Terrestrial, UAV-borne, and airborne laser scanning point clouds of central European forest plots, Germany, with extracted individual trees and manual forest inventory measurements

Article · May 2022

DOI: 10.1594/PANGAEA.942856

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Metadata Documentation – 2022-06-03

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Project: SYSSIFOSS - Synthetic structural remote sensing data for improved forest inventory models

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Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project number: 411263134

Funded by
Deutsche Forschungsgemeinschaft
German Research Foundation

1 DATA ACQUISITION

Point clouds were acquired in 2019 and 2020 by a) airborne laser scanning (ALS), b) UAV-borne laser scanning (ULS) and c) terrestrial laser scanning (TLS). Dates of acquisition are encoded in the filenames of the point clouds. Data acquisition was targeted at twelve forest plots of 1 ha each, which belong to the municipal forests of Bretten and Karlsruhe (Baden-Württemberg, Germany). An overview of the location of the study sites within southwest Germany is visualized in Fig. 1.

We extracted ALS point clouds with different buffers sizes around the 1-ha plots. The full ALS dataset (point cloud data and full waveform) is available for collaborators upon reasonable request. Each plot has a unique ID (e.g., “BR01”), which is encoded in the filename. TLS point clouds cover only smaller areas but overlap with ALS and ULS point clouds. Field inventory measurements were recorded for all trees within six of the 1-ha plots (outlined in purple in Figs. 2 and 3). The field inventory plots, the extent of the ALS data and the ALS flight trajectories are visualized in Figs. 2 and 3 for Bretten and Karlsruhe, respectively.

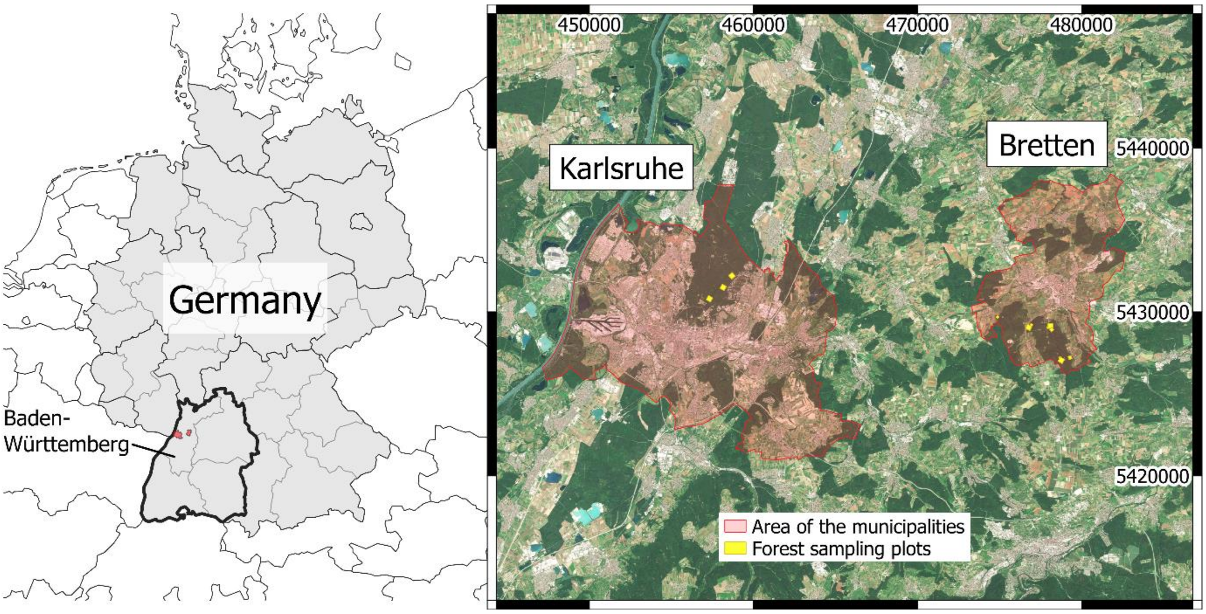

Figure 1: Location of the study sites in Karlsruhe and Bretten within Baden-Württemberg, Germany. Left: Overview map of Germany with the cities Karlsruhe and Bretten colored in red. Right: Plot locations (yellow) within the two municipalities (transparent red), cf. Figs. 2 and 3). Coordinates are given in the projected coordinate system ETRS89 / UTM zone 32 N (EPSG:25832), unit: meters. Imagery: ©European Union, contains Copernicus Sentinel-2 Data (2018), processed by the German Federal Agency for Cartography and Geodesy (BKG). Administrative boundaries: ©EuroGeographics (2021) and ©GeoBasis DE / BKG (2020).

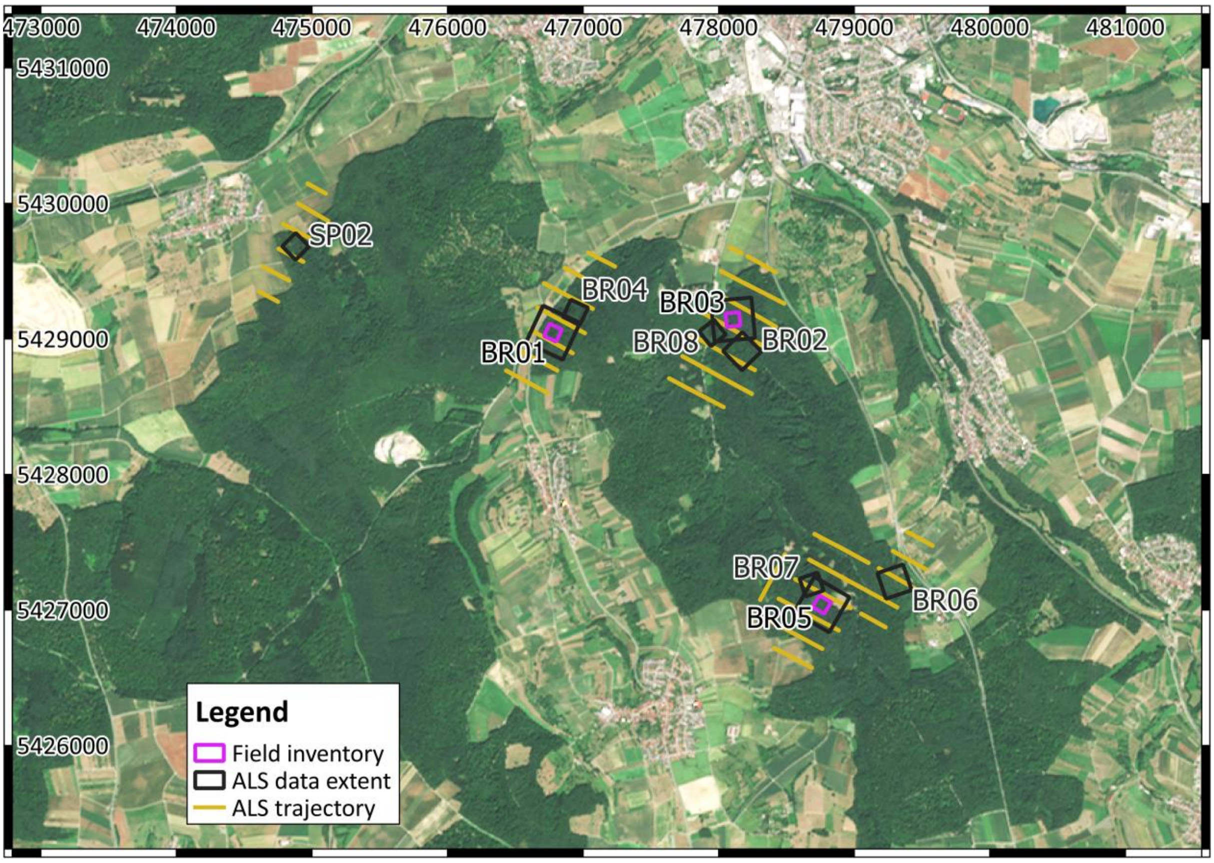

Figure 2: Forest plots and Airborne Laser Scanning (ALS) trajectory in the Bretten study site. Field inventories were conducted within the plots outlined in purple. Black outlined rectangles show the extent of the cropped ALS point cloud data and orange lines the respective ALS trajectories. Coordinates are given in the projected coordinate system ETRS89 / UTM zone 32 N (EPSG:25832), unit: meters. Imagery: ©European Union, contains Copernicus Sentinel-2 Data (2018), processed by the German Federal Agency for Cartography and Geodesy (BKG).

