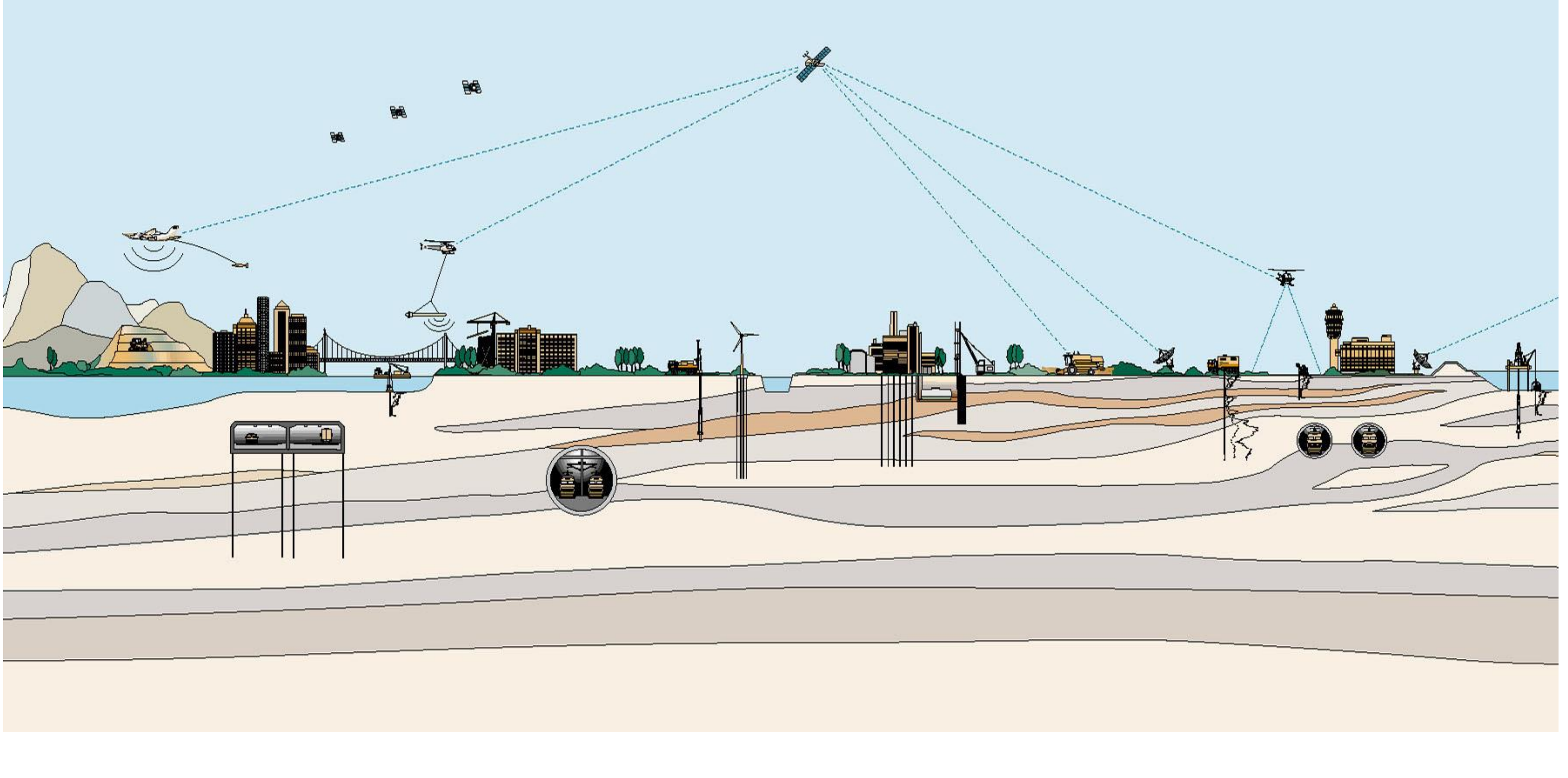
FUGRO GEOSPATIAL B.V.

Waddenzee LiDAR Survey
July 2015

Final Report

Datum: *1st September 2015*
Client: *Nederlandse Aardolie Maatschappij*
Author: *C. Marillat, Fugro Geospatial B.V.*
Reviewer: *P. Menting, Fugro Geospatial B.V.*
Project number: *ASM11515.150*
Version: *150901*



1. Introduction

In June and July 2015, 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 8^{th} time; the previous surveys were executed at the following moments:

- April 2010
- April 2011
- September 2011
- October 2012
- October 2013
- May 2014
- September 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 laser scanner, because it is concluded that using the Riegl scanner will lead to a higher point density and better reflectivity on these wet areas.

The flight plan applied for this survey was identical to the one used during previous campaigns.

Further processing was directly started after finishing the survey.

The final deliverables were sent in two copies to NAM on USB storage on the 7th of August 2015.

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 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.

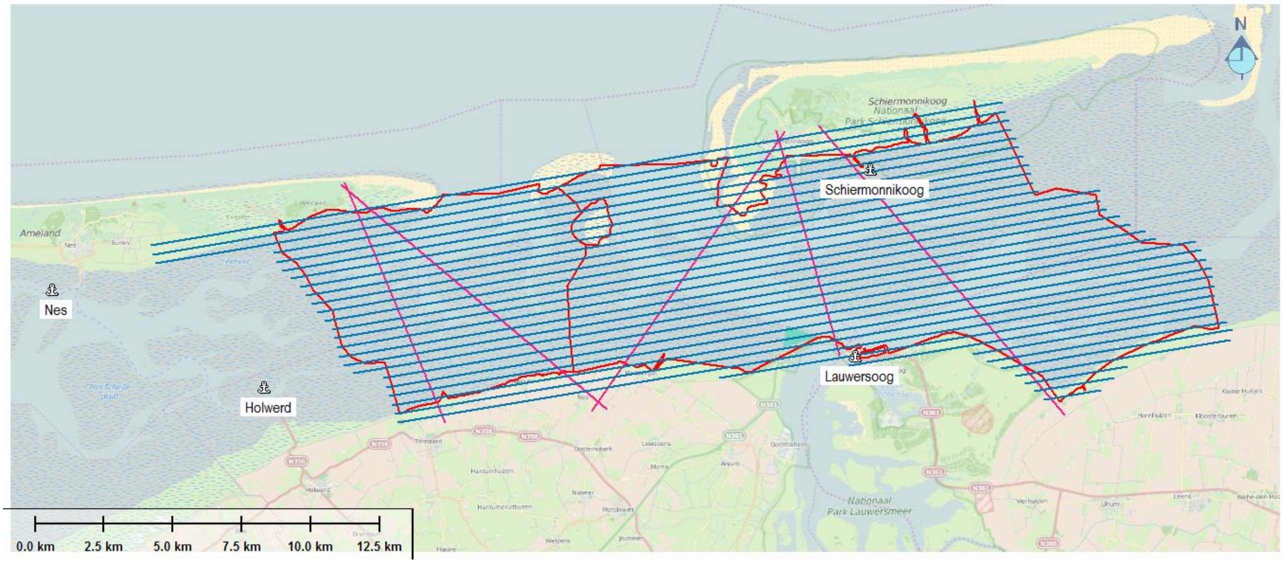


Figure 1: Project area, flightlines, and tidal stations

The digital boundary file is attached in **Appendix A**.

