Operational canopy height estimation via spaceborne images with uncertainty quantification

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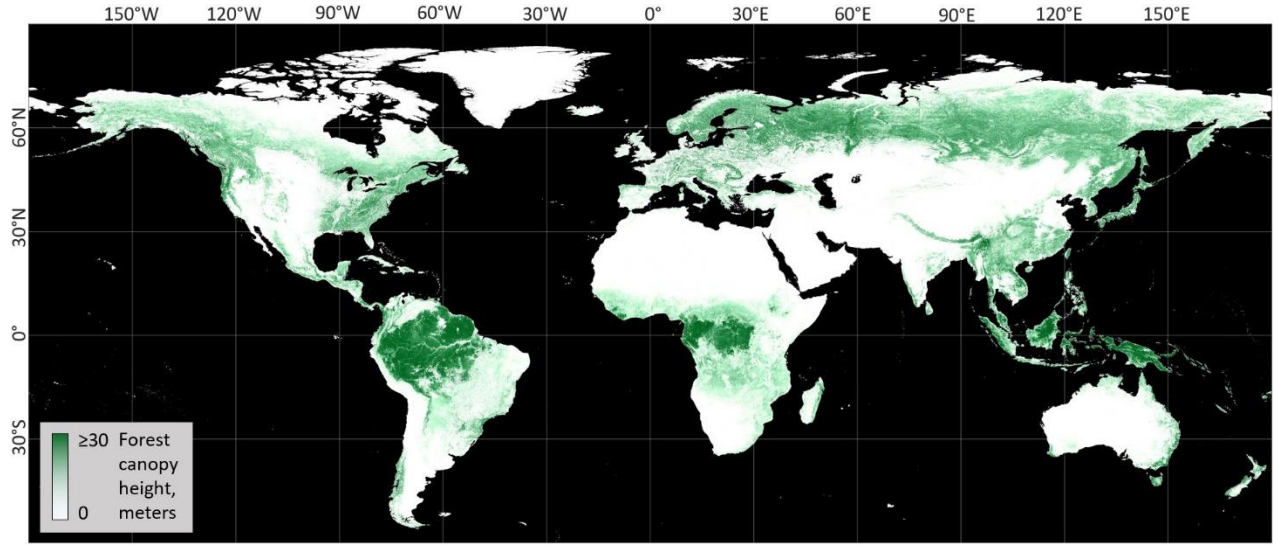
Canopy Height Model (CHM)

Canopy height of forests is a fundamental parameter for environmental studies and applications

Airborne LiDAR sensors:

- Yield measured 3-D point clouds
- Ground sampling distance (GSD) <1 m
- High accuracy considered as ground truth
- Limited to local scale due to high cost and lack of repetition



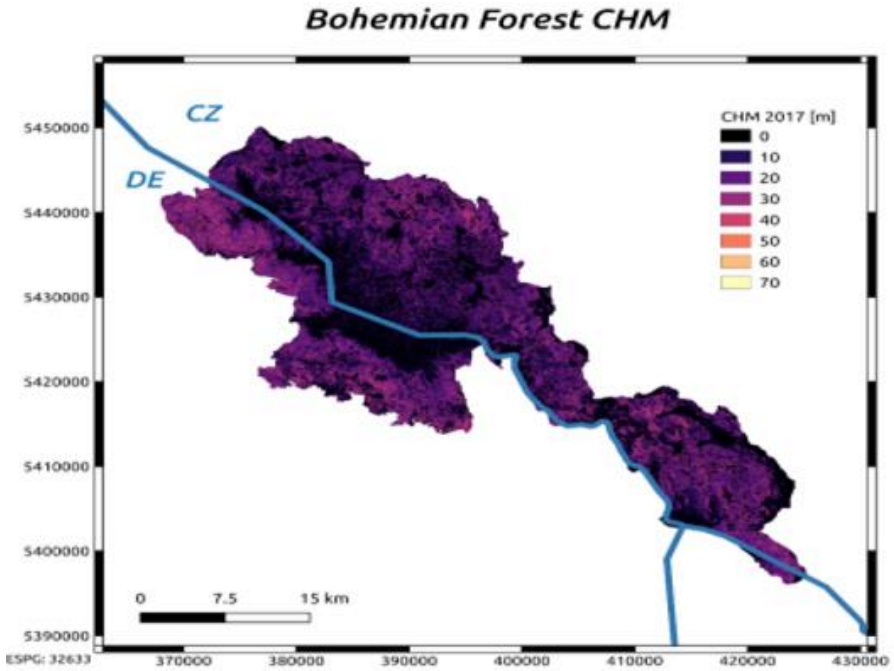
Source: https://glad.umd.edu/dataset/gedi

Study Area

- Bohemian Forest (BF) ecosystem
- Area: 942 km2
- Location: Borders between southeastern Germany and Czech Republic
- Forest area: Heavily forested mountains, altitudes ranging from 570 to 1453 m
- Dominant tree species: Norway spruce (Picea abies), silver fir (Abies alba), European beech (Fagus sylvatica)

Data Acquired

- Ground-truth CHM: LiDAR measurements with Riegl 680i sensor in June 2017
- Annual sequences of Sentinel-2 Level-1C products (2017, 2018-2021)
- Land cover map, used for evaluation and comparison with previous works

