Waddenzee LiDAR Survey
September 2014

Final Report

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Client: *Nederlandse Aardolie Maatschappij*
Author: *Fugro Geospatial B.V.*
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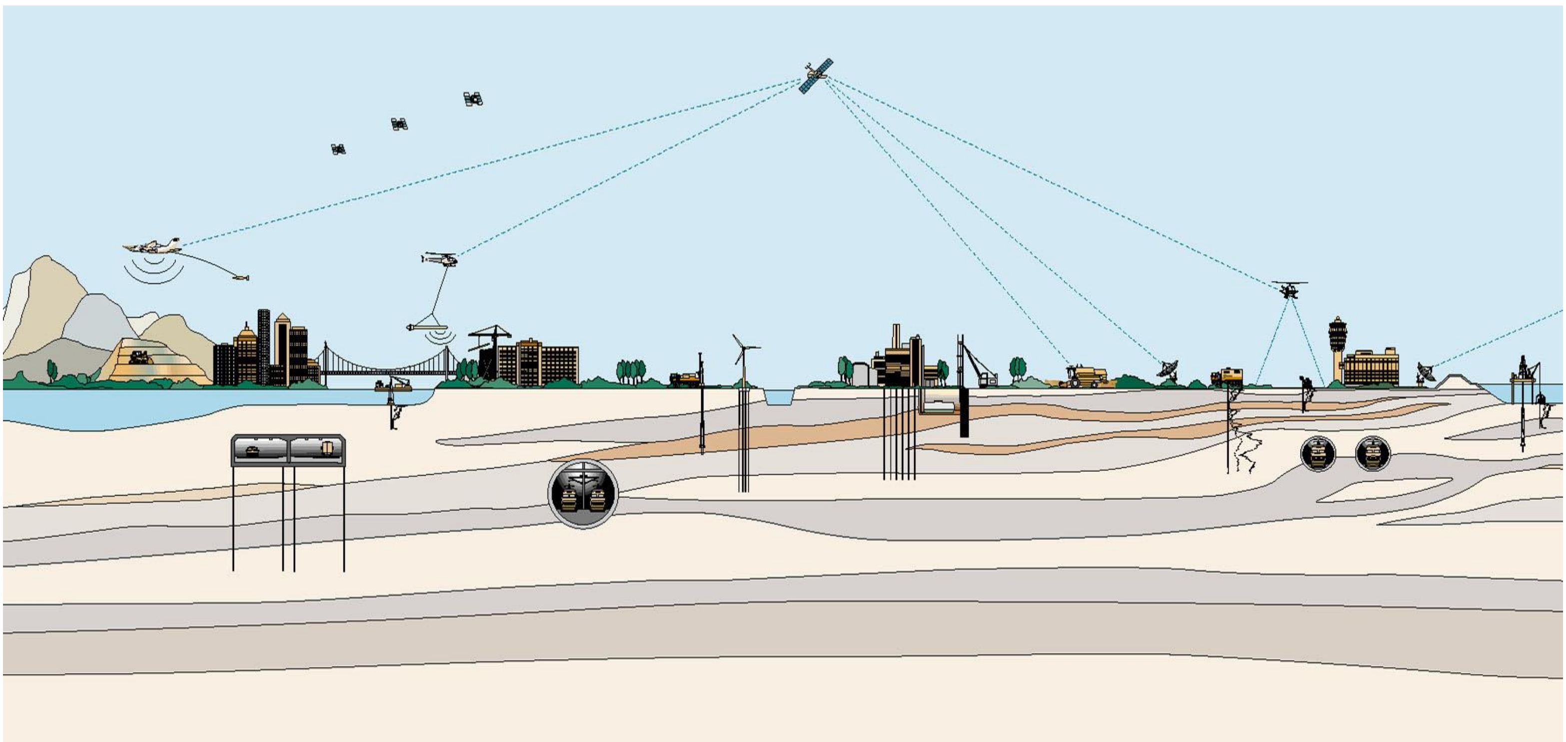

1. Introduction

In September 2014, Fugro Geospatial (Fugro in this document) carried out an airborne LiDAR survey for the Nederlandse Aardolie Maatschappij (NAM in this document).

The aim of this survey is to monitor the mudflat areas Pinkegat and Zoutkamperlaag in the Waddenzee.

This project was carried out for the 7th time; the previous surveys were executed at the following moments:

- April 2010
- April 2011
- September 2011
- October 2012
- October 2013
- May 2014

In the past, the surveys were carried out with the FLI-MAP 1000 scanner, but since 2013 it was carried out with a Riegl Q680i laserscanner, because it is concluded that using the Riegl scanner will lead to a higher point density and better reflectivity on these wet areas.

The applied flightplan for this survey was identical to the 2013 survey.

Further processing was directly started after finishing the survey. The end deliverables were delivered together with this report on a separate hard disk.

The final deliverables were delivered to Deltares (contracted analysis partner of NAM) and to NAM on a hard disk on the 21st of November 2014.

This report provides the relevant project information. After a short description of the project in Chapter 2, the data acquisition, data processing and data quality control are described in Chapters 3, 4 and 5 respectively. Chapter 6 consists of information about the creation of the end deliverables. In Chapter 7 a note on the comparison between different surveys is given and finally in Chapter 8 a summary of all conclusions is given.

Appendices are digitally attached to the report.

2. Project specifications

2.1. Project Area

The airborne survey covers the areas Pinkegat and Zoutkamperlaag. The survey area and flight lines are shown in Figure 1. The survey encompasses 820 kilometres of flight lines with an east-west orientation (indicated in blue) and five cross lines (indicated in pink). The area to be covered is indicated with the red line.

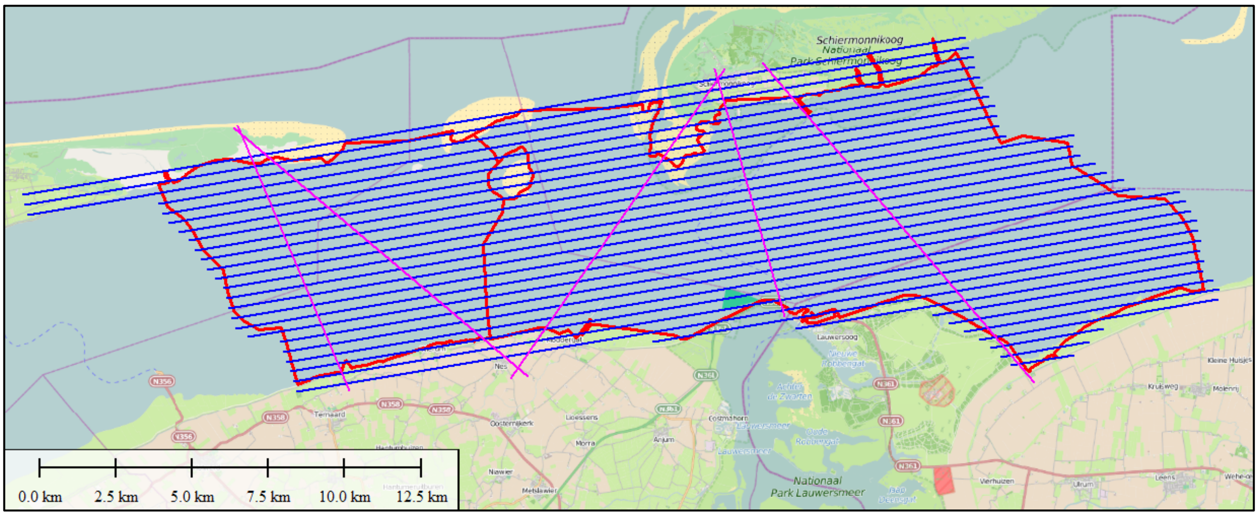

Figure 1: Project area and flightlines

The digital boundary file is attached in Appendix A.

2.2. Demands and conditions for survey

The project has been executed according to the tender (our reference OF-14-01-ASM11515) as stated by Fugro.

The survey needs to be executed while the water level is below -0.70m NAP at Nes tidal station.

The survey was executed with a Riegl Q680i scanner. Furthermore, five cross lines were flown to obtain a better relative accuracy (see Figure 1). The cross lines are situated over the control grids on the edges of the project area (see Figure 4:) to be able to check and enhance the absolute accuracy.

Simultaneously, aerial images are collected using a Phase One digital camera. These images were used to attach an RGB value to the laser points. Due to this requirement, the surveys could only be executed during daytime.

The Tables below show the specifications that were used during the survey.

