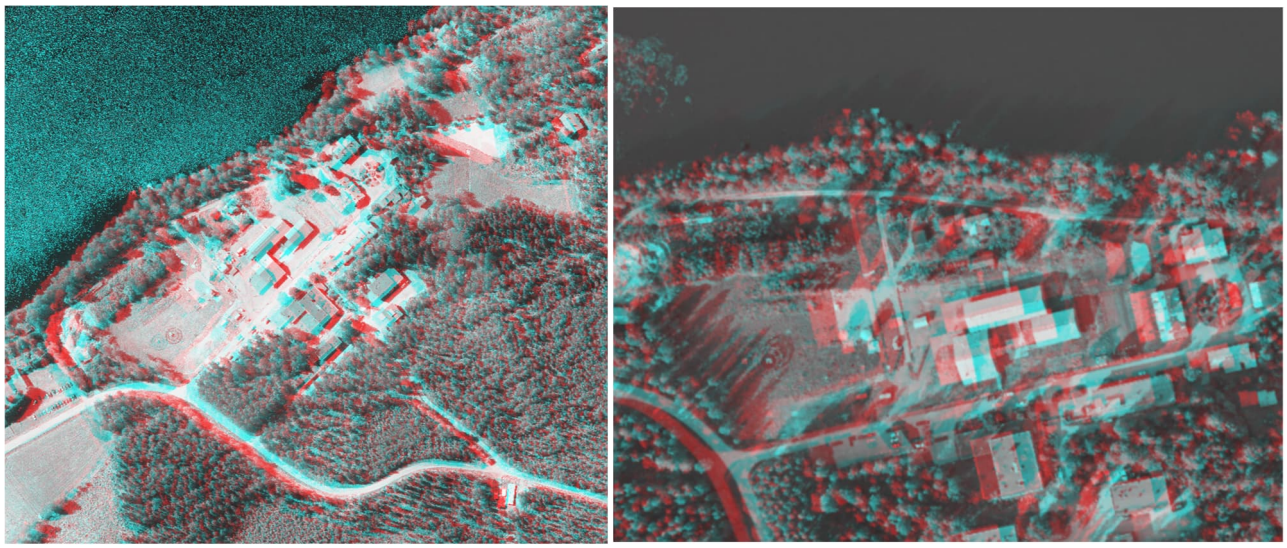
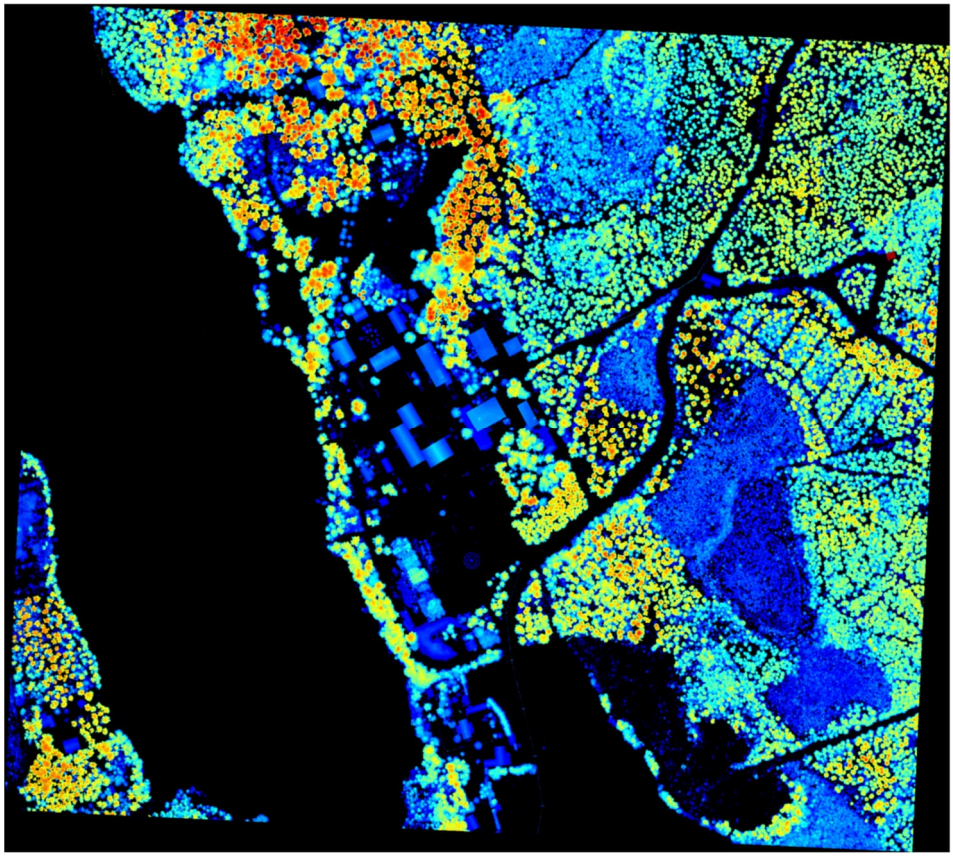
Hyytiälä aerial photographs and LiDAR 2023
Quality control September 25 - October 16, 2023
Ilkka Korpela



Anaglyph stereo pairs June 15, August 18



LiDAR, August 18

Summary

This document reports on the quality control of the Hyytiälä imaging and LiDAR campaigns, June 15 and August 18, 2023. The objective was to verify that the data will qualify for research – that the geometry and radiometry are accurate. The LiDAR data was also contrasted with the two earlier acquisitions from 2018 and 2020, which were acquired by Terratec, now a part of Field company.

The data disk was fetched from Teollisuuskatu 33 on Monday Sep 18. There were 274 GBytes of data. Processing and Q-control started on Sept 25 and took a total of 12 full workdays.

There are two sets of aerial images

- 3km images (n=51) from June 15 were acquired with a four-band photogrammetric sensor.
- 1 km images (n=86) from August 18 were acquired during the LIDAR campaign with an RGB sensor.

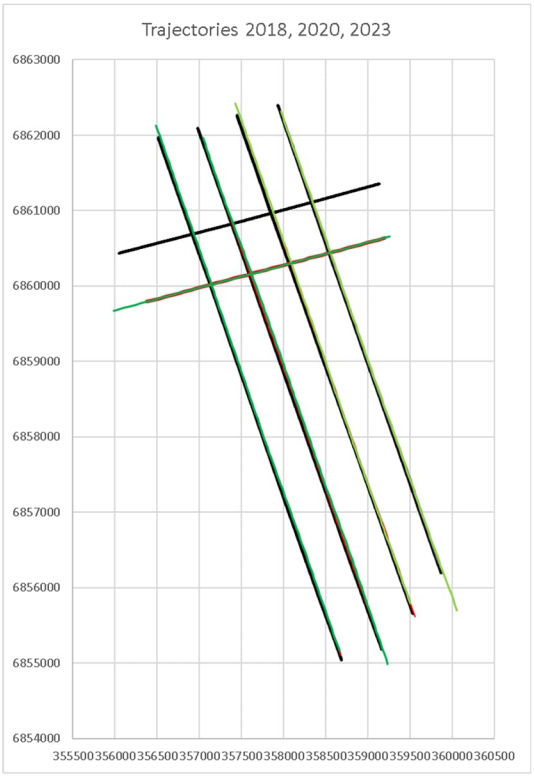
The accuracy of the exterior and interior orientation of the images was examined and the exterior orientation data that had been established in the ETRS-TM35FIN/N2000 coordinate system was also calculated to the old KKJ2/N60 coordinate system to match the time series (1946-). Lens-error free versions of the 1 km images were computed to make their later use easier. All 3-km image versions were tested (Lvl-2, Lvl-3). The 3-km Lvl3 CIR-images were asked to be recalculated (received Oct 10) had wrongly interpreted color model. The exact exposure times, weather data and solar angles were solved for the images. The exterior orientation of the images relied entirely on GNSS/IMU data collected during the flights. Points with known ground coordinates were available for the evaluation of the orientation.

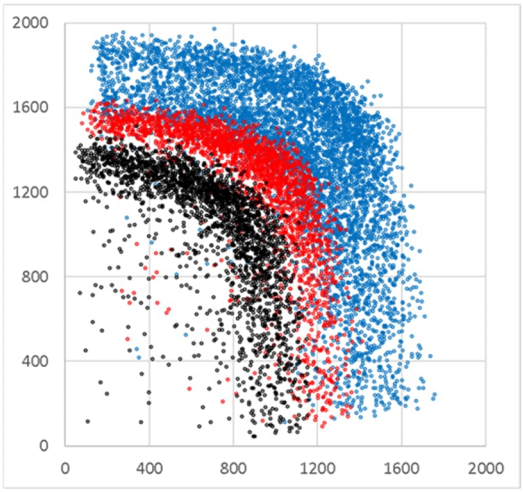
Apart from the minor post-processing fault of the CIR (Lvl3) 3-km images the data was deemed of good quality.

The XY-accuracy of the aerial images in forward ray-intersection was better than 20 cm. The Z values have a slight offset, 10-30 cm such that the intersected points "float" above the true coordinates. This, however, was not systematically examined in all parts of the imaged area. The 1 km images do not match between strips as accurately as they do within an image strip (between successive image pairs and triplets). This is probably due to remnant lens calibration errors, which are in the order of 1 pixel (8 cm), or a misinterpretation of the interior geometry of the undistorted images made by IK.

The LiDAR data was captured on August 18. This campaign repeats those of 2020 and 2018. The coordinates of the LiDAR points were transformed from ETRS-TM35FIN/N2000 to KKJ2/N60 and data were split to per-hectare files. These files have what is called comprehensive format, which is used throughout the Hyytiälä LiDAR time-series (2004-2023). In it, all echoes belonging to a pulse form a varying-length pulse record, and the 3D LiDAR position is also included in the record. Lastools software license was bought to enable the linking of the trajectory data with the time-stamped points. The geometry and radiometric analyses of the used Riegl 1560 sensor included that of two scanners (#1 and #2) that are operated in parallel. The geometry of the LiDAR data was accurate, offsets larger than 20 cm could not be observed. LiDAR intensity data of 2018, 2020 and 2023 campaigns do not match. They are in logarithmic scale and the same targets on the ground display quite different values in each campaign. Anyone using the intensity data needs to calibrate intensity values between acquisitions. Also, the 2018 data has slightly fewer echoes per pulse transmitted. Anyone comparing 2018 with 2020 and 2023 should investigate this topic.

Unfortunately, though, one of the five LiDAR strips was not repeated using the same trajectory in 2023.





The perpendicular LIDAR flight line #5 in 2023 was flown about 800 m off its expected path (left). LiDAR intensity data have considerable offsets between campaigns and is transformed to logarithmic (dB) scale, black =2018, red =2020, blue = 2023.

In all, the campaigns had succeeded well except for the failure to repeat the exact path of strip #5 in LiDAR.

Aerial images

3-km RGBN-PAN imaging June 15, 2023

These images were taken with Vexcel Eagle camera from 3.5 km, using two parallel flight lines. The exposures repeat the 2020 imaging, using the same camera and flight lines. There are 51 image exposures in total. Ground sampling distance is 13 cm for the PAN image (17004 by 26460 pixels) and 40 cm for the multispectral sensors (5668 by 8820 pixels).

Time was 11:35-11:44 GMT (early afternoon, 13:35-13:44 SMEAR II time). The exposure times were 4 milliseconds with a F-stop at 5.6. PH-SVZ flew from Parikkala to Hyytiälä in 35 minutes to complete the campaign. Imaging was carried out by a Dutch company (thus PH). Solar elevation was high, 49.54→49.16 degrees, and solar azimuth was 206.2→208.6 degrees. It is rare to have afternoon images as morning acquisitions prevail.

Vexcel Eagle has four cameras for producing a high-resolution virtual PAN-image and four cameras for the RED, GRN, BLU and NIR bands, that produce images with 16-bit pixels that are 3 times larger (on the ground) compared to the PAN-image. PAN-sharpening was used by the data provider to create so-called Lvl3 (8-bit) color-infrared (CIR) images as well as true-color RGB images that combine the geometry and radiometry of the PAN image with those of the RED, GRN, BLU and NIR images. The PAN-sharpened images as well as the original images (Lvl2) were a part of the delivered material as requested.

According to the flight documentation, the aerial triangulation was based on GNSS-observations made during the flight, and there was no ground control (as agreed). This QC tested the geometric match of the new images against old images, which have had ground control points. Slight vertical offset (20-40 cm) was noted (reconstructed 3D points “float” above the scene).

