Assessing The Impact of Tree 3D Representations on Urban Daylight Simulation Based on Airborne Laser Scanning Point Cloud Data

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Introduction

Introduction

- Natural light supports well-being and energy efficiency.
- Daylight simulations help integrate it in urban design.
- Trees shape urban microclimates through shade and cooling.
- Accurate tree 3D models are essential for simulation results.

Research Motivation

1

Need to explore more tree 3D representation from ALS data for daylight studies.

2

Seasonal variations in tree conditions are often overlooked.

To what extent can the tree ALS point cloud data increase the accuracy of daylight simulations?

Research Questions

Main question

To what extent can the tree ALS point cloud data increase the accuracy of daylight simulations?

Sub-questions

- How can ALS point cloud data be used for tree 3D representation in urban daylight simulation?
- What is the difference in accuracy of the results of the daylight simulation between diverse tree 3D representation approaches?
- How can the results of daylight simulation be evaluated?
- What is the impact of seasonal alterations of the tree canopy in urban daylight simulation?

Background

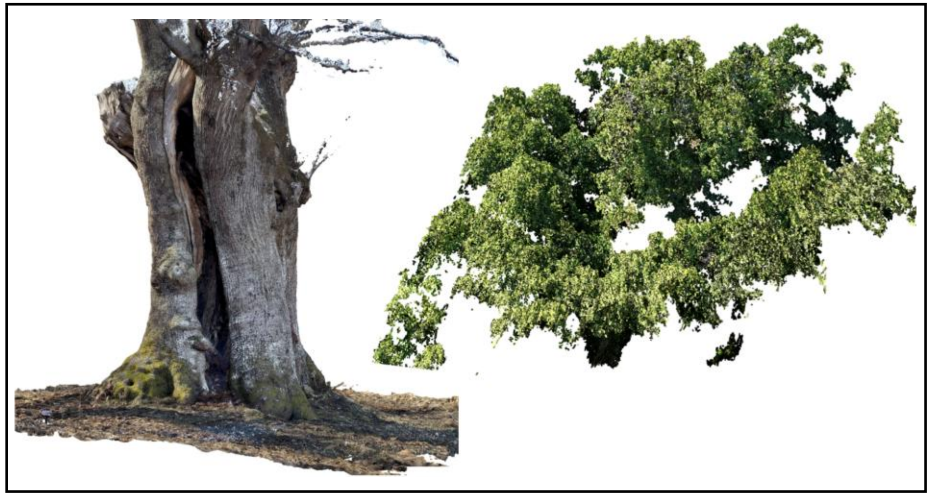
Background

Approaches of tree 3D representations

Daylight Simulation

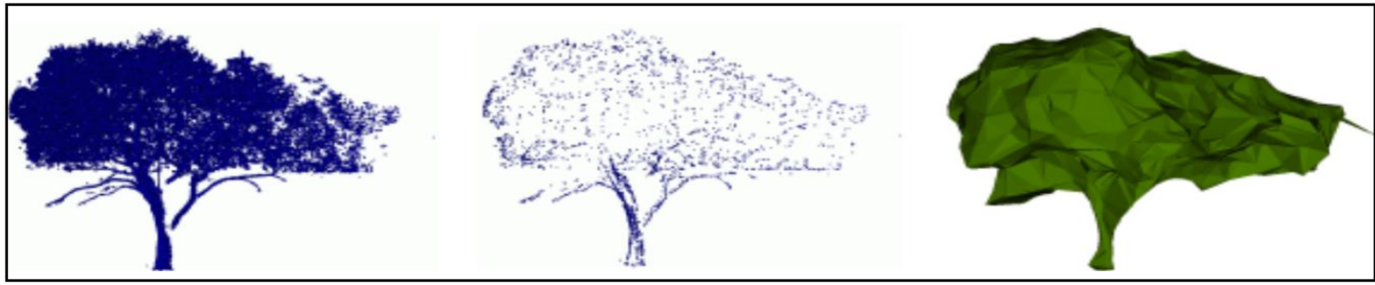
Approaches of tree 3D representations(i/ii)

- Point cloud data



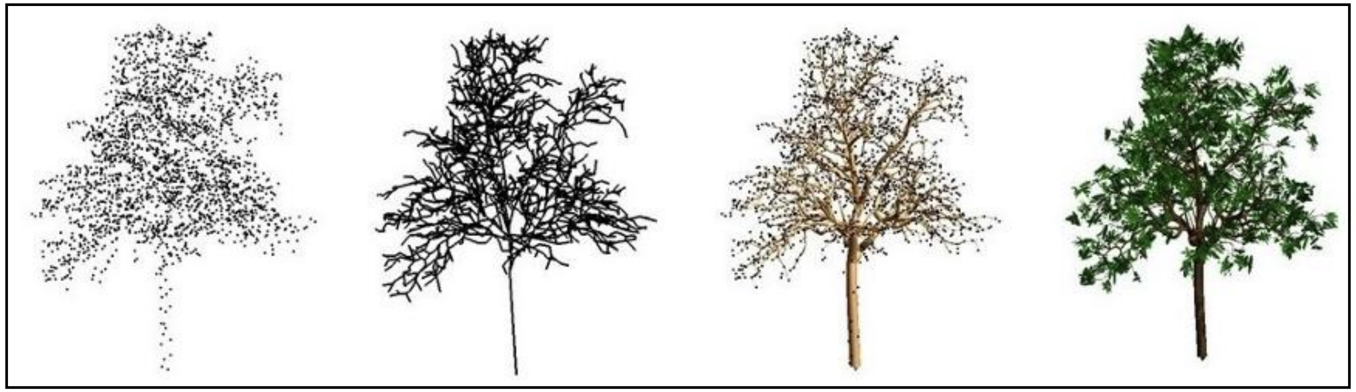
Balestra et al. (2023)

- Mesh representations



Zhu et al. (2008)

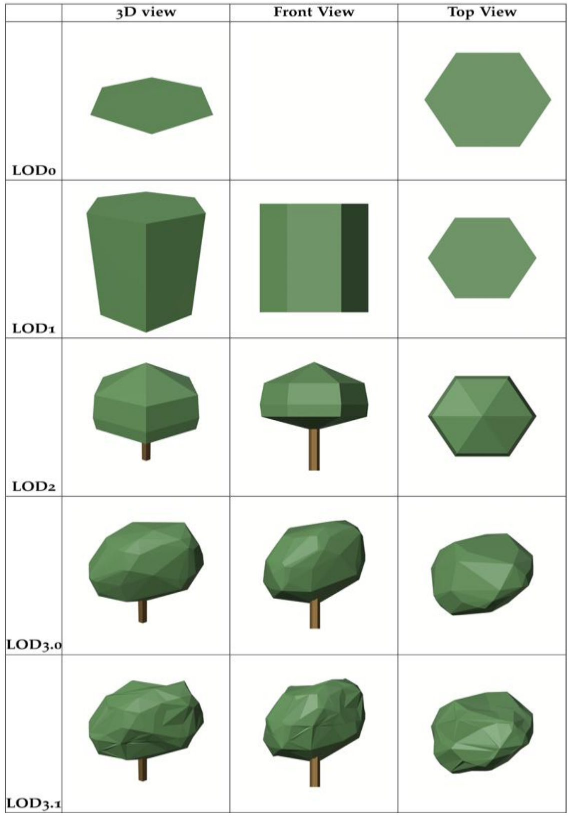
- Graph using skeletonization methods



Du et al. (2021)

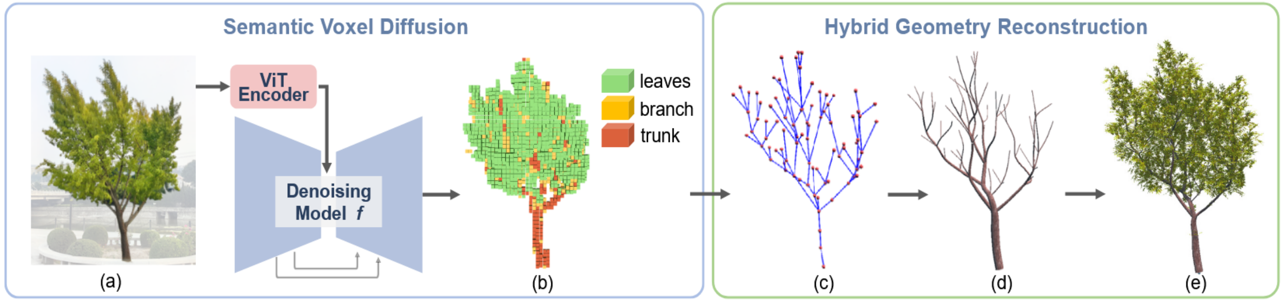
Approaches of tree 3D representations(ii/ii)

➢ Primitive shapes



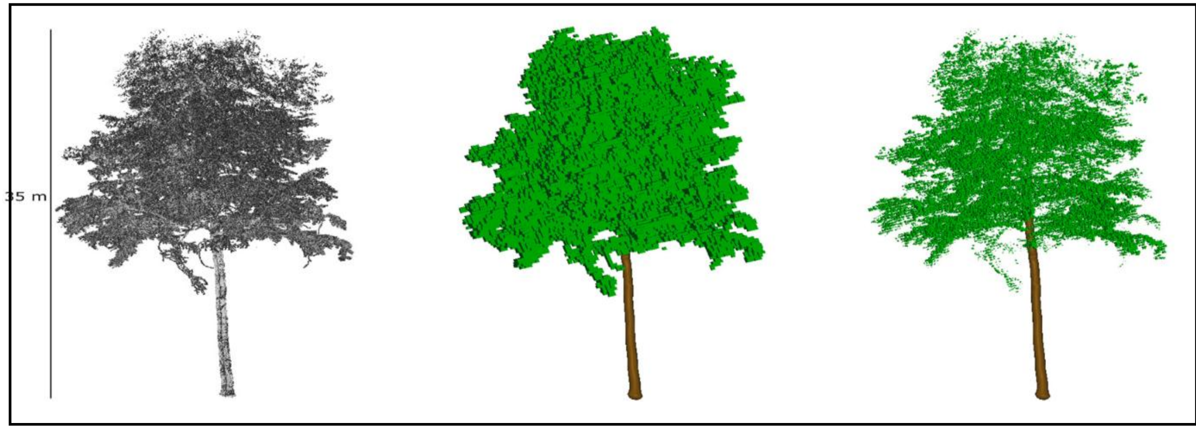
de Groot (2020)

➢ Voxel representations



Li et al. (2024)

➢ Combinations



Weiser et al. (2021)

Daylight Simulation

Illuminance describes the quantity of incident light that falls onto or illuminates a specific surface area ((lumens·m^{-2}) or lux).

- Tool used for daylight simulation: **ClimateStudio plugin of Rhino software.**
- Daylight Availability workflow (hourly illuminance time series during a whole year)

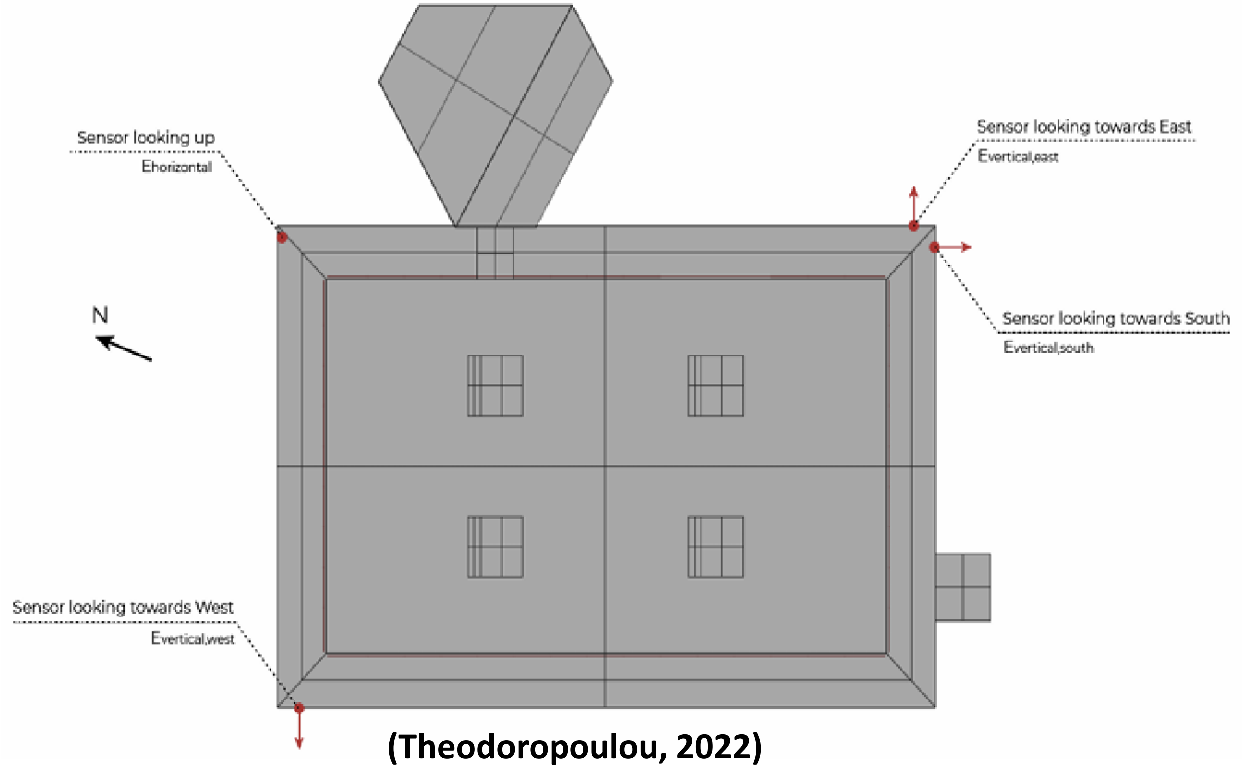
- Direct sunlight → solar position
- Diffuse ambient light → 145-patch Tregenza sky subdivision
- Sky model: Perez – All weather
- Matrix-based approach
- It resembles Radiance 5-Phase method.

Methodology

Study Area

Co-Creation Centre (CCC) Building in the Green Village of TU Delft Campus and the nearby tree area

It contains 4 illuminance sensors on the roof.



(Theodoropoulou, 2022)

Data (i/iv)

1. **Cleaned AHN 5 Point Cloud (acquired in February 2023)**

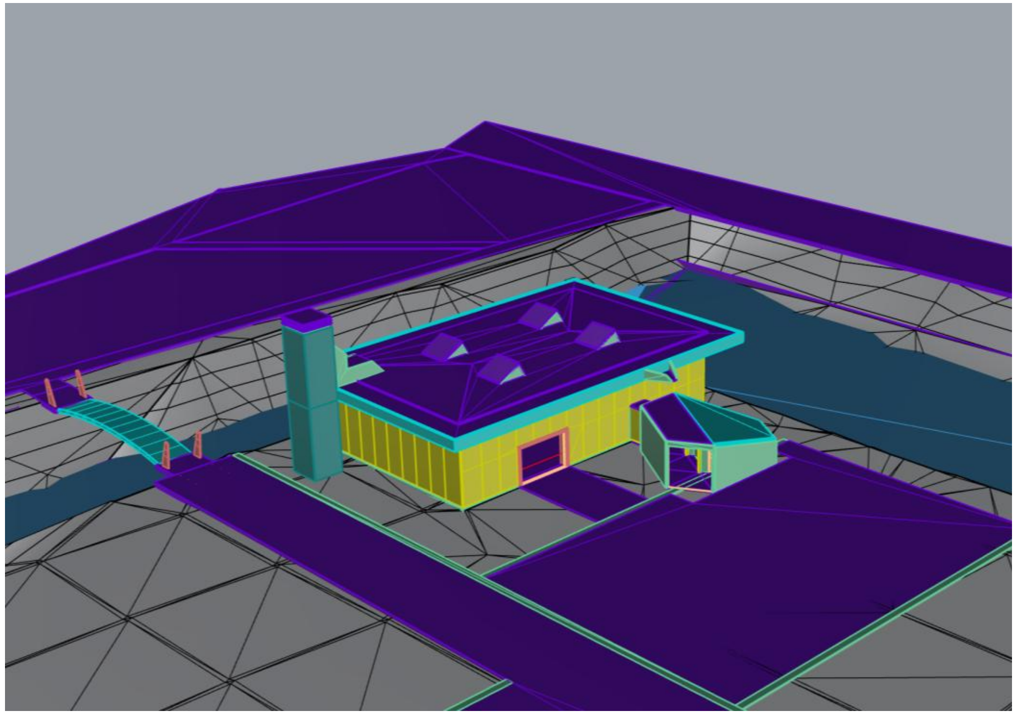
   Point number : 562,677
   Point density: 14.7 ± 5.9 pts per m^2

2. **Synthesized point cloud was generated. It consists of:**
   - Cleaned AHN 5 Point Cloud
   - Points derived from samples of synthesized leaves created using the **AdTree** algorithm (Du et al., 2019)

   Point number : 1,248,675
   Point density: 35.1 ± 16.3 pts per m^2

Data (ii/iv)

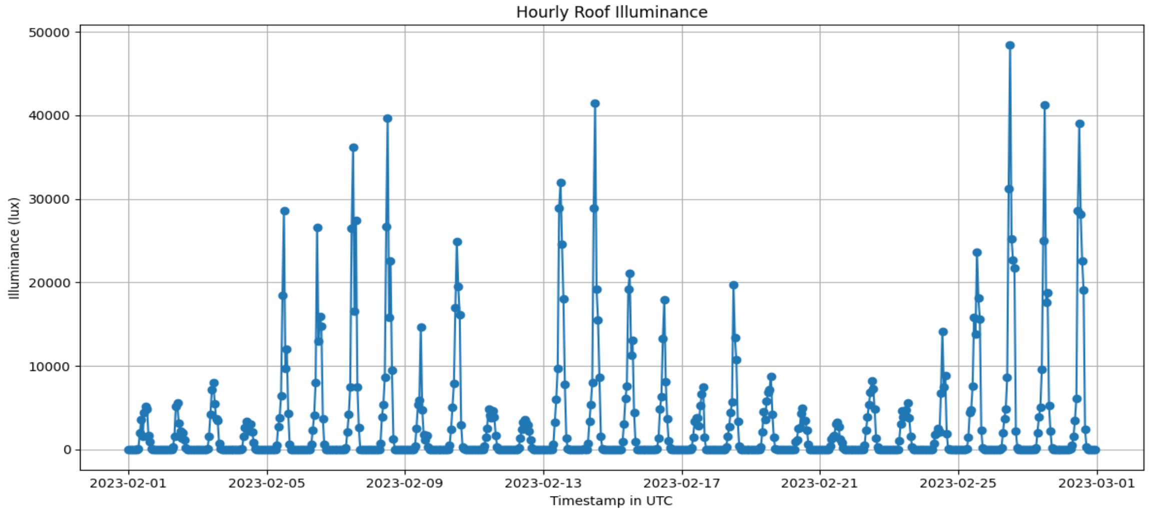
3. Detailed CCC Building 3D model → Georeference



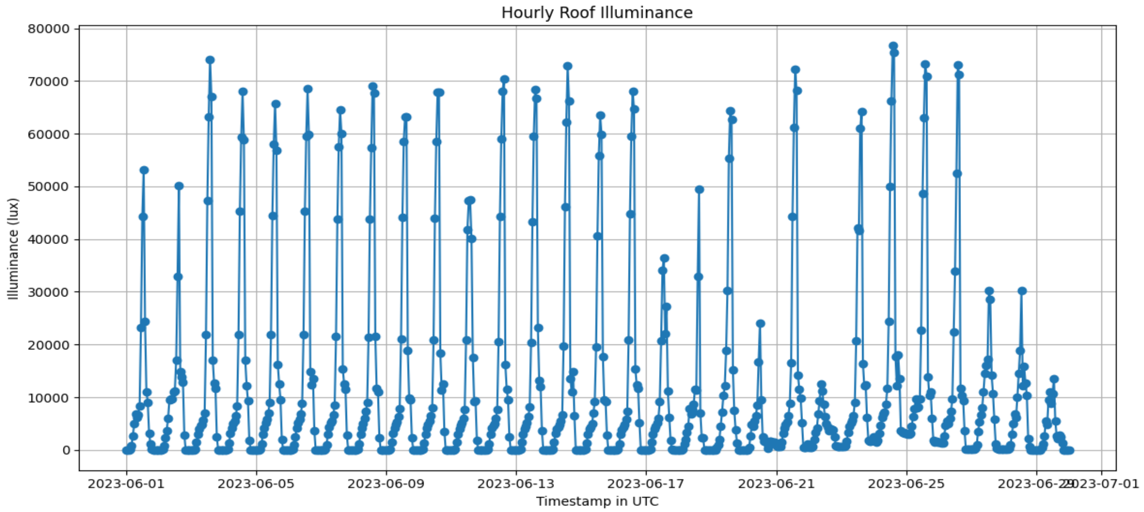
Data (iii/iv)

4. West Sensor Illuminance Data from the CCC Building

February 2023

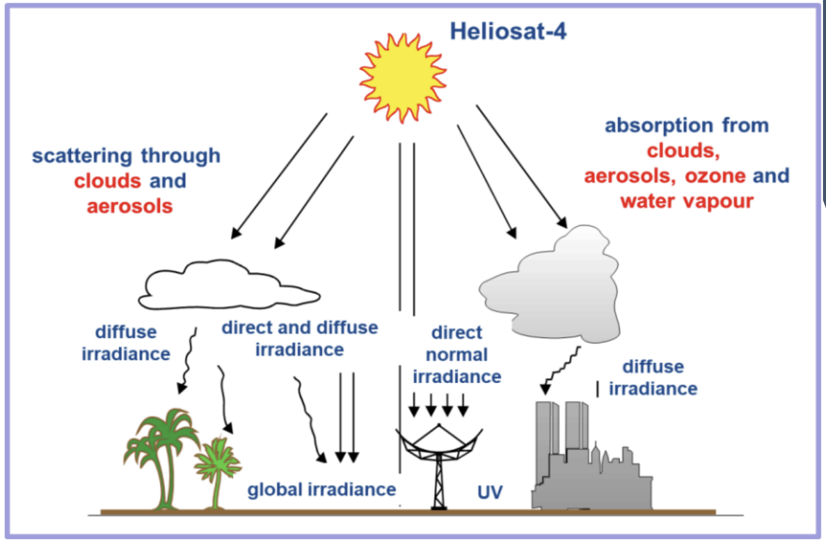


June 2023



Data (iv/iv)

5. Local Solar Irradiance Data of year 2023



source: *User Guide to the CAMS Radiation Service (CRS)*

Time series of:

1. Global Horizontal Irradiance
2. Direct Normal Irradiance
3. Diffuse Horizontal Irradiance

Adjusting weather data file based on GHI, DNI and DHI of the local Solar Irradiance Data of year 2023.