Survey platform:

#	Surveying platform	
1	Aircraft type and model	Piper PA31-350 (9H-FMH)
2	GPS/INS type and model	Trimble BD950 POS AV 510
3	Scanner type and model	Riegl Q680i
4	Aerial camera type and model	Phase One

Flight parameters:

#	Parameters	Value	Unit
1	Height AGL	440	m
2	Speed	120	kts
3	Flight direction	E-W	
5	Line spacing	338	m
6	Theoretical overlap between lines *	170	m
7	Number of lines	33	-
8	Number of cross lines	5	-

Scan parameters:

#	Parameters	Value	Unit
1	Scan Angle	(±)30	°
2	Frequency	200	kHz
3	Point density	4.3	pt/m²
4	MTA Zone	1	

Image specifications:

#	Specifications	Value	Unit
1	Focal length	50	mm
2	Size of CCD matrix	7752x10320	Pixel x Pixel
3	Pixel size	5.2	µm
4	Image GSD	4.2	cm

*The theoretical overlap is calculated from the height AGL (above ground level), the line spacing and the aperture angle of 60º. However, this overlap is also planned to compensate for flight dynamics, so the real overlap will be variable. However a certain overlap will be guaranteed, because no gaps are allowed.

2.3. Client communication

During the execution of the flights, the client was updated on a daily basis.

In accordance to the clients requirement Fugro delivered a frequent processing update per e-mail accompanied by an up to date schedule for delivery and progress.

2.4. Quality, Health, Safety and Environment

The mission of Fugro Geospatial is to be one of the leading and most innovative companies in Aerial Survey and Mapping Services in Europe, Middle East and Africa, with healthy financial results and long term continuity of services. Fugro Geospatial is committed to be a reliable supplier for its clients, to provide a healthy and safe workplace for all its employees and partners and to protect the environment in accordance with applicable laws and the HSE Policy defined by the Fugro mother company.

Fugro is supported in this by the certification and adherence to OHSAS18001 and ISO9001.

On base of the conditions stated by Shell Aircraft International (SAI) Fugro received approval after an aviation on-desk audit. Fugro was assessed as being acceptable on evidence of the overall standards observed during a desk-top assessment in the key areas of operations, engineering, safety management and the assurance of quality.

Fugro flew with a Piper PA31-350 Navajo Chieftain aircraft, registration 9H-FMF, flown by Guillaume Bertrand and Lucas Smit. Both aircraft and commander have been approved for that survey by SAI.

Fugro executed and adhered to a comprehensive risk assessment for this project. None of the stated risks did happen. In appendix B the risk assessment is attached.

3. Data acquisition

3.1. Flight overview

The project has been coordinated from the field office at Teuge airfield. The survey was executed by a twin engine Piper Chieftain with call sign 9H-FMF. This plane has been approved by Shell Aircraft international before the survey started.

In Table 1 and Figure 2 a brief overview of the daily status of the project is given.

Date	Activity
20-09-2014	Mobilisation
21-09-2014	Survey Lines 06-19, Cross Lines 1-5
22-09-2014	Survey Lines 20-28, Cross Lines 1-5
23-09-2014	Survey Lines 29-38, Cross Lines 1-5
24-09-2014	Weather Standby
25-09-2014	Weather Standby
26-09-2014	Demobilisation

Table 1: Daily activity overview

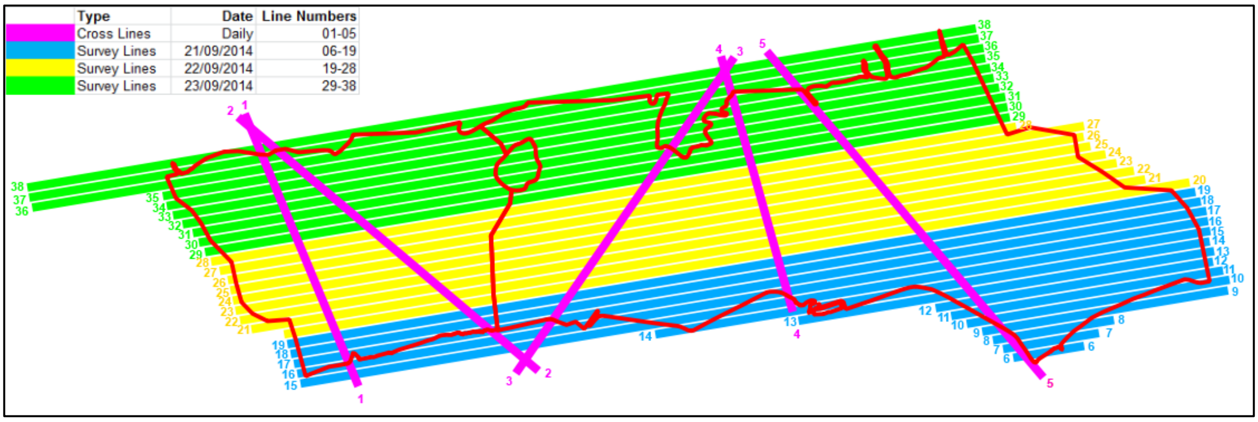

Figure 2: Flights of September 2014

3.2. Weather and tide

The weather was generally good, with mostly clear skies. The data acquisition was planned with tide level below the stated tide level -0.70m NAP, except for the cross lines. The majority of the regular lines have been flown within the stated tidal window. Lines 6 to 14 were flown with a higher water level (see Paragraph 3.2.1). The cross lines were flown before and after this window, with a slightly higher water level.

The cross lines are only used for matching of the regular flight lines. In order to be able to reliably match these lines, a dry surface has to be used anyway. Therefore, the fact that the cross lines are flown with a slightly higher water level it does not make very much difference.

Please see Appendix C for a more detailed overview of the weather and tide.

3.2.1. Lines 6 - 14

After the first survey day, it turned out the actual water level was higher than predicted for lines 6 to 14. An analysis was done straight after the survey to see what data was missed due to this higher water level. For this analysis the spring 2014 height data was coloured (see figure below) in the following way:

- Red: Data under the minimum water level (-0.70 cm NAP).
- Yellow: Data which might be lost by the higher water level.
- Green: Data above the maximum water level during survey.

Line	Measured Water Level
14	-0.67
13	-0.65
12	-0.62
11	-0.60
10	-0.57
9	-0.52
8	-0.50
7	-0.45
6	-0.43

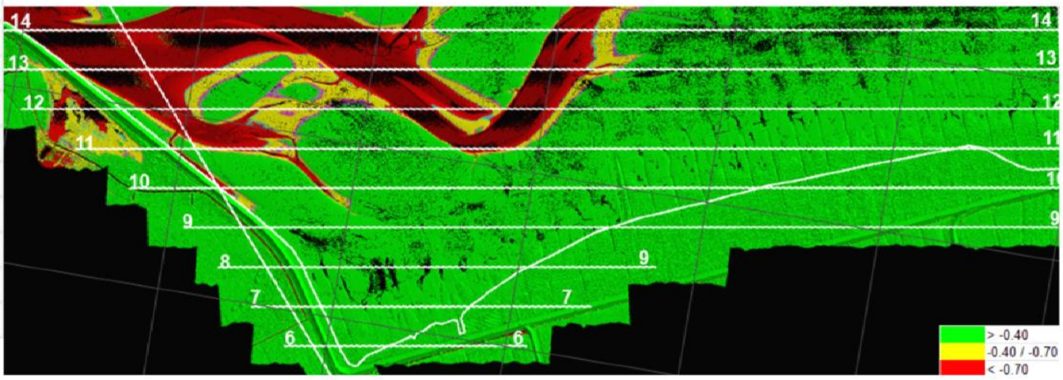

Figure 3: Water levels per line at the time of flight, incl. height data spring 2014

The lines were flown in sequence from south to north. From Figure 3 it can be seen that on the lines 6 to 10 no loss of data can be expected as a result of the higher water level during acquisition. The first problems might occur from line 11 onwards (bigger yellow areas in the image), however during acquisition the water level has already dropped to -60 cm NAP at line 11. Therefore the loss of data was kept to a minimum.

Therefore it was decided to first finish the project and if weather and tide would permit the lines would be re-flown. Unfortunately on Wednesday and Thursday the weather didn't allow for a re-flight of the lines.

3.3. Cross lines

The five cross lines have each been flown at least once per day, see Table 2. Every day 3 lines were flown before and 3 lines were flown after the survey

Date	Cross Line 1	Cross Line 2	Cross Line 3	Cross Line 4	Cross Line 5
21-09-2014	Before	After	Before and after	After	Before
22-09-2014	Before	After	Before and after	After	Before
23-09-2014	Before	After	Before and after	After	Before

Table 2: Number of times each cross line was flown

3.4. Ground control

To check the absolute accuracy (see Paragraph 5.6) terrestrial control grids have been used. During the survey of October 2013, already 8 control grids on hard surface were surveyed. As this survey took place less than a year ago, it was decided not to measure them again but use the existing elevations. It is however known that the mainland is also subsiding, so for future surveys a correction of the GCP's has to be taken into account.

Only for one location, GCP-1 a small adjustment took place. The reference bolt for this location was updated, therefore the grid has got a correction as well. This is however in the magnitude of a few millimetres, so it does not have a significant influence on the survey.