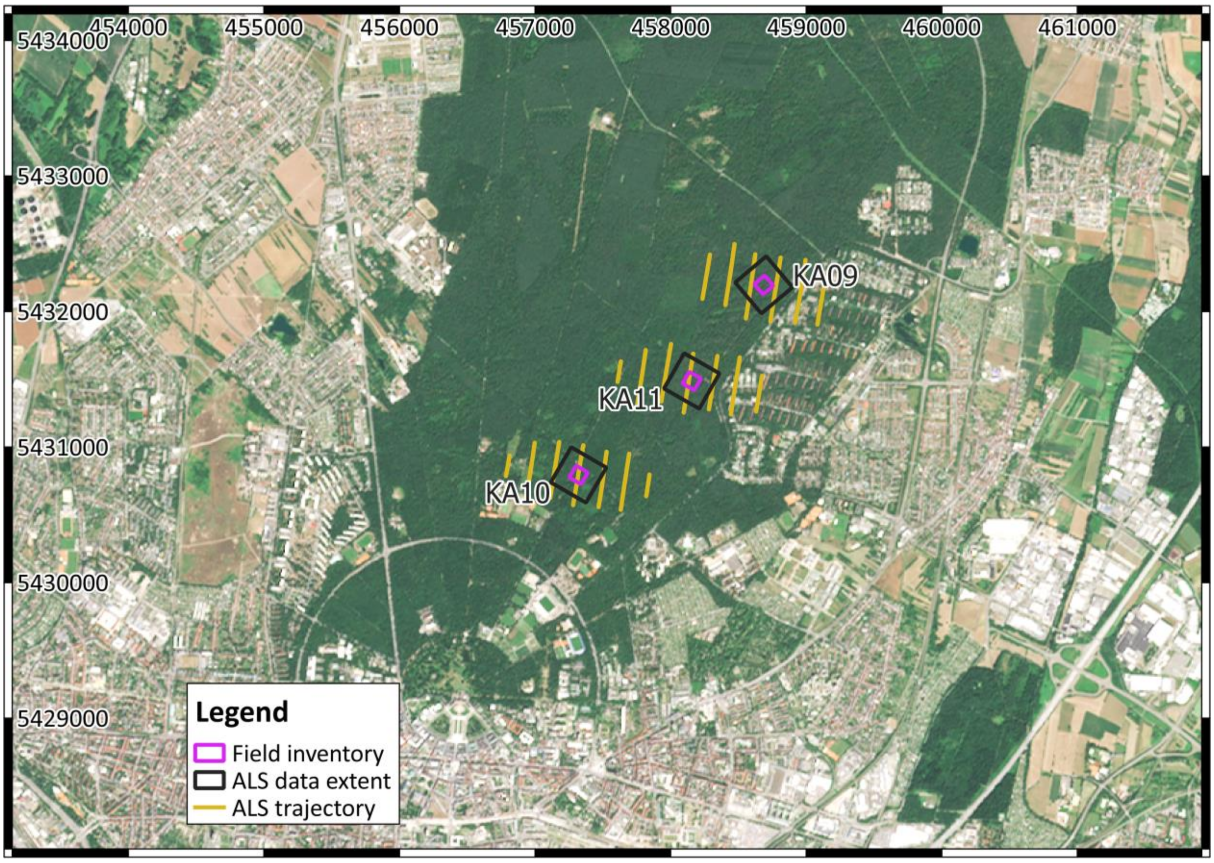

Figure 3: Forest plots and ALS trajectory in the Karlsruhe study site. Field inventories were conducted within the plots outlined in purple. Black outlined rectangles show the extent of the cropped ALS point cloud data and orange lines the respective ALS trajectories. Coordinates are given in the projected coordinate system ETRS89 / UTM zone 32 N (EPSG:25832), unit: meters. Imagery: ©European Union, contains Copernicus Sentinel-2 Data (2018), processed by the German Federal Agency for Cartography and Geodesy (BKG).

1.1 Airborne laser scanning (ALS)

ALS data was acquired on 5 July 2019 by MILAN Geoservice GmbH utilizing a RIEGL VQ-780i, mounted on an aircraft of type Cessna C207. The ALS instrument nominal specifications are listed in Tab. 1. More information can be found in the sensor datasheet by the manufacturer RIEGL LMS GmbH (2019). The ALS survey parameters are listed in Tab. 2 and the trajectory is visualized in Figs. 2 and 3.

Table 1: Instrument specifications for RIEGL VQ-780i (RIEGL LMS GmbH 2019).

Parameter	Specification
Accuracy	20 mm at 250 m scanning range
Precision	20 mm at 250 m scanning range
Laser beam divergence	≤ 0.25 mrad, full width measured at the $1/e^2$ points
Scanning mechanism	Rotating polygon mirror

Table 2: ALS survey parameters.

Instrument	RIEGL VQ-880i
Pulse repetition rate	1000 kHz
Scan frequency	225 lines per second
Flying altitude	650 m a.g.l.
Flying speed	~100 kn, i.e. ~50 m/s
Flight strip spacing	175 m
Scan angle	+/- 30° off-nadir
Swath width	750 m

1.2 UAV-borne laser scanning (ULS)

ULS point clouds were acquired with a RIEGL miniVUX-1UAV sensor mounted on a DJI Matrice 600 Pro using a flight plan which is made up of two grids where the second grid was rotated by 45° to achieve more viewing angles. Each grid consists of a set of parallel and orthogonal flight lines (Fig. 4). The instrument nominal specifications are listed in Tab. 3. More information can be found in the sensor datasheet by the manufacturer RIEGL LMS GmbH (2020c). The ULS campaigns took place in August and September 2019 under leaf-on conditions and repeated in December 2019, and March and April 2020 under leaf-off conditions. For plots KA10 and KA11, only leaf-on data is available. For plot BR04, no ULS data was acquired. The parameters of the ULS acquisitions are listed in Tab. 4. In additional to the twelve forest plots, urban control areas were scanned. They were used to control the positional accuracy of the ALS data (see Section 2.1). All ULS acquisitions were carried out by the 3DGeo Research Group Heidelberg.

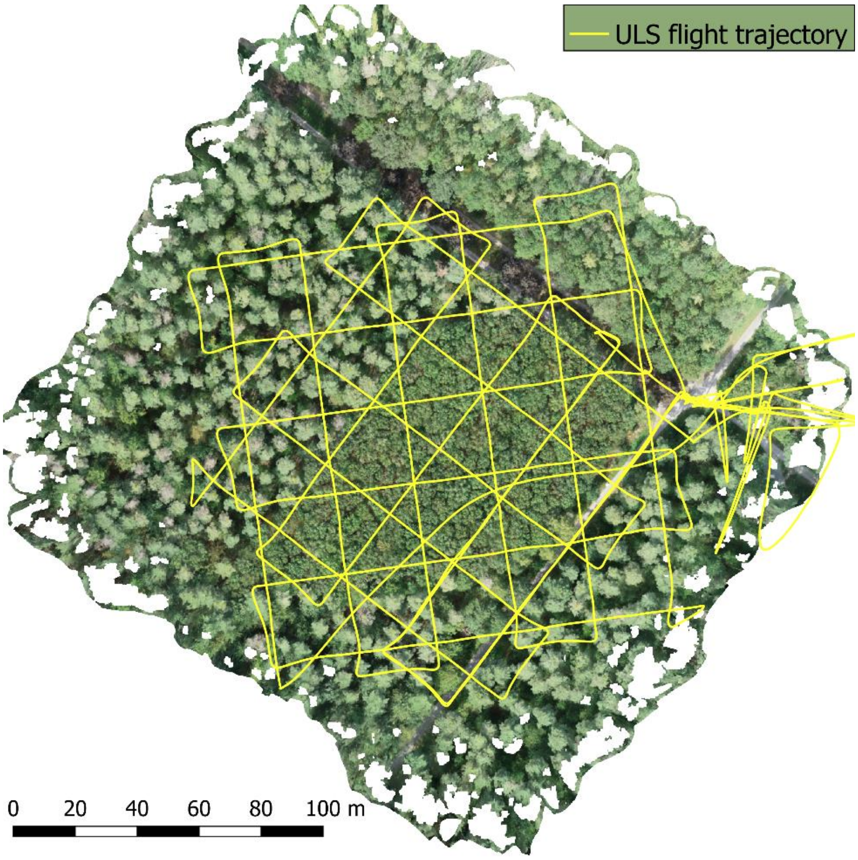

Figure 4: UAV-borne laser scanning (ULS) flight trajectory of Plot KA11. Background imagery: Orthophoto of the plot (own acquisition, available upon reasonable request).

Table 3: Instrument specifications for RIEGL miniVUX-1UAV (RIEGL LMS GmbH 2020c).

Parameter	**Specification**
Accuracy	15 mm at 50 m scanning range
Precision	10 mm at 50 m scanning range
Laser beam divergence	1.6 x 0.5 mrad, full width measured at 50% peak intensity (FWHM)
Scanning mechanism	Rotating mirror

Table 4: ULS survey parameters.

Instrument	RIEGL miniVUX-1UAV
Pulse repetition rate	100 kHz
Scan frequency	BR02 leaf-on, BR03 leaf-on, BR07 leaf-on, BR08 leaf-on, SP02 leaf-on: 100 lines per second All others, incl. all leaf-off acquisitions: 33.4 lines per second
Flying altitude	~60-75 m a.g.l.

Flying speed	3-5 m/s
Flight strip spacing	25-30 m
Scan angle	+/- 90° off-nadir

1.3 Terrestrial laser scanning (TLS)

31 TLS surveys for performed, covering smaller areas within the 12 forest plots. TLS point clouds were captured with a RIEGL VZ-400 mounted on a tripod from five to eight static positions per survey, distributed around a selected group of trees. At some positions, an additional scan was performed using a tilt mount, to capture the top of the trees at close proximity. Instrument specifications are listed in Tab. 5. More information can be found in the sensor datasheet by the manufacturer RIEGL LMS GmbH (2017). All TLS acquisitions were carried out by the 3DGeo Research Group Heidelberg.

Table 5: Instrument specifications for RIEGL VZ-400 (RIEGL LMS GmbH 2017).

Parameter	**Specification**
Accuracy	5 mm at 100 m scanning range
Precision	3 mm at 100 m scanning range
Laser beam divergence	0.3 mrad, full width measured at the $1/e^2$ points
Scanning mechanism	Rotating multi-facet mirror with rotating instrument head

Table 6: TLS survey parameters.