Research Pipeline

1. Data Processing

- Cleaning AHN 5 point cloud data
- Creating synthesized point cloud data
- Georeferencing the CCC building model
- Local irradiance data

2. Geometric tree 3D representations for February and June

- Point Cloud – based Case
- Voxel Grid Case
- Alpha Shape Case
- Convex Hull Case

3. Daylight simulations for February and June to produce simulated illuminance values

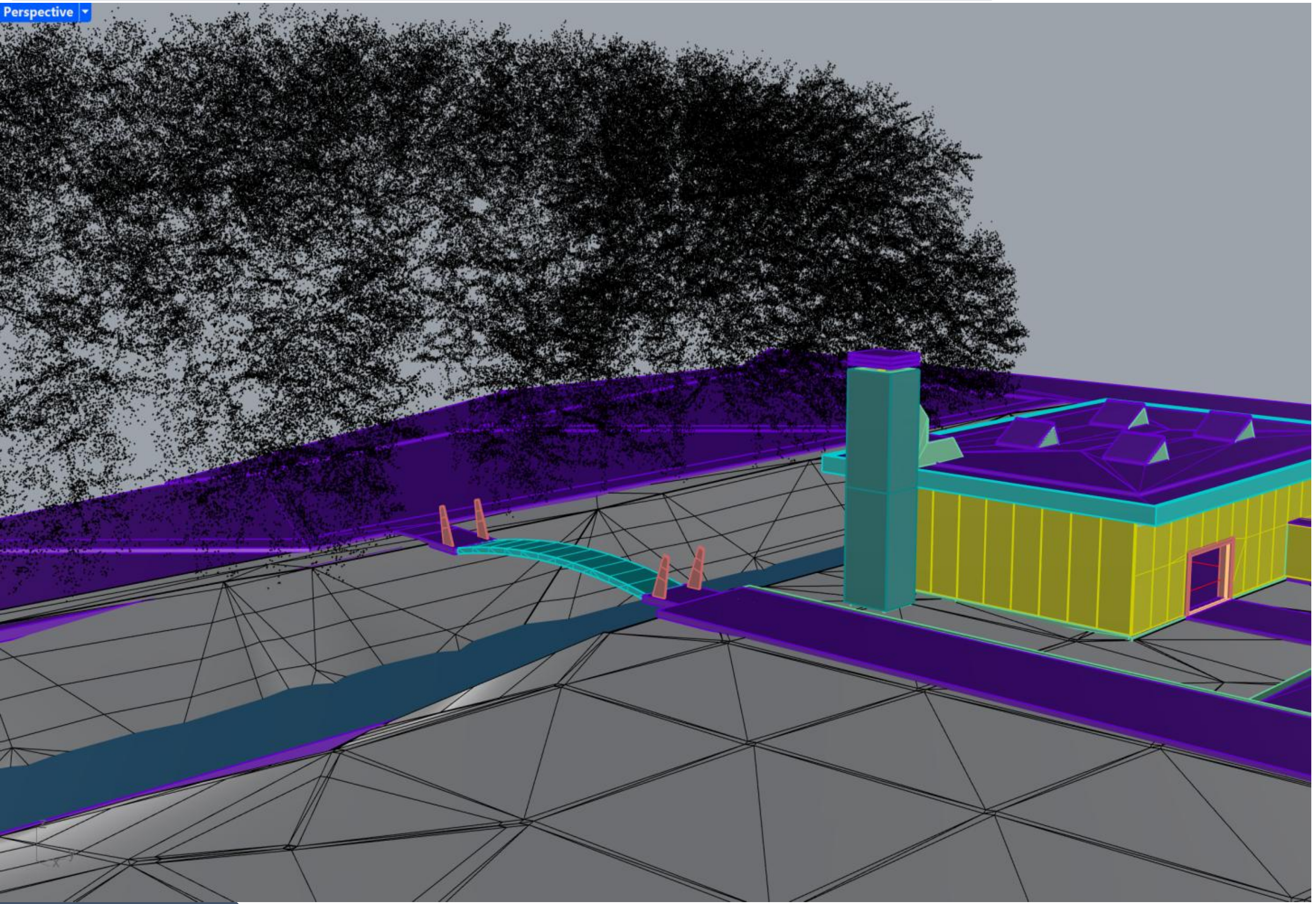
4. Simulation results evaluation (reference: west illuminance sensor data)

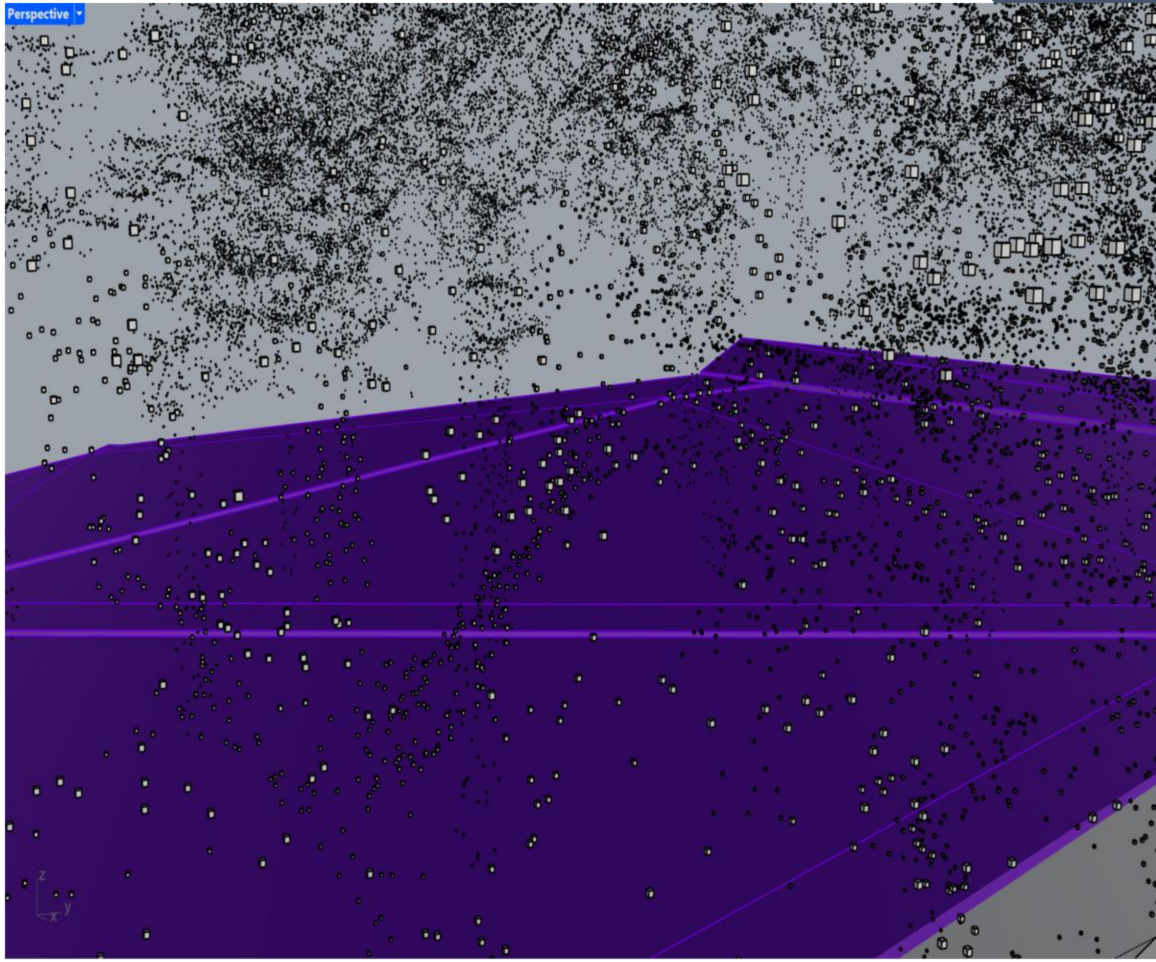
February		
Cases	Input	Material
Point Cloud - based	Cleaned AHN5 point cloud	Opaque
Voxel grid – 1rst ap.		
Voxel grid – 2^{nd} ap.		Transparent
Convex Hull		Opaque
Alpha shape		

June		
Cases	Input	Material
Point Cloud - based	Cleaned AHN5 point cloud + Leaf point cloud	Opaque
Voxel grid – 1rst ap.		
Voxel grid – 2^{nd} ap.	Synthesized Point Cloud	Transparent
Convex Hull		Opaque
Alpha shape		

Point Cloud - based Case

Conversion of point into cubes of 0.02 m





Voxel Grid Case

Voxel sizes (m): 0.03, 0.05, 0.07, 0.1, 0.3, 0.5

1st Approach

For February, voxel assignment as wood.

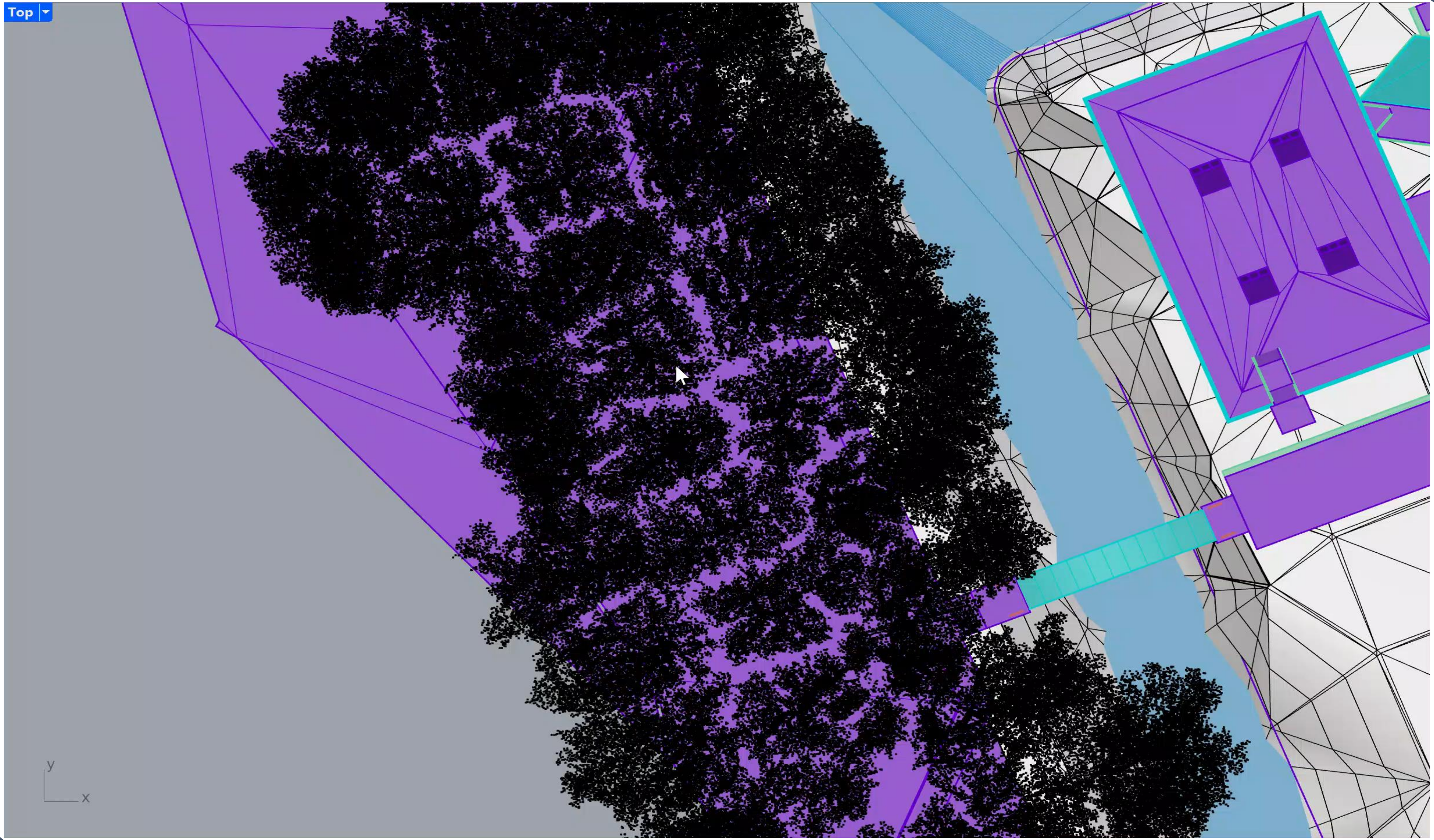
For June, classification depending on point labels.

2nd Approach

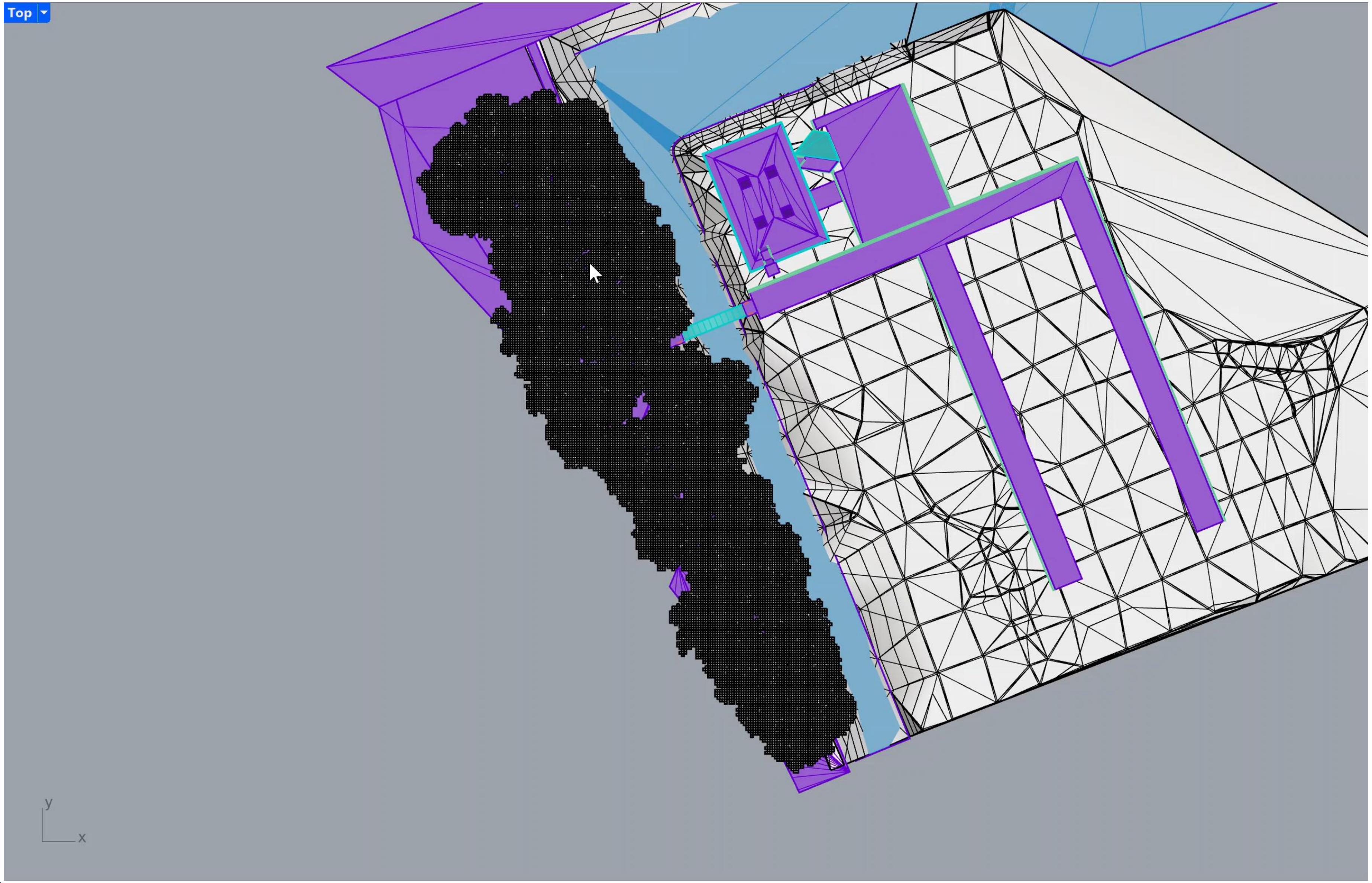
For February and June, calculation:

$$\text{Transmittance Index} = \frac{\text{Max Point Number} - \text{Voxel Point Number}}{\text{Max Point Number}}$$

Voxel Grid Case (size of 0.03 m)

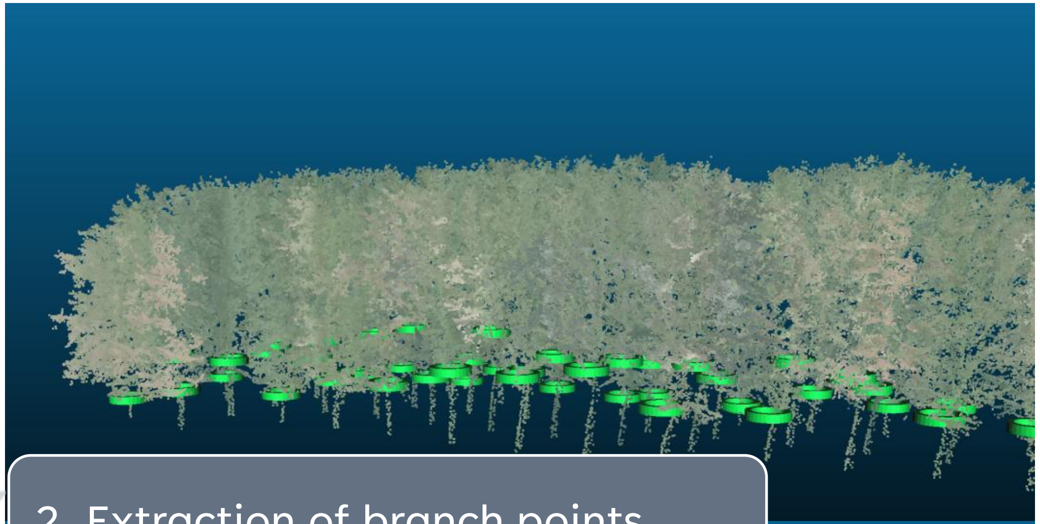


Voxel Grid Case (size of 0.5 m)