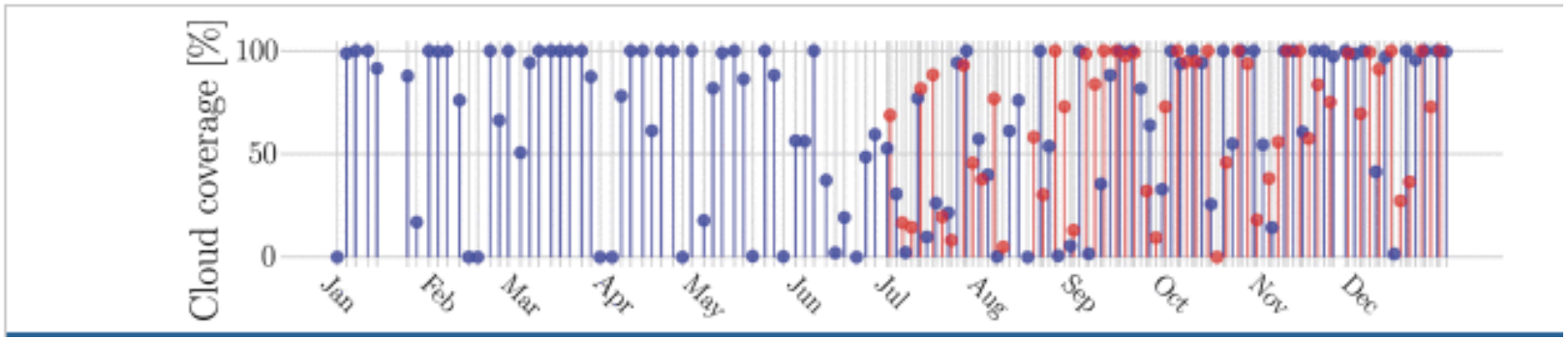


Our CHM approach (I)

- Local spectral signatures are determined by a large vector of parameters that include shadowing, tree type, vegetation density, atmospheric column information, and so on, and some of these parameters are proxies to canopy height.

- Our model exploits the spatial distribution of these signatures as captured by CNNs, which inherently capture the corresponding texture of the satellite images.

- We adopt a convolutional variant of a long short-term memory (LSTM) model for canopy height estimation from multi-temporal instances of Sentinel-2 products.

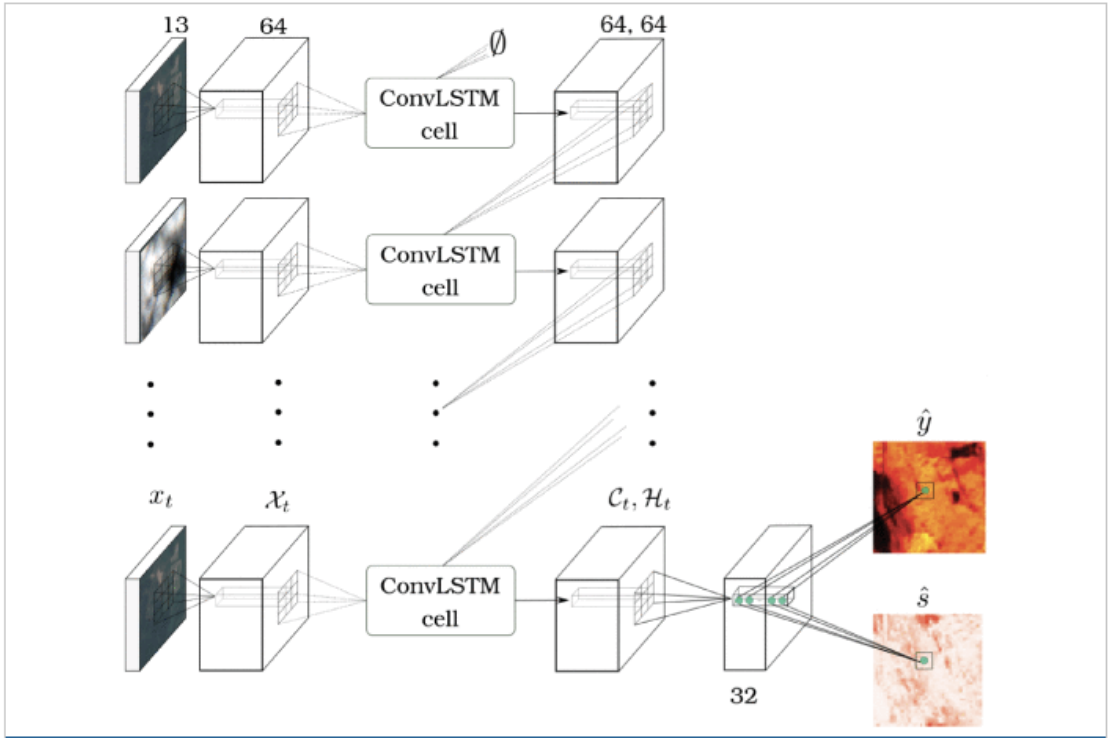


- Cloud coverage on all product dates of 2017.
- With blue color, S2A products are marked, and with red color, S2B products are marked.
- In total, 160 timeframes are available from the Sentinel-2 mission.
- The satellite S2B began providing data in the last semester of the year.

Our CHM approach (II)

- With this model architecture, we are seeking to capture the temporal evolution of the distribution that the image texture follows and map it to the space of vegetation heights.

