Validation study of SILAS

Study area: Maasmond (The Netherlands)

Deltares

Title
Validation study of SILAS

Client	Project	Reference	Pages
Rijkswaterstaat Water, Verkeer en Leefomgeving Locatie Lelystad	1207624-000	1207624-000-BGS-0006	157

Keywords
SILAS, acoustics, mud, navigability, nautical depth

Summary
The goal of the validation study is to ascertain that the SILAS acoustic system can detect density levels of mud (in this case 1.2 kg/L) and determine the bandwidth. For this purpose, a survey was carried out in the Maasmond in January 2013, consisting of 131 SILAS lines and 75 point measurements of density. The analysis of data consists of comparisons of results of more than 60 calibrations. Prior to the survey and analysis, eight research questions had been posed. The questions and answers to the research questions are summarized in chapter 2.

The most important conclusion is that using SILAS acoustics in combination with point measurements of density it is possible to obtain spatial information on density levels of fluid mud, ranging from 1.16 to 1.25 kg/L, with an accuracy comparable to the point measurements of density that are used for calibration. Point measurements of density remain necessary for calibration purposes. With SILAS, however, the number of point measurements can be decreased while the amount of spatial information of the 1.2 kg/L density level can be increased significantly, since SILAS is able to provide information (on lines) between the point measurements.

Version	Date	Author	Initials	Review	Initials	Approval	Initials
6	July 2013	G. Diaferia MSc		drs. R.S. Westerhoff		dr. R.M. Hoogendoorn	
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Appendices

1 Introduction

To assure the safe navigability of Dutch waterways with muddy water-bottoms, Rijkswaterstaat (RWS) has defined a guaranteed nautical depth based on the maximum density of mud of 1.2 kg/L. This density level has been determined by performing periodic point measurements of density using a radioactive device (Navitracker or D2Art). For laterally continuous information of mud thicknesses and to reduce the number of relatively expensive point measurements, RWS has bought the acoustic SILAS system, manufactured by STEMA.

The SILAS system uses calibrated acoustic impedances to determine the location of a desired density level. For the calibration, point measurements of the density are used. The relative energies of acoustic reflections are converted to absolute depth levels of a user defined density, e.g. the 1.2 kg/L level. To shed light into the black box of calibration, RWS has requested a validation study from Deltares. Moreover, the bandwidth of determination of the desired 1.2 kg/L level is unknown.

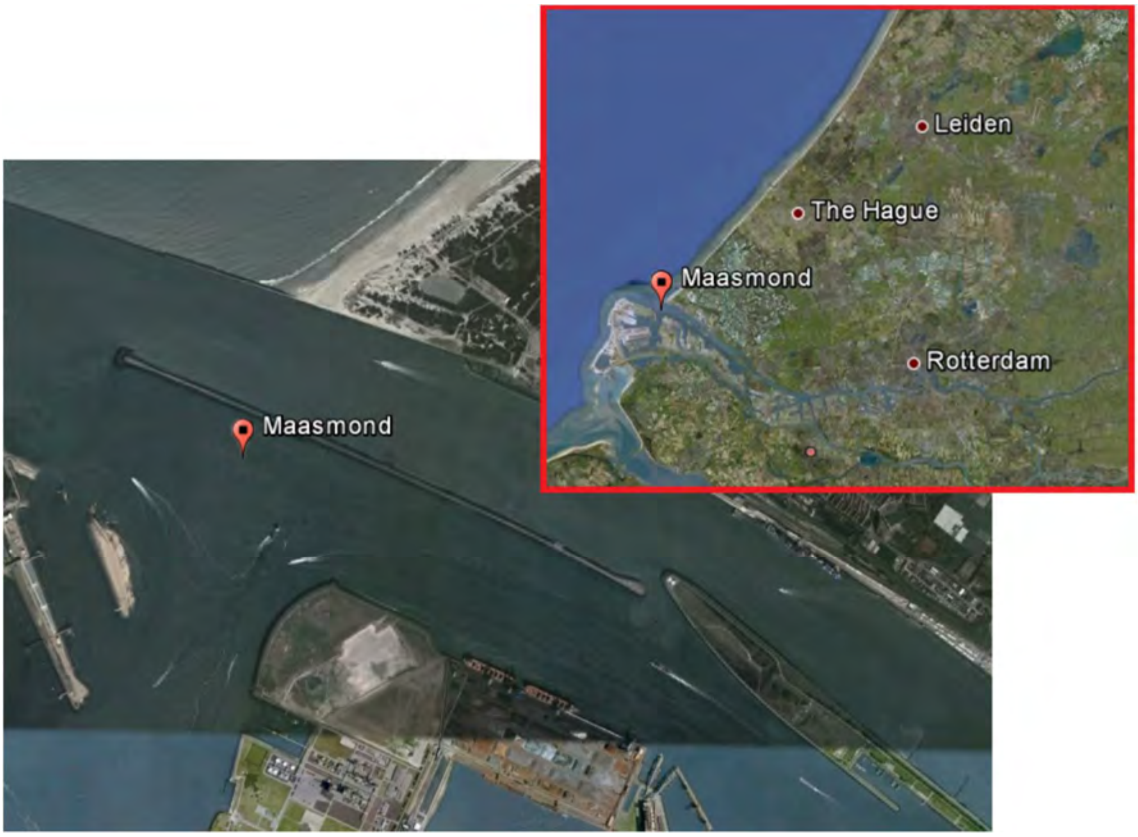


Figure 1.1 Location of the Maasmond, The Netherlands. Background image: Google Earth.

In the process of validating the SILAS system, the following Deltares reports were produced:

- “Assessment SILAS systeem - Onderzoek naar bepaling van slibdichtheid met een akoestisch systeem” (1205574-000-VEB-0001, February 2012). This assessment showed that the SILAS system has potential to visualize the spatial and temporal variability of the mud.
- “Plan van Aanpak voor de praktijkvalidatie van SILAS” (1206421-000-BGS-0012-v4-r, December 2012). This report describes a strategy to validate the SILAS system by means of test measurements. The presented a survey plan was agreed on by STEMA and RWS. It includes 7 research questions for the validation of the SILAS system.
- “Survey report SILAS Validation” (1207624-000-BGS-0004-v2-r-r, January 2013). This report describes the survey that was performed from 8 to 17 January 2013 in the Maasmond (the Netherlands) and contains the measurements needed for the validation. The location of the test area in the Maasmond is shown in Figure 1.1.

In the current report, chapter 2 states the research questions for validation. Chapter 3 summarizes the survey. In chapter 4, the processing of the SILAS data and quality control is described. Chapter 5 includes all calibrations applied to determine the 1.2 kg/L bandwidth. In chapter 6 the research questions are answered. The conclusions and recommendations are given in chapter 7.

2 Research questions for SILAS

In the report “Plan van Aanpak voor de praktijkvalidatie van SILAS” (1206421-000-BGS-0012-v4-r, December 2012), the research questions for the validation of the SILAS system were posed. The research questions were formulated by Deltares and RWS jointly. The questions are repeated below. Additionally, the answered are summarized. The full answers are given in chapter 6.

Question 1 What is the accuracy of individual density measurements?
This refers to the point measurements of density with the D2Art or Navitracker tool.

Answer 1 Mud thicknesses for a cluster of closely positioned points (within 8 m distance) show a standard deviation of 30 cm. Therefore, the repeatability and the spatial representativeness of the point measurements are limited.

Question 2 What is the representativeness of point and line measurements in space and in time?
This refers to the point measurements of density with the D2Art or Navitracker tool and the SILAS line measurements.

Answer 2 The derived amount of mud is variable over a couple of days and even within the same day. Point measurements and SILAS line measurements of one calibration line should therefore be completed within 2 hours.

Question 3 What are the accuracies related to model assumptions, measurement errors, processing assumptions and dynamics of mud system related to the SILAS procedure? What is the band of uncertainty in determining the 1.2 kg/L level with SILAS?

Answer 3 The resolving power for the density in SILAs is 0.01 kg/L. Depth levels for 1.2 and 1.21 kg/L are identical, whereas depths for the 1.19 and 1.22 kg/L levels are significantly different. The bandwidth of the depth level of the 1.2 kg/L relative to the 1.05 kg/L level or the first reflector (thickness) is approximately 30 cm (RMSE).

Question 4 How do different processing options influence the result?

Answer 4 The gradient method should not be used, because it is not based on the physical property of reflections on impedance contrasts. The cumulative method without vertical corrections is to be preferred over the cumulative method with vertical corrections, because of the averaging effect in depths of the determined 1.2 kg/L level.

Question 5 What is the optimal number of point measurements relative to the line measurements of SILAS?

Answer 5 The optimal number of point measurements for the test area is 30. For each area and point measurement method, the optimal number of point measurements should be determined, probably only once.

Question 6 How applicable is the SILAS system for measuring densities by RWS?

Answer 6 The statistical analysis showed that SILAS is able to track density levels from 1.16 to 1.25 kg/L. Analysis of root-mean-square-errors show that the bandwidth of derived SILAS depth or thickness is approximately 30 cm. This is comparable to the standard deviation in thickness of the point measurements of the clusters of closely positioned points. The bandwidth can be decreased with better quality point measurements, e.g. using dynamic positioning.

Question 7 How do SILAS measurements need to be included in the working processes of RWS?

Answer 7 Recommendations are given for the inclusion of SILAS in the working process in chapter 6.6. These include recommendations on the survey procedure, calibration method and determination of optimal number of point measurements for the entire Maasmond and IJmond area.

Additionally, an extra research question has been defined by RWS:

Question 8 What is the applicability of acoustic techniques for the determination of density levels? What are the possibilities, bottlenecks, assumptions and uncertainties?

Answer 8 It is expected that any acoustic system which penetrates the mud to the desired density level and with sufficient vertical resolution (i.e. appropriate frequency) will be able to make the conversion to density provided that a suitable calibration to actually measured densities is made. For any acoustic system, the same limitations hold as for SILAS. Therefore, the recommendations for SILAS will also apply to the alternative acoustic system.

3 Survey

The SILAS validation survey in the Maasmond, the Netherlands, was carried out between January 8-10th and January14-17th 2013 for a total of 7 days. The RWS survey vessel Corvus was used for the survey. The point measurements of density were performed using the D2Art tool by RWS for the majority of locations. On one survey day, the Navitracker tool was used operated from the RWS vessel Arca. A detailed description of the performed survey is given the 'Survey report' (*1207624-000-BGS-0004-v2-r-Survey report SILAS Validation*).

As a summary, Table 3.1 gives an overview of the performed measurements day-by-day. More than 100 SILAS lines were measured along a regular grid and 75 density measurements were carried out. SILAS lines are divided in:

- Calibration lines (amount 10): used to tie the SILAS data to the density measurements and extrapolate a defined density level to all lines in the area. The distance between calibration lines is 75 m. The direction is perpendicular to the dam in the close vicinity.
- Fill up lines (amount 50): perpendicular and parallel to the dam. The distance between the lines is 25 m.

Table 3.1 Performed day-by-day measurements in the Maasmond location (see 'Survey report' for further details).

Day	Date	Jobs
1	Tuesday 08-01-2013	Set up all systems
		Ramp test
		Calibration line 4
2	Wednesday 09-01-2013	Stationary measurements at mooring location
		Calibration line 7 – 10 – 1
3	Thursday 10-01-2013	SILAS with different speed
		Calibration line 13 -16
		Silas line over 3 cluster of 5 D2Art measurement each
weekend	Saturday	
	Sunday	
4	Monday 14-01-2013	Set up all systems
		Ramp test
		Calibration line 19 – 22
		SILAS line from 7 to 28
5	Tuesday 15-01-2013	Measure 31 SILAS lines (35 to 65) perpendicular to the calibration lines (parallel to dam)
		Repetition of SILAS lines 1-2-3-4 in high tide condition
6	Wednesday 16-01-2013	Navitracker measurements by ARCA on 20 locations, 5 per each line 7b (=repeat line), calibration lines 25, 28 and extra points to verify thickness given by SILAS calibration = line 40
		Stationary measurements over one location where mud is present (along calibration line 4)
		SILAS line on 5 – 6 – 25 – 28 and 40
		SILAS with different speeds
7	Thursday 17-01-2013	Attempt to do ADCP (Acoustic Doppler Current Profiler) measurements (failed) SILAS over calibration lines from line 4b to 28b

For the purpose of the study, some lines were measured several times in different conditions (different days, tides, vessel velocities) in order to test the influence of those factors on the SILAS acquisition and interpretation.

For the entire survey, the vessel ‘Corvus’ was provided by Rijkswaterstaat. The Corvus is equipped with Multibeam as well as 200/38 kHz echosounder. Data on those systems were continuously recorded along with the SILAS acquisition and made available for this study. The vessel ARCA was employed for 20 density measurements (tool: Navitracker) when the D2Art tool on the Corvus could not be used due to adverse weather conditions (temperature far below 0°C).

In Figure 3.1 an overview of the location of all surveyed lines and density point measurements is given. A larger image on A3 is provided in the appendix.

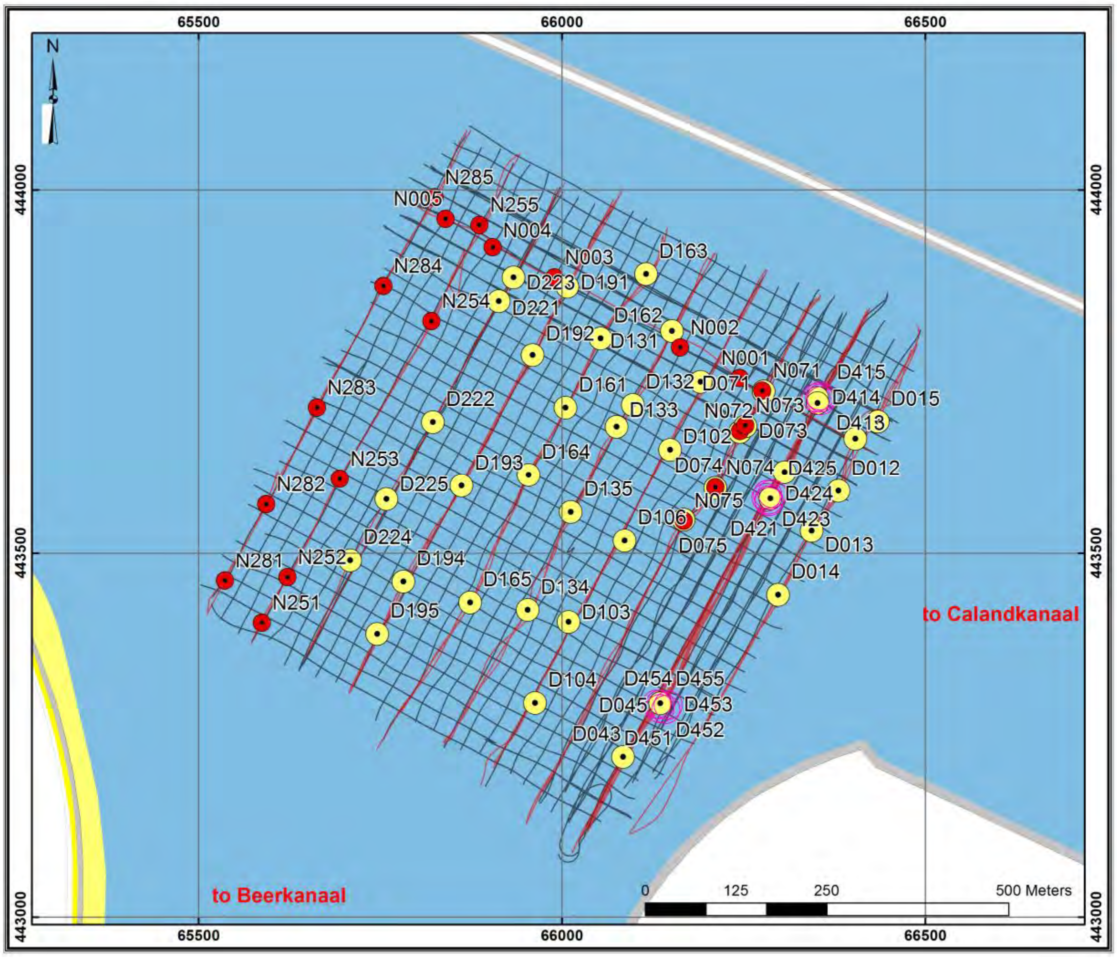


Figure 3.1 Location of calibration line (red) and fill-up lines (black). Yellow dots indicate density point measurements performed with the D2Art probe (vessel: Corvus). Red dots indicate the density measurements performed with the Navitracker density probe (vessel: ARCA). Pink circles indicate the clusters of density measurements performed with the D2Art probe. A larger image on A3 is given in the Appendix A .

4 Processing

4.1 Processing flow

For the processing, the SILAS processing package, version 3.1.3.0 was used. The processing flow was suggested by Stema. For proper processing, all lines were processed ‘day-by-day’. This is necessary because of the varying sound velocity in the water column. The sound velocity varies with temperature and salt content, which both change during the day because of tides. The SILAS software uses one single value of sound velocity for time-to-depth conversion. Therefore, for each day, the average of all velocities profiles have been calculated and inserted in SILAS.

The detailed processing work-flow used in SILAS is shown in Table 4.1.

Table 4.1 Processing steps

Step	
1	Preparation: a. Copy data to processing location b. Create new project (one per day), using January 9 as template c. Load seismic data (.SEI) and positioning data (.XYZ) d. Optional for January 8: shift of 1 second due to error in synchronization of GPS with SILAS 38 kHz transducer.
2	Sound velocity: a. Calculate average sound velocity from SVP from all velocity values measured on that particular day b. Insert average sound velocity of water for the conversion from time to depth
3	Define the top of the mud-layer by ‘autotracing’. In this procedure, SILAS automatically detects the first reflection in the acoustic records. Check quality of the layer for each line and manually correct if necessary. The top of the mud-layer is stored in the layer ‘bottom’.
4	Heave correction (line-by line): a. To remove the rhythmic motions caused by heave, a frequency filter (swell filter) is applied, using the program’s default settings as suggested by Stema. Check quality and manually edit line where necessary. b. Apply heave correction and overwrite the seismic file. c. Copy layer: i. Save the uncorrected sea-bottom layer in a new layer (‘Bottom_uncorr’). ii. Save the corrected sea bottom layer (depth1) to ‘Bottom’. d. Lock layer ‘bottom’ and ‘Bottom_uncorr’ to avoid accidental manual and non manual editing.
5	Tide correction: Load tide file for tide correction. Use default settings and invert the sign of the applied value.
6	Perform calibration

The position of the vessel and its instruments is influenced by the squat of the vessel. If a vessel is moving quickly through shallow water, it sinks slightly deeper than would be expected. However, no correction for squat has been applied. Comparing the autotraced bottom (see point 3 in Table 4.1) in SILAS with the 1.05 kg/L level measured by D2Art (both referred to NAP) no systematic shift was observed that could be explained by squat. Moreover, since (almost) all SILAS line have been acquired with the same speed, we assume that the squat is constant all lines (except for the varying speed experiment).

In this report, multiple examples of acoustic records are shown. Figure 4.1 is used to explain the graphic representation of the data. Depth is plotted on the Y-axis. The depth (in meter relative to NAP) is converted from the measured two-way-travel time of the acoustic signal and the sound velocity in water and mud. On the right side of the figure, an individual trace of the acoustic signal is plotted. The panel on the left side of the figure results from plotting all traces next to each other and color code them according to the amplitude in the wiggle. The X-axis thus represents the horizontal distance on the survey line. In the SILAS software, this is linked to coordinates, but not shown in the graphics. The ping rate of the transducer was 14 per second. With an average vessel speed of 2 m/s, this means that there is a trace every 14 cm (on average).

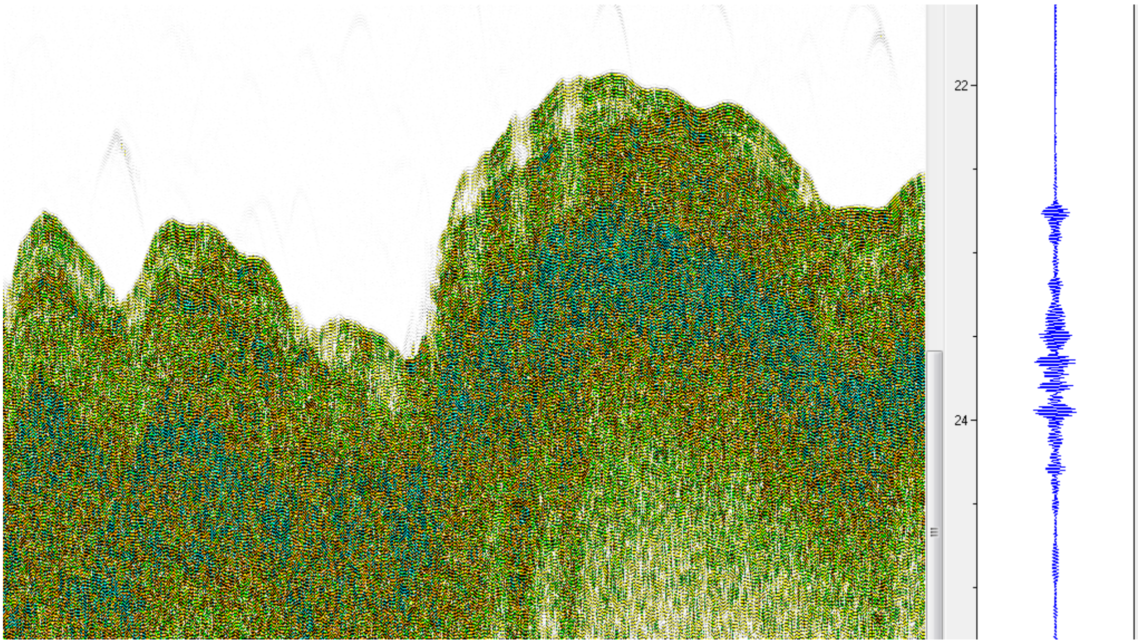


Figure 4.1 Example of acoustic records acquired using SILAS and the 38 kHz transducer. For explanation, see text.

During processing with the SILAS software, auto-tracing and heave correction is performed automatically (Table 4.1, step 3 and 4a). For the largest portion of the measured lines, the procedure works well. For steep slopes (e.g. near the dam), and for parts with SILAS data gaps (due to e.g. ship's traffic), the auto-tracing picks an incorrect level. The correct level has to be adjusted manually using the mouse. Adjustments are stored in the SILAS software automatically. In the following steps, the corrected levels are used. An example of a SILAS data gap, and adjusted bottom level, is shown in Figure 4.2.

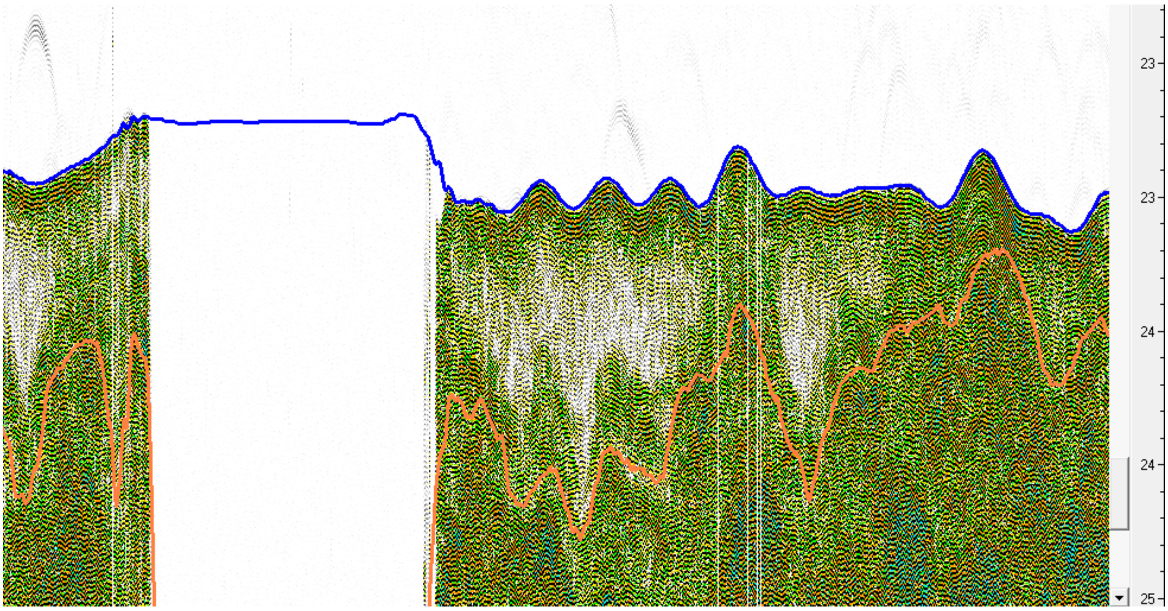


Figure 4.2 Example SILAS line S4 with a data gap, caused by ship's traffic. The blue line ("bottom") is manually adjusted (to approximately flat bathymetry). The orange line (1.2 kg/L level from basic calibration 1200_25cm_5m_cum) falls below the image on screen, at a depth of appr. 27 m. This is not corrected, because the error will be the same for all calibrations.

In the next sections, a detailed explanation of the main processing steps is given. Additionally, several quality control issues are discussed.

4.2 Heave correction

During the survey, the vessel underwent continuous movements around its center of mass, such as heave, pitch, yaw and roll. Such movements influence all the acoustic measurements that therefore have to be corrected. The SILAS processing software allows correction for heave in two ways:

1 By correction of actually measured heave from a motion sensor.
2 By application of a swell filter to the auto-traced sea-bottom.

During the start up of the survey, no physical link could be established between the Corvus's motion sensor and the 38 kHz SILAS transducer. Therefore, heave correction by actual heave was not possible. The second best option, to use a swell filter, has been applied in this project. Stema suggested to use the default parameters for filtering.

The default swell filter has been applied to all lines. In general, some manual editing was required, especially at the edges of the lines. Figure 4.3 shows example of the uncorrected sea bottom and corrected sea bottom after filtering. The rhythmic movements of the vessel are easily recognized in the green line and corrected in the blue line.

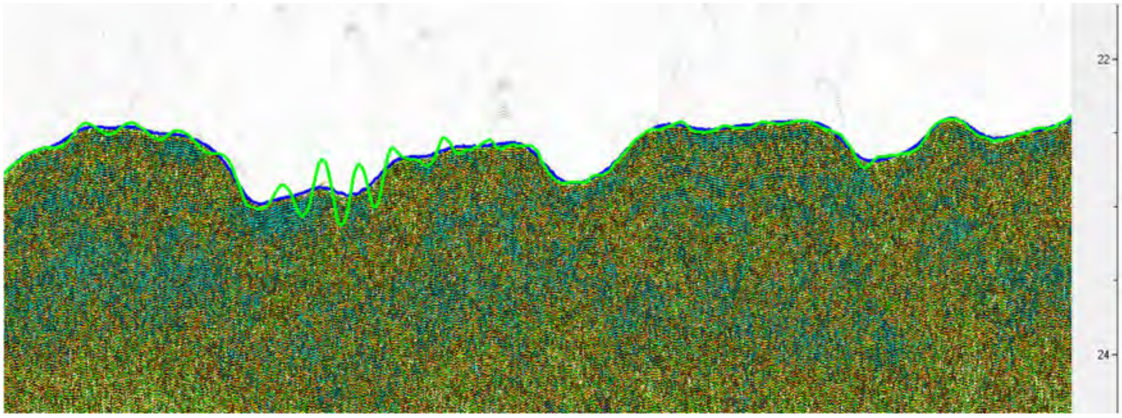


Figure 4.3 An example of SILAS line acquired in Maasmond. In green the raw sea floor (termed 'bottom' in SILAS) before heave correction. In blue the sea floor after 'swell filtering'.

4.3 Tide correction

For data consistency, all density measurements as well as the SILAS acquired data have to be referred to a fixed datum, in this case NAP. In the Maasmond, all data are affected by tidal variation during the day. The average tidal range is 1.74 m.

Several options for tide correction were available:
- Positioning of the D2Art instrument.
- Predicted tide for the Beerkanaal (close to the survey area).
- Measured tide for the Tennesseehaven.
- Qinsy positioning, node "waterlijn". The standard acoustic systems use the acquisition program Qinsy, with several nodes defined (positions with known distances to the GPS antenna). This is recorded only at times of Multibeam acquisition, which coincides with SILAS acquisition.