2.2. Demands and conditions for survey

Original requirement was that the survey had to be executed while the water level is below -0.70m NAP at Nes tidal station.
But the experience from previous surveys shows that, due to the specific configuration of this zone, the water height may vary up to 50 cm from one end of the survey area to the other end, at the same time. It was thus judged necessary by NAM to refine the assessment of the water level measurement. That's the reason why for this campaign, the water level has been assessed not only at Nes tidal station, but also at Holwerd, Lauwersoog and Schiermonnikoog (see location on Figure 1 above).

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 Digicam 50MP 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 (OO-ITC)
2	GPS/INS type and model	Novatel 512 + IGI IMU-IId
3	Scanner type and model	Riegl Q680i
4	Aerial camera type and model	Digicam 50MP

Flight parameters:

#	Parameters	Value	Unit
1	Height AGL	460	m
2	Speed	130	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	35	mm
2	Size of CCD matrix	8176 x6132	Pixel x Pixel
3	Pixel size	6.0	µm
4	Image GSD	7.9	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

Fugro updated NAM on progress on a weekly basis during project preparation, and every day during execution of the flights.

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

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.

Previous survey campaigns, until September 2014, were done with aircraft operated by Fugro. However in 2015 Fugro Geospatial updated their strategy into being to be a light-asset company, focused on serving client's need with high technical knowledge. Part of this updated strategy is the choice to outsource aerial data acquisition. For this project, the aerial data acquisition was subcontracted to Fugro's partner EUROSENSE BV.

EUROSENSE holds an ISO 9001:2008 approved Quality Management System.

On base of the conditions stated by Shell Aircraft International (SAI), EUROSENSE received approval after an aviation on-desk audit. EUROSENSE 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.
A first assessment, based on the use of Cessna 404 registered OO-GPS aircraft, was done by SAI on the 28/05/2015, and approval given on the 5/06/2015 (see **Appendix B**). But, since airspace restrictions and unfavourable weather conditions delayed the survey for several weeks, an additional assessment was done by on the 26/06 to extend the approved aircrafts to the alternate Piper PA 31-350 registered OO-ITC aircraft (see **Appendix C**).

Survey flights were eventually done with OO-ITC aircraft, pilot Douglas Strömberg, co-pilot Dimitri Vandermeiren. Aircraft and crew have been approved for that survey by SAI.

Note on audit: The SAI's audit requirements were based on the standards set by IAGSA (International Airborne Geophysics Safety Association), which are in our view are, for some of them, too stringent for the type of operation we're doing (flight in known country, in correct weather conditions, above 1500ft AGL). Lidar surveys are different than Geophysics aerial surveys, and applying IAGSA standards somehow delayed and complicated the audit process.

Fugro and EUROSENSE executed and adhered to a comprehensive risk assessment for this project. This document, presented in **Appendix D**, was created on the 11/05/2015, and was reviewed once more on the 28/06, before operation start.

No incident or accident was reported during this project execution.

3. Data acquisition

3.1. Flight overview

The survey was finally executed in two flights, with a twin engine Piper Chieftain Navajo (PA 31-350) registered OO-ITC, from Groningen (EHGG) airport. Equipment installation in the aircraft and field data QC has been done in Antwerp-Deurne airport (EBAW).

In Table 1, Table 2, Figure 2 and Figure 3 below, a brief overview of the daily status of the project is given.

Date	Activity
30/06/2015	Survey Lines 06-20, 34-38, and Cross Lines 1-5
01/07/2015	Survey Lines 21-33, 18, and Cross Lines 1-5
02/07/2015	Data QC
03/07/2015	Data QC and validation

Table 1: Daily activity overview

Date	Start *	End *	Note
30/06/2015	14:08	17:45	north > south, then south > north
01/07/2015	15:10	18:24	south > north

* : time of start or end on survey lines, in local time (UTC+2) ;

Table 2: Flight summary

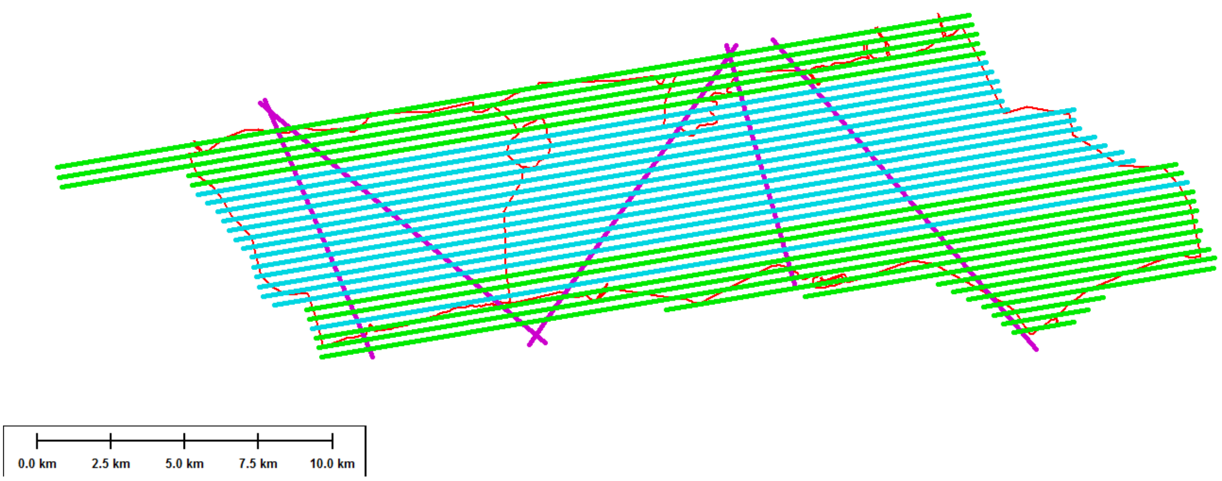


Figure 2: Lines flown on 30/06 (green), 01/07 (blue), and crosslines (purple)

Figure 3: Overview of flights 30/06 (left) and 1/07/2015 (right)

3.2. Flight operation and technical evaluation

Approval from Shell Aircraft International was received on the 5/06/2015, but we could not perform the first survey flight before the 30/06, because of:

- intense military activity blocking the targeted airspace in the period 9/06 to 12/06/2015
- adverse weather the rest of the time

Thanks to a favourable tidal window (wind blowing from land to sea, extending the astronomical tide by 30 to 40 minutes every day), we could complete the survey in two flights only, instead of the three flights planned.