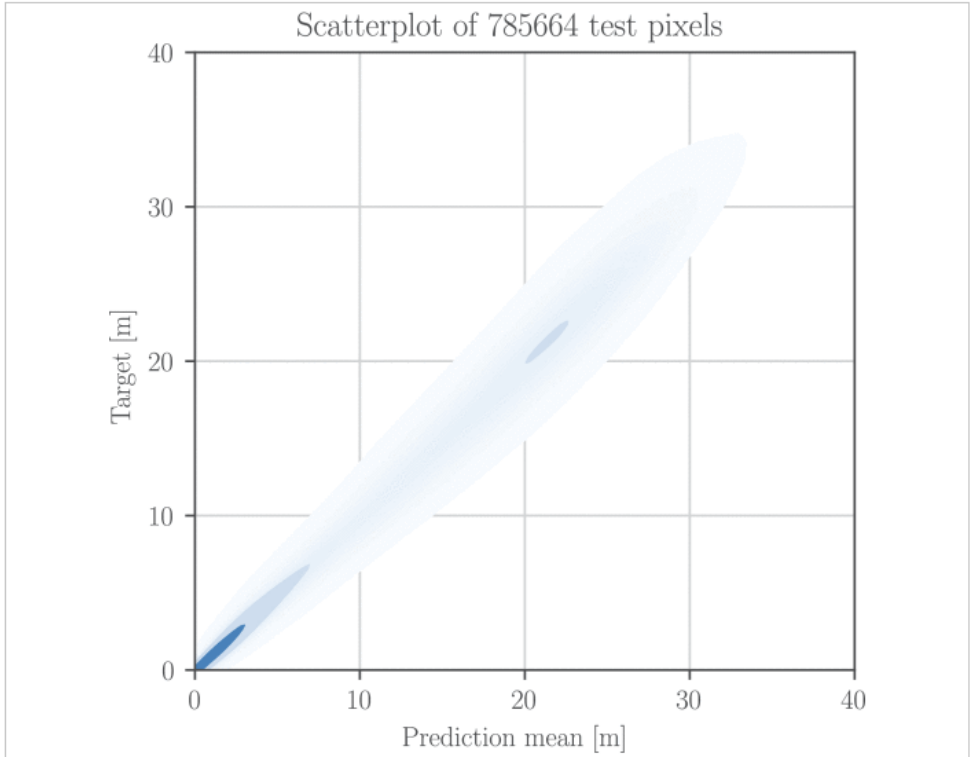
- Training and testing the model is based on different tiles of a total forest area of approximately 94K hectares, and comparison results with state-of-the-art studies are provided.



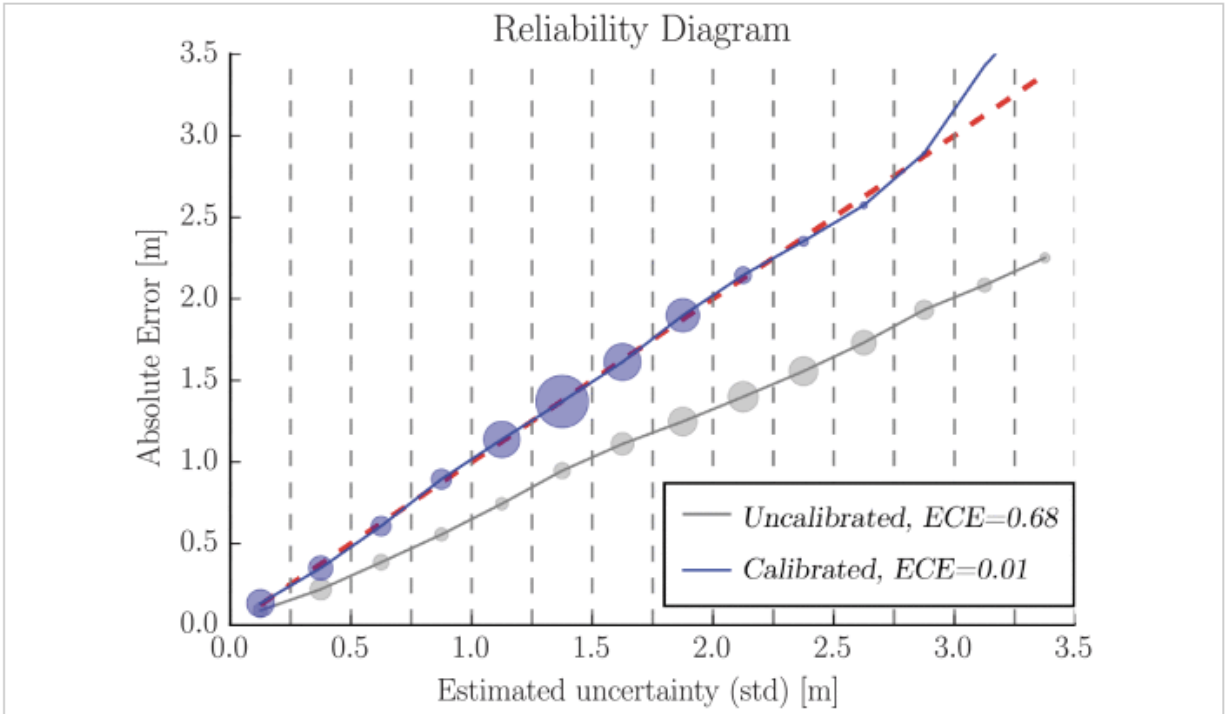
A sequence of 40 Sentinel-2 L1C tiles is used as input, {xt}Tt=1 , while the output consists of two maps with the same size as input representing estimated height mean value, y^ and log variance, s^

Our CHM approach (III)

Ground-truth versus estimated height values for more than 78 km^2 of test area.