Besides this grid, four control grids on the mud flats were surveyed. In contrary to the grids on hard surface, these locations have been measured again in the same period as the LiDAR survey. The control grids are surveyed using GPS-RTK.

In Figure 4: an overview of these locations is given. The locations indicated in green (GCP-1 to GCP-9) are the grids on hard surface, the others (in blue) are the grids on the mud flats. These areas are used to check the positioning of the flights. The cross lines are displayed as well, to show that these are planned over the hard surface GCP locations.

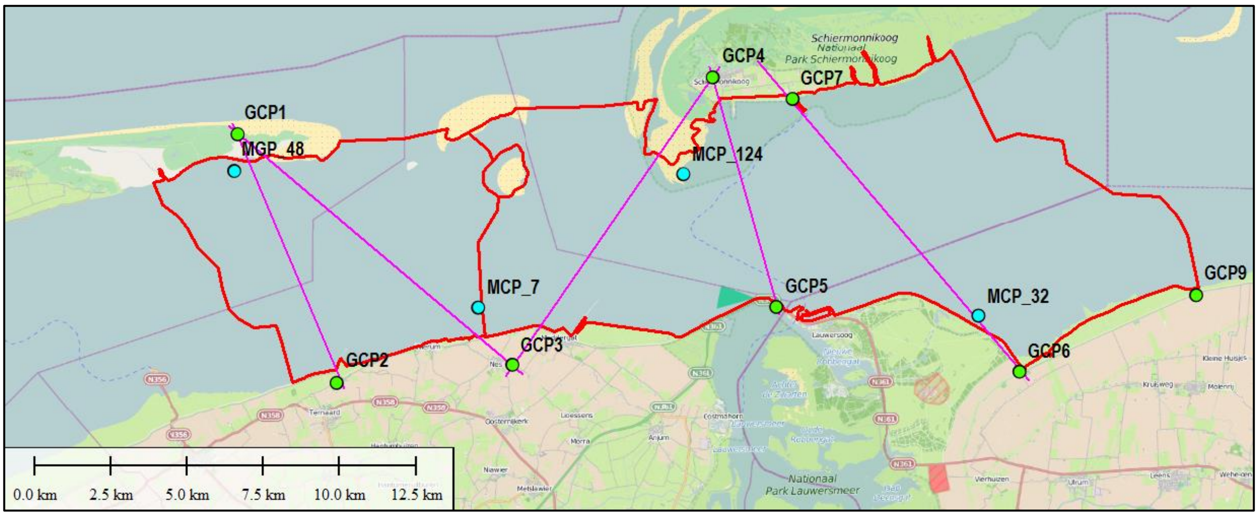

Figure 4: Overview of Ground Control Points and Mud Control Points

4. Data processing

4.1. Geodesy

4.1.1. Horizontal

The datum parameters used for this project are listed below:

Datum:	RD
Map projection:	Stereographic
Latitude of origin:	52º 09’ 22.178’’ N
Central meridian:	5º 23’ 15.500’’ E
False Easting:	155000
False Northing:	463000
Scale Factor:	0.9999079
EPSG Code:	28992
Ellipsoid:	Bessel 1841
Semi-major axis a:	6377397.155
1/f:	299.152812825

For the transformation between ETRS89 coordinates and RD the RDNAPTRANS 2008 correction grid is used.

4.1.2. Vertical

The NLGEO2004 geoid model is implemented in the RDNAPTRANS2008 transformation. This model is applied to transform the WGS-84 height to the orthometric NAP-heights. This is applied for both the LiDAR survey as the terrestrial surveys.

4.2. Base Stations

Fugro makes use of tightly coupled GPS-processing. A network of actual base stations or virtual base stations closely surrounding the flight is selected. The acquired data is used to calculate a base line between the reference stations and the GPS antenna on the aircraft. The GPS RMS is calculated and checked with the specifications. The forward/reverse flight path is calculated to check the reliability of the solution.

In this case the data from the 06-GPS stations Drachten, Ballum, Veendam and Borkum were used. The survey area is close to these four stations, leading to an optimal solution.

4.3. Field processing

Most of the data processing that was done in the field relates to Quality Control and Data Management. Quality Control is discussed in Chapter 5. Data Management activities in the field include making back-ups on separate hard disks, putting the data with correct file names in the right directories and complete the right data management forms.

Processing was mainly done with Riegl software for data extraction and tools from Fugro Horizons for QC (coverage, density and noise).

4.4. GPS and INS Flight Trajectory Calculations

The software package AEROoffice from IGI and POSGNSS from Applanix are used for flight trajectory calculations. Tightly coupled solution was used to process the observables of the CORS stations combined with inertial navigation and the GPS antenna attached to the aircraft.

The locations of the CORS stations are in the vicinity of the flight path of the aircraft with an interval of no greater than approximately 60 km to ensure a good calculation of the flight trajectory.

The processing workflow generally consists of four steps:

Step 1 – Processing the SBET (Smoothed Best Estimated Trajectory)
Step 2 – Extraction of LAS data and combining all of the LAS in a single project
Step 3 – Searching for corrections and adjusting of LAS data inside of the project.
Step 4 – Delivery.

So the corrections on the LiDAR data, based on overlaps between (cross)-strips and GCP's are determined in step 3. These corrections have been applied by adjusting the LAS data, using TerraMatch software, instead of adjusting the SBET, because this is a faster method.

4.5. RGB assignment

In order to make the Lidar point cloud more easy to interpret, natural RGB colours are assigned to the laser points. The Riegl laser scanner does however not capture these colours, therefore a different approach is followed where the aerial images are used.

After the data capture the images are georeferenced using the same trajectory as the Lidar data, to make sure these two data sets match well. By using specialized software for every laser point the nearest pixel in the aerial image is determined and the RGB value of that pixel is copied and assigned to the laser points.

5. Quality Control

In figure below, the processing and quality control procedure from acquiring the data to further end deliverables is shown. Every process needs a validation before the next step can be taken.

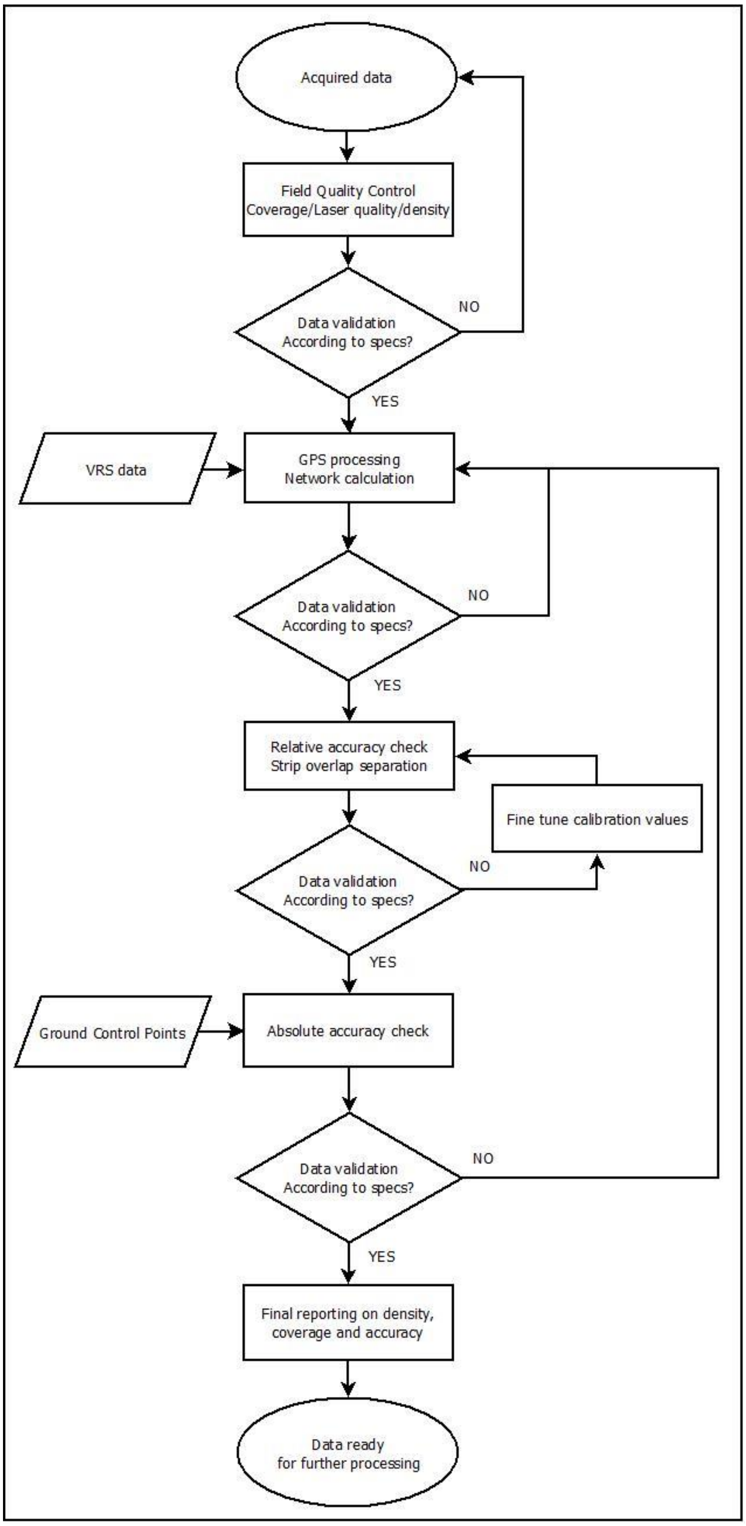

Figure 5: Processing flowchart

5.1. Laser quality

During and directly after the flight, some crucial checks are performed, to assure the data has been acquired up to the standards for further processing. The data is checked on:

- Reflection problems due to strongly absorbing material
- Lack of registered beams due to hardware glitches
- Excessive noise due to system failure

Analysing the error messages and quick views of the data concluded that no anomalies were present.

