# FLI-MAP survey for Nederlandse Aardolie Maatschappij

# Waddengebied
# Ameland en Schiermonnikoog
# Autumn 2011


**FINAL REPORT**

| | |
|---|---|
| Client: | NAM |
| Project nr: | 501.11871.002 |
| Version: | 111028_rev3 |

# 1. Introduction

At the end of September 2011, Fugro Aerial Mapping (Fugro in this document) carried out an airborne Lidar survey for Nederlandse Aardolie Maatschappij (NAM in this document)

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

With use of the FLI-MAP 1000, in-house developed high accuracy airborne LIDAR system, the project was executed for the third time. The first survey was carried out in the spring of 2010, the second in spring 2011 and this survey in end September 2011.

Further processing was directly started after finishing the survey. The end deliverables were delivered together with this report on a separate hard disk.
End deliverables were delivered to Deltares (contracted analysis partner of NAM) and to NAM on a hard disk on the 28th of October 2011.

# 2. REPORT CONTENT

This report provides the relevant project information. After a short description of the project area in chapter 3, the data acquisition, data processing and data quality control are described in chapters 4, 5 and 6 respectively. Chapter 7 consists of information about the creation of the end deliverables. In chapter 8 a summary of all conclusions is given.

Appendices are digitally attached to the report.

# 3. PROJECT AREA

The airborne survey covers the area's Pinkegat and Zoutkamperlaag. The survey encompasses 630 kilometers of flight lines, with an east-west orientation. (Yellow lines in the figure below).

During each survey flight a control line was surveyed (blue line in the figure below).


**Figure 1: Area of Interest NAM survey**

The final boundary file can be found in appendix A.

All flights were executed while the water level was below -0.70m NAP at Nes tidal station.

# 4. CLIENT SPECIFICATIONS

## 4.1. Demands and conditions for survey

Survey requirements and deliverables are according to the tender (our reference HH/11/45/501.871) as stated by Fugro.

As mentioned in the previous chapter the survey needed to be executed while the water level was below -0.70m NAP at Nes tidal station.

To guarantee the quality of the survey, a predetermined control line was flown each survey (see figure below blue line). The control line connects two grids (004 and 005) on the south shore of the project area. This way not only the relative accuracy between flights could be checked, but also the absolute accuracy of those flights.
Four more grids were placed on the edges of the project area (see figure below) to be able to check and enhance the absolute accuracy.


**Figure 2: Location control grids and control line**

Because the survey area covers a bird sanctuary, it was prohibited to fly lower than 1500ft. For this reason Fugro planned the flight lines at an altitude of 500m AGL (Above Ground Level).

The table below shows the sensors that were used during the survey. It also specifies the survey parameters and the additional specifications that were defined:

| **Survey Area and Sensors** | |
|---|---|
| Area to cover | See appendix A |
| **Laser**<br>☒ 150 kHz | ☒ FLI-MAP 1000 with embedded line scan camera |
| **Imagery** | ☒ 16 Mpix Down Camera |
| **Video** | ☐ Fwd /DownVideo wide angle |

**Survey Parameters**

| | **Camera** | **Minimal Required Coverage** | | | | **Planning** | | |
|---|---|---|---|---|---|---|---|---|
| Subproject | Pixel Size | Laser Width | Video Width | Photo Width | Point Density | Altitude | Speed | Line Spacing |
| General LiDAR survey | | 445m | | m | 4-5 / m2 | 500 | 110 knts | 400m |
| Camera required for interpretation only. No re-flights for gaps | 7.4cm | | | | | | | |

## 4.2. Geodesy

The National Grid of the Netherlands is based on the RDNAPtrans2008 datum and has a Transverse Mercator (TM) projection.

NLGEO2008 Geoid model has been implemented in NAPTRANS2008 the transformation. This model was applied on WGS-84 height data, in which FM1000 collects the data, to convert the data to NAP heights.

## 4.3. Client communication

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.

During the project in multiple instances the planning was slightly altered by Fugro in order to tune the route to end delivery. At no moment the schedule for the end delivery was jeopardized.

## 4.4. Quality, Health, Safety and Environment

The mission of Fugro Aerial Mapping is to be one of the leading and most innovative companies in Aerial Survey and Mapping Services in Europe and Africa, with healthy financial results and long term continuity of services. Fugro Aerial Mapping 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.

Quality within Fugro is ruled by the slogan: “First time, on time, right”.

On base of the conditions stated by Shell Aircraft International (SAI) Fugro received approval after a desktop audit. This desktop audit is valid till February 2012.

Fugro received an exemption on the 50 M $ third party liability clause and executed the project with a 20 M$ third party liability in place.

Fugro flew with the OY-NJV and G-AWNT aircraft, which were both approved for this survey by SAI.

Fugro executed and adhered to a comprehensive risk assessment for this project. None of the stated risks did happen, partially due to the anticipated actions.

In appendix B the report by SAI and risk assessment are attached.

# 5. OPERATIONAL IMPLEMENTATION

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 OY-NJV. This plane has been approved by Shell Aircraft international before the survey started.

The figure and table below gives a brief overview of the daily status of the project.

| Date | Activity | Flight | Color | Remarks |
|---|---|---|---|---|
| 23-Sep | Mobilisation | | | |
| 24-Sep | Survey | 110924i1 | | |
| 25-Sep | Survey | 110925i1 | | |
| 26-Sep | Survey | 110926i1 | | Clouds in the data |
| 27-Sep | Survey | 110927i1 | | Flight cloud gap lines |
| 28-Sep | Demoblisation | | | |


**Figure 3: Overview of the four flights**

## 5.1. Weather and tide

During the first two days (24th and 25th of September) the weather was perfect survey weather. Unfortunately clouds came in during the survey which introduced some gaps in the data. On the 27th Fugro was able to re-fly these gaps and subsequently the data affected by the clouds were disregarded in the further processing.

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

All flights were flown well below the stated -0.70m NAP. Mostly even below -1.50m NAP. As far as the delivered data is concerened the operational circumstances were optimal.

# 6. Processing and Quality Control

Below you find the processing and quality control procedure from acquiring the data to further end deliverables. Every process needs a validation before the next step can be taken.