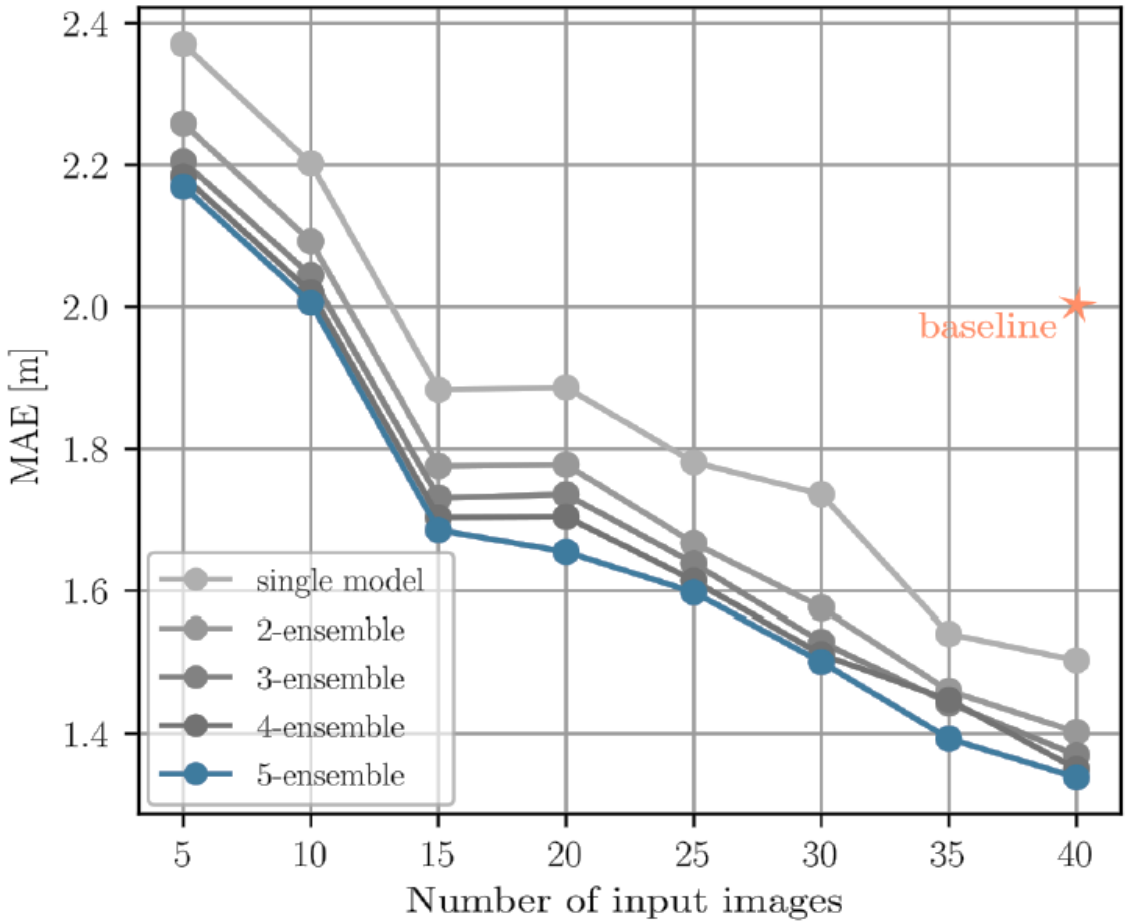


- We utilize deep ensembles technique for meaningful uncertainty estimation on the predictions and post-processing isotonic regression model for calibrating them.