Reflection problems on the wet area of mud flats are considered to be LiDAR technology limitation thus are not recognized as a peculiarity during QC process. The final QC on the data confirmed this statement in a later stage.

5.2. Coverage

The coverage of the laser sensor is checked in the acquisition phase. The area covered by the sensor is compared with the boundary file supplied by the client (see Figure 1).

In Figure 6 an overview of all collected data of the September 2014 survey is given. The colours depict the average elevation, indicated by a repeating rainbow. It can be seen that the entire project area is covered. The only areas without hits are caused by water.

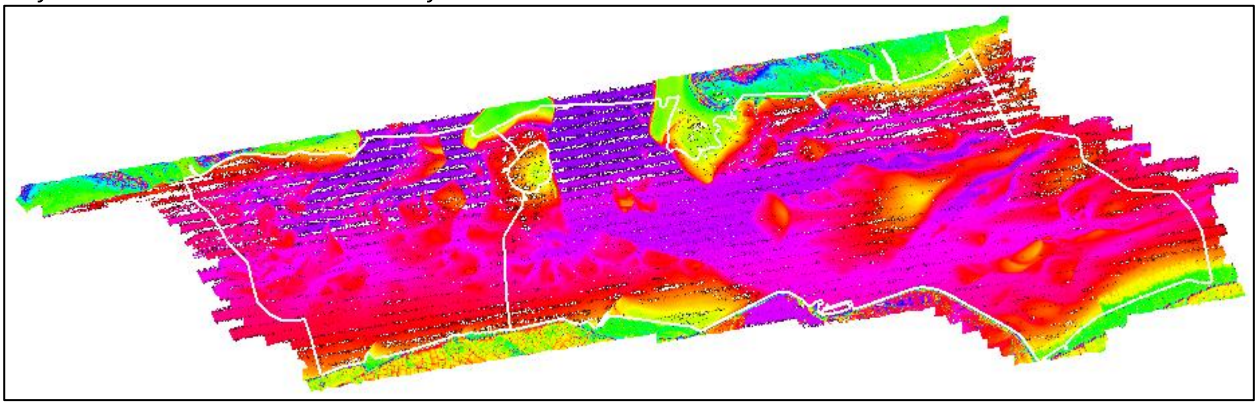

Figure 6: Coverage of the September 2014 survey

The coverage is also compared with the data set of the previous survey (May 2014), the results are shown in Figure 7 and Figure 8.

In Figure 7 the September 2014 data is projected over the May 2014 data:

- Red is the May 2014 data
- Green is the September 2014 data

Because the autumn 2014 data is on top, the red areas indicate the locations that were covered in spring 2014, but showed no hits in autumn 2014.

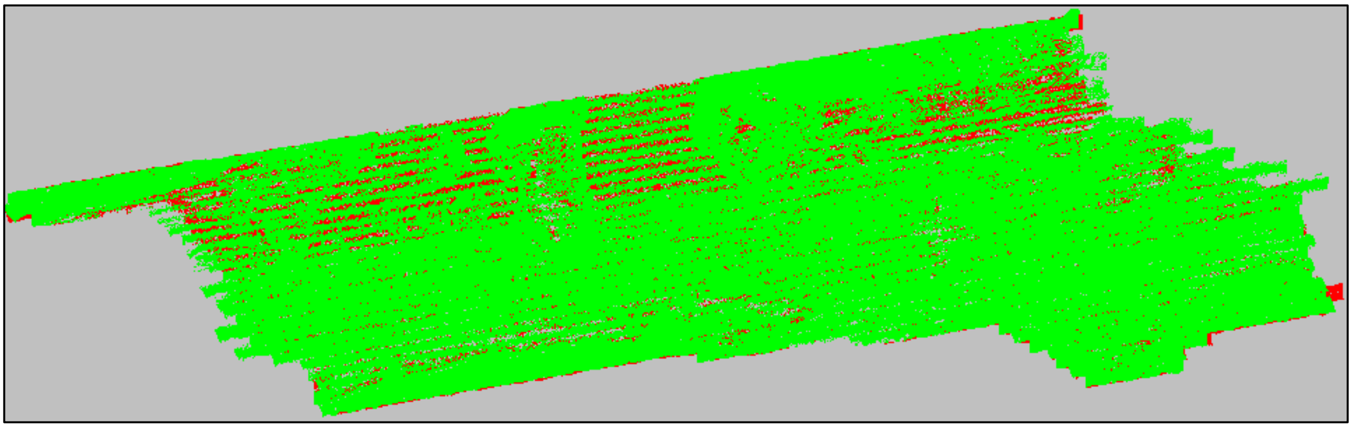

Figure 7: Coverage comparison, autumn 2014 over spring 2014

In Figure 8 the data is projected the other way around, using the same colour coding. So in these images the green areas indicate the locations that are covered in autumn 2014 but showed no hits in spring 2014.

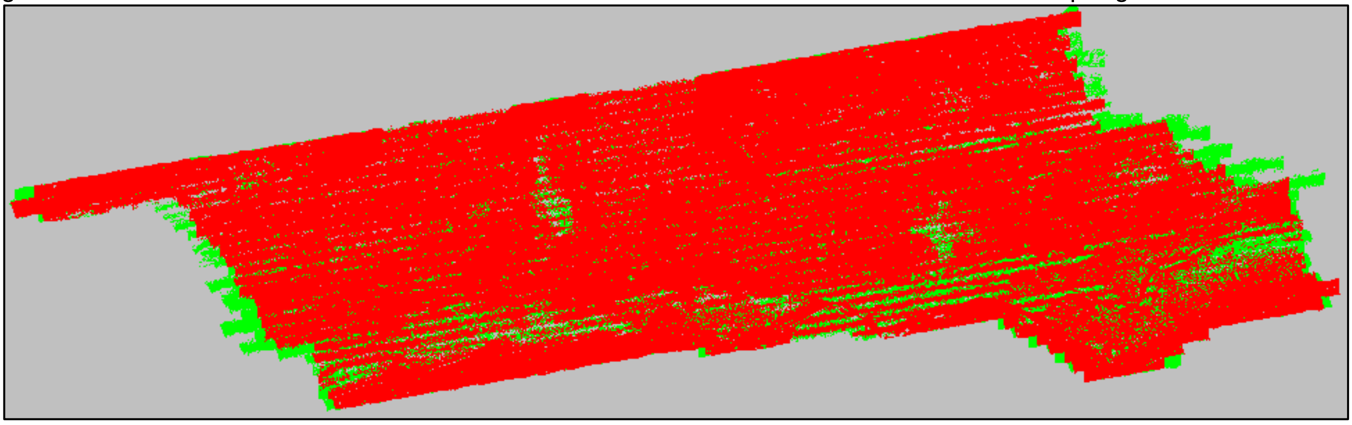

Figure 8: Coverage comparison, spring 2014 over autumn 2014

From these two images it can be concluded that, although local differences occur due to different conditions, the coverage with laser data is comparable. Due to the wet nature of the mud flats, there are more hits right below the aircraft and less to the side causing this striped pattern. However because the same flight plan was used in both surveys, this effect almost cancelled out.

5.3. Point Density

After the data acquisition a preliminary density check can be executed. The check on the point density requirements is executed in the post-processing phase. The amount of points per m^2 is calculated and according to a colour scheme visually checked on deviations from the expected point density. Point density reduction could take place in the following situations:

- Flight dynamics could cause local deviations in point density
- Lower reflection due to high absorbing material
- Terrain circumstances, like wet area's or steep terrain

Last two situations are considered to be LiDAR technology limitation thus the consequences (low density) of such are not mitigated or avoided during the acquisition phase.