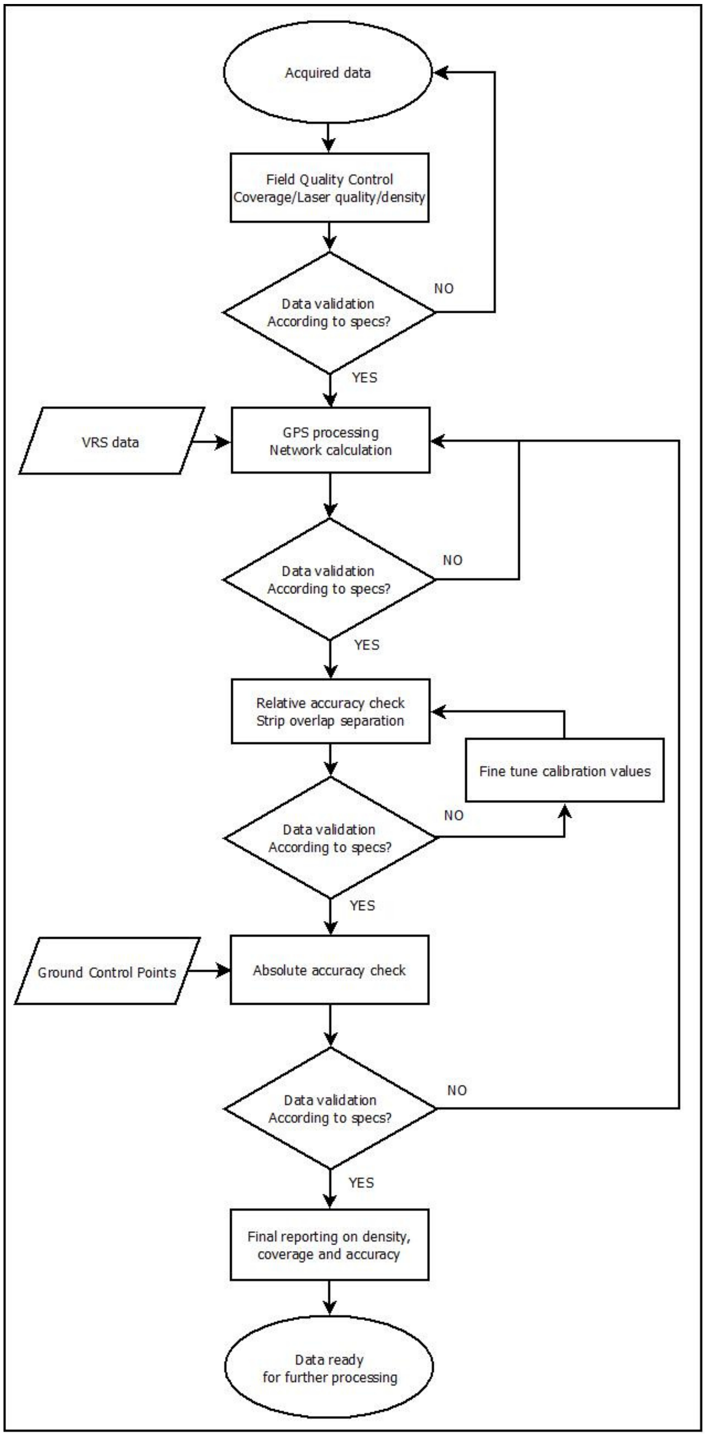



**Figure 4: Processing flowchart**

## 6.1. Laser quality

Only crucial checks are performed in the field. Checks to assure the data has been acquired up to the standards for further processing.

Right after acquisition the data is checked on any anomalies like:
- Reflection problems due to strongly absorbing material
- Lack of registered beams due to hardware glitches
- Excessive noise due to system failure

Analyzing the error messages and quick views of the data concluded that no anomalies were present. The anomalies are a deviation from the common rule, type, arrangement, or form. Reflection problems on the wet area of mud floods 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. Lower reflection due to strongly absorbing material is representative to the technology and not worse (even better) than last surveys, this due to dryer circumstances.

## 6.2. 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 3). Gaps are reported and re-flown.

Automatic cross profiles are being generated to spot any anomalies in the returns which can be masked in to the view coverage check. The cross profile below the clouds of flight 110926i1 clearly shows the returns on clouds.

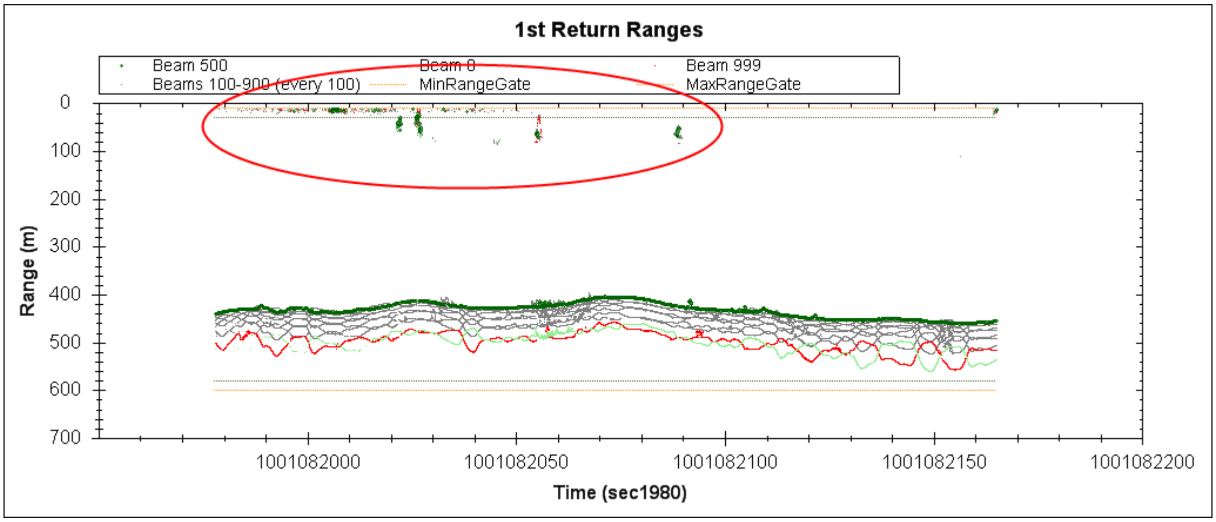
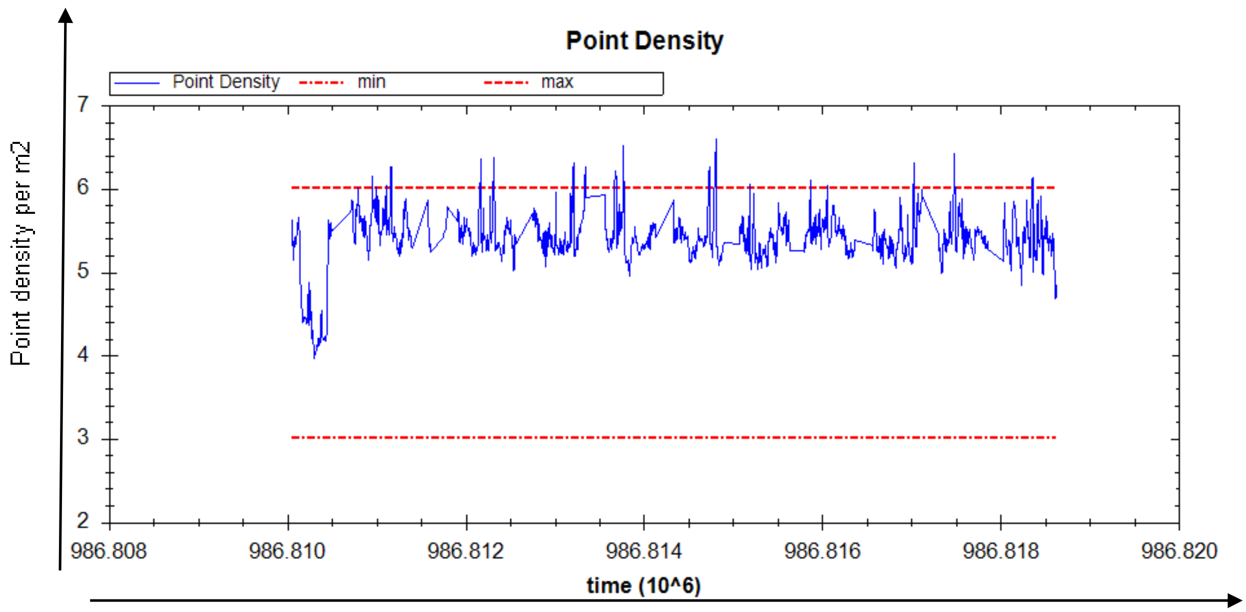