Compared to previous campaigns, we could also save time on operation by being based on Groningen airport (EHGG), which is less convenient but much closer from site than the previously used Teuge airport (EHTE).

The weather, tidal conditions and approval of the flight authority must have a go. In fact the first two we can predict but the military we cannot foresee for a long term.
The military have planned missions which are published, but also unplanned missions which we only know a day or a few days before.

Remarks and Lessons Learnt for future campaigns:

- The process of aircraft, pilot or company certification should be started earlier, to make sure that this process is complete at least one or two weeks before the expected start of survey operations.
- About certification: see also *Note on audit* in section 2.4.
- It could be wise to allocate a longer period in which the flight should be executed. This would give us more flexibility to plan the acquisition and to allocate the best opportunities within the survey period. This would reduce the actual stand by time and surveys could better be planned.
- We should continue using Groningen airport.

3.3. Weather and tide

After a long period of low clouds and rain, quite unexpected for this period of the year, the sky opened up from the 29/06 onward – for only a few days. Weather conditions were excellent on the 30/06, first day of survey, and good though slightly windy on the second day.

All of the Survey Lines have been flown with a water level inferior to -0.70 m NAP. In order to achieve this goal, two main actions were implemented:
- Survey windows were first planned using the *astronomical* tide table, and then refined on the morning of the flight using the *expected* tide provided by the Rijkswaterstaat http://www.rijkswaterstaat.nl/apps/geoservices/rwsnl/awd.php?mode=html&projecttype=waterstanden
- Water level for this campaign has been assessed not only at Nes tidal station, but also at Holwerd, Lauwersoog and Schiermonnikoog (see location on Figure 1 Page 3). Survey Lines have been flown when the entire lines were below -0.70 m NAP (according to *expected* tide tables)

Since the cross lines are only used for matching of the regular flight lines, some of them have been flown with a water level slightly higher than -0.70 m NAP. 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.

-70cm NAP or less		astro		expected		observed	
location	day	start astro	end astro	start expect	end expect	start obs	end obs
Holwerd	30/06/2015	15:10	17:50	15:10	18:00	14:59	17:59
Lauwersoog	30/06/2015	14:30	17:30	14:20	17:50	14:21	18:01
Nes	30/06/2015	14:20	17:00	13:55	17:15	14:05	17:20
Schiermonnikoog	30/06/2015	14:30	17:30	14:00	17:46	14:18	17:57
Holwerd	01/07/2015	16:00	18:30	15:45	18:48	15:37	18:47
Lauwersoog	01/07/2015	15:10	18:30	14:55	18:51	15:01	18:53
Nes	01/07/2015	15:05	17:57	14:36	18:07	14:45	18:09
Schiermonnikoog	01/07/2015	15:11	18:30	14:37	18:40	14:58	18:46

Table 3: Tide information in relevant Tide Stations, for ops days (hours in local time, UTC+2)

3.4. Cross lines

The five cross lines have each been flown at least once per day, see Table 4. 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
30/06/2015	Before	After	Before and after	After	Before
01/07/2015	Before	After	Before and after	After	Before

Table 4: Cross lines flown

3.5. Ground control

To check the absolute accuracy (see Paragraph 0), terrestrial control grids have been used. During the survey of October 2013, already 8 control grids of approx. 40 points on hard surface each were surveyed. The same control points were used during this campaign, with a vertical correction applied to their elevation to take into account the subsidence of this area, see Table 5. The corrections were provided by NAM on the 8/07/2015.

ControlGrid	Final Correction (m)
GCP1	-0.031
GCP2	-0.003
GCP3	-0.022
GCP4	-0.001
GCP5	-0.006
GCP6	-0.014
GCP7	-0.004
GCP8	-0.002
GCP9	-0.010

Table 5: Correction applied on 2013 GCP elevations

In the previous campaigns, additional grids were surveyed on the mudflats; however, NAM opted for not having such grids survey for this campaign.
GCP8 data could not be used, because GCP8 area has been re-worked since its survey in 2013.

An overview of Control Grids location is provided in Figure 4. 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 Control Grids locations.

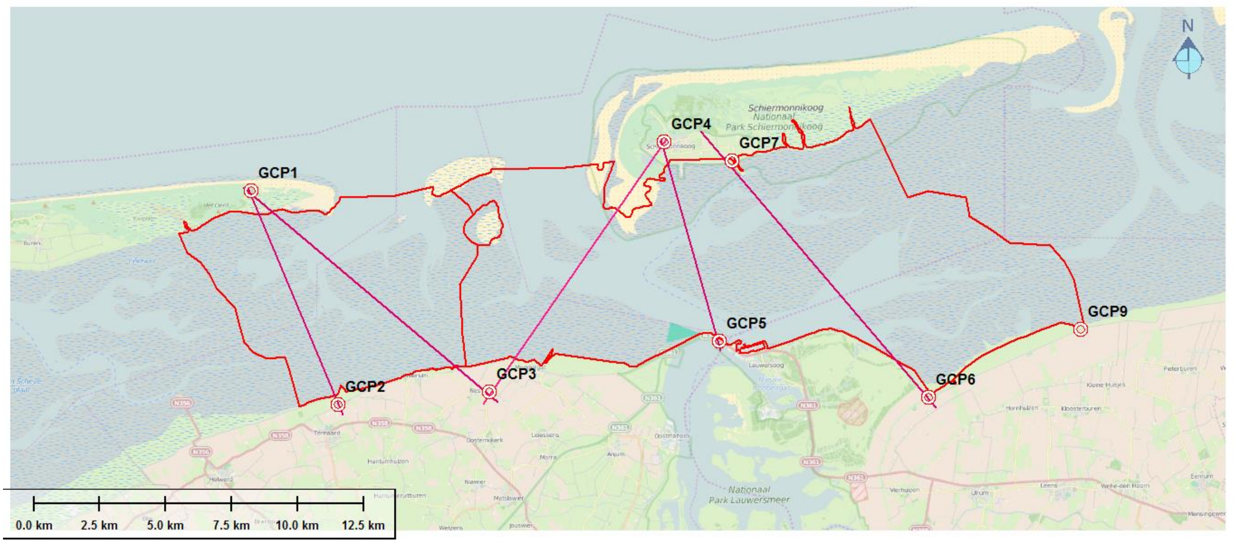


Figure 4: Overview of Ground Control Points

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

For trajectory processing, we made use of tightly coupled GPS-processing. A network of actual base stations and 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 against specifications. The forward/reverse flight path is calculated to check the reliability of the solution.

