20, pp. 1-5, 2023

Next step

Extend the analysis to **L-band InSAR time-series** in view of upcoming global interferometric datasets from NISAR and ROSE-L missions

L-Band Dataset| ALOS-2 Interferometric Coherence

Study area:

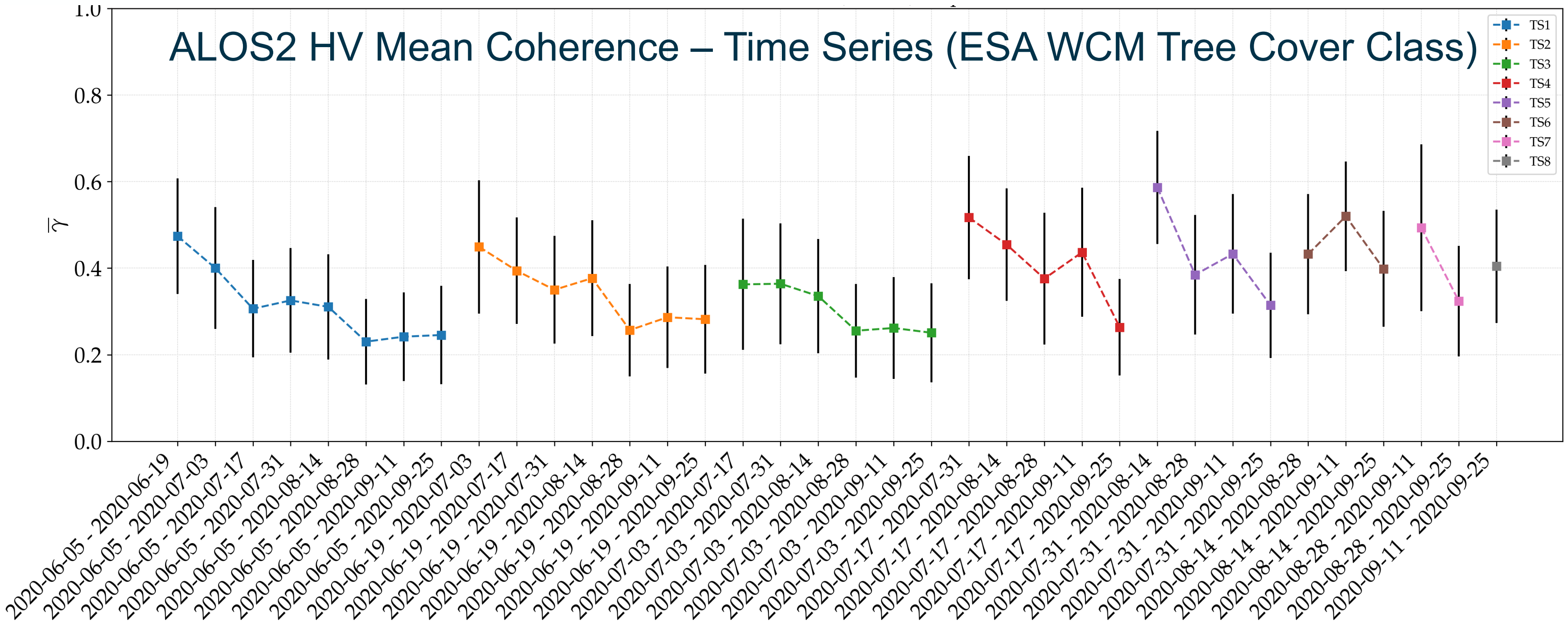
Spain, Asturias, Oviedo (Lon : -6.33°,-5.33° ; Lat: 42.98°, 43.68°)

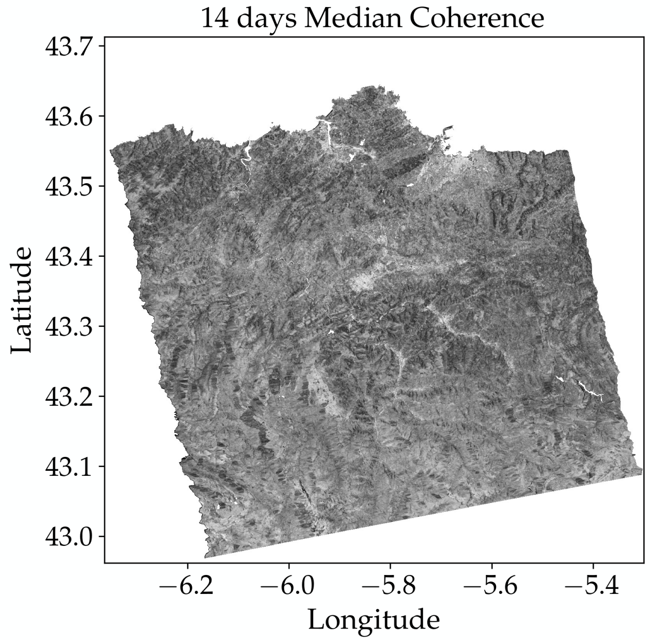
ALOS-2 DATA			
Obs. Mode	**Orbit and Obs. direction**	**Revisit Time**	**Polarization**
SM3 : Fine	ASCENDING - RIGHT	14 days	HV