**Figure 5: in the red circle “cloud returns”**

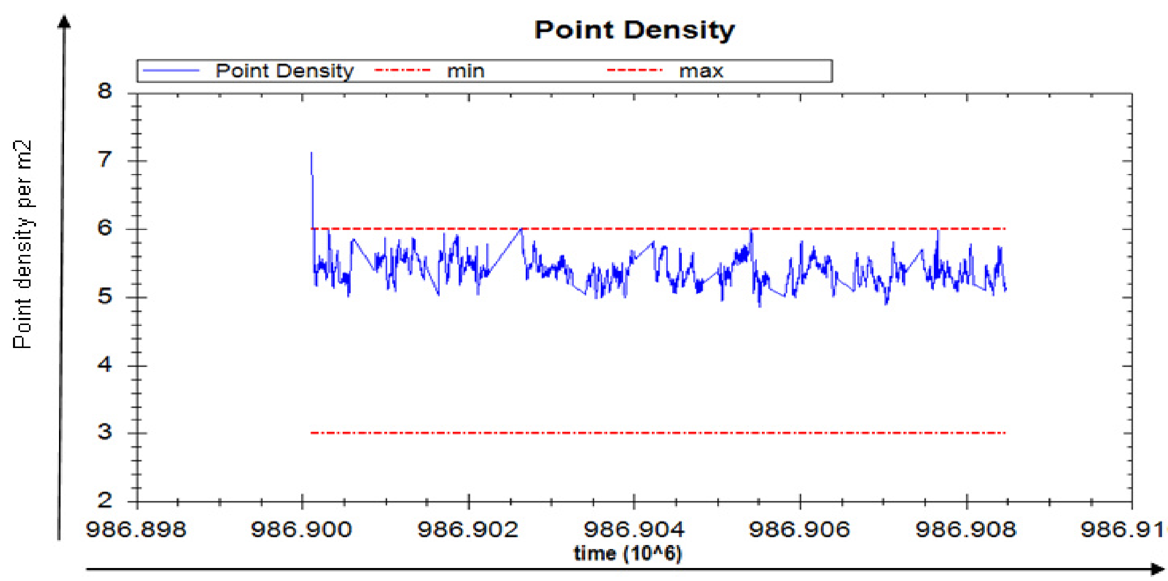
During the acquisition phase all reported gaps were re-flown. Coverage was checked and approved to the client boundary file.

## 6.3. Point Density

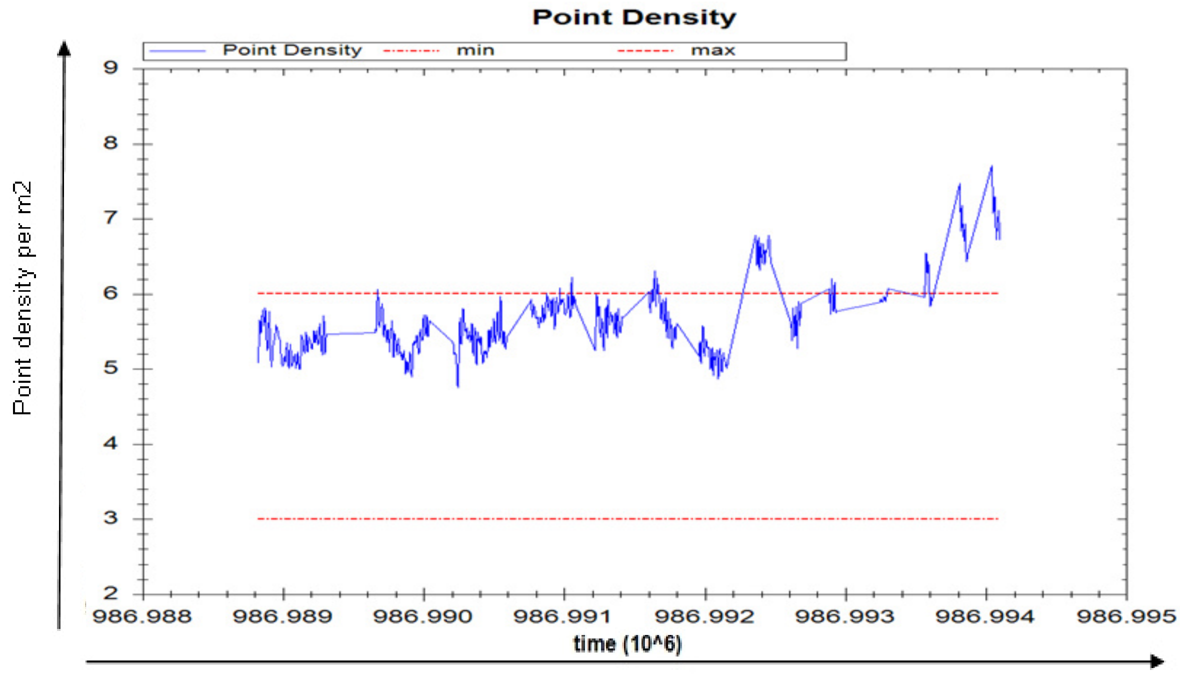
After the data acquisition a preliminary density checks can be executed. Based on the aircraft's speed and scanning rate a theoretical (expected) points density is calculate per strip, subsequently per flight (Figure 5.) and finally for the whole survey area.