Instrument	RIEGL VZ-400
Pulse repetition rate	300 kHz
Angular step width	
Vertical	0.017° (0.99° for acquisitions on 2019-06-03 and 2019-06-04)
Horizontal	0.017°

1.4 Forest inventory measurements

Forest inventory measurements were recorded in plots BR01, BR03, BR05, KA09, KA10 and KA11 in 2019 by the Institute for Geography and Geoecology (IFGG) Karlsruhe. The measurements comprise species, tree height [m], diameter at breast height (DBH) [m], crown base height [m], crown base height green [m], crown diameter [m] and state (alive/dead). DBH was measured with a DBH measuring tape at 1.3 m above ground. For the crown diameter, the estimated extent of the crown (drip line) was projected onto the ground and its diameter was measured in two orthogonal directions using a Haglöf Vertex-IV hypsometer. The crown diameter was then calculated as the mean of these two distance measurements. Crown base height was also measured with the Vertex-IV hypsometer. We define crown base height as the height of the lowest branch longer than 1 m and crown base height green as the lowest green (living) branch longer than 1 m. Since measuring tree height accurately with a hypsometer is difficult in dense forest stands where high treetops are barely visible, tree height measurements were only recorded for smaller trees (around 10 % of all trees).

2 POINT CLOUD PROCESSING

2.1 Airborne laser scanning (ALS)

ALS data was processed by MILAN Geoservices GmbH. First, the raw signal data was extracted and transformed to point cloud data with RiANALYZE (RIEGL LMS GmbH 2020b). The flight trajectory was estimated using correction data provided by the SAPOS differential GNSS network (http://www.sapos.de). Point cloud data and trajectory data were combined via the synchronized GPS timestamp and assigned geographic coordinates (ETRS89). Point cloud data were then transformed to Cartesian UTM-coordinates.

Strip adjustment was performed by MILAN Geoservice GmbH using an in-house IDL script, which minimizes the distance between planar areas in overlapping flight strips. In the adjustment, systematic effects stemming from the alignment of IMU, GNSS antenna, and laser scanner were estimated (boresight alignment and lever arm), leaving only random errors. Furthermore, absolute altitude accuracy was determined by MILAN Geoservice GmbH using reference recorded by the 3DGeo Research Group using ULS (Section 1.2). The heights of reference points were compared to the median height of ALS points within a radius of 0.3 m. The mean difference (mean standard deviation) was -0.003 m (±0.023 m), 0.006 m (±0.016 m), -0.016 m (±0.026 m) and -0.028 m (±0.029 m) for the four reference tiles in Bretten and -0.016 m (±0.017 m) for the reference tile in Karlsruhe. The alignment between ALS data and ULS control areas was furthermore visually examined on stable surfaces (e.g., rooftops) by the 3DGeo Research Group Heidelberg and documented with screenshots (Appendix B).

Independent quality control of the strip adjustment was carried out by the 3DGeo Research Group Heidelberg using OPALS version 2.3.2 (Pfeifer et al. 2014). Grids of the standard deviation of the interpolated height (sigmaZ) and of the distances between grid points and the center of gravity of data points (excentricity) were computed. For the quantification of strip differences, only last returns on areas with sigmaZ < 0.1 m and excentricity < 0.8 m were included. This way, most areas with high vegetation, where strip differences cannot be quantified reliably, were excluded. Histograms of strip differences are visualized in Appendix A, Fig A1.

The single strips were merged with the information on the flight lines encoded in the field “Point Source ID” and cropped to the extent of the buffered 1 ha forest plots using OPALS version 2.3.2. 100 m buffers were used for plots BR01, BR03, BR05, KA09, KA10 and KA11, 50 m buffers were used for BR02 and BR06 and 20 m buffers were used for BR04, BR07, BR08 and SP02. The final side length of the cropped point cloud extents is encoded in the suffix of the filenames.

2.2. UAV-borne laser scanning (ULS)

ULS data processing was conducted by the 3DGeo Research Group Heidelberg. Post-Processed Kinematics (PKK) GNSS reference was retrieved from SAPOS Baden-Württemberg (www.sapos-bw.de) by creating a Virtual Reference Station at the location of the flight. The trajectory was estimated in ETRS89/UTM 32N using Applanix POSPac MMS 8.3 (Applanix 2018) and imported into RiPROCESS version 1.4.2 (RIEGL LMS GmbH 2020a). In RiPROCESS, data was first converted from the scanner format to polar measurements (SDCImport), then transformed to world coordinates using the trajectory (RiWORLD). A strip adjustment was applied to correct for errors in the trajectory estimation (RiPRECISION). For this adjustment, only points with a scan angle < 45° off-nadir were considered. Subsequently, the point cloud (without the scan angle filter, but only points with reflectance between -22 dB and +10 dB and range between 5 m and 150 m) was exported in LAZ 1.4 format (see Section 3.3) including intensity and waveform (deviation) information in per-strip files. Timestamps correspond to the times in the trajectory. The single strips were merged using LAStools version 200509 (rapidlasso GmbH) with the information on the flight lines encoded in the field “Point Source ID”.

Quality control was carried out using OPALS version 2.3.2 (Pfeifer et al. 2014). Grids of the standard deviation of the interpolated height (sigmaZ) and of the distances between grid points and the center of gravity of data points (excentricity) were computed. For the quantification of strip differences, only last returns on areas with sigmaZ < 0.1 m and excentricity < 0.8 m were included. This way, most areas with high vegetation, where strip differences cannot be quantified reliably, were excluded. Remaining outliers in the histograms, visualized in Appendix A, Fig. A2, come from strip differences quantified on such vegetated areas.

2.3 Terrestrial laser scanning (TLS)

TLS data processing was conducted by the 3DGeo Research Group Heidelberg. TLS point clouds of single scan positions were registered in a common coordinate reference system using tie points (i.e., reflective targets) in the software RiSCAN Pro versions 2.8.0, 2.8.2 and 2.9.0 (RIEGL LMS GmbH 2020d). A fine alignment of single scans was performed with the Multi Station Adjustment (MSA) of RiSCAN, which uses a variant of the iterative closest point (ICP) algorithm based on planar areas in the point clouds. Over all 31 acquisitions, the average of the standard deviation of the distances between the corresponding plane patches used in the final iteration was approximately 0.005 m. The alignment was furthermore assessed visually, by projecting a narrow section of the point cloud onto a plane and coloring the points by their scan position. Manually extracted stem slices were used to assess the horizontal registration errors and cylindrical reflective targets for assessing vertical registration errors. No significant vertical registration errors were present in any of the point clouds. In 26 of the 31 point clouds, negligible horizontal registration errors (< 0.01 m) were observed. In five of the point clouds (TLS_BR03_2019-06-03, TLS_BR02_2019-06-13, TLS_BR01_2019-07-03, TLS_BR05_2019-07-10, TLS_BR08_2019-07-23), shifts of between 0.01 and 0.02 m were observed between the scans from the different positions (Appendix C, Fig. C1).

The full point clouds of each survey were initially georeferenced using RTK GNSS measurements obtained in the field. Because the GNSS measurements taken below the canopy often had low accuracy (< 1 m), the georeferencing accuracy was improved by aligning TLS point clouds to ULS point clouds in a registration workflow using OPALS version 2.3.2. The alignment of TLS point clouds to ULS point clouds was visually assessed and found to be sufficient for the purpose of automatically extracting trees from ULS and ALS point clouds from a single tree TLS point cloud using a nearest neighbor search, as described in the next section.

2.4 Individual tree segmentation

Single trees were automatically segmented from TLS point clouds with CompuTree software (Computree Group 2017) using a Euclidean clustering approach combined with a competitive Dijkstra's algorithm which is part of the SimpleTree plugin (Hackenberg 2017b). Video instructions for the segmentation algorithm are available on YouTube (Hackenberg 2017a). The results were manually corrected by two editors using the interactive segmentation tool of CloudCompare version 2.10.2 (CloudCompare 2019). Furthermore, tree point clouds were extracted manually with CloudCompare from the ULS and ALS point clouds. Because the laser scanning point clouds acquired from the different platforms are spatially overlapping and co-registered, we used tree point clouds extracted from one dataset as a template for tree extraction. This way, we only have to manually delineate each tree from one dataset, preferably the dataset of highest resolution and can extract it from the other point clouds using a nearest neighbor search. We used search radii of either 0.3 m, 0.5 m or 1.0 m based on visual examination of the extracted point clouds with different search radii. The code for the automatic tree point cloud extraction using template point clouds is on GitHub (https://github.com/3dgeo-heidelberg/syssifoss/blob/main/02_tree_extraction/get2clouds_fixed_search_radii.py).

For each tree, we determined the tree position from the point cloud, defined as the position of the tree stem at the ground level. Single tree point clouds were assigned a quality measure from q1 (highest) to q6 (lowest), indicated in the point cloud file name. Lower quality was assigned if there were obvious segmentation errors, if significant parts of the tree were occluded in the point cloud, if the scan position/flight strip alignment was poor or if there were wind effects (TLS only). Note, that this is based on subjective assessment of different editors and may be biased. In total, point clouds of 1491 trees are provided. While TLS single tree point clouds do not contain any ground points, ULS and ALS tree point clouds typically also contain points from the ground.

For 249 trees, point clouds from all platforms (ALS, ULS, TLS) are available. Fig. 5 shows a Beech tree acquired from the different platforms. For 1168 trees, both leaf-off and leaf-on ULS point clouds are available (Fig. 5).