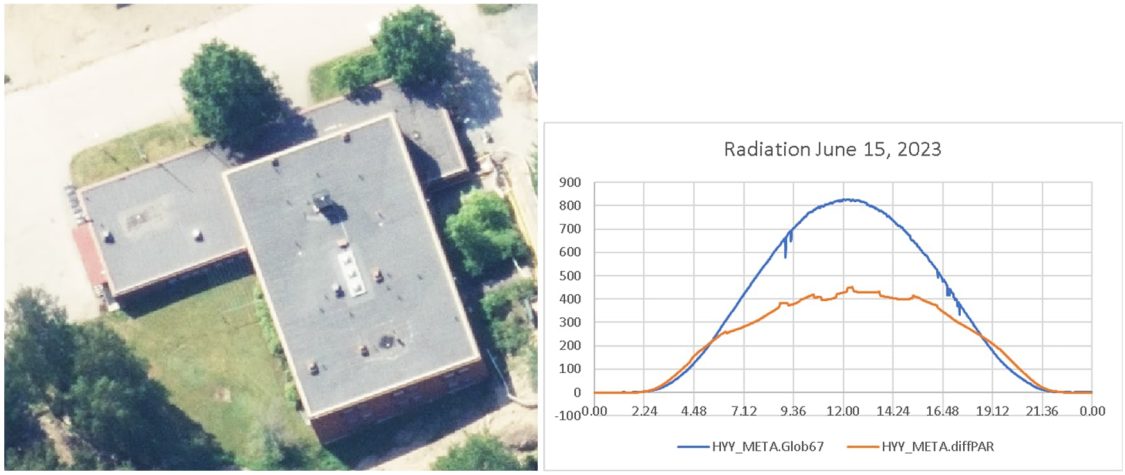


Figure 1. PAN-sharpened RGB image version with 13 cm pixels. Perfect clear-sky conditions (GMT+2h) prevailed on June 15, 2023.

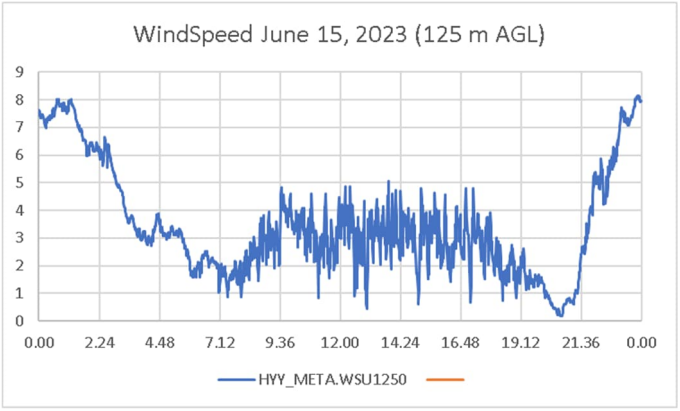


Figure 2. Wind speed June 15, 2023. Imaging took place at 13:35-13:50 SMEAR II time (mild winds at 2-3 m/s, even at 125 meters above the ground).

The camera calibration certificate was dated April 4, 2022. The interior orientation for the (Lvl3) CIR images is simple because the principal point of autocollimation is at (0.000,0.000), in pixel (8502, 13230). Focal length of the PAN-sharpened images is 0.1005 m. All lens distortions are corrected in the Lvl3 and Lvl2 images.

The solution of aerial triangulation by the data provider included rotations omega, phi and kappa and the coordinates of the projection center (UTM35 + N2000). They are found in the AT folder and listed below in Table 1. A conversion to KKJ2/N60 was done by mapping a grid of points in UTM35/N2000 to the images, and the coordinates of these points were converted to KKJ2/N60 (coordinate system of the Hyytiälä time-series) and used as ground control points in block triangulation (Ilkka Korpela's VB6/C++ software). The solution is listed below in Table 2.

There was a slight vertical offset such that the 2023 images are giving heights that are 30-40 cm above the expected (in forward ray intersection). The epipolar geometry works perfectly within an image line and it works also between images of the adjacent overlapping strips. The reason for the offset is the lack of ground control points, as 30 cm is 0.01% of the flying height at 3500 m. An error of 0.01 mm in the focal length of 100.5 mm (100.49…100.51) can cause the observed error, and/or an offset in the GNSS-antenna settings. The offset was not studied systematically across the imaged area, which needs to be done if highly accurate data are needed.

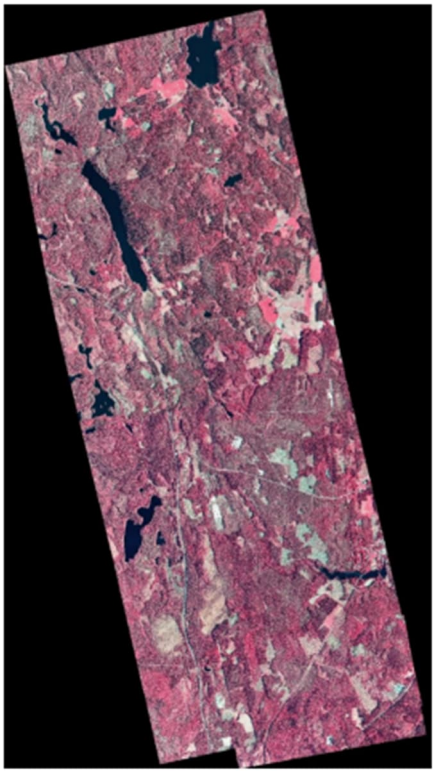


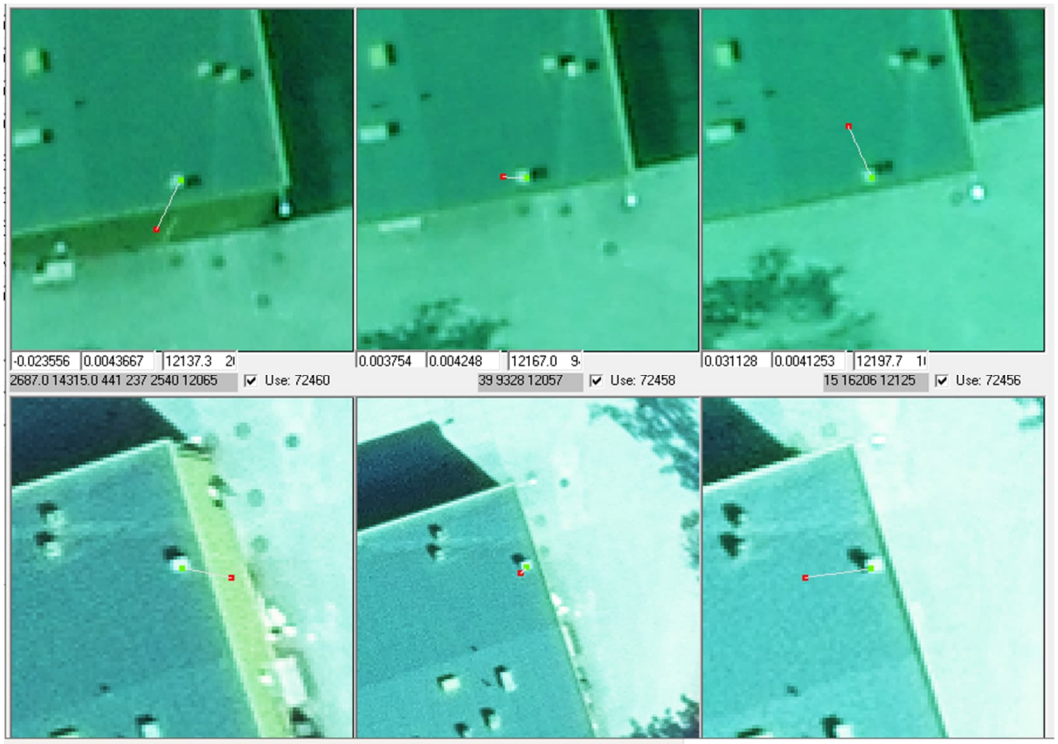
Table1. The exterior orientation in UTM35 / N2000 for the 51 images (in radians and meters):

Image	Omega	Phi	Kappa	X0	Y0	Z0
72426	0.0039711	0.0022118	1.7497853	360046.433	6851843.753	3498.158
72427	0.0089883	0.0047027	1.7505193	359964.439	6852289.328	3498.255
72428	0.0100066	0.0050297	1.7500207	359886.710	6852734.417	3496.350
72429	0.0085879	0.0055163	1.7494540	359811.636	6853180.217	3493.908
72430	0.0082424	0.0058757	1.7495431	359732.556	6853626.007	3493.935
72431	0.0067700	0.0040003	1.7494837	359649.276	6854070.297	3495.443
72432	0.0043330	0.0003541	1.7498567	359564.584	6854515.112	3495.425
72433	0.0053610	0.0022601	1.7494026	359482.855	6854959.634	3495.599
72434	0.0046715	0.0004808	1.7492854	359404.445	6855405.713	3494.274
72435	0.0045069	-0.0004761	1.7496188	359326.657	6855850.758	3493.703
72436	0.0054899	0.0011984	1.7491694	359249.039	6856296.908	3494.530
72437	0.0049367	0.0011984	1.7490977	359171.876	6856742.061	3494.828
72438	0.0046532	0.0013887	1.7491841	359094.462	6857188.287	3495.379
72439	0.0048293	0.0005155	1.7491254	359016.060	6857633.073	3494.747
72440	0.0047747	0.0005561	1.7506514	358936.095	6858078.912	3494.884
72441	0.0045192	0.0000614	1.7510006	358856.075	6858523.583	3495.724
72442	0.0046084	0.0005856	1.7487375	358779.909	6858969.885	3496.197
72443	0.0042270	0.0002364	1.7509381	358705.910	6859415.550	3494.367
72444	0.0047953	0.0005393	1.7508650	358631.210	6859862.228	3493.343
72445	0.0048889	0.0006000	1.7486321	358555.691	6860307.951	3494.254
72446	0.0044741	0.0007043	1.7504621	358480.228	6860754.186	3495.227
72447	0.0039837	0.0005338	1.7511638	358404.472	6861199.835	3495.218
72448	0.0042446	0.0002882	1.7494739	358326.383	6861645.641	3494.399
72449	0.0044177	0.0007288	1.7509032	358246.841	6862090.469	3494.876
72450	0.0051536	0.0005540	1.7505542	358167.817	6862536.243	3494.358
72451	0.0048698	0.0004530	1.7489985	358089.405	6862981.177	3494.686
72452	-0.0046681	-0.0013883	-1.3925640	356642.912	6862718.130	3494.974
72453	-0.0039685	-0.0004276	-1.3906865	356722.615	6862273.341	3494.828
72454	-0.0056198	-0.0010138	-1.3905350	356801.970	6861827.417	3494.627
72455	-0.0040822	-0.0004298	-1.3904414	356880.717	6861382.659	3495.628
72456	-0.0038497	-0.0003651	-1.3907229	356959.283	6860936.657	3495.911
72457	-0.0035275	-0.0008176	-1.3910562	357037.875	6860491.708	3494.451
72458	-0.0046348	-0.0006666	-1.3930780	357117.192	6860045.997	3494.317
72459	-0.0047215	-0.0001720	-1.3914265	357196.616	6859601.299	3496.116
72460	-0.0046329	-0.0002667	-1.3912628	357276.020	6859155.470	3498.610
72461	-0.0039391	-0.0003600	-1.3928732	357355.590	6858710.568	3498.142
72462	-0.0039747	-0.0009706	-1.3913256	357435.985	6858265.150	3496.891
72463	-0.0051255	-0.0008292	-1.3918316	357516.917	6857820.485	3497.531
72464	-0.0049680	-0.0005784	-1.3935312	357595.461	6857374.661	3498.571
72465	-0.0048497	-0.0006079	-1.3920958	357669.945	6856928.970	3498.416
72466	-0.0046197	-0.0005482	-1.3916503	357742.466	6856481.810	3497.094
72467	-0.0044502	-0.0007654	-1.3934182	357814.583	6856035.704	3496.962
72468	-0.0046307	0.0002320	-1.3918515	357887.978	6855588.734	3497.132
72469	-0.0044362	-0.0001133	-1.3908695	357962.727	6855143.191	3497.456
72470	-0.0042547	-0.0006327	-1.3940844	358039.302	6854696.671	3496.708
72471	-0.0043252	-0.0010870	-1.3917757	358116.241	6854251.790	3497.289
72472	-0.0052564	-0.0001756	-1.3919712	358192.886	6853806.487	3498.974
72473	-0.0036874	-0.0012734	-1.3932275	358270.945	6853360.450	3499.042
72474	-0.0043665	-0.0004137	-1.3911748	358352.074	6852916.016	3497.806
72475	-0.0052424	0.0000240	-1.3917337	358432.482	6852470.370	3497.811
72476	-0.0046810	-0.0006445	-1.3929874	358510.746	6852025.430	3498.146

The exterior orientation was solved in KKJ2/N60 by setting a grid of points with known UTM35/N2000 and calculating bundle block adjustment in this 3D geometry.

Table 2. Orientation parameters in KKJ2/N60 system. Radians and meters.