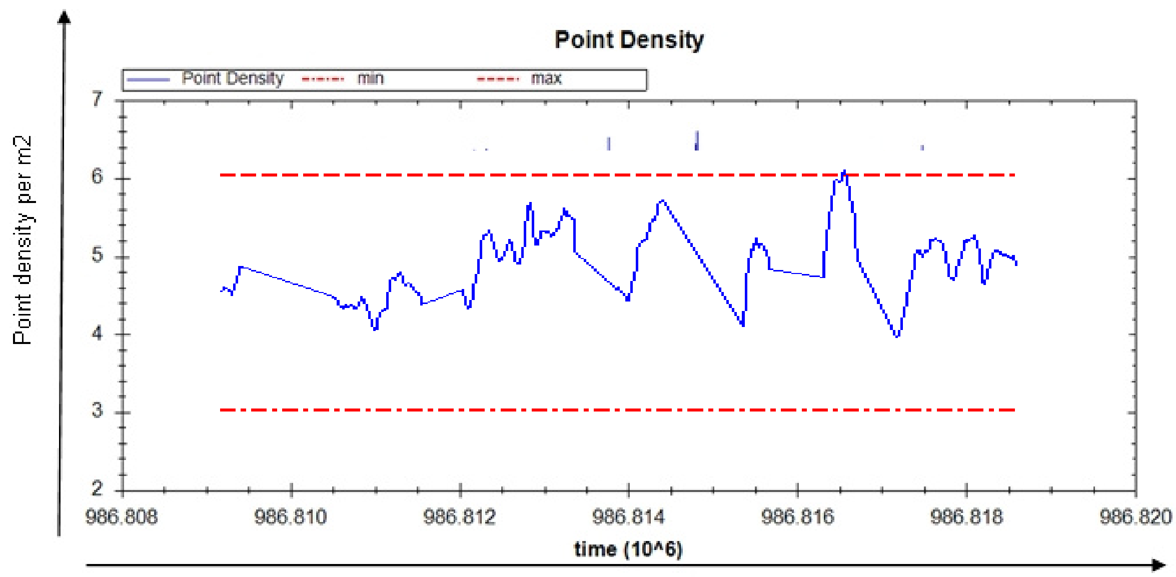

Flight 110924i1




Flight 110925i1




Flight 110926i1




Flight 110927i1

**Figure 6 Theoretical (based on actual speed and scanning frequency) point densities per flight**

A final check on the point density requirements is executed in the post-processing phase. The amount of points per m2 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.