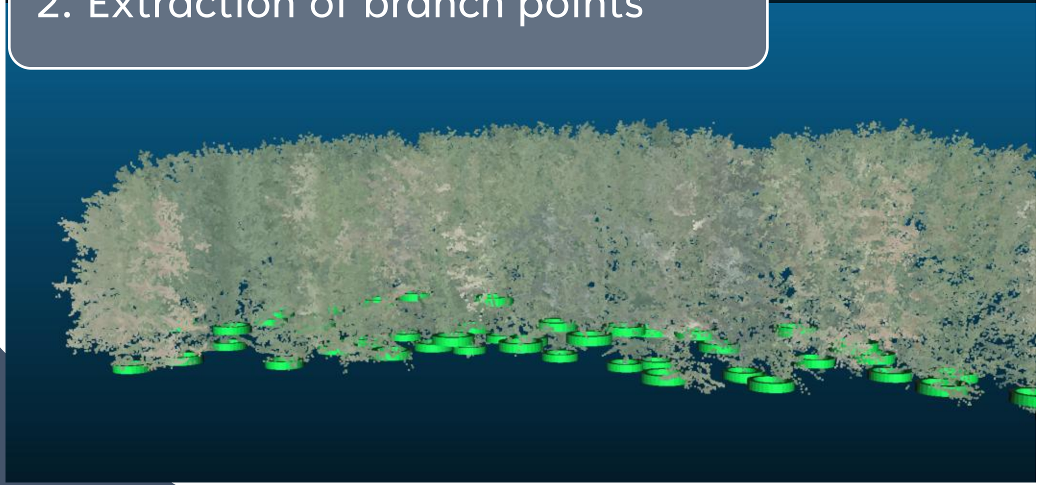


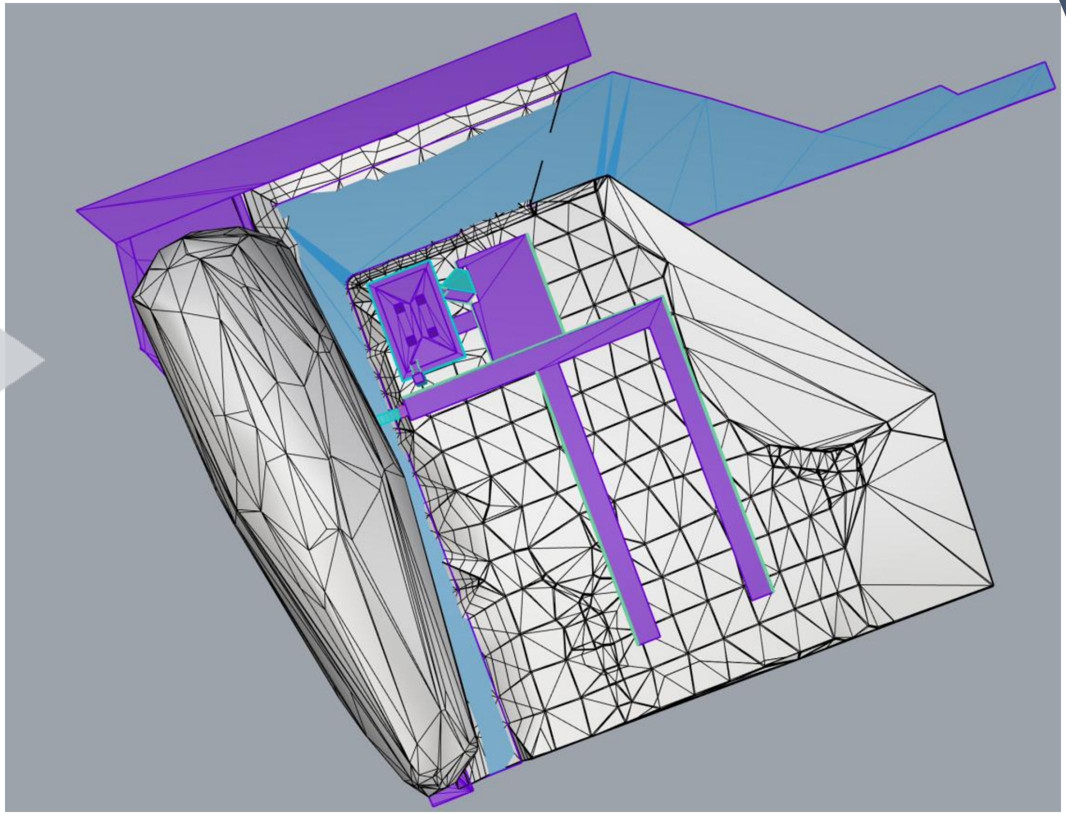
Convex Hull Case

1. Annulus generation for each tree at the location where the branches start.



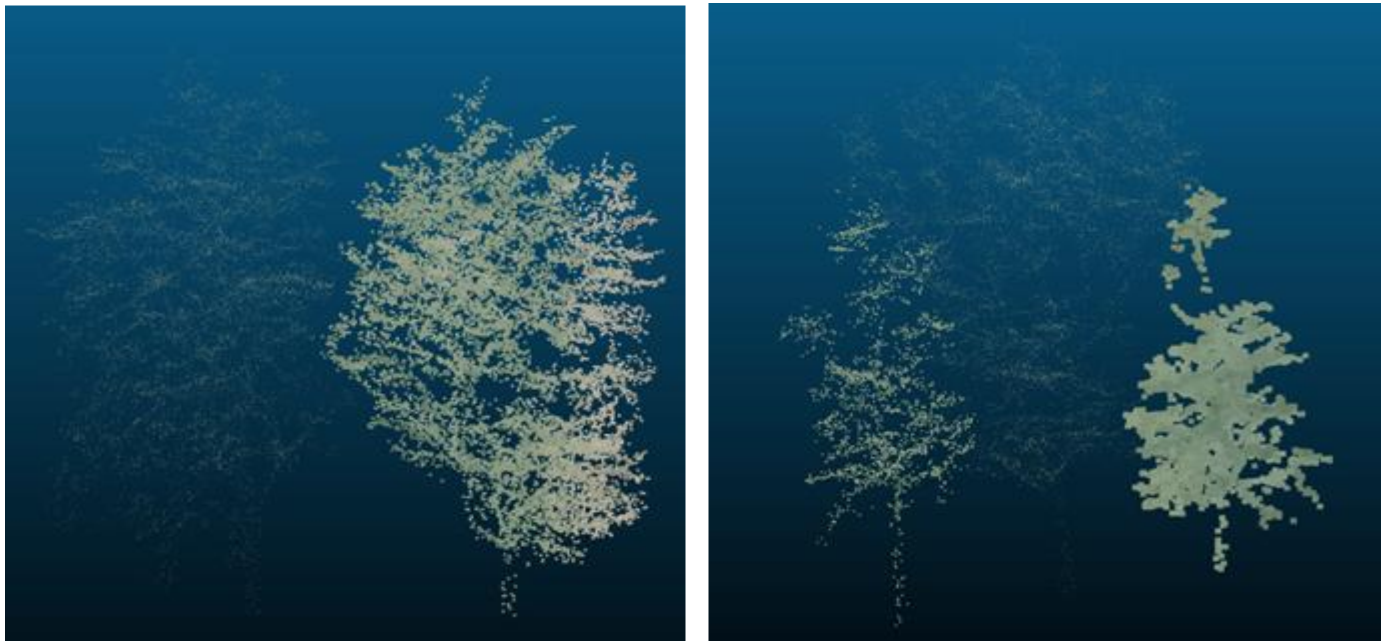
2. Extraction of branch points





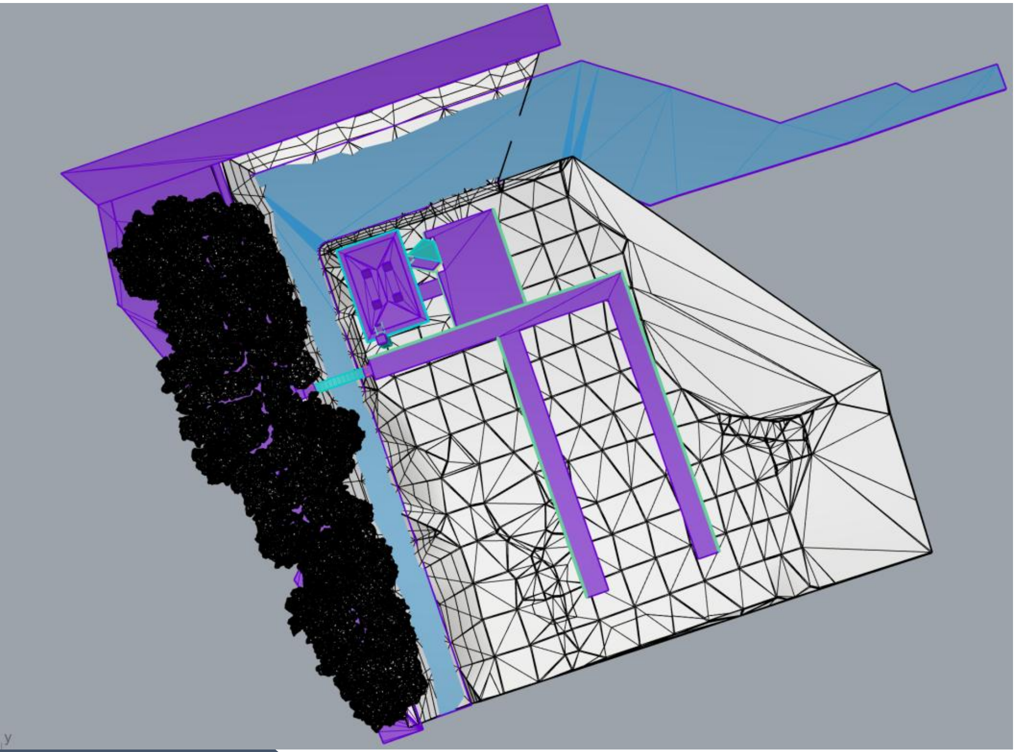
Alpha Shape Case (i/ii)

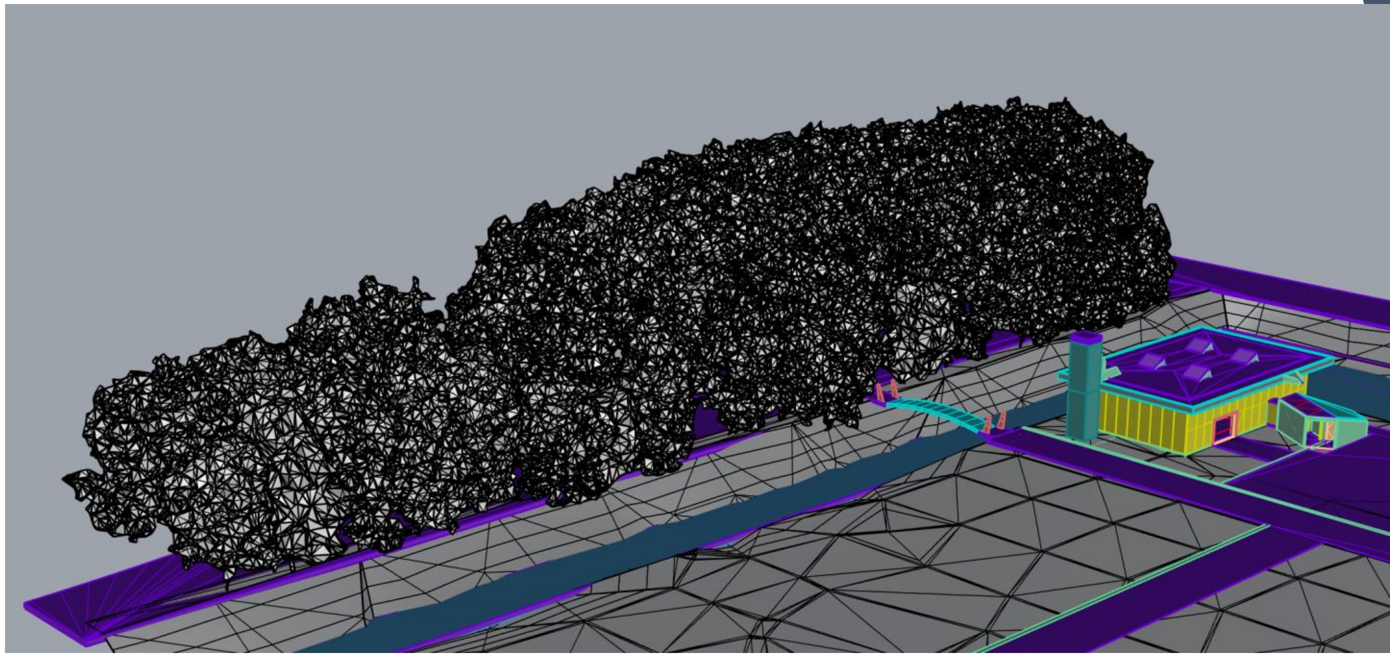
1. Segmentation into individual trees:
- Shortest distances to the lowest points on 10-NN graph
- Manual refinement



Alpha Shape Case (ii/ii)

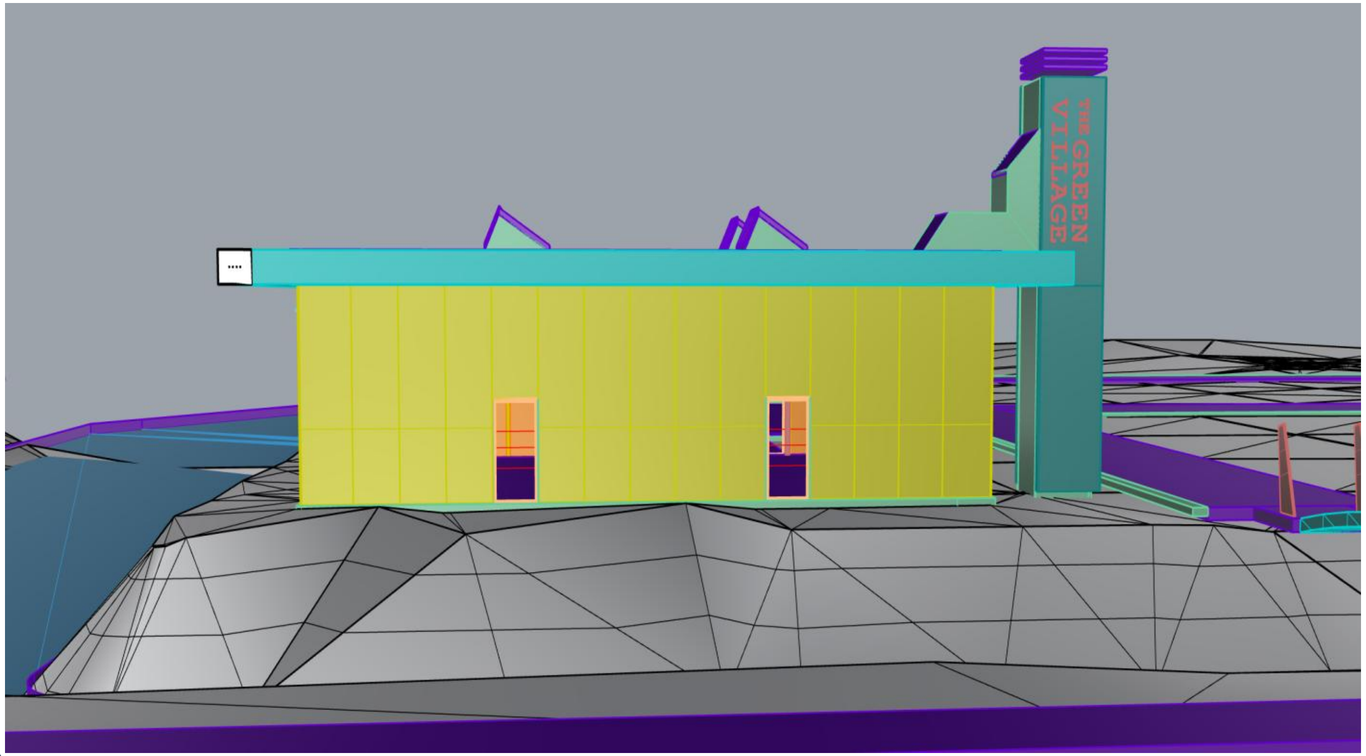
2. Assemble alpha shapes of separated tree point clouds

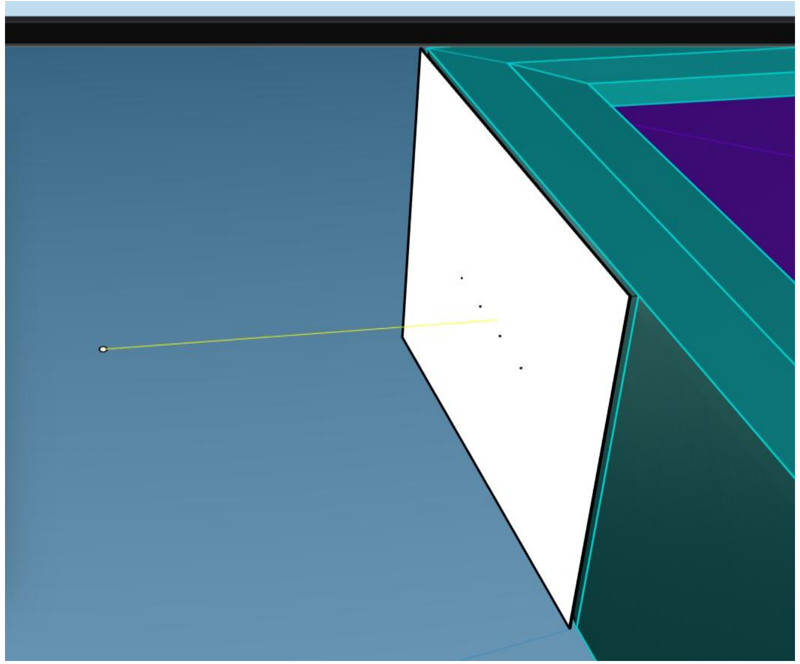




Simulation

A. Simulation surface area and four sensors





$\vec{v}$ = (-0.926, −0.376, 0)

Results

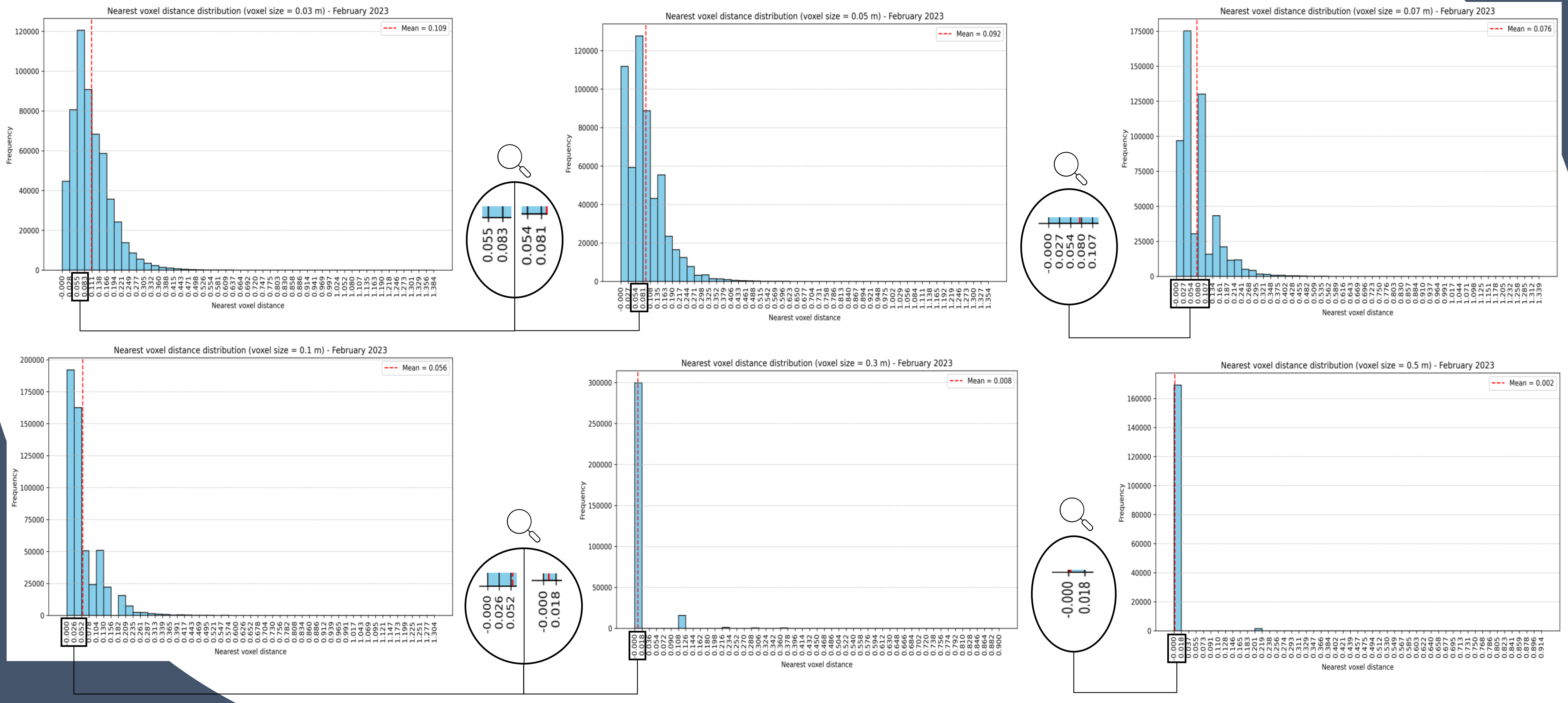
February overview

RMSE per February Case		
Point Cloud - based Case		
7714.33		
Alpha Shape Case		
4352.70		
Voxel Grid Case		
Sizes (m)	1st approach	2nd approach
0.03	6698.80	7125.65
0.05	4575.95	4941.21
0.07	3998.52	4012.75
0.10	4127.83	3656.13
0.30	4469.17	4216.66
0.50	4502.08	4398.05
Convex Hull Case		
4562.66		