Image	Omega	Phi	Kappa	X0	Y0	Z0
72426	0.0038655	0.0023983	1.7959445	2514104.256	6851715.644	3498.361
72427	0.0087649	0.0051136	1.7966755	2514001.761	6852157.019	3498.448
72428	0.0097611	0.0054990	1.7961763	2513903.605	6852598.139	3496.552
72429	0.0083311	0.0059101	1.7956087	2513807.995	6853040.039	3494.102
72430	0.0079640	0.0062549	1.7956963	2513708.423	6853481.794	3494.142
72431	0.0065762	0.0043175	1.7956387	2513604.733	6853921.850	3495.651
72432	0.0043148	0.0005706	1.7960108	2513499.622	6854362.337	3495.631
72433	0.0052500	0.0025074	1.7955586	2513397.400	6854802.697	3495.799
72434	0.0046432	0.0006959	1.7954382	2513298.475	6855244.750	3494.482
72435	0.0045357	-0.0002545	1.7957725	2513200.267	6855685.763	3493.907
72436	0.0054284	0.0014570	1.7953234	2513102.108	6856127.966	3494.738
72437	0.0048777	0.0014251	1.7952517	2513004.453	6856569.149	3495.029
72438	0.0045889	0.0016076	1.7953381	2512906.541	6857011.388	3495.578
72439	0.0048041	0.0007391	1.7952789	2512807.671	6857452.153	3494.954
72440	0.0047419	0.0007851	1.7968076	2512707.236	6857893.919	3495.094
72441	0.0045156	0.0002766	1.7971566	2512606.758	6858334.475	3495.926
72442	0.0045751	0.0008043	1.7948928	2512510.069	6858776.878	3496.405
72443	0.0042109	0.0004417	1.7970952	2512415.588	6859218.718	3494.572
72444	0.0047604	0.0007721	1.7970178	2512320.351	6859661.561	3493.548
72445	0.0048474	0.0008260	1.7947871	2512224.293	6860103.410	3494.456
72446	0.0044388	0.0009129	1.7966173	2512128.318	6860545.719	3495.426
72447	0.0039438	0.0007207	1.7973185	2512032.069	6860987.515	3495.421
72448	0.0042322	0.0004897	1.7956305	2511933.488	6861429.256	3494.604
72449	0.0043830	0.0009347	1.7970593	2511833.479	6861870.015	3495.086
72450	0.0051291	0.0008006	1.7967096	2511733.982	6862311.728	3494.568
72451	0.0048440	0.0006792	1.7951526	2511635.085	6862752.664	3494.900
72452	-0.0046126	-0.0016020	-1.3464074	2510202.038	6862423.148	3495.182
72453	-0.0039496	-0.0006063	-1.3445292	2510302.205	6861982.412	3495.036
72454	-0.0055538	-0.0012645	-1.3443784	2510402.074	6861540.489	3494.841
72455	-0.0040595	-0.0006185	-1.3442876	2510501.246	6861099.821	3495.837
72456	-0.0038141	-0.0005384	-1.3445684	2510600.338	6860657.790	3496.118
72457	-0.0034830	-0.0009704	-1.3449021	2510699.409	6860216.913	3494.660
72458	-0.0045974	-0.0008828	-1.3469228	2510799.175	6859775.272	3494.522
72459	-0.0047191	-0.0003788	-1.3452715	2510899.095	6859334.683	3496.328
72460	-0.0046098	-0.0004684	-1.3451074	2510999.002	6858892.867	3498.818
72461	-0.0039269	-0.0005417	-1.3467172	2511098.986	6858452.089	3498.348
72462	-0.0039170	-0.0011434	-1.3451708	2511199.895	6858010.726	3497.103
72463	-0.0050888	-0.0010660	-1.3456763	2511301.229	6857570.252	3497.740
72464	-0.0049516	-0.0008083	-1.3473786	2511400.276	6857128.486	3498.774
72465	-0.0048114	-0.0008220	-1.3459416	2511495.295	6856686.567	3498.620
72466	-0.0045899	-0.0007583	-1.3454959	2511588.358	6856243.176	3497.298
72467	-0.0044062	-0.0009713	-1.3472636	2511680.979	6855800.788	3497.176
72468	-0.0046394	0.0000232	-1.3456948	2511774.959	6855357.633	3497.341
72469	-0.0044241	-0.0003050	-1.3447163	2511870.223	6854915.926	3497.671
72470	-0.0042221	-0.0008183	-1.3479293	2511967.322	6854473.357	3496.916
72471	-0.0042764	-0.0012745	-1.3456186	2512064.723	6854032.444	3497.503
72472	-0.0052422	-0.0004163	-1.3458163	2512161.810	6853591.059	3499.184
72473	-0.0036330	-0.0014355	-1.3470736	2512260.399	6853149.059	3499.246
72474	-0.0043377	-0.0006068	-1.3450200	2512361.967	6852708.725	3498.022
72475	-0.0052525	-0.0002089	-1.3455768	2512462.869	6852267.262	3498.022
72476	-0.0046545	-0.0008511	-1.3468300	2512561.595	6851826.317	3498.354



Comparison of 2010 and 2023 image triplets – Konehalli showed a 35-cm vertical offset.

Figure 3Vuorijärvi roof crest shows a minor Z-offset between 2020 and 2023, again 2023 being 30 cm "up".

2517009.97, 6857165.51, 154.17 (2023 3km)
2517009.79, 6857165.82, 153.87 (2020 3km)
2517010.02, 6857165.65, 153.77 (2002 1:6000)
2517010.17, 6857165.78, 153.72 (1983 1:15000)

1.2 km (8 cm) RGB imaging during the LiDAR campaign, August 18, 2023

These images were captured during the LiDAR acquisition with an RGB-camera. There are 86 exposures from five LiDAR strips. Similar RGB images were captured during the 2018 and 2020 LiDAR campaigns.

F-stop was 4.5 and exposure time was 1/800 seconds. Image capture was at 06:28-06:45 GMT. Solar elevation was from 25.9 to 27.5 degrees. Solar azimuth was 111.7→115.33 degrees. Weather in 2023 was not favorable (cloud-free weather was scarce), and it was fortunate that the campaign could be finalized late in the summer.

The camera has 14204 x 10652 pixels (one RGB-array) and the pixel size (3.76 um) on the ground was 8.4 cm. A lens with 50-mm focal length was applied. The calibration certificate shows that the sensor's principal point of autocollimation is 7 and 70 μm off the image center. Radial distortion 3.4 cm away from the image center is 0.372 mm, which is almost 100 pixels. The lens distortion was expressed by a standard polynomial that combines radial distortion and decentering distortion. In camera calibration, the correction of distortion had had a mean residual of 0.143 pixels and 0.91 pixels maximally. Therefore, in principle, the images should qualify reasonably well for image matching. The mean residual of aerial triangulation by the data provider was 0.36 pixels. It was also based on GNSS data of the sensor position. The calibration certificate of the camera is dated August 16, 2021, which is rather old.

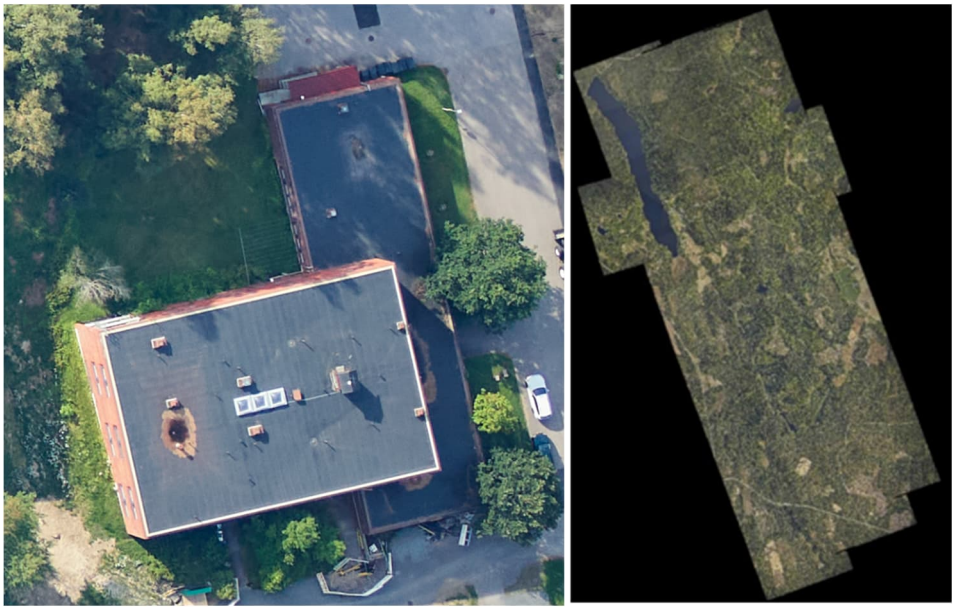


Figure 4. Phase One RGB-image patch with 8 cm pixels. (1.2 km). Mosaic of the images

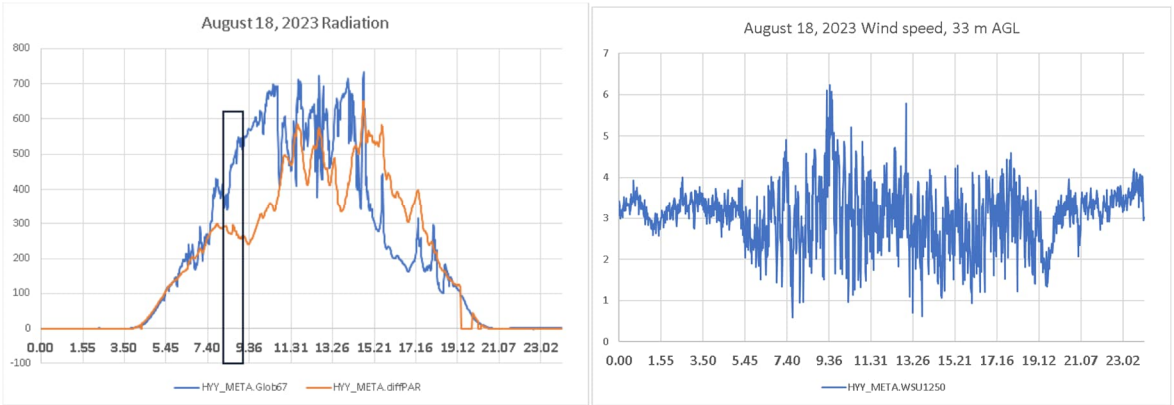


Figure 5. SMEAR II radiation observations (GMT+2h) reveal the appearance of small clouds in the area towards 06:50 GMT (08:50 local SMEAR II time). Mild winds prevailed during the LiDAR data capture (3 m/s) 33 m above the ground).

In AT, the exterior orientation of the images was solved successfully at 0.3-pixel RMS accuracy (by the data provider), and tie points were found across 2-11 photos. However, quite a few points were found between 4-11 photos. Namely four or more points tie photos adjacent/overlapping strips.

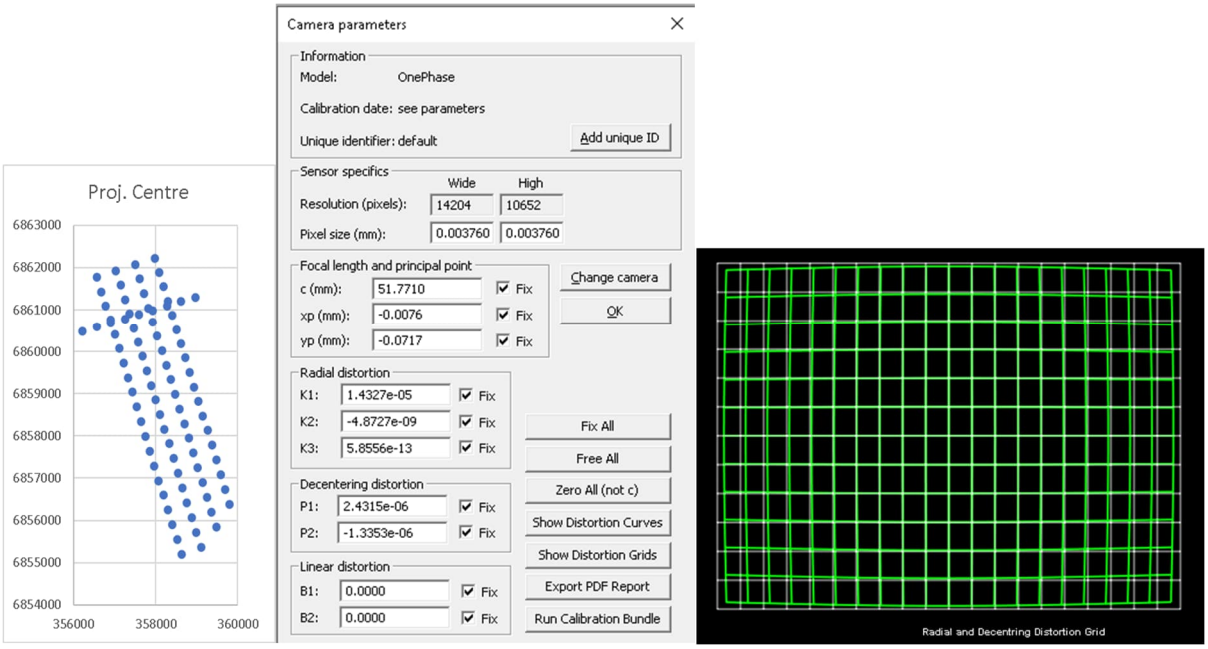


Figure 6. Positions of the projection centers on the map, camera model of the PhaseOne sensor, and the pattern of lens distortions (as seen in iWitness).