Interferometric processing
NASA JPL ISCE-2 software

Number of SLCs: 9

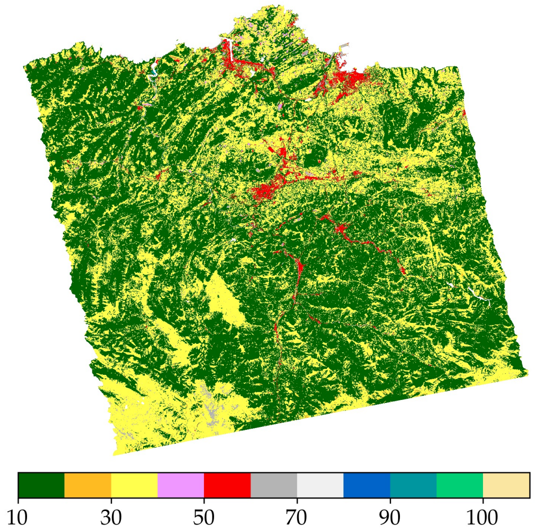
Number of Interferograms: 36



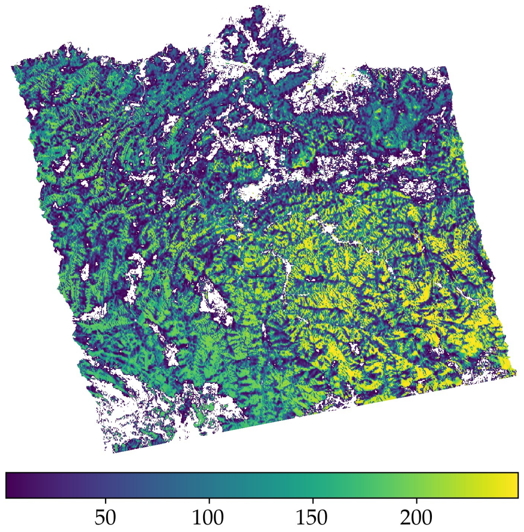


Study Site | Vegetation Species

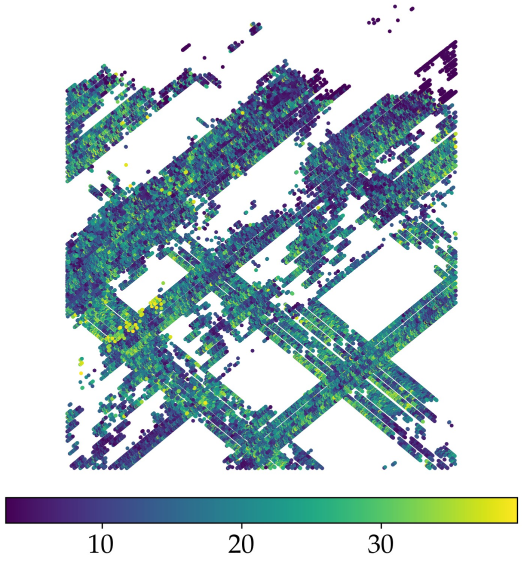
Location	Spain, Asturias, Oviedo (Lon : -6.33°,-5.33° ; Lat: 42.98°, 43.68°)
Biome	Temperate Broadleaf and Mixed Forests
ESA WCM	Tree cover (60%) , Grassland (36%)
Vegetation species	Eucalyptus globulus (19.5%), Castanea sativa (45.8%), Fagus sylvatica (25.9%)



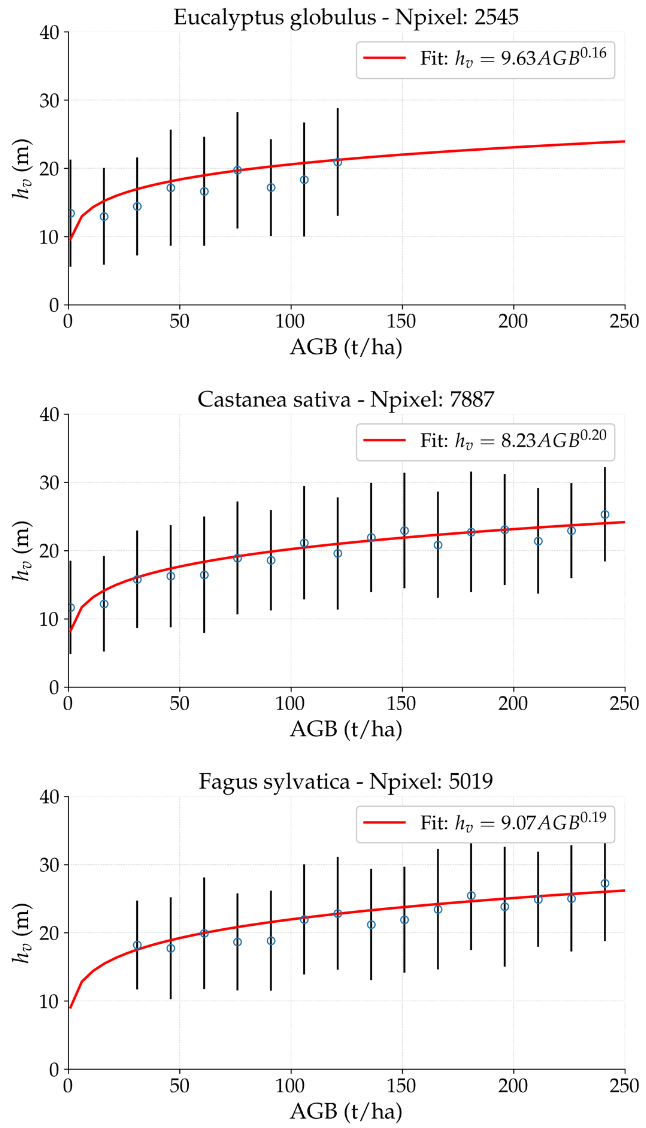
a) ESA WCM



b) AGB [Mg/ha]