From the individual tree point clouds, we derived tree height, crown base height, crown projection area (using the convex and the concave hull of crown points), crown diameter and stem diameter at breast height (only from TLS point clouds). All code is on GitHub (https://github.com/3dgeo-heidelberg/syssifoss/tree/main/03_metric_computation).

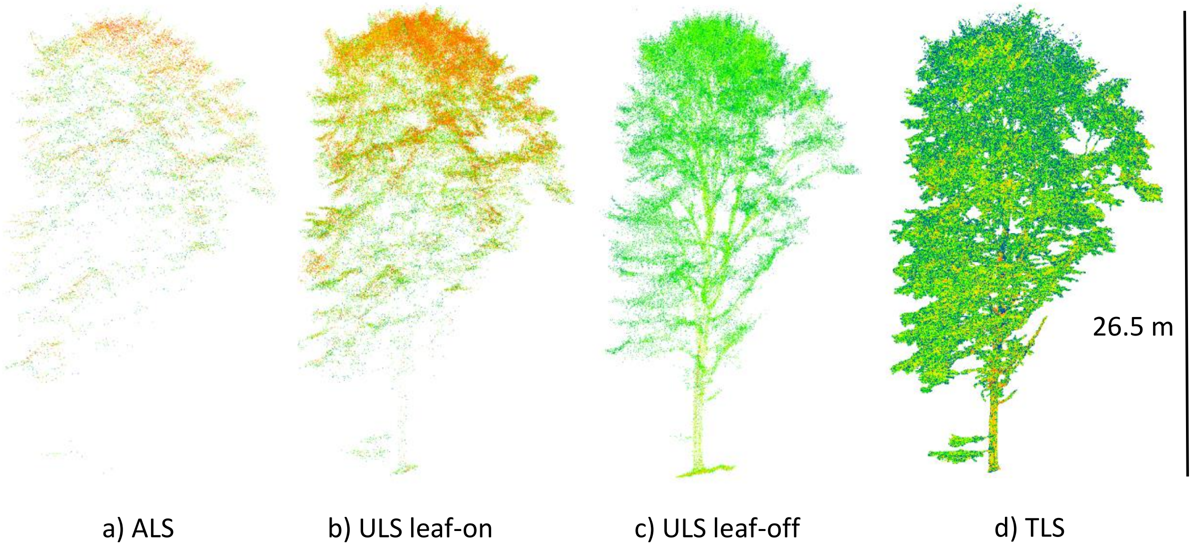

Figure 5: Point clouds of a European Beech (*Fagus sylvatica*, Tree-ID: FagSyl_BR05_P3T5), coloured by reflectance. a) ALS point cloud acquired under leaf-on conditions, b) ULS point cloud acquired under leaf-on conditions, c) ULS point cloud acquired under leaf-off condition, d) TLS point cloud acquired under leaf-on conditions. ALS = Airborne laser scanning, ULS = UAV-borne laser scanning, TLS = Terrestrial laser scanning.

3 Data Format and File Naming

3.1 File naming

Different information is encoded in the file names:

PLATFORM – acquisition platform [ALS, ULS, TLS]
CANOPYCONDITION – Canopy condition, i.e., [on, off] for leaf-on and leaf off, respectively
PLOTID – Plot identifier
SPECIESID – Species ID, consisting of the first three letters of both genus and species epithet (see Appendix D, Tab. D1)
TREEID -
YYYY – Year
MM – Month
DD – Day
QUALITY – quality of the point cloud from q1 (highest) to q6 (lowest) [q1, q2, q3, q4, q5, q6]
SUFFIX – For TLS campaigns, A, B, C, etc. are used as suffix to distinguish multiple surveys that were performed on the same day, i.e., cannot be distinguished by date alone. For ALS surveys, the suffix includes the side length of the square point cloud extract.

a) Point clouds of forest plots:

PLATFORM-CANOPYCONDITION_PLOTID_YYYY-MM-DD(_SUFFIX).laz
e.g. `ULS-on_BR01_2019-09-12.laz`

b) Trajectories (for ALS and ULS):

PLATFORM-CANOPYCONDITION_PLOTID_YYYY-MM-DD_trajectory.txt
e.g. `ULS-on_BR01_2019-09-12_trajectory.txt`

c) Scan positions (TLS):

PLATFORM-CANOPYCONDITION_PLOTID_YYYY-MM-DD(_SUFFIX)_scan_positions.txt
e.g. `TLS-on_BR01_2019-07-03_scan_positions.txt`

d) Single tree point clouds

SPECIESID_PLOTID_TREEID_YYYY-MM-DD_QUALITY_PLATFORM-CANOPYCONDITION.laz
e.g. `AceCam_BR01_P6T5_2019-07-05_q3_ALS-on.laz`

e) Single tree properties

SPECIESID_PLOTID_TREEID.geojson (containing all tree properties, measurements, and data records)
SPECIESID_PLOTID_TREEID_general.txt (containing species and position)
SPECIESID_PLOTID_TREEID_metrics.txt (containing tree metrics from different sources).
e.g. `AceCam_BR01_P6T5.geojson`
`AceCam_BR01_P6T5_general.txt`
`AceCam_BR01_P6T5_metrics.txt`

3.2 Coordinate reference system

All coordinates (point clouds, trajectories, scan positions) are given in ETRS89 / UTM Zone 32N (EPSG: 25832). Elevations are given above the GRS80 ellipsoid.

The tree positions are additionally provided in corresponding geographic coordinates (latitude and longitude) in WGS84 (EPSG:4326).

3.3 File formats

Point clouds in LAZ 1.4 format (ASPRS 2019) with the following extra bytes:

- Amplitude [dB]
- Reflectance [dB]
- Deviation, according to the definition by RIEGL LMS GmbH

Points from different flight strips or scan positions can be distinguished by the field “Point Source ID” in the LAZ files.

ALS and ULS flight trajectories in tab-separated ASCII files (txt) with the following attributes in columns:

- Easting [m] (EPSG:25832)
- Northing [m] (EPSG:25832)
- Height [m] (EPSG:25832)
- Time [s]
- Roll [deg]
- Pitch [deg]
- Yaw [deg]

TLS scan positions in tab-separated ASCII files (txt) with the following attributes in columns:

- Index
- Name
- Easting [m] (EPSG:25832)
- Northing [m] (EPSG:25832)
- Height [m] (EPSG:25832)

The Index corresponds to the Point Source ID in the LAZ point cloud file.

Tree properties in tab-separated ASCII files (txt) with the following attributes in columns:

a) *_general.txt:
   - Species (scientific name)
   - Latitude (EPSG:4326)
   - Longitude (EPSG:4326)
   - Easting [m] (EPSG:25832)
   - Northing [m] (EPSG:25832)
   - Height [m] (Ellipsoidal height, GRS80)

b) *_metrics.txt:
   - Source (i.e., FI, ALS, ULS, TLS)
   - Date (YYYY-MM-DD)
   - Canopy condition (i.e., leaf-on, leaf-off)
   - Tree height [m]
   - Crown base height [m]
   - Crown projection area, convex hull [m^2]
   - Crown projection area, concave hull [m^2]
   - Crown diameter [m]
   - Diameter at breast height [cm]

- Crown base height, green [m]
- State (i.e., dead, alive)

Tree properties in GeoJSON files

> We provide a GeoJSON file for each tree, which can be used as a file-based database of individual objects (point clouds, metrics) and their relation. Appendix E shows a template of such a GeoJSON file. In each GeoJSON, the "properties" contain the tree ID, the species, measurements, and data. The "geometry" contains the tree position as point coordinate in WGS84 coordinate reference system (EPSG:4326), as per the GeoJSON standard. Tree position is also given in the "measurements" in ETRS 89/ UTM Zone 32 N coordinates (EPSG:25832). The list of measurements further contains all tree metrics, either from the forest inventory (FI) or derived from the point cloud data. For measurements from each source (FI, ALS, ULS or TLS), including the acquisition data and canopy condition. The "data" key contains a list of available point cloud data, where the mode (i.e., acquisition platform), acquisition date, sensor, canopy condition, coordinate reference system, point count, filename and quality are provided for each entry.

4 Code Availability

Python code used for processing the point cloud data and computing the parameters is provided on GitHub under GNU General Public License v3.0: https://github.com/3dgeo-heidelberg/syssifoss.