All options show the same trend (see Figure 4.4). Absolute values of the tide relative to NAP differ considerably between the various options. The D2Art tide data were too 'noisy' to be used. Moreover, according to RWS, the top of the instrument was not constant during the day. The data extracted from Qinsy are also noisy, but defined relative to a fixed node and therefore more reliable. It appears, however, that the "waterlijn" node was not corrected for motions of the vessel. Since water level variations due to tide are smooth, the short temporal variations in the Qinsy "waterlijn" data were corrected by fitting a 4^{th} to 6^{th} grade polynomial. It has to be noted that a polynomial is only valid in the parts with data. That means that the red line in Figure 4.4, representing the polynomial, is only a good description of the data of the Qinsy export (bark blue line) and not for the parts in between. For example, between half past 10 and 12 o'clock no Qinsy export data is present. For that time period, the polynomial cannot be used. The Qinsy export is measured during Multibeam acquisition, which coincides with SILAS acquisition. Therefore, for all SILAS acquisition time periods, the polynomial functions are valid.

The Qinsy "waterlijn" node is also used for Multibeam processing. For consistency, all density and SILAS data have been corrected using the polynomial function through the Qinsy "waterlijn" data and therefore referred to the NAP datum.

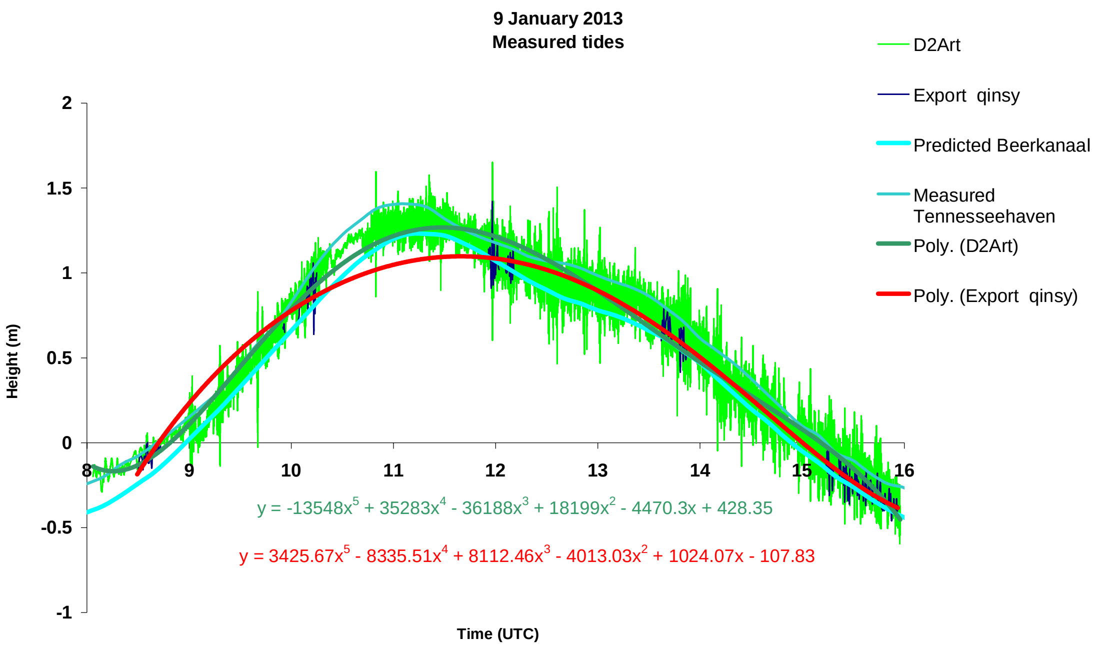


Figure 4.4 Plot of all tide measurements available for the study (example for the January 9th 2013).

4.4 Time shift (January 8th 2013)

On the first day of the survey, before proceeding with the actual survey, a so called "ramp test" was carried out. SILAS data and Multibeam data were acquired on the Maeslantkering: a steep sloping and solid underwater object. This test was executed in order to check, the consistency of the different acoustic tools and is part of standard quality tests for Multibeam acquisition.

The ramp test for SILAS serves for a check on horizontal and vertical positions. For the first survey day, a clear horizontal misfit was noted between the reconstructed sea-bottom by SILAS and the one obtained with the Multibeam as shown in Figure 4.5. On that day, there was a delay in communication between the Qinsy software and the SILAS acquisition package. In order to compensate for that delay, a time shift of 1 second has been applied to all data acquired for that day. At the start of the second day (January 9th), the delay between the acoustic systems was noted and corrected for. From January 9th on, both systems were synchronized regularly, so no time shifts were needed for the other days.

From Figure 4.5 is it clear that the height of the Maeslantkering is detected correctly. Therefore, no vertical shift was needed.

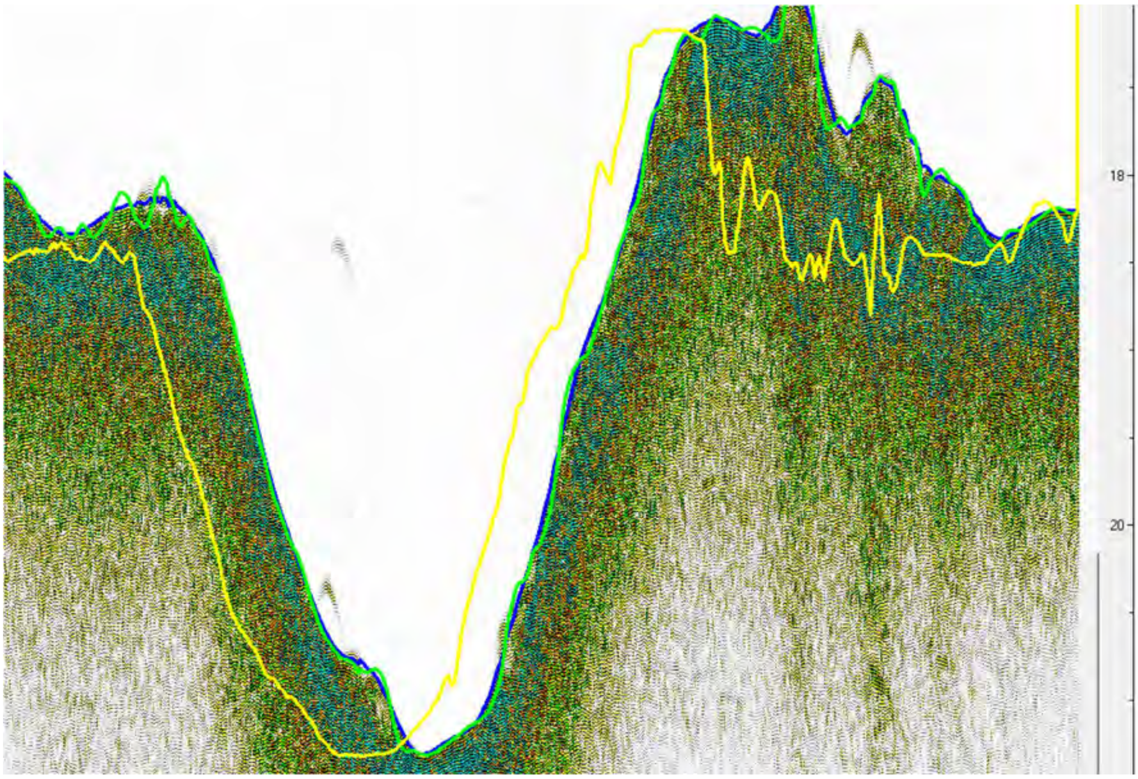


Figure 4.5 Multibeam data (yellow) and SILAS data (blue for bottom) for the ramp-test on the Maeslantkering on January 8th 2013. There is a horizontal shift, corresponding to 1 second. No vertical correction is needed.

4.5 L1 level and SILAS bottom comparison

The top of the mud (called “bottom” in SILAS software) is determined by SILAS as the first relevant reflection of the signal recorded by the 38 kHz echosounder. The density probe D2Art determines the top of the mud as the level where a density of 1.05 kg/L occurs in the water column.

For a reliable calibration the difference in the depth of top of the mud obtained between those two methods must be within 10 cm (value suggested by Stema). Figure 4.6 shows that this difference is larger than 10 cm for almost half of the available density measurements. There is no consistent pattern in the differences (e.g. linked to time of the day) or a constant systematic shift. The pattern cannot be explained. Nevertheless, the misfit is acceptable since SILAS, when performing a calibration, always places the 1.05 kg/L level on the top of the mud layer retrieved from acoustic data (“bottom” is SILAS software). In this way, the misfit in depth determination does not affect the calibration procedure.

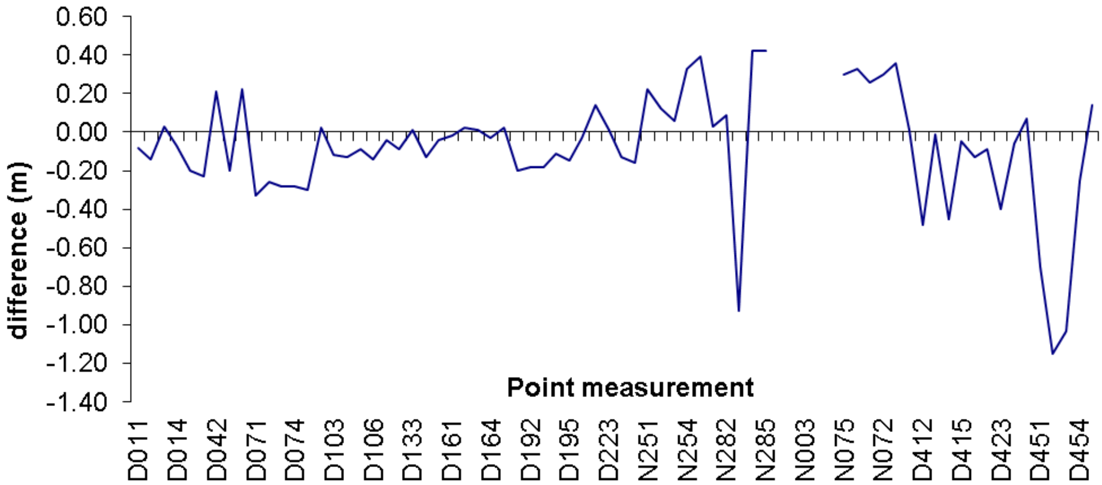


Figure 4.6 Difference between depth level of 1.05 kg/L from point measurements and top reflector in SILAS measurement for the calibration points. On the x-axis the calibration points are plotted consecutively, with codes plotted every 4th point. The data gap around N003 represents 5 data points that were not used in calibration and therefore not located on or near a calibration line.

4.6 Echosounder comparison

RWS and other hydrographic surveyors are used to echosounders of high frequency (200 to 210 kHz) and low frequency (24, 33 or 38 kHz) for the determination of the water bottom and silt bottom. The water bottom is usually taken as the digitized signal of the high frequency echosounder, meaning that the echosounder instrument returns one value of depth for each ping of the transducer. The digitized signal of the low frequency is taken as an indication of the silt bottom. Very roughly, the difference between the two depths would indicate mud thickness.

In the SILAS survey, Multibeam, both frequencies of echosounders and the full signal of the low frequency echosounder were recorded. In hydrography, dual frequency echosounder data are frequently used. Surveyors are used to echosounder data. It is therefore useful to compare the echosounder data to the SILAS data.

During the survey, it was clear that the digitization of the echosounders is not a smooth process. There are frequent data gaps. This is immediately clear when plotting the echosounder data and the full SILAS data (Figure 4.7). The digitized 38 kHz signal (pink) often clips (jumps out of the picture) by unsuccessful recovery of a depth value for all pings of the transducer; the digitized 200 kHz signal (green) is more stable. Because of the clipping of the digitized signal, no statistics can be derived from it, nor can mud areas be calculated to be compared to the SILAS calibrated ones. The following analysis is done based on visual inspection of SILAS profiles only.

The digitized 200 kHz signal is in agreement with the top of the mud according to SILAS. When we ignore the data gaps in the 38 kHz digitized signal, the pattern resembles the 1.2 kg/L level of the SILAS data (for calibration, see chapter 5). However, there is a strong - but not constant - offset of almost 1 m. In Figure 4.8, the depth profile from the digitized 38 kHz is plotted; together with the position of the density levels (see section 6.3.4 for calibration of density levels). From this, it appears that the digitized 38 kHz level is below all calibrated density levels with the maximum of 1.25 kg/L. In conclusion, the digitized 38 kHz signal is not useful for determination of mud thicknesses.

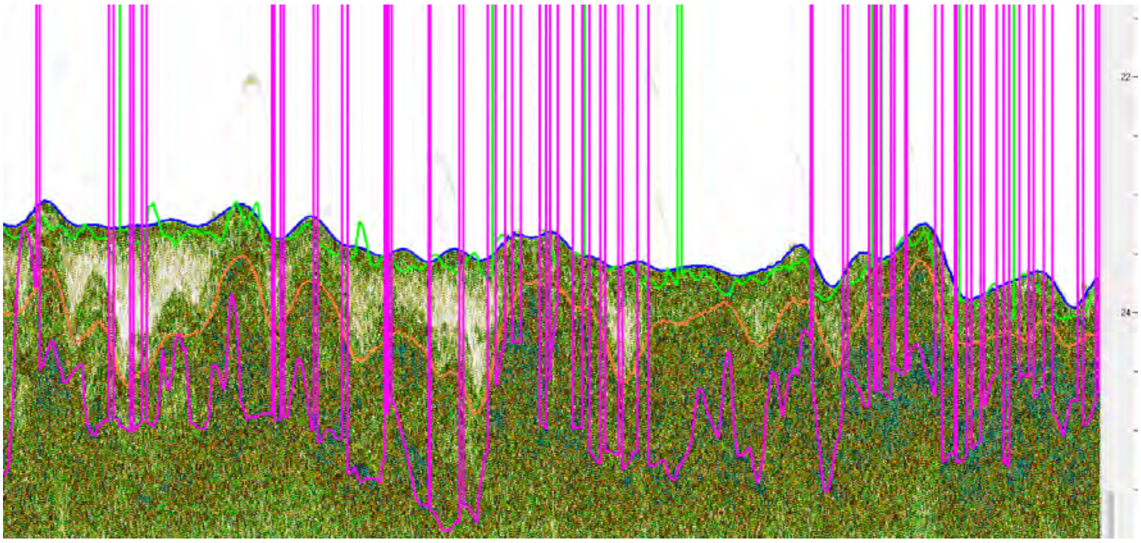


Figure 4.7 SILAS example (line 0022_S1b) showing the top of the digitized 200 kHz (green), digitized 38 kHz signal (pink), the top of the mud according to 38 kHz SILAS (blue) and the 1.2 kg/L level derived from SILAS (orange).

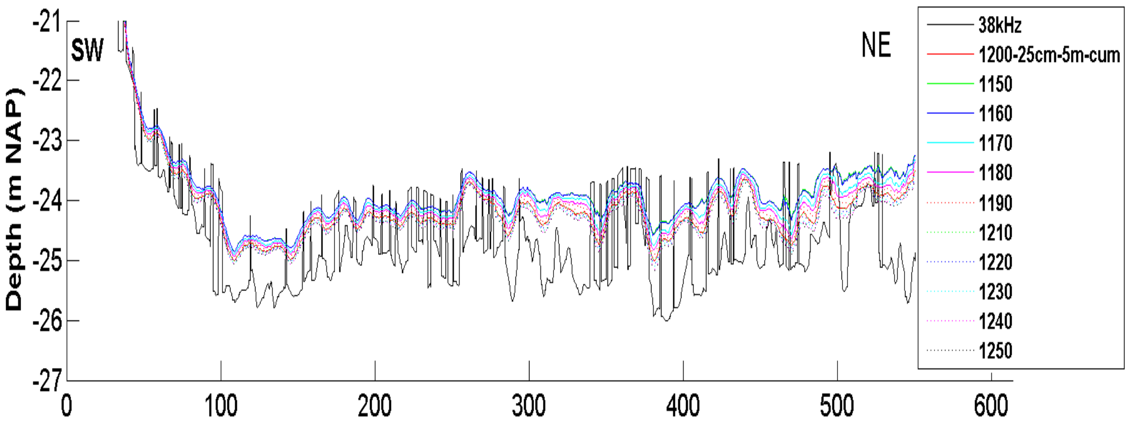


Figure 4.8 Depth profiles of 38 kHz digitized echosounder signal (black line) and several density levels (all other colors). X-axis represents distance along the survey line, for line 0022_S1b.

5 Calibrations

5.1 Calibration methods

In the SILAS system, the term ‘calibration’ refers to the mathematical relation that ties the acoustic data (low frequency echosounder signal) to the density measurements for a certain location and for a chosen density level.

In short, the calibration procedure consists of conversion of the acoustic record to a synthetic density profile, using standard formulae for acoustic impedances. The synthetic density profile is then compared to the measured density profile. The best fit is determined for the entire suite of measured point density profiles. The full explanation of the calibration algorithm is given in appendix B.

The determination of the best fit can be accomplished in three ways: the cumulative model with or without vertical corrections and the gradient model. The explanation of the three options, advantages and limitations were provided by Stema (see appendix C). A summary of the three options is provided below.

5.1.1 Cumulative model

Three density levels obtained from a density tool (e.g. Densitune, Rheotune, D2Art or Navitracker) are needed to calibrate the data. The first level (1.05 kg/L called ‘lutocline’) is assumed to be the level at which the first significant reflection occurs in SILAS. A second density level, for which the calibration is performed (e.g. 1.2 kg/L), is defined by the user. A third density level is defined (e.g. 1.25 kg/L), but not used in the calibration procedure.

Using an iterative method, SILAS matches the acoustic impedances in the seismic data with the density level of interest (i.e. 1.2 kg/L). Based on the law that relates properties of the sediment (density) and acoustic velocity, SILAS calculates a synthetic density profile based on the seismic trace and ‘’arrival power” of the signal for each location of the density measurements is varied iteratively. The arrival power with the smallest misfit between actual and synthetic profiles defines the formula used to derive the 1.2 kg/L level from the seismic traces. An example of a good and a bad fit between the synthetic and measured densities is given in Figure 5.1. An example of 1.2 kg/L level extrapolated with this method is given in Figure 5.2.

<u>Advantages</u>: a calibration is retrieved using all points. Possible error due to wrong positioning and incorrect density measurements are averaged out.

<u>Disadvantages</u>: spatial calibrations variations due to different seabed composition and related variations in attenuation and sound velocity are not taken into account. A combination of cumulative model and vertical correction can be used to solve this limitation.

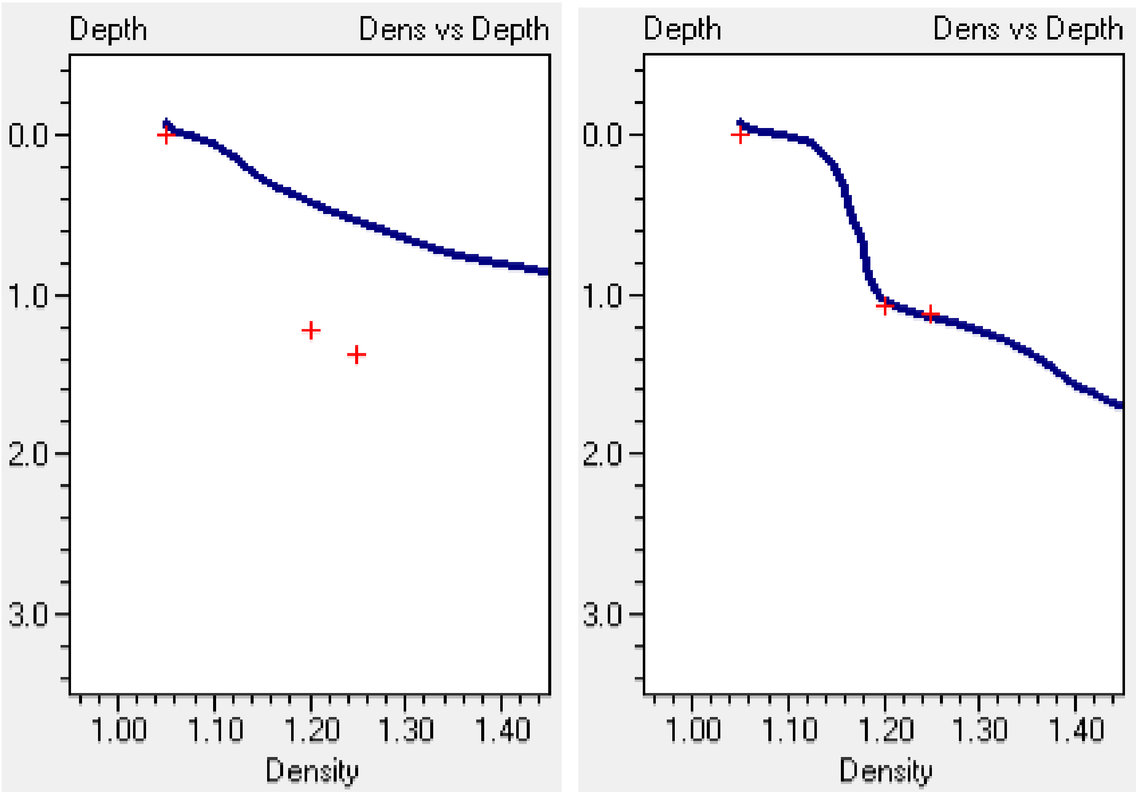


Figure 5.1 Example of a bad fit (left, D105) and good fit (right, D072) between the D2Art density level (red crosses) and the synthetic density profile (blue) used in the calibration procedure of SILAS data.

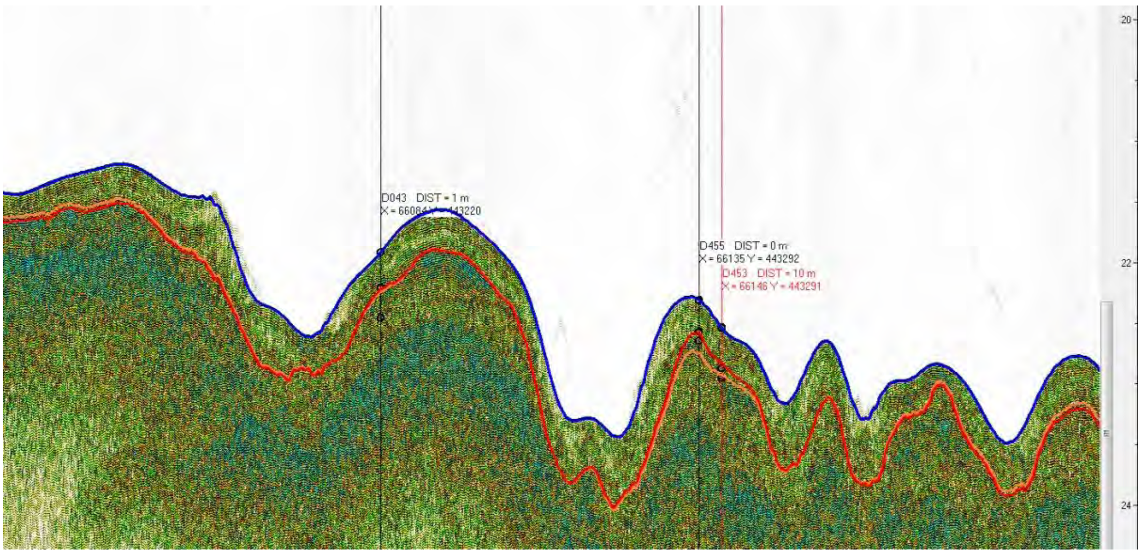


Figure 5.2 Example of SILAS measurement for line 0009_S4b for the first calibration test (50 points). In orange the 1.2 kg/L level retrieved with the cumulative model. In red the same level after vertical corrections. The vertical lines indicate the locations of the density point measurements (D043, D445 and D453 (red= not used) from left to right). The circles on the line indicate the 1.05, 1.20 and 1.25 kg/L density levels.

5.1.2 Cumulative model with vertical correction

This method is identical to the cumulative model, with the only difference consisting in the fact that the vertical misfit between synthetic and actual data is calculated for each location of the density measurement. A kriging method ('inverse to distance') is then used to model all these vertical differences that are finally applied to the calculated density level. An example of 1.2 kg/L level extrapolated with this method is given in Figure 5.2. This means that the 1.2 kg/L level from the seismic traces (red line) will fit through all the 1.2 kg/L density levels from the point measurements.

<u>Advantages</u>: possible variations in sediment composition as well as in acoustic velocity are taken into account.

<u>Disadvantages</u>: the method assumes that the geophysical density measurements are not affected by errors (incorrect positioning, distance of the density measurement from the SILAS line).

5.1.3 Gradient model

For the gradient method, both bottom and silt bottom are autotraced (and adjusted manually if necessary). For each calibration point, the relative position of the 1.2 kg/L level is determined, defined by the ratio: (Depth of 1.2 kg/L level – depth of bottom) / (Depth of silt bottom – depth of bottom). If the 1.2 kg/L level is below the silt bottom, then the depth of the silt bottom is taken. Those ratios are modeled for all point measurements with a kriging method ('inverse to distance'). Subsequently, the interpolated ratios are applied to the bottom and silt bottom of all lines to define the 1.2 kg/L level. An example of 1.2 kg/L level determined with this method is given in Figure 5.3.

<u>Advantages</u>: independent of arrival power. Accurate results in areas where density gradients are not acoustically detectable.

<u>Disadvantages:</u> An additional auto-tracing of a deeper reflector is needed (highly subjective and error prone). The determination of the 1.2 kg/L level is strictly dependent on automatically determined 'silt layer' by SILAS. It frequently happens that this layer is above the 1.2 kg/L level of a density measurement leading to erroneous results in the determination of the 1.2 kg/L level in SILAS (see Figure 5.3). Amplitude information in the seismic data is entirely ignored. There is no physical background (acoustic impedances for reflections) for this method.

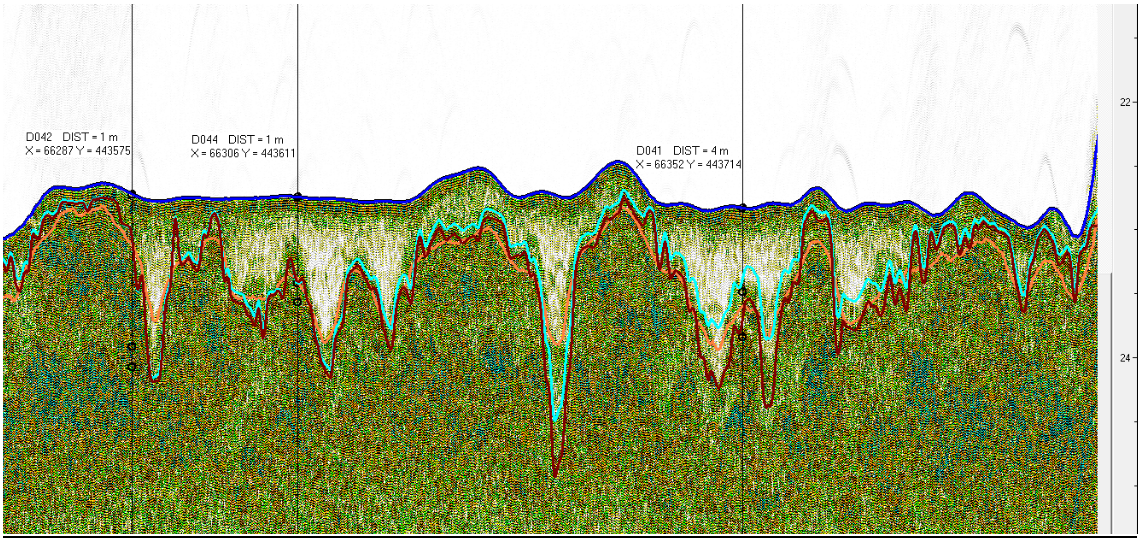


Figure 5.3 Example of SILAS measurement of line 0009_S4b for the first calibration test (50 points). In orange the 1.2 kg/L level retrieved with the cumulative model. In red the 'silt bottom layer is indicated and the layer in blue represents the 1.2 kg/L density level obtained with the gradient model. The vertical lines indicate the locations of the density point measurements (D042, D044 and D041 from left to right). The circles on the line indicate the 1.05, 1.20 and 1.25 kg/L density levels. Note that for density point D042 the 'silt layer' is above the 1.2 kg/L level leading to an incorrect extrapolation of the 1.2 kg/L layer in SILAS.

5.1.4 Calibration models to be tested

Stema has suggested that the gradient model should not be considered for the current study, given the relevant disadvantages described above. The choice between the cumulative model and the cumulative model with vertical corrections strongly depends on the quality, abundance and distribution of density measurements. For relatively few, unreliable or irregularly spaced point measurements, the standard cumulative model should be used. For well distributed, reliable and abundant density measurements, the cumulative model with vertical correction can be employed. Part of the study consists in the determination of the most suitable and reliable calibration method to be applied to the Maasmond data.