For this campaign, we used data from VRS stations generated by Netpos, and 06-GPS station Schiermonnikoog.

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 AeroOffice software for data QC (coverage, density and noise).

4.4. GPS and INS Flight Trajectory Calculations

The software package GrafNav from Novatel and AeroOffice from IGI were used for flight trajectory calculations. Tightly coupled solution was used to process the observables of the CORS stations and the GPS antenna attached to the aircraft in GrafNav; this GPS-only solution was then combined with inertial navigation in AeroOffice.

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, and more accurate for this particular job.

4.5. RGB assignment

In order to make the Lidar point cloud more easy to interpret, natural RGB colours were 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.

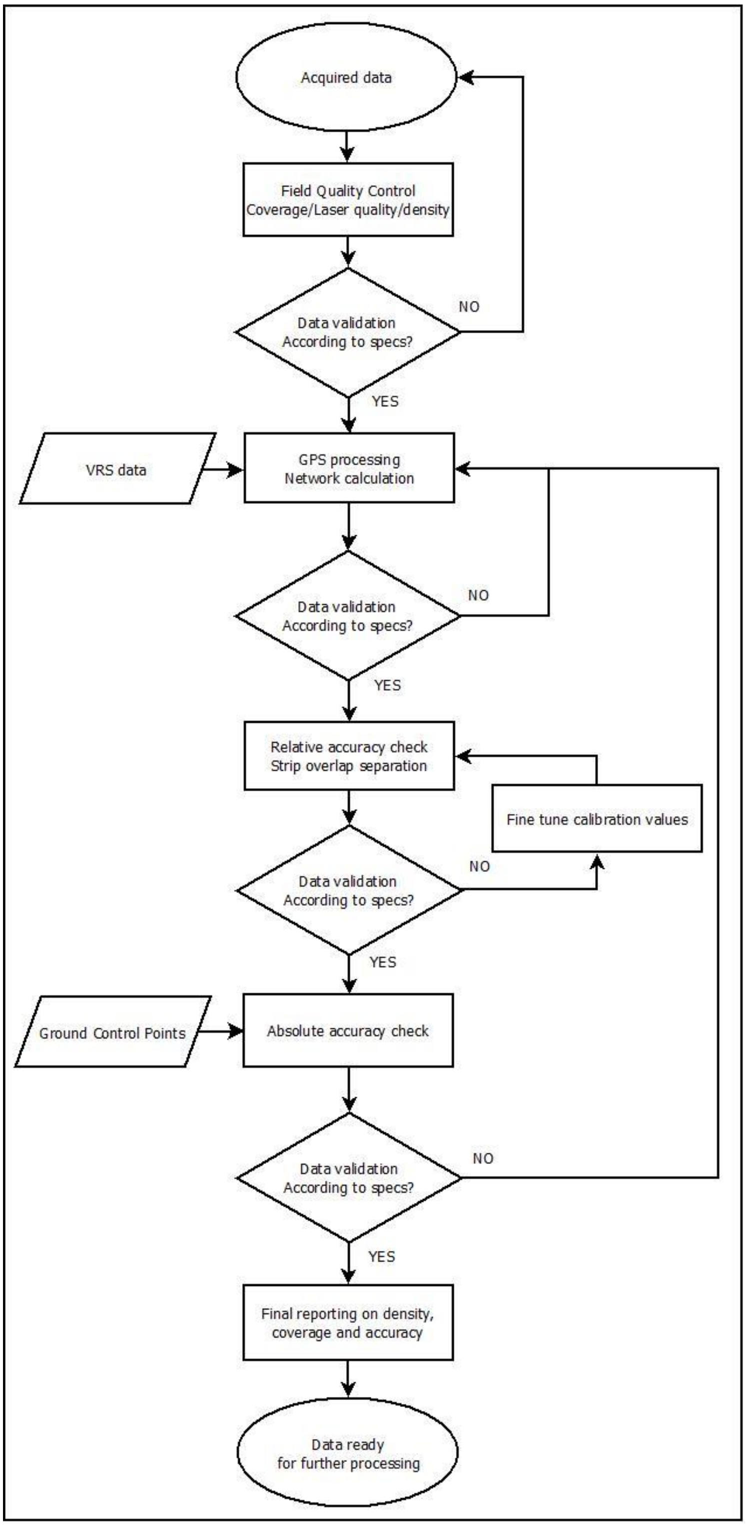


Figure 5: Processing flowchart

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 (see Figure 1).

In Figure 6 an overview of all collected data of the July 2015 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.