The delivered TIF-images were resampled into undistorted "pinhole camera" images in iWitness software (its program XYRectify) such that the influence of the lens errors was removed with the distortion model. The size of the undistorted images is larger (14604 x 11052), but the original focal plane pixel size of 3.76 um is retained in these images. Additional pixels are added (needed) to the image borders to have the undistorted image fit rectangular image plane.

The affine terms that work with the pinhole images (in Kuvamitt-software) are
265957.4468 0 7303.978723 0 265957.4468 5506.930851

The center pixel in the undistorted image is 7302, 5526 – so the PPA_X, PPA_Y that produced reasonable accuracy between strips was 7303.97, 5506.93 in Kuvamitt.

There is a slight offset in Z in these images, in the order of 20-40 cm. As with the 3 km images, forward ray-intersected points have too large Z-values.

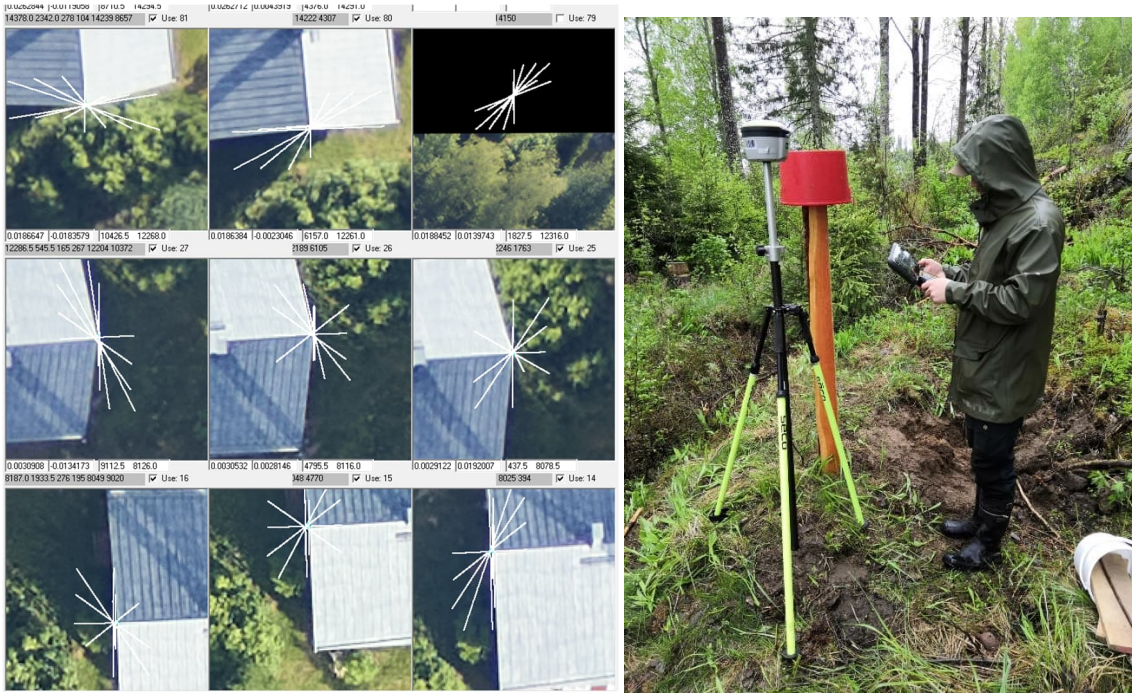


Figure 7. Epipolar geometry in 8 overlapping images (Pilvilinna roof crest). Z was 30 cm above that in 2002 images (considering the 32 cm offset between N60 and N2000).

Figure 8. GNSS-measured targets showed an offset of 0.3-0.4 m in Z, with XY-errors of <15 cm. Here we see that the images of adjacent strips (flown in opposite direction) do not match, and XY-coordinates measured in the two pairs deviate 15 cm from each other.

Omega	Phi	Kappa	X0	Y0	Z0	Image
-0.001345	0.000041	0.358735	2516937.95	6855209.49	1316.38	1
0.002700	-0.000020	0.359579	2516808.71	6855552.63	1321.57	2
0.002297	-0.000667	0.351325	2516678.38	6855895.40	1318.79	3
0.001173	-0.000558	0.352757	2516552.11	6856237.82	1317.39	4
0.001349	-0.001064	0.346121	2516426.26	6856579.27	1317.11	5
0.001515	-0.000998	0.349551	2516299.67	6856921.63	1316.86	6
0.001219	-0.000763	0.347874	2516174.37	6857265.21	1317.06	7
0.001601	-0.001166	0.343295	2516049.71	6857609.64	1317.60	8
0.001877	-0.000826	0.339567	2515925.96	6857955.21	1317.85	9
0.001464	-0.000545	0.340464	2515802.74	6858298.71	1317.89	10
0.001557	-0.001550	0.346086	2515680.44	6858639.49	1318.08	11
0.001305	-0.000543	0.349210	2515557.25	6858980.07	1318.14	12
0.001375	-0.000481	0.342700	2515434.29	6859320.90	1318.09	13
0.001163	-0.001377	0.339465	2515313.00	6859660.30	1318.29	14
0.001995	-0.000592	0.346552	2515191.07	6859999.56	1318.35	15
0.000974	-0.000950	0.358047	2515065.23	6860335.83	1318.64	16
0.001325	-0.000961	0.347968	2514940.02	6860672.91	1318.49	17
0.001937	-0.000490	0.348650	2514817.32	6861008.28	1318.46	18
0.001158	-0.001015	0.350957	2514693.38	6861345.71	1318.59	19
0.001499	-0.001155	0.347475	2514568.87	6861686.99	1318.54	20
0.010288	-0.002111	-2.787091	2515026.05	6861854.45	1321.67	21
0.014891	-0.004185	-2.797870	2515149.01	6861520.16	1321.61	22
0.016739	-0.004885	-2.790652	2515272.33	6861183.54	1321.44	23
0.014258	-0.003585	-2.788024	2515395.97	6860848.54	1321.32	24
0.002706	0.000017	-2.790494	2515519.11	6860513.74	1321.32	25
-0.002562	0.001247	-2.795856	2515641.35	6860178.09	1321.45	26
-0.002557	0.001843	-2.796050	2515762.95	6859843.45	1321.45	27
-0.001881	0.000951	-2.799139	2515886.52	6859502.93	1321.52	28
-0.000836	0.000941	-2.794731	2516010.96	6859162.11	1321.73	29
-0.001821	0.001490	-2.796953	2516134.28	6858823.20	1321.52	30
-0.002225	0.001675	-2.792519	2516259.08	6858481.55	1321.48	31
-0.001671	0.000793	-2.795844	2516383.06	6858143.11	1321.38	32
-0.001531	0.001076	-2.794832	2516507.70	6857802.77	1321.36	33
-0.002032	0.001471	-2.788880	2516633.63	6857460.56	1321.41	34
-0.001756	0.000952	-2.795115	2516760.07	6857116.33	1321.26	35
-0.000948	0.000991	-2.796767	2516884.32	6856773.03	1321.43	36
-0.001242	0.000654	-2.788937	2517011.57	6856425.61	1321.46	37
-0.001199	0.001175	-2.781773	2517141.18	6856079.90	1321.59	38
-0.001954	0.000668	-2.785818	2517271.33	6855734.41	1321.80	39
-0.001432	0.001242	-2.781722	2517401.56	6855388.04	1321.85	40
0.001666	-0.001118	0.356275	2517749.02	6855879.47	1327.74	41
0.001480	-0.001770	0.352582	2517619.54	6856226.30	1327.82	42
0.001590	-0.001286	0.346103	2517492.76	6856573.57	1327.57	43
0.001526	-0.000819	0.350342	2517364.97	6856922.98	1327.78	44
0.001517	-0.001637	0.349218	2517237.99	6857267.67	1327.84	45
0.001706	-0.000940	0.349289	2517111.50	6857612.63	1327.83	46
0.001849	-0.000843	0.354750	2516984.52	6857956.97	1327.90	47
0.001150	-0.001697	0.350278	2516858.49	6858295.87	1327.77	48
0.001245	-0.000229	0.353035	2516732.29	6858638.27	1327.45	49
0.001284	-0.001109	0.352551	2516605.21	6858978.30	1327.50	50
0.001835	-0.001056	0.342966	2516480.28	6859319.63	1327.44	51
0.001921	-0.001374	0.352390	2516355.61	6859661.47	1327.63	52
0.001375	-0.001775	0.353299	2516229.35	6860001.97	1327.72	53
0.001339	-0.001039	0.349927	2516105.51	6860338.19	1327.65	54
0.002117	-0.001074	0.351532	2515980.83	6860673.64	1327.77	55
0.001201	-0.001429	0.345000	2515855.82	6861010.56	1327.67	56
0.001163	-0.000742	0.338834	2515735.16	6861349.34	1327.35	57
0.001583	-0.000999	0.350706	2515612.90	6861686.82	1327.64	58
0.000557	-0.001381	0.347623	2515489.76	6862023.35	1327.73	59
-0.001809	0.001759	-2.803721	2515963.14	6862197.00	1317.33	60
-0.000090	0.002863	-2.797883	2516082.55	6861864.23	1318.23	61
-0.001173	0.002174	-2.798619	2516203.82	6861528.25	1318.51	62
-0.001605	0.001526	-2.802383	2516323.64	6861193.39	1318.60	63
-0.001952	0.001515	-2.799663	2516444.29	6860858.34	1318.49	64
-0.001596	0.001405	-2.800972	2516564.94	6860525.41	1318.46	65
-0.001137	0.001158	-2.788528	2516687.27	6860191.49	1318.42	66
-0.001426	0.001119	-2.792243	2516811.19	6859853.14	1318.39	67
-0.001648	0.001262	-2.795828	2516934.16	6859515.10	1318.27	68
-0.001447	0.001200	-2.798003	2517057.93	6859174.85	1318.36	69
-0.001049	0.001322	-2.790145	2517182.26	6858837.02	1318.44	70
-0.001729	0.001252	-2.796031	2517306.30	6858499.45	1318.51	71
-0.001417	0.001499	-2.792261	2517430.13	6858161.24	1318.63	72
-0.001039	0.001375	-2.790563	2517555.35	6857820.06	1318.88	73
-0.001486	0.000984	-2.794995	2517679.83	6857477.54	1318.79	74
-0.001301	0.001745	-2.796058	2517805.62	6857131.12	1318.61	75
-0.001589	0.001474	-2.796720	2517930.88	6856785.66	1318.64	76
-0.001276	0.000930	-2.788876	2518056.31	6856442.61	1318.83	77
-0.001014	-0.001129	-1.244091	2514275.58	6860375.83	1322.89	78
-0.001268	-0.001482	-1.245161	2514614.52	6860491.47	1322.63	79
-0.001502	-0.001286	-1.246506	2514954.34	6860606.48	1322.54	80
-0.001511	-0.001662	-1.243075	2515294.43	6860721.91	1322.41	81
-0.001127	-0.001646	-1.231205	2515633.09	6860840.25	1322.34	82
-0.001336	-0.001645	-1.235494	2515969.87	6860959.51	1322.26	83
-0.001481	-0.001340	-1.232305	2516306.85	6861078.45	1322.34	84
-0.001847	-0.001341	-1.228063	2516642.82	6861198.80	1322.36	85
-0.001897	-0.001180	-1.233604	2516982.68	6861319.79	1322.27	86

LiDAR

The project code by Field (formerly Terratec) is 41847, Hyytiälä LiDAR 2023.

There were four parallel SSE-NNW oriented strips and one perpendicular strip, which repeat the capture of the 2018 and 2020 LiDAR (also by using the same sensor model and strips). The flying height was 1310-1365 m, i.e., 1.2 km above ground. A (less optimal) large field-of-view of 60 degrees (+/- 30-degree scan angles) was applied again, to have the data match the earlier campaigns.