5.2 Datasets of point measurements of density

As explained in section 5.1, the calibration of seismic data depends on the method employed. Another factor of relevant influence is the dataset of density measurements used in the calibration. Abundance of data, reliability of the instruments and the procedure employed for data collection are all factors whose effect on calibration will be addressed. For this purpose, several density measurement datasets have been tested in the calibration. The different datasets are described below. The table in appendix D gives an overview of the statistics (number of point used, standard deviation of calibration).

Datasets for calibration:

- *Full dataset*: all 75 point measurements of density, consisting of both D2Art and Navitracker measurements.
- *First test dataset:* 50 point measurements positioned on the 10 calibration lines, excluding the three clusters on line S4.
- *Basic dataset*: 44 point measurements of density with mud thickness > 25 cm and distance to nearest SILAS line < 5 m.

- *Random datasets*: 40, 30, 20, 10 points taken randomly from the basic dataset. For each amount of random points, 5 different data sets were selected.
- *'Thick' mud dataset*: 38 density measurements with mud thicknesses exceeding 50 cm.
- *'Thin' mud datasets*: 37 density measurements with mud thicknesses less than 50 cm.
- *Datasets with different density levels*: 1.15 kg/L to 1.25 kg/L with 0.01 kg/L steps. Same points as the basic dataset, but for levels other than 1.2 kg/L.
- *Day-by-day datasets*: set of density measurements collected on the same day.

5.3 First calibration test

As a first test, we performed the three methods of calibrations and discussed the results with RWS. For this test, 50 point measurements from the 10 calibration lines (excluding the points in clusters) were used. The results are shown in Figure 5.2 and Figure 5.3 in section 5.1. In Figure 5.2 a comparison is shown between the cumulative model (orange) and the cumulative model with vertical corrections (red). As expected, when the vertical correction is implemented the retrieved density level is forced to cross the 1.2 kg/L of each density profile. Apart for this characteristic, the density level retrieved with these two methods looks similar. On the other hand, the gradient method (see Figure 5.3) leads to very different, more irregular results. As already mentioned, the gradient model requires the determination of a deeper density level ('silt bottom layer' in SILAS). This level can be rather uncertain and subjective, and thus represents a relevant source of error. In fact, the determination of the density level of interest is strongly dependent on the 'silt bottom layer' determination. In many SILAS lines in this study, the silt bottom level appears to be above the 1.2 kg/L density level measured by the D2Art tool. As a consequence, the extrapolated 1.2 kg/L density layer lies at shallower depths than the actually measured level.

The locations of the density measurements are usually within a certain distance from the surveyed SILAS line. Such distance is dependent on positioning accuracy, heave and current drift. The SILAS software allows selecting a certain threshold value above which density measurements are discarded and not taken into account for calibration. Values of 10, 5 and 1 m for this threshold have been tested in order to choose the more appropriate value to use for the rest of the study. In Figure 5.4 a comparison of the 1.2 kg/L level after calibration with those different thresholds is given for line number S4b. The retrieved levels show a certain difference but they mainly show the same trend. Nevertheless, the use of density measurement farther away than 5 m is discouraged due to the expected spatial variability of mud thickness (as will be shown in section 6.1.1). In practice, it is very difficult maneuvering the point measurement and the SILAS line within 1 m distance. Therefore, a threshold of 1 m is too strict as it would cause leaving out a large amount of the carried out density measurements. A threshold of 5 m appears to be a good trade-off between reliability of the density measurements and abundance in the dataset.

In summary, the gradient model has revealed to be not feasible for a reliable calibration of the data in this study. On the other hand, the cumulative model with and without vertical corrections give sensible results in the first test. It was therefore decided by Deltares and RWS to use the cumulative model with and without vertical corrections only in the following calibration tests. Moreover, a threshold of 5 m has been chosen as maximum distance of density point measurements from the nearest line.

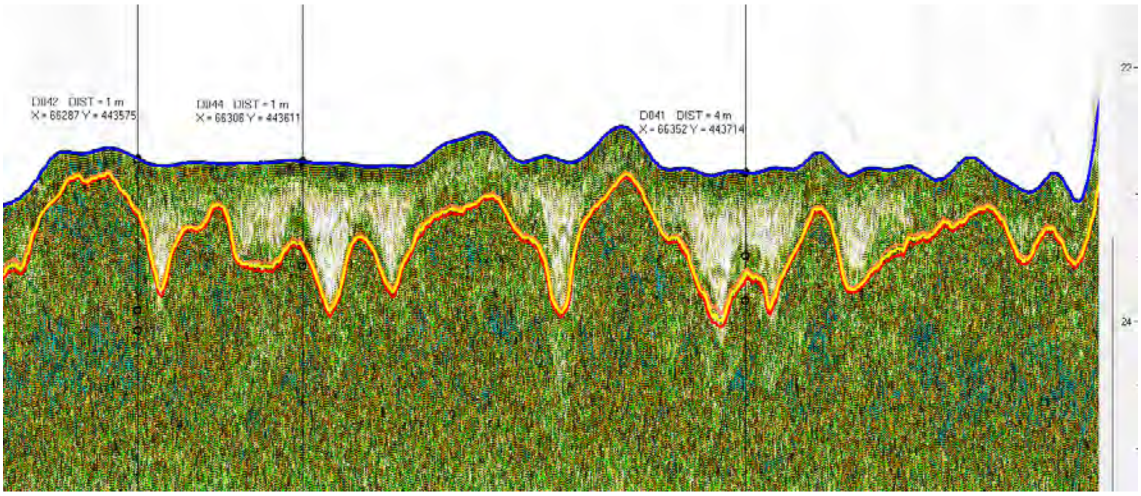


Figure 5.4 Example of SILAS measurement of line 0009_S4b 4b. Comparison of the 1.2 kg/L level retrieved by calibration with 10 m (yellow), 5 m (orange) and 1 m (red) threshold for the distance of the density measurement from the SILAS line.

5.4 Test: sound velocity in silt

In processing, SILAS uses two sound velocities for the conversion from time to depth. The first one is a constant velocity of sound in the water. The second is the velocity of sound in the silt. That second velocity is important for the determination of the amount of mud that is present according to the SILAS measurement.

SILAS takes a standard offset between the sound velocity in water and in silt of 30 to 35 m/s, based on literature values (see appendix 7.2C). For the Maasmond study area, Stema suggests that a silt sound velocity should be taken that is 5 m/s higher than at the base of the water column.

As calculated by Stema in appendix C, an error in silt velocity of 30 m/s gives rise to an error in thickness of 4 cm. This is in the order of errors in depth of the point measurements due to ship's movements. In this section, we investigate whether it is worthwhile to adjust the processing flow in order to use the correct silt velocity. The test has been performed for data measured on January 9th 2013. This day was chosen, because of the relative abundance of point measurements on that day (15). Since SILAS uses a standard value for addition to the sound velocity in water, the software has to be "tricked" to be able to insert the right silt velocity.

As explained in section 4.1, data acquired on the same day have been processed simultaneously in SILAS. For time-to-depth conversion the values of sound velocity over the water column for all SVP (Sound Velocity Profile) for that day have been averaged out (see Figure 5.5). This value is used by SILAS for conversion up to the sea-bottom. For the signal below this level, the value of sound velocity used is increased by SILAS with 35 m/s (red dashed line in Figure 5.5).

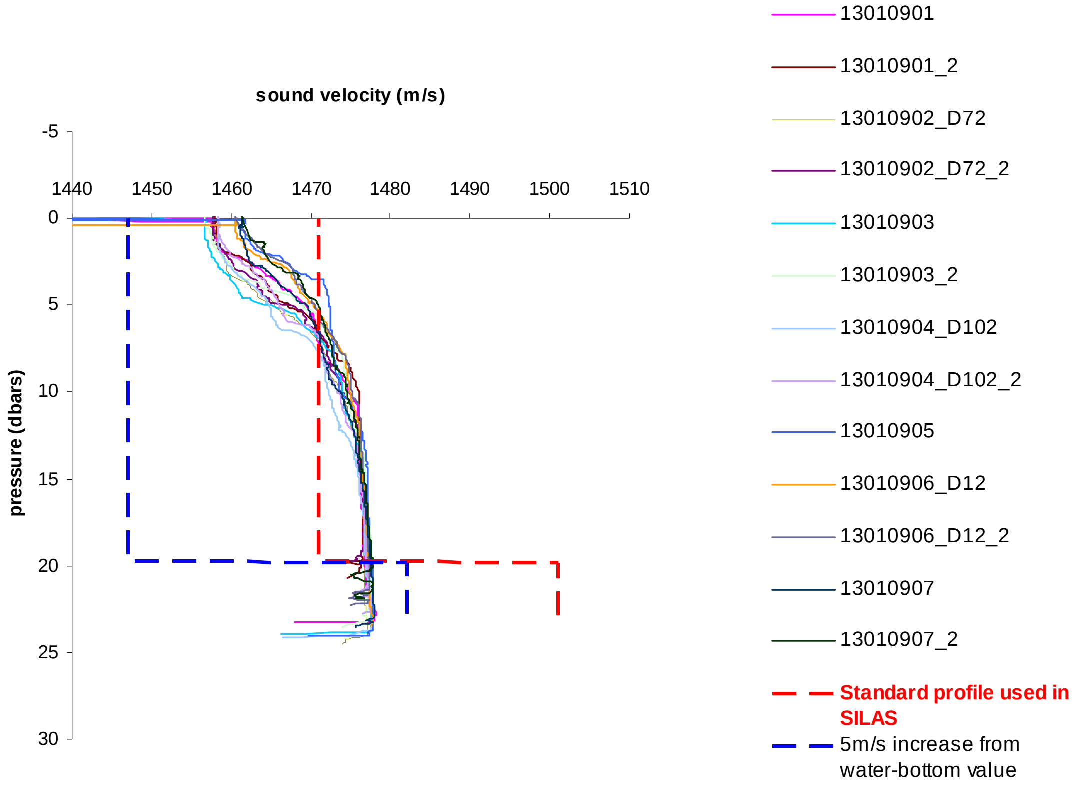


Figure 5.5 Sound velocity profiles along the water column acquired on January 9th 2013. The Y-axis is given in pressure, which is related to depth (1 m depth corresponds to approximately 1 decibar). The red dashed line indicates the average value along the water column among for sound velocity measurements for this day; the velocity increase of 35 m/s is also indicated at arbitrary depth. The blue dashed line indicates the velocity profile implemented in SILAS in order to obtain a velocity increase of 5m/s relatively to the velocity at the water bottom.

Stema pointed out that for the Maasmond area an increase of 5 m/s relative to the sound velocity at the sea-bottom would be more suitable (see Appendix C). SILAS does not allow the user to choose or change the velocity increase in the silt layer. Therefore, in order to test the use of a 5 m/s increase in the mud layer, the following procedure has been used:

a. Add 5 m/s and subtract 35 m/s (i.e. subtract 30 m/s) from the average day value of sound velocity at the water-bottom (1477 m/s) measured for January 9th.
b. Use this value for time-to-depth conversion. SILAS automatically adds 35 m/s to obtain the silt sound velocity.
c. Perform density calibration of the data of January 9th.This results in calibration files with the correct silt sound velocity.
d. Set sound velocity in water back to the average along the column for that day (1471 m/s). Export the 1.2 kg/L density level for all lines of that day.

In Table 5.1, the sound velocity values used by SILAS for the two scenarios are listed. The 1.2 kg/L density layer (using the basic calibration) has been compared to the case with the correct silt sound velocity.

Table 5.1 Sound velocities used for time-to-depth conversion for the two tested scenarios. The 'standard' scenario consists in using the average sound velocity along the column, resulting in a silt velocity increased by 35 m/s (automatically done by SILAS). The other scenario consists of using a silt velocity 5 m/s greater than the velocity at the water bottom, as suggested by Stema.

	Layer	Standard (35 m/s increase at the sea bottom)	5 m/s increase at sea bottom
A	Water (average)	1471	1447 (B-30 m/s)
B	Water-bottom	1477	-
C	Silt (A+35 m/s)	1506	1482

The histogram in Figure 5.6 shows that most of the differences in the 1.2 kg/L density level are within 6 cm for an average value of only 4 mm. Given such insignificant differences between the two approaches, we conclude that it is not worthwhile to adjust the processing flow to use the correct sound velocity in silt. Therefore, for the whole following processing the standard average sound velocity for each day has been used and no correction has been carried out for the silt layer.

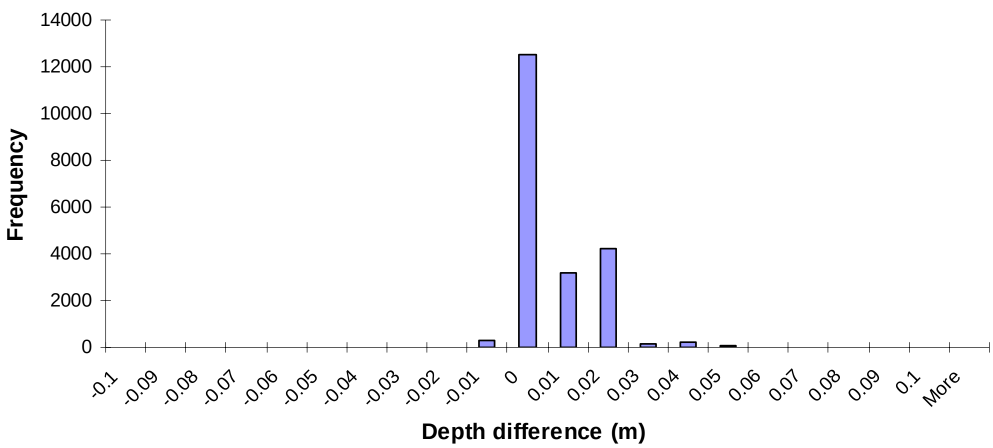


Figure 5.6 Frequency histogram of the differences in depth of the 1.2 kg/L level extrapolated with SILAS using the 'standard' average sound velocity and the one increased by 30 m/s.

6 Answers to research questions

More than 40 calibrations have been performed in order to be able to answer the posed research questions. In the following sections, a basic calibration file will be often referred as 'basic'. It has been calculated as follows:

- Density level: 1.2 kg/L.
- All density measurements with mud thickness < 25 cm are discarded.
- Only density points measurements within 5 m from the nearest calibration line are considered.
- Calibration method: cumulative (without vertical corrections).

The aforementioned features of this calibration file are summarized in its filename: *1200_25cm_5m_cum*. The same criterion is used when naming all other calibration files.

The obtained results are presented in the same order as the research questions. Questions 3, 4 and 5 are answered in the same section. The error sources part of question 3 is answered in a separate section.

6.1 Question 1: Accuracy of individual point density measurements

Research question 1 is: What is the accuracy of individual point density measurements?
Answer summary: The repeatability and the spatial representativeness of the point measurements are limited.

The analysis of the research question and the answer are described in sections 6.1.1 and 6.1.2.

6.1.1 Analysis of closely spaced point measurements

In this context, the accuracy is defined as the ability to give the same value as several measurements of a certain quantity are performed.

The accuracy of density measurements on a certain location is strongly affected by:
- Accuracy of the instrument;
- Noise due to heave motions;
- Accuracy in positioning.

The accuracies for each individual point measurement is linked to the accuracy of the instrument (see Table 6.12). Deviations between point measurements are primarily caused by other factors. In brief, the ability to give representative and reliable density profiles over a certain point strongly depends on the ability of maintaining the same position with the vessel and instrument. This is usually a difficult task due to currents, heave and maneuvering limitations.

In order to asses the repeatability of measurements done by the D2Art instrument, three clusters of five measurements each were collected. Each cluster had a maximum radius of 8 m (see Figure 6.1). The locations of the clusters were selected to be at two locations with thick mud layers (D041, D042) and one location with a thin mud layer (D045) on calibration line S4b. The mud thickness retrieved for each density measurement in those clusters is given in Figure 6.2. The average thickness and standard deviation is given in Table 6.1.

For the D041 and D042 clusters mud thickness is rather high. In both cases it can be as high as 1.4 m. Nevertheless, the mud thickness shows significant variation within the same cluster, even though the density measurements are closely located. Such difference can be has high as 0.8 m for both D041 and D042 clusters. For the two clusters with a thick mud layer, the standard deviation (1 σ) of the average thickness is around 0.3 m.

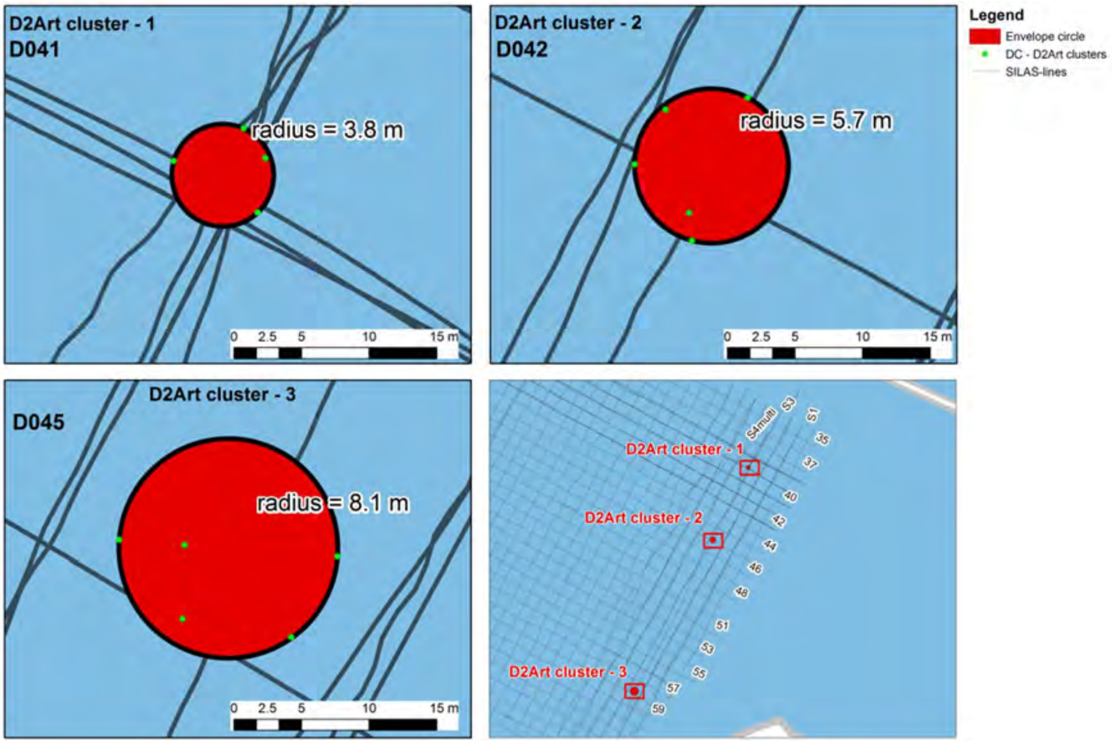


Figure 6.1 Location of the 3 clusters of density point measurement (green) performed with the D2Art tool along line 4b. Note that the performed measurements are always within a radius of 10 m.

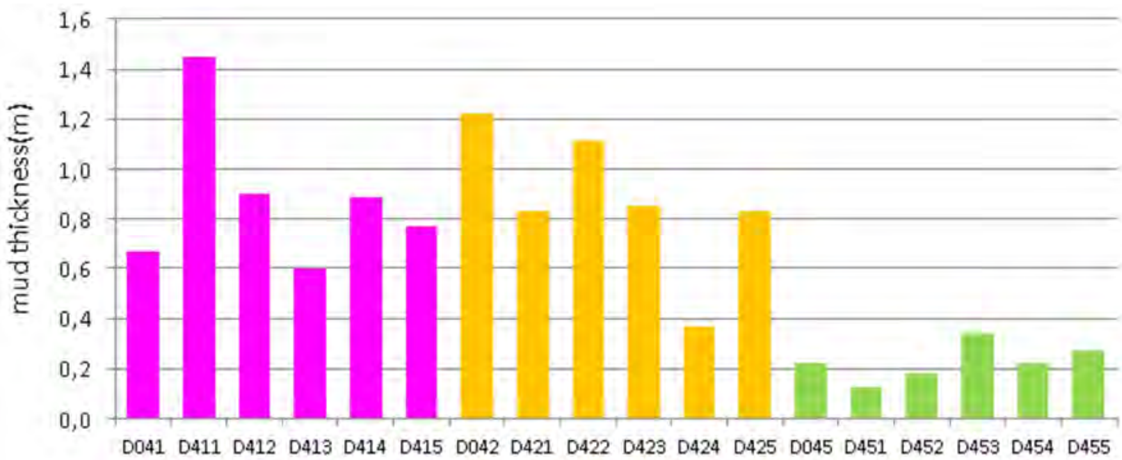


Figure 6.2 Mud thickness for each point measurement in the three clusters. The cluster around D041 is represented in pink, the cluster around D042 in orange and the cluster around D045 in green.

Table 6.1 Statistics of the three clusters of point measurements.

Cluster	Average depth (m)	Standard deviation (m) 1σ
Around D041	0.88	0.30
Around D042	0.87	0.29
Around D045	0.23	0.07

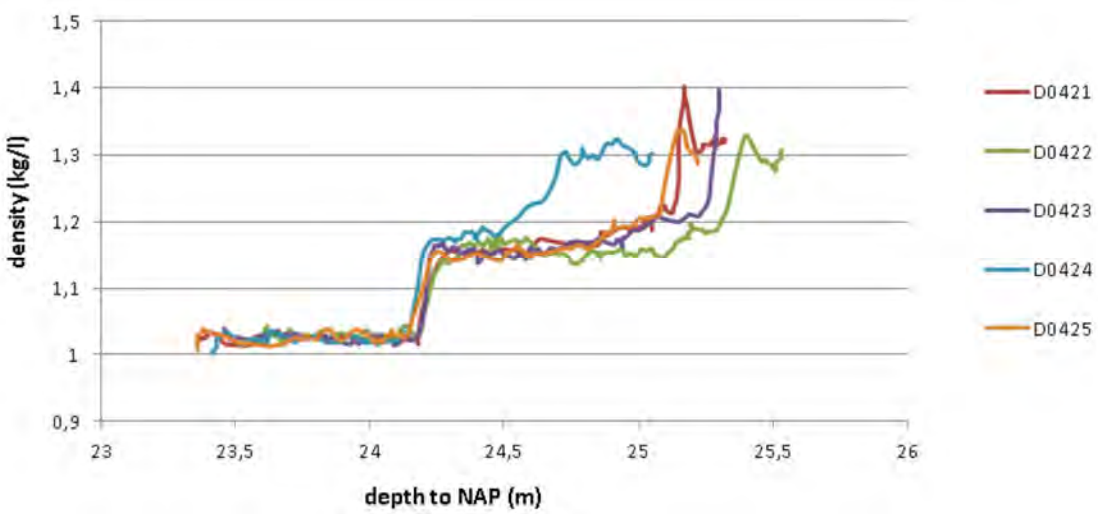


Figure 6.3 Comparison of density profiles for the D042 cluster

The different mud thickness within a single cluster can be seen in Figure 6.3 where the density profiles for the D042 cluster are shown. The profiles are rather similar up to a density of 1.15 kg/L. For higher values, the profiles show a relevant deviation that explains the strongly different values of mud thickness within the cluster. On the other hand, mud thickness is small and more homogenous within cluster D045, compared to the aforementioned clusters.

A reason for the significant variations in the amount of mud observed in the D041 and D042 clusters might be related to an irregular sea-bottom and/or an irregular 1.2 kg/L level. At the two locations of the clusters, the sea-bottom appears rather flat and homogenous (Figure 6.4 and Figure 6.5). The 1.2 kg/L level, however, shows a steep gradient at both locations. This results in large variations in derived mud thicknesses for closely located points. On the other hand, for cluster D045 both the sea-bottom and the 1.2 kg/L level show the same pattern (Figure 6.6). This results in a relatively constant mud thickness between the points in the cluster on this location.

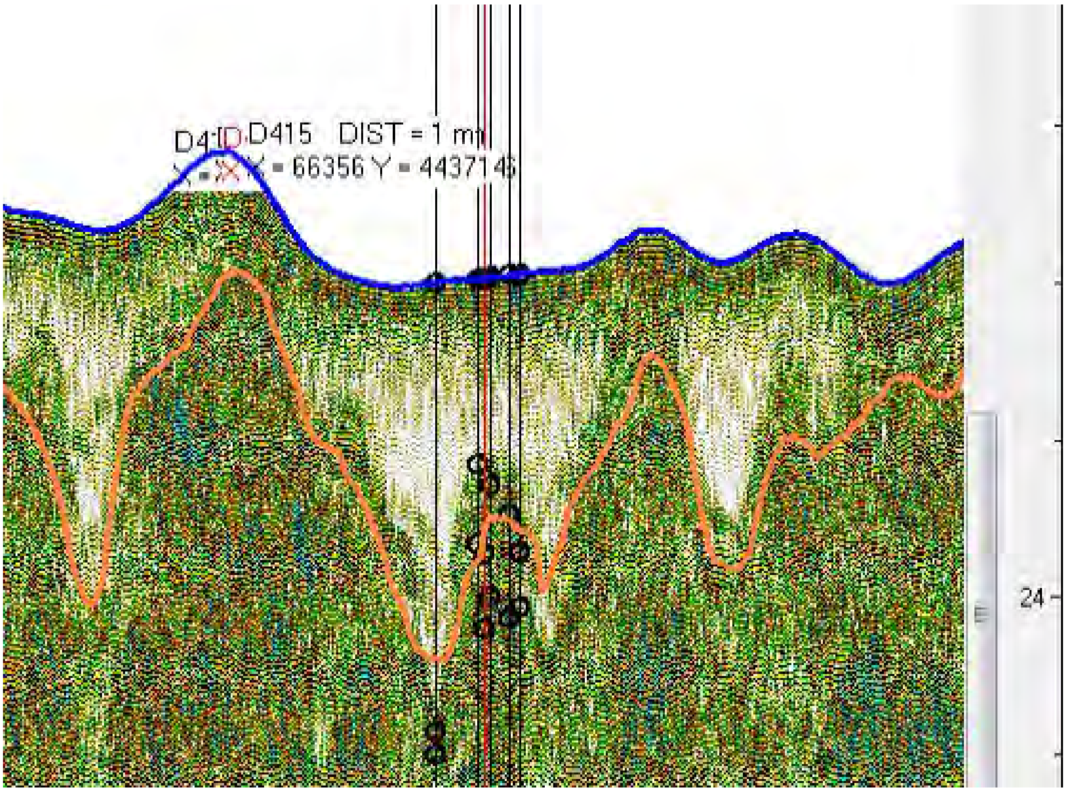


Figure 6.4 Example of SILAS measurement showing the cluster around D041. The orange line represents the 1.2 kg/L level from the basic calibration (1200_25cm_5m_cum).

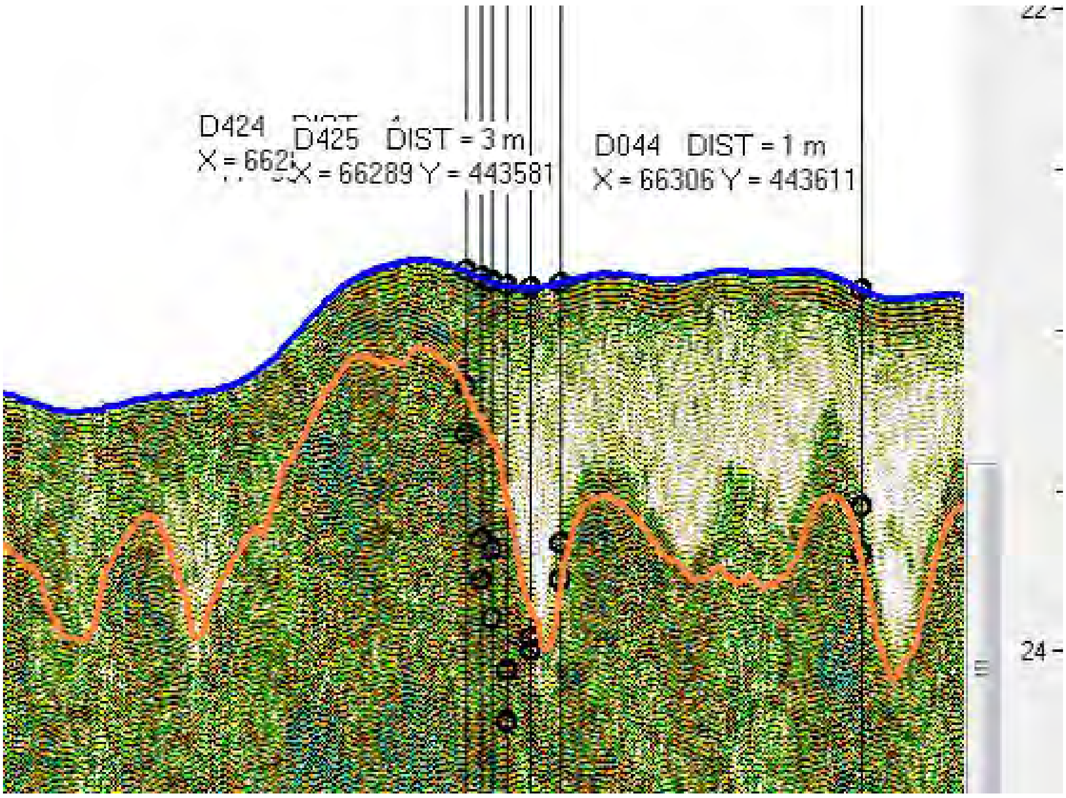


Figure 6.5 Example of SILAS measurement showing the cluster around D044. The orange line represents the 1.2 kg/L level from the basic calibration (1200_25cm_5m_cum).