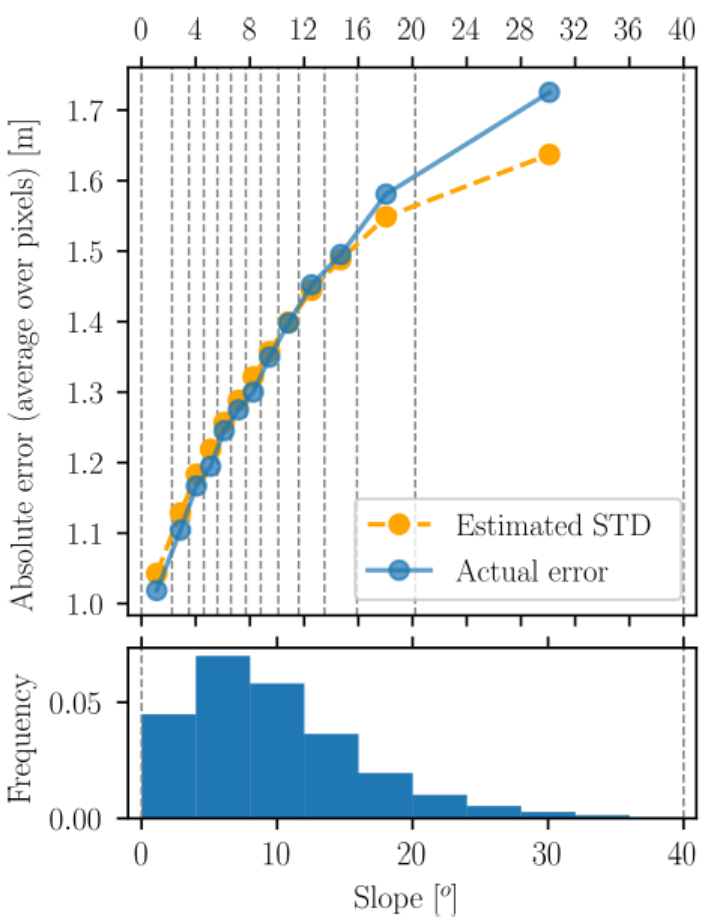


Input data series vs. performance

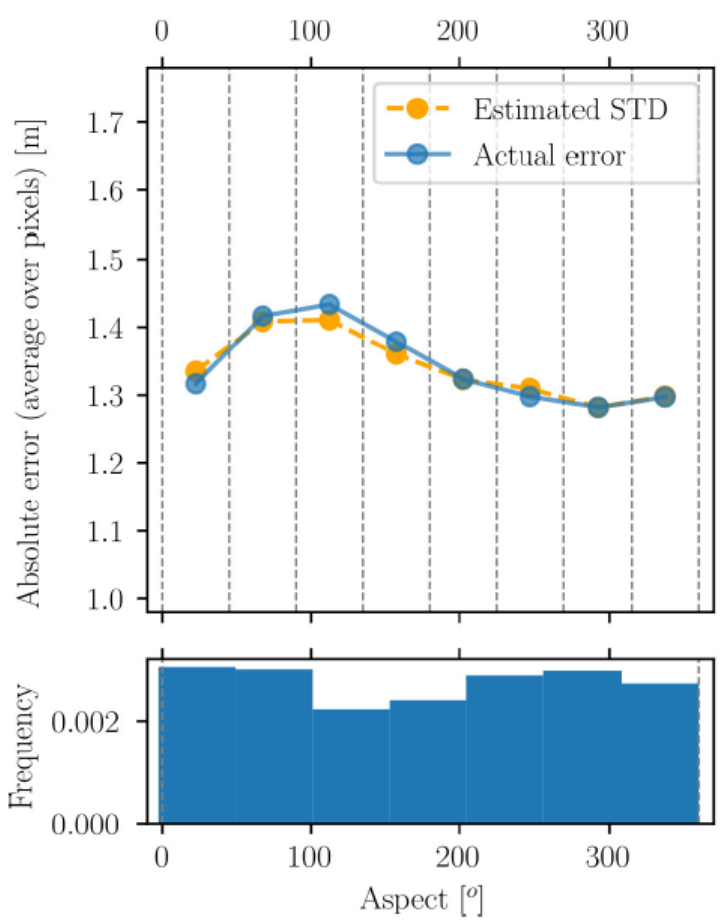
Mean absolute error of the model for different **input sequence length**



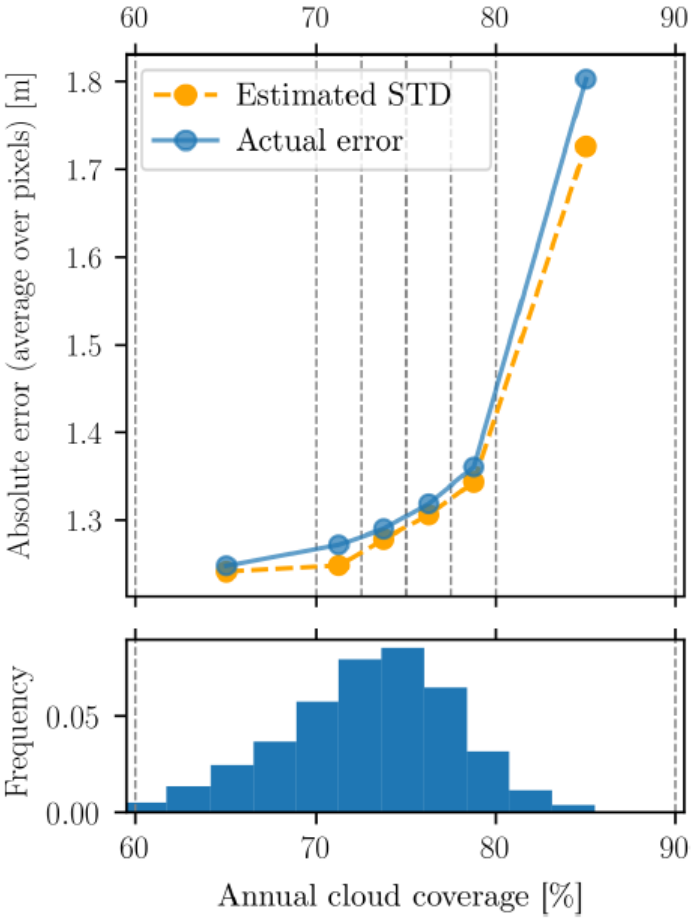
Influence of topography & cloudiness factors



(a) Error vs slope



(b) Error vs aspect



(c) Error vs annual cloud coverage

Experimental Results

Pixel-wise comparison of spatiotempCHM model with state-of-the-art results

Our **lightweight model** (320k trainable parameters) achieves mean absolute error **MAE=1,29m** in the Bohemian forest.