MBE per February Case		
Point Cloud - based Case		
-1982.30		
Alpha Shape Case		
1061.87		
Voxel Grid Case		
Sizes (m)	1st approach	2nd approach
0.03	-1628.73	-1808.02
0.05	-614.10	-899.17
0.07	109.00	-131.93
0.10	714.37	-149.34
0.30	1159.34	1049.28
0.50	1180.15	1173.23
Convex Hull Case		
1267.58		

February results (i/vii)

Nearest voxel distance distribution per voxel size



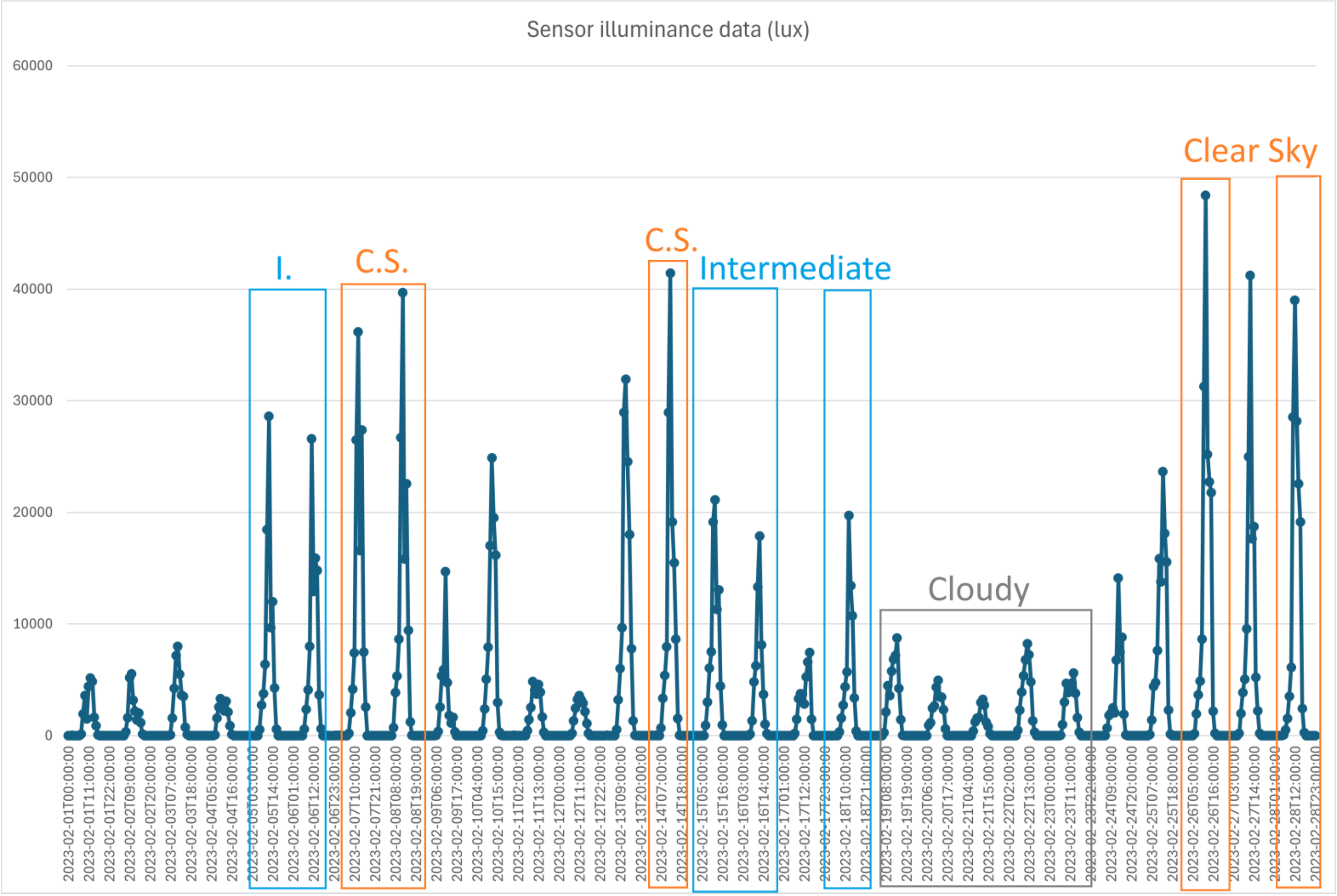
February results (ii/vii)

Voxel distributions by size and transmittance class

Grids	0.03 m	0.05 m	0.07 m	0.10 m	0.30 m	0.50 m
1st (transmittance: 88 %)	0	0	0	505,979	252,691	127,057
2nd (transmittance: 63 %)	560,281	553,232	539,381	27,025	60,649	38,153
3rd (transmittance: 38 %)	1,311	4,918	11,767	1,353	3,595	5,240
4th (transmittance: 12.5 %)	1	41	225	49	64	235

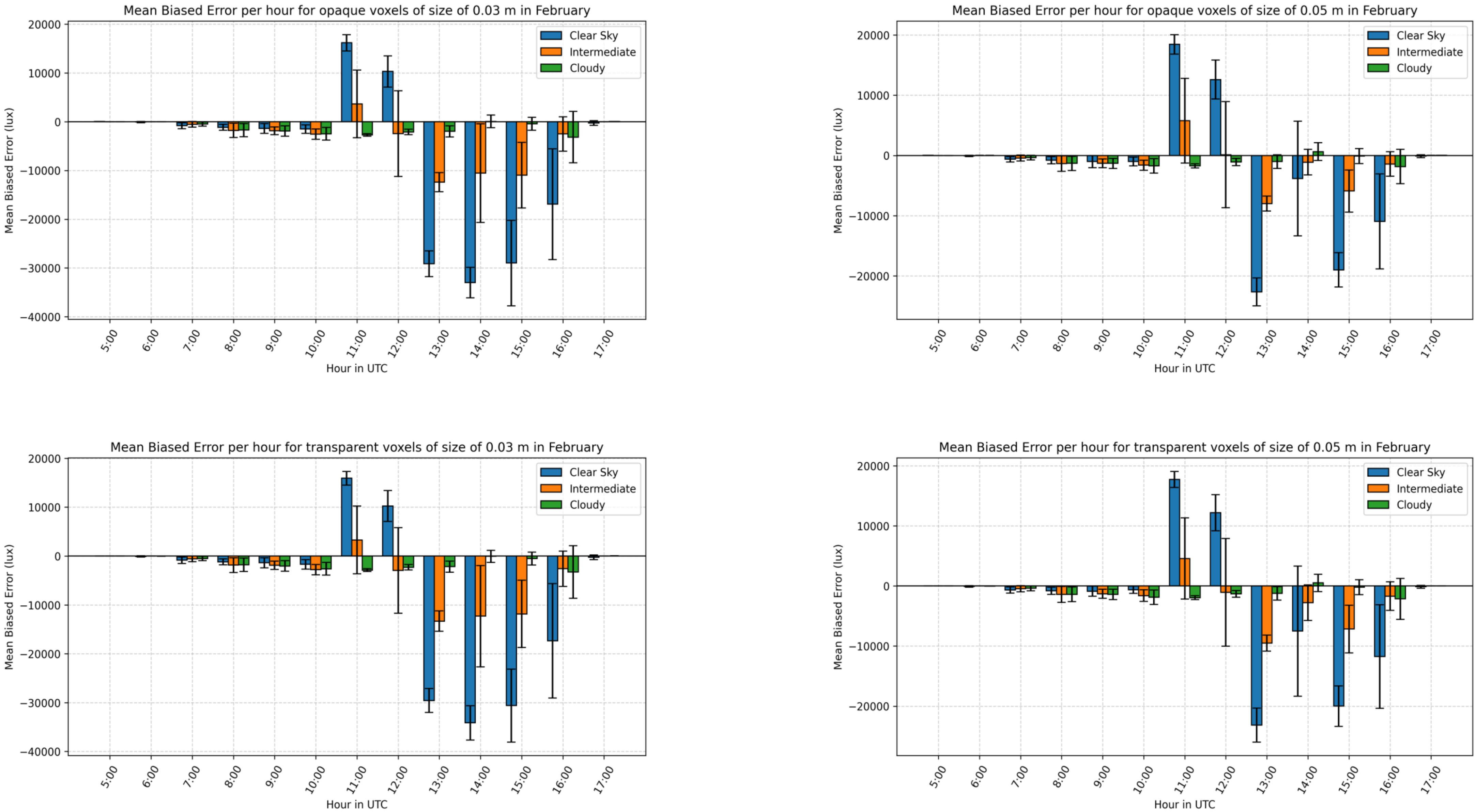
February results (iii/vii)

Analysis in terms of different sky conditions



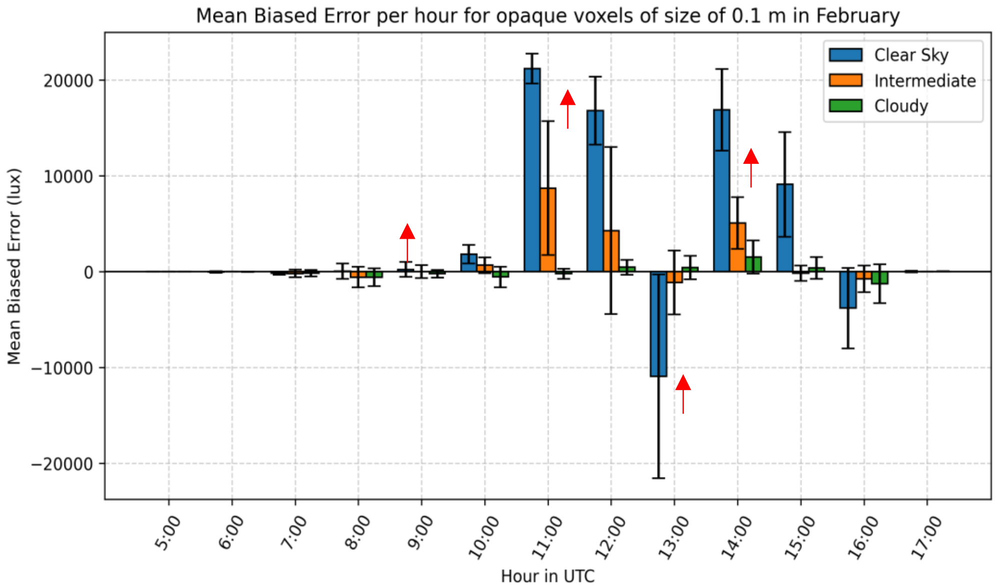
February results (iv/vii)

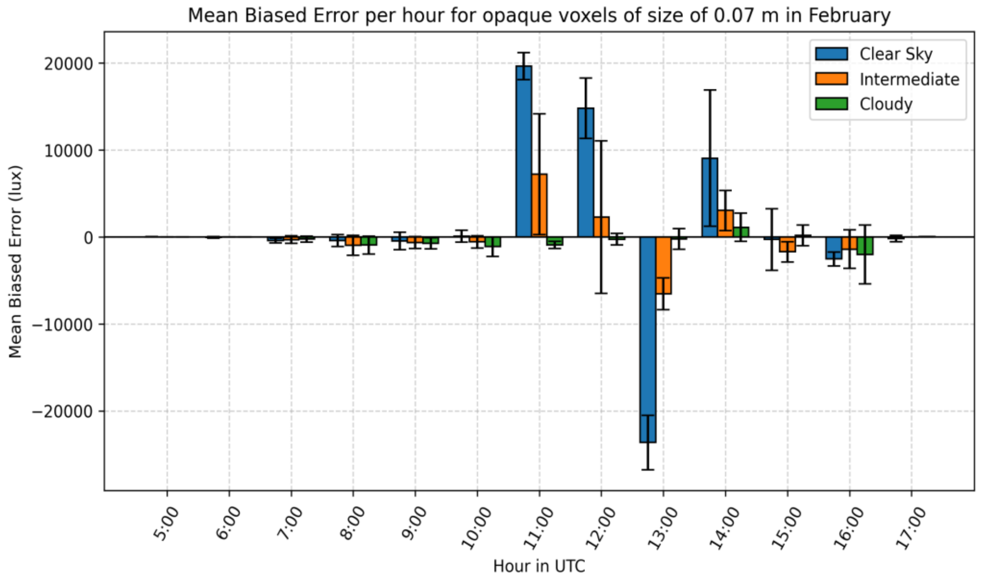
MBE for opaque and transparent voxels under clear sky, cloudy, and intermediate conditions at 0.03 and 0.05 m

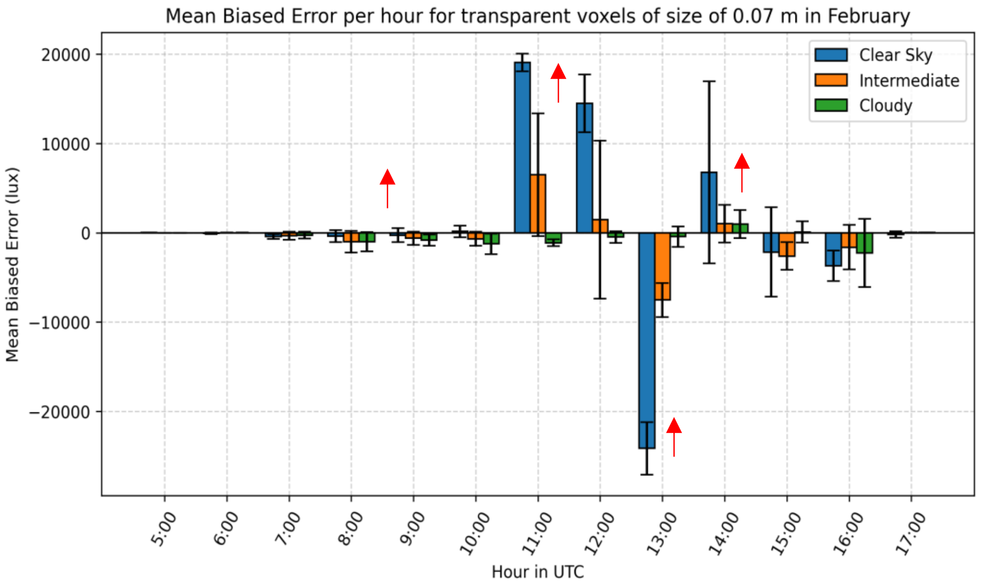


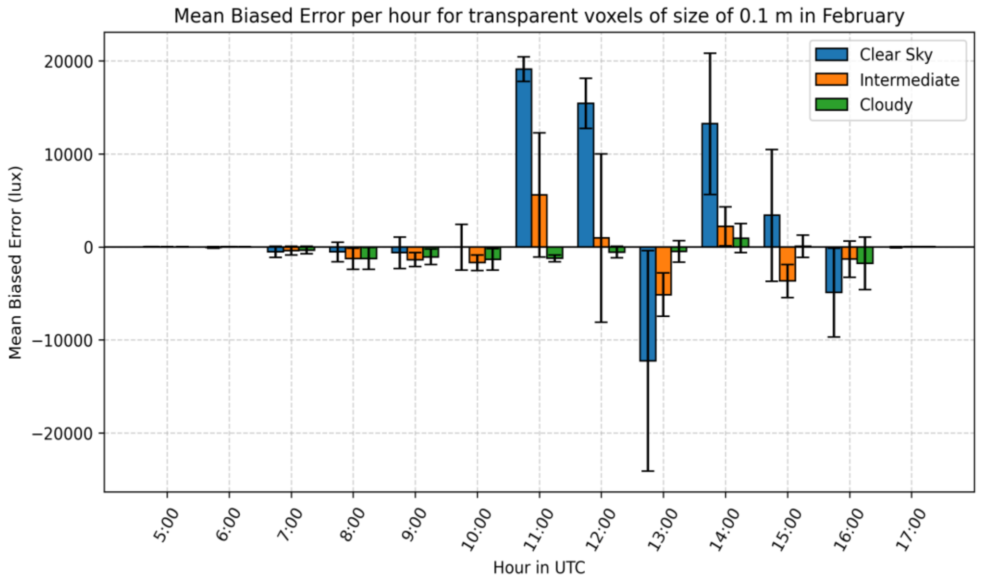
February results (v/vii)

MBE for opaque and transparent voxels under clear sky, cloudy, and intermediate conditions at 0.07 and 0.1 m