C) GEDIL2 RH100 [m]



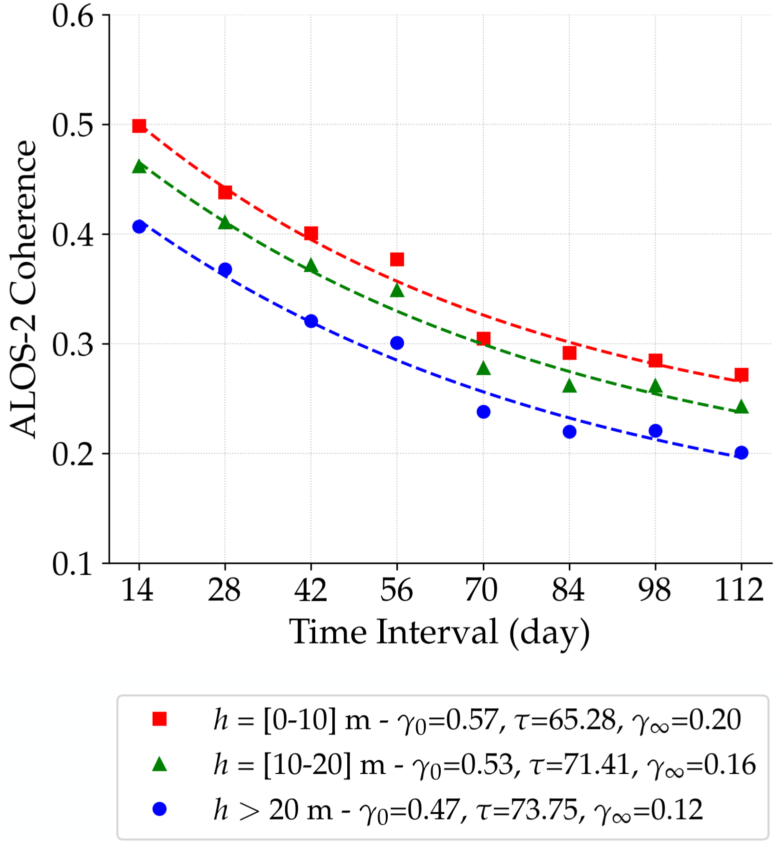
ALOS-2 Coherence Sensitivity to Tree Height

Coherence decay over time at different vegetation height– **Exponential Fitting**

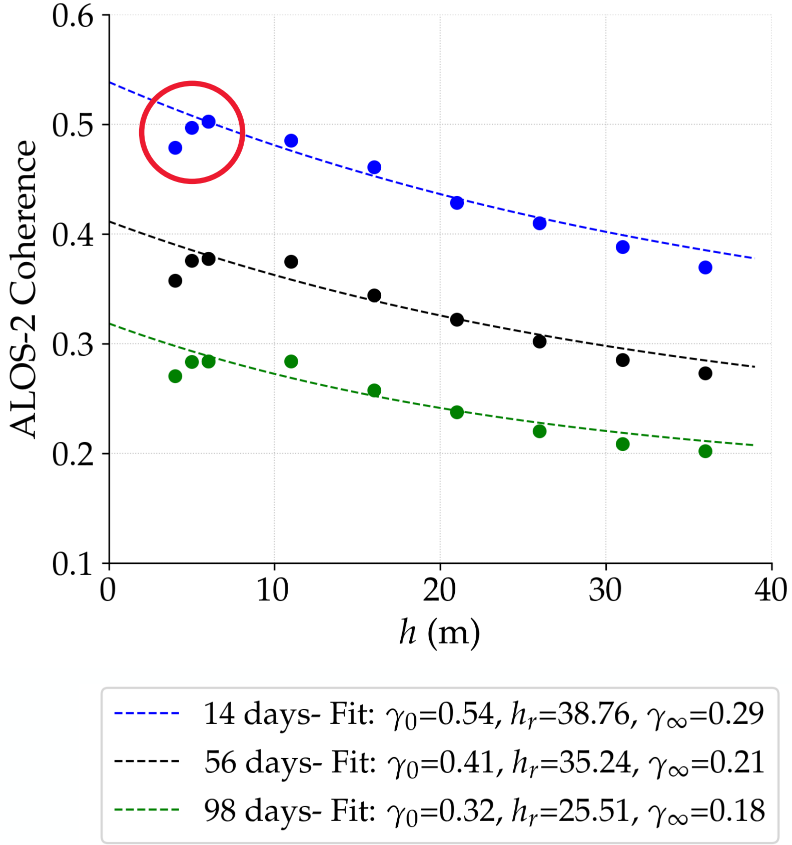
Decorrelation Effects

- Very short vegetation is more sensitive to the **changes of soil moisture**
- When h approaches 5-6 m the ground decorrelation becomes less significant
- Tall trees (h>10 m) are mostly affected by the **movement of the scatterers** within the canopy

$$\gamma_t = (\gamma_0 - \gamma_\infty)e^{-T/\tau} + \gamma_\infty$$



$$\gamma_t = (\gamma_0 - \gamma_\infty)e^{-h/h_r} + \gamma_\infty$$



Forest Parameter Estimation| Extinction Coefficient - κ

ALOS2 mean backscatter used in conjuction with **Water Cloud Model** and GEDI L2A height to retrieve **extinction coefficient** $\boldsymbol{\kappa}$