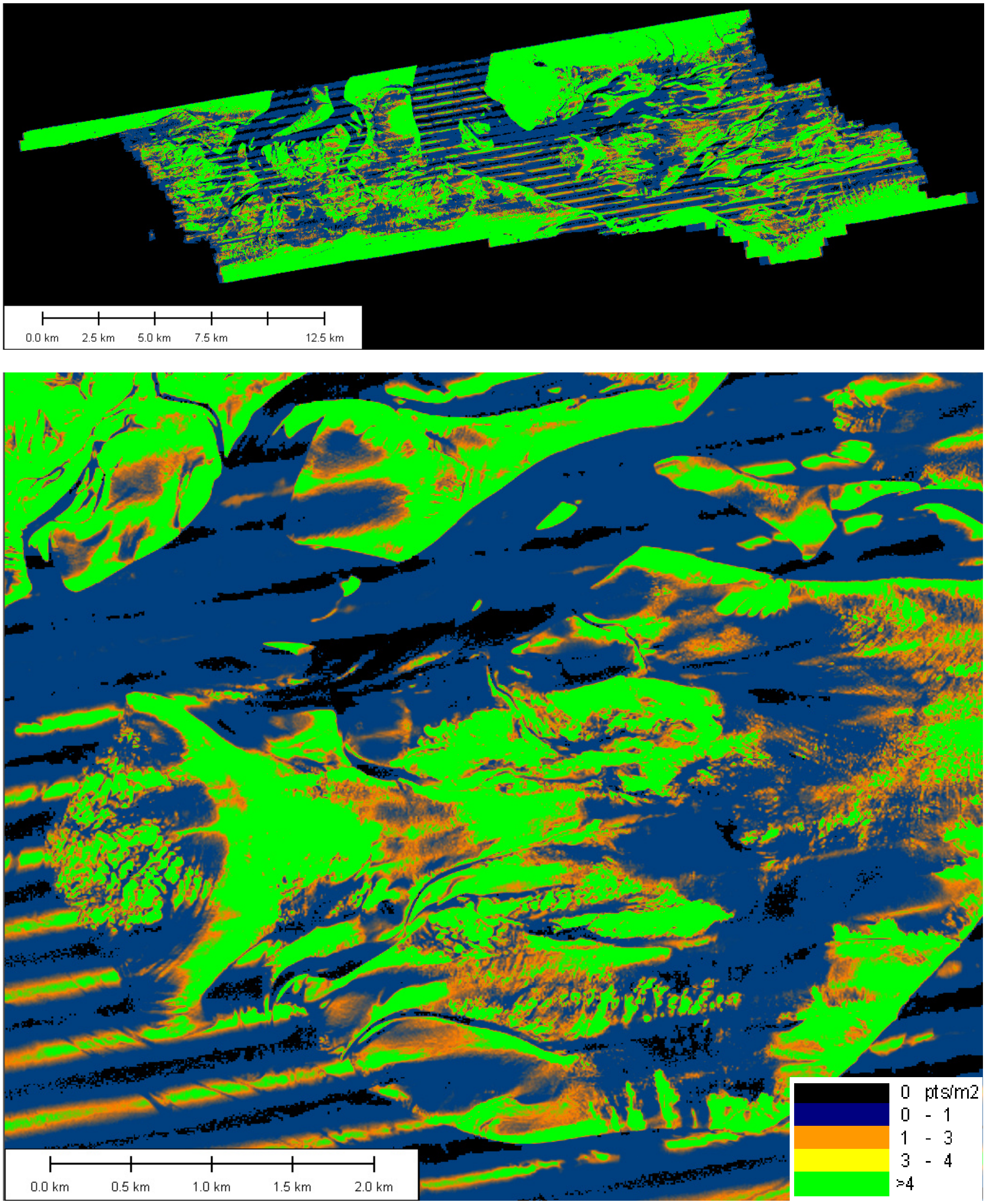



**Figure 7: Example of point density check in the project**

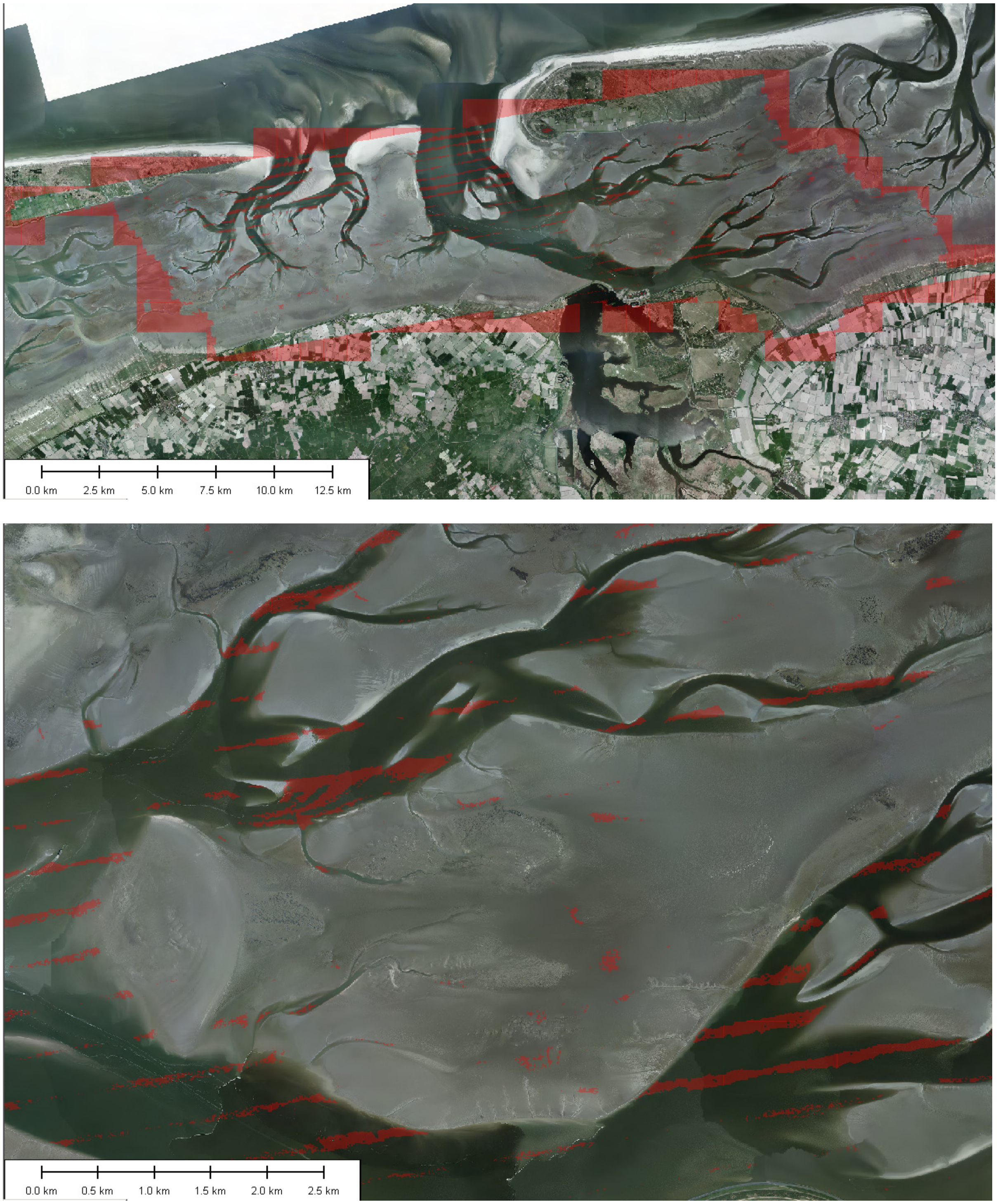



**Figure 8: Example of point density check in the project. Transparent – red = density 0 pts/m2 – no reflection**

On the mainland south and north of the area the point density was more than 4 points per square meter. A slight decrease in point density can be identified on the mudflats. On occasion there is also area with 0 density values representing lower reflection due to high absorbing material (water).
Point density is better than the previous two surveys due to dryer circumstances (lower/longer low tide and warm). See section weather and tide.

## 6.4. Theoretical accuracy

Flying at an altitude of 500m with a speed of 110kts and laser frequency of 150 kHz the following theoretical accuracies were expected.

| **Elevation** | **500** | **m AGL** | **Speed** | **110** | **kts** | **Scan speed** | **150** | **KHz** |
|---|---|---|---|---|---|---|---|---|
| **Foutenbron** | **Opmerking** | **Effect op XY of Z** | **Orde van grootte** | **(eenheden)** | **Effect op XY (in meters)** | | **Effect op Z (in meters)** | |
| | | | | | **Nadir** | **Rand** | **Nadir** | **Rand** |
| Positie meetsysteem | GPS | XY | 0.02 | (meter) | 0.020 | 0.020 | - | - |
| | | Z | 0.03 | (meter) | - | - | 0.030 | 0.030 |
| Stand meetsysteem | Heading | XY | 0.0100 | (graden) | 0 | 0.040 | 0 | 0 |
| | Pitch | XY en Z | 0.0075 | (graden) | 0.065 | 0.066 | 0 | 0.008 |
| | Roll | XY en Z | 0.0075 | (graden) | 0.065 | 0.078 | 0 | 0.032 |
| Range ruis | | XY en Z | 0.015 | (meter) | 0 | 0.006 | 0.015 | 0.014 |
| Hoekmeting laserstraal | Ruis | XY en Z | - 0.0000001 | (seconde) | - 0.012 | - 0.013 | - 10e-7 | - 0.005 |
| Uitlijning rotatieas | | XY | 0.025 | (mrad) | 0.006 | 0.006 | - | - |
| Footprint | Straaldivergentie | XY | 0.012 | (meter) | 0.040 | 0.043 | - | - |
| | | | 0.45 | (mrad) | | | | |
| Tijdregistratie | | | 0.00010 | (seconde) | 0.006 | 0.006 | - | - |
| **Totale fout** | | | **Systematisch** | (meter) | **0.075** | **0.103** | **0.015** | **0.035** |
| | | | **Stochastisch** | (meter) | **0.064** | **0.073** | **0.021** | **0.027** |

The accuracy for each dimension (x, y 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 3.5 cm**
- **Stochastic height error of 2.7 cm**

| | **Z accuracy between laser and ground control points** |
|---|---|
| 1 sigma | 68% < 6.2 cm (1*2.7 cm+3,5cm) |
| 2 sigma | 90% < 8.9 cm (2*2.7 cm+3,5cm) |
| 3 sigma | 99,6% < 11.6 cm (3*2,7cm + 3,5cm) |

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% < 10.8 cm |
| 2 sigma | 90% < 14.6 cm |
| 3 sigma | 99,6% < 18.4 cm |

All mentioned above are the maximum theoretical errors; the real errors can be less because errors can cancel each other out.

## 6.5. GPS processing and network calculation

Fugro makes use of Smartbase 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. In case of Smartbase GPS-processing this base line is kept short by calculating a virtual reference station on the antenna position. This way the highest accuracy can be obtained. The GPS RMS is calculated and checked with the specifications. The forward/reverse flight path is calculated to check the reliability of the solution.

To be able to tie the data set in the requested datum and proof the reliability of the base station locations used a network calculation could be executed. In case of a homogenous geodetic network and proven reliability of Virtual Reference stations this was omitted in this survey.

## 6.6. Relative Accuracy Check

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 surface 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. Because of the method (gridding two data sets before analyzing the difference), a few notes have to be made:
- Vegetated area's do not give a reliable view on the accuracy, see red areas below
- If flights are far apart in time, circumstances could have changed, resulting in strip overlap
- Moving circumstances (e.g. water) or objects (car) are not suitable for this method

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

Below the results of the relative accuracy check for this project are presented.

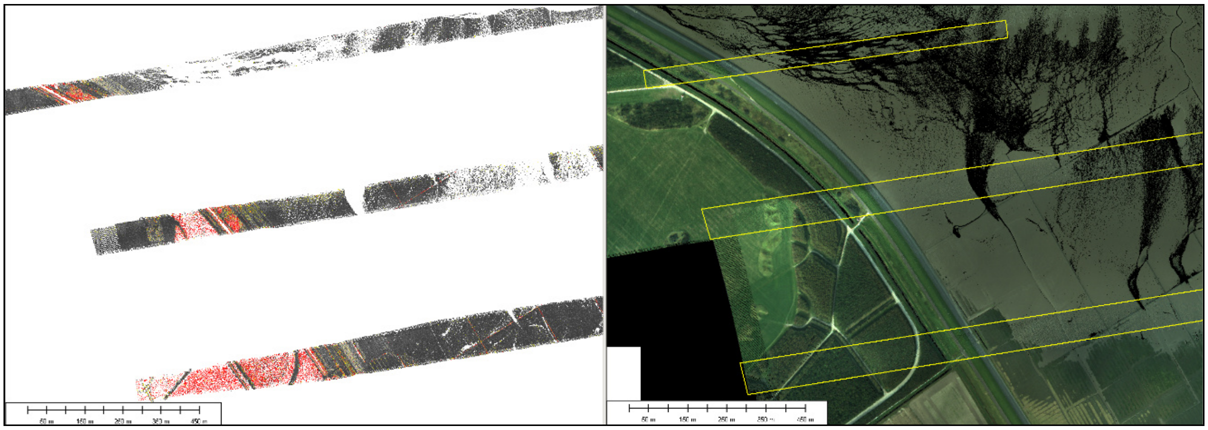


**Figure 9: Left the separation analysis and right the line scan**

All overlaps were checked using the following criteria:

| | | | |
|---|---|---|---|
| | | 0 | 5 |
| 68.3% < 10.8cm | | 5 | 10 |
| 95.4% < 14.6cm | | 10 | 15 |
| 99.7% < 18.4cm | | | >15 |