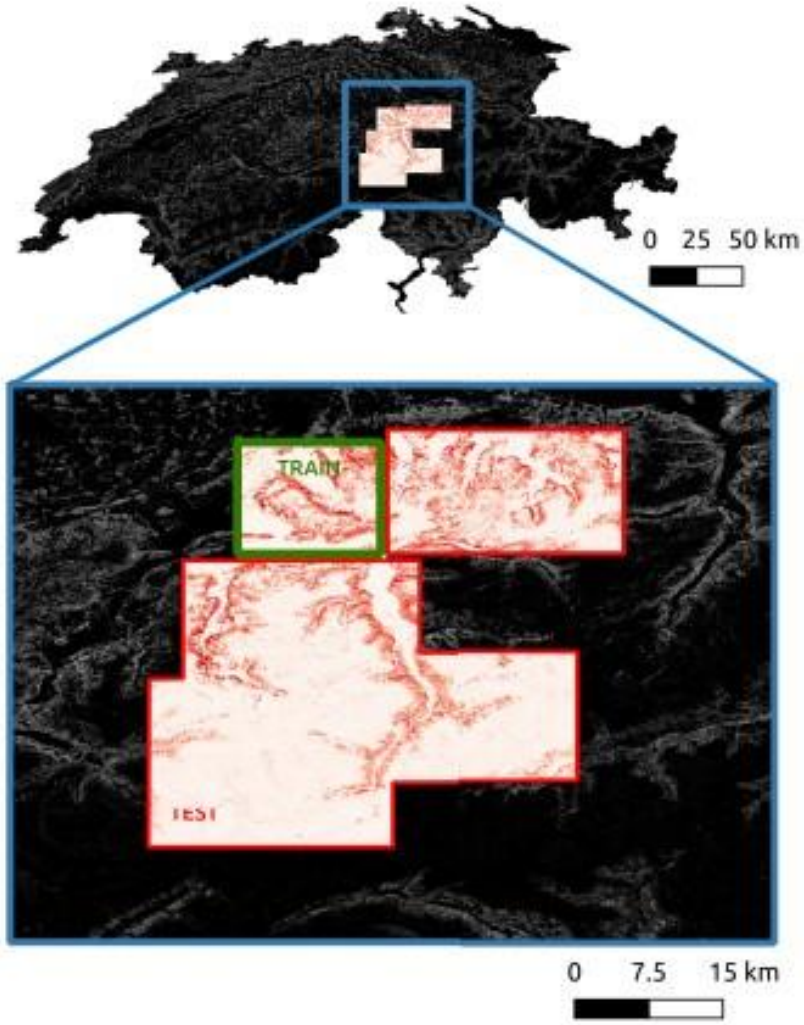
Method	Location	Area	MAE $[m]$	RMSE $[m]$
Lang et al. [1]	Switzerland	91Mpx	1.7	3.4
Lang et al. [1]	Gabon	25Mpx	4.3	5.6
`ConvEnc-Dec` [2]	BF	9.4Mpx	2.29	3.15
`ConvEnc-Dec-mean40`	BF	9.4Mpx	2.04	3.05
`spatioTempCHM`	BF	9.4Mpx	**1.29**	**1.87**

[1] Lang, N., et al., (2019). Country-wide high-resolution vegetation height mapping with Sentinel-2. Remote Sensing of Environment, 233, 111347.
[2] Alagialoglou, L. et al.,(2021). Canopy Height Estimation from Spaceborne Imagery Using Convolutional Encoder-Decoder. In MultiMedia Modeling: 27th International Conference, MMM 2021, Prague, Czech Republic, June 22–24, 2021, Proceedings, Part II 27 (pp. 307-317). Springer International Publishing.

Transferability in location (I)

- Transferability Study Area: **Switzerland**
- Ground truth CHM: **stereo aerial imagery** [1 × 1 m GSD]
- Photogrammetric image matching used for map generation

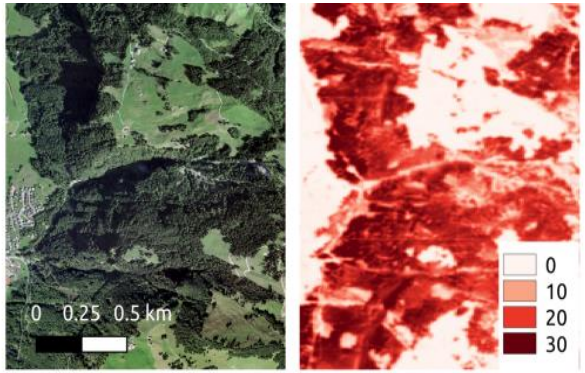
The trained model is transferable in Switzerland using a fine-tuning area of as low as 2km² with MAE = 1,94m.



