Report

Coverages: 41700

Project: Waddenzee – LiDAR acquisition for 2022

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1. General information

1.1 Customer

Name:	Nederlandse Aardolie Maatschappij B. V.
Address:	Schepersmaat 2 9405 TA Assen PO BOX 28000 9400 HH Assen The Netherlands
Contact person:	Raoul Quadvlieg Geomatics Manager NAM

1.2 The project

Name:	Waddenzee – LiDAR acquisition for 2022
Number:	41700
Area:	Pinkegat and Zoutkamperlaag in the Wadden Sea, in the north of the Netherlands

1.3 Contractor

Name:	Terratec AS
Address:	Vækerøveien 3 0281 Oslo Norway
Project manager:	Andreas Velle Wiger
Project number:	10456

1.4 Coordinate system

Horizontal datum:	Amersfoort
Projection:	RD New (Oblique Stereographic)
Vertical datum:	Normaal Amsterdams Peil (NAP)

1.5 General project description

The Wadden Sea in the north of the Netherlands is the ultimate interface between land and sea and because of its mudflats and tidal shallows it is very sensitive to changes in dynamics such as erosion by sea level rise, marine sedimentation and surface subsidence due to gas production.

The objective of this survey is to acquire and process LiDAR data in order to monitor the dynamic process of the mudflat in Pinkegat and Zoutkamperlaag in the Wadden Sea using airborne LiDAR. Given the measured time-lapse topography over time change of morphological parameters such area, height and volume of the mudflat can be derived. The deviation of the morphological parameters is subject to an independent analysis which is out of scope of this project.

1.6 Project coverage

The figure below shows the location of coverage the 2 areas in the Waddenzee project.

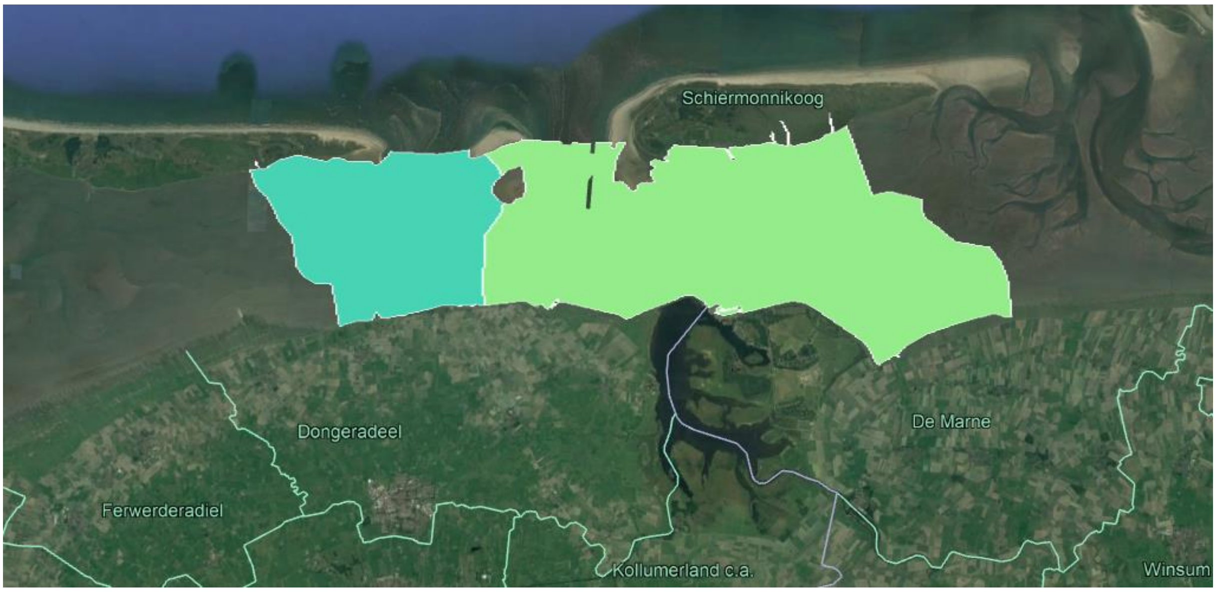


Figure 1: Project area Waddenzee

1.7 Quality assurance

The project is executed according to Terratecs quality assurance system. On this project, the following aspects have been emphasized.

- Calibration of sensor system
- Crossing calibration lines
- Matching of flight lines
- Adjustments and control by measured points

2. Ground control points (GCP)

Ground control points are delivered by the customer. These points are high accuracy measurements of surfaces.

The CP's are grid measured on a flat area that are spread in the project as shown on the image below. The average of difference between CP's and laser points in all areas are used for adjusting the dataset.