Height difference of 0cm to 10cm: good
Height difference of 10cm to 15cm: research is required, if it is structural.
Height difference bigger than 15cm: research is required


**Figure 10: Control points distribution over the project area**

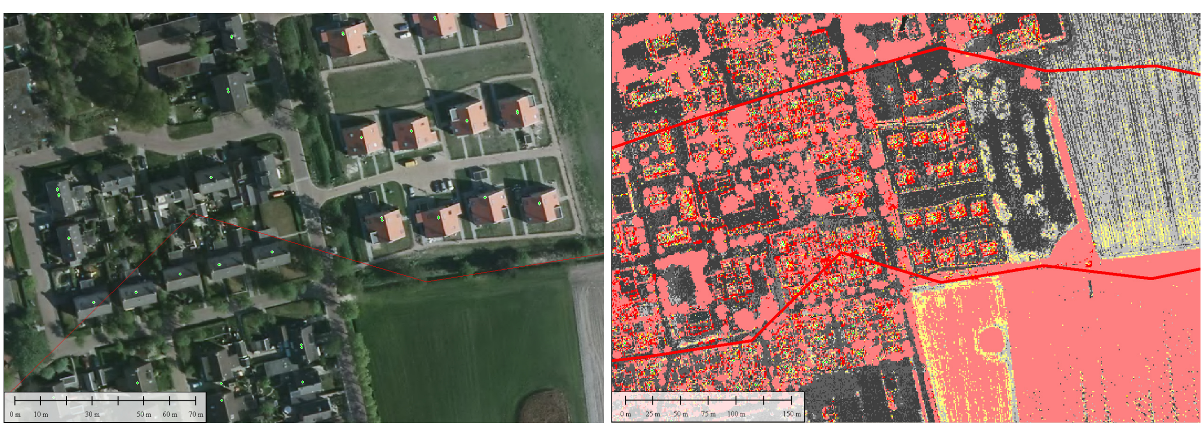
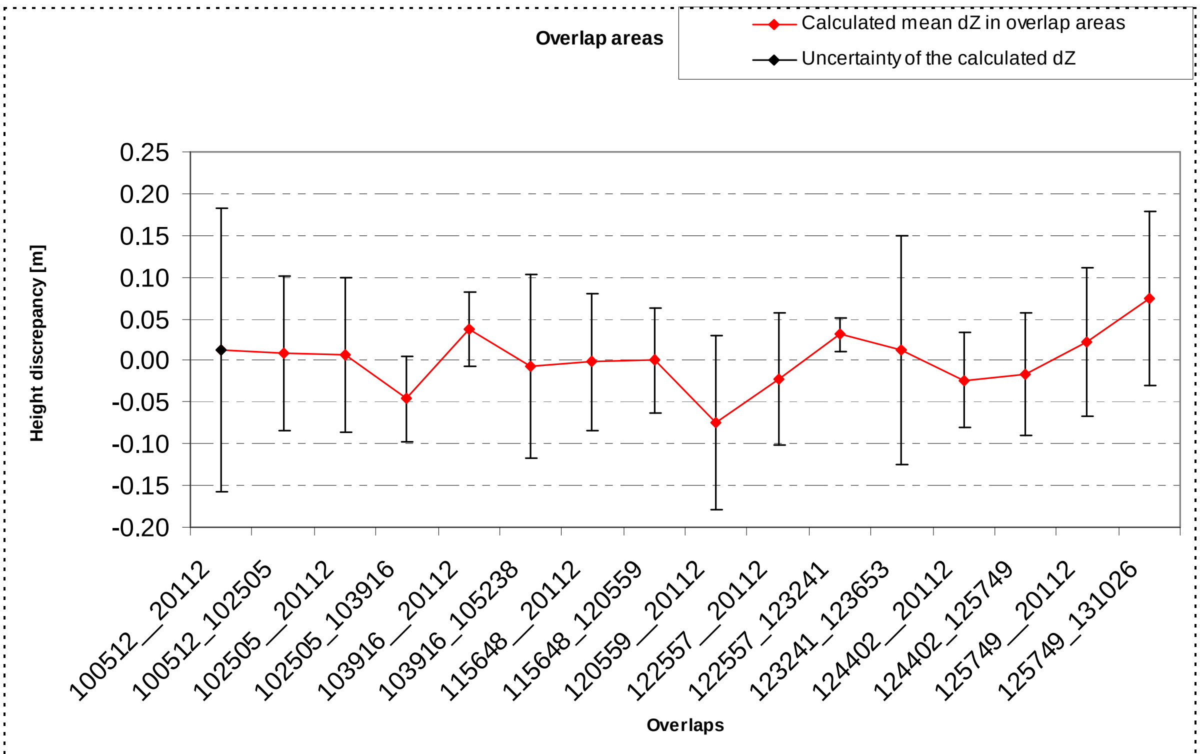


**Figure 11: Left control points on the roof ridges and right the vertical separation analysis**

Based on cell values of the separation grid a histogram of the relative height discrepancy between the strips can be generated for the entire overlapped area. As expected, the histograms for each 16 overlaps show that the relative height differences between adjacent strips have a random normal distribution. The mean discrepancy value and its standard deviation per overlap are calculated. The mean value of discrepancies per overlap (red dots on Graph 1) is not the same and does not equal zero. Also no systematic behaviour can be observed in Graph 1. It confirms that the systems (laser scanners, mount, GPS/IMS etc.) are well calibrated, thus the data is free of the systematic errors. The standard deviation on Graph 1 (uncertainty of the calculated dZ separations) is mainly caused by:
- Vegetated area’s - do not give a reliable view on the accuracy,
- If flights are far apart in time (a day or two), circumstances could have changed
- Moving circumstances (e.g. water) or objects (cars).




**Graph 1: The mean value of discrepancies per overlap**

Fugro concludes that the relative accuracy is 10 cm for 1 sigma (68.3%). Taking into account the conservative calculation by this method, due to above mentioned reason, actual relative accuracy will be higher. Above stated error is typically divided over two strips and thus due to the stochastic nature $\sqrt{2}$ times smaller.

There might still be a cumulative effect of the relative RMSE values present, where adjacent strips forms “stairs” structure. In order to mitigate that risk, absolute control points are planned and absolute accuracy is tested.