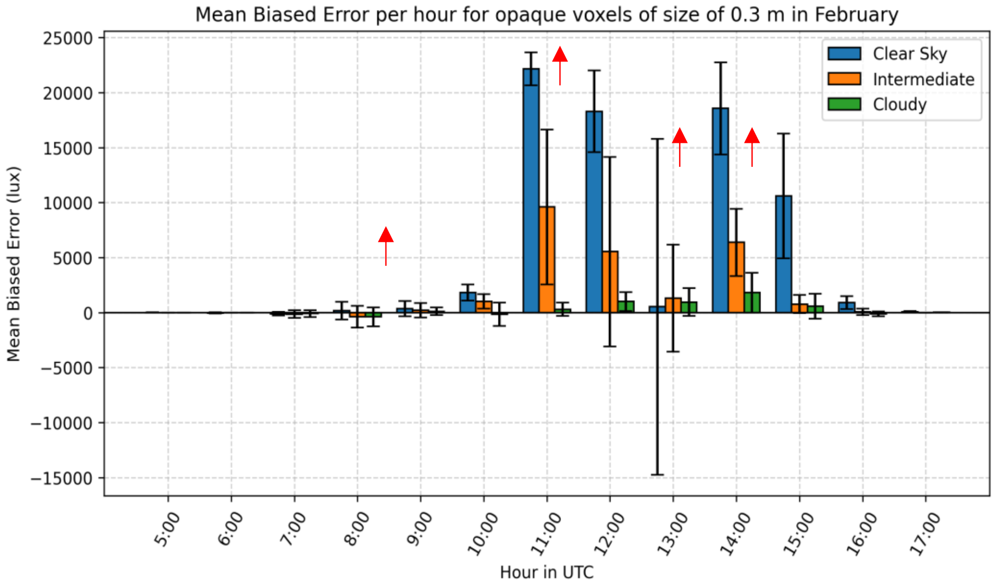


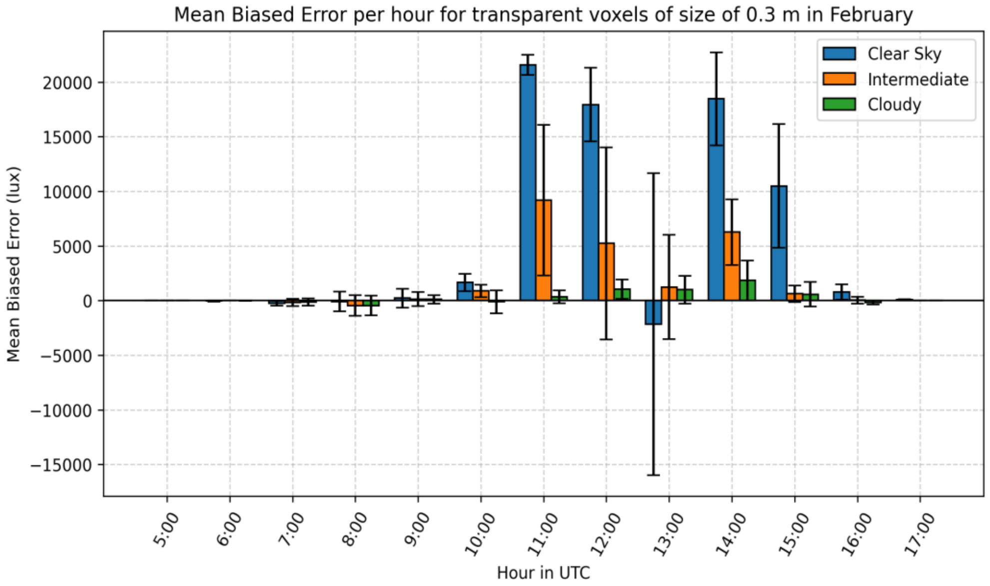


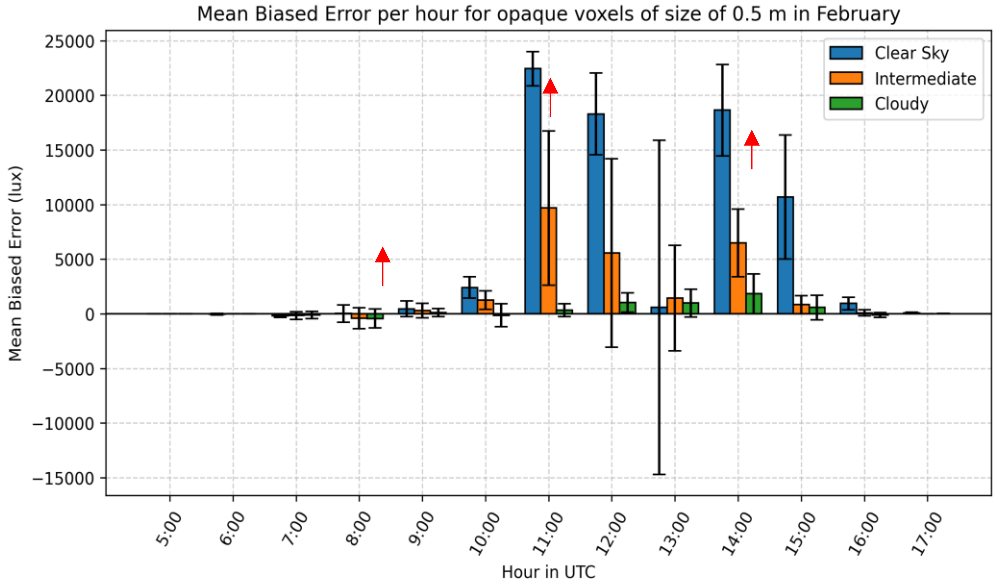


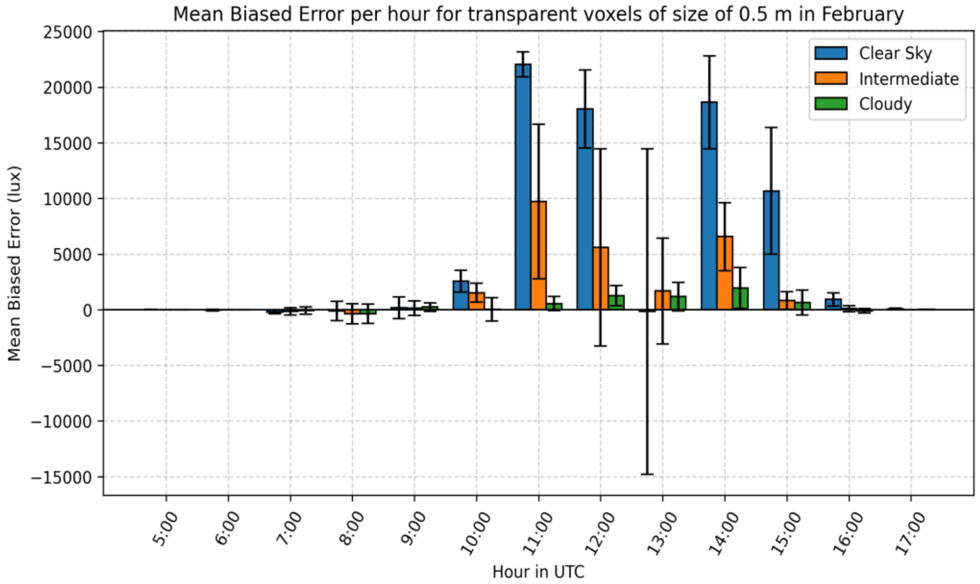
February results (vi/vii)

MBE for opaque and transparent voxels under clear sky, cloudy, and intermediate conditions at 0.30 and 0.50 m









February results (vii/vii)

RMSE of MBE values per voxel size and material under different sky conditions (in lux)

			Clear sky			
Material	0.03 m	0.05 m	0.07 m	0.1 m	0.3 m	0.5 m
Transparent	16741.47	11079.33	**9691.37**	**8609.63**	9790.57	9922.81
Opaque	16261.37	10770.65	9818.54	9747.62	9954.52	10030.00
			Cloudy			
Transparent	1831.49	1225.61	921.11	909.41	692.58	766.83
Opaque	1737.41	1094.04	834.34	**633.28**	**669.74**	685.16
			Intermediate			
Transparent	6268.63	3729.79	**2955.98**	**2560.76**	3445.00	3665.13
Opaque	5716.27	3303.43	2989.39	3072.98	3588.14	3632.39

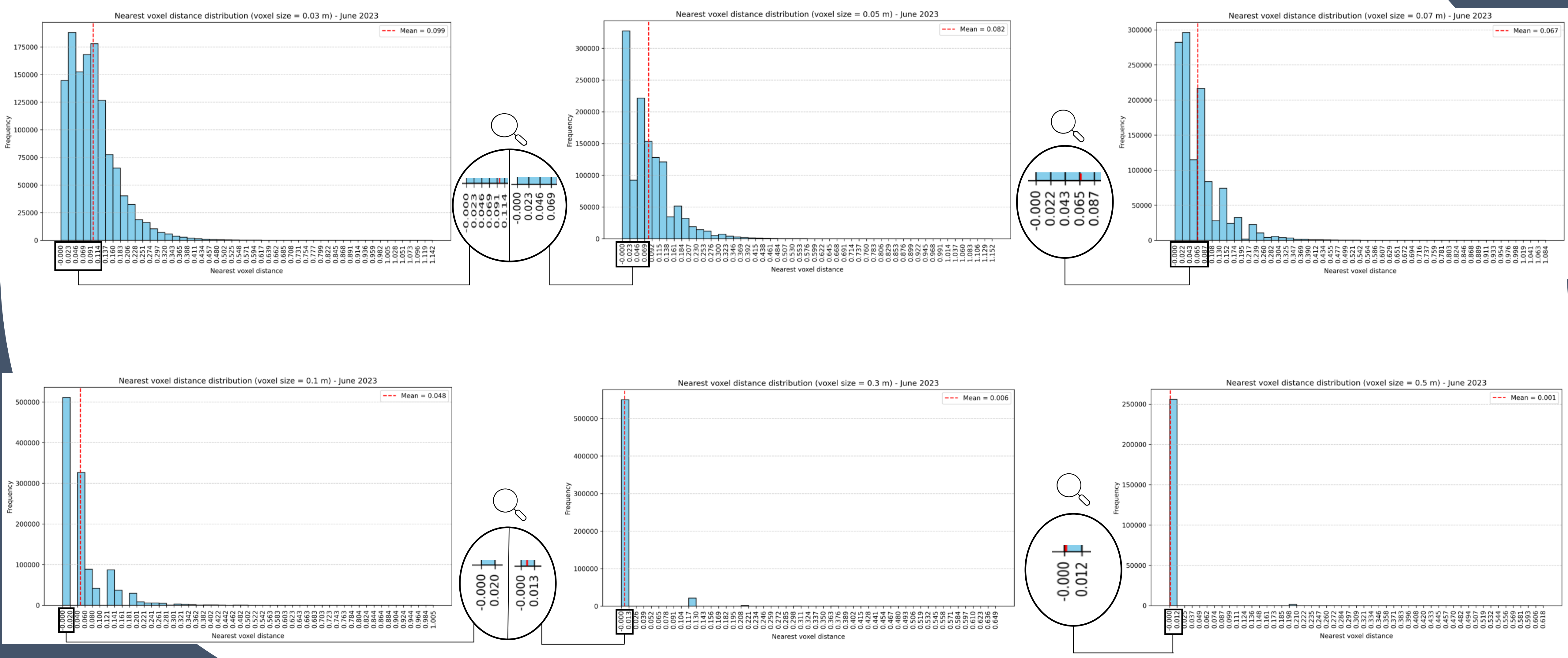
June results

RMSE per June Case		
Point Cloud - based Case		
12634.49		
Alpha Shape Case		
9793.44		
Voxel Grid Case		
Sizes (m)	1st approach	2nd approach
0.03	11690.99	12010.18
0.05	9588.92	9945.00
0.07	9555.12	10315.16
0.10	9741.06	9896.88
0.30	9869.44	9899.31
0.50	9368.68	9655.70
Convex Hull Case		
7885.72		

MBE per June Case		
Point Cloud - based Case		
-4337.18		
Alpha Shape Case		
1668.56		
Voxel Grid Case		
Sizes (m)	1st approach	2nd approach
0.03	-2960.44	-3396.45
0.05	-683.79	-1355.18
0.07	312.57	-1793.85
0.10	1129.29	-474.26
0.30	1570.62	1135.84
0.50	1832.69	1321.15
Convex Hull Case		
3021.98		

June results (i/vii)

Nearest voxel distance distribution per voxel size



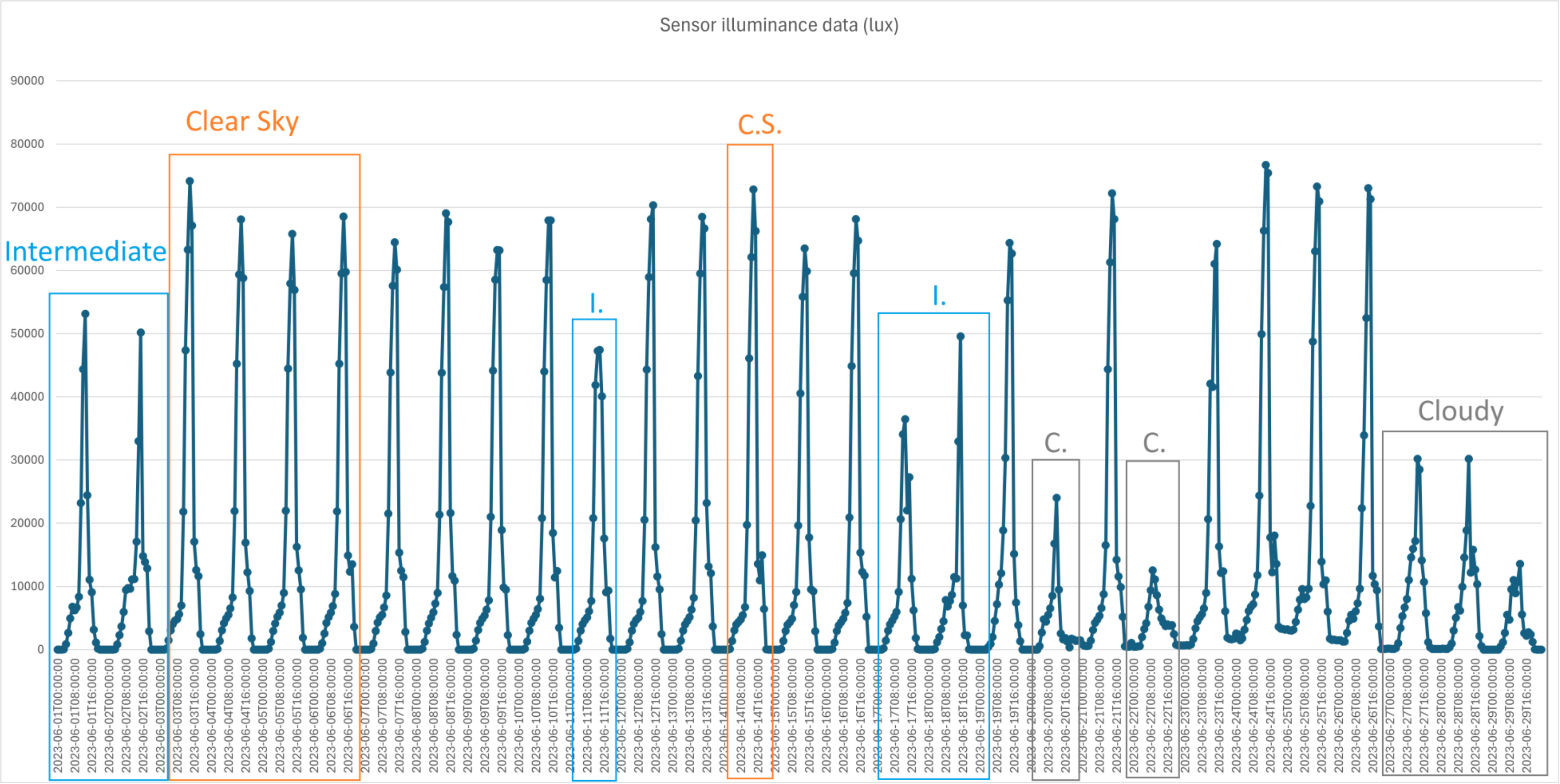
June results (ii/vii)

Voxel distributions by size and transmittance class

Grids	0.03 m	0.05 m	0.07 m	0.10 m	0.30 m	0.50 m
1st (transmittance: 88 %)	998	4,255	1,171,244	1,069,268	541,576	232,092
2nd (transmittance: 63 %)	1,238,001	1,211,073	37,141	86,380	30,360	22,609
3rd (transmittance: 38 %)	5,148	16,741	1,445	711	1,763	2,178
4th (transmittance: 12.5 %)	25	282	56	6	62	105

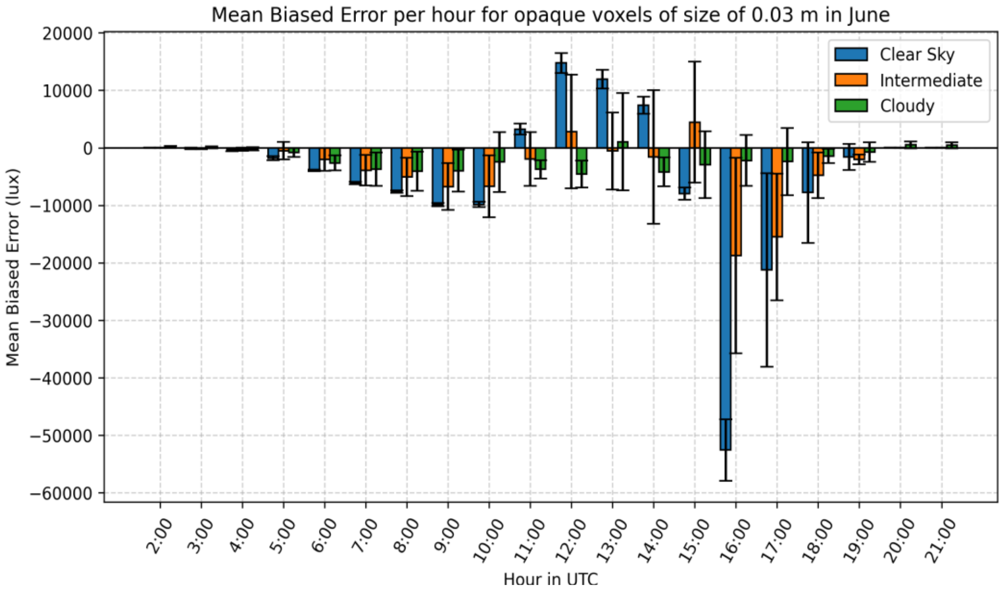
June results (iii/vii)

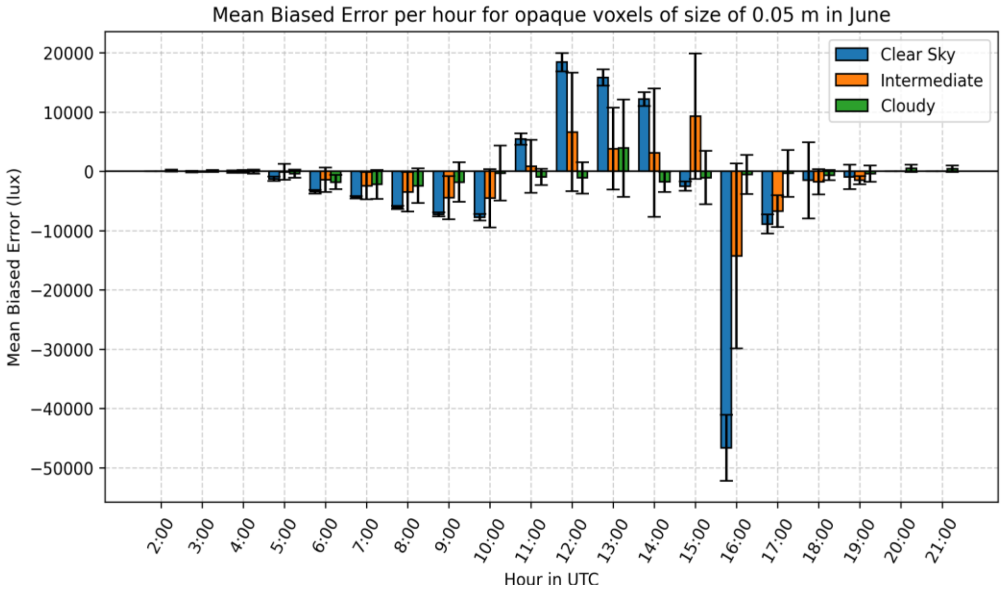
Analysis in terms of different sky conditions

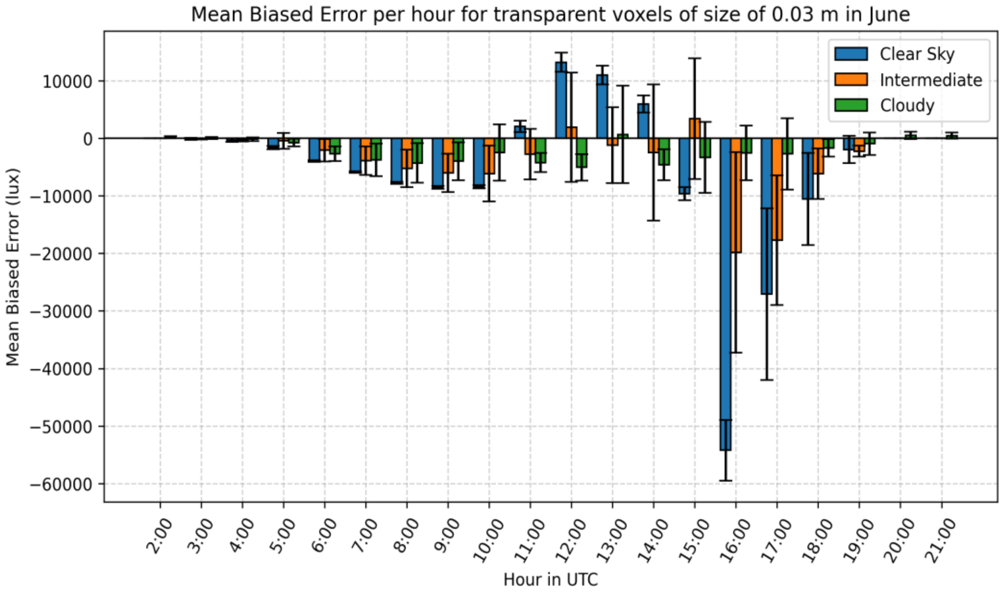


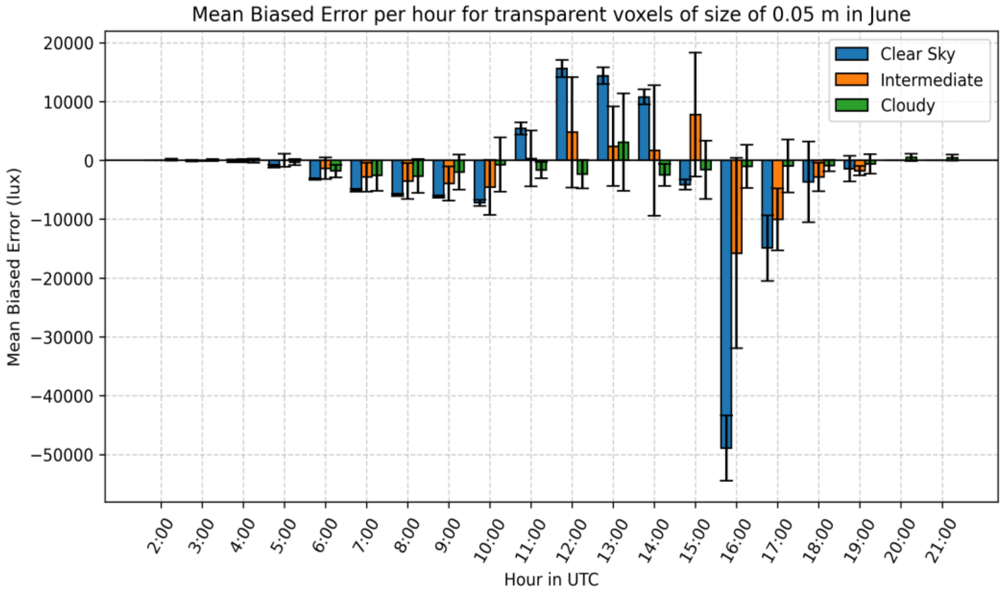
June results (iv/vii)