In
Figure 9 an overview of the point density over the project area is given. The legend of this overview is as follows:

- Green: 4 or more points per m^2
- Red: < 4 points per m^2
- Black: No data or below -0.70 m NAP (so deep water areas)

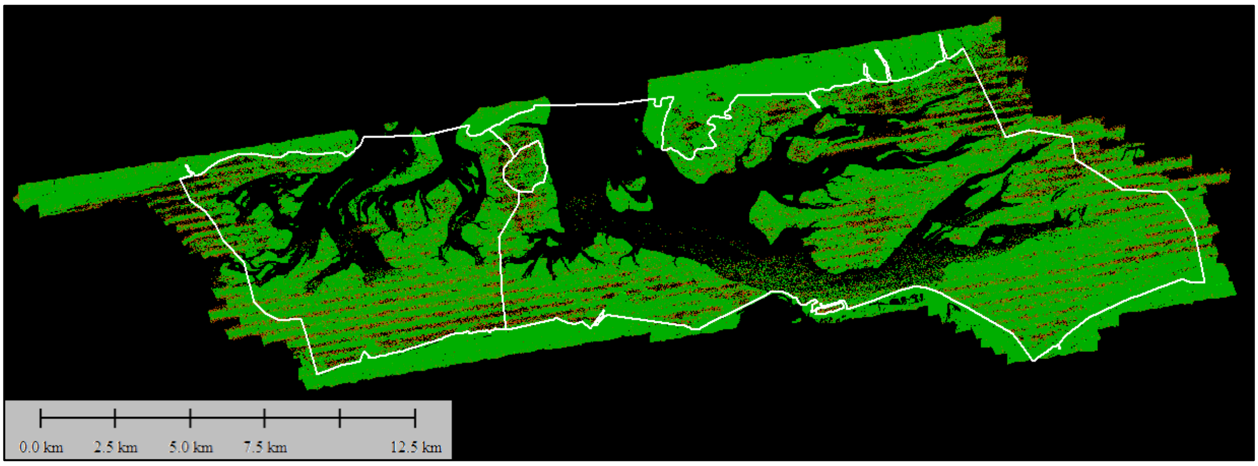

Figure 9: Point density overview

It is clearly visible that on the mainland and the islands the point density is always more than 4 points per m^2. On the mudflats the point density is generally also more than 4 points per m^2, however due to the lower reflections on wet areas there are some areas with a lower point density.

In deeper water only a few point just below the aircraft are collected, resulting in the striped pattern. In Figure 10 a detail of the point density plot is given.

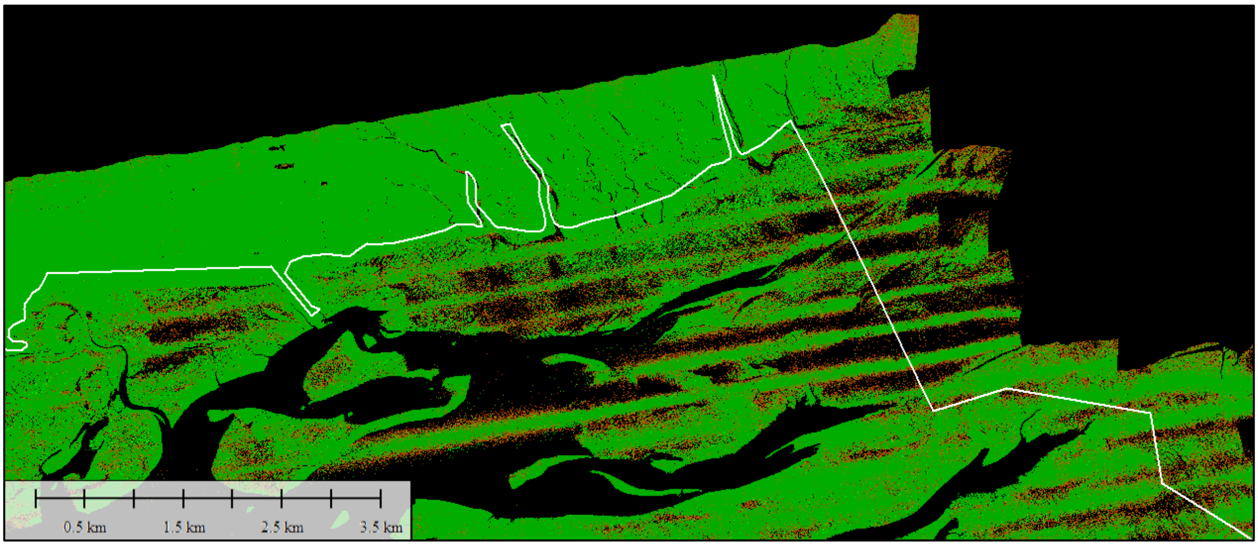

Figure 10: Detail of the point density plot

5.4. Theoretical accuracy

5.4.1. Theoretical errors of a single strip

In LiDAR surveys, usually a stochastic and a systematic error can be discriminated. The stochastic error indicates the high frequent noise of the LiDAR measurement system. Most of this noise will disappear when the data is gridded to a larger cell size. The systematic error indicates the low frequent navigational error. This error will remain constant over short periods of a couple of seconds, when GPS constellation and flight circumstances do not change. However, within a flight strip, and even more between two flight strips, this will change significantly. In fact, this error has a stochastic character, but due to the long wavelength it can locally considered to be constant.

Flying at an altitude of 440 m with a speed of 120 kts and laser frequency of 200 kHz the following theoretical accuracies were expected:

Error source	Remark	Effect on XY or Z	Order of magnitude	Unit	Effect on XY (in meters)		Effect on Z (in meters)	
					Nadir	Edge	Nadir	Edge
Location Survey system	GPS	XY	0.02	Meter	0.020	0.020	-	-
		Z	0.03	Meter	-	-	0.030	0.030
Position Survey system	Heading Pitch Roll	XY XY & Z XY & Z	0.0100 0.0075 0.0075	Degree Degree Degree	0 0.058 0.058	0.045 0.058 0.077	0 0 0	0 0.007 0.038
Range noise		XY & Z	0.020	Meter	0	0.010	0.020	0.017
Angle measurement Laser beam	Noise	XY & Z	0.0000001	Second	0.009	0.010	10e-7	0.005
Rotation axis alignment		XY	0.025	Mrad	0.006	0.006	-	-
Footprint	Beam divergence	XY	0.012 0.50	Meter mrad	0.039	0.044	-	-
Time registration			0.00010	Second	0.006	0.006	-	-
Total error				**Systematic Stochastic**	**0.068 0.061**	**0.100 0.075**	**0.015 0.025**	**0.038 0.030**

Table 3: Theoretical accuracies

The accuracy for each dimension (X, Z and Z) consists of various error sources (as shown above). For this project the height accuracy is very important, for which the following theoretical accuracies are calculated:

- Maximum systematic height error of 3.8 cm
- Maximum stochastic height error of 3.0 cm

	Z accuracy between laser and ground control points
1 sigma	68% < 6.8 cm (1*3.0 cm+3.8 cm)
2 sigma	95% < 9.8 cm (2*3.0 cm+3.8 cm)
3 sigma	99,6% < 12.8 cm (3*3.0 cm + 3.8 cm)

So given the values above, systematic errors of 3.8 cm magnitude can be expected. As explained earlier, this error is not systematic over the entire survey, but has a long wavelength within the survey. As a result, within strips variations up to +/- 3.8 cm can occur. By applying cross strips, it is avoided that the errors between strips add up thus ensuring that the survey meets the requirements. Systematic errors that apply to the entire survey are eliminated by adjusting the data to the control grids.

5.4.2. Theoretical differences between strips

Between two overlaps there are √2x stochastic error and a double systematic error. With the following formula it is possible to check the overlaps between two laser files:
(Sigma x √2 x stochastic error) + (2x systematic error) =

	Z accuracy between two passes
1 sigma	68% < 11.8 cm
2 sigma	90% < 16.1 cm
3 sigma	99,6% < 20.3 cm

All mentioned above are the maximum theoretical errors; the real errors can be less because errors can cancel each other out. Besides, these values of based on the maximum errors, which occur at the edge of a beam. In nadir (centre of the beam) the errors are less, as can be seen in Table 3.

5.4.3. Comparison of different independent surveys

The technique of airborne LiDAR implicates that different strips are being flown, which generally do not exactly match. As described in Paragraph 5.4 within a strip and between individual strips, elevation differences up to approximately 4 cm can occur. Whenever two independent surveys of the same area are compared, this means that even when both surveys perfectly meet the requirements, local differences of up to two times the systematic error can be expected. In this case, differences of +/- 8 cm between two independent surveys can be present.

Because these systematic errors in surveys have a long wavelength and are strongly correlated in time, the differences will show a striped pattern similar with the direction of the flight lines. It is not possible to make the strips perfectly match each other without extremely smoothing. Therefore, small differences between strips will always be visible. Provided that the differences are within the specified magnitude, the resulting DTM will meet the requirements.