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APPENDIX

Appendix A: Histograms of strip differences

OPALS workflow: Navigate into the directory with the single strips as LAS/LAZ files or imported ODM files. To import and filter for only last returns:

```
OpalsImport -inf <infile.las> -outf <outfile.las> -filter "Generic[EchoNumber == NrOfEchos]"
```

Then run:

```
opalsQuality -inf *.las -o resultsQuality -t tempdir -subScripts qltStripDiff
```

or

```
opalsQuality -inf *.odm -o resultsQuality -t tempdir -subScripts qltStripDiff
```

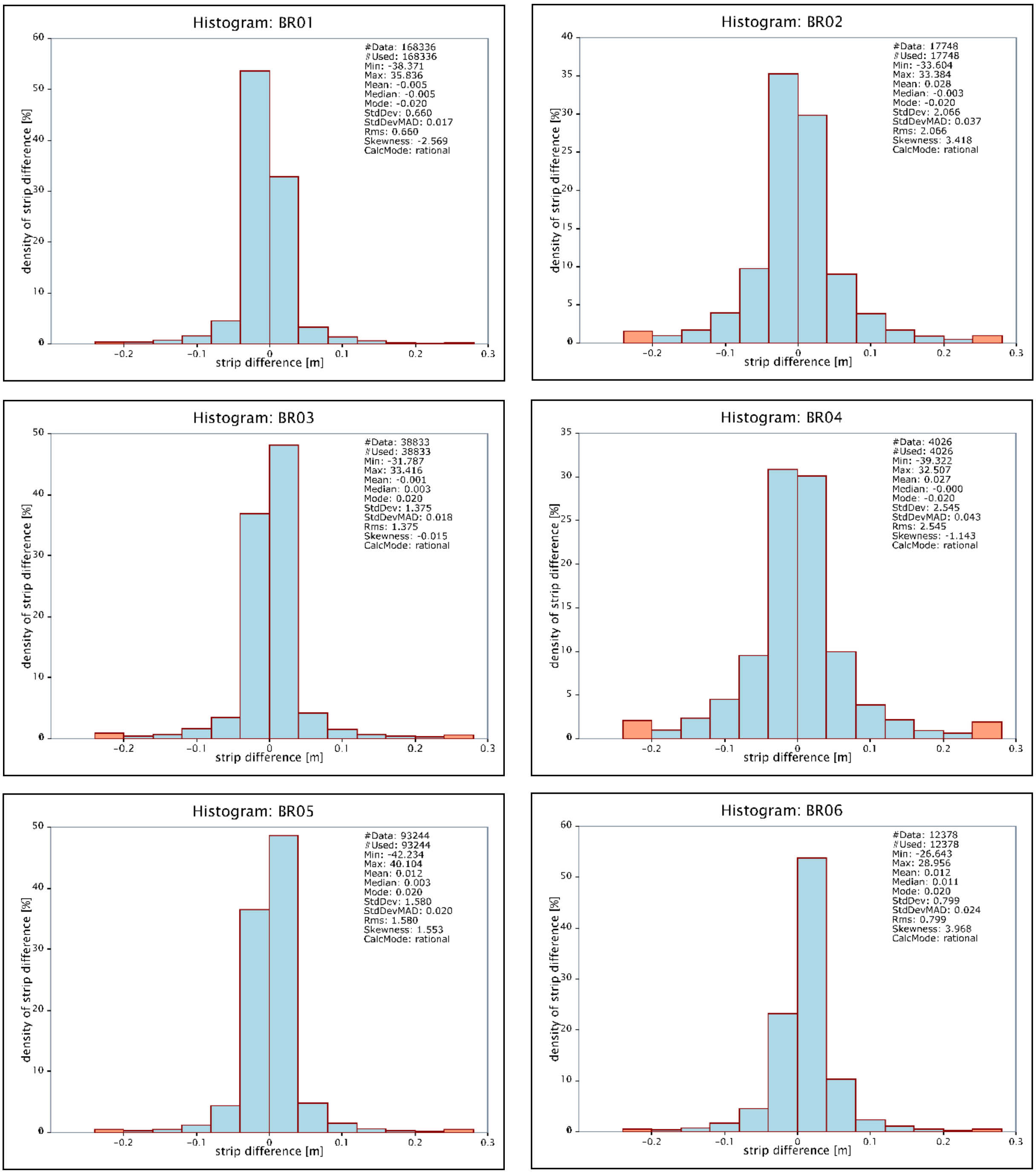


Figure A1: ALS strip differences quantified in each forest plot using only last returns on areas with no high vegetation (*cont.*)

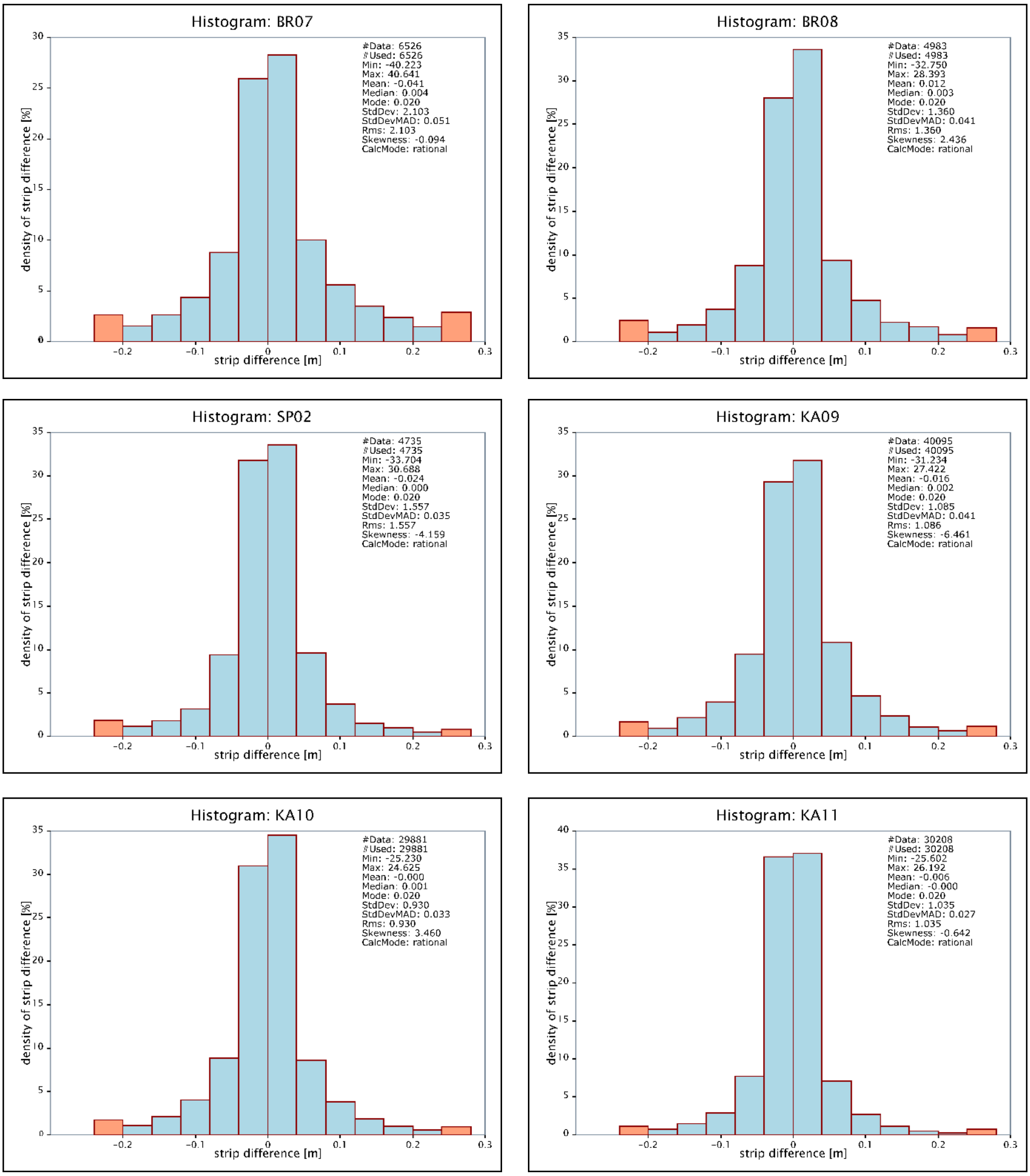


Figure A1: Histograms of ALS strip differences quantified in each forest plot using only last returns on areas with no high vegetation.