Transferability in location (II)

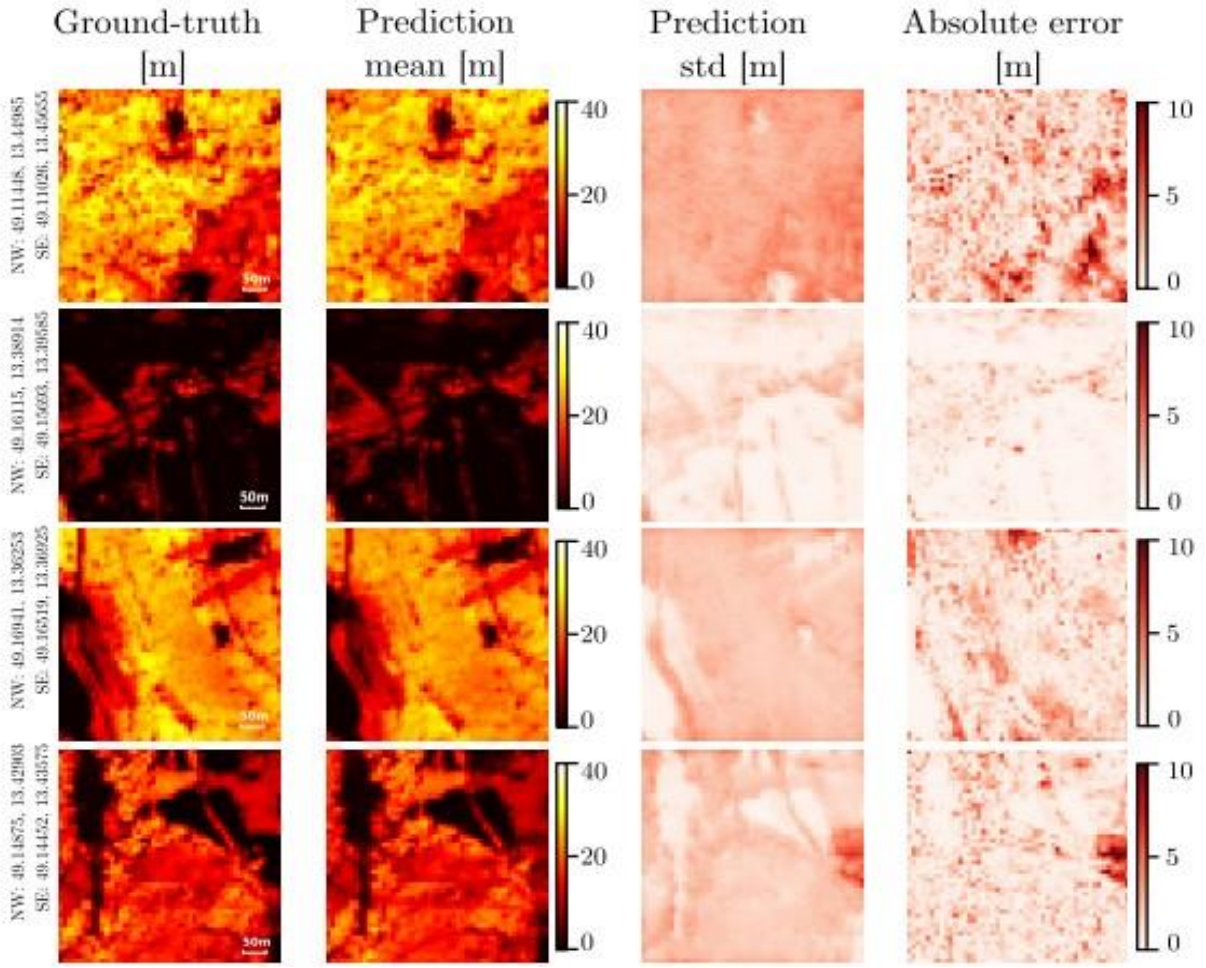
Location Train → Test	Fine-tune area	Test area	MAE [m]	RMSE [m]	ECE [m]	ECE uncalibrated [m]
BF → BF (random split)	no fine-tune	$79km^2$	1.29	1.87	0.01	0.68
BF → BF (location-based split)	no fine-tune	$72km^2$	1.76	2.50	0.09	0.44
BF + CH all $\xrightarrow{fine-tune}$ CH	$320km^2$	$2200km^2$	1.52	2.92	0.30	0.47
BF + CH 1/8 $\xrightarrow{fine-tune}$ CH	$40km^2$	$2200km^2$	1.49	2.99	0.38	0.51
BF + CH 1/16 $\xrightarrow{fine-tune}$ CH	$20km^2$	$2200km^2$	1.57	3.07	0.31	0.66
BF + CH 1/32 $\xrightarrow{fine-tune}$ CH	$10km^2$	$2200km^2$	1.65	3.24	0.30	0.29
BF + CH 1/64 $\xrightarrow{fine-tune}$ CH	$5km^2$	$2200km^2$	1.69	3.26	0.31	0.40
BF + CH smallest $\xrightarrow{fine-tune}$ CH	$\mathbf{2.30km^2}$	$\mathbf{2200km^2}$	**1.94(SD : .04)**	**3.83(SD : .01)**	**0.56(SD : .19)**	**0.52(SD : .02)**
BF → CH	no fine-tune	$2200km^2$	2.60	4.16	- [2]	1.16

[2]Interestingly, if we calibrate the model by using as little as $0.23km^2$ of the Swiss region, the ECE drops significantly to $0.44m$.