5.5. Relative Accuracy Check

The relative accuracy is checked by comparing the overlaps between flights.

Overlaps are typically planned for the following reasons:
- parallel flight lines where two adjacent flight lines will show a lateral overlap (to cover a larger area that cannot be recorded in a single pass)
- crossing flight lines where an area is covered by more than one laser file with different flight direction
- At the borders of sections, to avoid data gaps flights are planned in such a way that subsequent sections will have a slight overlap with earlier recorded data.

Strip overlap separation calculation is a method for estimating the relative accuracy of laser data, a decreased accuracy can be caused by:
- Calibration issues, often manifested as separations on roof tops and lateral to the flight line.
- GPS/INS processing, often manifested as separations along the flight line.

The relative height offsets are obtained by measuring the height separation between overlapping regions from adjacent strips. Height separation can be computed between totally overlapped footprints from the two strips. For these purposes two different grid data sets are constructed, one for each strip, and then the cell values of these surfaces are compared.

By applying a colour scheme to the separation values, a clear analysis can be made of the relative accuracy of the laser data. In Figure 11 an overview of the strip overlaps is given. The overlaps are indicated with the following colour coding:

	Overlap magnitude
	0 - 3 cm
	3- 6 cm
	6- 10 cm
	> 10 cm

The overlaps were checked using the following criteria:

- Height difference of 0 cm to 6 cm: good
- Height difference of 6 cm to 10 cm: research is required, if it is structural.
- Height difference bigger than 10cm: research is required

Note that these values do not match the maximum theoretical error values as mentioned in Paragraph 5.4. As stated, the values from Paragraph 5.4 are the maximum statistically allowed errors, whereas from practical experience the errors are usually less. Therefore different test values, based on experience, are generally used in this test.

A conclusion of this method could be to revise the INS/GPS processing or fine tune the calibration values.

It can be seen that in general most of the overlaps are grey, indicating the relative accuracy is good. However still some yellow and red areas are visible. However this can mainly be explained by the method of work (gridding two data sets before analysing the difference). Therefore, a few general notes have to be made:

- Vegetated and built-up areas do not give a reliable view on the accuracy. This is due to the fact that the laser pulse does not always reflect on exactly the same spot. In case of vegetation for example, the laser pulse will likely reflect on different branches resulting in poor overlap differences. A similar issue occurs with buildings, when the laser pulse may either hit the roof top or the ground (or half-half), also resulting in poor overlap differences. Therefore these areas are not reliable for this test, only large flat areas such as fields or roads are suitable.
- If flights are far apart in time, circumstances could have changed, resulting in strip overlap differences. However, in this specific project the time span between the flights is rather short, so this should not be the case.
- Moving circumstances (e.g. water) or objects (e.g. cars) are not suitable for this method.

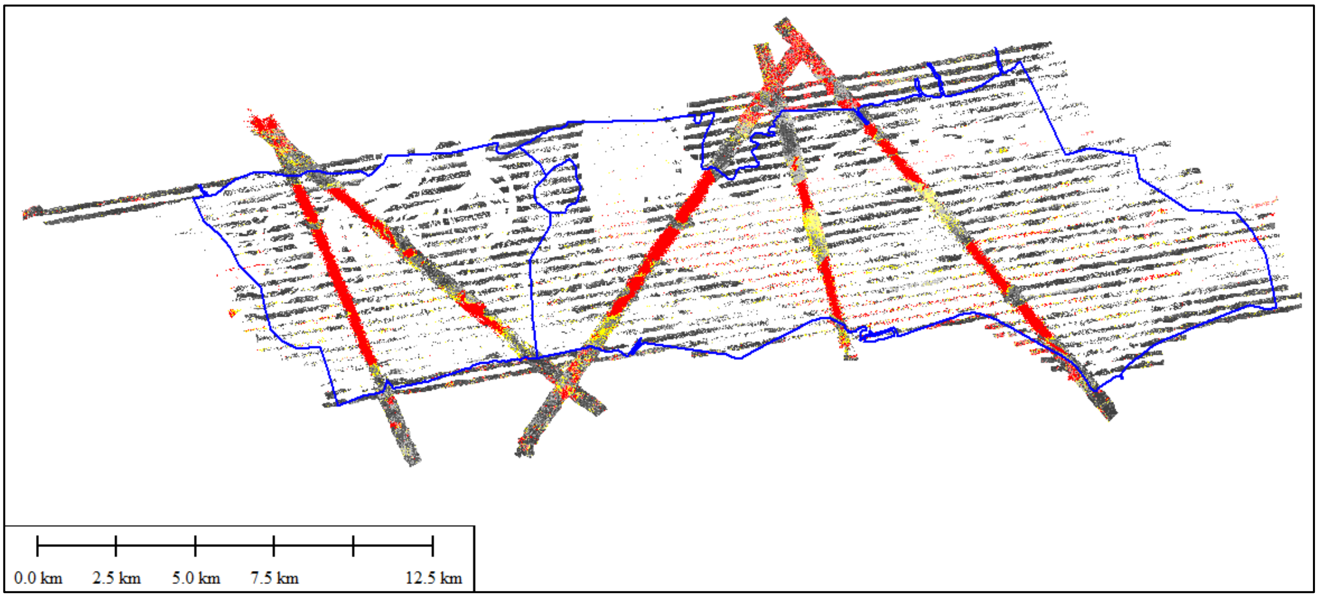

Figure 11: Overview of the overlaps

This becomes clearer when the overview is viewed in more detail, see for example Figure 12. Onshore, it can be seen that the overlap differences are generally very good at flat areas such as road and fields with low or no vegetation. The red and yellow areas are either vegetated (trees or crop fields) or built-up areas.

It can be seen that the overlaps between the regular passes are generally good, even on the mud flats. The overlaps with the cross passes sometimes turn yellow and red on the mud flats, but this is due to the fact that they were flown at a different time and tidal level. Figure 13 shows a detail over the mud area, where it is visible that the overlaps on the dry areas are very good, only in deeper water the overlaps are not reliable.