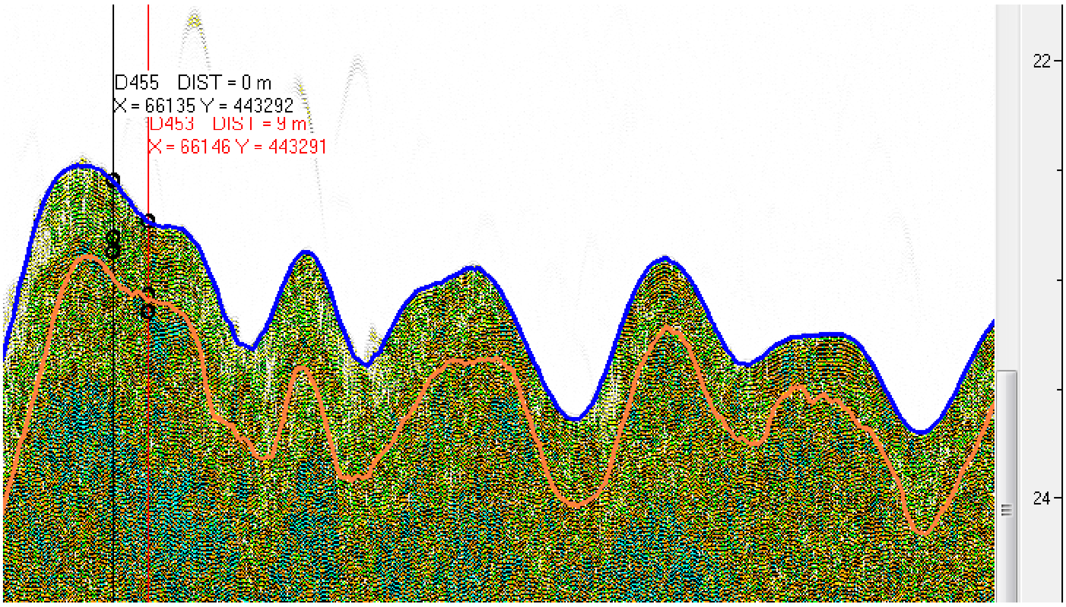


Figure 6.6 Example of SILAS measurement showing the cluster around D045. The orange line represents the 1.2 kg/L level from the basic calibration (1200_25cm_5m_cum).

With the analysis of the three clusters it is demonstrated that the spatial representativeness of a single density measurement is rather low. The selection of location with thick mud does not improve the reliability or accuracy of the density measurement, since large variation in the amount of mud can be observed even within a radius of few meters. The standard deviation of the average thickness is around 0.3 m for thick mud layers of the clusters. This high value is related to the steep gradient in the 1.2 kg/L level present at the cluster locations.

Based on the analysis of the three clusters, we recommend choosing the locations of point measurements at sites where the mud thickness appears to be constant, unless the mud thickness is insufficient to be used in calibration (< 25 cm).

6.1.2 Comparison between D2Art and Navitracker

A calibration of SILAS data has been performed for each of the days of the survey. For each calibration, the statistics have been compared; for days from January 8th to 16th. On January 8th to 14th, the point measurements of density were carried out using the D2Art tool on the Corvus vessel of RWS. On January 16th, the density measurements were carried out using the Navitracker tool with the vessel ARCA by RWS. This vessel has dynamic positioning system that permits to compensate for drift (due to currents, heave motions) while employing the density probe. As a result, the density measurements acquired with this tool are mostly within 2 m from the nearest SILAS line (see Table 6.2).

Table 6.2 Statistics on distances from nearest line for the two employed density tools. Navitracker was mounted on the vessel ARCA (RWS) that has dynamic positioning system.

	Average distance from nearest line (m)	Standard deviation of distance from nearest line(m)	Standard deviation of SILAS calibration per day (cm)
D2Art	2.01	1.94	24 to 35
Navitracker	1.12	0.96	12

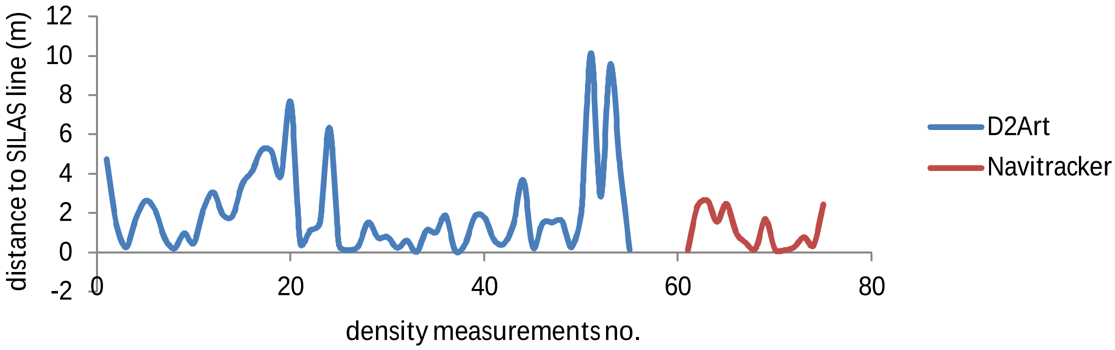


Figure 6.7 Distance of the density measurements by the D2Art and the Navitracker tool to the nearest SILAS line.

The statistics of the calibrations done day by day have been compared (see Appendix D). For the days from January 8th to 14th (when using the D2Art tool) the maximum standard deviation of the calibration is 35 cm and the minimum is 24 cm. Stema indicated that a standard deviation below 20 cm is representative of an adequate and reliable calibration procedure. A value below this threshold (12 cm) has been obtained when employing the Navitracker tool. Apparently, the higher accuracy of positioning of the ARCA vessel has a direct influence on the reliability of the calibration. The standard deviation is comparable to the root-mean-square-error (RMSE), discussed in section 6.3.5.

A comparison between the density profiles acquired with both tools over the same location (calibration line S7, measurement point no. 5) is shown in Figure 6.8. Especially in the 1.05 to 1.20 kg/L density range the profile obtained by Navitracker is less noisy, showing a gradual and clear increase in density with depth. On the contrary, the D2Art tool data shows more irregular behavior. The smoother density curve retrieved by Navitracker can be explained by the higher velocity in performing the measurements, by measuring a larger volume, possibly by better precision of the instrument or by less location variations during the measurement.

Concluding, the effect of the dynamic positioning is relevant. The largest effects are considered to be the smaller distance to the SILAS lines selected for calibration and the smaller variation in location during performance of the measurement.

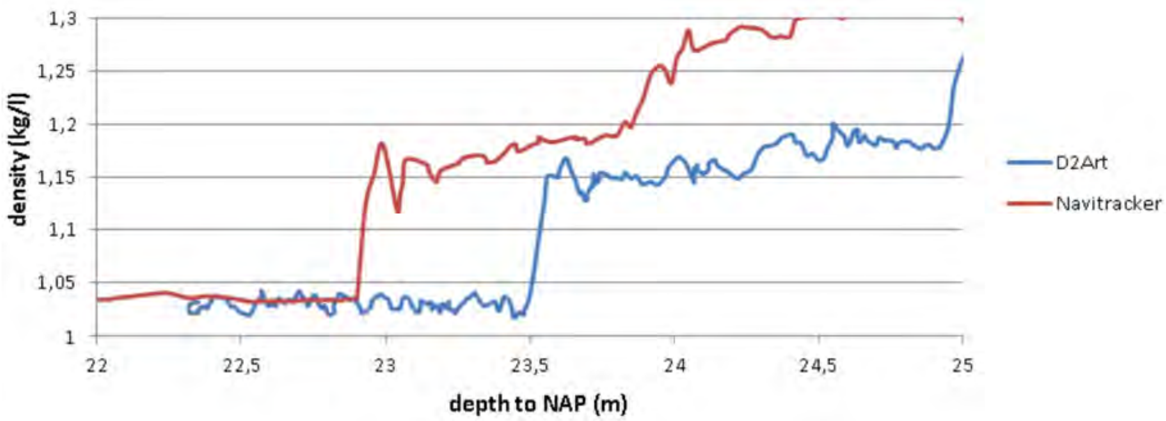


Figure 6.8 Density profile measured on the same location (line S7, point measurement D075 and N075) with two different density tools. Note the less noisy and irregular behavior of data acquired with the Navitracker tool. The difference in depth is partly (20-30 cm) explained by exporting procedure of data from Navitracker while the rest can be explained by sea-bottom morphological variations due to highly moveable mud. Both measurements were taken one week apart.

6.2 Question 2 and 5: representativeness in space and time

Research question 2 is: What is the representativeness of point and line measurements in space and in time?
Answer summary: The derived amount of mud is variable over a couple of days and even within the same day. Point measurements and SILAS line measurements of one calibration line should therefore be completed within 2 hours.

Research question 5 is: What is the optimal number of point measurements relative to the line measurements of SILAS?
Answer summary: The optimal number of point measurements for the test area is 30.

The analysis of the research questions and the answers with regard to the representativeness are described in sections 6.2.1 to 6.2.4.

6.2.1 Multiple measurements of the same line

Several calibration and ‘fill-up’ lines were measured multiple times in order to asses the temporal variability of mud. These lines were measured on different days and/or on different phases of the tidal curve.

For each of these multiple measured lines, the basic calibration (i.e. 1200_25cm_5m_cum) has been applied. The mud thicknesses acquired on these lines were compared. One of the most instructive examples is calibration line S4, which was measured six times with standard survey velocity (Table 6.3). The variability of mud thickness in time is undoubtedly relevant for the whole line. Often the differences can be as high as 1.5 m (see Figure 6.9 and Figure 6.11). This reflects the dynamics of mud in the area, even for a short temporal scale of a couple of days.

Table 6.3 Date and tide condition for SILAS acquisition over calibration line S4 and S28

	Filename	Date	Tide condition
Line S4	0007_S4_0001	08/01/2013	Low
	0008_S4_0001	08/01/2013	Low
	0009_S4b_0001	08/01/2013	Low
	0036_S4multi_0001	10/01/2013	Medium
	119_S4b_0002	15/01/2013	High
	0142_S4b_0001	17/01/2013	Medium
Line S28	0073_S28_0001	14/01/2013	High
	0127_S28b_0001	16/01/2013	Medium
	0151_S28b_0001	17/01/2013	Medium

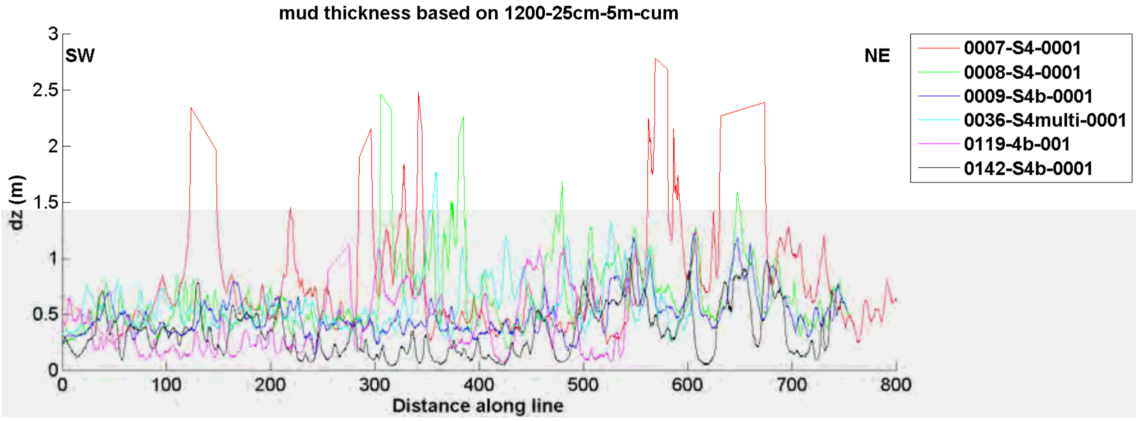


Figure 6.9 Mud thickness along line S4 for multiple measurements (see Table 6.3). Mud thickness calculation is based on the 1200_25cm_5m_cum calibration. Areas with SILAS data gaps are recognized by the sudden jumps to high mid thickness values, e.g. around 120 m for the red line.

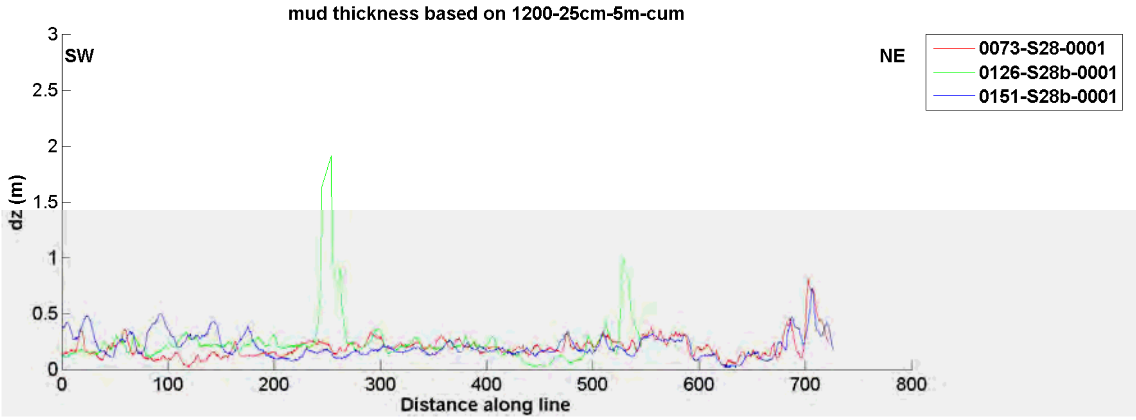


Figure 6.10 Mud thicknesses along line S28 for multiple measurements. The variability of mud thickness.is less severe compared to line S4.Mud thickness calculation is based on the 1200_25cm_5m_cum calibration.

Nonetheless, mud variation does not always have the same magnitude. Calibration line S28 (Figure 6.10 and Figure 6.11) is an example of a multiple line with better repeatability. The variation in mud thickness is much smaller. On this line, however, the average mud thickness is low, 30 to 35 cm. The figures of the other multiple measured lines are shown in appendix E.

Statistics over the total amount of mud for all lines measured multiple times are given in Table 6.4. For line S4, the average amount of mud calculated over a total of 1 week is 401 m^2 with a standard deviation of 177 m^2. It can be observed that mud variation can be rather severe even for a short time interval (1-2 days) between measurements on the same line. However, the statistics are biased due to the parts in the SILAS profiles with no SILAS data due to e.g. bubbles from other ship's traffic.

In general, even measurements made on the same day lead to a large variation in the amount of mud. Concluding, the time representativeness of SILAS measurements is rather low especially for areas where mud is abundant.

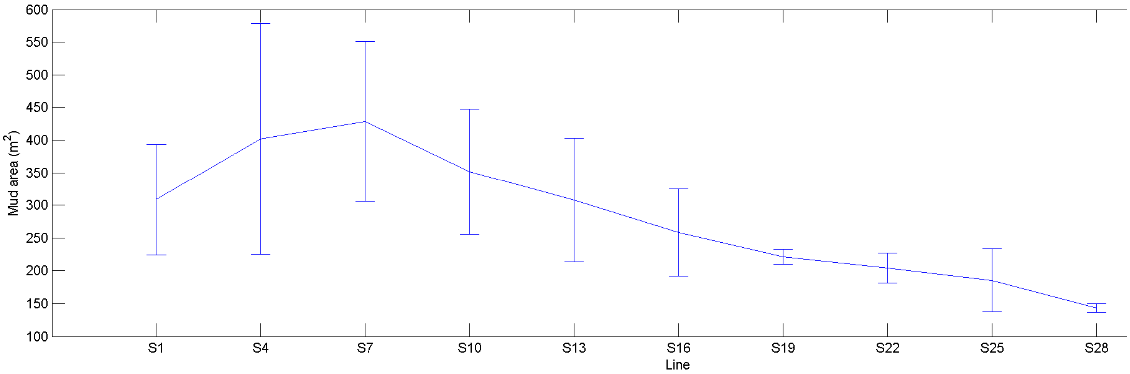


Figure 6.11 Total average mud area for calibration lines measured several times. The bars indicate the standard deviation. The calculation of the amount of mud is based on the 'basic' calibration. Averages and standard deviations are biased due to data gaps in some of the SILAS lines, giving rise to erroneous large amounts of mud.

Table 6.4 Total mud area for each of the multiple measured lines. The average and standard deviation for each set is calculated.

LINE	DATE	MUD AREA	LINE	DATE	MUD AREA	LINE	DATE	MUD AREA
0021_S1	2013-09-01	412,4	0007_S4	2013-08-01	698,3	0017_S7	2013-09-01	498,5
0022_S1	2013-09-01	339,5	0008_S4	2013-08-01	509,1	0018_S7b	2013-09-01	563,8
0115_S1b	15/1/2013	222,0	0009_S4b	2013-08-01	374,4	0049_S7b	14/1/2013	252,4
0149_S1b	17/1/2013	261,2	0036_S4multi	2013-10-01	355,0	0128_7c	16/1/2013	361,9
			0119_4b	15/1/2013	225,7	0143_S7b	17/1/2013	464,9
			0142_S4b	17/1/2013	248,9			
AVERAGE		308,8			401,9			428,3
STANDARD DEVIATION		84,6			177,0			122,5

LINE	DATE	MUD AREA	LINE	DATE	MUD AREA	LINE	DATE	MUD AREA
0044_S19	14/1/2013	231,1	004647_S22	14/1/2013	227,7	0069_S25	14/1/2013	163,3
0045_S19b	14/1/2013	224,6	0048_S22_b	14/1/2013	202,6	0124_S25b	16/1/2013	152,3
0063_S19b	14/1/2013	204,4	0148_S22b	17/1/2013	181,6	0150_S25b	17/1/2013	240,4
0147_S19b	17/1/2013	224,2						
AVERAGE		221,1			204,0			185,3
STANDARD DEVIATION		11,6			23,1			48,0

LINE	DATE	MUD AREA	LINE	DATE	MUD AREA
0019_S10	2013-09-01	387,4	0031_S13	2013-10-01	334,6
0020_S10b	2013-09-01	441,9	0032_S13b	2013-10-01	429,2
0053_S10b	14/1/2013	358,4	0057_S13b	14/1/2013	248,9
0144_S10b	17/1/2013	217,6	0145_S13b	17/1/2013	219,6
AVERAGE		351,3			308,1
STANDARD DEVIATION		95,6			94,3

LINE	DATE	MUD AREA	LINE	DATE	MUD AREA
0073_S28	14/1/2013	141,0	0033_S16	2013-10-01	320,3
0126_S28b	16/1/2013	137,6	0034_S16b	2013-10-01	311,0
0151_S28b	17/1/2013	150,9	0060_S16b	14/1/2013	189,9
			0146_S16b	17/1/2013	212,6
AVERAGE		143,2			258,4
STANDARD DEVIATION		6,9			66,8

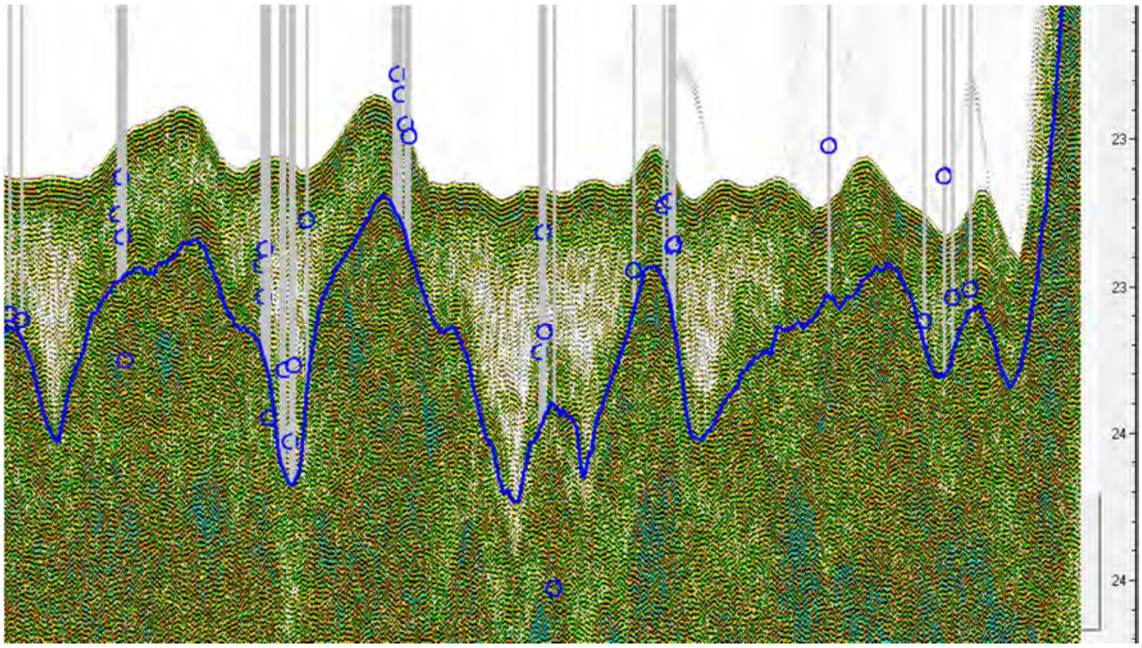
6.2.2 Analysis of crossings

In general, measured and determined levels on crossing SILAS lines should match. The SILAS software allows for analysing the fitting of a calculated density level at the crossings of all lines. A good fitting indicates a reliable, spatially representative calibration method.

A total of 3834 crossings were analysed for the basic calibration method (1200_25cm_5m_cum). This includes perpendicular crossings of the lines measured in a grid and the crossings of the more ore less overlapping lines that were measured several times. For each crossing, a misfit value of the depth of the density level is given. In addition, the crossings can be visualized over the SILAS lines as shown in Figure 6.12.

In order to determine the quality of the calibration method, a quantitative, statistical analysis of the misfit has been carried out. The results are visualised in Figure 6.13 and summarized in Table 6.5. The average misfit value is 0.38 m. From the statistical analysis in section 6.3.5, the uncertainty in depth of the 1.2 kg/L density level is around 0.3 m. 71% of the crossings fall within this bandwidth of 0.3 m. Some very large deviations at crossings (> 2.0 m) are related to data gaps: one line shows good data and a reliable 1.2 kg/L level while the crossing line has a data gap, with a 1.2 kg/L level automatically referred to the maximum depth of the SILAS profile.

It is worth noticing that for this crossings analysis, all survey lines acquired over a period of 10 days have been considered. Part of the crossing lines were measured on different days. Therefore, part of the misfit between the crossings can be explained by the dynamics of the mud.



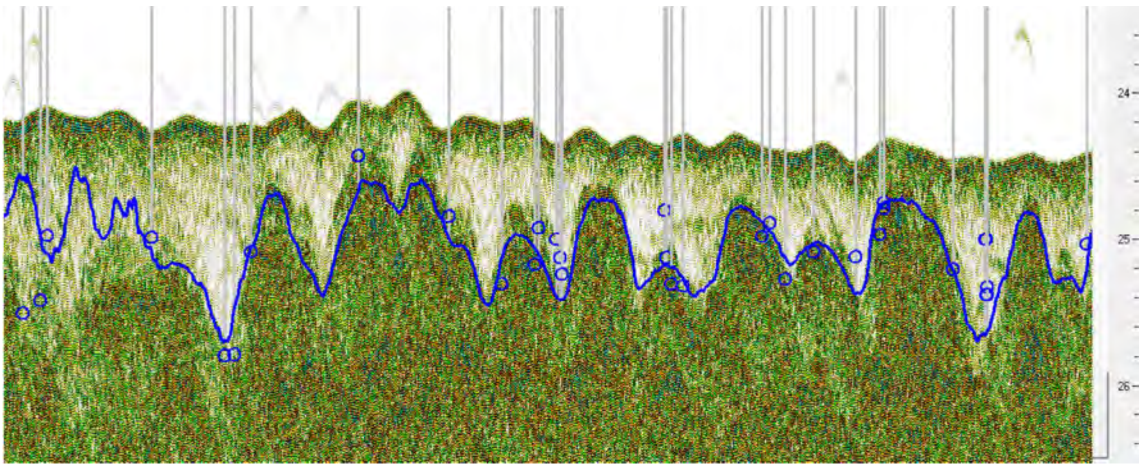


Figure 6.12 Example of visualization of the crossings for line S4b (top) and S10 (bottom). The grey lines represent the crossing lines with the selected one. The 1.2 kg/L level calculated using the basic calibration (1200_25cm_5m_cum) is represented by the blue line. The 1.2 kg/L levels at the crossings are indicated by blue circles.

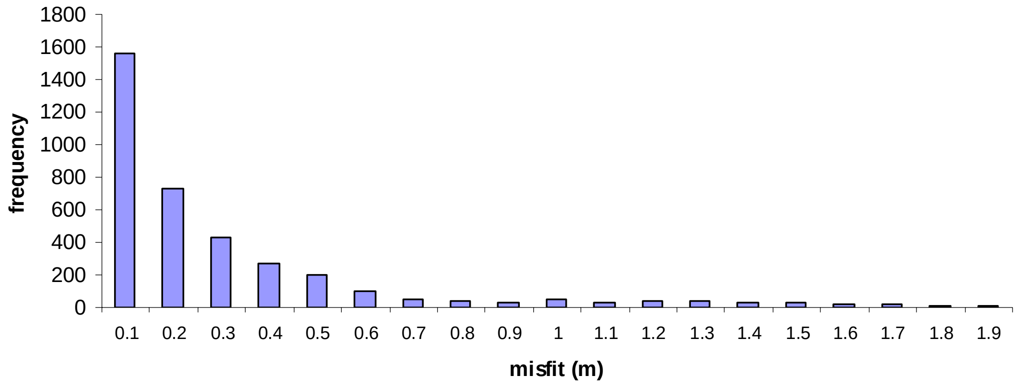


Figure 6.13 Frequency histogram of the misfit in depth of the basic density level of 1.2 kg/L (calibration dataset: 1200_25cm_5m_cum) at the line crossings.

Table 6.5 Statistical analysis of the misfit value at the crossings for the 1.2 kg/L (calculated with the basic dataset).

Misfit (m)	% cross points
< 0.1	41
< 0.2	60
< 0.3	71
< 0.4	78
< 0.5	83
More than 0.5	17

Additionally, an analysis of the crossings for each measurement day was performed, in order to reduce the effect of the dynamics of the mud over the 10 day period of the survey. In the SILAS software, accuracy levels of 68% and 95% are provided. The results of the SILAS analysis of the crossings per day are summarised in Table 6.6. The maps of the crossings of the SILAS lines and the histograms of the data are given in Appendix H.

Table 6.6 Statistical analysis of the crossings analysed per survey day.

Date	Total # of crossings	Accuracy (m) 68%	95%	Type of crossings	Remarks
08-01-2013	77	0.51	0.61	nearly parallel	slope effect on kering
09-01-2013	26	0.09	0.11	nearly parallel	lines measured closely in time
10-01-2013	80	0.24	0.54	nearly parallel	wrong tide correction (for 1 line)
14-01-2013	45	0.04	0.06	nearly parallel	large time difference between some of the crossing lines
15-01-2013	113	0.69	0.72	perpendicular	wrong tide correction (for part of the lines)
16-01-2013	111	0.06	0.17	mixed	large time difference between some of the crossing lines
17-01-2013	0	-	-	none	only single, parallel lines

For 9, 14 and 16 January 2013, the 68 % accuracy level is in the order of several cm; the 95 % accuracy level is several cm to dm. The fit of the 1.2 kg/L level at the crossings for those days is good.