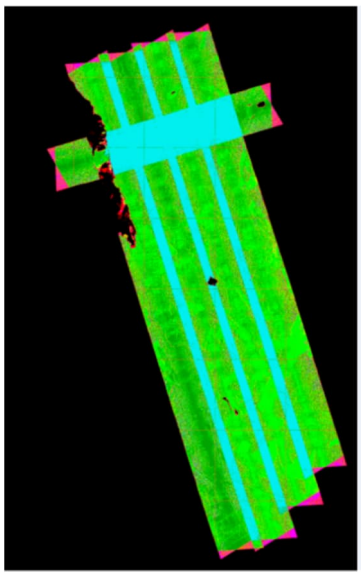


Figure 9. Pulse density maps of the LiDAR strips. Lake Kuivajärvi, Kaakkolammi, Vuorijärvi and Silmäpäänlammi water bodies show as no-data areas. The "reddish crosses" at the start and end if the strips are due to the two-scanner design of the used sensor as the scanners are aligned in an angle with respect to each other and do not point directly downwards.

The conditions as registered by the operator were: "*LN-TER-2, L505 completed 41847. Small cumulus around project area and they started popping up, but I think we managed to avoid them all. Some cloud-shadows from clouds around project area. Had problem with INS-GPS which also froze tracker and exited program.*"

Flightplan #	LiDAR Disk-ID	Camera Disk-ID	Digitizer Disk-ID	Flight	Line ID:	Run no:	Course	Remarks
41847_01_01	D1016	D1023		1	230818_063221	1	n	Needs to be checked if these lines can be used even though I lost gps connection before flying crossline.
41847_01_01	D1016	D1023		1	230818_063538	2	s	Needs to be checked if these lines can be used even though I lost gps connection before flying crossline.
41847_01_01	D1016	D1023		1	230818_063856	3	n	Needs to be checked if these lines can be used even though I lost gps connection before flying crossline.
41847_01_01	D1016	D1023		1	230818_064212	4	s	Needs to be checked if these lines can be used even though I lost gps connection before flying crossline.
41847_01_01	D1016	D1023		1	230818_064833	5	E	CL
41847_01_01	D1016	D1023		1	230818_065131	4	s	CLOUDS ON LINE. OR .LA . LOST INS-GPS CONNECTION
41847_01_01	D1016	D1023		1	230818_065937	2	s	Small cloud on start of line. LA. OR.
41847_01_01	D1016	D1023		1	230818_070311	3	s	cloud on line. LA. OR

Figure 10. The log reveals that three of the strips were flown again. The crossing line is strip #5. Strips were flown 06:32-07:03 (extra ones not included in the data). What is "LA" perhaps line aborted?

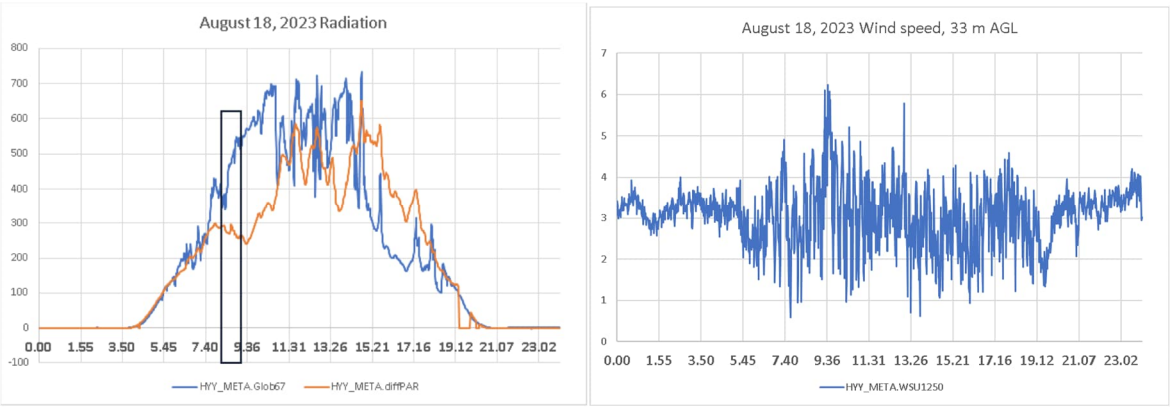


Figure 11. Weather: SMEAR II radiation observations (GMT+2h) reveal the appearance of small clouds in the area towards 06:50 GMT (08:50 local SMEAR II time). Mild winds prevailed during the LiDAR data capture.

Trajectory, LAS, and per-hectare binary (comprehensive) files

The delivered trajectory files have observations every 0.02 seconds for the UTM coordinates, ellipsoidal height and the roll, pitch, heading angles. The files were included in the delivery so that pulse vectors (3D points of sensor) could be reconstructed (interpolated) using the time stamps in the LiDAR data and the trajectory data. This created what is called "comprehensive format".

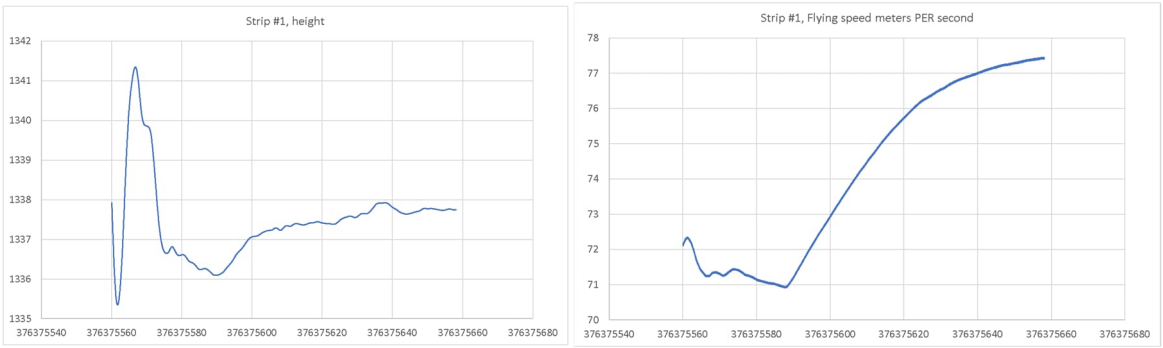


Figure 12. Examples of trajectory data: Flying height (meters above the ellipsoid) in strip #1, and the ground speed (m/s) of the aircraft. Strip #1 took 98 seconds to capture (length of 7.35 km).

The delivered (five) LAS-files were in LAS1.4 format. LAS 1.4 supports point records only, and the point record format was that of #6, which stores each point (echo) with 30 bytes. In total, the LiDAR data was 31.884.990.535 Bytes. Some pulses had resulted in up to 11 echoes. The number of pulses sent is approximately 50% of the pulses transmitted meaning that the average number of echoes was 2 per pulse transmitted.

File	Points	Size
00001.las	244,085,527	7,322,567,999
00002.las	252,167,032	7,565,013,149
00003.las	236,605,777	7,098,175,499
00004.las	215,350,218	6,460,508,729
00005.las	114,624,099	3,438,725,159
Sum	1,062,832,653	31,884,990,535

The LAS-files have in total 1.062.832.653 echoes. Each strip comprises one file. Each binary LAS-file had a header of 2189 bytes, followed by the point records that were 30 bytes each. Point XYZ coordinates were stored as integers and should be multiplied by 0.01 to get the UTM35 coordinates and ellipsoidal heights, in meters (cm-level nominal accuracy). Each point has an associated intensity (unsigned 2-byte integer), return number (4 bits), number of returns in the pulse (4 bits), etc. as listed in the LAS1.4 Point type 6 spec below.

Table 15: Point Data Record Format 6

Item	Format	Size	Required
X	long	4 bytes	yes
Y	long	4 bytes	yes
Z	long	4 bytes	yes
Intensity	unsigned short	2 bytes	no
Return Number	4 bits (bits 0-3)	4 bits	yes
Number of Returns (Given Pulse)	4 bits (bits 4-7)	4 bits	yes
Classification Flags	4 bits (bits 0-3)	4 bits	no
Scanner Channel	2 bits (bits 4-5)	2 bits	yes
Scan Direction Flag	1 bit (bit 6)	1 bit	yes
Edge of Flight Line	1 bit (bit 7)	1 bit	yes
Classification	unsigned char	1 byte	yes
User Data	unsigned char	1 byte	no
Scan Angle	short	2 bytes	yes
Point Source ID	unsigned short	2 bytes	yes
GPS Time	double	8 bytes	yes
Minimum PDRF Size		*30 bytes*	

Figure 13. Attributes in the LiDAR data. Two bytes need to be read for data stored in bits sequences of length 1, 2 or 4.

The scan angle is a signed two-byte integer, and the scan angle (mirror) in the instrument in degrees is obtained by multiplying the integer with 0.006 (resolving a movement of 12.6 cm on the ground from a height of 1.2 km). The sensor has two scanners with rotating hexagonal mirrors, which are tilted such that the scan angle does not correspond to scan zenith angle on the ground but underestimates it slightly. The field-of-view of the sensor is 58 degrees, not 60 because of the scanners' tilts. Therefore, scan zenith angle can only be resolved by forming the pulse vectors, ranging from the XYZ position of the lidar to the point XYZ. Scanner channel takes values 1 or 2 indicating which of the two scanners produced the echo. There were two bytes, which need to be interpreted using bitwise reasoning. Delivered data was non-classified, i.e. all points have the classification value of 1. GPS-time is in seconds, and for example strip #5 started at second 376376531.692090 and ended at 376376574.781906. That is about 11.92 years from some (unknown, c.f. GPS week rollover) start time. In the May 2020 data, GPS time indicates that it was acquired 3.206 years earlier, which makes sense. Since the two scanners operated at a 1-MHz pulse rate, the accuracy of the time data suffices barely for identifying the echoes of a pulse, but together with the scan mirror angle, all points had a unique combined identifier that linked them with a particular transmitted pulse.

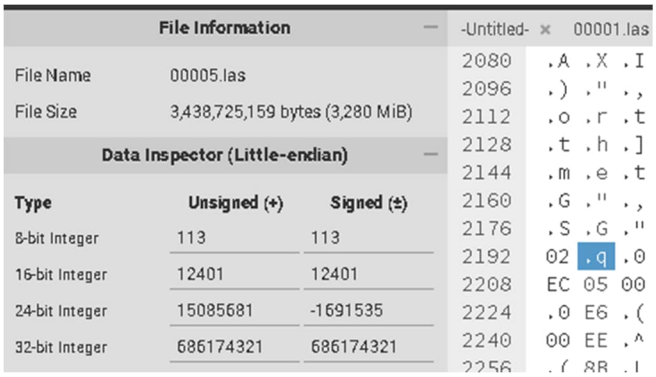


Figure 14. At offset 2193 bytes, the 4 bytes correspond to the Y coordinate of the first point in the LAS-files. The integer 686174321 multiplied by 0.01 is 6861743.21 meters (UTM35 North). (Hex-editor view to Byte 2194)

LIDAR data was computed into what is called "comprehensive format", in which the points of a pulse are merged (found in the unsorted LAS data) into a pulse-record, that also has the position of the LIDAR, so that the 3D path of the pulse (pulse vector) can be computed. The data structure in Excel VBA-language is given below:

```
Type Point_3d   ' 3D point structure with .x, .y and .z, floats, 20 bytes
 X As Double
 Y As Double
 z As Single
End Type

Type EchoRiegl_1560A          ' Echo structure, there cane be a varying number of echoes
 pos As Point_3d              ' XYZ, 20 bytes
 Intensity As Integer         ' Intensity, signed short, 2 bytes
 class As Byte                ' Classification Unsigned char, 1 byte
End Type

Type PulseRIegl_1560          ' A pulse-record
  echocount As Byte           ' Tells how many echoes pulse consists of, 1 byte
  GpsTime As Double           ' Seconds, 8 bytes
  ByteLAS As Byte             ' Byte copied from LAS-file
  ScanAngle As Byte           ' "Scan Angle Rank" -field copied from LAS
  PosLidar As Point_3d        ' XYZ of LiDAR, 20 bytes
  Receiver As Byte            ' #1 or #2 for the scanner in Riegl 1560
  StripNum As Byte            ' Identifier for a strip
  Echoes() As EchoRiegl_1560A ' Array of echoes, varying length, 23 bytes each record
End Type

Public Lidr1560() As PulseRIegl_1560

LiDR1560(1).Echoes(1).pos.x  The X-coordinate of the first echo of the first pulse stored in the array-
```

The pulse-records were stored in per KKJ2-hectare files (tiling) to make their reading faster. User's of the LiDAR data can use these *.bin files or the original LAS files, LAS-format being a widely used standard. LAS format was not developed in 2004, when the collection of the LiDAR time-series started, and LAS does not directly support comprehensive format. The hectare filenames have ##1_##2.bin format, where ##1 and ##2 are three-digit numbers.

```
xr = 2510000: yr = 6850000    ' origin of the hectare file address
If DataType = "ALTM1233" Then ' in 2004 data we had this origin, unchanged after 17 years
  xr = 2514000
  yr = 6855000
End If
FN1(1) = Format$(Int((X_sol - xr) / 100), "000")
FN2(1) = Format$(Int((Y_sol - yr) / 100), "000")
```

For example, point (X_sol, Y_sol) == (2515334.79,6859217.32) maps to hectare file 053_092.bin

Analyses of Geometry

Absolute geometric calibration is out of reach, as there were no 3D monuments in the scene with accurately known coordinates. Elevation reference data exists from forest roads (2008-2015), but the roads are repaved occasionally. Point clouds were therefore compared against existing LiDAR data sets using 3D monuments found in the scene.