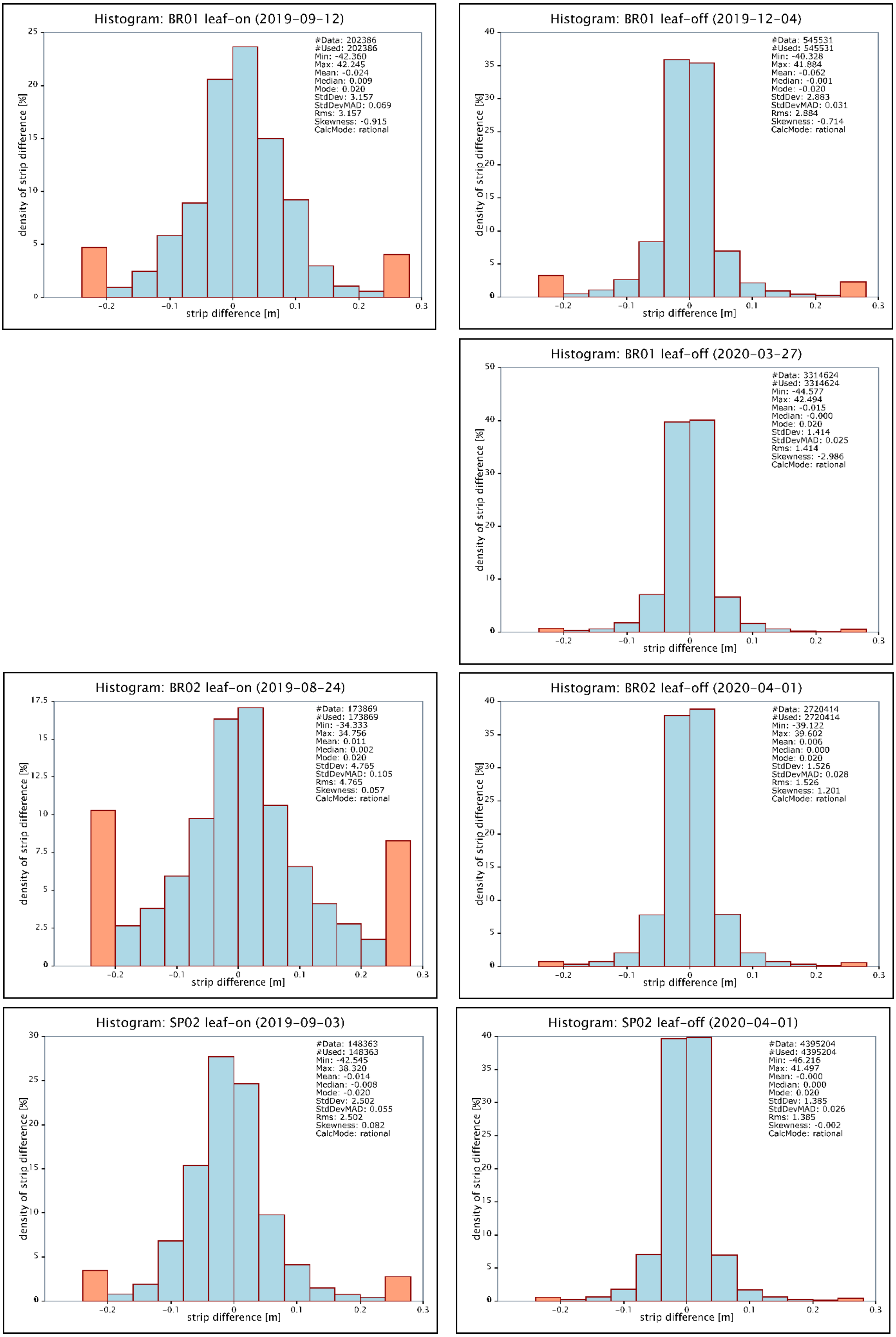


Figure A2: Histogram of ULS strip differences quantified for each acquisition using only last returns on areas with no high vegetation. Left column: leaf-on, right column: leaf-off (*cont.*)

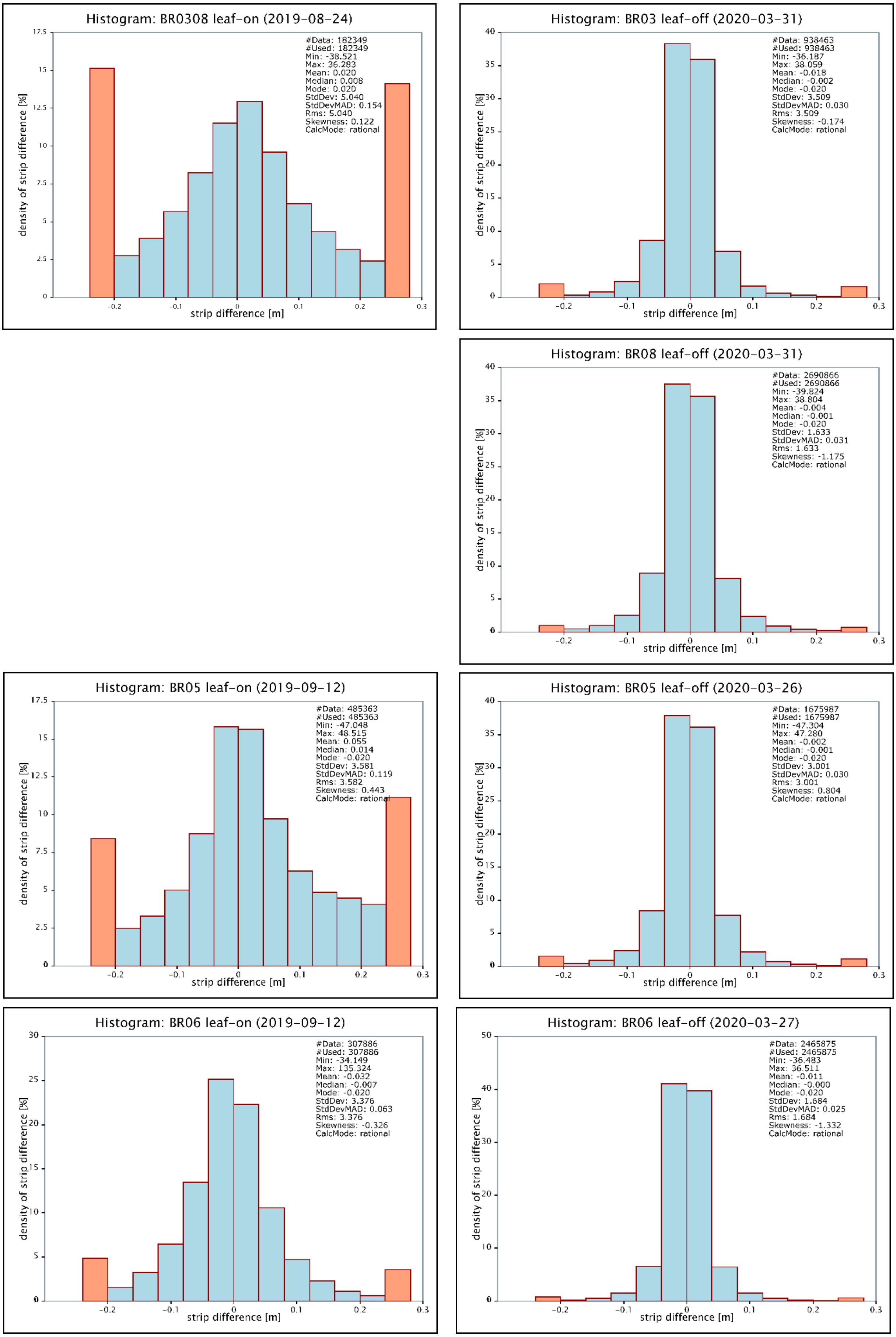


Figure A2: Histogram of ULS strip differences quantified for each acquisition using only last returns on areas with no high vegetation. Left column: leaf-on, right column: leaf-off (*cont.*)

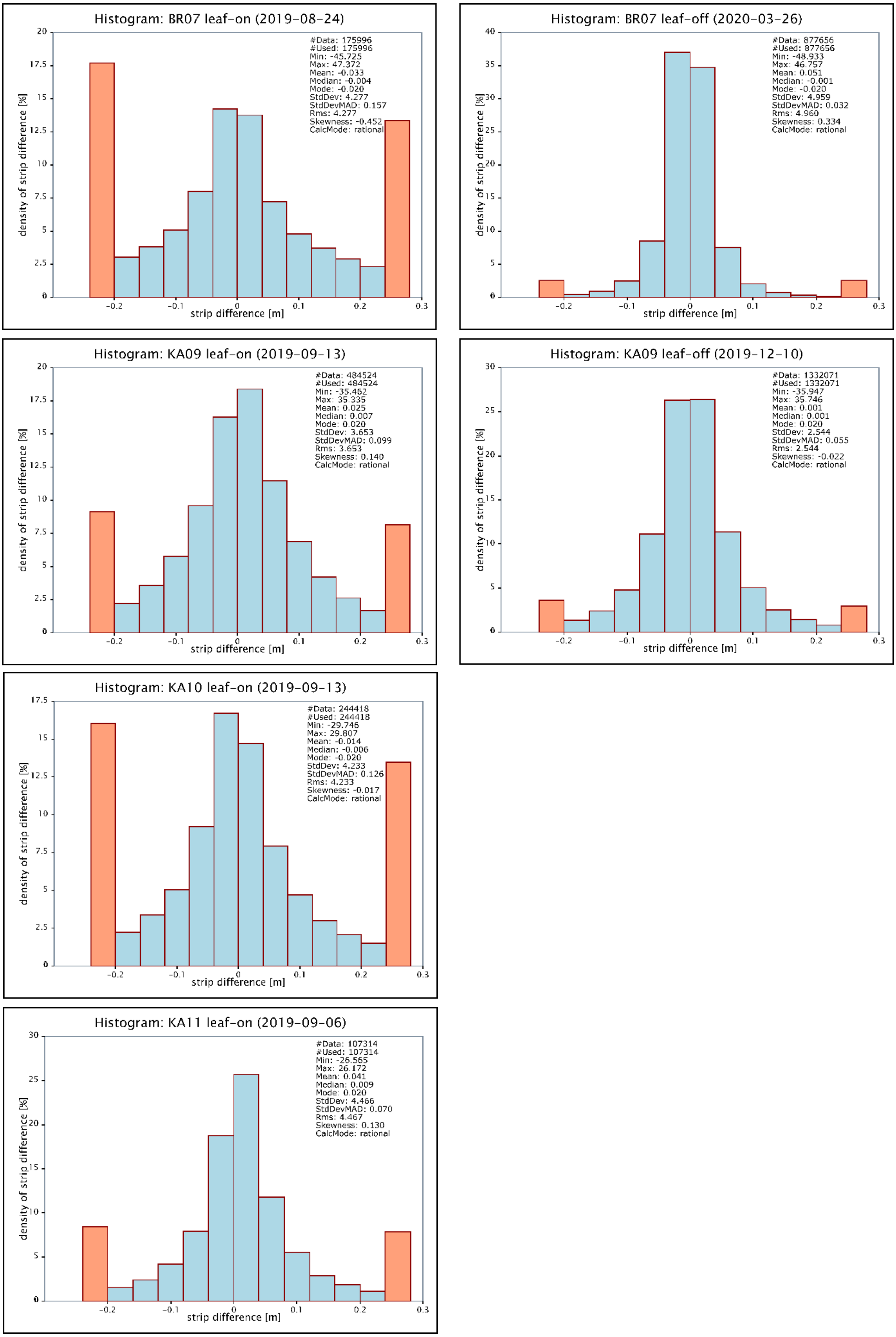
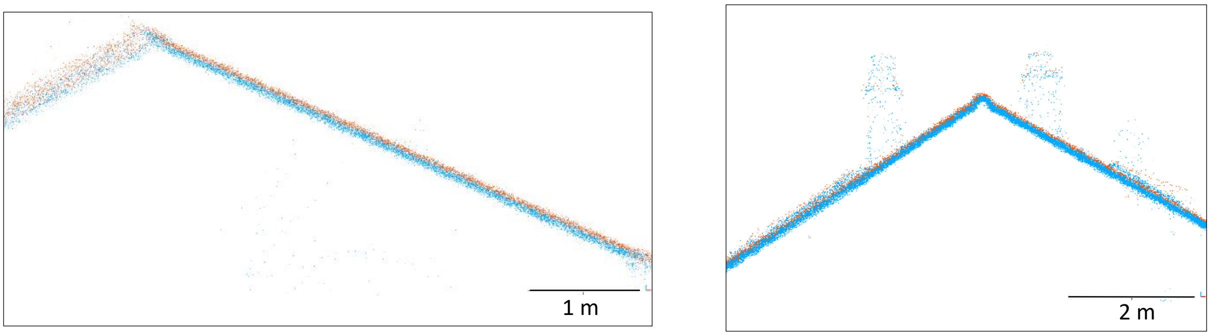
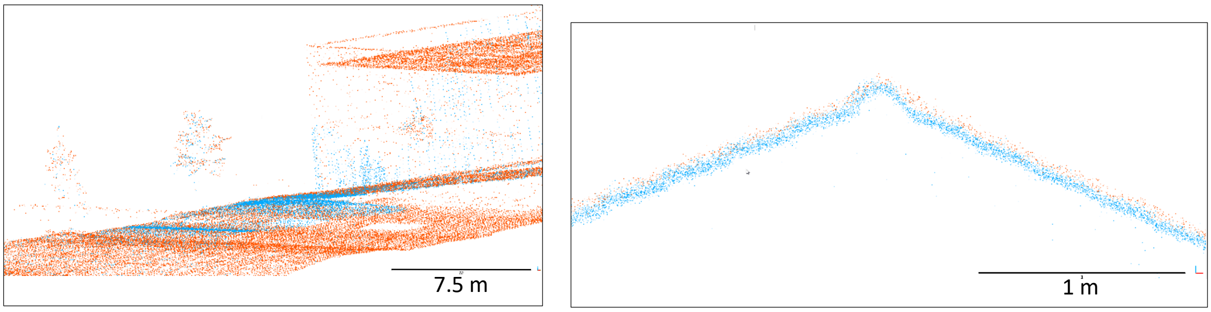