MBE for opaque and transparent voxels under clear sky, cloudy, and intermediate conditions at 0.03 and 0.05 m



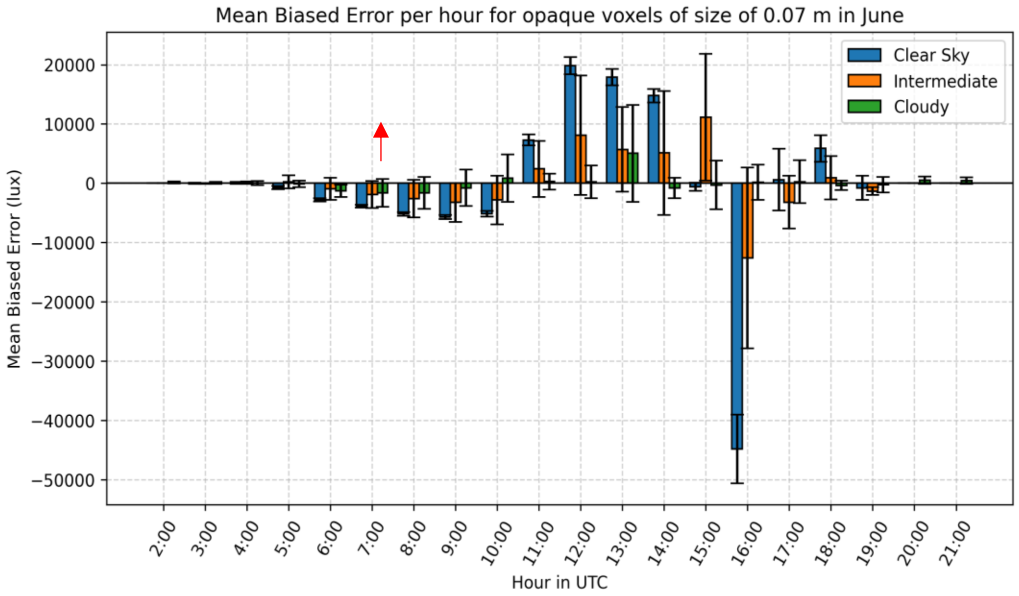


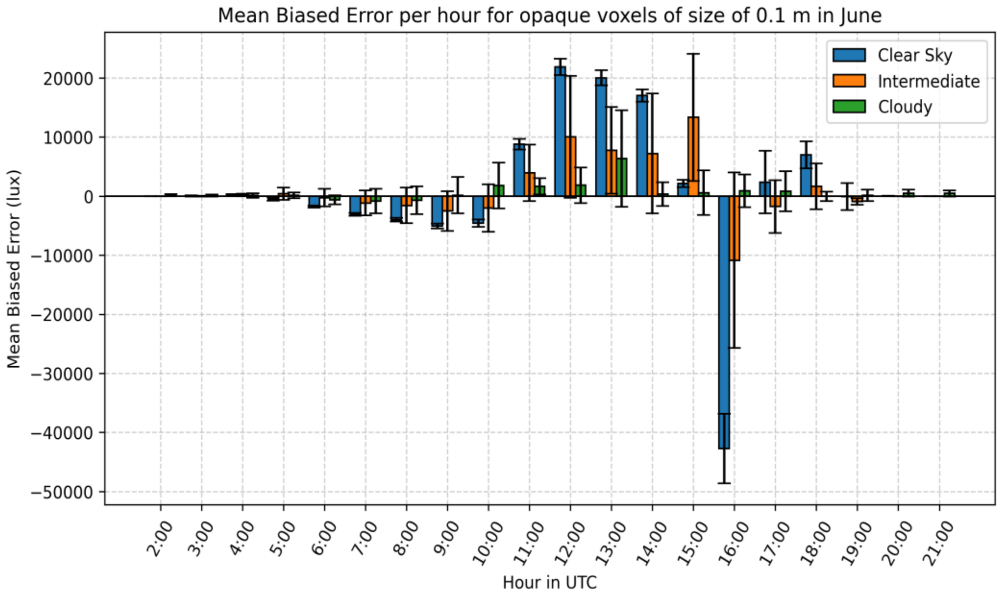


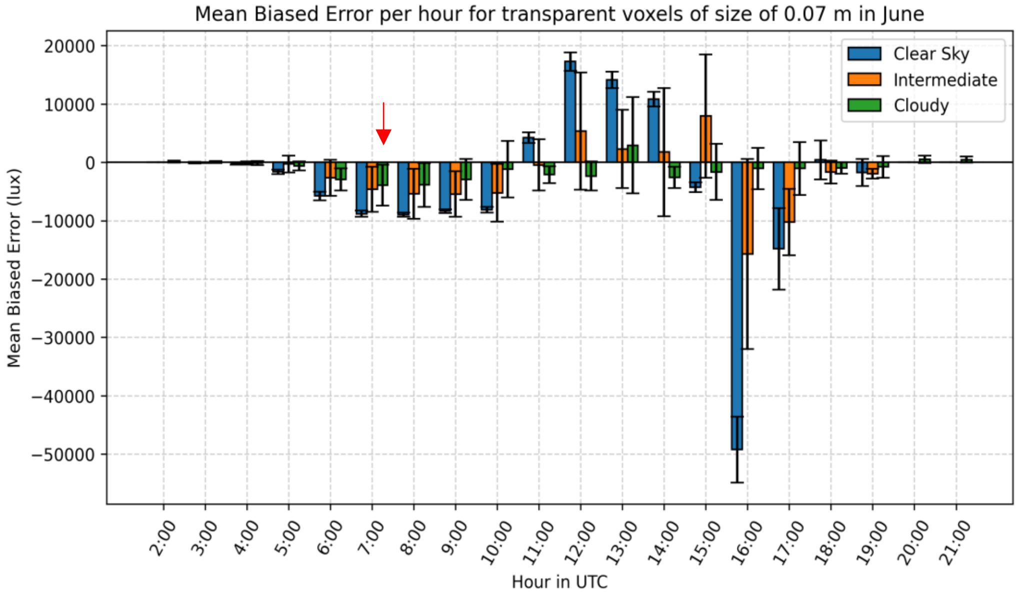


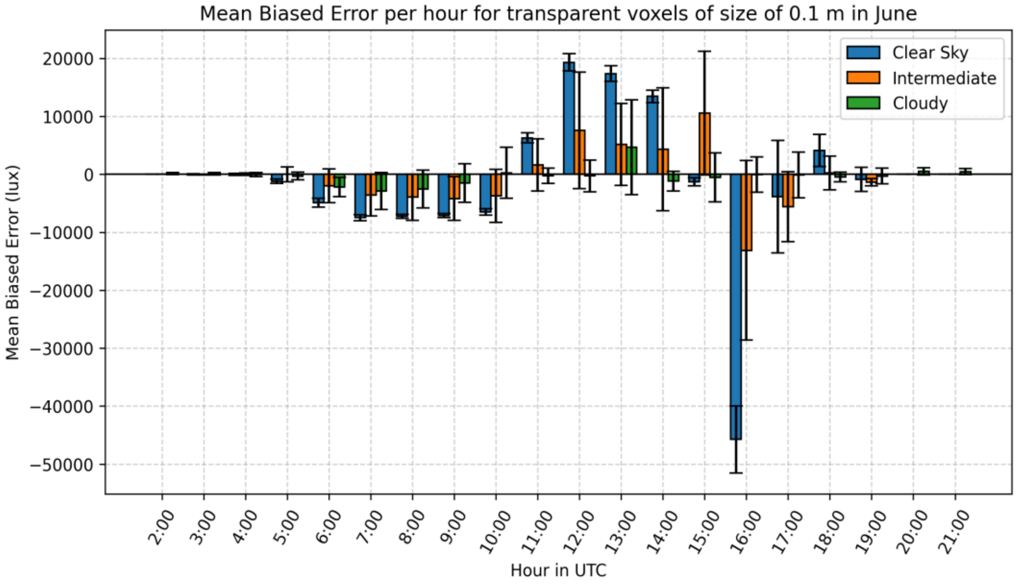
June results (v/vii)

MBE for opaque and transparent voxels under clear sky, cloudy, and intermediate conditions at 0.07 and 0.1 m



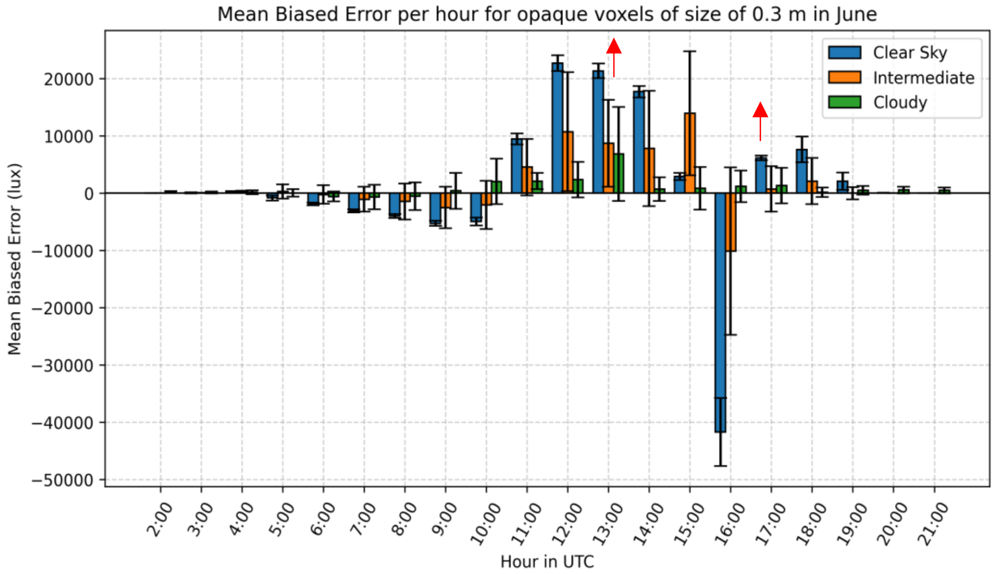


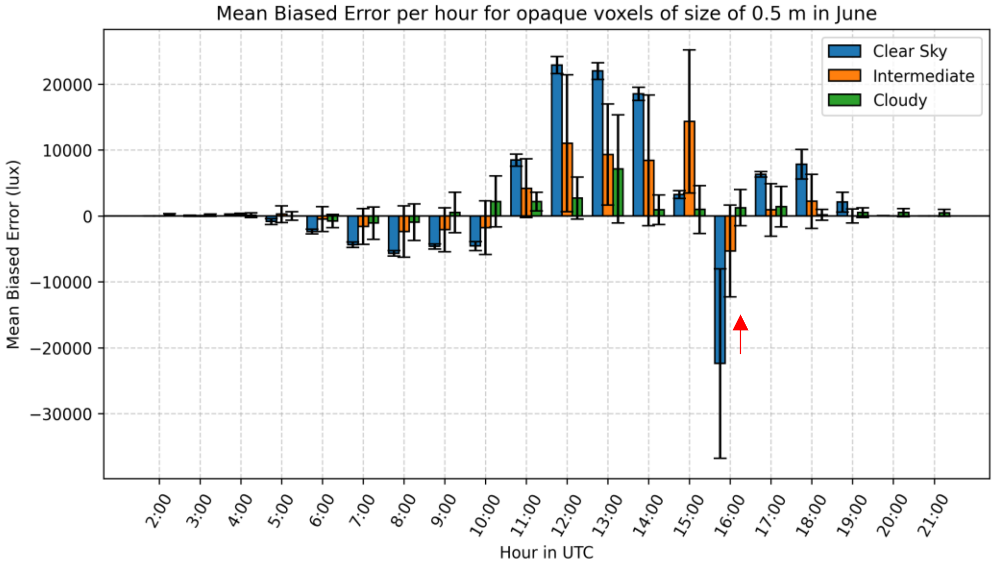


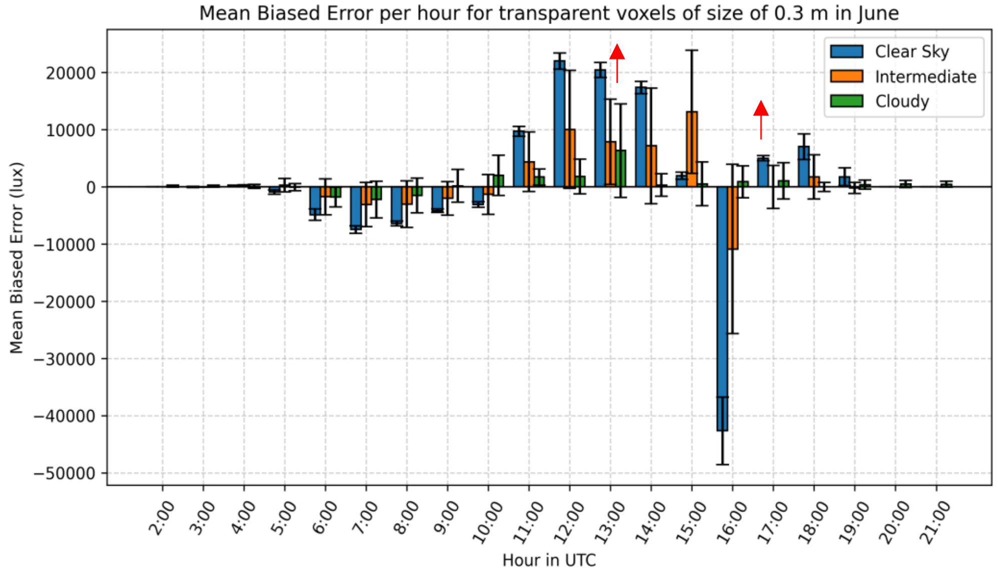


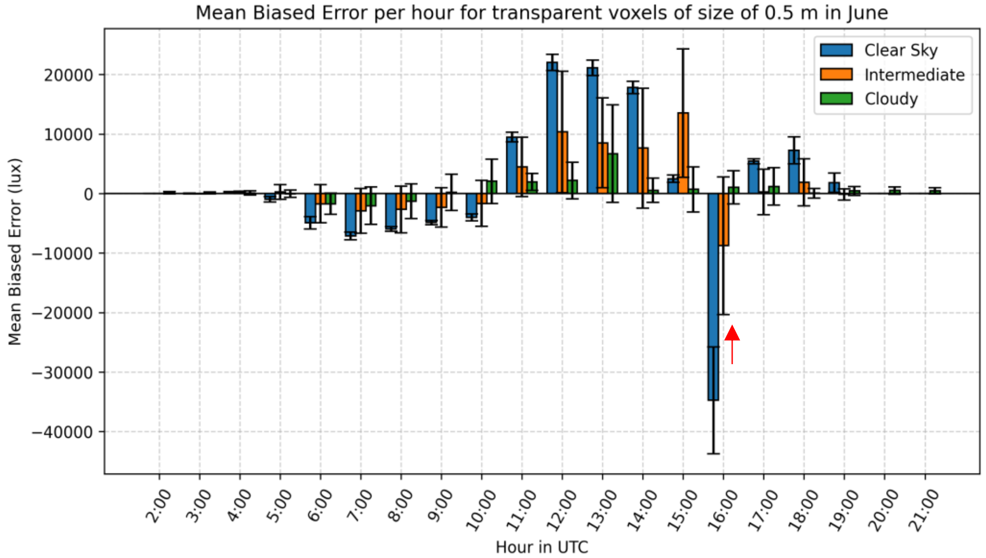
June results (vi/vii)

MBE for opaque and transparent voxels under clear sky, cloudy, and intermediate conditions at 0.30 and 0.50 m









June results (vii/vii)

RMSE of MBE values per voxel size and material under different sky conditions (in lux)

			Clear sky			
Material	0.03 m	0.05 m	0.07 m	0.1 m	0.3 m	0.5 m
Transparent	14957.56	13047.18	13465.99	12740.00	12941.43	**11809.91**
Opaque	14285.57	12674.99	12528.77	12659.84	12845.66	**10335.17**
			Cloudy			
Transparent	2802.18	1608.36	2024.04	1525.17	1787.83	1873.84
Opaque	2610.71	**1418.71**	**1334.89**	1636.62	1822.08	1955.87
			Intermediate			
Transparent	6719.75	5060.05	5354.93	4929.79	5265.39	5231.38
Opaque	6279.36	**4846.23**	**4777.49**	5222.30	5417.51	5255.87

Conclusions

Sub-questions (i/ii)

- **How can ALS point cloud data be used for tree 3D representation in urban daylight simulation?**

1. For capturing the geometric structure of trees.
2. For estimating radiative behaviour.

- **What is the difference in accuracy of the results of the daylight simulation between diverse tree 3D representation approaches?**

1. Point Cloud - based representation from ALS → overestimated results → porous representation **BUT** potentially better results with more detailed point cloud
2. Mesh representations e.g. Alpha Shape and Convex Hull → underestimated results → not easily permeable, important factor: assigned material
3. Voxel representations → highly dependent on voxel size and material

   Cases of sizes less than 0.07 m → overestimated results

   Cases of sizes more than 0.10 m → underestimated results

Sub-questions (ii/ii)

- **How can the results of daylight simulation be evaluated?**

  Robust assessment → analysis of complete time series and subsets representing different sky conditions

  Important to examine whether cases align!

- **What is the impact of seasonal alterations of the tree canopy in urban daylight simulation?**

  June simulations showed higher errors due to:

  I. Insufficient point density

  II. Greater system sensitivity under clear sky

Main research question

To what extent can the tree ALS point cloud data increase the accuracy of daylight simulations?

- Point Cloud–based case: Insufficient point density → inaccurate sunlight obstruction
- Convex Hull case: Highest abstraction → underestimation of illuminance
- Alpha Shape case: Moderate abstraction → less underestimation than Convex Hull
- Voxel Grid case: Most flexible → adjustable voxel sizes (0.03–0.5 m)

February simulations:

1. Voxel size around 0.10 m gives best balance between porosity and solidity.
2. Optimal material type remains unclear; varies with sky condition

June simulations: Lower accuracy

Limitations

Tree 3D Representations

- LiDAR acquisition errors.
- Georeferencing uncertainties (CCC Building).
- Synthesized point cloud used for June simulations.
- Voxel Grid: only size and material parameters analyzed.

Simulations

- ClimateStudio: less accurate under clear-sky conditions.
- Rhino material definitions introduced uncertainties.
- Glass material – tree relationship not examined.

Future Work

- Explore alternative methods for acquiring point cloud data and tree 3D representations.
- Test higher ray sample counts for improved simulation accuracy.
- Evaluate other software, e.g., Honeybee.
- Study different voxel material properties and spatial voxel parameters.

Thank you for attention!

Any questions?

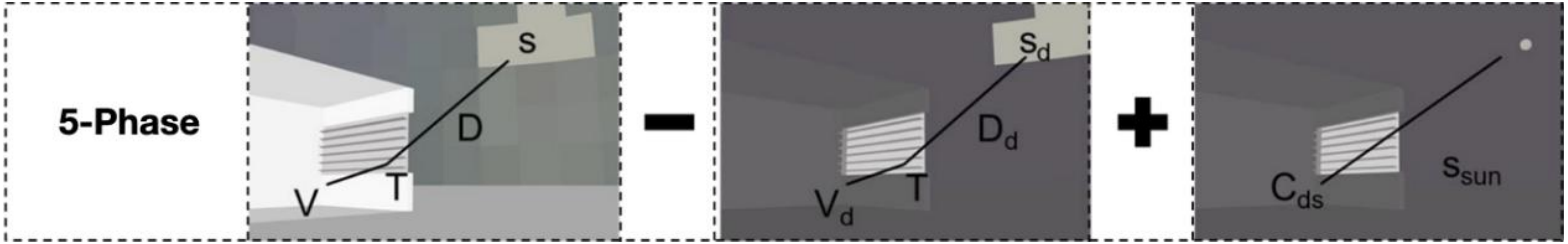
Appendices

Daylight Simulation

- Direct sunlight → solar position
- Diffuse ambient light → 145-patch Tregenza sky subdivision
- Sky model: Perez – All weather
- Matrix-based approach
- It resembles Radiance 5-Phase method.

$$\text{Illuminance}_{5\text{-phase}} = \boxed{\text{Illuminance}_{3\text{-phase}}} - V_d \cdot T \cdot D_d \cdot S_d + C_{ds} \cdot S_{sun}$$

$$V \cdot T \cdot D \cdot S$$



Subramaniam (2017)

Point Cloud - based Case

Input

For February:
Cleaned AHN 5 point cloud

For June:
1. Cleaned AHN 5 point cloud
2. Leaf point cloud

Conversion of point into cubes of 0.02 m

Output

For February:
One OBJ file (Branches/stem), Assigned material: Reflectance of 35.9 %

For June:
Two OBJ files (Branches/stem + Leaves)), Assigned materials: Reflectance of 35.9 % (for branches/stem) and Reflectance of 13.7 % (for leaves)

Voxel Grid Case (1st approach)

Input

For February:
Cleaned AHN 5 point cloud

For June:
1. Cleaned AHN 5 point cloud
2. Leaf point cloud

For June, classification depending on point labels.