Figure 2: Image shows location of collected GCP's

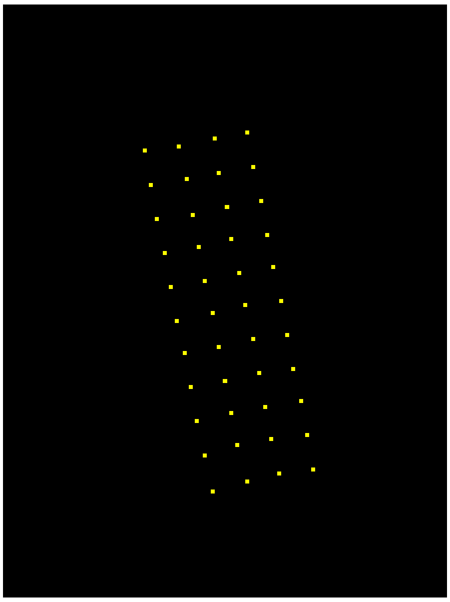


Figure 3: Top view of GCP-5 distribution

3. Data capture

3.1 Survey platform specifications

The survey was performed with one LiDAR sensor - the Riegl VQ-1560 II-S - mounted in the aircraft LN-LOL, a Cessna 208B. The same LiDAR scanner was used for the previous survey in 2021 but has since been upgraded from the older VQ-1560 II.

<table>
<tr><th colspan="2">Sensor</th><th colspan="6">Mount / navigation / LiDAR control</th></tr>
<tr><td>Manufacturer, type</td><td>Riegl, VQ-1560 II-S</td><td colspan="2">Gyro mount</td><td colspan="4">SOMAG GSM4000</td></tr>
<tr><td>Serial number</td><td>S2224041</td><td rowspan="6">Navigation system</td><td>Manufacturer, type</td><td colspan="4">Applanix PosTrack 610 V6
s/n 10486</td></tr>
<tr><td>Focal length (mm)</td><td>N/A</td><td rowspan="2">GNSS-receiver</td><td rowspan="2" colspan="4">Trimble BD982
s/n 5828C00373</td></tr>
<tr><td>Rev nr.</td><td></td></tr>
<tr><td>Last calibration</td><td>2022-03-01</td><td>GNSS-antenna</td><td colspan="4">Trimble AV39
(AERAT1675_180)</td></tr>
<tr><td>FMC</td><td>N/A</td><td>IMU</td><td colspan="4">Applanix IMU-57
s/n 19515</td></tr>
<tr><td>Radiometric res.</td><td>N/A</td><td>Logging rate (Hz)</td><td>GNSS</td><td>5</td><td>IMU</td><td>200</td></tr>
<tr><td colspan="2">Aircraft</td><td colspan="2">LiDAR control system</td><td colspan="4">Riegl RiACQUIRE</td></tr>
<tr><td>Manufacturer /type</td><td>Cessna 208B</td><td colspan="2" rowspan="2">Boresight-calibration</td><td colspan="4" rowspan="2">2022-03-18
(ID: L504_2022_01)</td></tr>
<tr><td>Registration</td><td>LN-LOL</td></tr>
<tr><td>Pressurized</td><td>No</td><td colspan="2">IMU-initialization</td><td colspan="4">S-turn before first flight line/
after last flight line</td></tr>
</table>

3.2 Acquisition parameters

The following acquisition were used for all lines in the project:

LiDAR:	
Flying altitude:	1750 m AGL
Max ground speed:	155 knots
Sensor:	Riegl VQ-1560 II-S
Total lines:	18
Total length:	239 nautical miles
FOV:	60 degrees
PRF per channel:	810 kHz
Total scan rate:	144 Hz
Laser Power Mode:	100%
Min. pt. density:	5,7 pts/m^2
Strip width:	1960 m
Lateral overlap	55 %

Out of the total of 18 flight lines, 5 of these are crossing lines used for matching purposes, and the remaining 13 are project flight lines. The customer requested a total surveying time of 3 hours. Based on this, a flying altitude of 1750 m above ground was chosen and other flight plan parameters have been adjusted to this.

3.3 Flight Plan

Project lines are represented in blue, while crossing lines are drawn in green. Water level stations are marked with red crosses, see Appendix 1 for full flight plan:

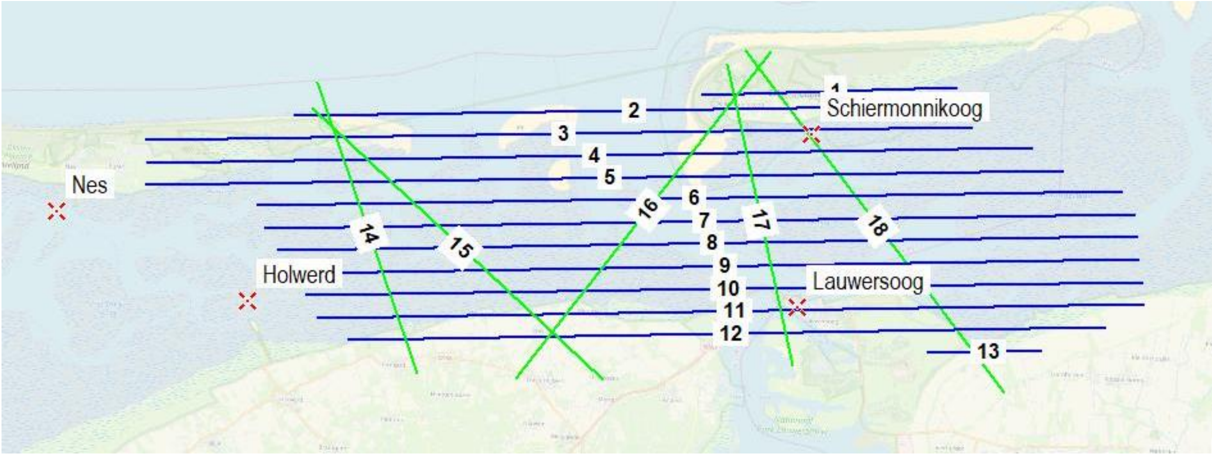


Figure 4: Flightplan and waterlevel stations

3.4 Execution of data capture

Mobilization from Rakkestad, Norway to Groningen Airport, The Netherlands was done on the 11th of July 2022. The survey, consisting of 13 project lines and 5 crossing lines, was done in one single flight with take-off and landing at Groningen Airport, on the 18th of July 2022. The return flight to Rakkestad, Norway was done the same day, on the 18th of August 2022.

Note: The airborne survey was planned to be take place on the 12th of July but could not be executed due to military activity in the airspace. Due to poor weather conditions the following days, the crew de-mobilized and returned to Groningen a few days later when the weather conditions changed for the better. The survey plane, LN-LOL, stayed at Groningen between the 11th and the 18th of July.

Due the opening hours at Groningen Airport, the survey was started 20 minutes after the predicted start time of the accepted tidal window. The predicted window was still long enough to complete the capture of the entire flight plan in one flight. When analyzing actual tidal levels during the acquisition, it became clear that measured water level at Holwerd deviated significantly from the forecasted values. However, only the northern flight lines (1-5) were captured during the high tide at Holwerd. For these lines, the water level at Nes and Schiermonnikoog are more representative. The crossing lines 14, 15 and 16 were re-flown at the end of the flight during low tide at all water level stations.

The total flying hours, including mobilization and de-mobilization can be seen in the table below:

Date:	**Take-off Airport / Time:**		**Landing Airport / Time:**		**Duration:**	**Purpose:**
2022-07-11	ENRK	12:45	EHGG	15:20	2:35	Mobilization
2022-07-18	EHGG	04:40	EHGG	08:00	3:20	Datacapture
2022-07-18	EHGG	10:40	ENRK	13:30	2:50	De-mobilization
Total:					**8:45**	

All times UTC
EHGG = Groningen Airport Eelde (HOL)
ENRK = Rakkestad Airport Åstorp (NOR)

3.4.1 All flown flight lines sorted by local time

Line number:	Date	Time (GMT+2)	Schiermonnikoog (cm)	Lauwersoog (cm)	Nes (cm)	Holwerd (cm)	Highest (cm)	Lowest (cm)
~~1~~	~~18.07.2022~~	~~06:58:48~~	~~-73~~	~~-104~~	~~-98~~	~~-41~~	~~-41~~	~~-104~~
1	18.07.2022	07:05:32	-79	-110	-103	-45	-45	-110
2	18.07.2022	07:09:30	-83	-114	-107	-47	-47	-114
3	18.07.2022	07:18:09	-92	-121	-114	-55	-55	-121
4	18.07.2022	07:27:09	-100	-126	-121	-61	-61	-126
5	18.07.2022	07:36:47	-106	-126	-128	-69	-69	-128
18	18.07.2022	07:47:57	-113	-133	-136	-80	-80	-136
17	18.07.2022	07:53:34	-116	-136	-138	-86	-86	-138
~~16~~	~~18.07.2022~~	~~07:58:28~~	~~-118~~	~~-138~~	~~-140~~	~~-91~~	~~-91~~	~~-140~~
~~14~~	~~18.07.2022~~	~~08:03:40~~	~~-120~~	~~-140~~	~~-142~~	~~-97~~	~~-97~~	~~-142~~
~~15~~	~~18.07.2022~~	~~08:08:05~~	~~-122~~	~~-142~~	~~-144~~	~~-101~~	~~-101~~	~~-144~~
6	18.07.2022	08:15:38	-125	-145	-146	-109	-109	-146
7	18.07.2022	08:24:43	-127	-149	-147	-119	-119	-149
8	18.07.2022	08:34:02	-130	-151	-144	-128	-128	-151
9	18.07.2022	08:43:07	-130	-148	-138	-136	-130	-148
10	18.07.2022	08:52:01	-128	-145	-134	-143	-128	-145
11	18.07.2022	09:00:45	-126	-144	-129	-149	-126	-144
12	18.07.2022	09:10:27	-124	-140	-120	-155	-120	-140
14	18.07.2022	09:20:35	-120	-137	-108	-156	-108	-137
15	18.07.2022	09:24:57	-119	-134	-102	-153	-102	-134
13	18.07.2022	09:32:26	-117	-127	-91	-146	-91	-127
16	18.07.2022	09:38:41	-114	-122	-80	-139	-80	-122

- *Crossing lines are represented in grey font. Project lines in black.*
- *Water levels are given in cm NAP (Normaal Amsterdams Peil) and are given for the start time of each flight line.*
- *The values for “Highest” and “Lowest” water level of flight lines captured outside of the allowed water level of -70 cm NAP are highlighted in red.*
- *Flight lines that are excluded from the delivery are written in “strikethrough”: ~~example~~*

3.5 Survey risk assessment

See "Appendix 8 – Survey Risk Assessment"

3.6 Reports of near-miss and incidents

No near-misses, accidents or any other events compromising the safety of the crew occurred during the project survey.