For 8, 10 and 15 January 2013, the accuracy levels are much larger, meaning that the fit at the crossings is worse. We analysed the cause of the larger deviations by looking at which SILAS lines showed the large deviations. The explanation for large values of the accuracy levels is given below:

- 8 January 2013: deviations are caused by measurements on the slope of the Maeslantkering, measured in two directions. Because of the beamwidth of the transducer, depths at slopes are projected at the wrong location, causing differences in depths at the crossings. An example of SILAS lines at the Maeslantkering is included in Appendix H. Additionally, a shift of 1 second was necessary on 8 January. This shift might not have been constant during the day, causing additional errors in depths at crossing lines.
- 10 January 2013: there is a shift of around 0.5 m for line 0036_S4multi. Upon checking the tide files, there was no data in the Qinsy export after 13:20 hrs (GMT). In the “waterlijn” data, only data lines with zeros are included in the file after 13:20 hrs. Line 0036_S4multi, however, was measured at 15:26 hrs (GMT). SILAS automatically applies the tide correction which is closest in time to the time of measurement, in this case the correction at 13:30 hrs. The actual tide difference between 13:20 hrs and 15:26 hrs is approximately 50 cm, explaining the peak around that value in the histogram of misfits. The tide graph is provided in Appendix H
- 15 January 2013: in the histograms there are many misfits with values between approximately 1 and 1.7 m. This is related to erroneous tide corrections as well. The last entry (without zeros) in the Qinsy export dates from13:57 hrs (GMT), while lines 0113 to 0119 were measured after that, between 14:34 and 15:39 hrs (GMT). The tide is rising fast after 13:57, causing deviations up to 1.7 m. An example of a SILAS line with crossings on an erroneous tide correction and the tide graph are provided in Appendix H.

This error in tide correction was discovered at the very end of the project. Lines 0036 and 0113-0119 are not crucial for the analysis of performance of SILAS. Therefore, RWS agreed that the entire analysis did not have to be repeated with the correct tide information. Additionally, the analysis at the start of this section, including all crossings is biased due to the presence of the 8 lines with erroneous tide corrections.

6.2.3 Random datasets

In order to test the representativeness of datasets and the size of the datasets used in the calibration, several calibration tests were performed with different numbers of calibration points.

In the basic calibration, 45 point measurements of density were included. In order to asses the quality of the calibration procedure depending on the amount of density measurements, the following data sets were used for calibration:

- R40 = 40 points randomly selected from the 45 points of the basic data set
- R30 = 30 points randomly selected from the 40 points data set
- R20 = 20 points randomly selected from the 30 points data set
- R10 = 10 points randomly selected from the 20 points data set

- R40b – R40e: 4 more datasets of 40 points, randomly selected from the 45 points of the basic data set
- R30b – R30e: 4 more datasets of 30 points, randomly selected from the 45 points of the basic data set
- R20b – R20e: 4 more datasets of 20 points, randomly selected from the 45 points of the basic data set
- R10b – R10e: 4 more datasets of 10 points, randomly selected from the 45 points of the basic data set.

The spatial distribution of points included in the random data sets is shown in Appendix A.
All calibrations based on the random data sets have been compared to the ‘basic’ calibration (1200_25cm_5m_cum). An example of comparison among 1.2 kg/L levels are shown for the different datasets is given in Figure 6.14; the 40, 30 and 20 datasets give comparable results while, when using only 10 density points, a large offset is noted.

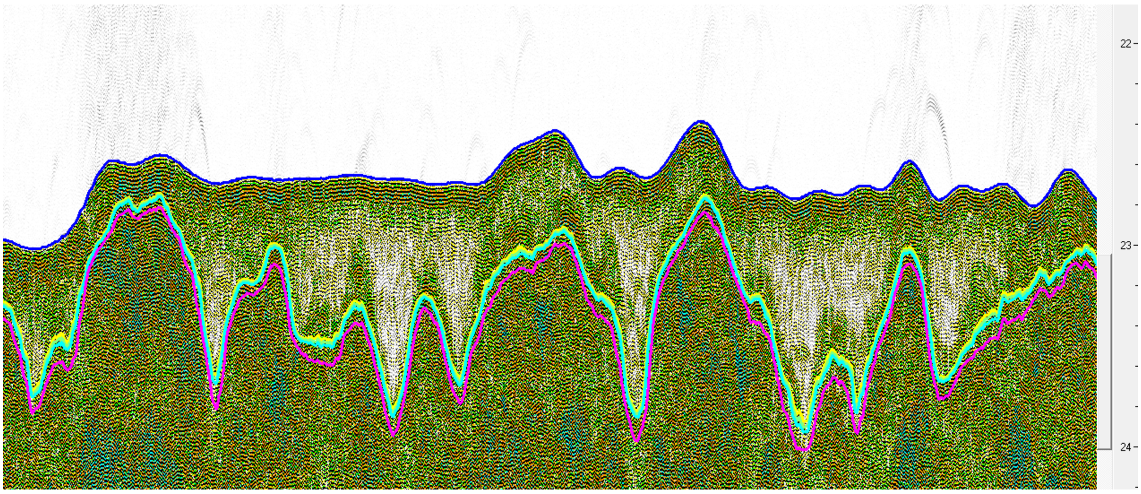


Figure 6.14 Example of SILAS measurement (portion on calibration line S4b) showing the basic calibration (1200_25cm_5m_cum, orange), together with the levels determined by randomly selected datasets of 40 (yellow), 30 (green), 20 (cyan) and 10 (pink) data points.

This observation is clearer when comparing the measured amount of mud with the different random datasets and for all lines (Figure 6.15). It is clear that when using either 30 or 20 density measurements the variation in calculated mud area hardly exceed 5%. When employing a dataset with only 10 points, a large misfit (up to 30-35%) is observed in mud estimation. From this figure only, it appears that an amount of 20 points could be enough to lead to results that are comparable to the ones obtained with more than double data points and with a threshold for mud thickness (25 cm).

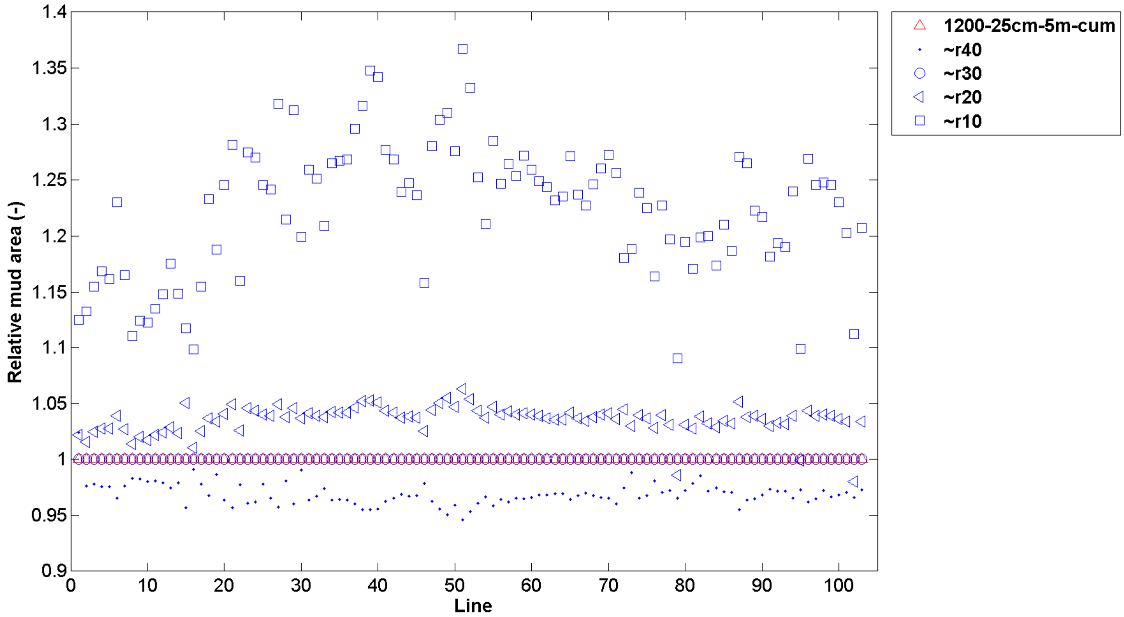


Figure 6.15 Mud area for each SILAS line according to calibrations performed with 4 different datasets of 40, 30, 20 and 10 randomly selected density measurements (1.2 kg/L level). Values are normalized by the amount of mud of the basic calibration (1200_25cm_5m_cum) on each line.

However, the result might be the result of the choice of the points included in and excluded from the calibration. Therefore, extra tests were performed with 4 more random datasets per total amount of points included in the calibration. The examples of the variation among 5 calibrations made from different data sets with the same amount of points is shown in Figure 6.16. For progressively decreasing amounts of the density measurements included in the calibration, the variability of the resulting 1.2 kg/L levels increases. A large variation of the 1.2 kg/L level is observed for the random datasets consisting of 20 and 10 points demonstrating in the example in Figure 6.16. This suggests that 20 or 10 points is insufficient for a reliable calibration. On the other hand, the variation of the 1.2 kg/L obtained with the random sets of 30 points is rather identical to the ones obtained from the 40 points data sets.

In Figure 6.17 to Figure 6.20, the relative amount of mud is shown for all lines, with one amount of calibration points for each figure. From these figures it is clear that there is a large variation in derived mud areas for the various calibrations that are based on the same number of calibration points. For the random data sets of 40 calibration points, the deviations from the basic calibration are between approximately +5 and -20 %. For 30 random points deviations are between +5 and -10% (some outliers up to -25%). For 20 random points the deviations are larger: between +30 and -20%. For 10 random points, the deviations are largest: between +55 and -10%. The variation in retrieved mud areas is comparable for the 40 and 30 point calibration data set. The variation for the smaller data sets is clearly larger. From this analysis, we conclude that for this Maasmond data set, the optimal size of the data sets used for calibration consists of 30 point measurements of density. Additionally, the bandwidth of the retrieved mud areas is around 15%.

The optimal number of data points is probably also related to the quality of the point measurements. For a different instrument, this test should be repeated. For a different survey area (e.g. the entire Maasmond area of RWS or IJmond), this test should be repeated as well.

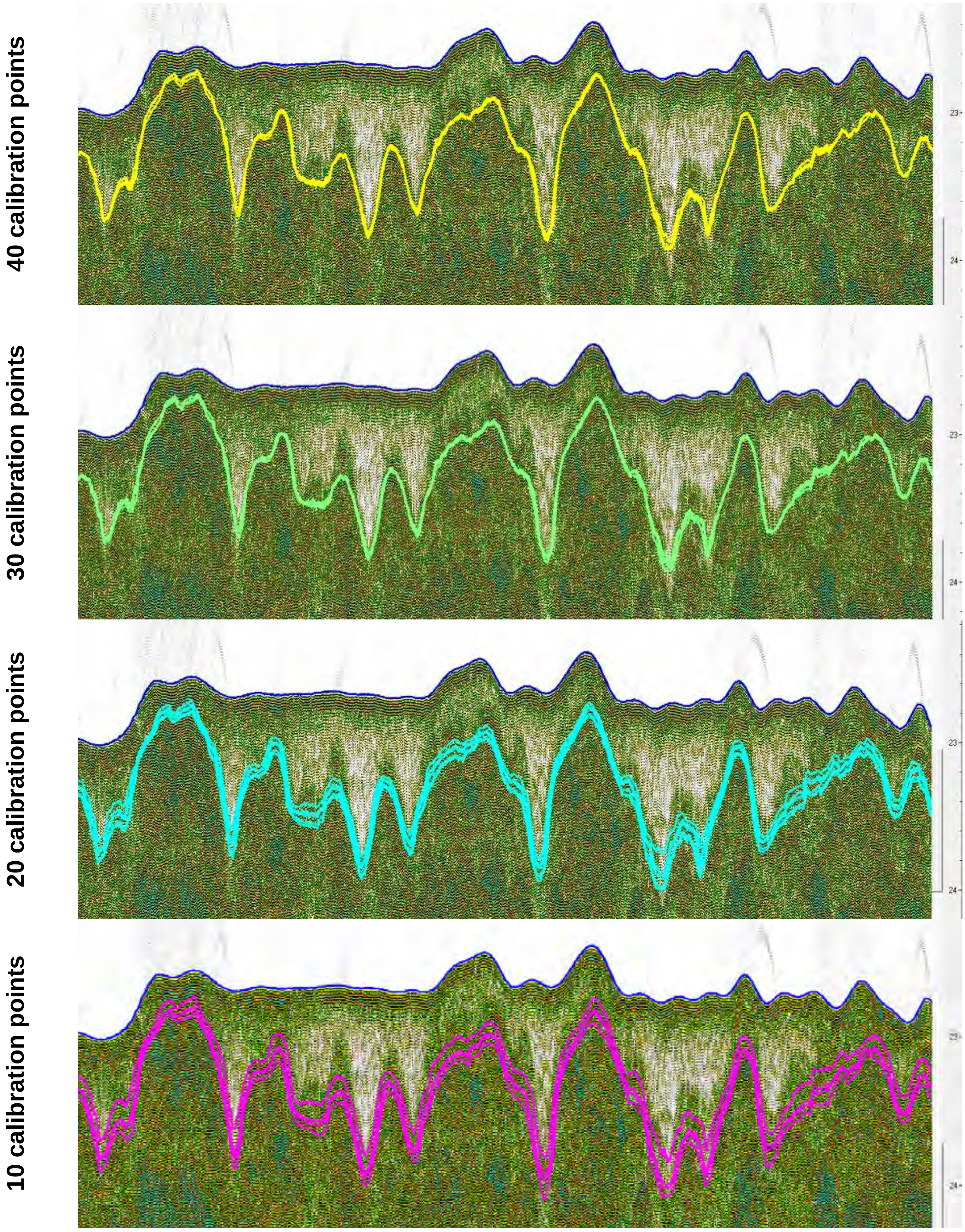


Figure 6.16 Comparison 1.2 kg/L levels retrieved after calibration of random data sets of (from top to bottom) 40, 30, 20 and 10 density measurements. SILAS profile of part of calibration line S4b.

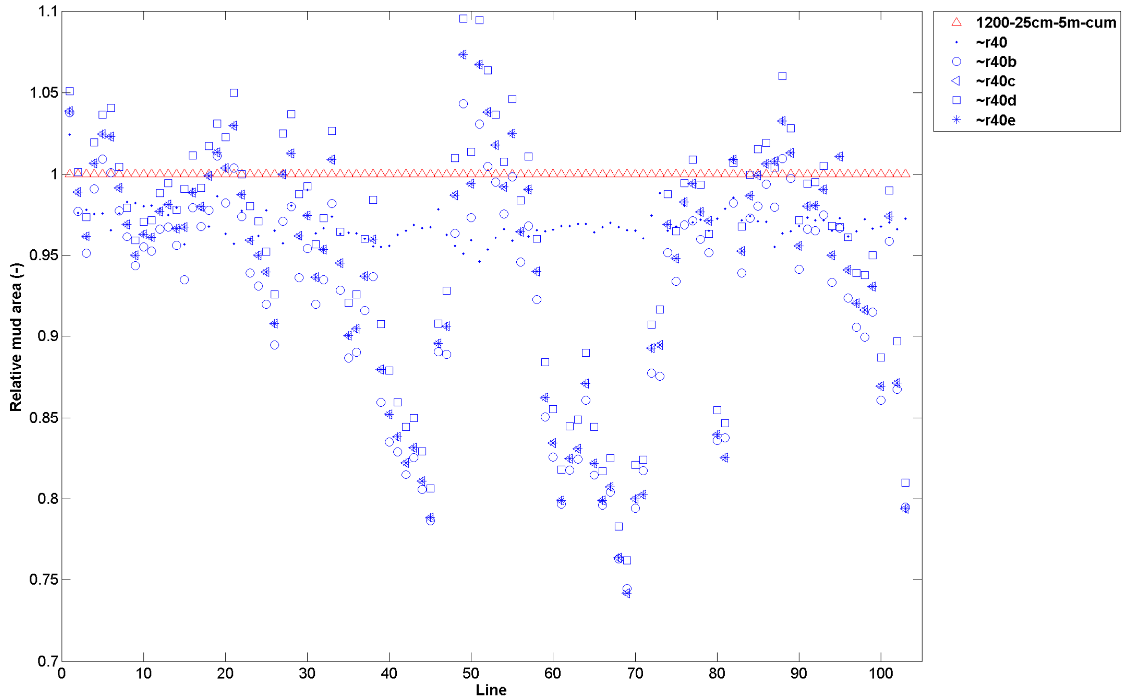


Figure 6.17 Mud area for each single surveyed line according to calibrations performed with 5 different datasets of 40 randomly selected density measurements (1.2 kg/L level). Values are normalized by the amount of mud of the basic calibration (1200_25cm_5m_cum) on each line.

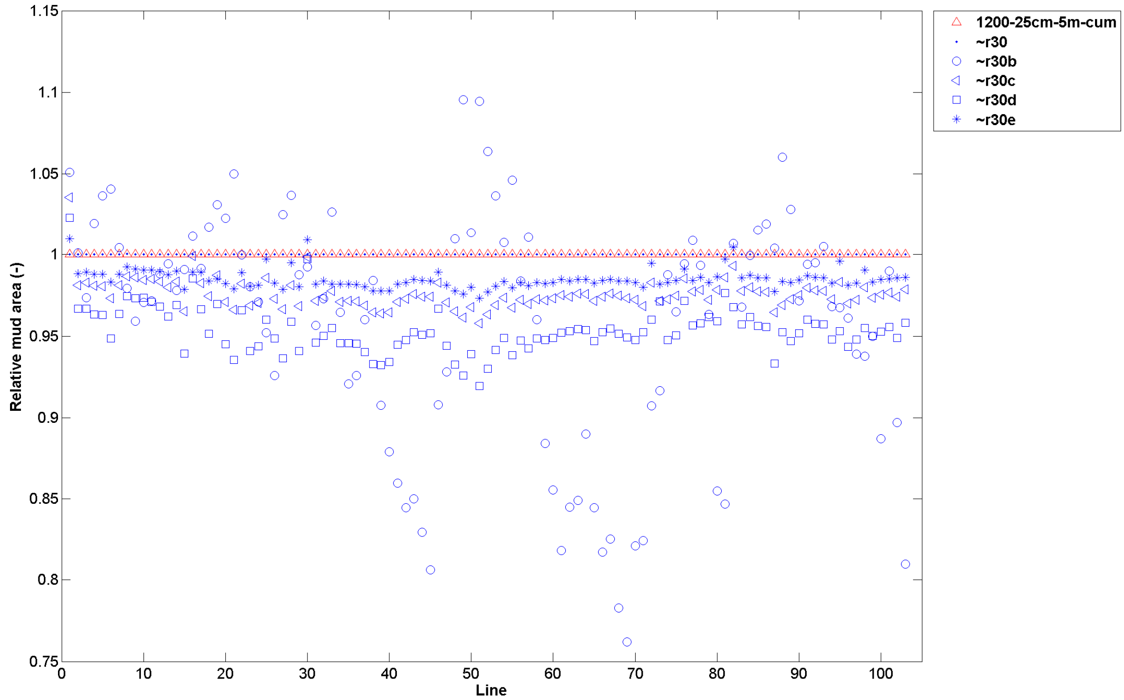


Figure 6.18 Mud area for each single surveyed line according to calibrations performed with 5 different datasets of 30 randomly selected density measurements (1.2 kg/L level). Values are normalized by the amount of mud of the basic calibration (1200_25cm_5m_cum) on each line.

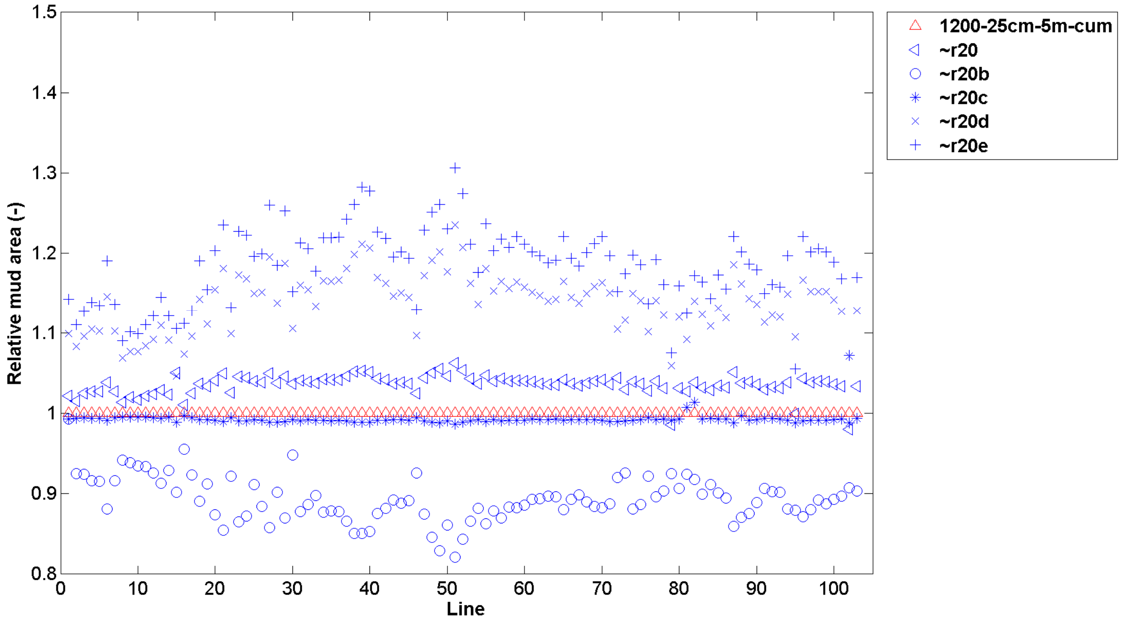


Figure 6.19 Mud area for each single surveyed line according to calibrations performed with 5 different datasets of 20 randomly selected density measurements (1.2 kg/L level). Values are normalized by the amount of mud of the basic calibration (1200_25cm_5m_cum) on each line.

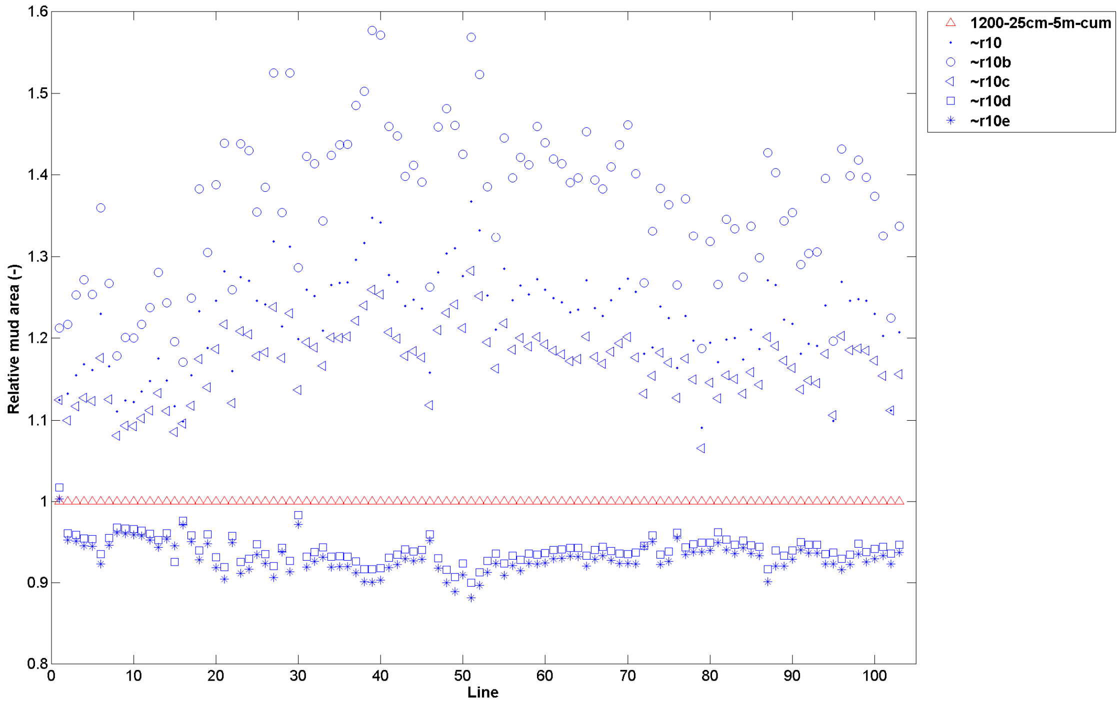


Figure 6.20 Mud area for each single surveyed line according to calibrations performed with 5 different datasets of 10 randomly selected density measurements (1.2 kg/L level). Values are normalized by the amount of mud of the basic calibration (1200_25cm_5m_cum) on each line.

6.2.4 Data points not used in calibration

During the survey, several extra point measurements were performed that could serve as a check for the calibration. The point extra measurements were done by Navitracker. They are numbered N001 to N005, and were randomly situated on or near line S40. The points are plotted in the SILAS seismograms in Figure 6.21 and Figure 6.22. The basic calibration (1200_25cm_5m_cum) is plotted as well. The orange line of the basic calibration should pass through the 1.2 kg/L circle for each point. It is clear from figures a and b that the fit between the 1.2 level according to SILAS and according to the point measurement do not always agree well. The differences between the 1.2 levels are given in Table 6.7. As a check, the distance to the nearest SILAS line is given in Table 6.7. It is always within 2.2 m, so within the 5 m threshold used in calibration. The difference in depth level determined by Navitracker and SILAS can be up to 40 cm. From Figure 6.21, Figure 6.22 and the other SILAS figures in this report it is apparent that the 1.2 kg/L level for the points that are used in the calibration can be off with several decimeters as well.

Although ideally the difference between the 1.2 kg/L levels for the extra random points, the difference is in agreement with the points used for calibration. Therefore, we consider the test with the extra random points as successful.

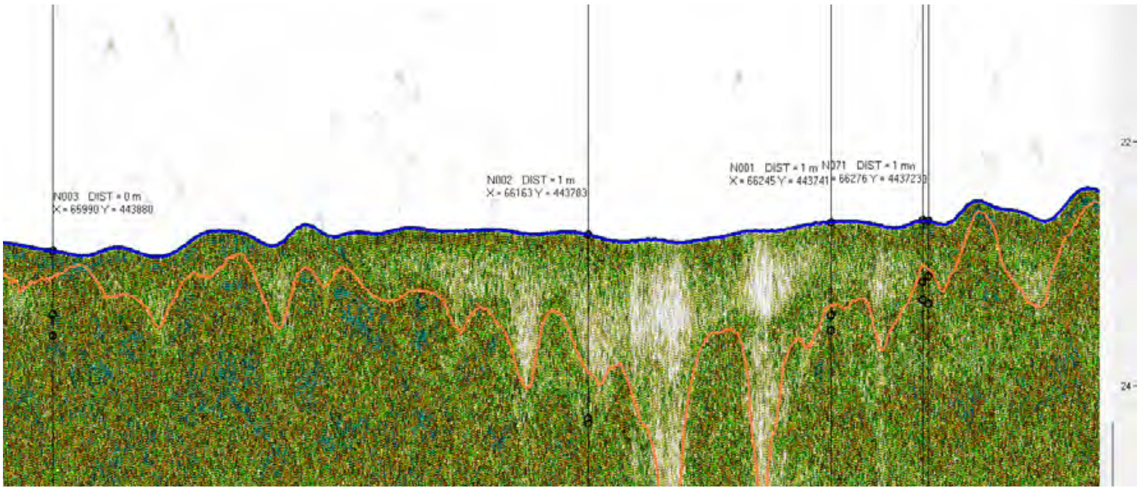


Figure 6.21 SILAS line 0131_S40 with extra random points (from left to right) N003, N002 and N001. The two vertical lines to the right of N001 represent point measurements used in the standard calibration. Orange line indicates 1.2 kg/L level from basic calibration (1200_25cm_5m_cum). Circles on the point measurement line are (top to bottom): 1.05, 1.2 and 1.25 kg/L level from the Navitracker measurement.