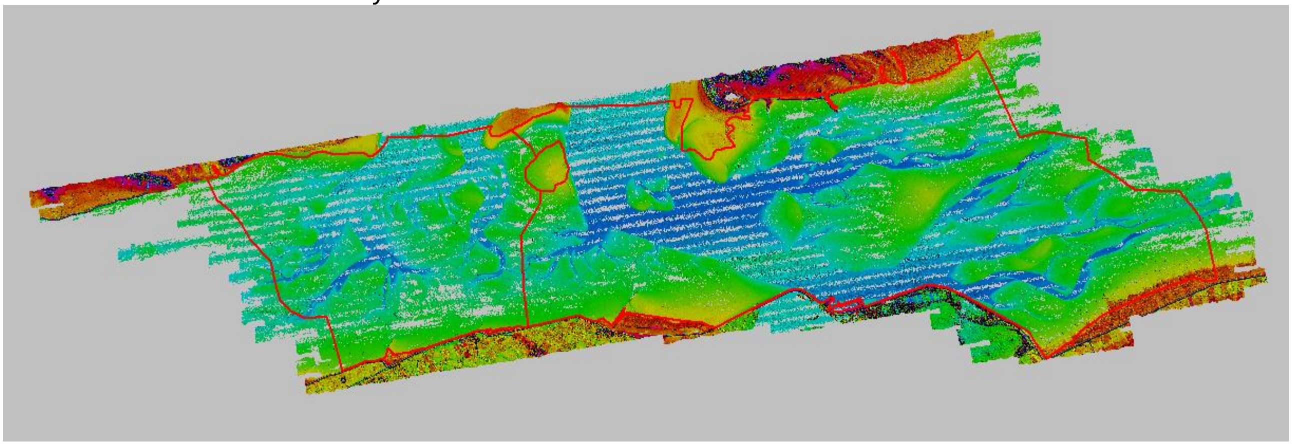


Figure 6: Coverage of the July 2015 survey

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

- Yellow is the September 2014 data
- Blue is the June 2015 data

In Figure 7, because the July 2015 data is on top, the yellow areas indicate the locations that were covered in September 2014, but showed no hits in July 2015.

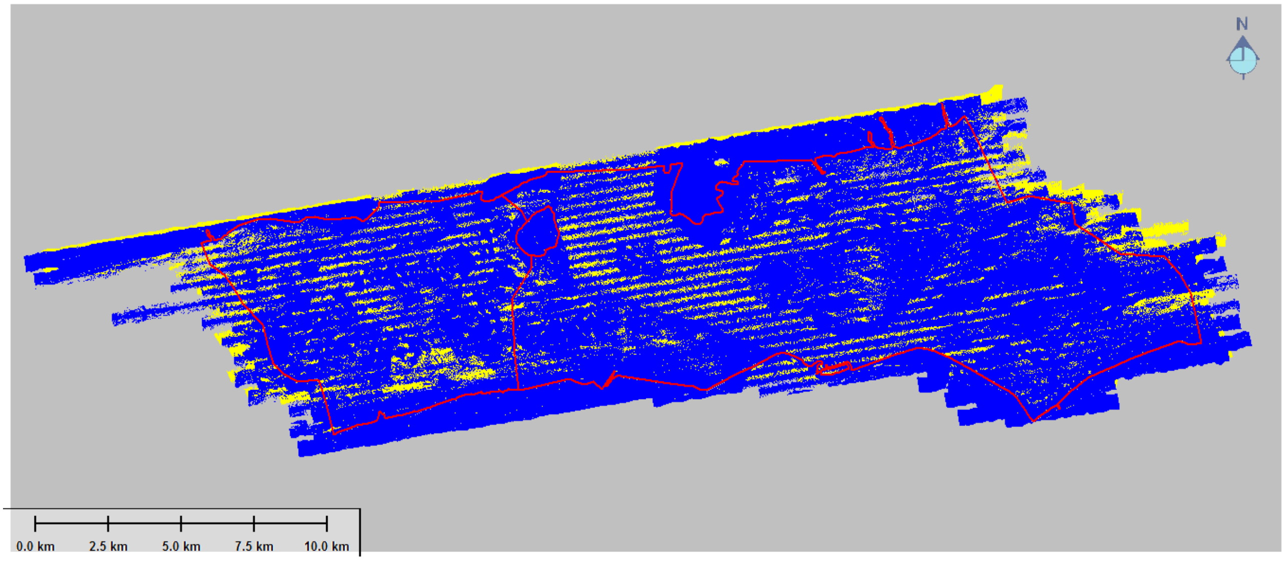


Figure 7: Coverage comparison, spring 2015 (this campaign) over autumn 2014

In Figure 8 below, the data is projected the other way around. So in these images the blue areas indicate the locations that are covered in July 2015 but showed no hits in September 2014.

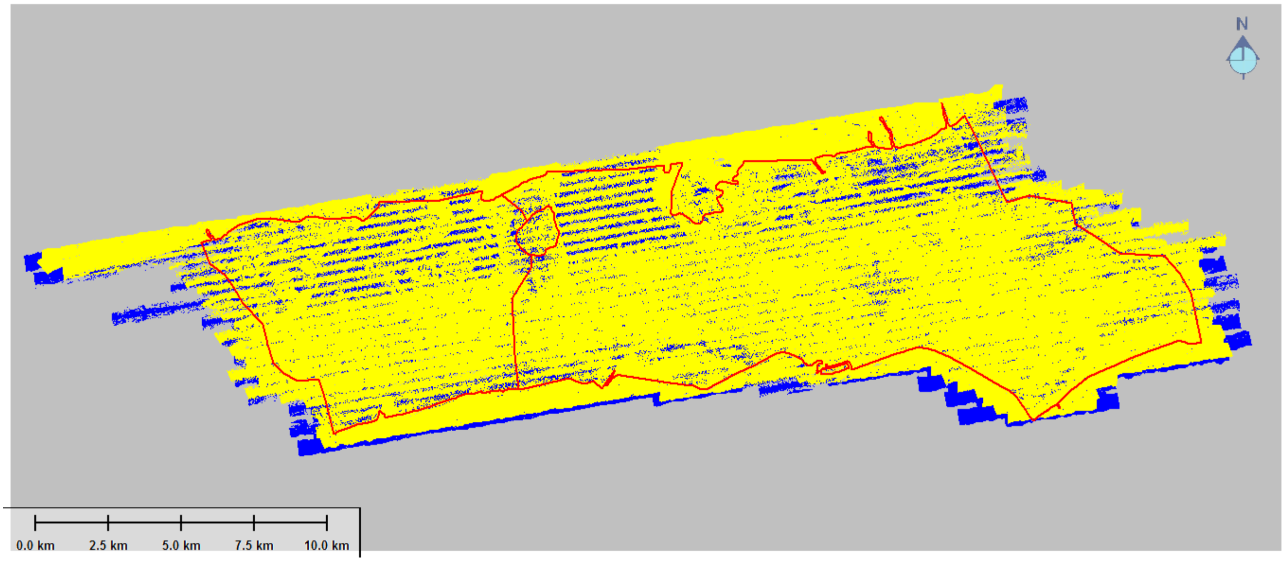


Figure 8: Coverage comparison, autumn 2015 over spring 2014 (this campaign)

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:

- Black: 4 or more points per m^2
- Red: 2 or 3 points per m^2
- Blue: 1 point per m^2