4. Navigation

4.1 Navigation processing

To form trajectories of position and orientation (angles), GNSS (Global Navigation Satellite Systems) and IMU (Inertial Measurement Unit) observations are post processed using one common Kalman filter, followed by a backwards filter recursion ("Rauch-Tung-Striebel-smoother"). This tightly coupled processing strategy ensures an optimal parameter estimation and error detection capability. The GNSS estimation integrated in this process follow the PPP (Precise Point Positioning) -processing strategy where linear combinations of code and phase observations from at least two frequencies, from at least GPS and GLONASS satellite systems are the main observables.

As part of the navigation processing, the (from calibration known) GNSS antennas phase center eccentricities and -variations, together with the observations (angles) from the sensor's gimbaled mount, are used to ensure high accuracy on the varying eccentricity between IMU mounted on the sensor, and the GNSS-antenna mounted on the outside of the aircraft.

The navigation post processing is performed using the software TerraPos, developed and maintained by Terratec AS. For lidar data, the software version used is specified in the report from each processing result, while for image data, the version is specified in the header of the corresponding EO (Exterior Orientation) -file. Formal precision of position and attitude is also documented in the same documents.

4.1.1 Evaluation of the navigation processing result

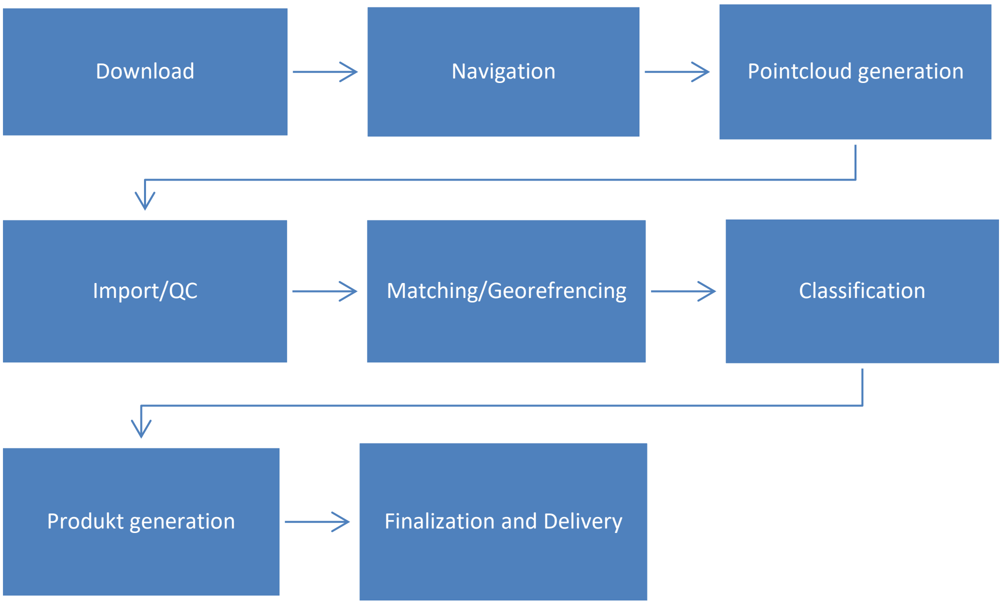
All navigation processing results used in this project has been evaluated against a Quality Control check list. This evaluation includes (but are not limited to) verifying that the data set is suited for PPP processing, evaluating number of detected and repaired cycle slips, code and phase observation residuals, and fraction of observations detected as outliers.

All navigation solutions (trajectories) used in this project has passed the quality control without remarks.

See appendix 3 for navigation quality plots.

5. Laser scanning execution

5.1 Workflow



5.2 Software

Navigation:

- Terrapos (vers 2.5.90)

Laser Processing:

- RiProcess (vers 1.8.5)
- Terrasolid (vers 19)
  - TerraMatch
  - TerraScan
  - TerraPhoto
  - TerraModel

5.3 Sensor calibration

Calibration of our sensors are performed by both the sensor manufacturer and Terratec.

5.3.1 Factory calibration

The manufacturer performs a sensor calibration. The calibration report and system parameter set are delivered along with the sensor. Factory calibration is also performed after repairs/upgrades and periodically according to service and maintenance plan.

See appendix 4 for factory calibration report

5.3.2 Calibration of installed system

A calibration is performed at first time installation in aircraft, with changes in factory calibration or changes in the physical installation. In this calibration angle differences between components are solved and lever arms between GNSS antenna, IMU- and laser sensor are estimated. The lasers' range correction parameters are controlled against surveyed control points on ground.