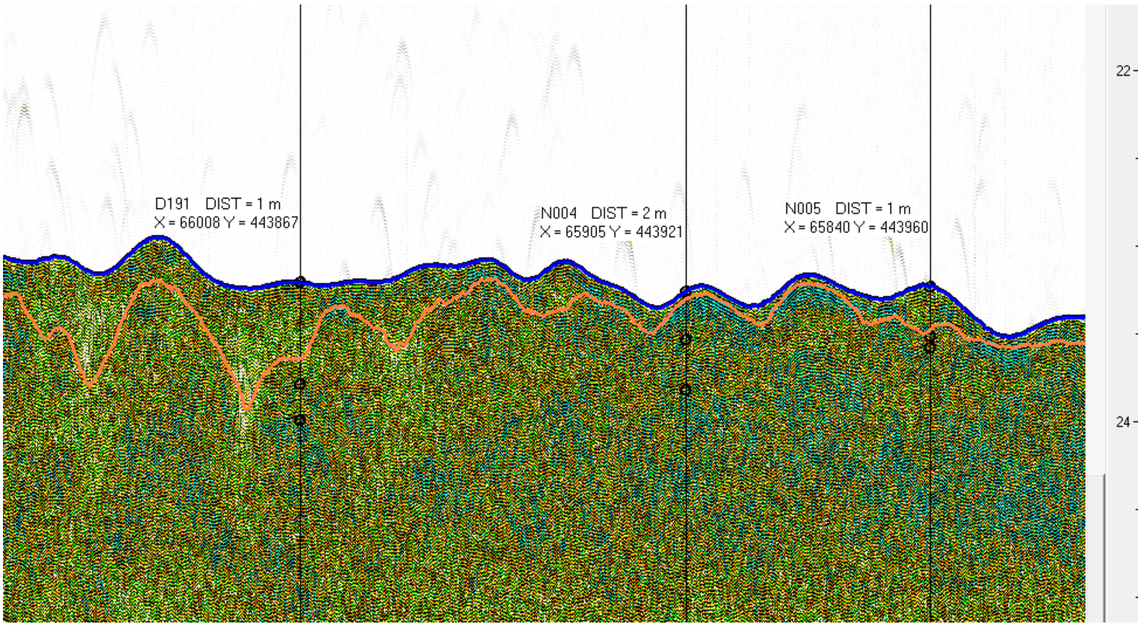


Figure 6.22 SILAS line 0136_S40 with extra random points (from left to right) D191 (used in calibration), N004 and N005 (both not used). Orange line indicates 1.2 kg/L level from basic calibration (1200_25cm_5m_cum). Circles on the point measurement line are (top to bottom): 1.05, 1.2 and 1.25 kg/L level from the Navitracker measurement.

Table 6.7 1.2 kg/L level for the extra random points on line S40

Point measurement	1.2 kg/L level SILAS (m-NAP)	1.2 kg/L level Navitracker (m-NAP)	Difference (m)	Distance to line (m)
N001	23.99	24.08	0.09	1.03
N002	24.56	24.96	0.4	0.85
N003	23.77	24.08	0.31	0.22
N004	23.58	23.82	0.24	2.32
N005	23.77	23.8	0.03	0.99

6.3 Question 3 and 4: bandwidth of 1.2 kg/L level

Research question 3 is: What are the accuracies related to model assumptions, measurement errors, processing assumptions and dynamics of mud system related to the SILAS procedure? What is the band of uncertainty in determining the 1.2 kg/L level with SILAS?
Answer summary: The resolving power for the density in SILAs is 0.01 kg/L. Depth levels for 1.2 and 1.21 kg/L are identical, whereas depths for the 1.19 and 1.22 kg/L levels are significantly different. The bandwidth of the depth level of the 1.2 kg/L relative to the 1.05 kg/L level or the first reflector (thickness) is approximately 30 cm (RMSE).

Research question 4 is: How do different processing options influence the result?
Answer summary: The gradient method should not be used, because it is not based on the physical property of reflections on impedance contrasts. The cumulative method without

vertical corrections is to be preferred over the cumulative method with vertical corrections, because of the averaging effect in depths of the determined 1.2 kg/L level.

For RWS, the SILAS system can only be incorporated in the standard processes if the level determined by SILAS represents the desired density level within a certain bandwidth. In order to determine the bandwidth of the 1.2 kg/L level, several calibration tests were performed. The tests consist of comparisons of the 1.2 kg/L levels determined for:

- “Thick” and “thin” data set. The thick dataset comprises point measurements with mud thickness of more than 0.5 m; the thin dataset of less than 0.5 m (section 6.3.1).
- Cumulative model and cumulative model with vertical corrections (section 6.3.2).
- Different vessel speeds (section 6.3.3).

Next, the positions of the density levels of 1.15 to 1.25 with 0.01 kg/L steps were determined (section 6.3.4). Comparison between these levels results in a bandwidth of densities that SILAS is able to determine from the data. Additionally, a statistical analysis has been performed on the 1.2 kg/L level by comparison of the deviations between point measurements and SILAS levels for the various random datasets (section 6.3.5).

For each type of calibration, the amount of mud on all measured SILAS lines was calculated. This is done by calculating the area between the top of the mud and the density level resulting from the calibration. No interpolation between the lines has been applied and therefore no volumes are calculated.

Additionally, the error sources are identified in a separate section (section 6.4).

6.3.1 Calibration based in “thin” and “thick” mud layers

In order to asses the effect of mud thickness over the reliability of calibration in SILAS, two density measurement datasets were tested. The “thin” dataset comprises all density measurements with L2-L1 is less or equal to 50 cm; the “thick” dataset with L2-L1 larger than 50 cm. The results are visualized in Figure 6.23. The 1.2 kg/L level for the “thick” dataset coincides with the basic calibration. For this SILAS line, the “thin” dataset results in a 1.2 kg/L level at shallower depths, resulting in smaller mud areas. This pattern is observed for all lines.

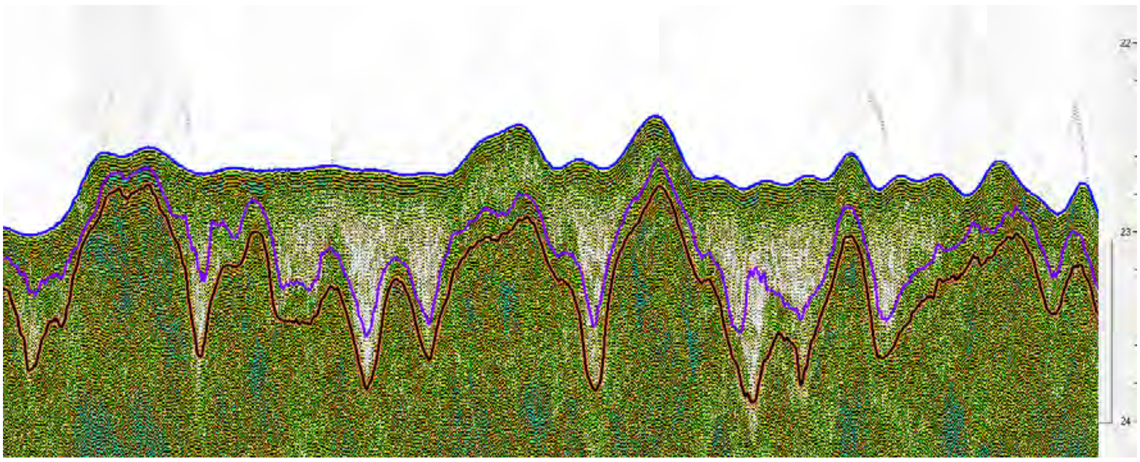


Figure 6.23 Example of SILAS line (0009_S4b) with the 1.2 kg/L level for the basic calibration (orange line), the “thick” dataset (black line, mud thickness > 0.5 m for calibration) and “thin” dataset (purple line, mud thickness < 0.5 m for calibration).

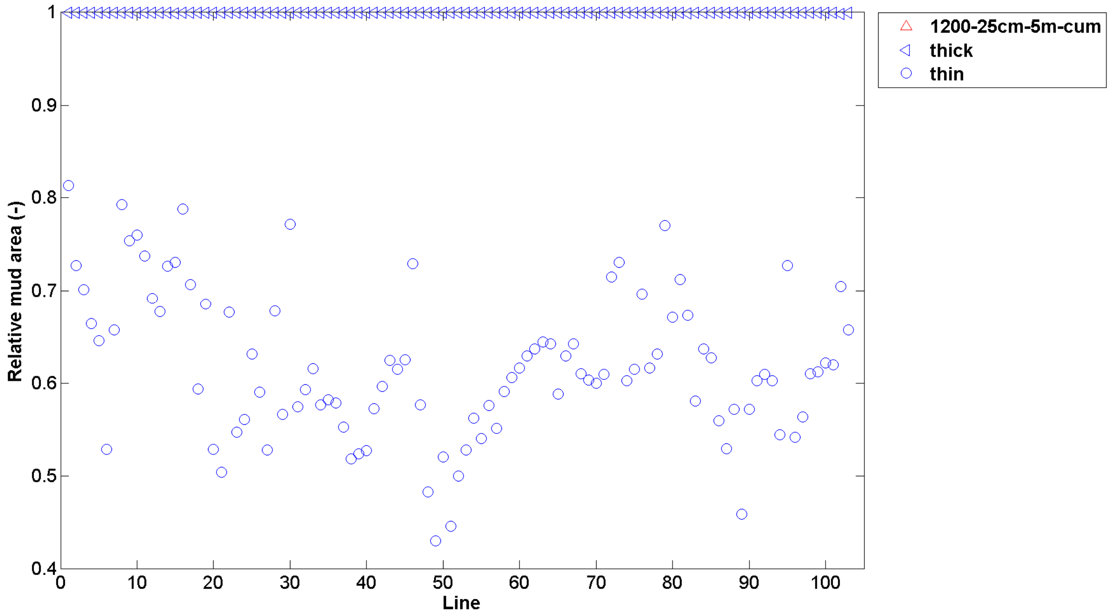


Figure 6.24 Relative mud areas for all lines. Values are normalized by the amount of mud of the basic calibration (1200_25cm_5m_cum) on each line. The calibration using the "thick" dataset (blue triangles) plot on top of the basic calibration (red triangles), causing the red triangles to be invisible. The "thin" calibration results in areas 20 to 50% lower.

Figure 6.24 shows the total amount of mud (relative to the maximum obtained for each line) for all lines. The result obtained using the "thick" dataset is equivalent to the basic calibration. For the "thin" dataset, however, the derived amount of mud is 20 to 50% lower.

It is difficult to define which of the three approaches is correct. Both "thin" and "thick" calibrations are based on approximately the same amount of point measurements. It is striking that the standard deviation of the "thin" calibration (18 cm) is much smaller than the standard deviation of either "thick" (32 cm) basic calibration (29 cm). It might be related to the fact that for thicker mud layers, the repeatability of the measurement, as shown by the analysis of the clusters in section 6.1.1 is rather small, resulting in a larger standard deviation compared to the thin layers.

6.3.2 Cumulative model with or without vertical corrections

In section 5.1, the advantages and disadvantages of the cumulative model with or without vertical corrections are listed. The most relevant advantage of the cumulative model without vertical corrections is that possible errors due to mismatch, positioning errors and errors in the geophysical point measurements are averaged out. The analysis of the clusters (section 6.1.1) showed that the repeatability of the point measurements is rather low. Therefore, we expect that the cumulative model without vertical corrections will produce the best results.

Figure 5.2 in section 5.1.1 shows a SILAS example of the basic calibration with the cumulative model with and without vertical corrections applied. In general, the difference between the two levels is small. In Figure 6.25the differences between the relative mud areas for all lines are visualized for different datasets. All mud areas are normalized to the mud area of the basic calibration (1200_25cm_5m_cum).

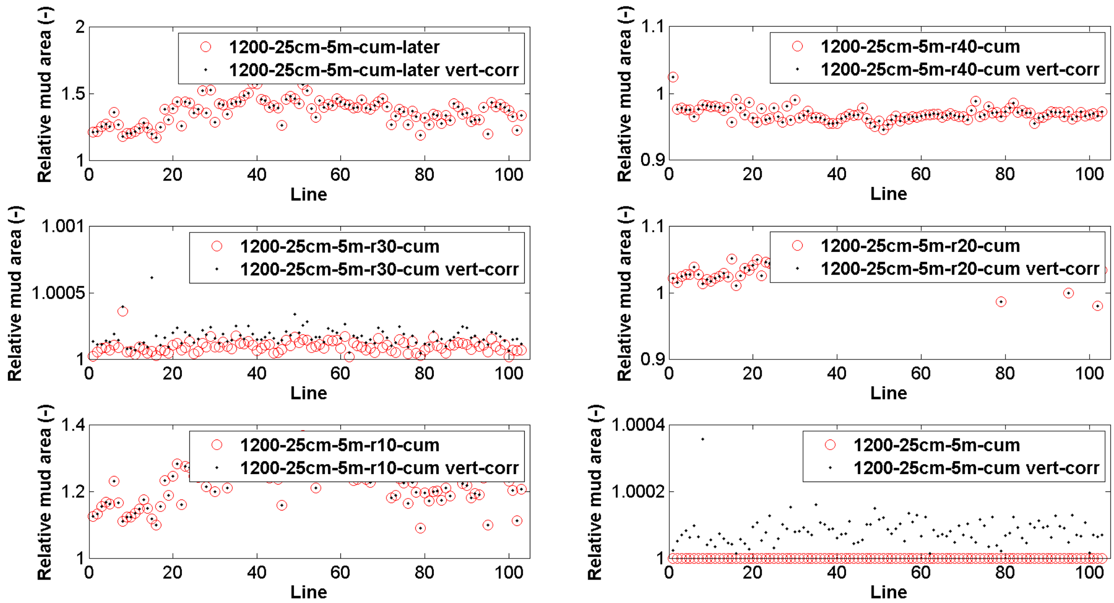


Figure 6.25 Relative mud areas for all lines. Values are normalized by the amount of mud of the basic calibration (1200_25cm_5m_cum) on each line. Note the different ranges of the Y axis.

In general, the difference between the resulting areas determined by the cumulative model with of without vertical corrections is very small. For the basic calibration (Figure 6.25, bottom right panel), the differences are within 0.04 %. For the other types of calibration, the cumulative model with and without vertical corrections are (almost) identical as well. The difference between the calibrations done with various datasets is much larger than the difference between vertical corrections applied or not. We conclude that the differences between the results from the cumulative model with and without vertical corrections are insignificant.

6.3.3 Comparison between different vessel velocities

Multibeam surveys are usually performed with a vessel speed of 4 m/s. In earlier tests with SILAS, data quality degraded at this vessel speed. Therefore, during the survey a standard vessel speed of 2 m/s was applied. It saves a lot of time, however, if the standard 4 m/s vessel speed could be applied. A test with different vessel speeds (2, 3 and 4 m/s) was performed on line S4. Some additional tests with 3 and 3.5 m/s were performed on lines (see appendix F).

Figure 6.26 shows three consecutively measured SILAS lines with increasing vessel speeds. The images are stretched so that the horizontal axis represents the same distance. For increasing speed, the effect of heave is less severe. For the highest velocity (4 m/s), the quality of the seismogram is still acceptable. Some details, however, such as a bump on the left side of the figure, are not registered.

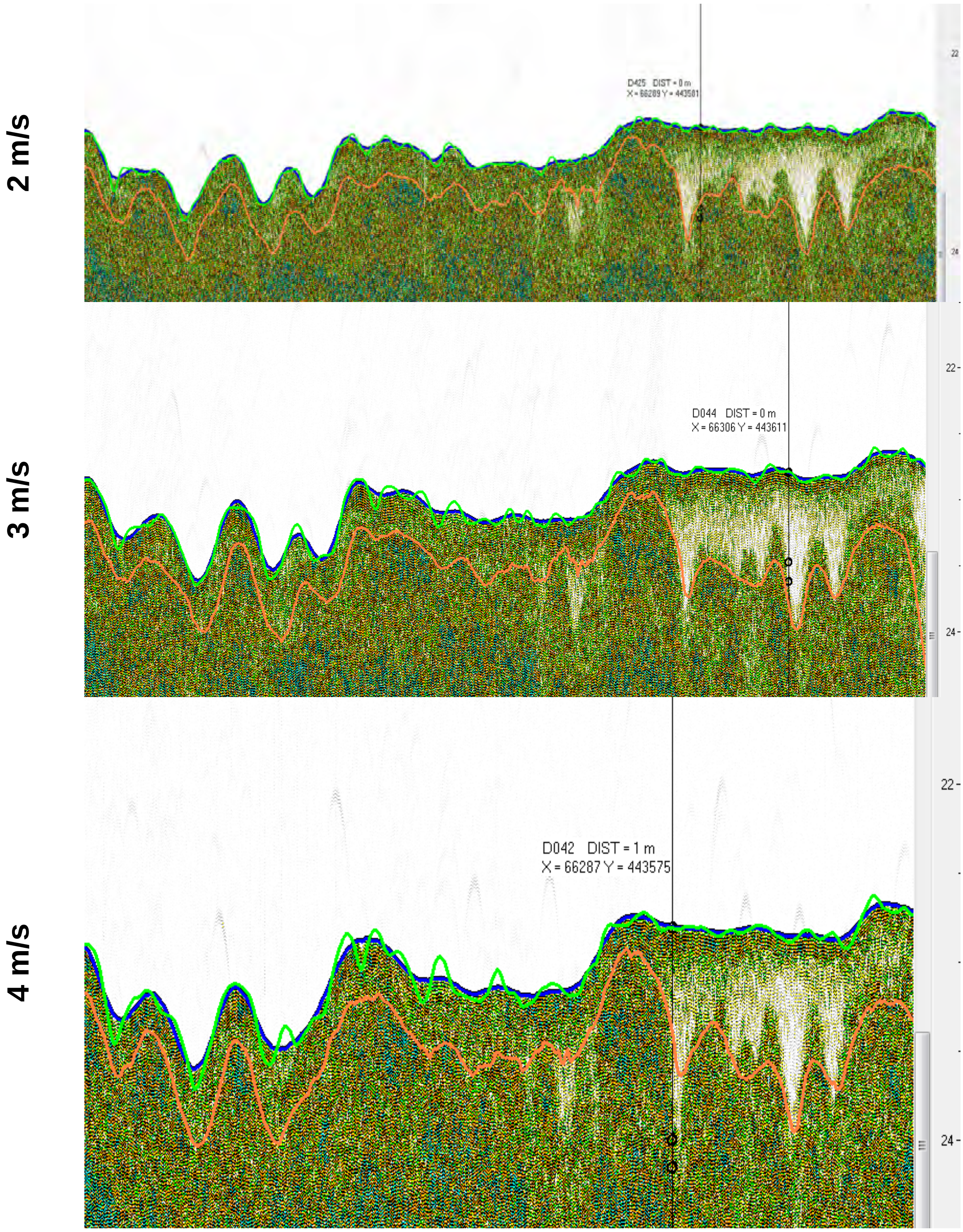


Figure 6.26 SILAS measurements of part of line S4 (length 145 m) with different vessel speeds: 2 m/s (top panel), 3 m/s (middle panel), 4 m/s (bottom panel). Green line represents uncorrected data, showing heave. Blue line is the heave corrected bottom, orange line is the 1.2 kg/L level for the basic calibration (1200_25cm_5m_cum).

The resulting mud thickness of line S4 is given in Figure 6.27. For the other lines, the figures are given in appendix F. In all three measurements of line S4, there are stretches with no SILAS data present (e.g. due to bubbles from other ship's traffic). These are recognized by the peak in mud area, e.g. between 100 and 200 m distance along the line for the 2 m/s data (red line). For parts with good quality SILAS data, the thicknesses determined for the different speed datasets correspond rather well.

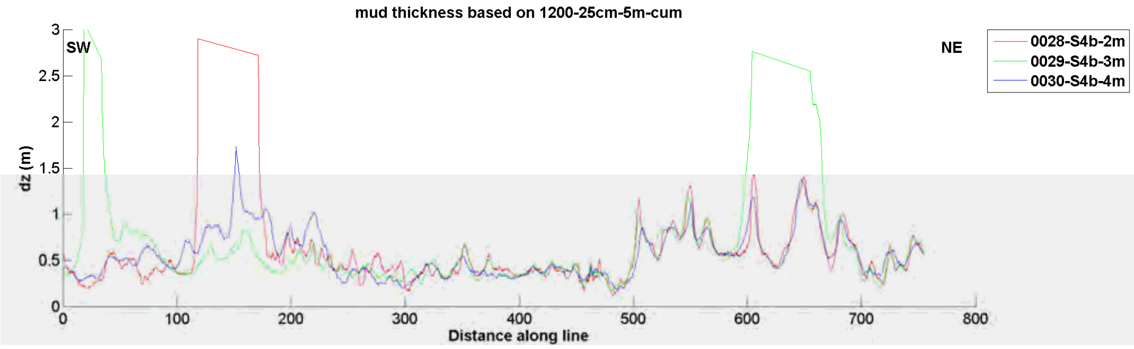


Figure 6.27 Mud thickness for different vessel speeds plotted versus distance along the line. The high peaks represent parts of the SILAS line with no SILAS data.

The statistics of the mud areas with different vessel speeds are given in Table 6.8 for line S4 and in Table 6.9 for the other lines. For the part with good quality SILAS data in line S4, the mud areas agree well. The average mud area is 190.5 m^2 with a standard deviation of 4.9 m. The statistics are not representative of the fit between the lines if peaks due to SILAS data gaps are included. For the entire S4b line, the average mud area is 503.8 m^2 with a large standard deviation of 72.7 m^2. However, two of the lines have large data gaps. For the other lines, the faster lines generally give larger amounts of mud than the 2 m/s line. For these lines, however, there are several effects that cannot be distinguished:

1. There are SILAS data gaps present in some lines.
2. The 2 m/s line was measured on a different day than the 3 and 3.5 m/s lines.

Therefore, no conclusions can be drawn for these lines.

Based on the good quality data parts of line S4 and the level of detail in the lines with different speeds, the maximum vessel speed of 3 m/s is a good compromise between horizontal resolution and SILAS data quality.

*Table 6.8 Mud thickness statistics for line S4b with different vessel speeds. Left columns for overlapping good quality SILAS data, right columns for the entire line, including SILAS data gaps. *) indicates that a SILAS data gap is present in the line.*

Line (part of)	Date	Mud area (m^2)	Line (entire line)	Date	Mud area (m^2)
0028_S4b_2m/s	10/1/2013	196.1	0028_S4b_2m/s *)	10/1/2013	517.8
0029_S4b_3m/s	10/1/2013	188.5	0029_S4b_3m/s *)	10/1/2013	568.4
0030_S4b_4m/s	10/1/2013	187.0	0030_S4b_4m/s	10/1/2013	425.1
Average		190.5	Average		503.8
Standard deviation		4.9	Standard deviation		72.7

*Table 6.9 Mud thickness statistics for lines with different vessel speeds. *) indicates that a SILAS data gap is present in the line.*

LINE	Date	Mud area (m^2)	Line	Date	Mud area (m^2)
007879_38_2m/s	15/1/2013	224.7	0081_39_2m/s	15/1/2013	266.2
0133_S38_3m/s *)	16/1/2013	241.3	0132_S39_3m/s	16/1/2013	355.4
0134_S38_3.5m/s *)	16/1/2013	355.9	0135_S39_3.5m/s	16/1/2013	313.2
Average		273.9	Average		311.6
Standard deviation		71.5	Standard deviation		44.6
LINE	Date	Mud area (m^2)	Line	Date	Mud area (m^2)
0083_41_2m/s	15/1/2013	251.3	0084_42_2m/s	15/1/2013	261.4
0139_S41_3.5m/s	16/1/2013	340.2	0141_S42_3m/s	17/1/2013	358.1
0130_S41_4m/s	16/1/2013	356.8	0140_S42_3.5m/s	17/1/2013	329.7
Average		316.1	Average		316.4
Standard deviation		56.7	Standard deviation		49.7
Line	Date	Mud area (m^2)			
0082_40_2m/s	15/1/2013	243.8			
0129_S40b_2m/s	16/1/2013	274.1			
0131_S40_3m/s	16/1/2013	335.5			
0136_S40_3.5m/s	16/1/2013	257.8			
Average		277.8			
Standard deviation		40.4			

6.3.4 Different density levels

To determine which density levels SILAS is able to distinguish, a set of calibrations is performed for the density levels of 1.15 kg/L with 0.01 kg/L increments up to 1.25 kg/L, for the cumulative model with and without vertical corrections. All point measurements were included, with the restriction of a maximum distance of 5 m to the nearest calibration line. A representative SILAS result is shown in Figure 6.28. Visually, the increase in density level with depth is clear. The distance between the density levels is not constant. Some levels are closer together than others. For point D415, there seems to be a large jump between 1.16, 1.17 and 1.18 kg/L. This is in accordance with the density profile measured at that location. The inversion in density, as seen in the D145 profile, however, is not reflected in the SILAS result.

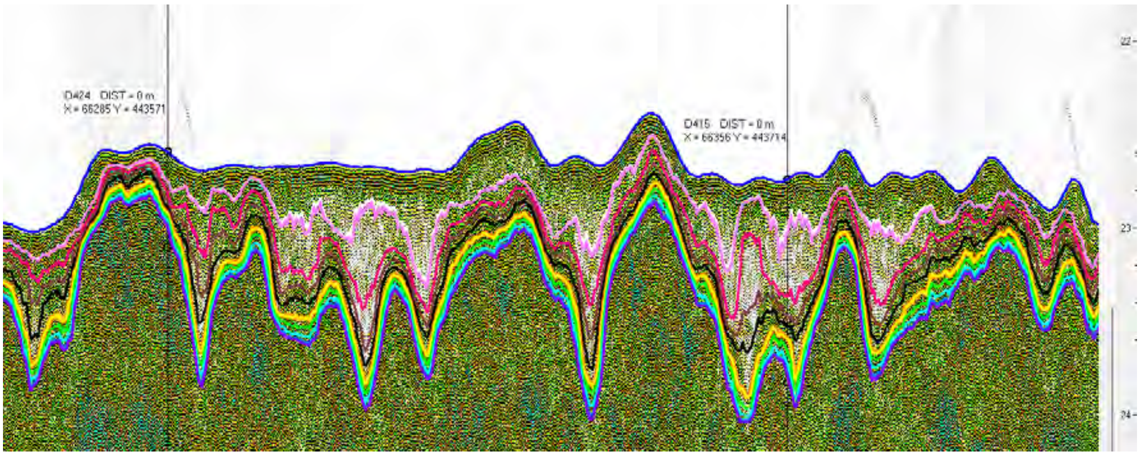


Figure 6.28 Example of SILAS line (0009_S4b) with different density levels. From top to bottom: blue = bottom, white = 1.15, pale pink = 1.16, pink = 1.17, brown = 1.18, black = 1.19, orange = 1.20, yellow = 1.21, green = 1.22, cyan = 1.23, blue = 1.24, purple = 1.25 kg/L level. The density levels of 1.20 kg/L (orange) and 1.21 (yellow) overlap.

Figure 6.29 shows the relative mud areas for all lines for all density levels. For all lines, the level of 1.21 kg/L coincides with the 1.20 kg/L level. This means that SILAS is not able to distinguish between these two levels. The levels of 1.19 and 1.22 kg/L are clearly different, resulting in 19% smaller and 10% larger mud areas (on average) relative to the 1.2 or 1.21 kg/L level. Figure 6.30 shows the average relative mud areas for all lines for the different density levels. From this figure, we can read that a density range of 1.195 to 1.22 kg/L corresponds to a variation in mud area of ± 10% around the desired 1.2 kg/L level.

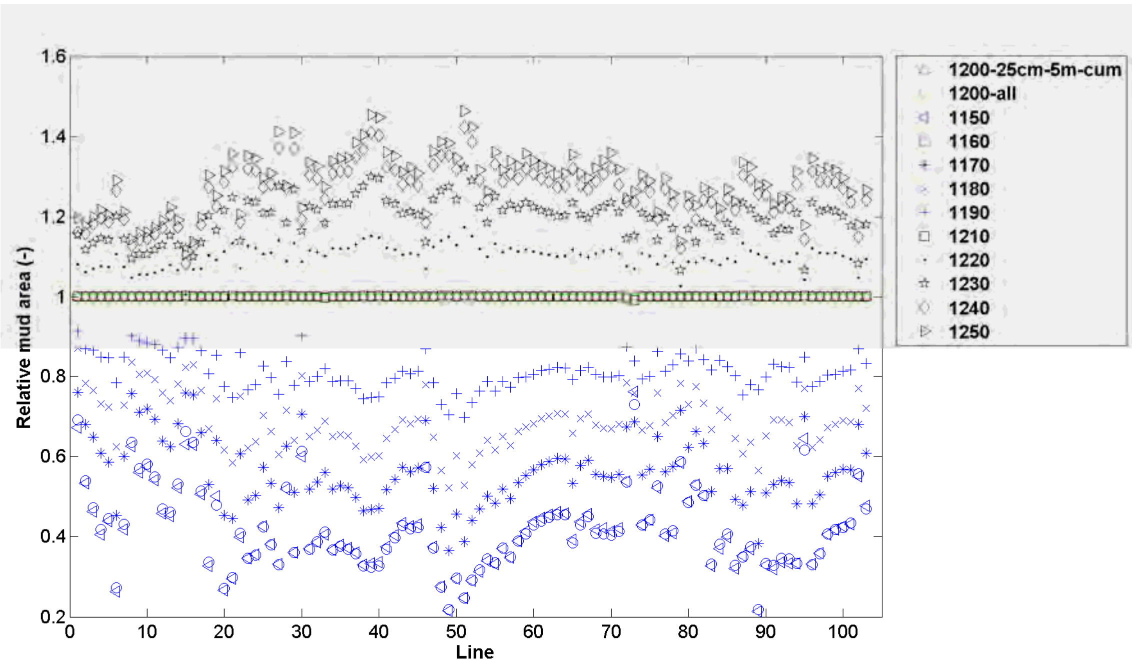


Figure 6.29 Relative mud areas for all lines for the different density levels. Values are normalized by the amount of mud of the basic calibration (1200_25cm_5m_cum) on each line.