Figure A2: Histogram of ULS strip differences quantified for each acquisition using only last returns on areas with no high vegetation. Left column: leaf-on, right column: leaf-off.

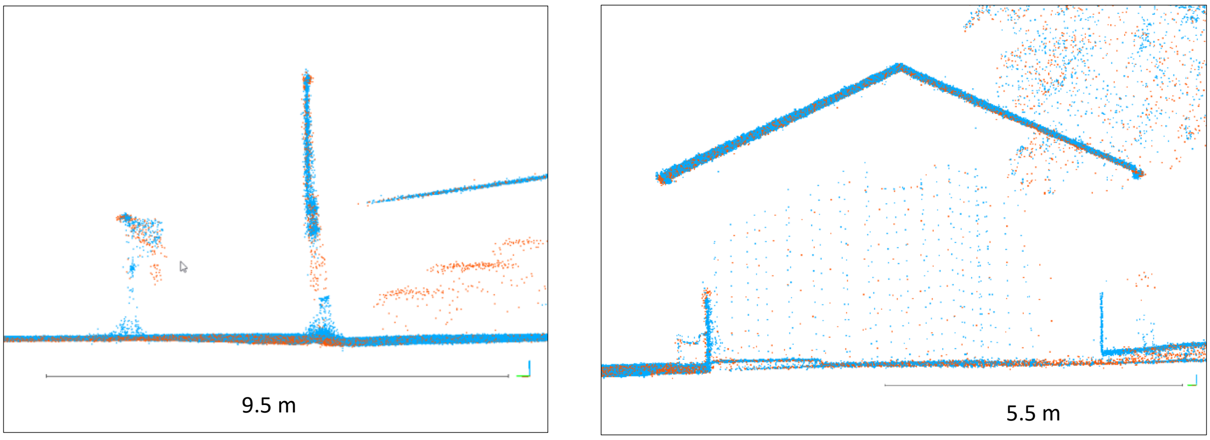
Appendix B: Alignment between ALS and ULS in the control areas