5.3.3 System calibration

A system calibration is performed at a calibration field in Fredrikstad, Norway. This is to verify that the system is within specifications and to calibrate the sensor to ensure best possible quality. Boresight angles and range correction values are the most important parameters to control in the project calibration.

There is also an estimation of boresight angles and performed on the actual project data. This is done to eliminate small residual errors locally.

5.4 Transformations

The navigation solution in TerraPOS is processed in WGS84. Transformation to Amerfoort/RD New with NAP heights is done with software TerraScan from Terrasolid OY.

5.5 Point cloud processing

The point cloud is processed using the system manufacturers' software. Factory calibrated values and installation values are used to calculate point clouds for each flight line. The point clouds are outputted in WGS84 geocentric.

5.6 Project calibration

A calibration per flight session is performed. Correction values for Heading, Roll, Pitch and Z are estimated and applied if they are found significant and reliable.

Evaluation of results:

No abnormal values have been found during this process.

Results from the project calibration is shown in appendix 6.

5.7 Flight line matching

A relative matching is performed to solve for random deviations between flight lines. Best match in roll and Z between lines are calculated. All flight lines are involved in the calculations. The matching is evaluated by calculating elevation differences between flight lines in areas where they overlap.

5.8 Lidar coverage control

A manual inspection is done to ensure that the whole area of interest is covered by the point cloud.

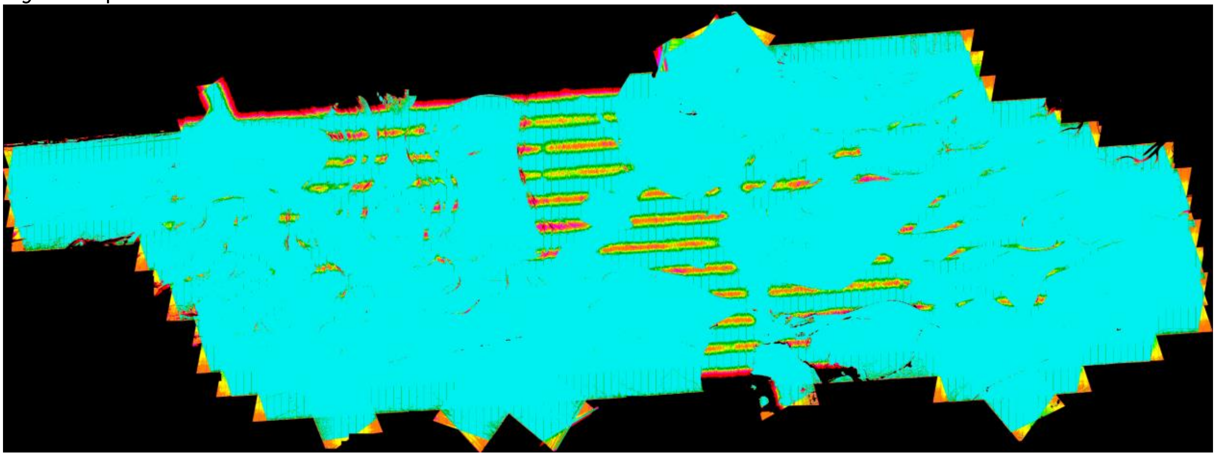


Figure 5: 4pkt/m2 on a 10m grid

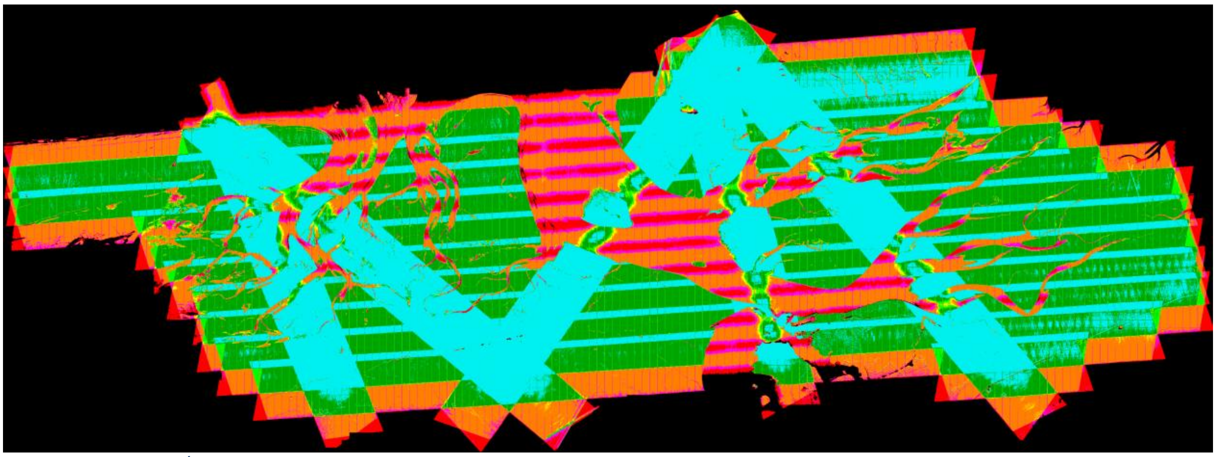


Figure 6: 10pkt/m2 on a 10m grid

Palette used in images:

4pkt/m2 pallet

0	0,4	10 %	
0,4	1,6	40 %	
1,6	2,4	60 %	
2,4	3,4	85 %	
3,4	4	100 %	
4	4,6	115 %	
4,6	6	150 %	
6	100	> 150 %	

10pkt/m2 pallet

0	1	10 %	
1	4	40 %	
4	6	60 %	
6	8,5	85 %	
8,5	10	100 %	
10	11,5	115 %	
11,5	15	150 %	
15	100	> 150 %	

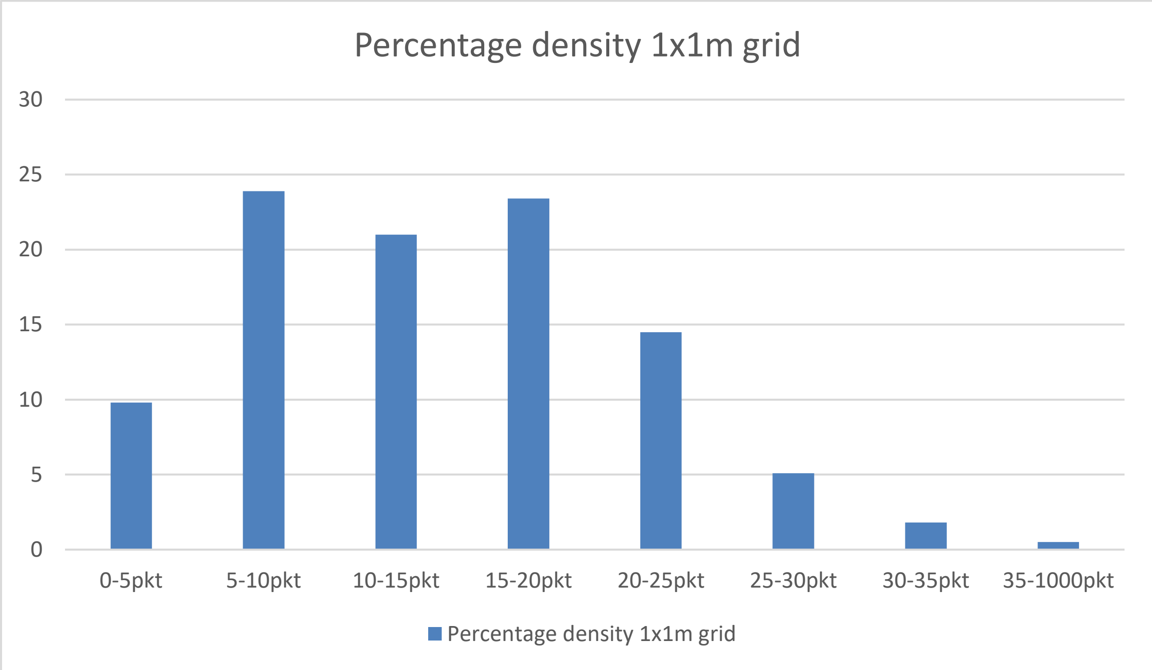


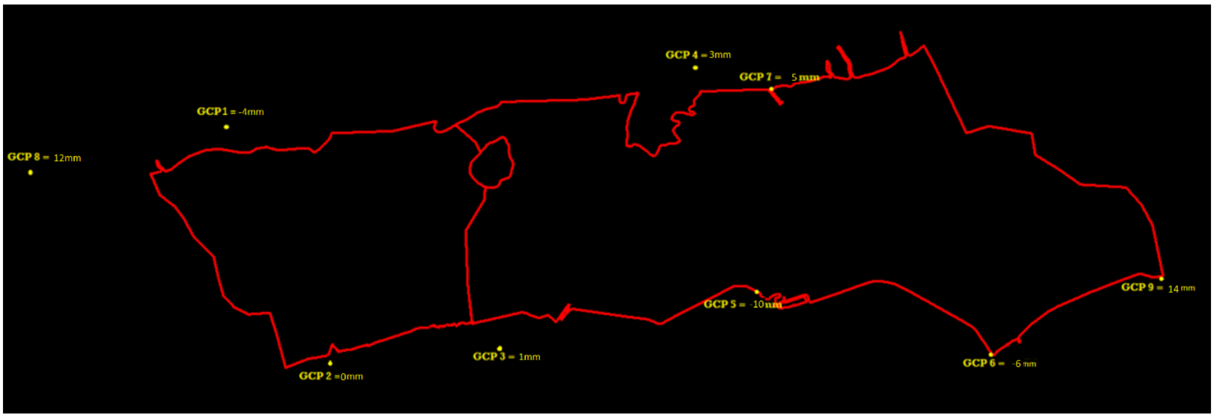
Figure 7: Project density histogram. Y-axis shows percentages of 1x1m tiles with specific density.