## 6.7. Absolute Accuracy

To evaluate the accuracy of a dataset, a comparison must be performed. A dataset's accuracy is evaluated by comparing the coordinates of several points, which are locatable easily in all the dataset(s) with an independent dataset of greater accuracy. For this research, LIDAR data were compared to GPS points collected separately with RTK GPS and leveling 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.

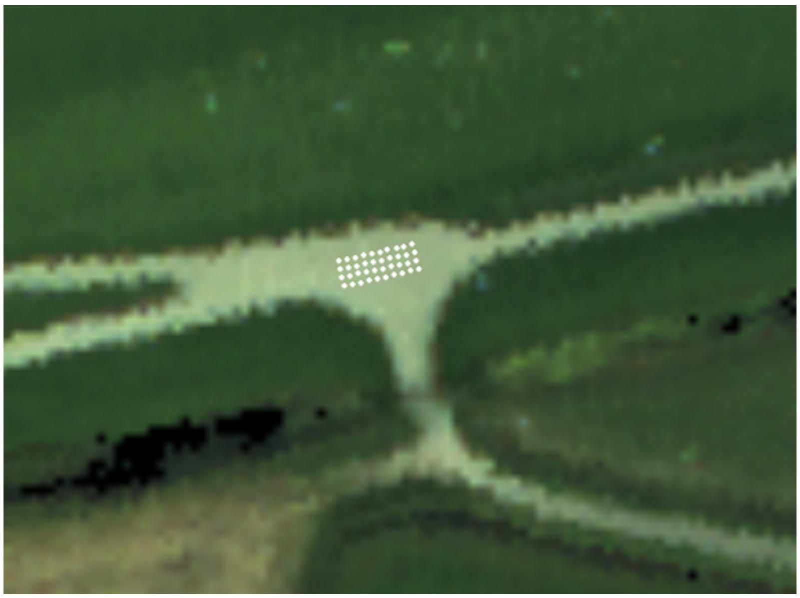


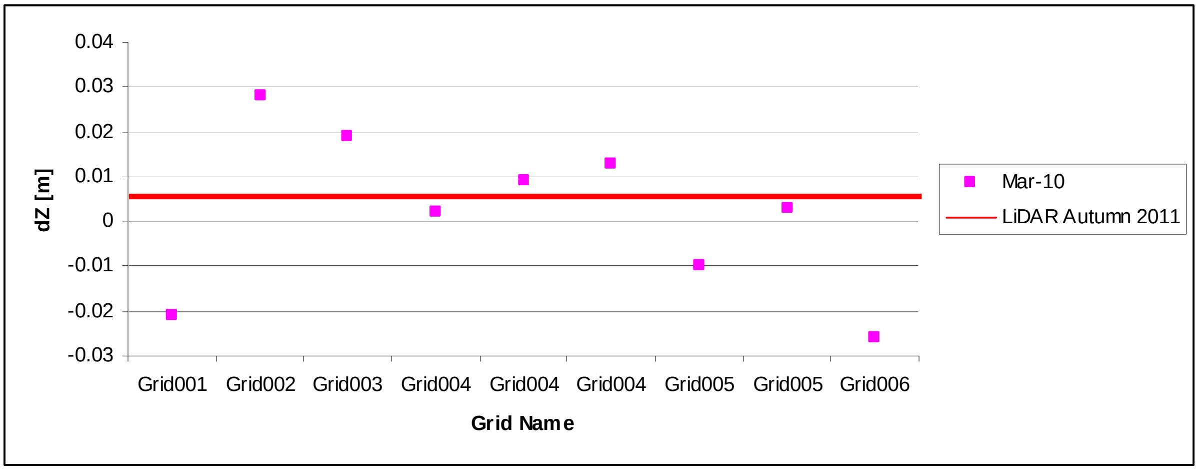
**Figure 12: Example of one of the GCP's used for this project**

All grid checks were checked using the following criteria:

| Z difference between laser and grid | Theoretical specifications |
|---|---|
| 100% < 3.0 cm | 68.3% < 6.2cm |
| | 95.4% < 8.9 cm |
| | 99,7% < 11.6 cm |

The control grids were measured in 2010. In this autumn flight, the control line of each flight covered Grid 004 and Grid 005. The other control grids are also covered by various flights as can be seen in the table below.

| | Control Grid (2010) | | | | | |
|---|---|---|---|---|---|---|
| | Grid001 | Grid002 | Grid003 | Grid004 | Grid005 | Grid006 |
| 110924i1 | -0.021 | N/A | N/A | 0.002 | -0.010 | -0.026 |
| 110925i1 | N/A | 0.028 | 0.019 | 0.009 | 0.003 | N/A |
| 110926i1 | N/A | N/A | N/A | 0.000 | -0.007 | N/A |
| 110927i1 | N/A | N/A | N/A | 0.013 | 0.000 | N/A |




**Graph 2: Z difference between laser data and control grids**

Please see appendix D for a more detailed overview of the absolute accuracy check.

After removing the systematic errors during relative accuracy analysis only remaining random error is expected. Graph 2 shows a bias in the differences of -0.001 m with a standard deviation of ±0.02 cm. That means that the average height of the laser data points included in the project area are higher than the surveyed ground by 0.001 m. The total computed RMSE of the project data from the ground reference was about 3 cm... This number represents the real standard deviation of the LIDAR data heights. Fugro concludes that the data met a priory absolute accuracy of 6.2 cm for 1 sigma (68.3%).

Apart from Fugro's control measurements additional 11 locations were supplied by NAM. Only 6 were covered b y laser data and only those were taken into further calculations.

The points were surveyed using spirit levelling technique, relative to the main benchmark, which was accurately measured by GPS for a length of 5 days (Static GPS survey techniques). The land survey was executed in August 2010 and May 2011, which does not coincide with the Lidar survey dates and as the height of the sandbanks can vary overtime and per season, the height values cannot be considered absolute. However, it is an independent dataset of higher accuracy that corresponds to the data being tested. In contrast to the control grids surveyed by Fugro, NAM control measurements are located well inside the project area. Thus it was taken into Fugro's accuracies analysis.

A TIN model was constructed based on laser data points and the corresponding levelling control grids were selected. Then the height of each node of the control grid is compared with the corresponding height interpolated from the surrounding laser points. Since the points are near by and the surface is flat, a linear interpolation was used. Direct differencing is then applied to compute the offset dZ between the two data sets from the laser and ground (the laser height was subtracted from the ground interpolated height). More than 10 (on average 20) differences were computed per locations. Based on histogram of the differences a RMSE can be calculated.

On occasion there was no laser data (poor reflectivity on the mudflats) overlapping with the control measurements or the control grid was not levelled in both periods Aug 2010 or May 2011 - such locations were omitted in the comparison.