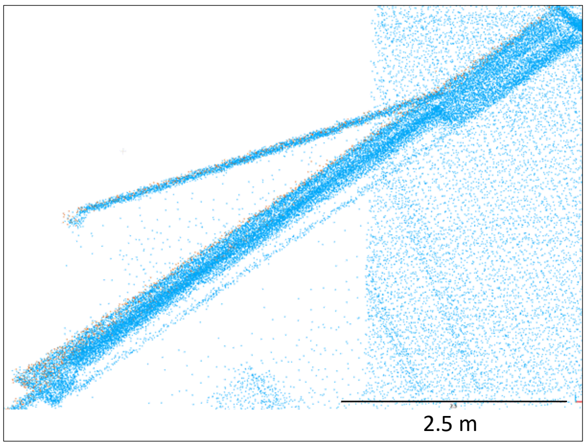
Karlsruhe, control area 1



Karlsruhe, control area 2

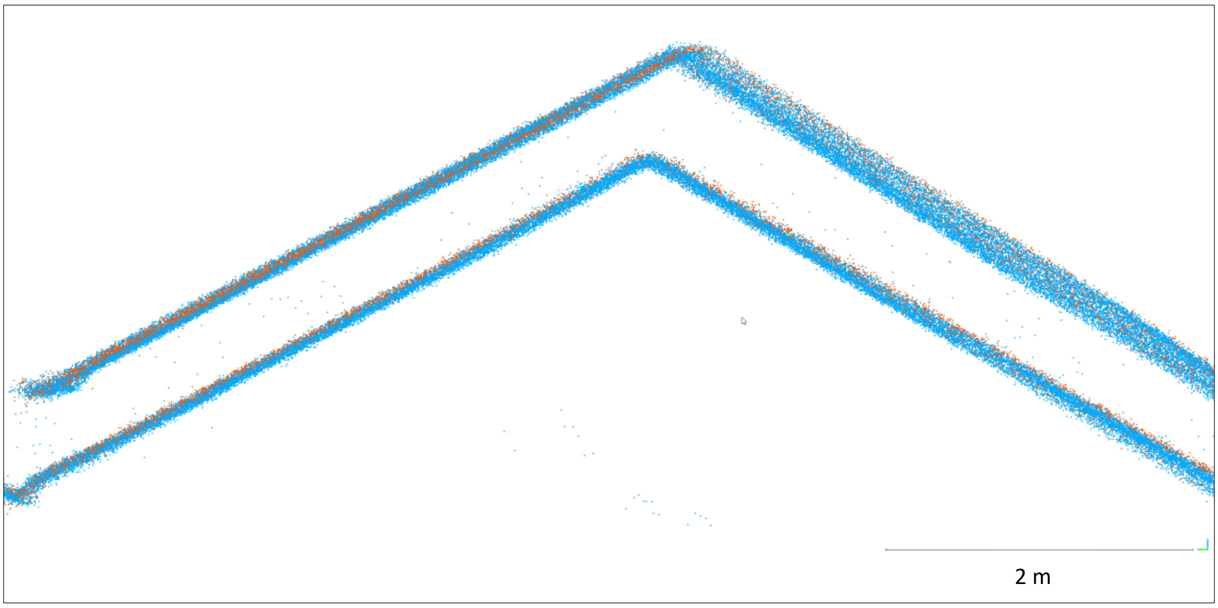


Karlsruhe, control area 3

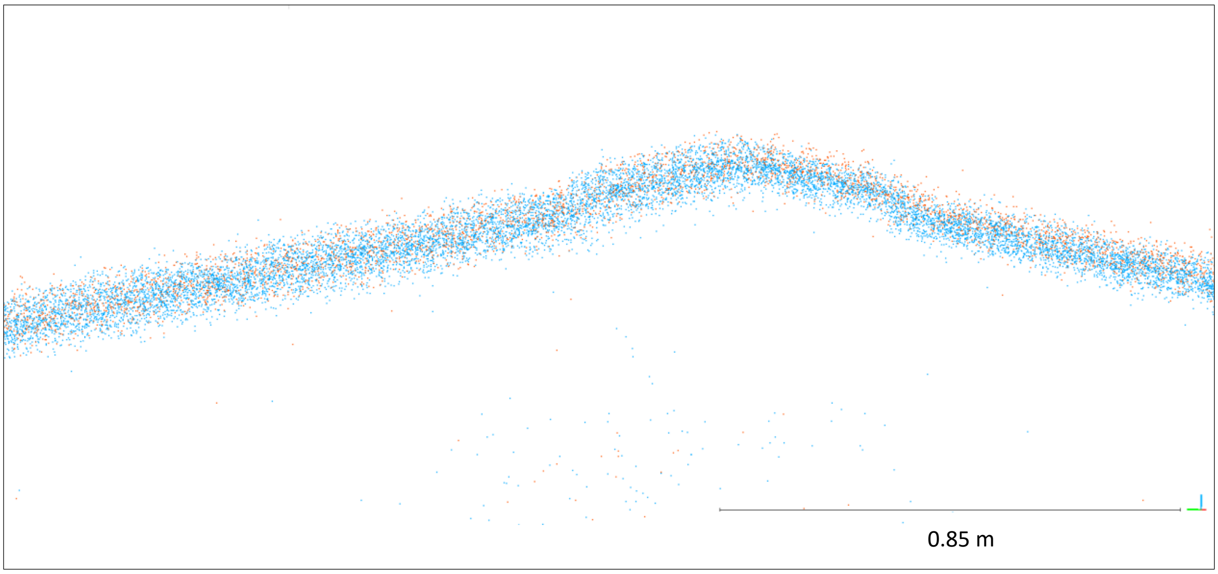


Karlsruhe, control area 4

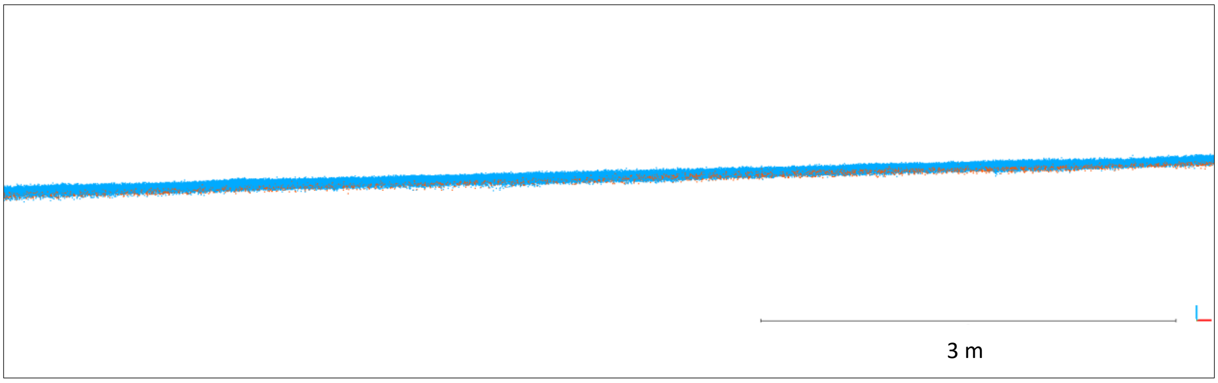
Figure B1: Alignment between ALS points (red) and ULS points (blue) on stable surfaces in the control areas in Karlsruhe.



Bretten, control area 1



Bretten, control area 2



Bretten, control area 3

Figure B2: Alignment between ALS points (red) and ULS points (blue) on stable surfaces in the control areas in Bretten.

Appendix C: Assessment of horizontal and vertical registration errors

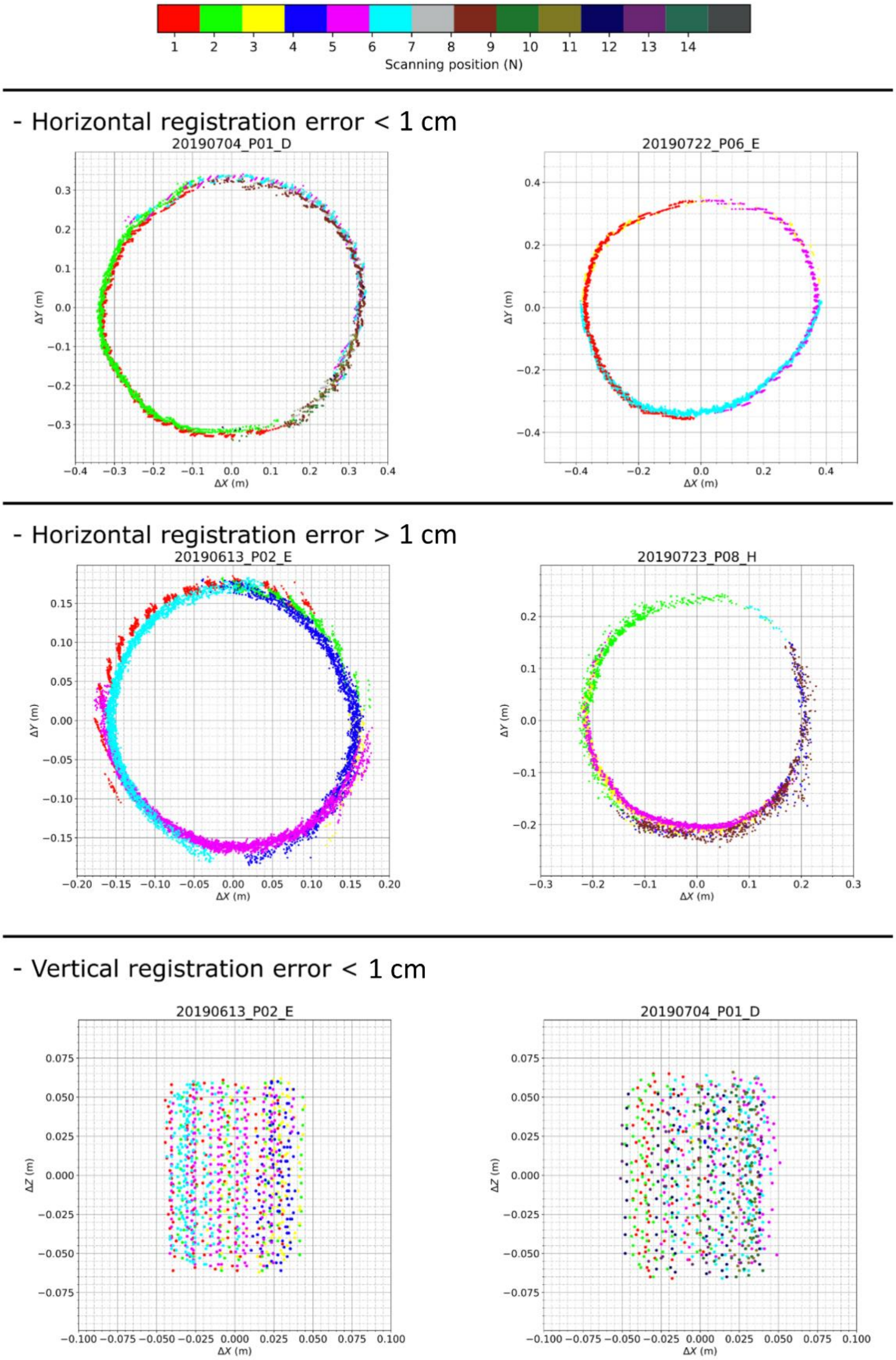


Figure C1: Examples of stem slices for horizontal registration assessment with registration errors < 0.1 cm and registration errors between 1 cm and 2 cm and cylindrical reflective targets with registration errors < 1 cm.

Appendix D: List of species

Table D1: Species-ID, scientific name, and common name of all tree species in the database.

Species-ID	Species name	Common name
AbiAlb	*Abies alba*	Silver fir
AceCam	*Acer campestre*	Field maple
AcePse	*Acer pseudoplatanus*	Sycamore
BetPen	*Betula pendula*	Silver birch
CarBet	*Carpinus betulus*	European hornbeam
FagSyl	*Fagus sylvatica*	European beech
FraExc	*Fraxinus excelsior*	European ash
JugReg	*Juglans regia*	Common walnut
LarDec	*Larix decidua*	European larch
PicAbi	*Picea abies*	Norway spruce
PinSyl	*Pinus sylvestris*	Scots pine
PruAvi	*Prunus avium*	Wild cherry
PruSer	*Prunus serotina*	Black cherry
PseMen	*Pseudotsuga menziesii*	Douglas fir
QuePet	*Quercus petraea*	Sessile oak
QueRob	*Quercus robur*	Common oak
QueRub	*Quercus rubra*	Northern red oak
RobPse	*Robinia pseudoacacia*	Black locust
SalCap	*Salix caprea*	Goat willow
SorTor	*Sorbus torminalis*	Wild service tree
TilSpe	*Tilia spec.*	Linden
TsuHet	*Tsuga heterophylla*	Western hemlock

Appendix E: Structure of the GeoJSONs

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{
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    "properties": {
        "id": "SPECIESID_PLOTID_TREEID",
        "species": Species,
        "measurements": [
            {
                "source": Source,
                "date": "YYYY-MM-DD",
                "DBH_cm":"…",
                "crown_base_height_m": "…",
                "crown_base_height_green_m": "…",
                "height_m": "…",
                "mean_crown_diameter_m": "…",
                "crown_projection_area_convex_m2": "…",
                "crown_projection_area_concave_m2": "…",
                "state": "…"
            },
            {
                …
            },
        …
            {
                "crs": "epsg:25832",
                "position_xyz": [
                    Easting,
                    Northing,
                    Height
                ]
            }
        ],
        "data": [
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                "type": "pointcloud",
                "mode": "PLATFORMID",
                "date": "YYY-MM-DD",
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                "sensor": "…",
                "point_count": …,
                "crs": "epsg:XXXX",
                "file": "SPECIESID_PLOTID_TREEID_YYYY-MM-DD_QUALITY_PLATFORM-
                                                  CANOPYCONDITION.laz ",
                "quality": "…"
            },
        …
            {
                …
            }
        ]
    },
    "geometry": {
        "type": "Point",
        "coordinates": [
            Latitude,
            Longitude,
            Height
        ]
    }
}
```