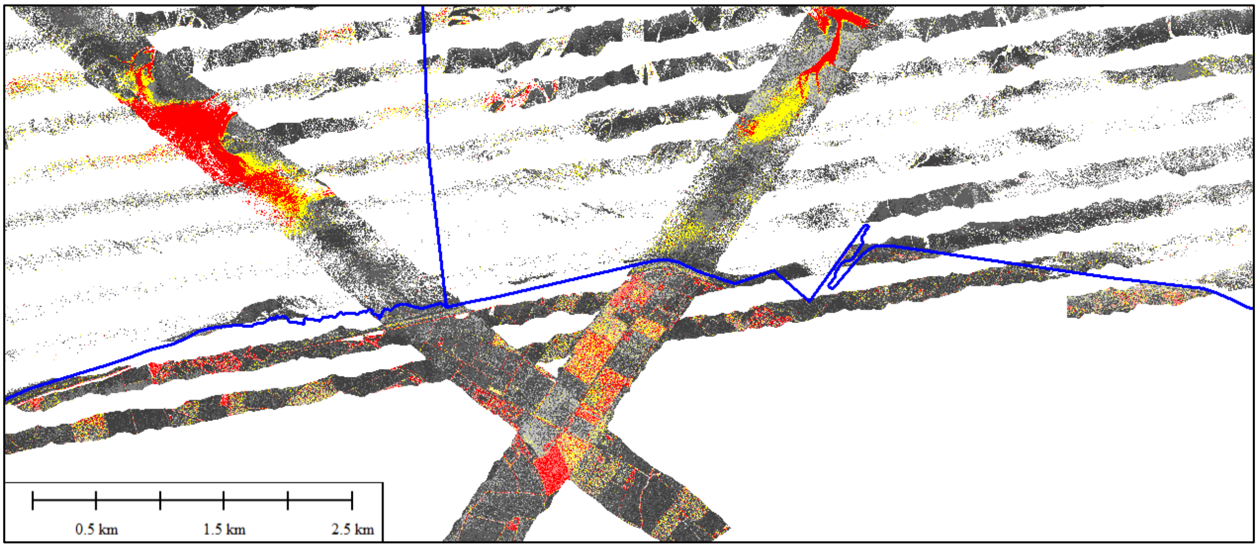

Figure 12: Detail of the overlap overview, for the mainland

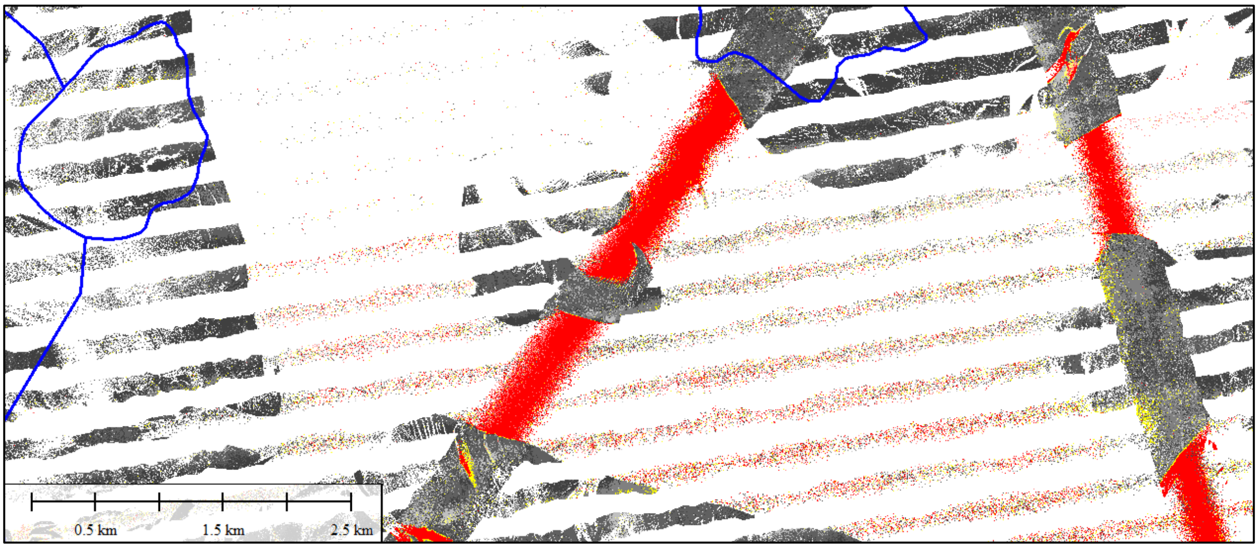

Figure 13: Detail of the overlap overview, for the mud flats

So although the relative accuracy cannot be quantified exactly an analysis of these overlap figures prove that the relative accuracy is within expectations.

5.6. Absolute Accuracy

To evaluate the accuracy of a dataset, a comparison must be performed between the coordinates of several points, which are locatable easily in all the dataset(s), and an independent dataset of higher accuracy. For this research, LIDAR data were compared to Ground Control Points collected separately with RTK GPS and levelling equipment. Those points were used as a ground truth to estimate the absolute accuracy of the Z of the laser. A Grid Comparison method was used to develop grids of various resolutions. Points in these grids were extracted and compared to one another to perform accuracy assessments.

As already shown in Figure 4, 8 control grids on hard surface and 4 control grids on the mudflats were used. For the grids on hard surface, the measurements of the survey in October 2013 are used, these grids were not measured again for this particular survey because it can be assumed that the terrain has not significantly changed in the intermediate period. For the mud grids however this assumption does not hold, therefore they have been updated in September 2014. All land surveys have been performed by Fugro GeoServices B.V.

In Figure 14 an example of one of the control grids on hard surface is given.

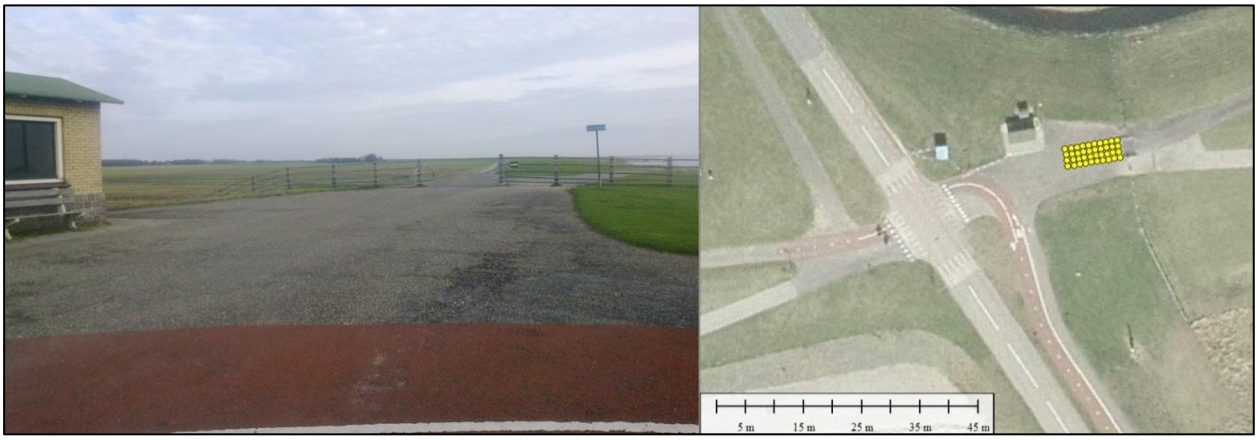

Figure 14: Example of one of the GCP's uses for this project

The flights were first matched in a relative way, see Paragraph 5.5. After that, the complete data set is checked with the ground control points to check if for any systematic errors and adjust the entire dataset to match the ground control points. After this, the final check is done on the same Ground control points. For this test, a small TIN is made from the laser data, at the control grid locations. The Z value of the control point is the compared with the Z-value extracted from the TIN at the terrestrially surveyed coordinate.

All grid checks were checked using the following criteria:

Maximum systematic error (Average dz)	**Maximum stochastic error (standard deviation)**
100% < 3.8 cm	68.3% < 3.0 cm
	95.4% < 6.0 cm
	99,7% < 9.0 cm

The complete results of the checks are included in Appendix D; a summary is given in Table 4.

To get a better view on the fitting of the individual passes on the ground control grids, the test is done per strip. Therefore the number of observations is more than the number of grid points.

Control Grid	**GCP1**	**GCP2**	**GCP3**	**GCP4**	**GCP5**	**GCP6**	**GCP7**	**GCP9**
Average dZ	-0.010	-0.004	0.002	-0.004	0.005	-0.008	0.001	0.023
St.Dev dZ	0.021	0.015	0.014	0.013	0.013	0.010	0.013	0.019
# Points	240	180	359	379	107	144	193	107

Table 4: Absolute accuracy check for grids on hard surface. Dz is calculated as laser Z minus known Z

Part of grid 5 was surveyed incorrectly, resulting in fewer points for that grid.

When the all grids points together are analysed, this results in the values shown in Table 5.

Parameter	Average of all points
Average dZ	-0.001
St. Dev dZ	0.017
# Points	1708

Table 5: Absolute accuracy check, results on all points

These results show that the systematic error as well as the stochastic error is well within the expected maximum errors.

Apart from the 9 control grids on hard surface, four grids on the mudflats were measured. These grids have been measured by GPS-RTK, using a base station of our own that was placed on the land. The base station was levelled relative to an official NAP benchmark. See Figure 15 for an example of such a grid.

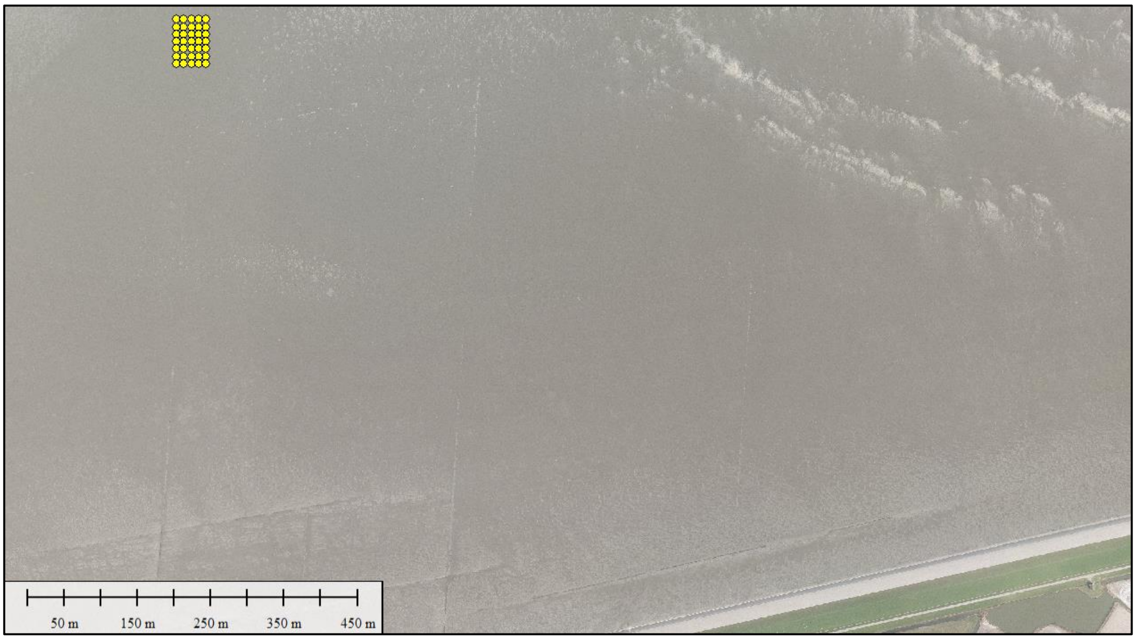

Figure 15: Example of a grid on mudflats

As these grids are located on the mudflats, which may vary over time and per season, they have been surveyed in the same period as the LiDAR acquisition. Ideally they would have been measured at the exact same day, but this was operationally impossible.