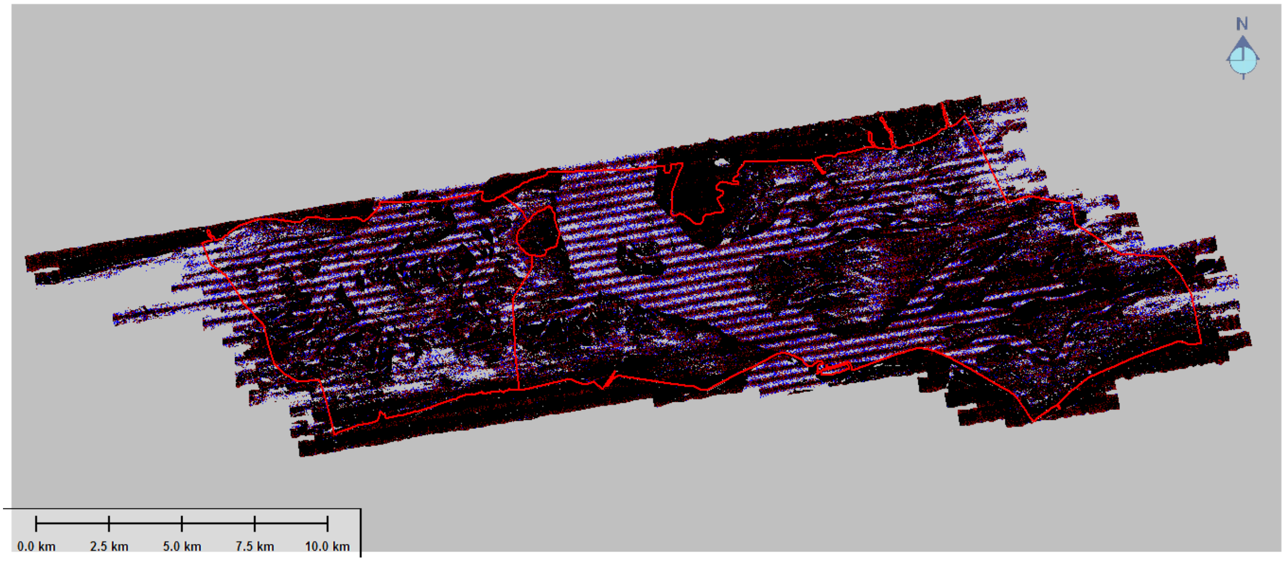


Figure 9: Point density overview

It is clearly visible that on the mainland and the islands the point density is always equal or superior to 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.

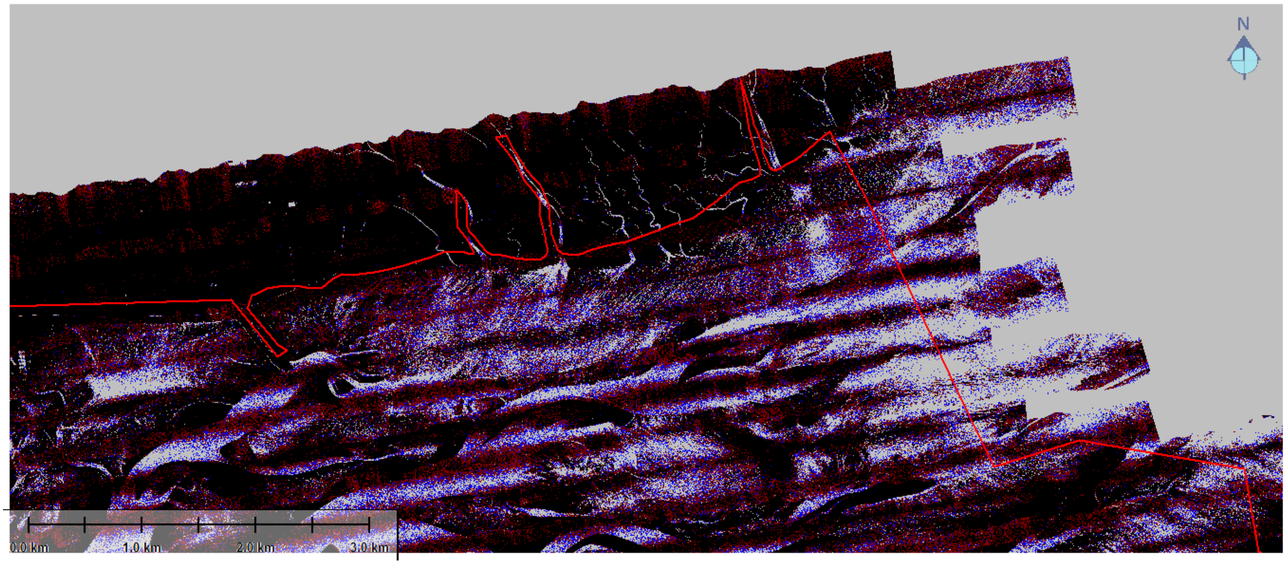


Figure 10: Detail of the point density plot

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 460 m with a speed of 130 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 6: 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 6.

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 earlier 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
(dark grey)	0 - 3 cm
(light grey)	3- 6 cm
(yellow)	6- 10 cm
(red)	> 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 0. As stated, the values from Paragraph 0 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.

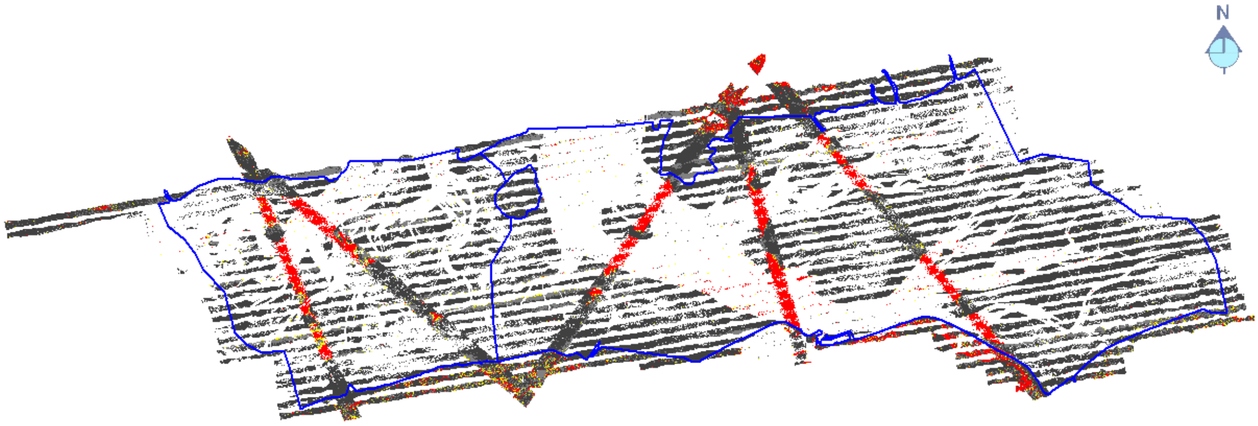


Figure 11: Overview of the overlaps

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 yellow or red areas are here vegetated area (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.