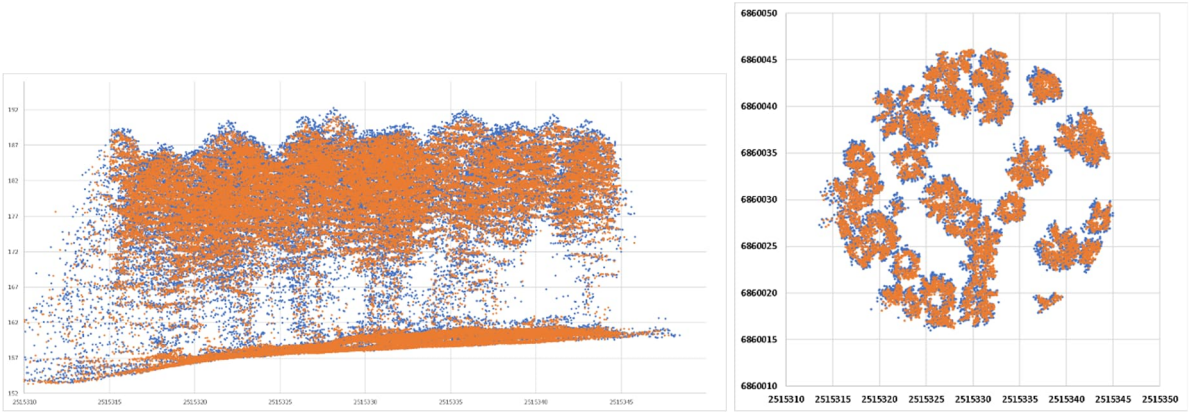


Figure 15. Circular (radius 15 m) plot in Muistokuusikko comparing LiDAR of 2018 and 2023. < 20 cm mismatches.

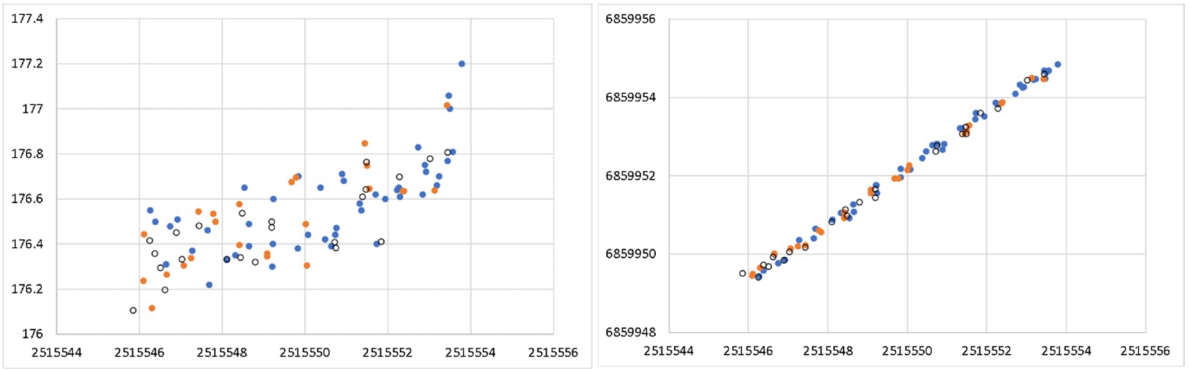


Figure 16. Power cables 8 m above the ground (to SMEAR), 2023 (blue), 2018 (orange), 2015 black. < 20 cm mismatches.

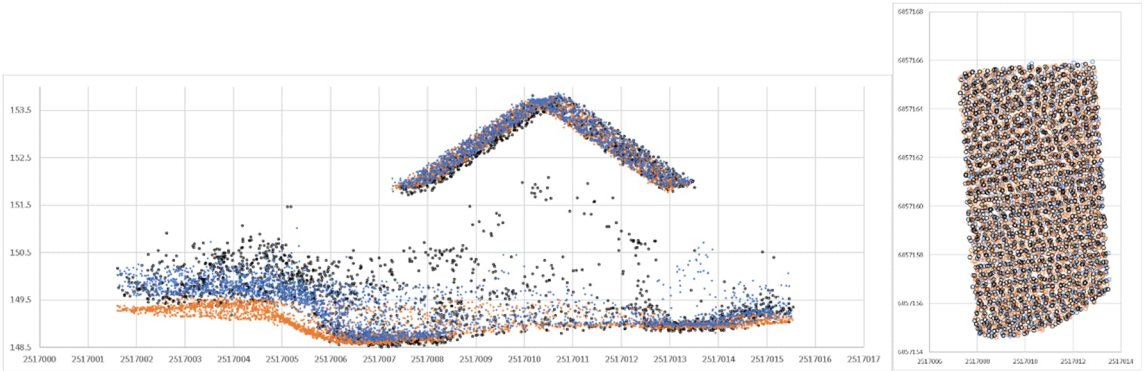


Figure 17. Vuorijärvi farm's roof in the 2015, 2018 and 2023 data. < 20 cm mismatches.

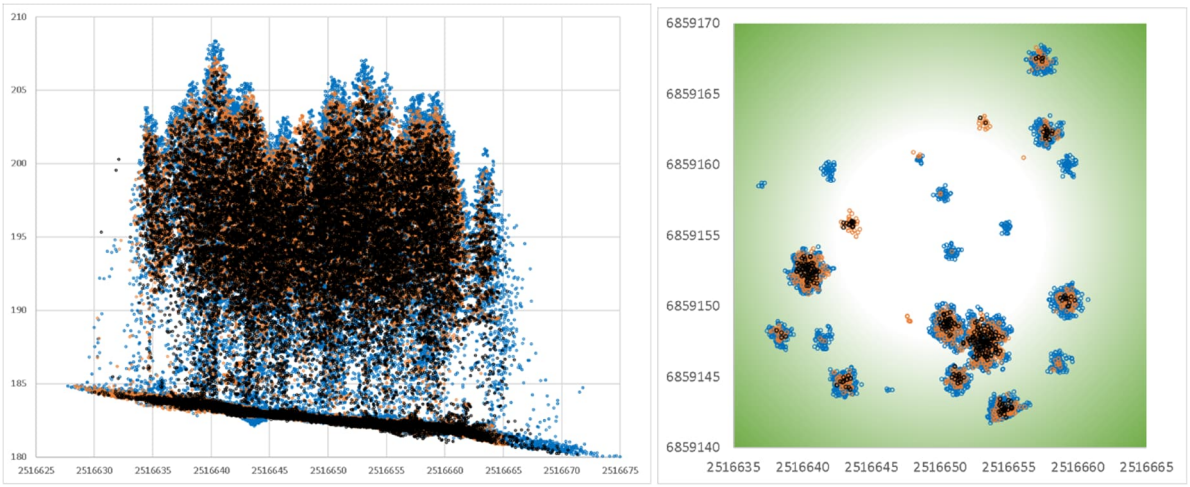


Figure 18. Spruce plot S5. 2015, 5/2018 and 8/2023 data. Height limit 20 m. < 20 cm mismatches.

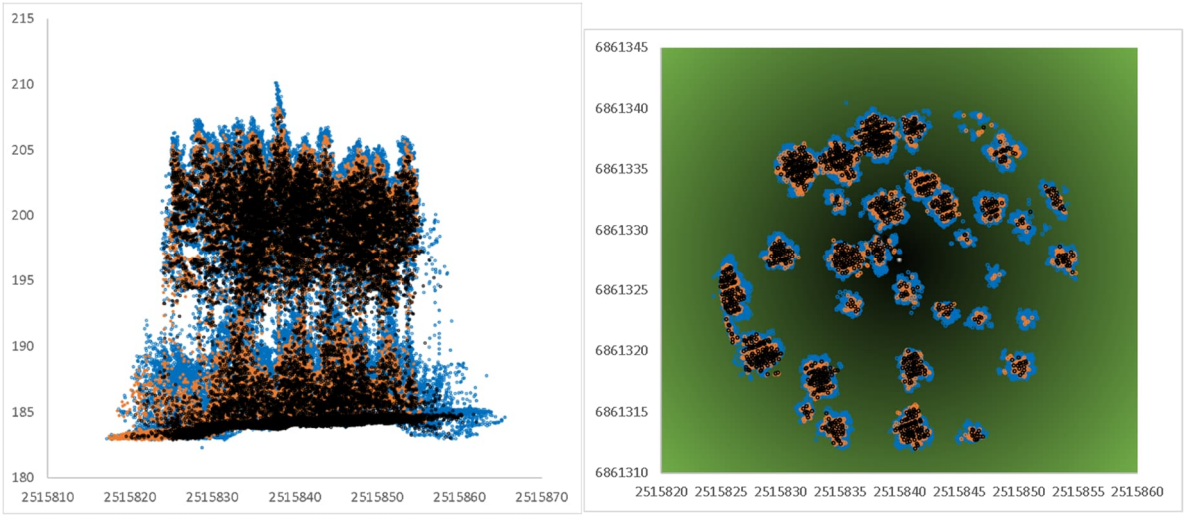


Figure 19. Pine plot P1 in 2015, 5/2018 and 8/2023 LiDAR. Height limit in the XY plot is 18 m. < 20-cm mismatches.

Analysis of radiometry and sensor functioning

Fine sand

Intensity data was first analyzed in fine sand, which is relatively reflective on 1064 nm (reflectance of approximately 0.2). There is a small Z-offset in the data, as 2020 "floats" approximately 8 cm above the points of 2018 and 2020. The intensity data shows normal dependence on scanning range (lidar-target distance), however the signal levels deviate substantially between campaigns and show some between-scanner offsets. The dB (logarithmic) scale of the intensity values influences direct comparisons.

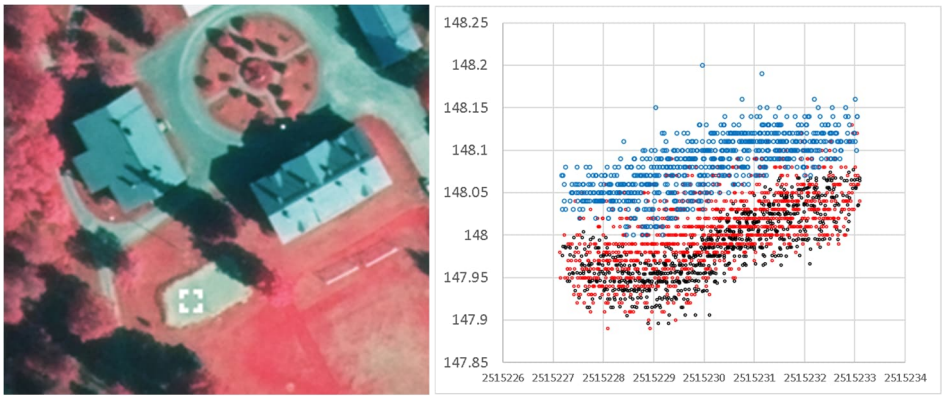


Figure 20. LiDAR of 2018 (black), 2020 (red) and 2023 (blue) in fine sand. There's a vertical (relative) offset of 8-10 cm in the 2023 data. The volleyball field's surface may not be that stable (geometry).

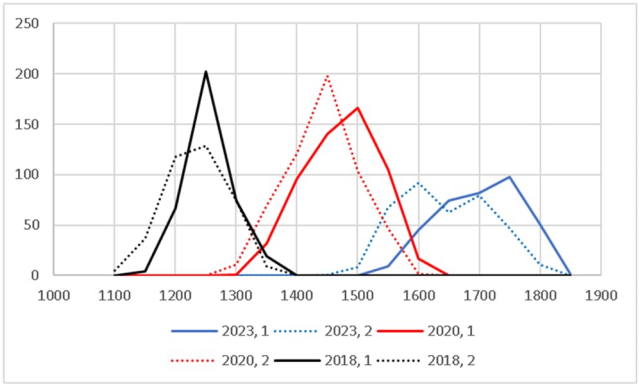


Figure 21. Intensity distributions in fine sand in 2018, 2020 and 2023 data by scanner (1 and 2).