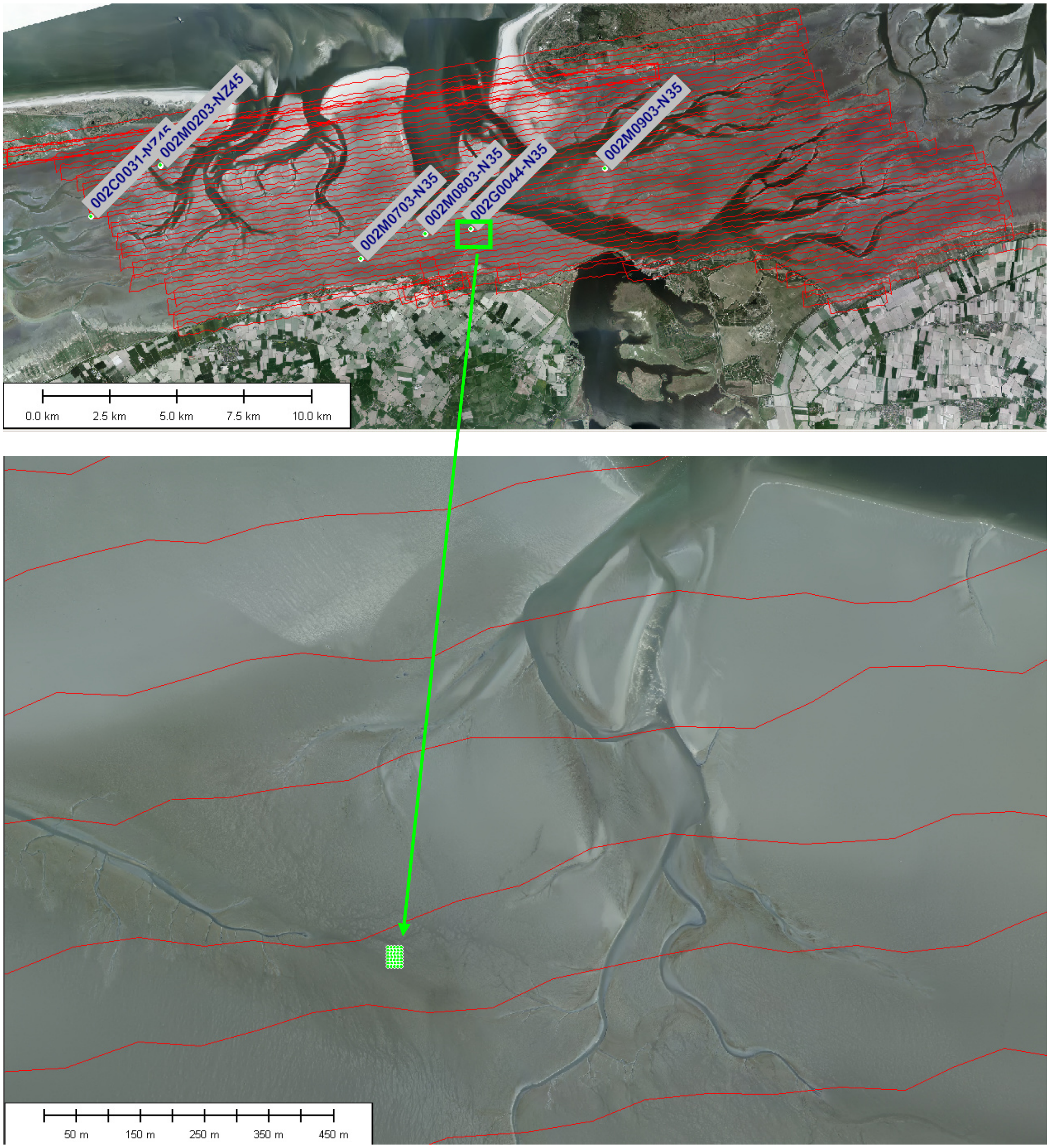
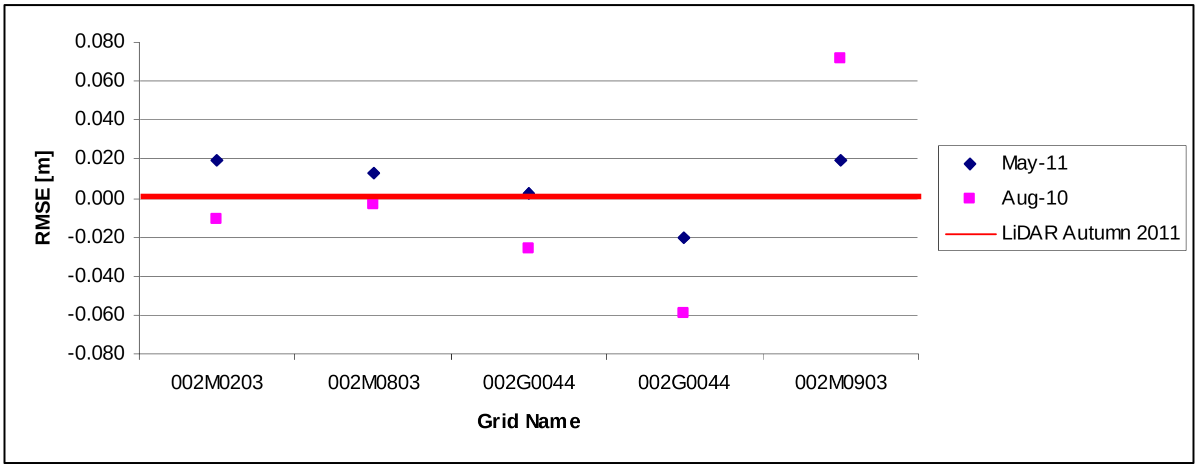



**Figure 13: The levelling grids supplied by NAM**

The results from the RMSE analysis for a total of 5 checked location (levelling spirit surveyed points) using the derived control planar features from the LiDAR point from August 2010 and May 2011 are listed in the table below.

| Aug-10 | # pts | RMSE [m] |
|---|---|---|
| 002M0203 | 10 | -0.011 |
| 002M0803 | 22 | -0.003 |
| 002G0044 | 22 | -0.026 |
| 002M0703 | 23 | -0.060 |
| 002M0903 | 18 | 0.071 |

| May-11 | # pts | RMSE [m] |
|---|---|---|
| 002M0203 | 10 | 0.020 |
| 002M0803 | 22 | 0.013 |
| 002G0044 | 22 | 0.002 |
| 002M0703 | 23 | -0.020 |
| 002M0903 | 18 | 0.020 |




Analyzing the graph a trend can be observed in the fluctuation of the grid heights, which most likely can be correlated with a periodical sedimentation of the sandbank. As expected, almost no improvement in the Vertical accuracy is observed since detected biases in the system parameters mainly affecting the horizontal accuracy were already removed during relative accuracy estimation. Fugro concludes that the data met the absolute accuracy of an a-priori 6.2 cm with 68.3% confidence level.

# 7. DELIVERABLES

The following data has been delivered to Deltares and NAM on the 28th of October:

- ASC 1m average grids
- LAS Files with outliers removed
- XYZ files with X,Y,Z,Intensity,R,G,B

The data has a tile dimension of 1000x1250m.

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

# 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 | 6 Ground control grids to check the absolute z- accuracy < 62 mm | Average dz (cm) 0.0<br>SD dz (cm ) 1.6 | Approved |
| Relative accuracy | Allowed difference between overlapping flights | 68.3% < 10.8cm | Approved |
| Classification ground/non-ground | Should be of sufficient quality to create reliable ground model | Quality controlled | Approved |
| Laser quality | Check on anomalies in laser quality | No anomalies found | Approved |