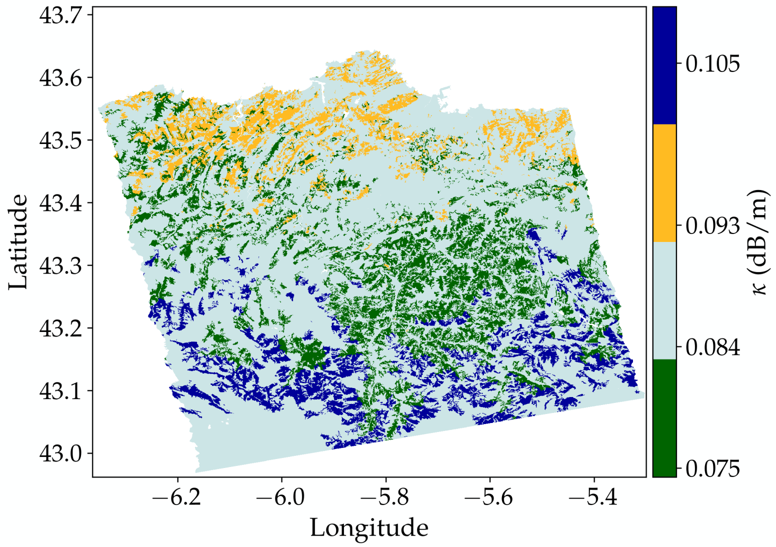
Water Cloud Model

$$\sigma^0_{for}(t) = \sigma_g(t)K(t) + \sigma_v(t)[1 - K(t)]$$

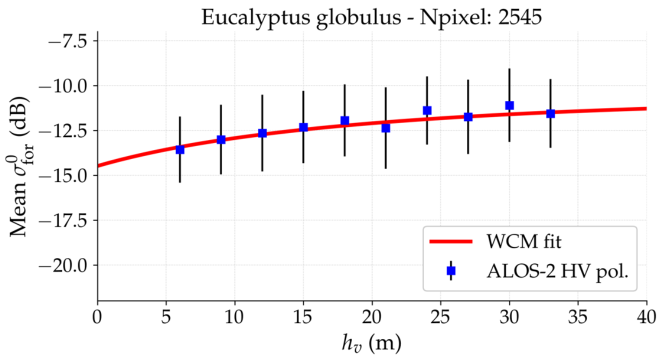
$$K(t) = 1 - \eta + \eta \exp[-\frac{2\kappa(t)}{\cos\theta}]$$

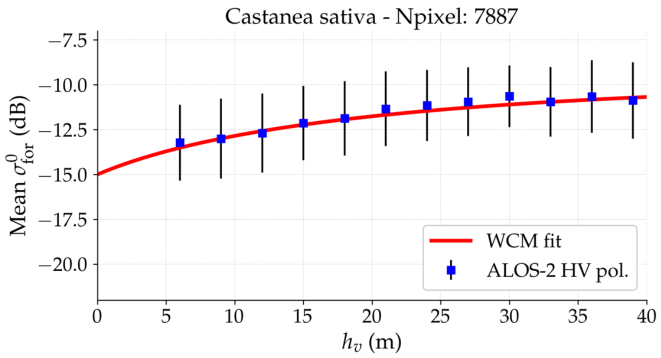
- Mean Backscatter Map – HV pol.
- GEDI L2A Tree Height

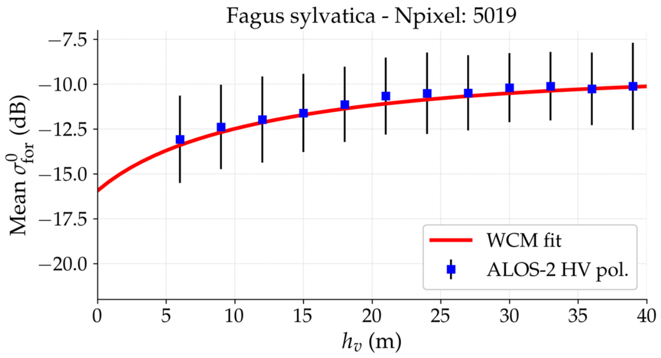
Estimated Extinction κ



Species	Extinction - HV pol	Extinction - HH pol
Eucalyptus	0.093 dB/m	0.071 dB/m
Castanea	0.075 dB/m	0.080 dB/m
Fagus	0.105 dB/m	0.206 dB/m
Other	0.084 dB/m	0.090 dB/m