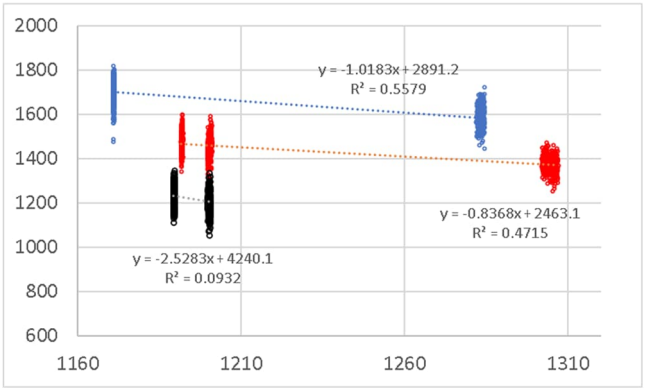


Figure 22. Intensity as a function of range. 2018 (black), 2020 (red) and 2023 (blue) in fine sand

Bitumen roof

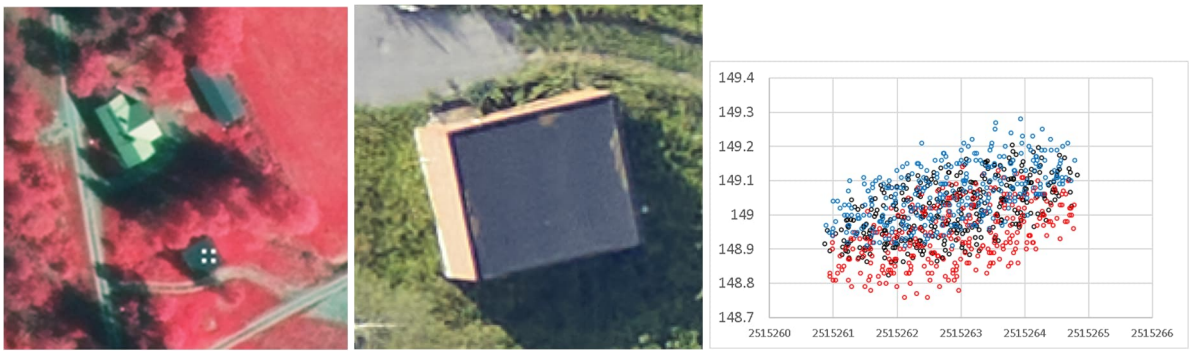


Figure 23. The roof is dark at 1064 nm, reflectance is about 2-3 % only.

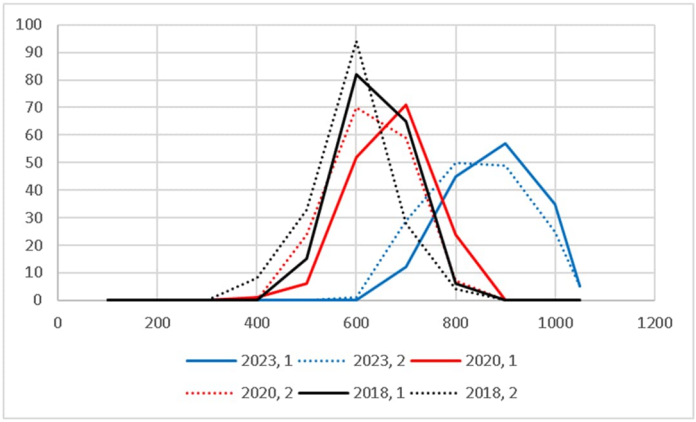
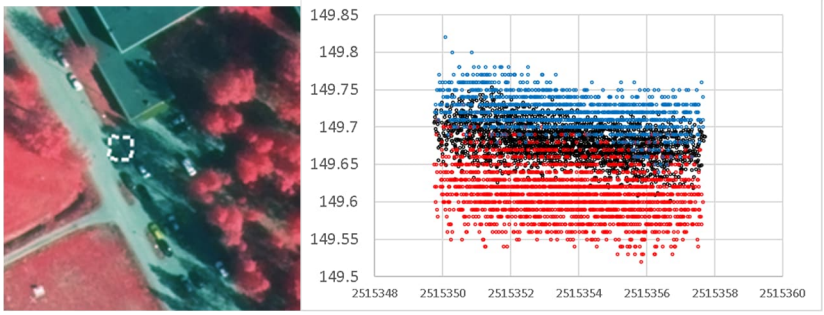


Figure 24. Frequency distributions of intensity in bitumen, by campaign and scanner #. Z-offsets are visible.

Asphalt



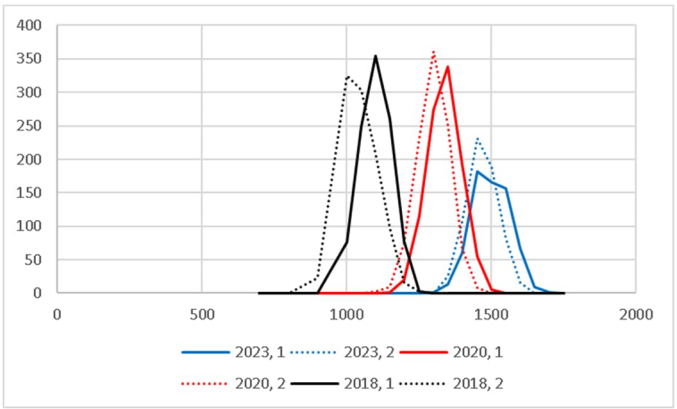
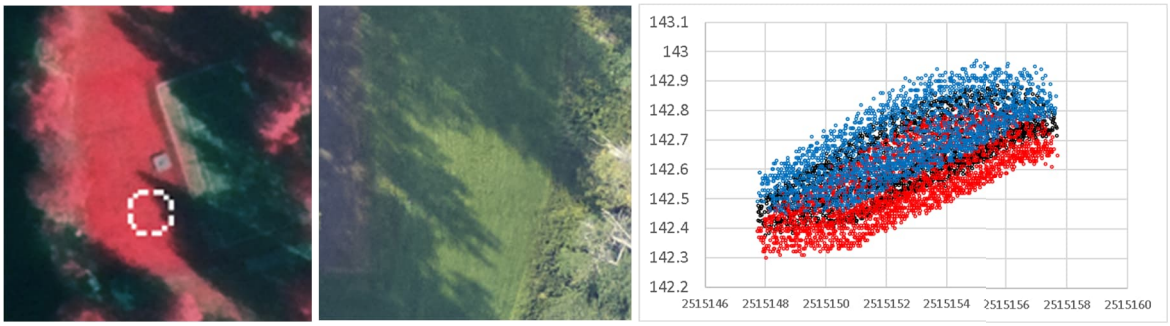


Figure 25. Z-offsets of 3-5 cm in Asphalt.

Grass



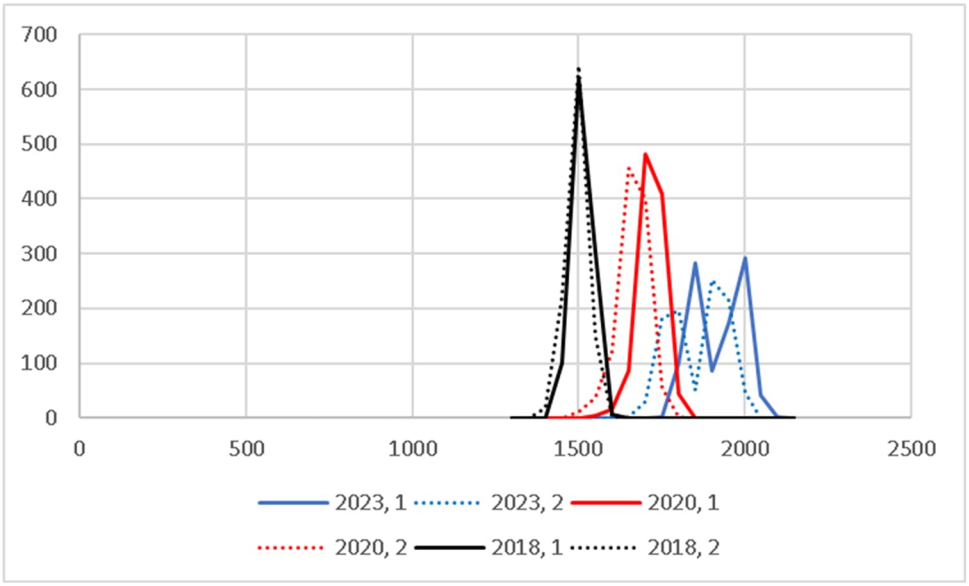
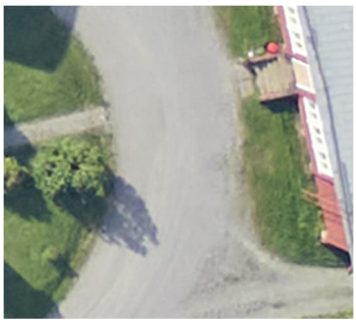
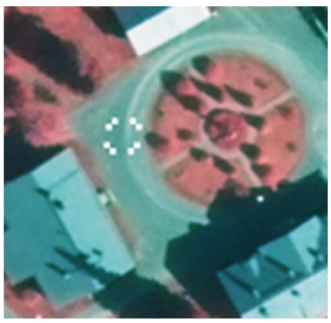
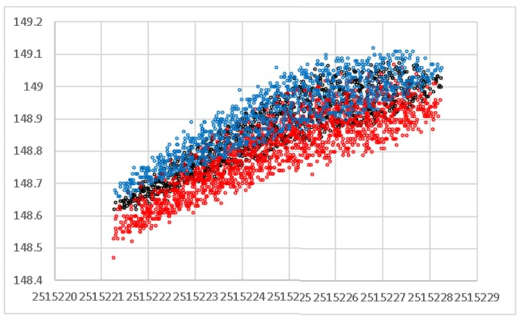


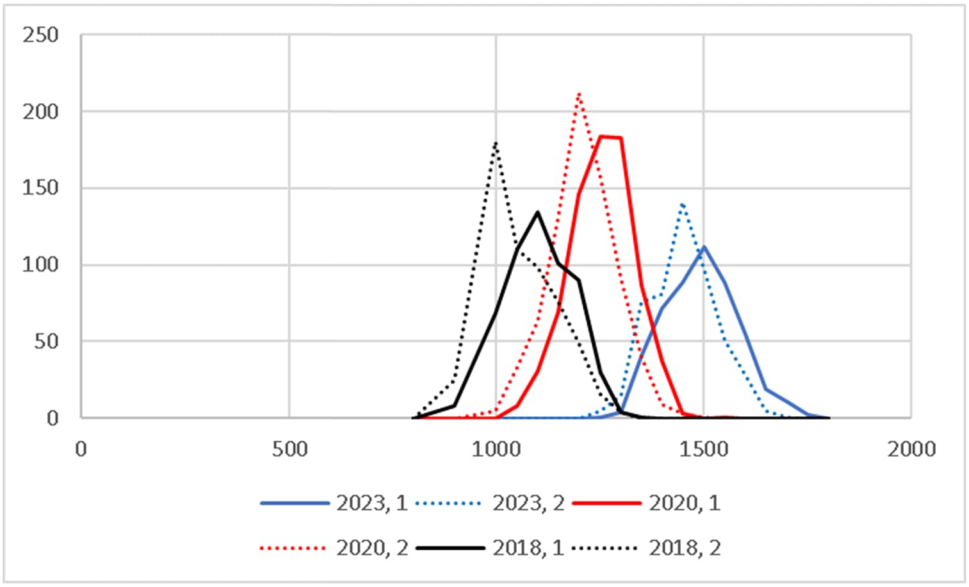
Figure 26. Grass site was partly wet in August 2023 LiDAR (bimodal distribution). Z-offsets of +/- 8 cm vsible here as well.

Gravel



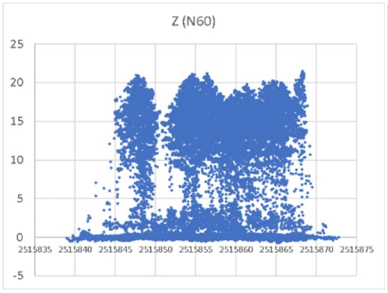


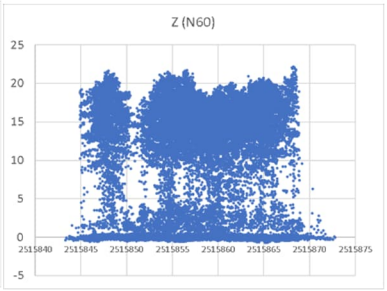

149.2
149.1
149
148.9
148.8
148.7
148.6
148.5
148.4
251522025152212515222251522325152242515225251522625152272515228251522

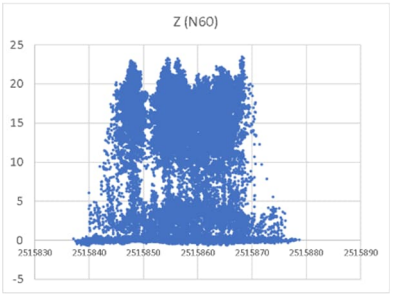

250
200
150
100
50
0
0
500
1000
1500
2000
2023, 1
2023, 2
2020, 1
2020, 2
2018, 1
2018, 2

Pine canopy

The plot radius is 12 m. The trees were planted in 1973. The distribution of pulses with N echoes differs for 2018, which has just one pulse with 6 echoes. This needs to be investigated, since this may be a LAS1.2 vs. LAS 1.4 issue, as LAS1.2 supports only 2^3 = 8 echoes per pulse, and pulses with many echoes may have been misinterpreted (bits read/masked wrongly) when reading the LAS-file (or TerraMatch output).