These four grids were surveyed on the following days:

Point	Location	Survey Date
002D0049	Ameland	22 September 2014
002G0124	Schiermonnikoog	23 September 2014
002H0032	Groninger wad	20 September 2014
2M007	Fries wad	29 September 2014

2M007 has been measured later than planned, due to bad weather circumstances on Wednesday and Thursday.

These grids have been checked with the LiDAR data as well, in the same way as the grids on hard surface. However, the grids on the mudflats are less accurate, because the points cannot be idealized as good as points on a hard surface and can therefore not be surveyed as accurate. Besides that, the grids may show a difference due to variation in time. Therefore these grids have only been used to check the data and not to fit the data.

The passes that cover location 2H32 are flown with a higher tide, thus the LiDAR points are actually not on the mud flats but on water. This control grid hasn't been taken into account.

The results from the analysis for the three remaining locations using the derived control planar features are listed in Table 6. The full results are attached in Appendix D.

Parameter	Grid 002D0048	Grid002G0124	Grid 2M007
Nr. of points	35	35	35
Nr. of observations	4	14	7
Average dz	0.067	0.061	0.086
Std deviation	0.050	0.013	0.005

Table 6: Absolute accuracy check for grids on mudflats

5.7. DTM

From the point cloud average grids are produced, with a cell size of 1 x 1 metre. The DTM is based on the ground filtered data, so all points above ground (mainly buildings) have been taken out. Furthermore, the data is clipped to the project boundary and the cells without data have not been interpolated causing areas without data. The DTM is checked on coverage and whether it is a correct representation of the terrain.

The results of the coverage check are given in figure below.

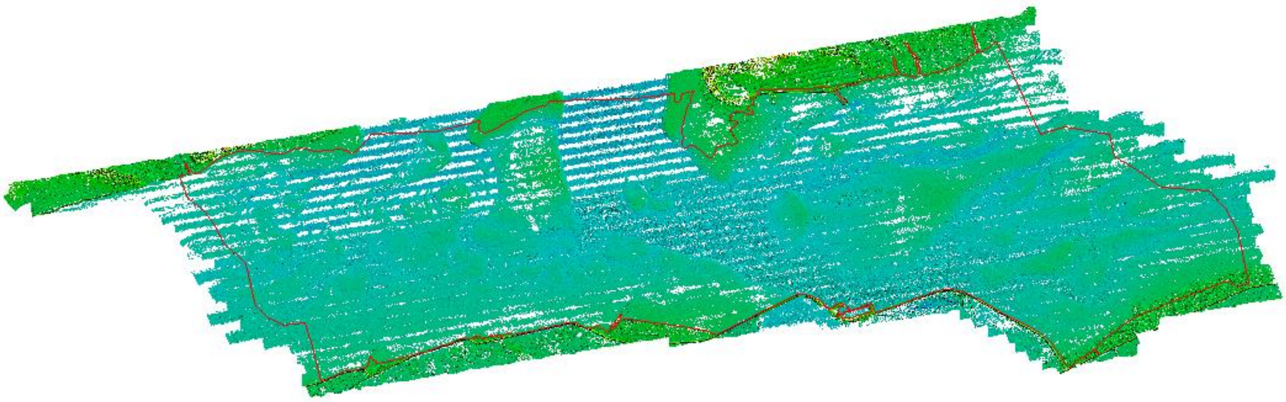

Figure 16: DTM of the project area

Several spot-checks have been done to visually determine if the grids are representative. The check is specifically aimed to determine locations with unexpected big height differences. No anomalies were found in this test. In Figure 17 a detail of the DTM is shown.

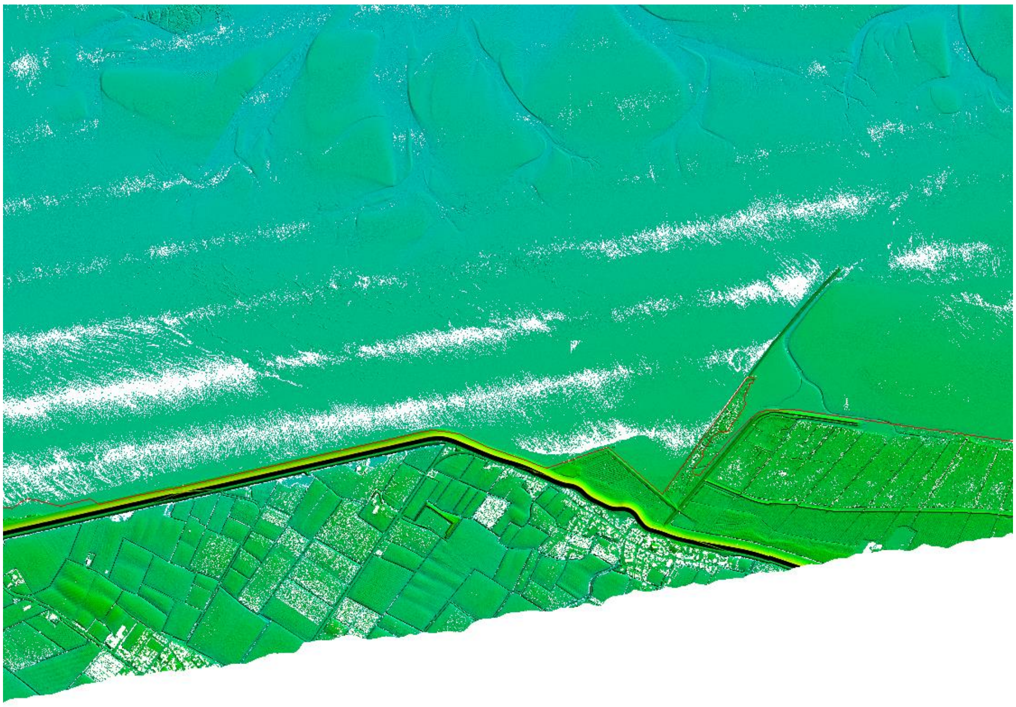

Figure 17: Detail of the DTM. Areas without data, or where data has been filtered from the ground, remain white

6. Deliverables

The following data has been delivered to Deltares and NAM on the 21st of November:

- LAS Files
- DTM as 1m average grids in ASC and XYZ format

The data has a tile dimension of 1000x1000m.

The LAS files contain RGB values, which have been extracted from simultaneously captured aerial images and are attached in post-processing. Only at the edges of the data set, some point don't have RGB attached, because the coverage of the laser swath was a little more than the image coverage and therefore no image covers these particular locations.

A basic ground filtering has been applied to the laser data, which discriminates between surface points and non-surface points such as buildings or vegetation. Please note that no dedicated classification of water has taken place, so the points are classified as "ground" might as well be water.

Fugro can supply further products like differential grids and imagery for identification at request.

7. Note on comparison of different surveys

The technique of airborne LiDAR implicates that different strips are being flown, which generally do not exactly match. As described in Paragraph 5.4 within a strip and between individual strips, elevation differences up to approximately 4 cm can occur. Whenever two independent surveys of the same area are compared, this means that even when both surveys perfectly meet the requirements, local differences of up to two times the systematic error can be expected. In this case, differences of +/- 8 cm between two independent surveys can be present.

Because these systematic errors in surveys have a long wavelength and are strongly correlated in time, the differences will show a striped pattern similar with the direction of the flight lines. It is not possible to make the strips perfectly match each other without extremely smoothing. Therefore, small differences between strips will always be visible. Provided that the differences are within the specified magnitude, the resulting DTM will meet the requirements.

8. Conclusion

Below a summary is given of the conclusions and approvals made in the quality report.

Specification	Condition or requirement	Conclusion	Approved
Absolute accuracy	8 Ground control grids to check the absolute z- accuracy < 68 mm	Average dz (cm): -0.1 SD dz (cm): 1.7	Approved
Relative accuracy	Allowed difference between overlapping flights	Quality checked	Approved
Classification ground/non-ground	Should be of sufficient quality to create reliable ground model	Quality check	Approved
Laser quality	Check on anomalies in laser quality	No anomalies found	Approved
Laser coverage	The entire area inside the boundary must be covered	With exception of deep waters the entire area is covered with laser points	Approved
Point density	Point density should be more than 4 points per m^2 on dry areas	Point density on representative locations is more than 4 points per m^2.	Approved
DTM	Check on coverage	Entire project area covered.	Approved
DTM	Check on correct representation	Inside project boundary no anomalies were found. Only at the edges some anomalies were found due to interpolation issues	Approved