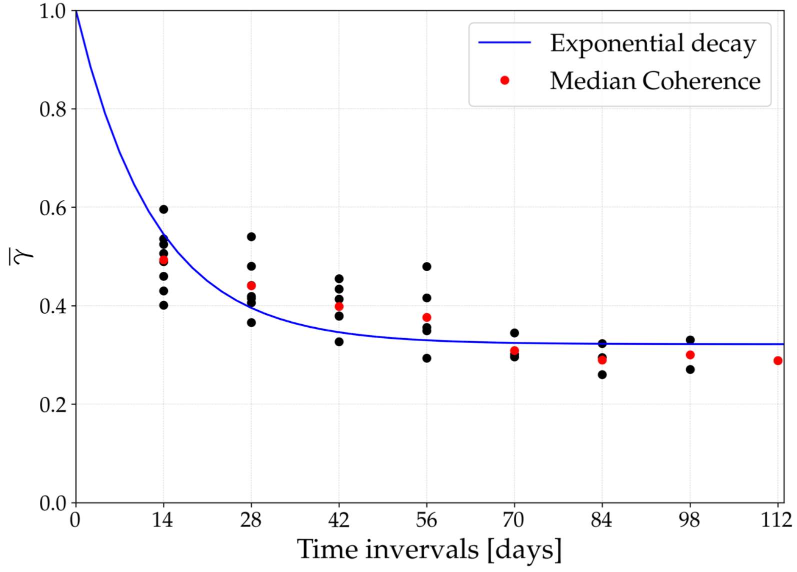


Forest Parameter Estimation | Ground-to-Volume Ratio - μ

Ground-to-volume ratio μ_∞ is derived from ALOS2 **long-term coherence map** γ_∞ assuming $\boldsymbol{\mu}$ **unchanged between acquisitions**

Long-Term Coherence Estimation

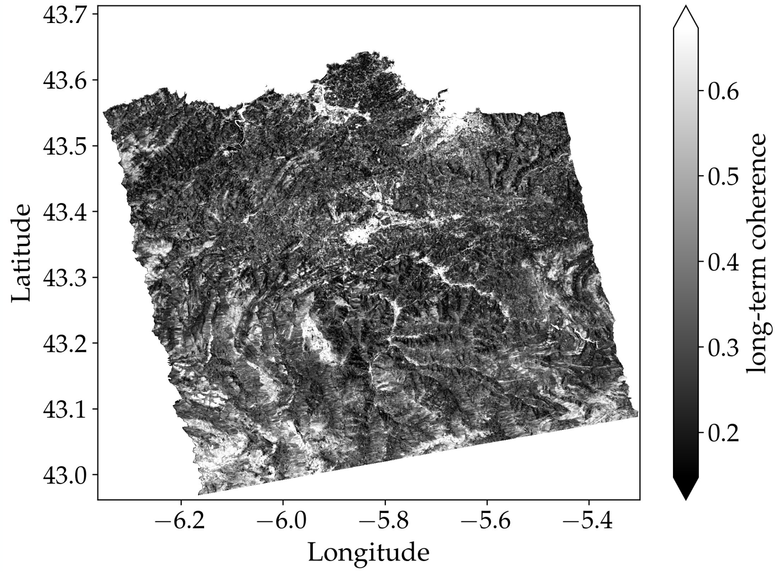
$$\gamma_t = (\gamma_0 - \gamma_\infty)e^{-T/\tau} + \gamma_\infty$$

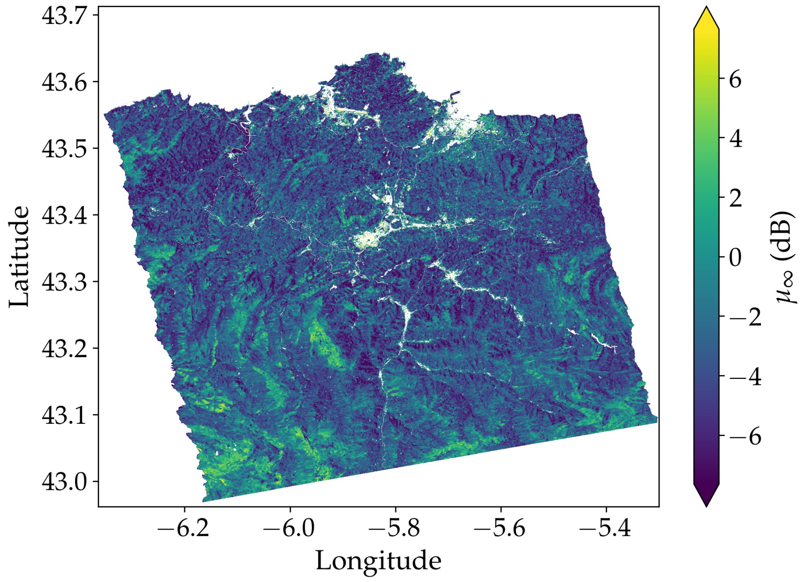


RMoG Long-Term Coherence – G/V Ratio Estimation

$$\gamma_\infty = \frac{\sqrt{\mu_1 \mu_2}}{\sqrt{(\mu_1 + 1)(\mu_2 + 1)}}$$

Ground-to-Volume Ratio μ_∞





Model-Based Estimation of Canopy Motion Rate Std - δ_v

Values of canopy motion rate std δ_v (t) are obtained over GEDI L2 locations **for each temporal gap** by fitting the ALOS2 coherence with the **RMoG model**