Voxel sizes (m): 0.03, 0.05, 0.07, 0.1, 0.3, 0.5

Output

For February:
One OBJ file → Voxel Grid of branches/stem, Assigned material: Reflectance of 35.9 %

For June:
One OBJ file → Voxel Grid of branches/stem, Assigned material: Reflectance of 35.9 %
One OBJ file → Voxel Grid of leaves, Assigned material: Reflectance of 13.7 %

Voxel Grid Case (2^{nd} approach)

Input

For February:
Cleaned AHN 5 point cloud

For June:
Synthesized Point Cloud

Calculation:

$$\text{Transmittance Index} = \frac{\text{Max Point Number} - \text{Voxel Point Number}}{\text{Max Point Number}}$$

Voxel sizes (m): 0.03, 0.05, 0.07, 0.1, 0.3, 0.5

Output

```
void glass First
0
0
3 0.88 0.88 0.88
```

```
void glass Second
0
0
3 0.63 0.63 0.63
```

```
void glass Third
0
0
3 0.38 0.38 0.38
```

```
void glass Forth
0
0
3 0.125 0.125 0.125
```

Creation of an OBJ file of each voxel grid

Convex Hull Case

1. Input

For February:
Cleaned AHN 5 point cloud

For June:
Synthesized Point Cloud

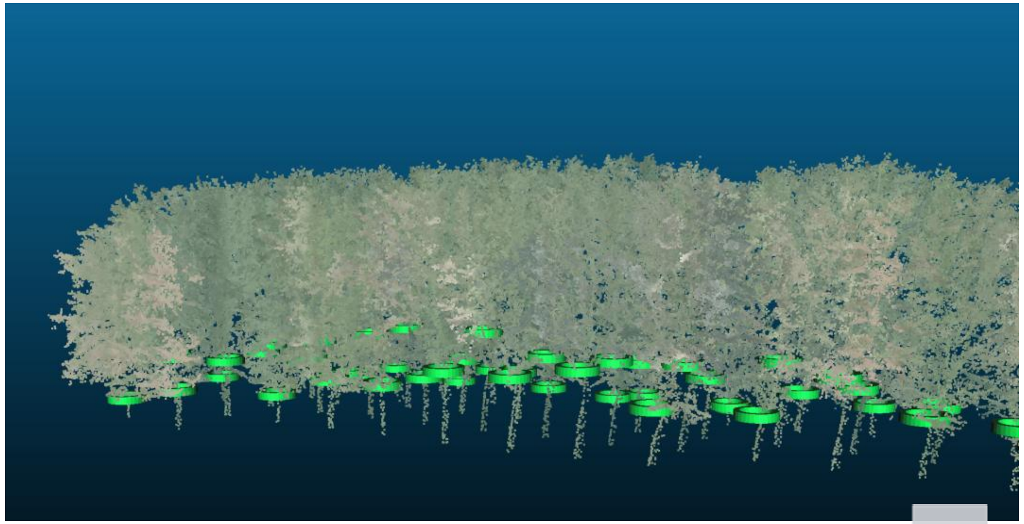
2. Involvement of DBSCAN with parameters: radius = 0.8, minimum included points = 3 for lower points

3. Segmentation into individual las files

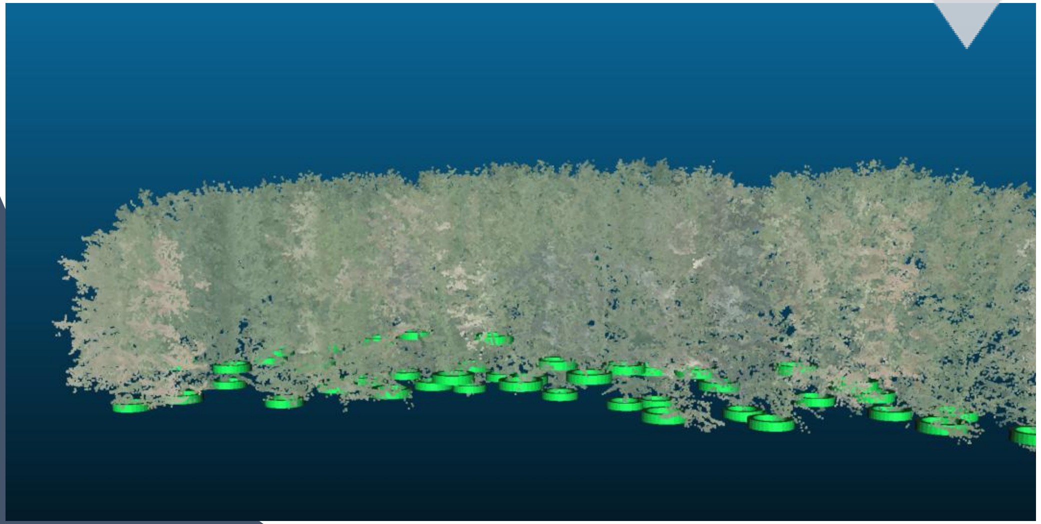
4. For each las file:
Annulus at the point with these coordinates (np.mean(las.x), np.mean(las.y), np.min(las.z))
+ dimensions -> inner radius = 1.5, outer radius= 2.0, and height = 0.8

5. Replication of annulus vertically until branches

Convex Hull Case



4. Extraction of branch points

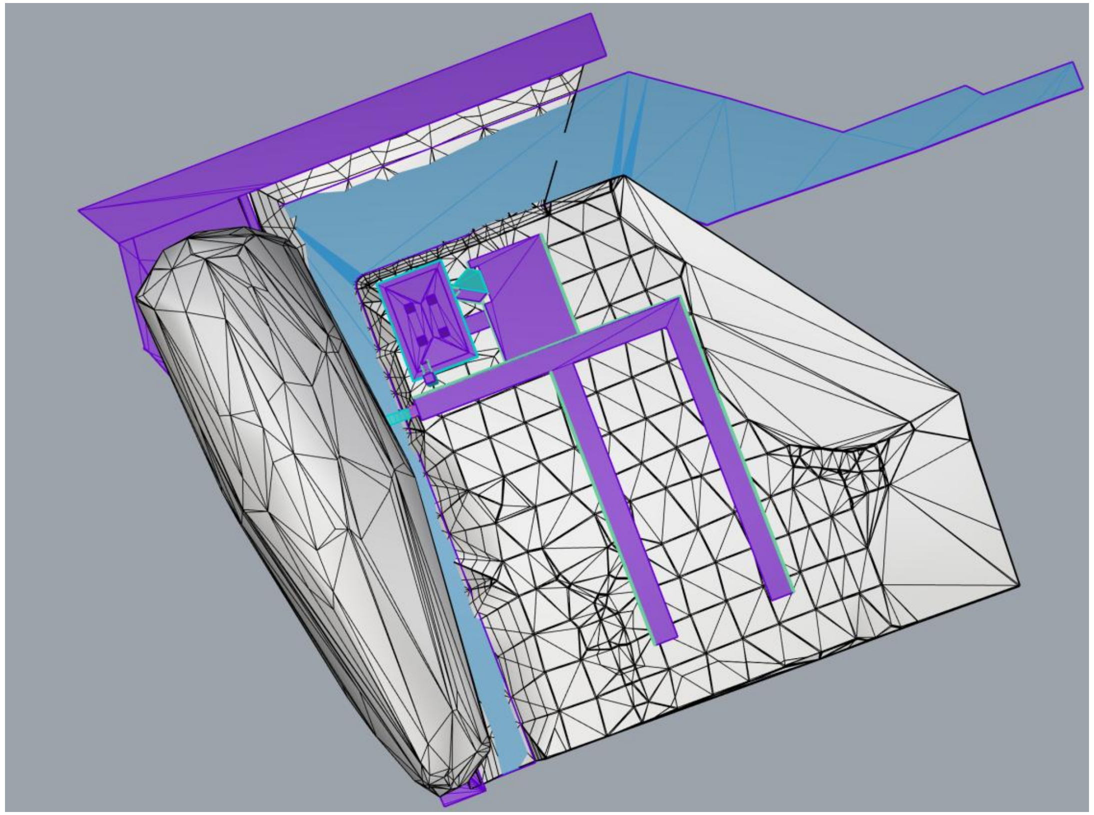


5. Output

Creation of the OBJ file of convex hull of branches

For February:
Assigned material:
Reflectance of 13.7 %

For June:
Assigned material:
Reflectance of 35.9 %



Convex Hull Case

For February

1.Input

Cleaned AHN 5 Point Cloud

For June

1. Input

Synthesized Point Cloud

2. Extraction of points with height lower than 1.5 m

3. DBSCAN with parameters: radius = 0.8, minimum included points = 3

4. Segmentation of the point cloud (of height lower than 1.5 m) into individual trees.

5. Exclusion of the clusters not belonging to trunks

6. For each of the separated las files:

a. Annulus generation the point (np.mean(las.x), np.mean(las.y), np.min(las.z))

b. Replication of the annulus along the Z-axis with a spacing of 1 m

c. Retention of the first annulus that containing points between its inner and outer rings

Alpha Shape Case

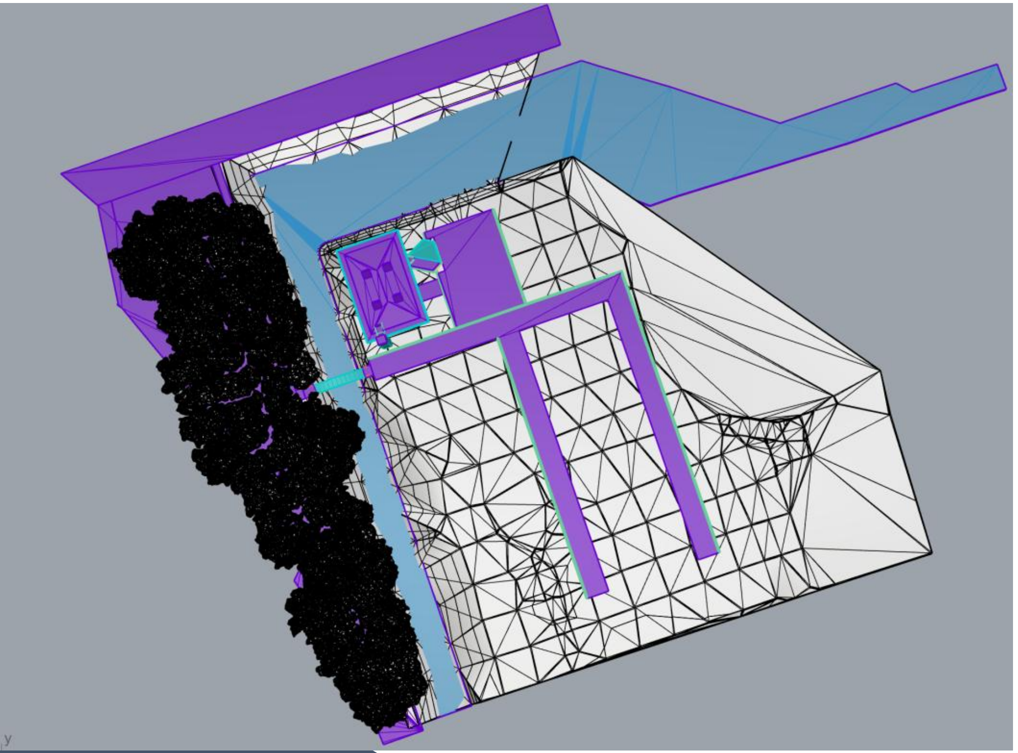
7. Output

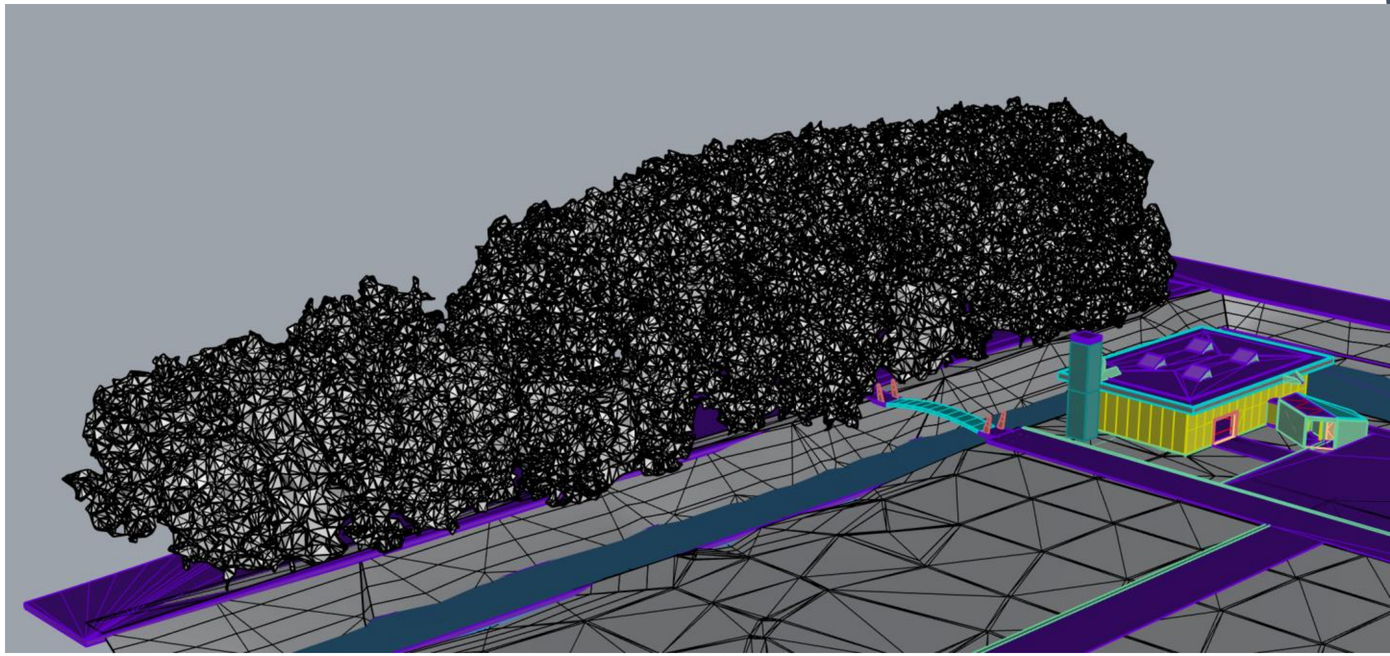
Alpha shape parameters: 0.5, 1.0, and 1.5.

Assembled OBJ files of alpha shapes of separated trees

For February:
Assigned material:
Reflectance of 13.7 %

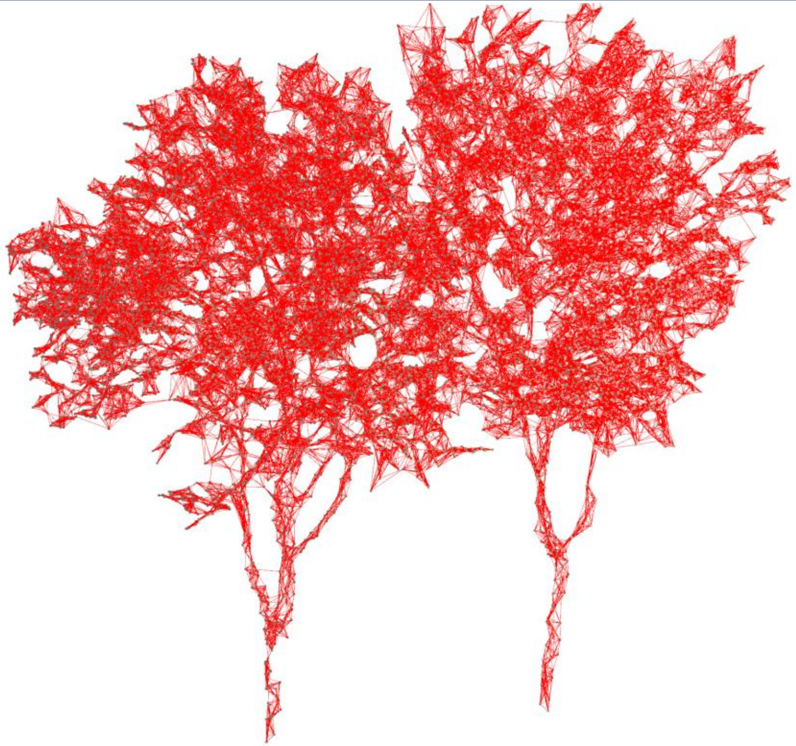
For June:
Assigned material:
Reflectance of 35.9 %





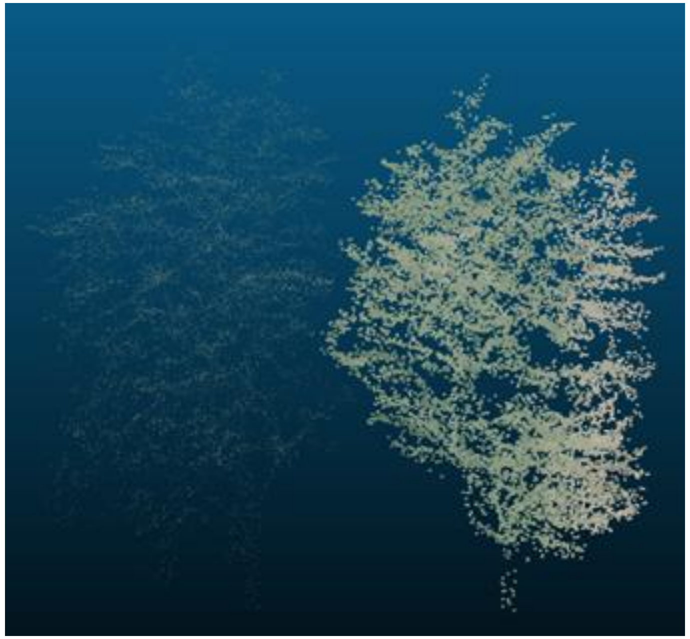
Alpha Shape Case

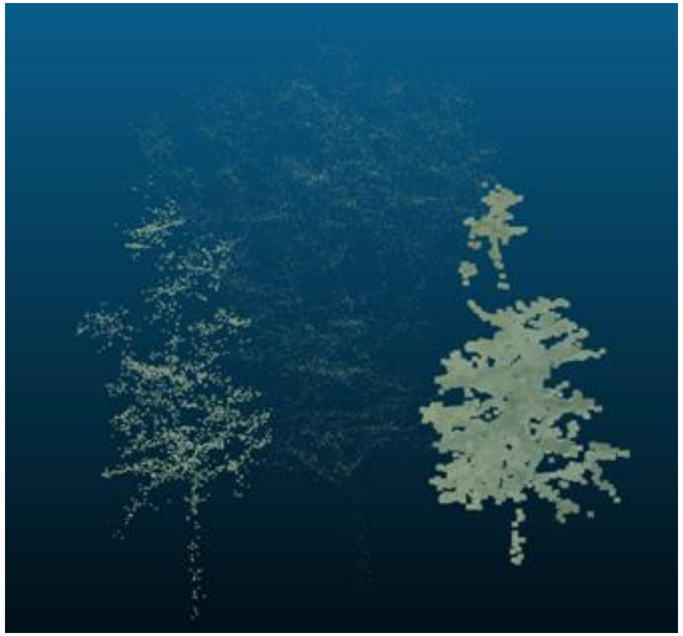
2. Creation of the 10-NN graph of points of the input point cloud