5.9 Height accuracy

Control against ground control points:

The height quality of the point cloud has been controlled by comprehensive manual inspections against the GCPs. The overall manual inspections have shown avg height deviations of no more than 1-2cm. The result is shown in the table below.

Control Surface	Average dZ (m)	Minimum dZ (m)	Maximum dZ (m)	Average magnitude (m)	RMS	Std. Dev
GCP - 1	-0.004	-0.015	0.024	0.007	0.009	0.008
GCP - 2	-0.000	-0.023	0.020	0.008	0.010	0.010
GCP - 3	0.001	-0.027	0.023	0.009	0.011	0.011
GCP - 4	0.003	-0.021	0.020	0.008	0.010	0.009
GCP - 5	-0.010	-0.043	0.014	0.013	0.016	0.013
GCP - 6	-0.006	-0.028	0.015	0.009	0.011	0.009
GCP - 7	0.005	-0.012	0.043	0.009	0.012	0.011
GCP - 8	0.012	-0.038	0.042	0.017	0.020	0.016
GCP - 9	0.014	-0.030	0.049	0.019	0.023	0.018



Figur 5 Overview of Control Surfaces after adjustment

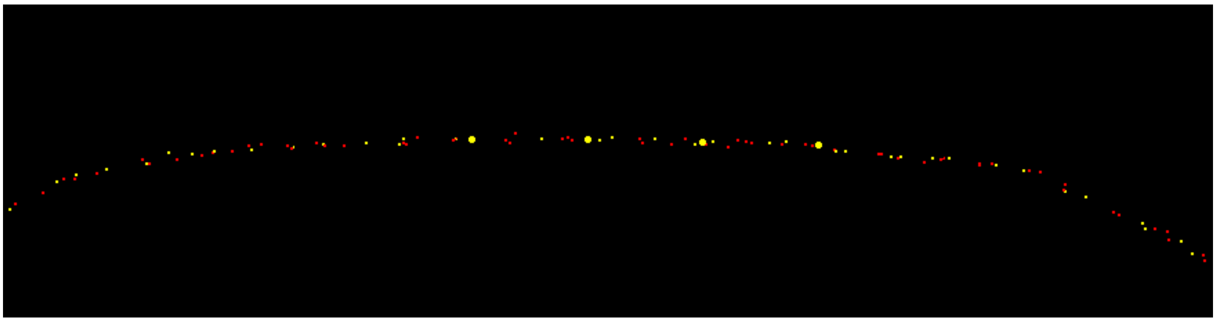


Figure 9: Control surfaces (yellow) after adjusting laserdata. The different colors represent different flightlines

<u>Evaluation of result:</u>

The delivered CP points delivered from customer are well distributed at the edges of the project, with adjustment results within specs. Giving good CP adjustment as seen in images above. The deviations shown in the table are within expectations. The CP adjustment done has been a direct linear height adjustment, which is identical in the entire project.

5.10 Conclusion georeferencing

The results from calibrations, matching and control against known points shows that the data is of very good quality and well within the expected values.

5.11 Reflectance

The data has been produced with reflectance. Reflectance is amplitude corrected for range – i.e. the effect of amplitude reducing with range of intensity spectrum. This gives intensity values for the same object homogeneous values no matter scan angle returns.

Amplitude – The raw measurement of the power strength of the return echo. It is the value of the power of the light that we receive back from the target. Later on, during real-time post processing, we receive amplitude which is defined as the ratio of the actual detected optical amplitude of the echo pulse versus detection threshold of the instrument. Thus, the value of the amplitude reading is a ratio, given in the units of decibel (dB). By introducing amplitude readings in this way we can use it to improve the object classification. Amplitude depends on the distance, further away the scanner is from the target the less power it receives.

Reflectance – A target property. Refers to the optical power that is reflected by that target at a certain wavelength. RIEGL's V-Line instruments provide a reflectance reading for each detected target as an additional attribute. The reflectance provided is a ratio of the actual, optical amplitude of that target to the amplitude of a diffuse white flat target at the same range reading is given in decibel (dB). Negative values indicate diffusely reflecting targets, whereas positive values are usually retro-reflecting targets. Reflectance is distance independent, thus is a perfect attribute for many different classifications and further processing.