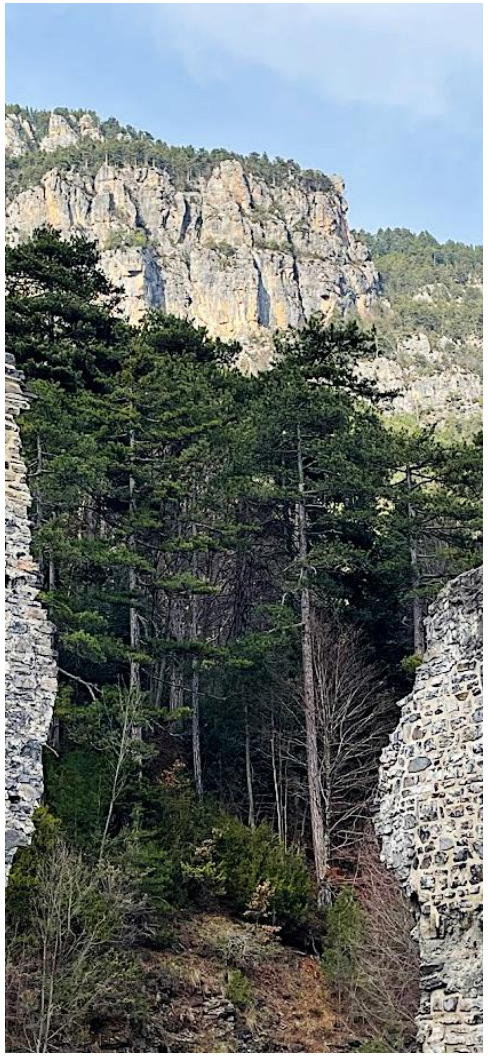


Our CHM solution

- **Annual** Canopy Height map estimation
- Based on **sequences of Sentinel-2** images
- Lightweight NN model (320k trainable parameters)
- State-of-the-art results | Comparison with single-shot approaches
- **Calibrated Uncertainty Quantification**
- Transferable in time
- Transferable in location with very limited fine-tuning dataset



Contributions



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With a smile and a vision

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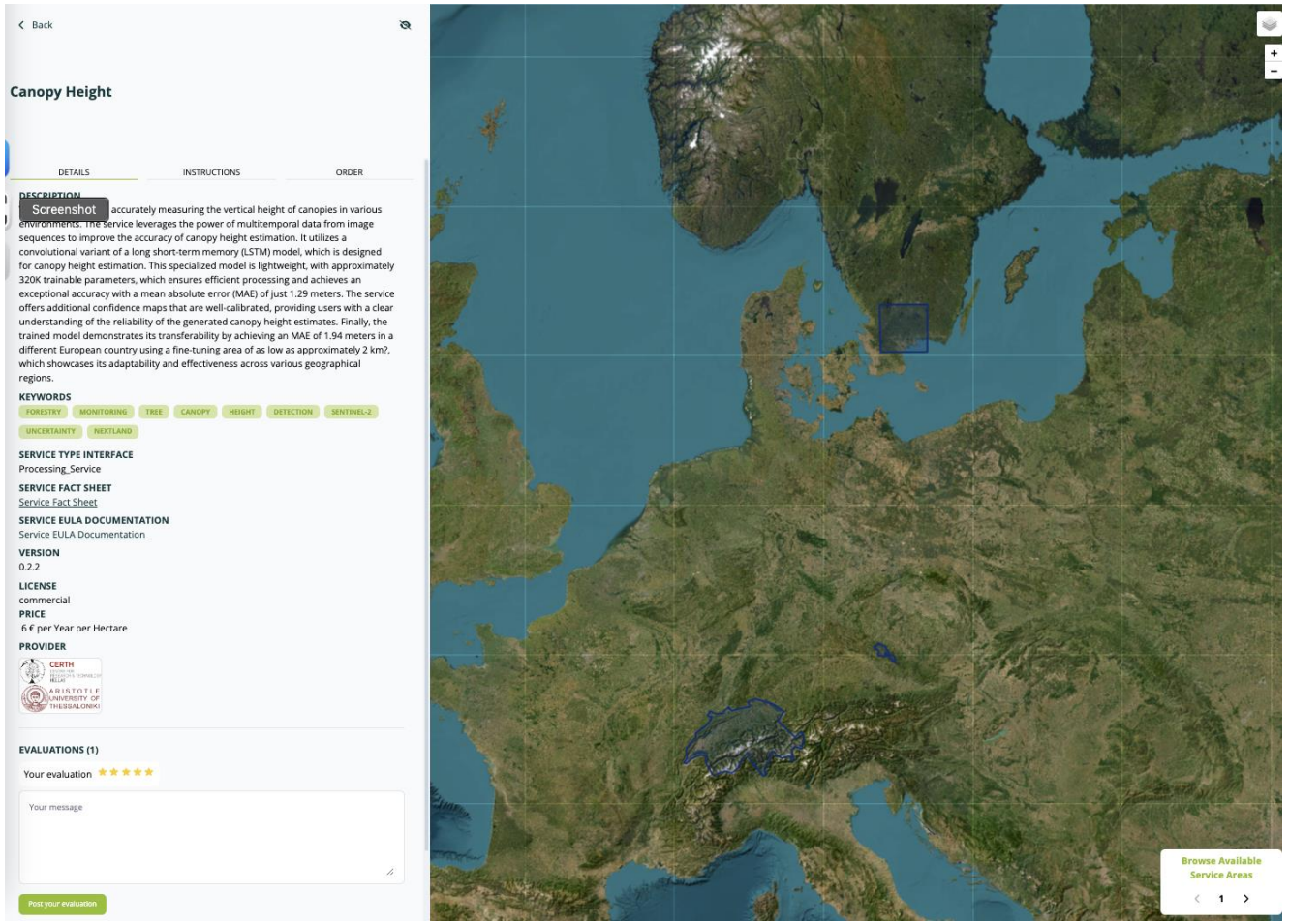

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