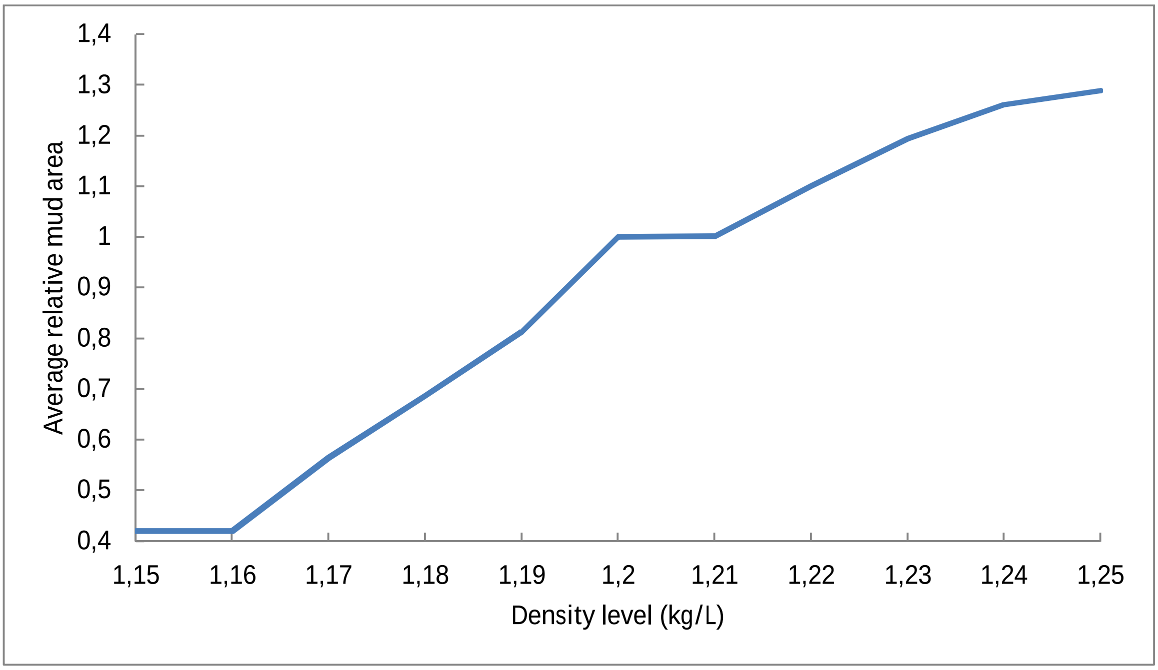


Figure 6.30 Relative mud areas averaged for all lines for each density level.

The depth levels of the various density layers determined by SILAS can be compared to the actual depths measured by the density tools. For each calibration point, the SILAS data point closest to this point was selected. From the different calibrations, the depth level of the density value concerned is extracted. Combining all depths of density levels (1.15 to 1.25 kg/L), a synthetic density profile is constructed, assembled from the different calibrations. The synthetic curves are plotted with the measured curves relative to the L1 level (D2Art) or the first reflector (SILAS) in Figure 6.31 for calibration line S4. The full results are shown in appendix G. In the SILAS processing, the algorithm is not able to cope with density inversions (i.e. density decreases with depth). Considering this, the fit for D041 and D044 is remarkably good. D043 is an example of a perfect fit. The fit for D045 is acceptable and for D042 is off. Differences in fit can be explained by the fact that the repeatability of the point measurements is not perfect. Moreover, for calibration, the fit of all calibration points is optimized, resulting in better and worse fits for the individual point measurements. The general picture of quality of fit (varying between good, reasonable and poor) is confirmed in the plots of all measured and reconstructed density profiles in appendix G. The plots are judged visually (Table 6.10): For the majority of density plots (71%) the form of the density profile is reconstructed well. The derived depths are reconstructed well for 44% of the cases and reasonably well for 27% of the cases.

Table 6.10 Quality of fit in percentage of the total of 75 point measurements between measured and SILAS reconstructed density profiles, based on visual inspection of the graphs.

	Good fit	**Acceptable fit**	**Poor fit**
Form of profile	71 %	17 %	12 %
Correct depth	44 %	27 %	29 %

The analysis of the calibration points on line S4 convincingly shows that the SILAS algorithm is able to track a desired density level for the majority of the point measurements of density. As shown above (Figure 6.29), this can be done with a resolving power of approximately 0.01 kg/L.

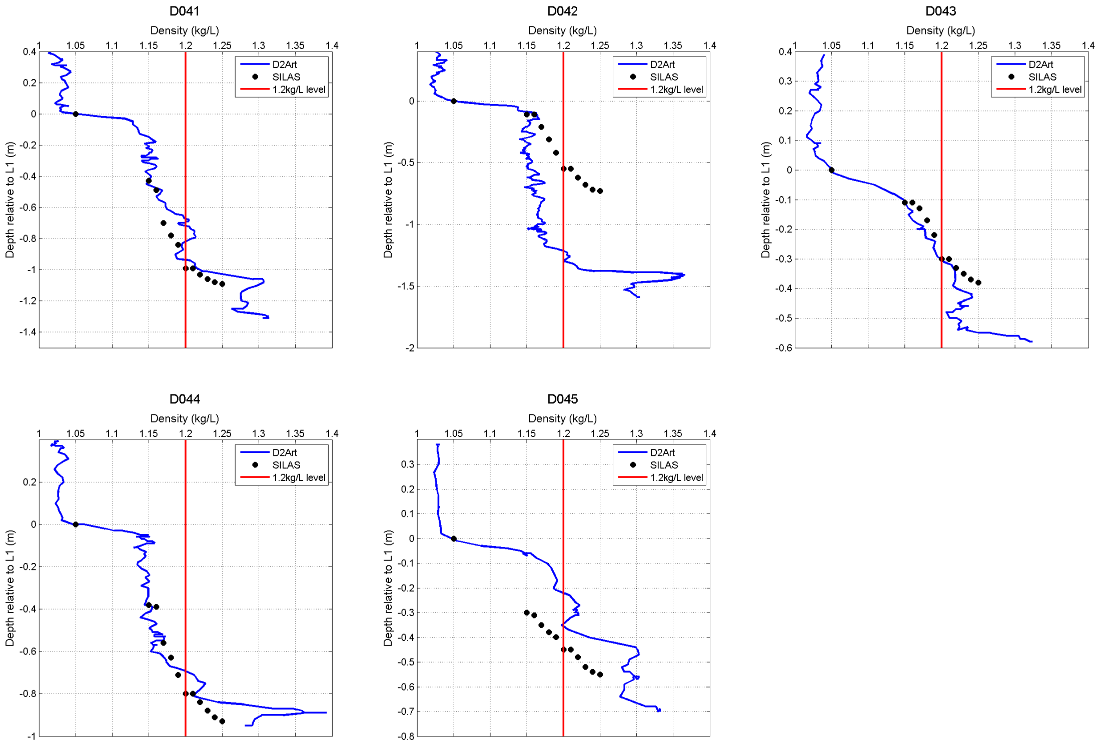


Figure 6.31 Measured (D2Art) and assembled synthetic density profiles from the 1.15 to 1.25 kg/L calibrations (0.01 kg/L steps).

6.3.5 Statistical analysis point measurements and SILAS density levels

The analysis in the previous section is based on the visual inspection of the measured density levels and the recovered density levels by SILAS. The visual analysis is supported by a statistical analysis in this section. This is done in several ways:

- Comparison of the depths of the various density levels relative to L1 (1.05 kg/L level) for each point measurement, by distributions, bias, root-mean-square-error (RMSE) and t-test.
- Comparison of the 1.2 kg/L depth relative to L1 for points included in the calibration and for points not included in the calibration for the various random data sets, by bias and RMSE.

Density levels

Each calibration of the density levels of 1.15, 1.16 etc. kg/L up to 1.25 kg/L results in the thickness of the mud up to that density relative to L1 for each of the point measurements (see appendix G). The distribution of thicknesses from the point measurements and those recovered from the SILAS calibrations is shown in Figure 6.32. From this figure it is clear that the two methods display comparable distributions of mud thickness for each density level.

The difference in depth between the two methods is calculated. The distributions are shown in Figure 6.33. All distributions of the differences are normally distributed around 0, except for the 1.15 kg/L level. For this level, the distribution is shifted to negative values.

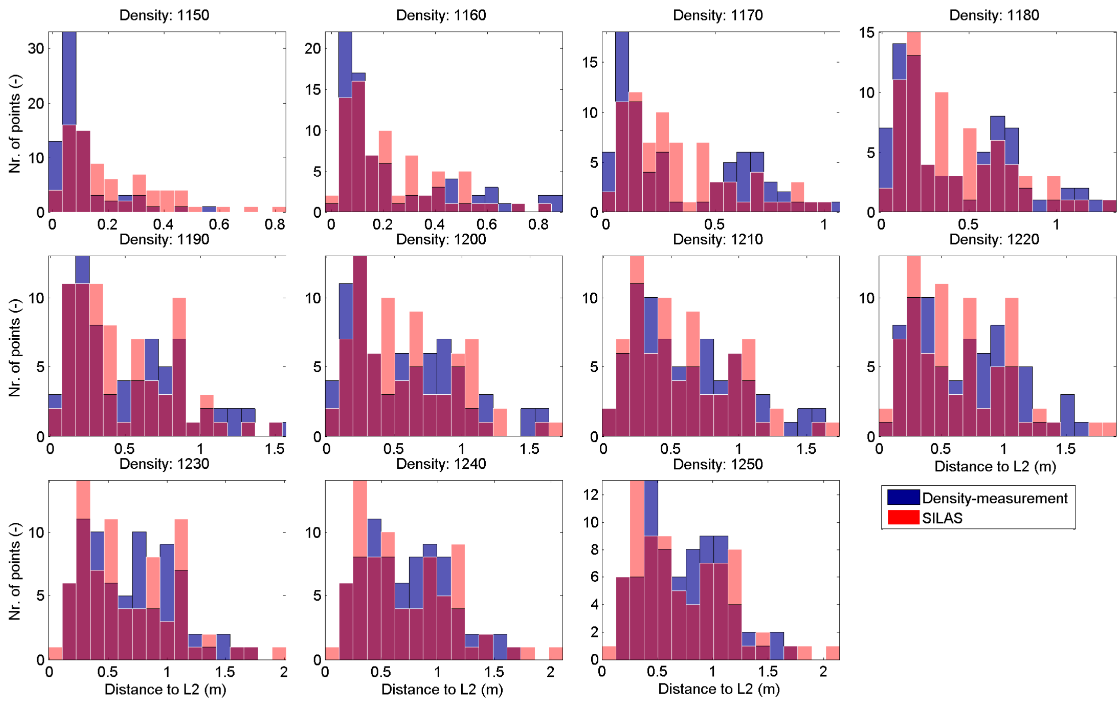


Figure 6.32 Distributions of mud thickness from the point measurements (blue) and derived from the SILAS calibrations for the sweep of density levels (red).

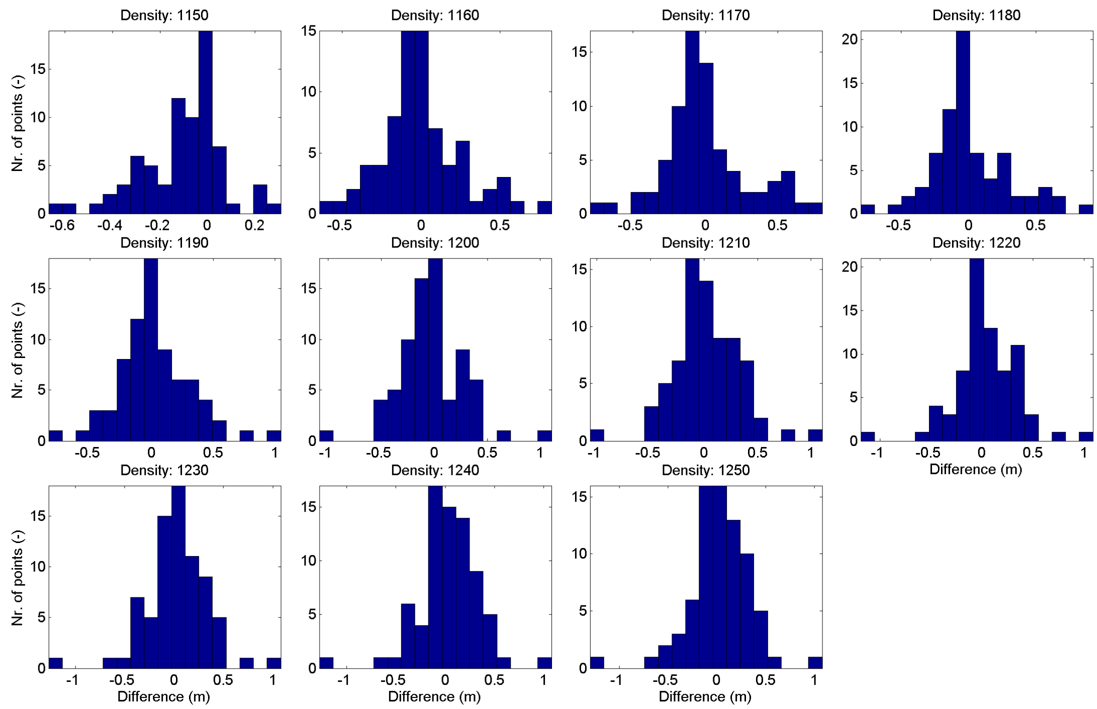


Figure 6.33 Distributions of the difference in thickness up to the specified density determined by the point measurements of density and recovered from the SILAS calibration of the corresponding density level.

Next, for each point location, the bias is calculated over all density levels. The bias is the average deviation between the thickness values determined by the two methods. The figures in Appendix G show that the difference between the two methods is sometimes positive and sometimes negative. If for one location, part of the density levels have a positive and part have a negative difference, the bias is small (e.g. for D044). Figure 6.34 shows the bias for all locations of point measurements. The bias is both positive and negative. Therefore, there is no systematic difference between point measurement and recovered levels from SILAS.

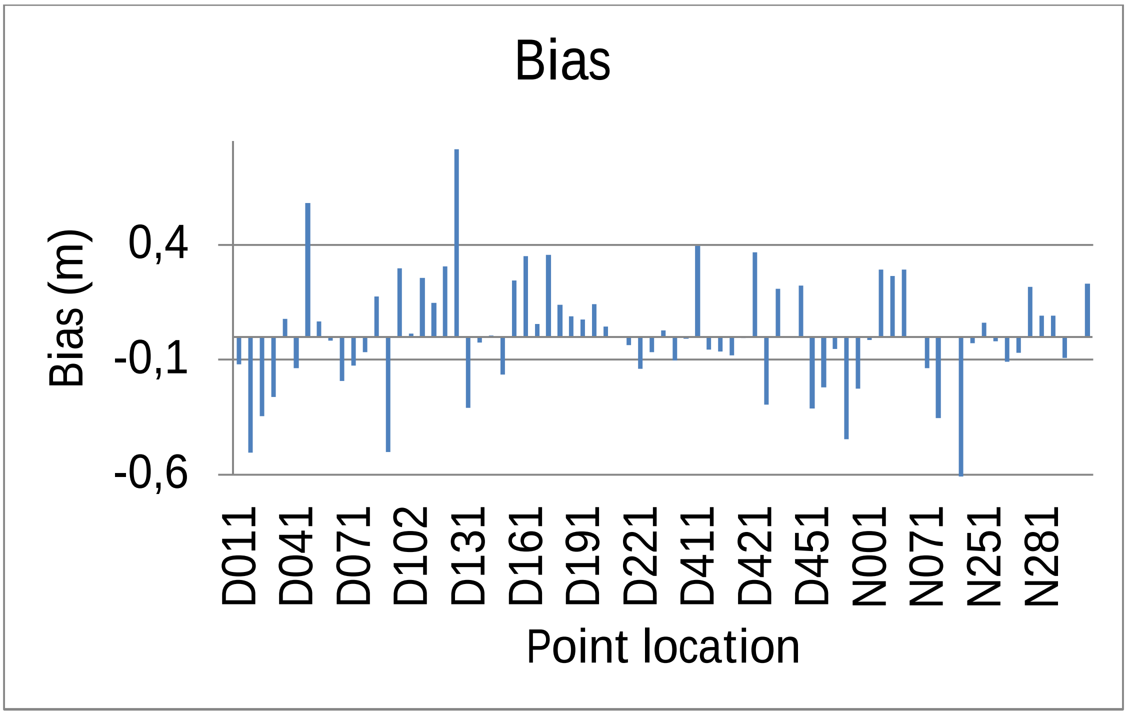


Figure 6.34 Bias of the all density levels (1.15 … 1.25 kg/L) for each location of point measurements. Not all labels are shown on the x-axis, whereas all values are displayed.

While the bias shows there are no systematic errors, the root-mean-square-error (RMSE) gives the (average) error between the two methods. For the calculation of the RMSE, the differences are first squared (so all values are positive), then averaged and the last step is taking the root of the average. The result is therefore a distance in meters. Figure 6.35 shows the RMSE for all locations of point measurements. The average RMSE for all 75 points is 23 cm. This means that the average difference of the various density levels and the density measurement (e.g. the black points and blue line in Figure 6.31) is 23 cm. Around half of the points have a RMSE value smaller than 20 cm.

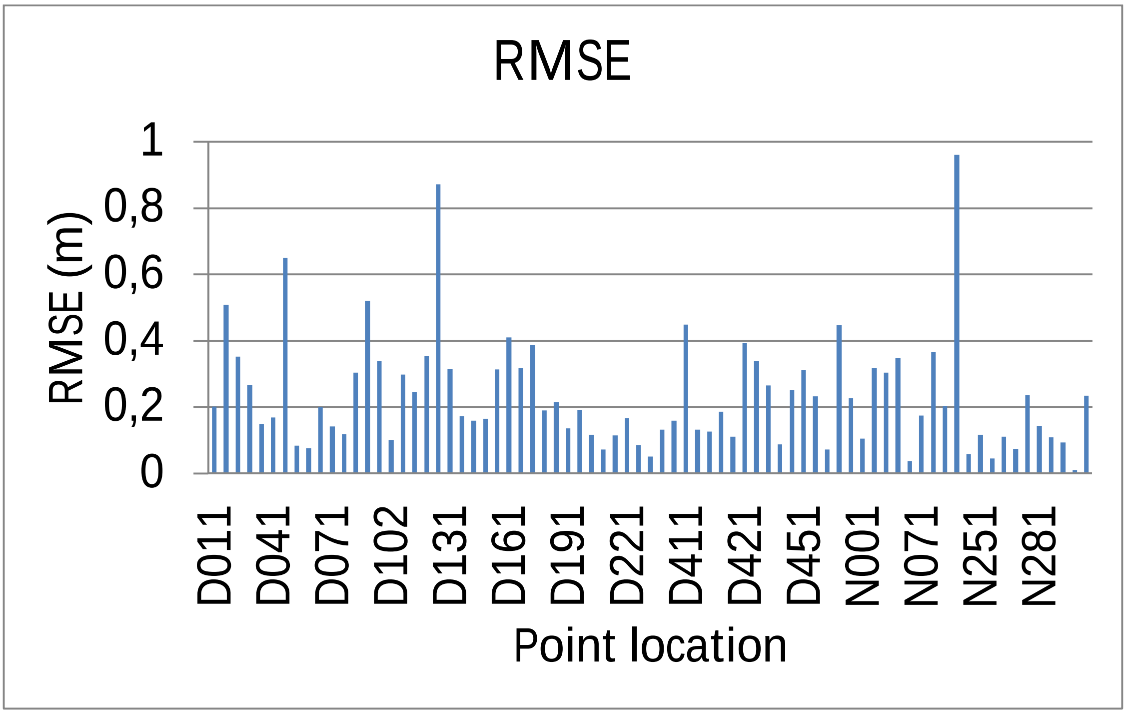


Figure 6.35 Root-mean-square-error (RMSE) of the all density levels (1.15 … 1.25 kg/L) for each location of point measurements. Not all labels are shown on the x-axis, whereas all values are displayed

To analyse whether the two methods give statistically comparable results, a t-test can be applied to the average thickness values. The null hypothesis of the t-test is that the averages of two subsets are equal. If the p-value (probability) is smaller than 0.05, the null hypothesis H_0 should be rejected. This means that the averages of the two subsets are statistically not equal. For each density level, the thickness distribution of the point measurements has been compared to that of the recovered SILAS thickness (Table 6.11). This is done for all 75 points and only for points that were included in the basic calibration (1200_25cm_5m_cum). The results are comparable for both analyses. The null hypothesis is rejected for the level of 1.15 kg/L only. This means that the results from the point measurements and the recovered level from SILAS are not the same for the 1.15 kg/L level. For all other density levels, the null-hypothesis is accepted. This means that there is no evidence to suggest that the two samples come from populations having different means.

Table 6.11 P-vales and results for the t-test (two-tailed, paired) performed for the distributions of thickness values from the point measurements and recovered thickness values from SILAS (using basic calibration, 1200_25cm_5m_cum). For all 75 points or for only those points included in the standard calibration.

	level (kg/L)										
Subset	1.15	1.16	1.17	1.18	1.19	1.2	1.21	1.22	1.23	1.24	1.25
All 75 points : p-value	0.00001	0.99	0.95	0.88	0.66	0.73	0.63	0.56	0.65	0.68	0.66
All 75 points : result	Reject H_0	Accept H_0									
Points of basic calibration: p-value	0.00150	0.25	0.19	0.27	0.24	0.70	0.31	0.30	0.47	0.52	0.50
Points of basic calibration: result	Reject H_0	Accept H_0									

From the analysis of RMSE values and the t-test of all density levels we conclude that SILAS is able to give the right level for desired density levels between 1.16 and 1.25 kg/L. SILAS can do this with a bandwidth of 23 cm (average RMSE) for this range of density levels.

Level of 1.2 kg/L

The statistical analysis has been extended to get a better grip on the errors of the 1.2 kg/L level. This level was investigated further, because of the relevance of this particular level for RWS. The main question in this part of the analysis is whether there are differences between the points used in the calibration and points not used in calibration. This analysis has been performed for all random data sets described in section 6.2.3.

Figure 6.36 shows the differences in the depth of the 1.2 kg/L level (relative to 1.05 kg/L or first reflector level) for points included in and excluded from the calibration. This figure shows that all differences are normally distributed around 0. There is no difference in distributions of point in or out of a calibration.

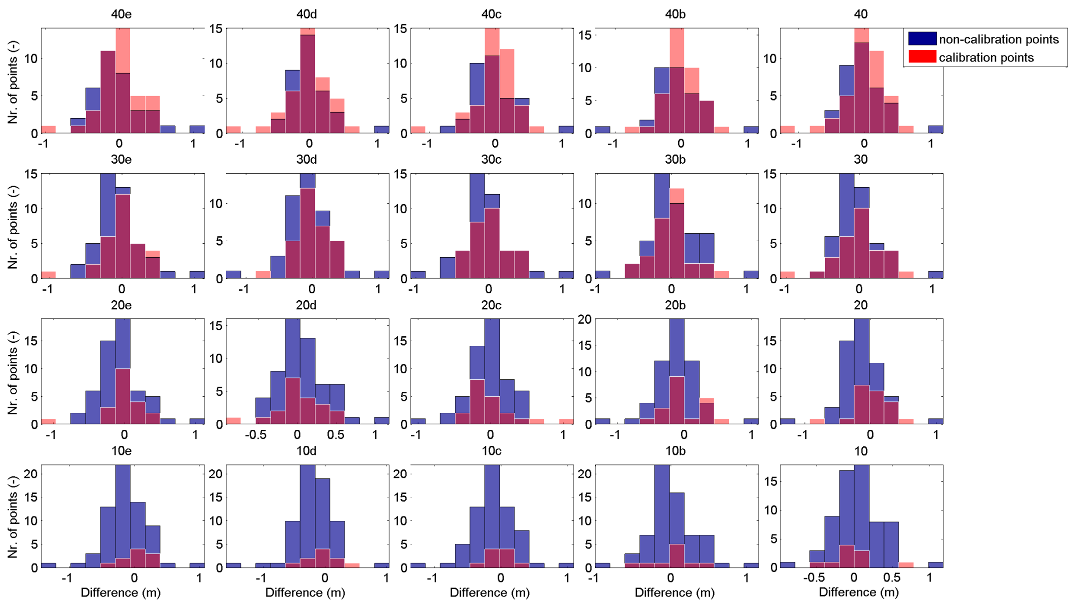


Figure 6.36 Distributions of the difference in depth of the 1.2 kg/L level (relative to 1.05 kg/L or first reflector level) from the point measurements and derived for the 1.2 kg/L level calibration using the random data set shown in each title of the graph. Red distributions for the points included in the calibrations; blue distributions for points excluded from the calibration.

Again, the bias was calculated. In this case for the 1.2 kg/L density level for

- all points used in calibration and
- for all points not used in that calibration. The result is shown in Figure 6.37. The bias is small (< 5 cm) for almost all calibrations of R40 and R30. The bias is larger (around -15 cm) for points not used in calibration for R20 and R10.