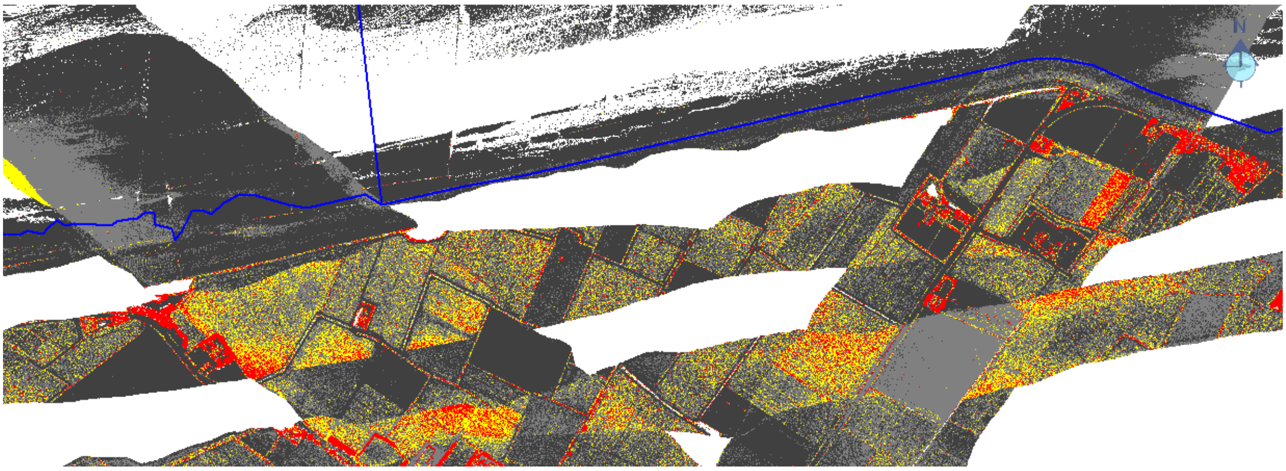


Figure 12: Detail of the overlap overview, for the mainland

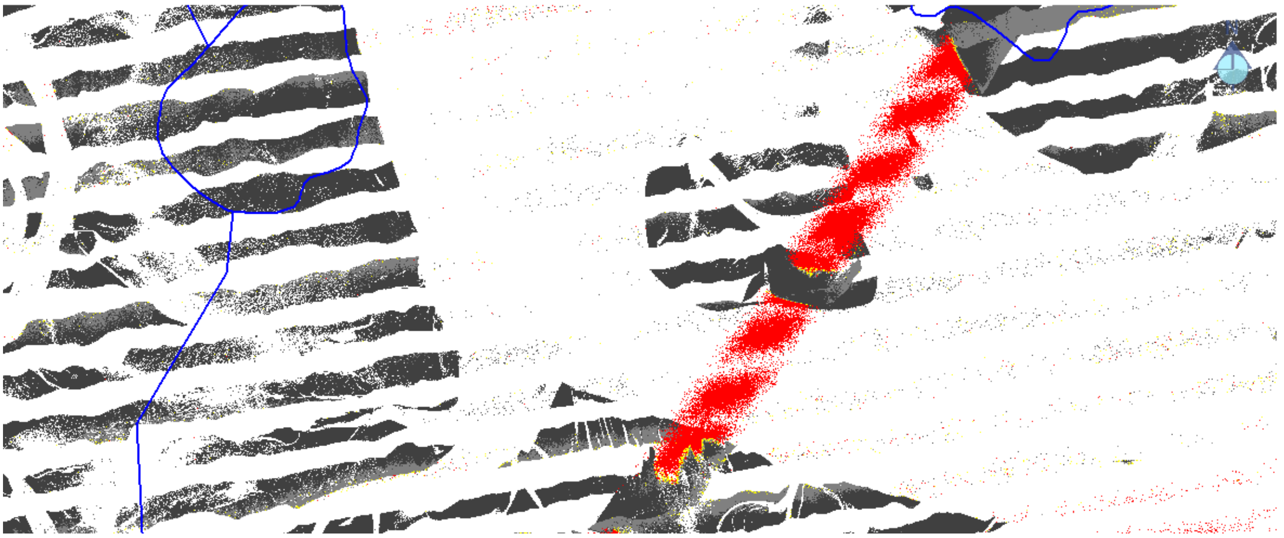


Figure 13: Detail of the overlap overview, for the mudflats

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 Paragraph 0, 8 control grids on hard surface were used. For the grids on hard surface, the measurements of the survey done in October 2013 by Fugro GeoServices B.V. are used, with point altitude updated to take into account the subsidence of this particular area.

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

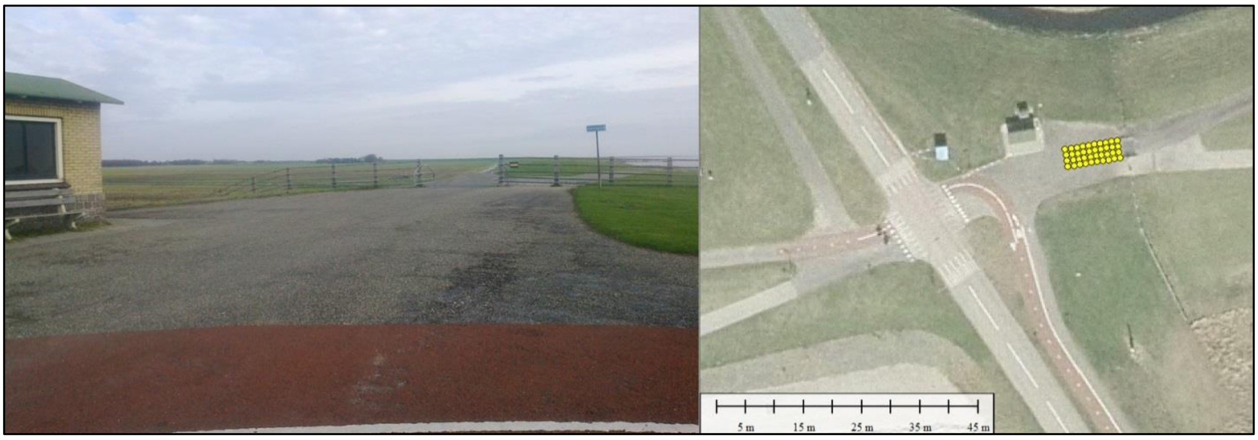


Figure 14: Example of one of the GCP's uses for this project

The flights were first matched in a relative way, see Paragraph 0. 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 E**; a summary is given in Table 7.