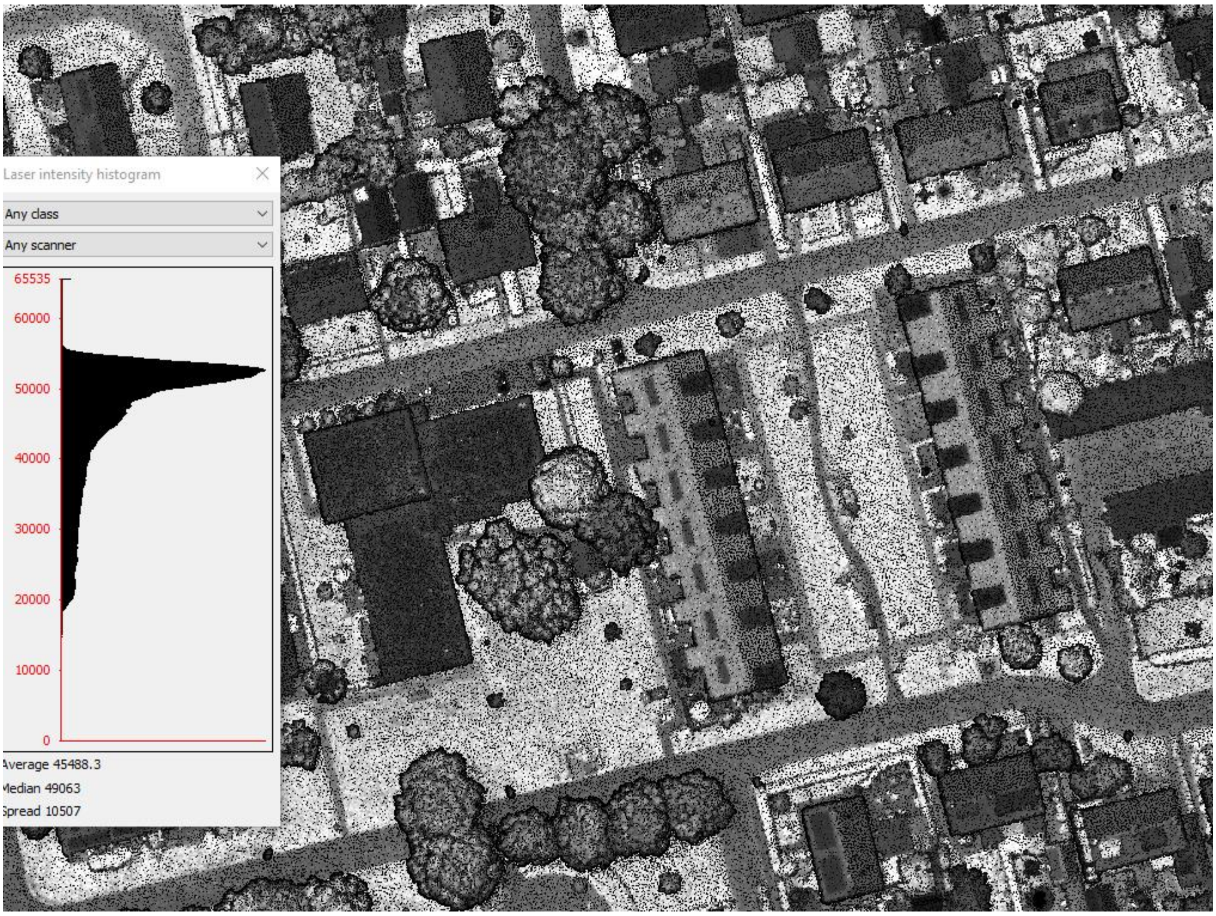


Figure 10: Image shows intensity values in top view with histogram

Figure 11: Image shows intensity in cross section / 3D view

6. Point cloud classification

Automatic methods are used to classify the point cloud. In this project the laser data is divided into following classes:

1) Unclassified
2) Ground
7) Noise

6.1 Ground classification

Terrain surface points are classified as class 2. This class also contain points on water surfaces where these have reflected the LIDAR beam.

Classification of ground points is the most time-consuming part of classification. In this process automatic filtering through defined algorithms is performed. The challenge with this filtering is to find the parameters that is best at picking out points that are describing details in the terrain surface not adding vegetation or other features that are not considered ground. Factors that influence the choice of parameters are point density, topography and the density of vegetation coverage.

In this project, only the automated ground classification has been done, there has been no manual editing of the data.

6.2 «Noise» filtering

Noise points are filtered out. These are erroneous registered points caused by multi path reflections, airborne particles (e.g. water, dust) or objects like for example birds. Most of these points are filtered out by automated classification routines.

6.3 Classification «non-ground»

Points that are not considered to be ground or noise are classified as class 1.

6.4 Evaluation of classification

This project has been automatically classified using TerraScan. Classification is good considering that there has not been performed any manual editing.

7. Delivery of point cloud

7.1 Overview of files in the delivery

- Laserdata
  - Tiled in 250x250 blocks
  - Per flightline
- Navigation
  - SBET, full navigation for laser
  - TRJ – files per laserline

7.2 Folder structure

- 10456 Waddenzee 2022 (41700)
  - 01_Report
  - 02_Lidar
    - 01_LiDAR_Block_Tiles
      - Lidar_Block_Tiles_Laz.rar
    - 02_LiDAR_Per_Flight_Line
      - Flight_Line_Laz.rar
    - 03_NAVIGATION
      - 01_SBET
      - 02_TRJ

8. Appendixes

Appendix 1: Flight Plan Waddenzee 2021 - 41415_01_01_FW_L500

Appendix 2: LiDAR_flightreport_LN-LOL-2_20220718

Appendix 3: GNSS-INS

Appendix 4: Factory Calibration VQ-1560 II-S, S2224041

Appendix 5: System Calibration VQ-1560 II-S, L504_2022-1

Appendix 6: HPR Correction

Appendix 7: dZdR Correction

Appendix 8: Risk Assessment Shell (C208B)