RMoG Coherence

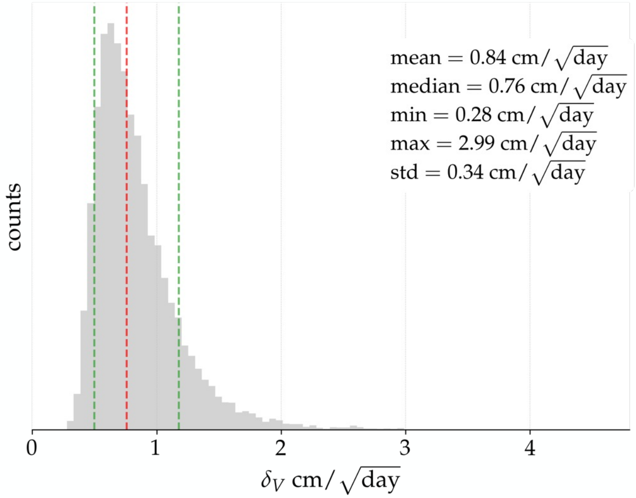
$$\gamma(t_1, t_2) = \frac{\sqrt{\mu_1 \mu_2}\, \gamma_g + \gamma_v}{\sqrt{(\mu_1 + 1)(\mu_2 + 1)}}$$

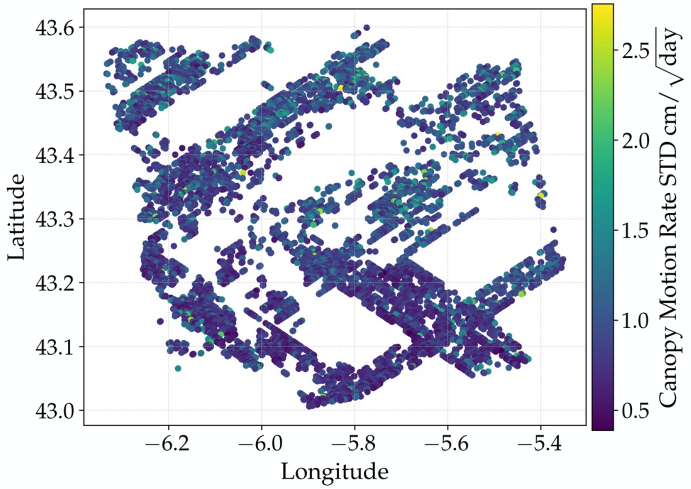
Input

- ALOS2 Time Series
- Estimated Extinction
- Estimated GTV ratio
- GEDI L2 tree height
- No Ground Decorrelation

δ_v is the only unknown parameter

Estimated Canopy Motion Rate STD @ **14 days time interval**





The Canopy motion rate STD δ_v **increases over time**

- At short-time intervals (<56 days) δ_v is approximately 1 $\frac{cm}{\sqrt{day}}$
- At long-time intervals (70 up to 112 days) δ_v is greater than 2 $\frac{cm}{\sqrt{day}}$

which **limits the coherence sensitivity to tree height**

Model-Based Estimation of Vegetation Height - h

ALOS-2 coherence **time-series** data set are fit with RMoG model to estimate tree height

RMoG Coherence

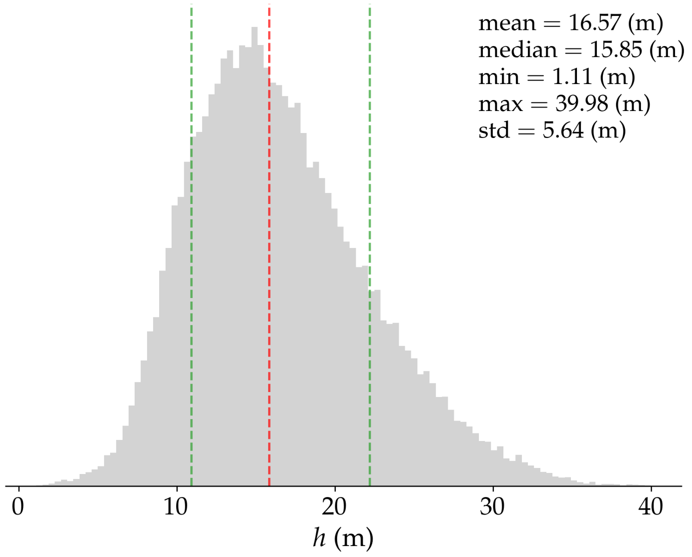
$$\gamma(t_1, t_2) = \frac{\sqrt{\mu_1 \mu_2}\,\gamma_g + \gamma_v}{\sqrt{(\mu_1 + 1)(\mu_2 + 1)}}$$

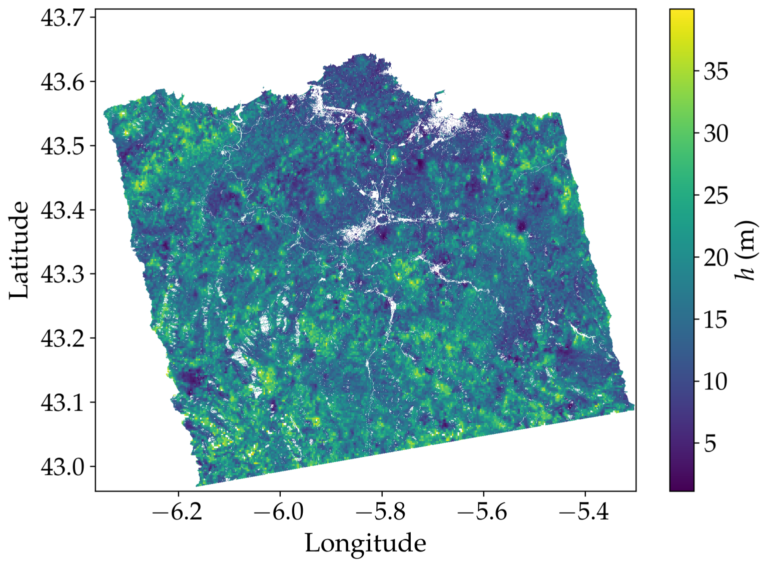
Input

- ALOS2 Time Series
- Estimated Extinction
- Estimated GTV ratio
- Interpolated Maps of Estimated Canopy Motion Rate STD
- No Ground Decorrelation