3. Segmentation into individual trees:

- Shortest distances to lowest points
- Manual refinement

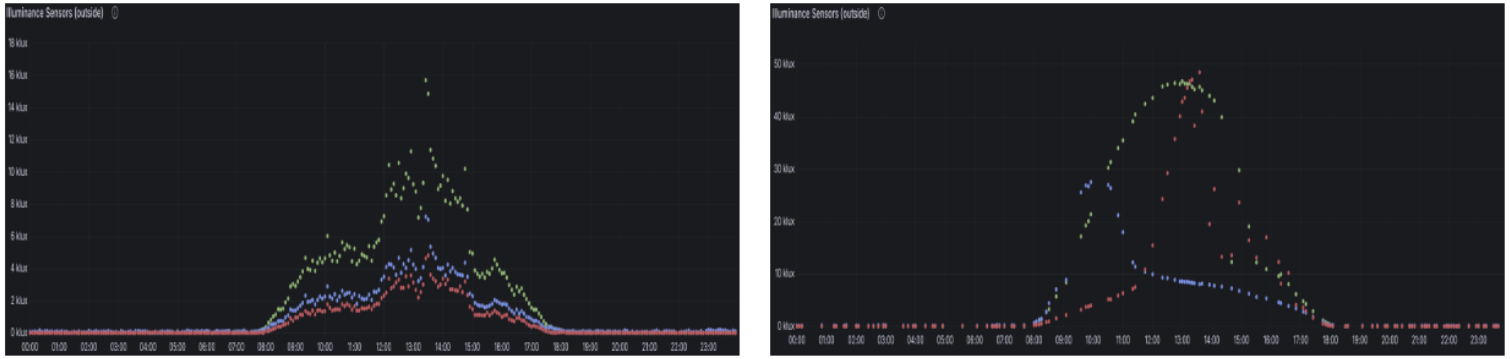




Simulation

B. Material properties of the rest objects

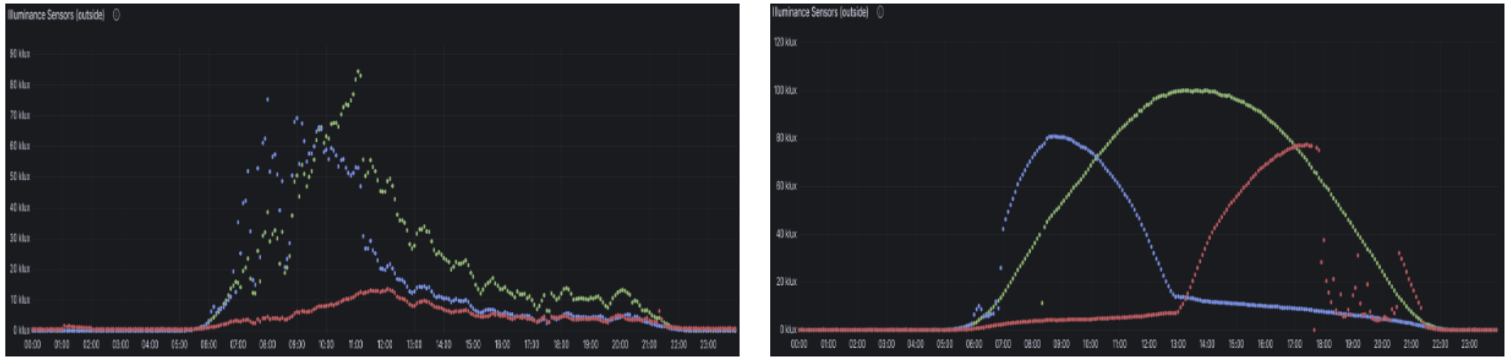
Object Category	Reflectance (%)
Ground	15.7
Building Parts (walls, roof, columns, floor)	43.24
Door	44.16
Glass on the Facade	15
Bridge	43.24



(a) Cloudy day in February 2023 (21/2/2023)

(b) Clear sky day in February 2023 (14/2/2023)

Figure 3.8.: Global horizontal (green dots), east (blue dots) and west (red dots) illuminance sensor graphs (values in klux) for a cloudy day and a clear sky day in February 2023 from Grafana platform.



(a) Cloudy day in June 2023 (22/6/2023)

(b) Clear sky day in June 2023 (14/6/2023)

Figure 3.9.: Global horizontal (green dots), east (blue dots) and west (red dots) illuminance sensor graphs (values in klux) for a cloudy day and a clear sky day in June 2023 from Grafana platform.

Georeference

Based on the information from 3D BAG webpage ([2] and [1]) at **Figure** 4.4, the Root Mean Square Error (RMSE) of the 3D distances between the AHN 5 point cloud and the LOD 2.2 model of CCC Building is **0.141** m.

Figure 4.4.: LOD 2.2 model of the CCC Building from the 3D BAG website and its attributes, including b3_RMSE_lod22

Georeference

Horizontal

Table 4.4.: $RMSE_x$, $RMSE_y$ and RMSE in meters

$RMSE_x(m)$	$RMSE_y(m)$	$RMSE(m)$
0.095	0.098	0.136

Vertical

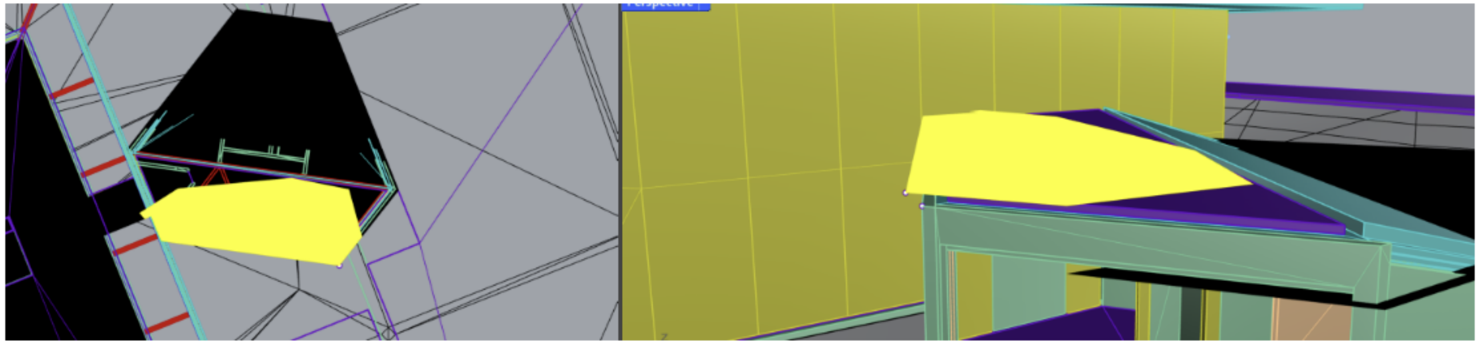
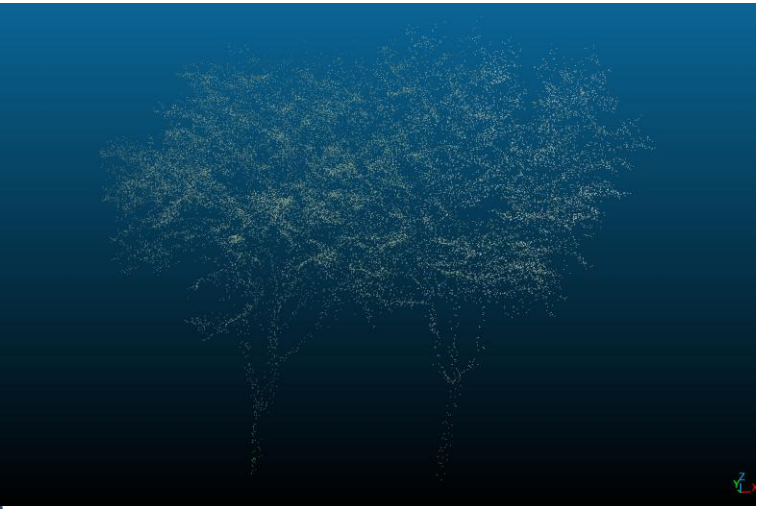
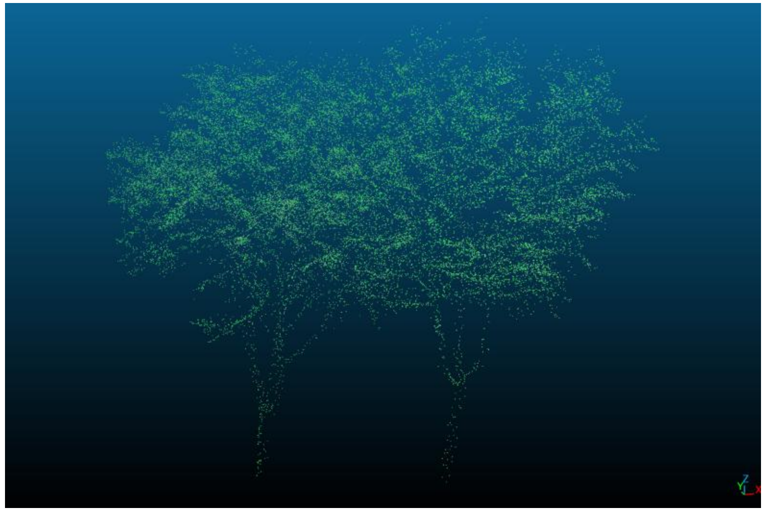


Figure 4.10.: Points to evaluate the final height of small part of CCC Building

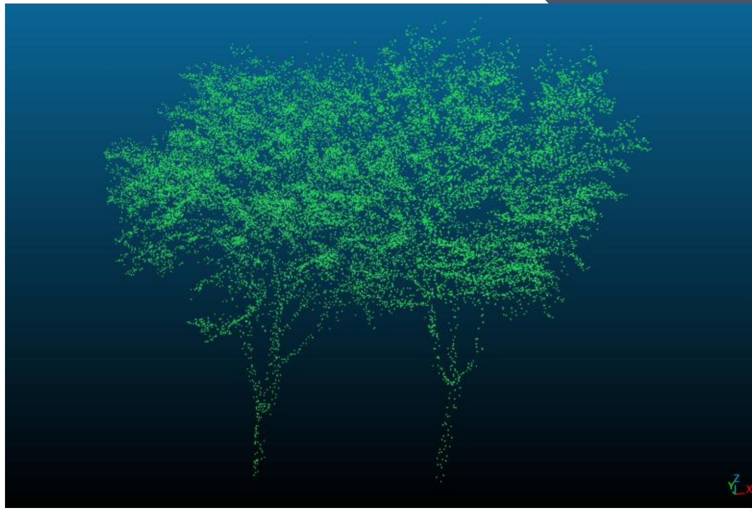
Height difference: 0.116 m



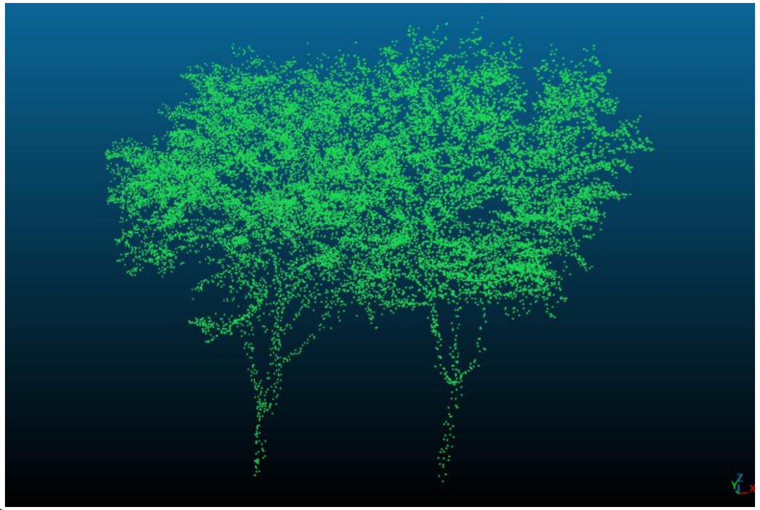
Point Cloud



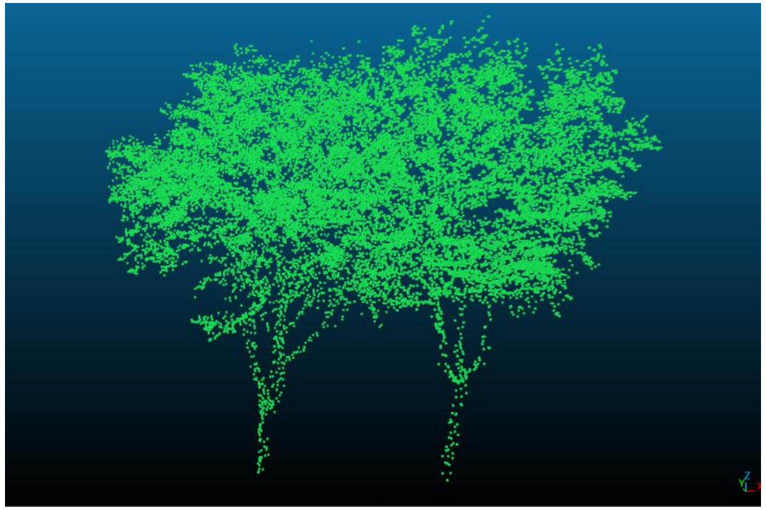
Voxel Grid (0.03 m)



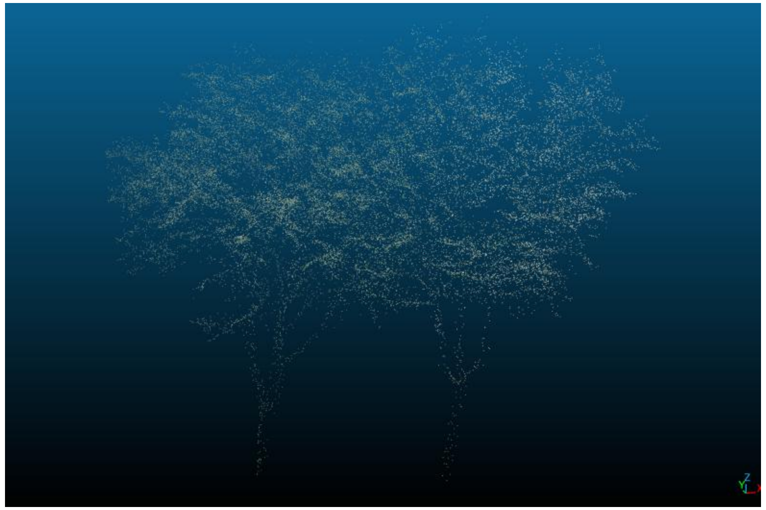
Voxel Grid (0.05 m)



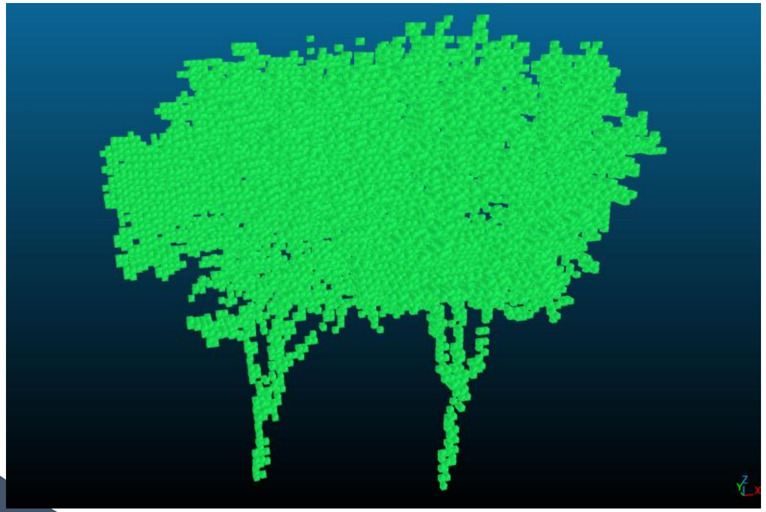
Voxel Grid (0.07 m)



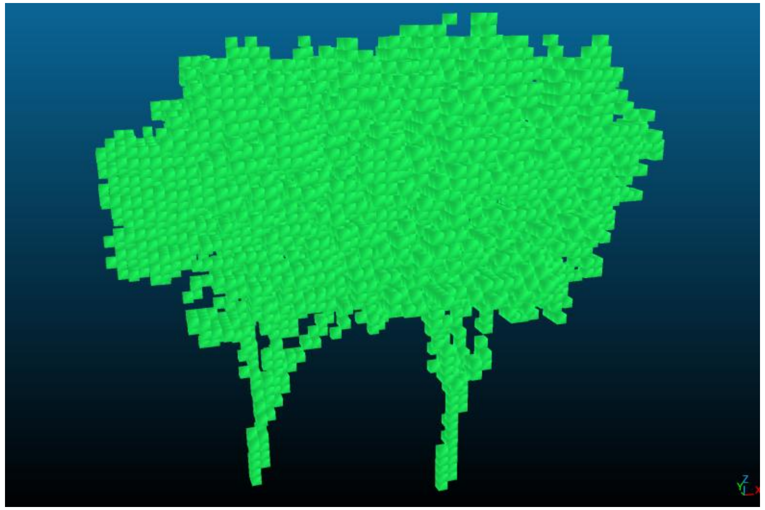
Voxel Grid (0.10 m)



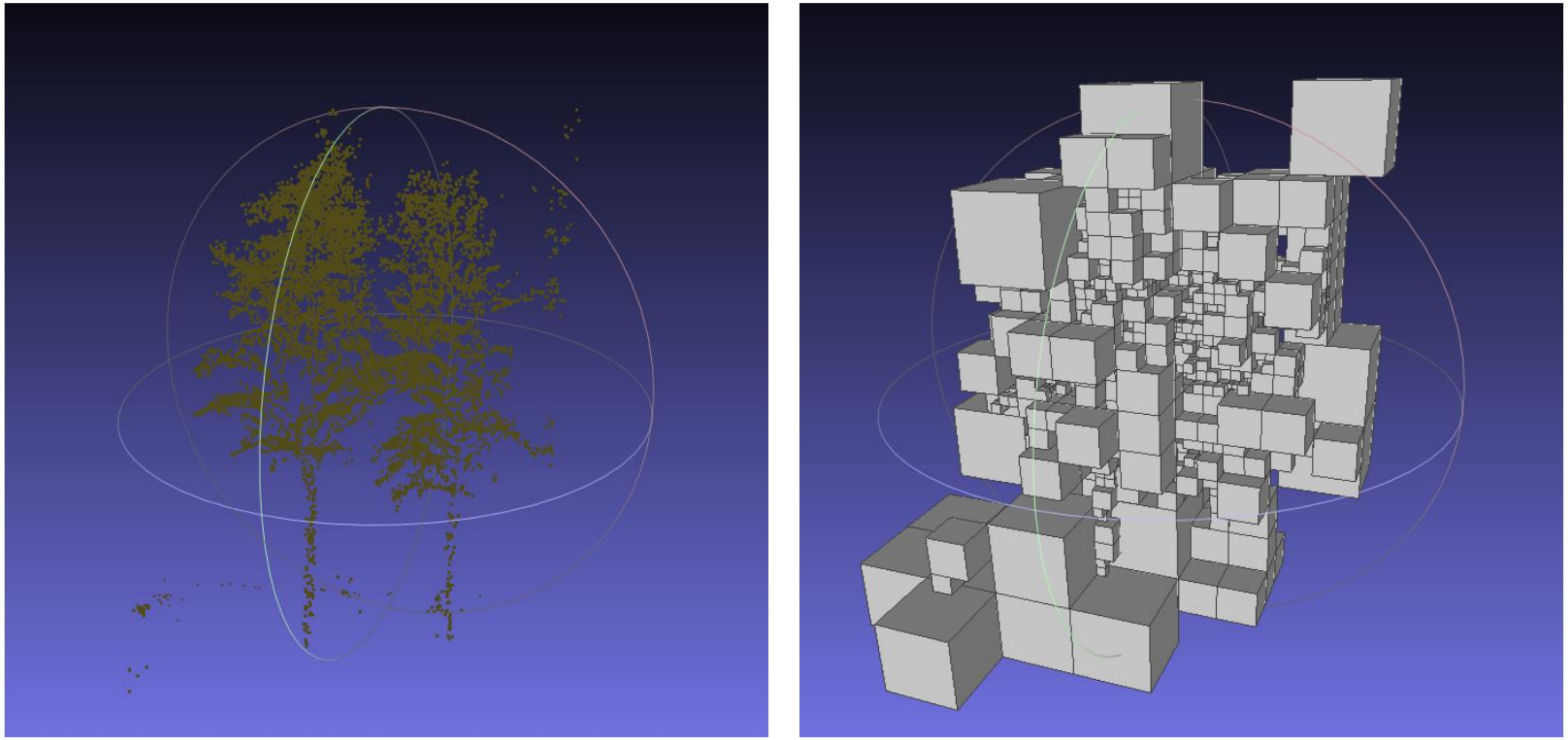
Point Cloud



Voxel Grid (0.30 m)



Voxel Grid (0.50 m)



(a) Example of input point cloud. (b) Output of voxel grid with varying voxel size.

Figure 3.1.: Example of the voxelization process applied to a tree point cloud, illustrating the transformation from the original point cloud (a) to the corresponding voxel grid representation with varying voxel sizes (b).