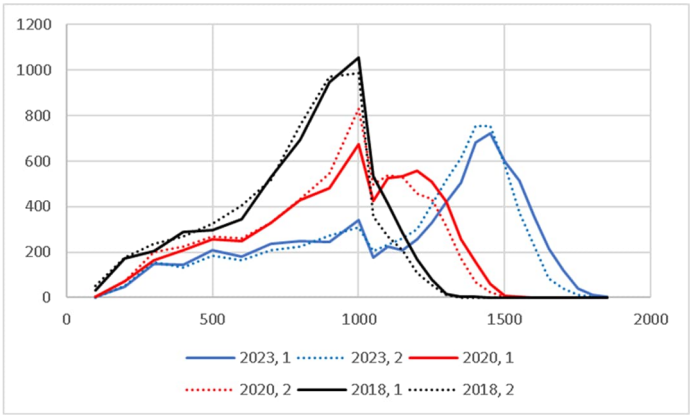




	Echoes	Pulses with N echoes	
1	17517	7483	42.72
2	10034	6221	35.51
3	3813	3101	17.70
4	712	694	3.96
5	18	17	0.10
6	1	1	0.01
7	0	0	0.00
8	0	0	0.00
	Total	17517	

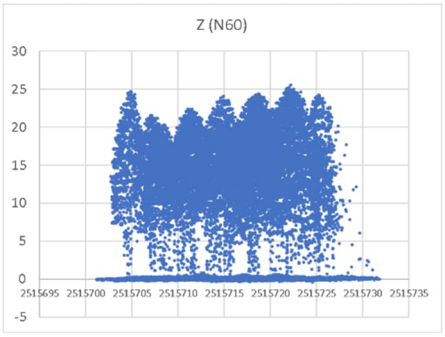
	Echoes	Pulses with N echoes	
1	17836	5861	32.86
2	11975	5580	31.29
3	6395	4350	24.39
4	2045	1700	9.53
5	345	307	1.72
6	38	32	0.18
7	6	5	0.03
8	1	1	0.01
	Total	17836	

	Echoes	Pulses with N echoes	
1	18061	4730	26.19
2	13331	5142	28.47
3	8189	4643	25.71
4	3546	2525	13.98
5	1021	807	4.47
6	214	183	1.01
7	31	28	0.16
8	3	3	0.02
	Total	18061	

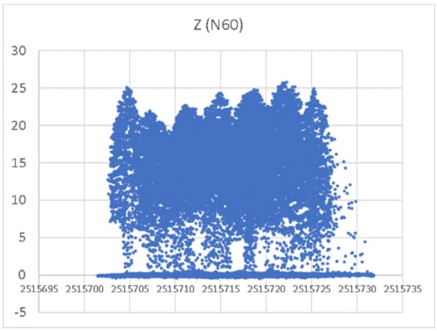


Spruce canopy

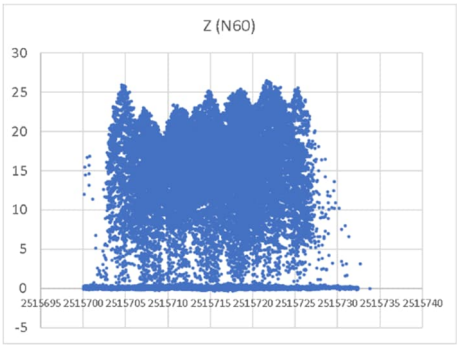
In this site the different behavior of 2018 was observed as well.



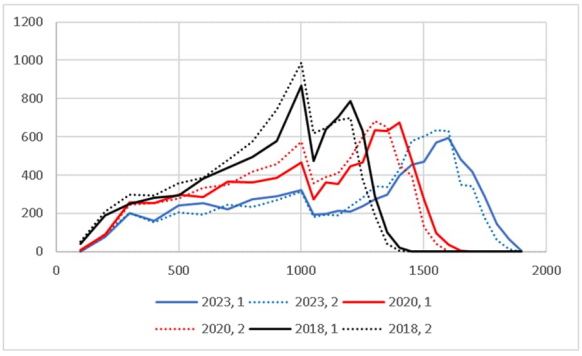
	Echoes	Pulses with N echoes	
1	19529	8495	43.50
2	11034	6693	34.27
3	4341	3380	17.31
4	961	918	4.70
5	43	42	0.22
6	1	1	0.01
7	0	0	0.00
8	0	0	0.00
	Total	19529	

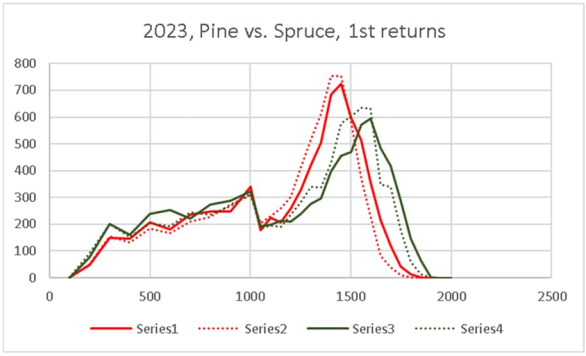


	Echoes	Pulses with N echoes	
1	19186	6435	33.54
2	12751	5807	30.27
3	6944	4456	23.23
4	2488	1914	9.98
5	574	475	2.48
6	99	92	0.48
7	7	7	0.04
8	0	0	0.00
	Total	19186	

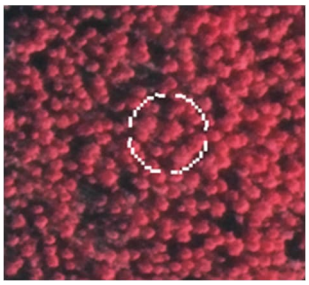


	Echoes	Pulses with N echoes	
1	17955	5242	29.20
2	12713	4955	27.60
3	7758	4197	23.38
4	3561	2291	12.76
5	1270	934	5.20
6	336	266	1.48
7	70	59	0.33
8	11	11	0.06
	Total	17955	

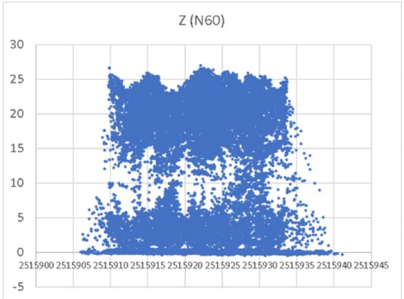




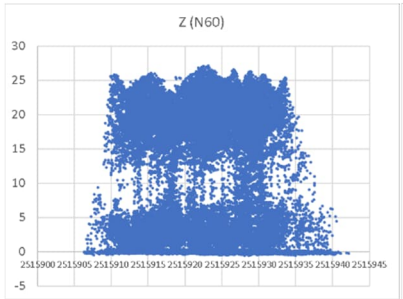
Birch canopy



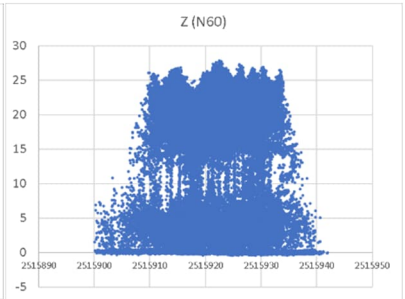
Three strips of 2023 cover this stand. Oddly, the 2018 and 2020 intensity distributions match (while they did not in pine and spruce). Both 2018 and 2020 are early summer acquisitions and the match is possibly due to phenology.



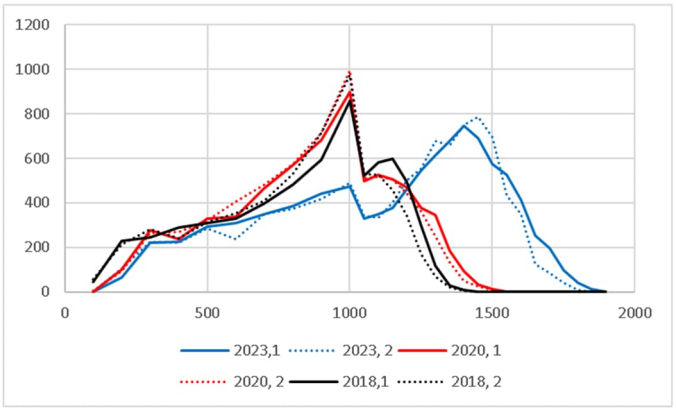
	Echoes	Pulses with N echoes	
1	18405	6762	36.74
2	11643	6783	36.85
3	4860	3654	19.85
4	1206	1123	6.10
5	83	81	0.44
6	2	2	0.01
7	0	0	0.00
8	0	0	0.00
	Total	18405	



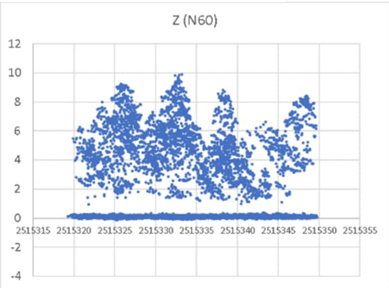
	Echoes	Pulses with N echoes	
1	19107	3597	18.83
2	15510	6153	32.20
3	9357	5450	28.52
4	3907	2853	14.93
5	1054	876	4.58
6	178	165	0.86
7	13	11	0.06
8	2	2	0.01
	Total	19107	

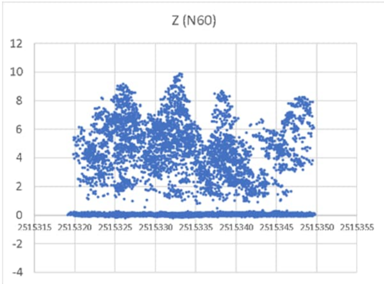


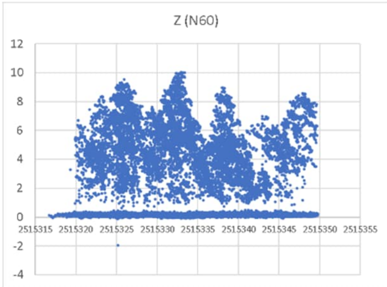
	Echoes	Pulses with N echoes	
1	24530	3328	13.57
2	21202	6405	26.11
3	14797	7154	29.17
4	7643	4987	20.33
5	2656	1996	8.14
6	660	568	2.32
7	92	82	0.33
8	10	9	0.04
	Total	24529	



Pine bog



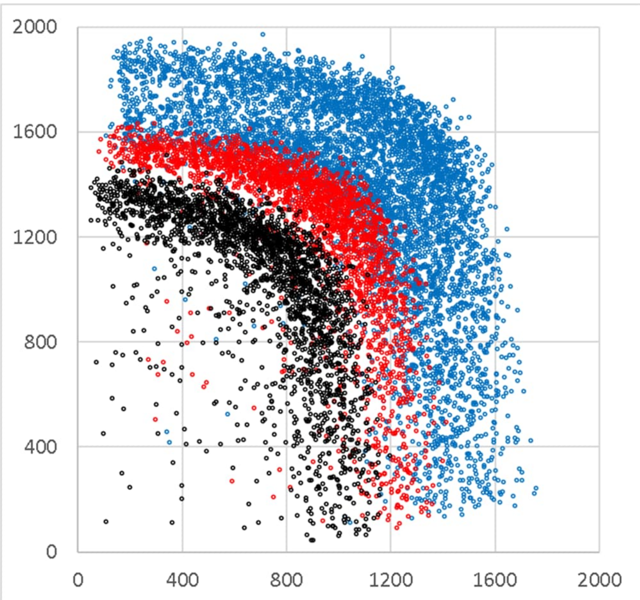




	Echoes	Pulses with N echoes	
1	10061	7209	71.65
2	2852	2344	23.30
3	508	464	4.61
4	44	44	0.44
5	0	0	0.00
6	0	0	0.00
7	0	0	0.00
8	0	0	0.00
	Total	10061	

	Echoes	Pulses with N echoes	
1	9357	6332	67.67
2	3025	2339	25.00
3	686	569	6.08
4	117	109	1.16
5	8	8	0.09
6	0	0	0.00
7	0	0	0.00
8	0	0	0.00
	Total	9357	

	Echoes	Pulses with N echoes	
1	18275	11027	60.34
2	7248	5363	29.35
3	1885	1542	8.44
4	343	304	1.66
5	39	37	0.20
6	2	2	0.01
7	0	0	0.00
8	0	0	0.00
	Total	18275	



Contents of the delivery

\AT

\CIR

\Kameroiden_kalibrointitodistukset

\Kuvien_EO_Tiedot

Lidar

\LVL2TIFF

\Misc

\PhaseOne_Kuvat

\RGB