h is the only unknown parameter

Estimated Tree Height Map





RMoG model inversion is performed over the time-series of 14- up to 56-days coherence maps which show the highest sensitivity to tree height

Forest Parameters Estimation Performance| Residuals

Training dataset

- Tree height is well retrieved where δ_v is accurately estimated (slight bias: ~0.2 m)

Test dataset

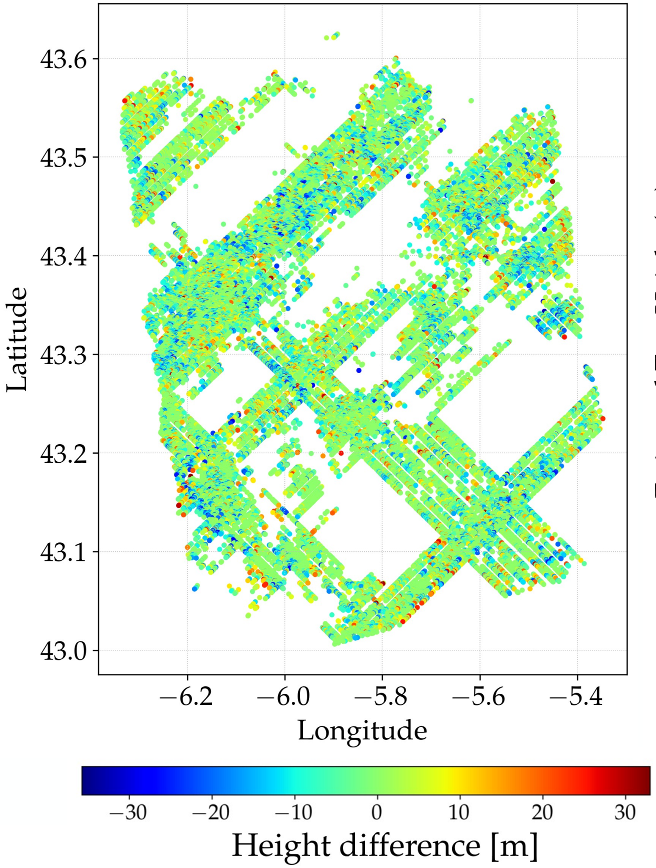
- Good estimation performance for 10-20 m tree height

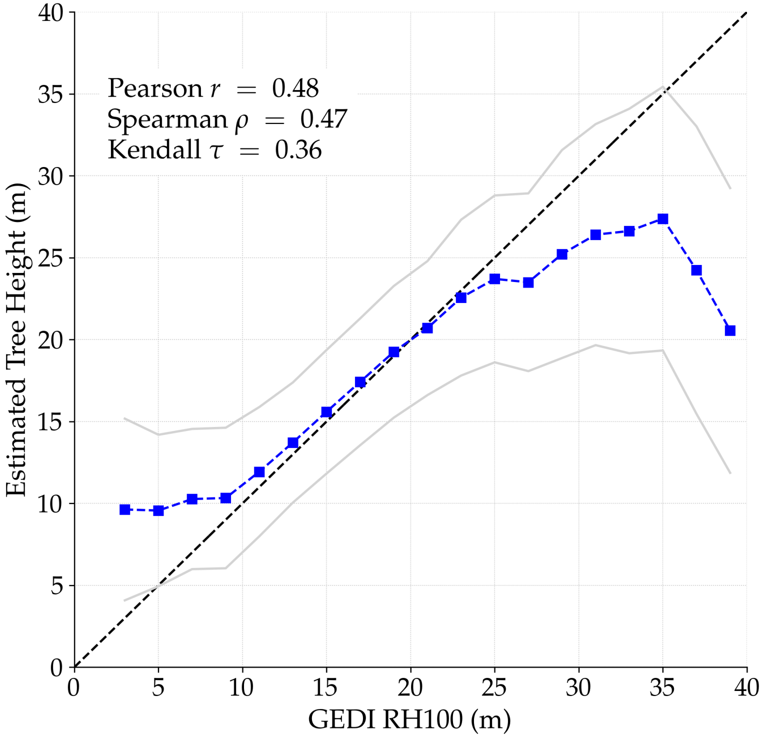
- Very short vegetation is overestimated whereas tall vegetation is underestimated

Error sources

Model assumptions, other uncompensated decorrelation effects, GEDI geolocation errors, low RMoG model sensitivity to tall stands, algorithm's design to be optimized