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 (m)	-0.026	-0.032	-0.008	-0.022	0.009	-0.004	0.013	0.018
St.Dev dZ (m)	0.024	0.016	0.02	0.02	0.008	0.011	0.005	0.005
# Points	70	107	72	103	60	63	36	36

Table 7: Absolute accuracy check for grids on hard surface. Dz = laser_Z - known_Z

Note that the cross strips are not taken into account for this final accuracy check.

When the all grids points together are analysed, this results in the values shown in Table 8.

Parameter	Average of all points
Average dZ	-0.007
St. Dev dZ	0.014
# Points	547

Table 8: 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.

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.

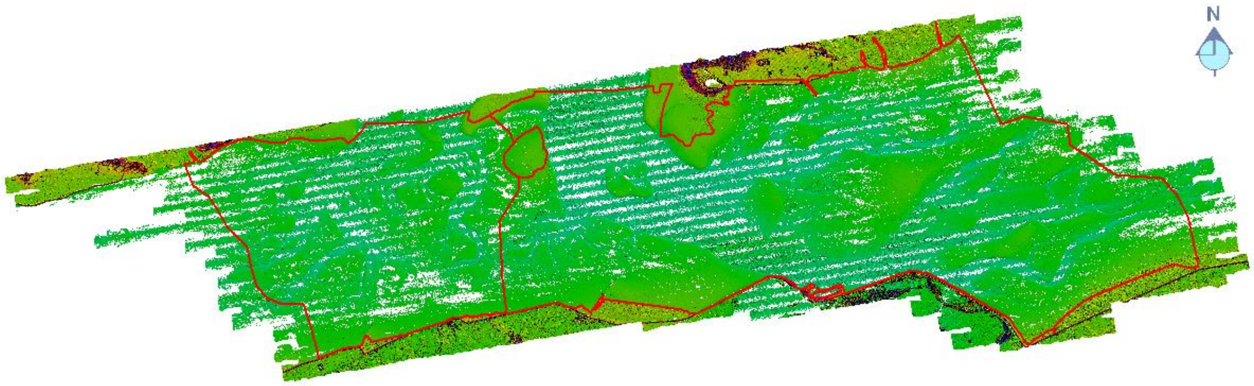


Figure 15: DTM of the project area

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.

6. Deliverables

The following data has been delivered in two digital copies to NAM on the 6th of August:

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

The data has a tile dimension of 1000x1000m.

All LAS points within AOI contain RGB values, which have been extracted from simultaneously captured aerial images and are attached in post-processing.

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. 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: -0.7 cm StdDev dz: 1.4 cm	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

APPENDICES

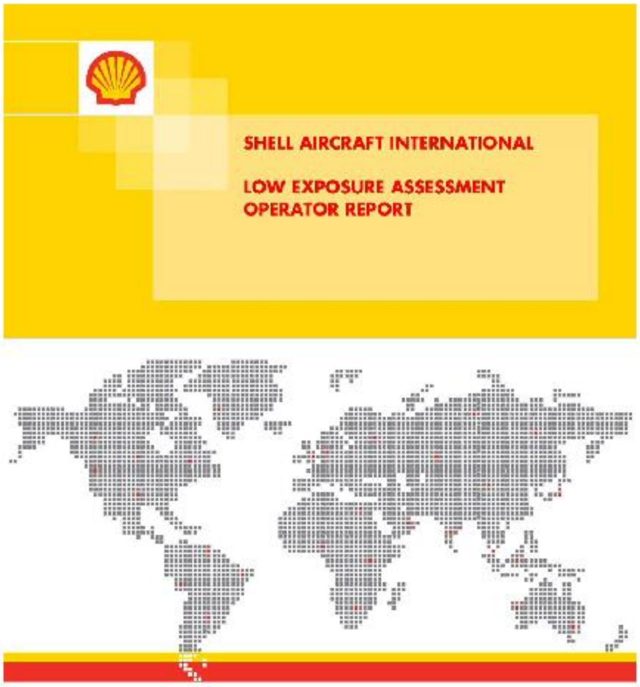
Appendix A. Area of Interest

ASM11515_To_Cover.dxf

Appendix B. Assessment of Shell Aircraft International, 5/06/2015

Shell Aircraft International
ASAG004V5

Limited Distribution: Contractor and Shell Staff only



Name of Operator	:	**Eurosense Belfotop bvba**
Location	:	**Belgium**
Assessor	:	**Jose Lopez**
Effective Date of Assessment	:	**28th May 2015**
To be passed to the operator by	:	**David Goede**

Appendix C. Assessment of Shell Aircraft International, 26/06/2015

Shell Aircraft International
ASAG004V5

Limited Distribution: Contractor and Shell Staff only

SHELL AIRCRAFT INTERNATIONAL

LOW EXPOSURE ASSESSMENT OPERATOR REPORT

Name of Operator	**:**	**Eurosense Belfotop bvba**
Location	**:**	**Belgium**
Assessor	**:**	**Jose Lopez**
Effective Date of Assessment	**:**	**26th June 2015**
To be passed to the operator by	**:**	**David Goede**

Appendix D. Risk Assessment

Fugro Geospatial EMEA
HSEP-090 Project Risk Assessment

Project Risk Assessment

Fugro Geospatial EMEA
HSSE Management System

Revision History

Ver.	Rev.	Created by	Approved by	Date	Description	Sections Affected
1	2	J.Murray	R.Hoddenbach	2014/03/25	Contact List Added	Contact Numbers
1	1	J.Murray	R.Hoddenbach	2013/10/31	Workflow, Reformat	Workflow,All
1	0	J.Murray	R.Hoddenbach	2013/07/26	Original	All

Version:	Revision	Created by:	Approved by:	Date:	Page:
1	2	J.Murray	R.Hoddenbach	2014/03/25	1 of 7

Note: If this is a printed copy please check the online BMS to ensure that it is the latest version

Appendix E. Absolute accuracy check

final_Gridcheck.txt