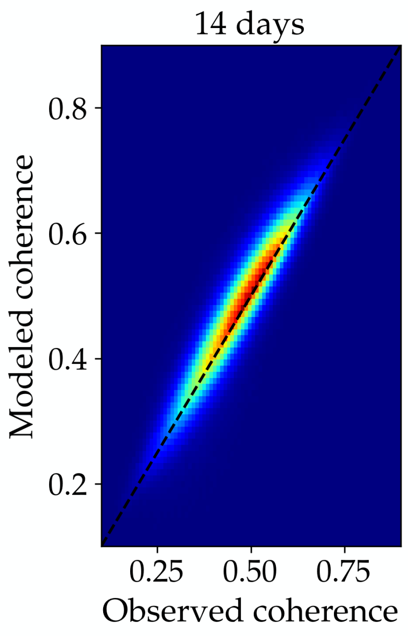
Estimated Tree Height vs GEDI RH100

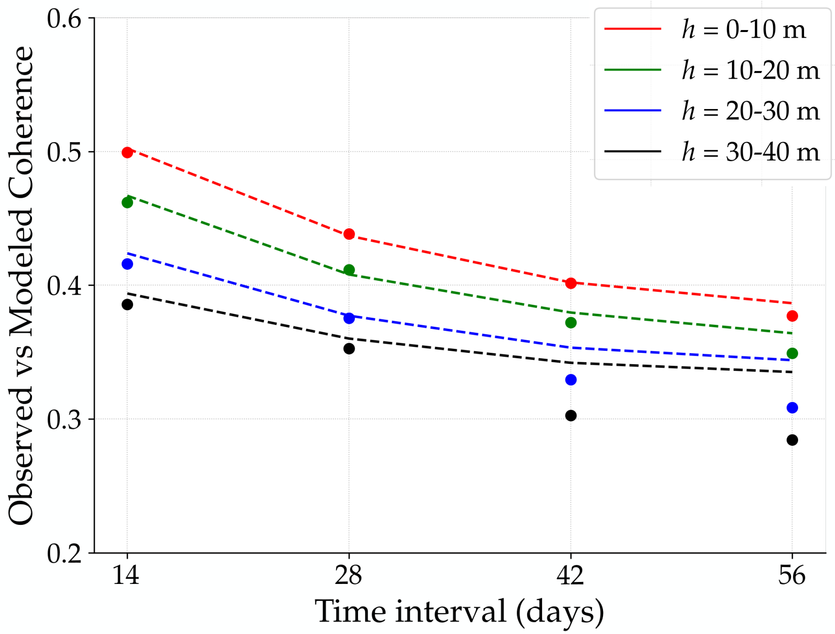


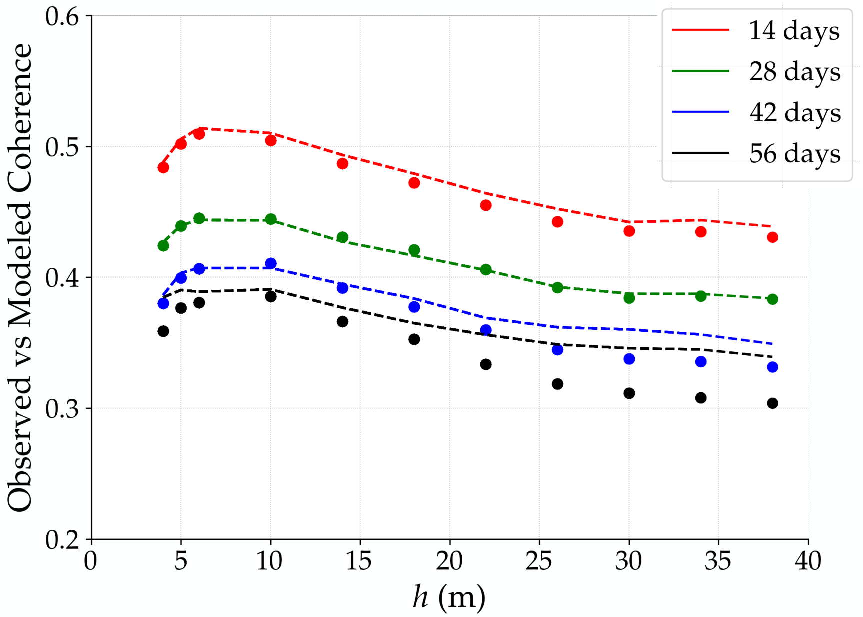


RMoG Model Fitting

- μ derived from γ_∞ is likely to absorb the overestimation of short vegetation → This effect can be mitigated by compensating for γ_{SNR} and μ changes over time
- Overestimation of 42-, 56-days coherence is likely due to inaccuracy in δ_v estimation which affect the underestimation of tall stands → This effect can be mitigated by improving the overall estimation strategy







Take-Home Messages and Future Work

- The objective of this work is to define a **model-based approach** to estimate **forest properties** from the **time-series** of interferometric coherence at **near zero-spatial baseline**

- **Preliminary attempt to retrieve tree height from time-series of L-band InSAR coherence** shows reasonably good performance for 10-20 m tree height but shorter and taller stands are not properly estimated

- **Future works** will address the opportunities to enhance the tree height estimation by:
    - improving the **pre-processing** of the data set
    - relaxing some of the model **assumptions**, including other data layers and/or refining the RMoG model
    - addressing the effect of topography and site's characteristics by comparing different study areas
    - optmizing/modifying **the overall estimation strategy**

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