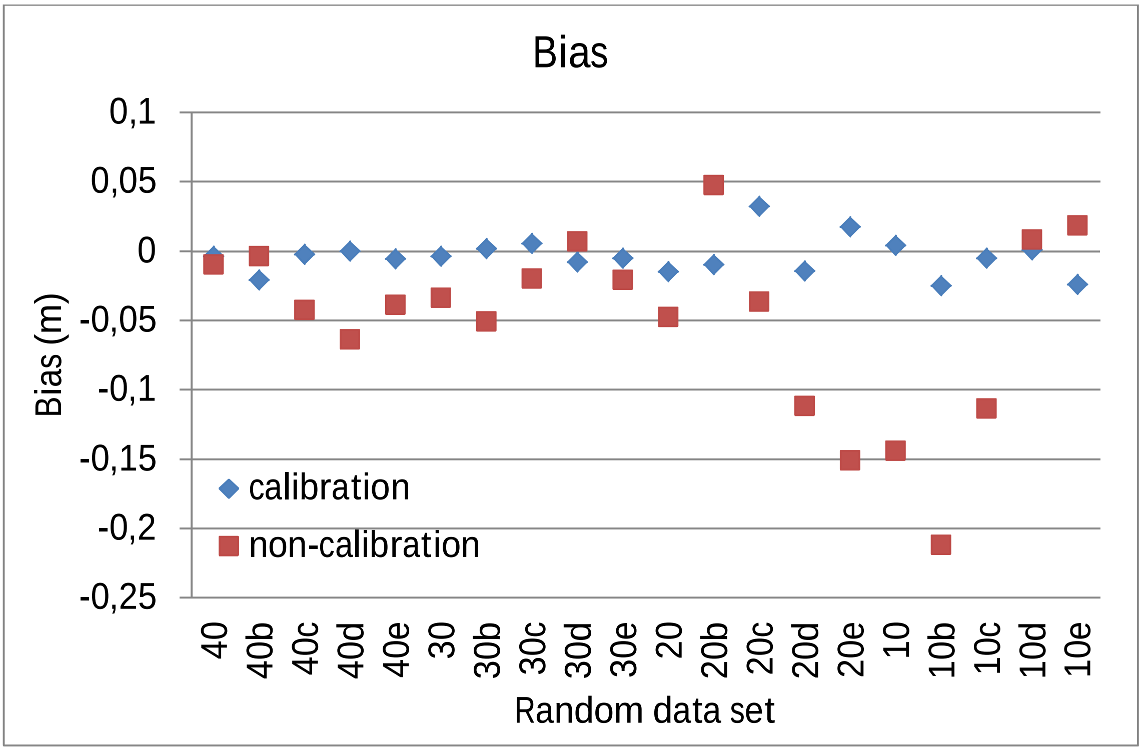


Figure 6.37 *Bias for the 1.2 kg/L level, defined as the total or average difference between the depth (relative to 1.05 kg/L or first reflector) from the point measurements and recovered from the SILAS calibration. For two subsets: points included in the calibration (blue) and points excluded from that calibration (red).*

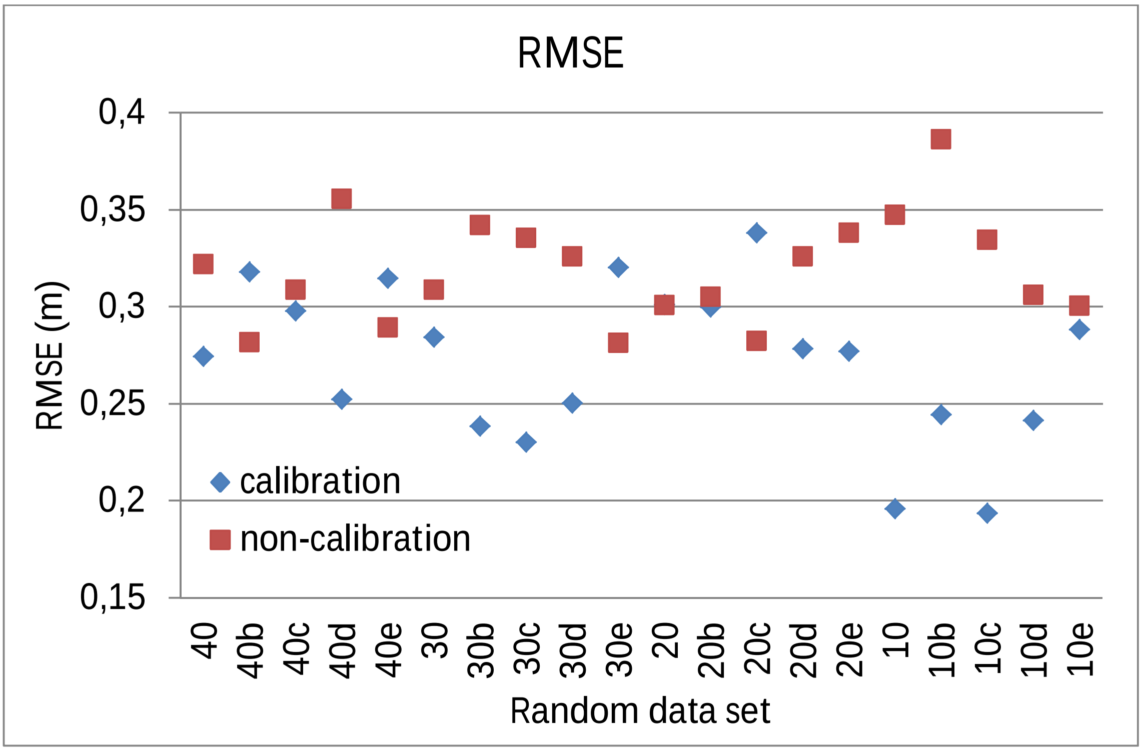


Figure 6.38 *Root-mean-square-error (RMSE) for the 1.2 kg/L level, defined as the total or average difference between the depth (relative to 1.05 kg/L or first reflector) from the point measurements and recovered from the SILAS calibration. For two subsets: points included in the calibration (blue) and points excluded from that calibration (red).*

Figure 6.38 shows the RMSE values for the 1.2 kg/L density level. For the R40 random data sets, there is hardly any difference between used and not used in calibration. For the other random data sets, the RMSE values are larger for the points not used in calibration. This is to be expected since the data is not calibrated on these points. Generally, the RMSE value is approximately 30 cm. This means that the 1.2 kg/L thickness can be determined by SILAS with a bandwidth of ± 30 cm. This level could be reduced when using better quality data for the calibration points (e.g. using DP).

The analysis of differences between NAP levels of L1 and the first reflector in SILAS (section 4.5), the clusters of closely located point measurements (section 6.1.1) and the statistical analysis (this section), all show variations RMSE values of around 30 cm for the differences between point measurements and SILAS. This suggests that the total bandwidth in depth or thickness of the 1.2 kg/L level is ± 30 cm.

6.4 Question 3: Error sources

Several error sources contribute to the bandwidth of the 1.2 kg/L density level determined by SILAS. The errors can be divided into these categories:

- Accuracy of measurements.
- Model assumptions.
- Processing assumptions.
- Dynamics of the mud.

Accuracy of measurements

The accuracy of the individual measurements adds to the total error. The sources are to be found in positioning, motion compensation, tide corrections, stability of acoustic systems and individual density profile measurements.

The positions are determined by RTK-GPS. With correct use of this system, accuracy is better than 10 cm in x, y and z (2 standard deviations). Positioning errors of the antenna can therefore be neglected.

The instruments that take the measurements are mounted on a vessel, and therefore move with this vessel due to pitch, roll and heave. In order to obtain the correct positions of all instruments at all times, these motions have to be corrected for using a motion sensor. For the acoustic systems (Multibeam, echosounder transducers), this is effectuated, so the positions are correct. For the point measurements, however, motions of the vessel during the measurement (up to 2 minutes) gives rise to errors in position of the instrument node, as well as of the measurement device at depth. Currents add to the uncertainty in position of the instrument at depth. Depending on the presence of dynamic positioning, the position of the vessel can be fixed within approximately 1 m (DP), or will drift several meters (no DP). For measurements with the D2Art, the accuracy of the position of the measurement at depth is estimated to be several meters. For measurements with the Navitracker, the accuracy is probably better, ca. 1 to 2 m due to DP.

The specifications of the Navitracker and the D2Art are given in Table 6.12. For the densities of mud considered here, the absolute error is approximately 0.006 kg/L, which is very small. The absolute error in depth for the D2Art is approximately 2 cm, which is slightly smaller than that for the Navitracker.

Table 6.12 Specifications of Navitracker and D2Art (provided by RWS).

Item	Navitracker	D2Art
Measuring volume horizontal	14 cm	14 cm
Measuring volume vertical	5 cm	2.5 cm
Drop speed	20 cm/s	20 cm/s
Accuracy in depth	5 cm	0.1% of depth
Accuracy in density	0.5% of density	0.5% of density
Update rate	6 Hz	6 Hz
Mass	200 kg	75 kg
Source	6 mCi Cs-137	10mCi Ba-133
Detector	40/35 Na(Ti) crystal	Scionix, model 30 BRS 30 / 1.1-HV-E3-BGO-X
Range pressure sensor	5 bar	5 bar

Multibeam systems have a standard quality control. In general, the errors in depths determined by echosounder are in the order of several centimeters. Echosounder depths are very sensitive to the settings of the instrument for digitization. The 200 to 210 kHz signals, with correct settings and sound velocity, have an accuracy of several centimeters.

Apart from the X and Y position of the density tools, the errors in depth are introduced by the conversion from pressure to depth. According to RWS, errors in depth are in the order of several centimeters. The accuracy of the density is not specified. According to RWS, the accuracy is high. Values of density measured by D2Art and Navitracker are considered to be true, without an error bar.

As show in section 4.3, the tide corrections pose another source of error. For the conversion of depth relative to the water surface to depth relative to NAP, a tide correction is necessary. Since SILAS uses depth relative to L1 and relative to the first reflector only, the effect of the tide correction is limited.

Model assumptions
The most important model assumption is that a desired density level gives rise to a reflection and therefore an acoustic impedance contrast that the SILAS algorithm can detect. In theory, this is a sound physical assumption as explained in the report “Plan van Aanpak voor de praktijkvalidatie van SILAS” (1206421-000-BGS-0012-v4-r, December 2012). In section 6.3.4 we demonstrate that SILAS can indeed detect density levels in the range of 1.15 to 1.25 kg/L for a significant amount of point measurements of density.

One of the model assumptions is the constant velocity of sound in water and the fixed offset in sound velocity in silt. In section 5.4 we showed that the effect of this is in the order of a few centimeters. Therefore, we consider this effect as insignificant.

Processing assumptions
In the preparation of the SILAS data for calibration, one of the operations is heave correction. Due to the absence of motion sensor data for the 38 kHz signal, heave had to be filtered out. In Figure 4.3, the heave movement is in the order of several decimeters. Visually, filtering seems work quite well. However, errors in depth due to filtered heave correction might be in the order of a few cm.

The type of calibration gives rise to variations in derived density levels for 1.2 kg/L. The gradient method was discarded in section 5.1.3. From the comparison between the cumulative model with and without vertical corrections (section 6.3.2) we conclude that the results are almost identical.

Another setting in the processing is the threshold value of the distance between the point measurements and the SILAS line. The threshold values of 1, 5 or 10 m to nearest SILAS line were tested in section 5.3. The threshold value of 5 m is a good compromise between the feasible distance while performing the measurement and the size of the dataset used for calibration.

Dynamics of the mud
In the Maasmond area, the mud is mobile due to currents, tides, etc. The analysis of multiple measured lines shows that the topography of the top of the mud and of the 1.2 kg/L level varies with time (section 6.2.1). For the same line, measured one day later, the differences in depth can be up to 20-30%. When the lines are measured consecutively, however, the differences in depths are probably due to errors in X and Y, rather than due to the dynamics of the mud.

The analysis of the time difference between the point measurement and the SILAS line used in the calibration (section 6.2.1), shows that the mud dynamics have a severe effect on the calibration and the derived mud areas. Therefore, it is recommended that the point measurements and the SILAS line should be separated by a short time, with a maximum of 2 hours. Earlier tests done by RWS, with point measurements on one day, and SILAS lines on the day after or before probably give erroneous amounts of mud.

Additionally, the topography of the top of the mud and the 1.2 kg/L level is variable. Even at one moment, the repeatability of the point measurements is low (section 6.1.1).

6.5 Question 6: Applicability of SILAS for RWS

Research question 6 is: How applicable is the SILAS system for measuring densities by RWS?

The SILAS acquisition and processing software has been demonstrated to be a reliable (within limits) and efficient tool for mud identification and estimation (section 6.3.4). The visual inspection of measured and reconstructed density profiles gives us confidence that SILAS can be used to obtain line data the 1.2 kg/L. This observation is supported by the statistical analysis. The results of t-tests for all calibration points comparing the average thickness of the density level measured by Navitracker/D2Art and reconstructed from the SILAS calibration show that SILAS is able to find density levels of 1.16 to 1.25 kg/L. Only for the 1.15 kg/L level the averages of the two methods are statistically different.

One of the assumptions in SILAS is that the density increases with depth. In some point measurements, inversions in the density profile are present. This means that the density sometimes decreases with depth. This pattern is visible in in only part of the points. Overall, the SILAS calibration does not seem to be affected by the density inversions.

The error in depth of the desired density level is influenced by several individual errors of measuring components (density probe, positioning, acoustics), variability of the bathymetry and mud distribution. The analysis of clusters showed that the individual point measurements have a standard deviation around 30 cm. This means that the points that form the basis of the calibration have a large error.

The analysis of the retrieved density level by SILAS show a similar RMSE, of around 30 cm. This means that the SILAS levels are determined with approximately comparable accuracy as the point measurements of density. SILAS, however, gives much more information on the spatial distribution of the 1.2 kg/L density level, because this level is determined on lines rather than on points.

The determination of economical impact of the accuracy level, or whether this is acceptable or not for RWS, is beyond the scope of this work. We believe that there are possibilities to improve the accuracy level, e.g. by using dynamic positioning.

To assure sufficient data quality and reliability, data must be acquired and processed according to the recommendations presented in the following section.

6.6 Question 7: SILAS in working process of RWS

Research question 7 is: How do SILAS measurements need to be included in the working processes of RWS?

The results from this study allow defining the optimal and most efficient procedure to be followed for acquisition and processing of data with SILAS. In this way, accuracy, efficiency and representativeness of the results are assured. The recommendations are divided into aspects of the acquisition procedure (section 6.6.1) and the processing procedure (section 6.6.2).

6.6.1 Acquisition procedure

Positioning issues
Coordinates of all systems should be registered using RTK-GPS or dGPS. The positions of the systems relative to the GPS antenna should be implemented so correct positions of all systems are reliable at all times. Particularly for the SILAS system, synchronization needs to be checked every couple of hours. This is to ensure that there is no time difference (which translates to a horizontal offset) between the SILAS data and the other systems.

For data quality, a ramp test, such is standard procedure in Multibeam acquisition is required. Sound velocity profiles need to be measured several times during the day. The standard Multibeam procedure for ramp test (with speed of 3 m/s) and number of sound velocity profiles can be applied to SILAS. No extra measurements are needed.

Data have to be corrected for tide and heave. Particularly for tide, a standardized and efficient method has to be developed: a local, reliable node on the vessel itself is suggested that is motion corrected. For heave correction, a motion sensor connected to SILAS would represent the optimal choice. In the case that a link between the motion sensor and the SILAS acquisition setup cannot be established, the swell filter available in SILAS processing represent an acceptable alternative. However, when the Corvus would be used in future for SILAS acquisition, it is strongly recommended to establish the link between the motion sensor and SILAS.

Quality of point measurements

The performance of SILAS is influenced by the quality of the point measurements used for calibration. For the best quality of the point measurements, it is recommended to collect them using dynamic positioning. The location of the point measurements should be as close as possible to the SILAS line, but surely within 5 m.

Multiple acoustic systems

For the Corvus, acquisition of SILAS and Multibeam can be performed simultaneously. There is no interference between the acoustic systems. For other vessels, it has to be checked whether SILAS and Multibeam show interference. If not, then efficient, simultaneous acquisition can be done.

However, there is a limitation in vessel speed. For Multibeam, the standard survey velocity is 4 m/s. For SILAS, this is too fast. For good quality data on both systems, with sufficient detail, a maximum survey speed of 3 m/s should be used. If surveyors chose to operate on 4 m/s velocity, horizontal resolution of SILAS data decreases.

Survey speed during measurement of regular SILAS lines and SILAS lines for calibration should be equal, to minimize the effect of differences in squat of the vessel.

SILAS acquisition for calibration

In order to select good locations for point measurements, i.e. locations with a constant and sufficiently large (> 0.25 m) thickness of mud, it is recommended to first measure the entire area with a regular grid of SILAS lines and subsequently measure SILAS calibration lines. After SILAS measurements of the entire survey area, an indication of mud presence and thickness can be obtained using an old calibration file. Based on this, the locations of the point measurements can be properly chosen. After determination of the locations of the point measurements, SILAS calibration lines of should be acquired using the following procedure.

The standard procedure in the selection of location and measure of density is the following:

1 Measure a SILAS line (a-line);
2 Visualize the acquired line and select approximately 5 locations where mud is clearly present. The locations should preferably be chosen where bathymetry is flat and mud thickness is uniform. In SILAS, use the target function to obtain the coordinates of those points;
3 Transfer the target file to Quinsy;
4 Maneuver to the coordinates of the targets, within 5 m. Perform the density measurements on those points;
5 Re-measure the SILAS line acquisition along the exact location of the density measurements location (b-line); Both a and b-lines are input for the calibration.

This entire procedure should be concluded as soon as possible; mud conditions and distributions are variable due to changes in tide, ship traffic and current. A total duration of 2 hours is suggested for this procedure. In this SILAS study, the measurement of a SILAS line of approximately 800 m, 5 point measurements, a sound velocity profile and the repeat measurement of the line could generally be finished within 2 hours. This time limit is a best estimate based on experience during the project and on tide cycles.

Particular care should be paid to avoid data gaps in the SILAS line. If there are frequent data gaps (exceeding more than 5-10% of the total length), the acquisition of (part of) the line should be repeated.

Number of point measurements
For the survey area of this SILAS study, a total number of 30 locations for density measurements is suggested. For the entire Maasmond area, the representativeness of the point measurements needs to be checked in a survey of the entire area. The distribution of the locations should be spatially equally distributed. The full dataset of the standard 62 point measurements usually done for mud thickness determination can be used for that purpose. A similar procedure of randomly selected point measurements with smaller amounts (section 6.2.2) can be used to determine the optimum number of data points for the entire Maasmond area (and for the IJmond area as well).

6.6.2 Processing procedure

Heave correction should be implemented either using true heave (preferably) or using the swell filter. Tide corrections should be inserted from a reliable and smooth tidal curve.

For time to depth conversion, SILAS needs one single value for sound velocity in water. It can be obtained by averaging all sound velocity profiles over the full depth range for the particular day. In SILAS no correction, other than the standard one that is implemented in SILAS, is needed for the silt velocity.

When selecting the density measurement dataset, there is no need of any threshold for minimum mud thickness. However, a threshold of 5 m as maximum distance to the nearest SILAS line (a-line or b-line) should be employed. This value represents an acceptable trade-off between accuracy of the density measurements and abundance of available points.

The calibrations should be carried out with the ‘cumulative method’, without vertical corrections. The advantage is that inaccuracies in the point measurements are averaged out.

During processing, data gaps in SILAS need to be handled manually. This is for both the “bottom” layer (first reflector) and for the determined density level. For the “bottom” layer, this needs to be done for all files, since it affects all processing steps after auto-tracing of the first reflector. For the desired density level, it is best to fill the data gap with data from an overlapping line. If this is not available, it is suggested to fill the data gaps with a straight line for the density level (linear interpolation).

Any density level from 1.16 to 1.25 kg/L can be extrapolated in SILAS. When extracting the 1.2 kg/L level after calibration, an accuracy of 0.01 kg/L is expected.

From this single survey, we cannot determine the validity of the calibration file over time. For example, it is not known yet whether the calibration file is valid for one week, one month or longer. This means that when RWS starts using SILAS in their operational process, for each survey a calibration needs to be performed. When the variations in ‘arrival power’ over time prove to be small, the performance of a calibration might be limited to once every few surveys.

6.7 Question 8 Applicability of acoustic techniques for density levels

Research question 8 is: What is the applicability of acoustic techniques for the determination of density levels? What are the possibilities, bottlenecks, assumptions and uncertainties?

From a theoretical point of view, acoustic impedances are caused by changes in density and/or velocity of sound. As stated in the report “Assessment SILAS systeem - Onderzoek naar bepaling van slibdichtheid met een akoestisch systeem” (1205574-000-VEB-0001, February 2012), it was expected that an acoustic system such as SILAS could theoretically be able to determine a density level provided that a reflection occurs at that density level. In the current validation study of SILAS, it is shown that this acoustic method using a penetrating echo sounder, together with point measurements of density and the calibration procedure is able to determine a certain density level, in this case any level from 1.16 to 1.25 kg/L.

As demonstrated in this work, the mud thickness can largely vary due to its high dynamicity in intertidal area. For this reason, the spatial representativeness of density measurements is rather low. Therefore, the use of acoustic data represents an added value for constraining the density data. Using the cumulative method, small spatial deviations at the point locations are averaged out.

It is expected that any acoustic system with a constant signal that penetrates the mud up to the desired density level and with sufficient vertical resolution can be employed for the determination of a certain density level. Calibration of the acoustic system with point measurements of density is always necessary to link the acoustics to the density. The reliability of the results is mainly controlled by the accuracy of the calibration that relates the density measurements and to the acoustic one.

For an acoustic system, different from SILAS, it should be demonstrated that the results from the calibration are statistically comparable to the point measurements used in the calibration in a similar fashion as is done in section 6.3.5. Moreover, the optimal number of calibration points should be assessed using tests of various numbers of randomly selected point measurements (section 6.2.3).

For any acoustic system, the same limitations hold as for SILAS: the bandwidth of the density level is related to the quality of the point measurements used for calibration and their representativeness in space and time. Moreover, our recommendations for SILAS are applicable to any other acoustic system used for density determinations.

The general advantage of using acoustics and point measurements is to merge two different, independent but related types of data. The point measurements of density assure reliable, one dimensional information while the acoustic data allows a larger, time-effective spatial 2D or 2.5D (close grid of 2D) coverage of the survey area.

7 Conclusions and recommendations

7.1 Conclusions

The aim of the validation study is to determine whether the SILAS acoustic system is able to detect density levels of mud (in this case 1.2 kg/L) within an acceptable bandwidth. If so, the recommendations for the reliable and efficient use in standard RWS operations need to be provided.

A total amount of 131 SILAS lines and 75 density point measurement of density were acquired in a 7-day long survey in the Maasmond area in the Rotterdam Harbor.

The SILAS data were processed (chapter 4) applying tide correction (based on the Qinsy positioning record), swell filter to remove heave effect on the data and a time shift (only necessary for the first day of survey).

Several datasets have been used for calibration in order to give answers to the questions posed by RWS concerning accuracy and representativeness of density measurements in space and time (section 6.2). The most important conclusion derived from these answered questions is that SILAS is able to track density levels from 1.16 to 1.25 kg/L when using a sufficient amount of point density measurements with the same level of accuracy as the individual point measurements.

The bandwidth is composed of two parts: related to density and to depth levels. The resolving power of detectable density in SILAS is 1.2 ± 0.01 kg/L. The error in depth is estimated in several ways. The standard deviation in D2Art thickness for the closely spaced points in the clusters is approximately 30 cm. This is related to the steep gradient in 1.2 kg/L level at the locations of the clusters. The root-mean-square-error (RMSE) of the depth level of 1.2 kg/L determined by point measurements and recovered from SILAS after calibration is approximately 30 cm. The level of accuracy of the 1.2 kg/L level determined by SILAS could be improved by reducing the uncertainty in point measurements used for calibration. It is important to strain that point measurements of density remain necessary for calibration purposes.

When using SILAS, however, the number of point measurements can be decreased while the amount of spatial information of the 1.2 kg/L density level can be increased significantly, since SILAS is able to provide information (on lines) between the point measurements.

Additionally, we conclude the following from the test calibrations:

- Digitized 200/210 and 38 kHz echosounder reading do not provide a useful indication of mud thickness (section 4.6).
- No correction for the sound velocity in silt is needed, other than the standard one provided by SILAS (section 5.4).
- The cumulative method for calibration, without vertical corrections performs best for the study area. A threshold of 5 m to the nearest SILAS line was used (sections 5.3 and 6.3.2).
- Mud thickness varies considerable within 8 m deduced from the clusters of closely spaced point measurements. The spatial representativeness of point measurements is therefore limited (section 6.1.1).

- The calibration procedure for one line, including point measurements of density and acquiring SILAS data, should be completed within 2 hours. This time limit is based on project experience and tide cycles. Data from SILAS and point measurements one or several days apart should not be used in calibration (section 6.2.1).
- 30 data point measurements of density for calibration suffice for the test area (section 6.2.2). This is roughly one point per 2 hectare, but points are unevenly spatially distributed due to mud thickness variations.

7.2 Recommendations

The recommendations are given in section 6.6. They are summarized below:
- Need for adequate positioning, motion sensor and tide information.
- Simultaneous acquisition of SILAS and Multibeam is possible if no interference occurs and with a survey speed of 3 m/s (on Corvus).
- Standard quality control procedures for Multibeam (ramp test, sound velocity profiles) suffice for SILAS.
- The acquisition of one calibration line (including both SILAS and point measurements) should be finished within 2 hours.
- Improvement of the quality of the individual point measurements of density, e.g. using dynamic positioning.
- The optimum number of points for the test area is 30. The optimum for the entire Maasmond area and the IJmond area needs to be established. However, we expect that this needs to be determined only once.
- The validity in time of one calibration needs to be established. This means that when RWS starts using SILAS in their operational process, for each survey a calibration needs to be performed. When the variations in ‘arrival power’ over time prove to be small, the performance of a calibration might be limited to once every few surveys.
- Average sound velocity in the water is determined over the entire depth range for all sound velocity profiles measured on one day. Heave and tide data need to be implemented in the processing.
- For calibration, the threshold distance of the point measurement to the nearest SILAS line is 5 m. SILAS a-lines and b-lines are used in calibration; lines that are measured earlier or later are not used in calibration. The cumulative method is used, without vertical corrections.
- The acquired calibration file can be applied to all SILAS lines. This results in 2D data of the 1.2 kg/L level. The conversion of these 2D data to a 3D interpolation of mud thickness falls outside the scope of this validation study. Due to the presence of dredging tracks in the Maasmond, the correct interpolation to a 3D image of the mud thickness requires a study in itself.

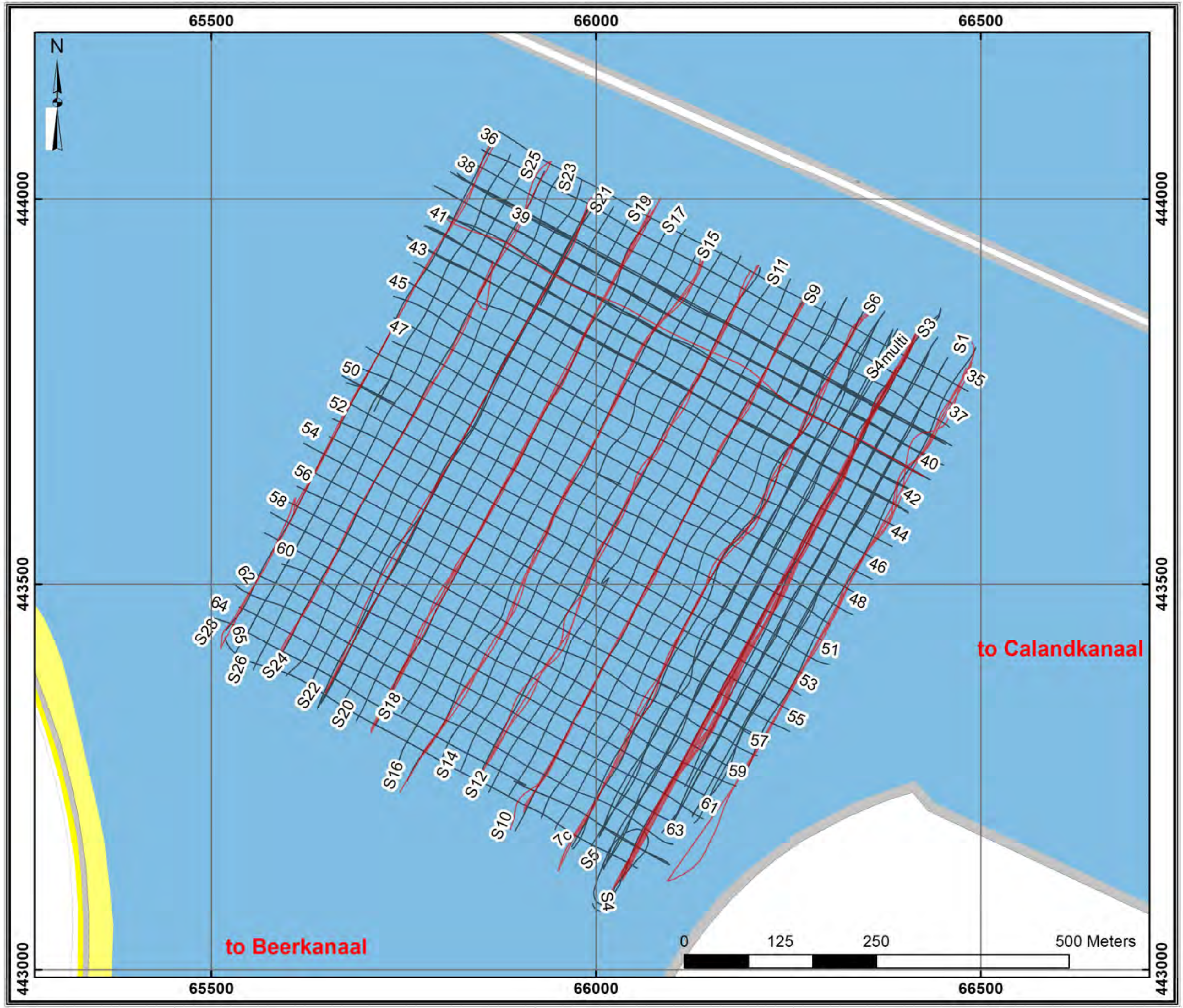
A Overview of survey lines and point measurements

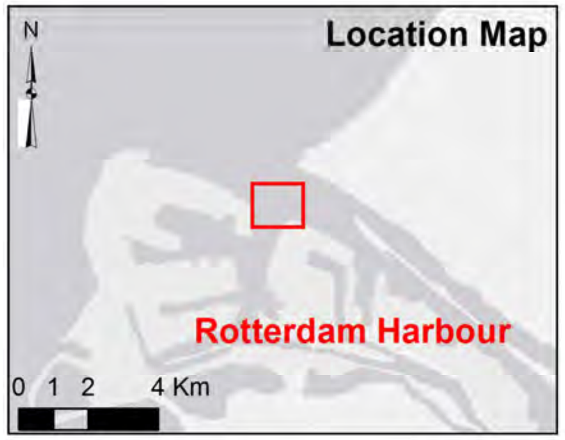
Including maps op A3 of:

- Location of SILAS lines;
- Distribution of measurement tools;
- Distance of point measurement to closest SILAS line;
- Location of point measurements used in basic calibration;
- Location of point measurements included in the random data sets;
- Location of point measurements with ‘thin’ or ‘thick’ mud layer.

Position of SILAS-lines

project nr: 1207624





Legend

- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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Measurement instrument

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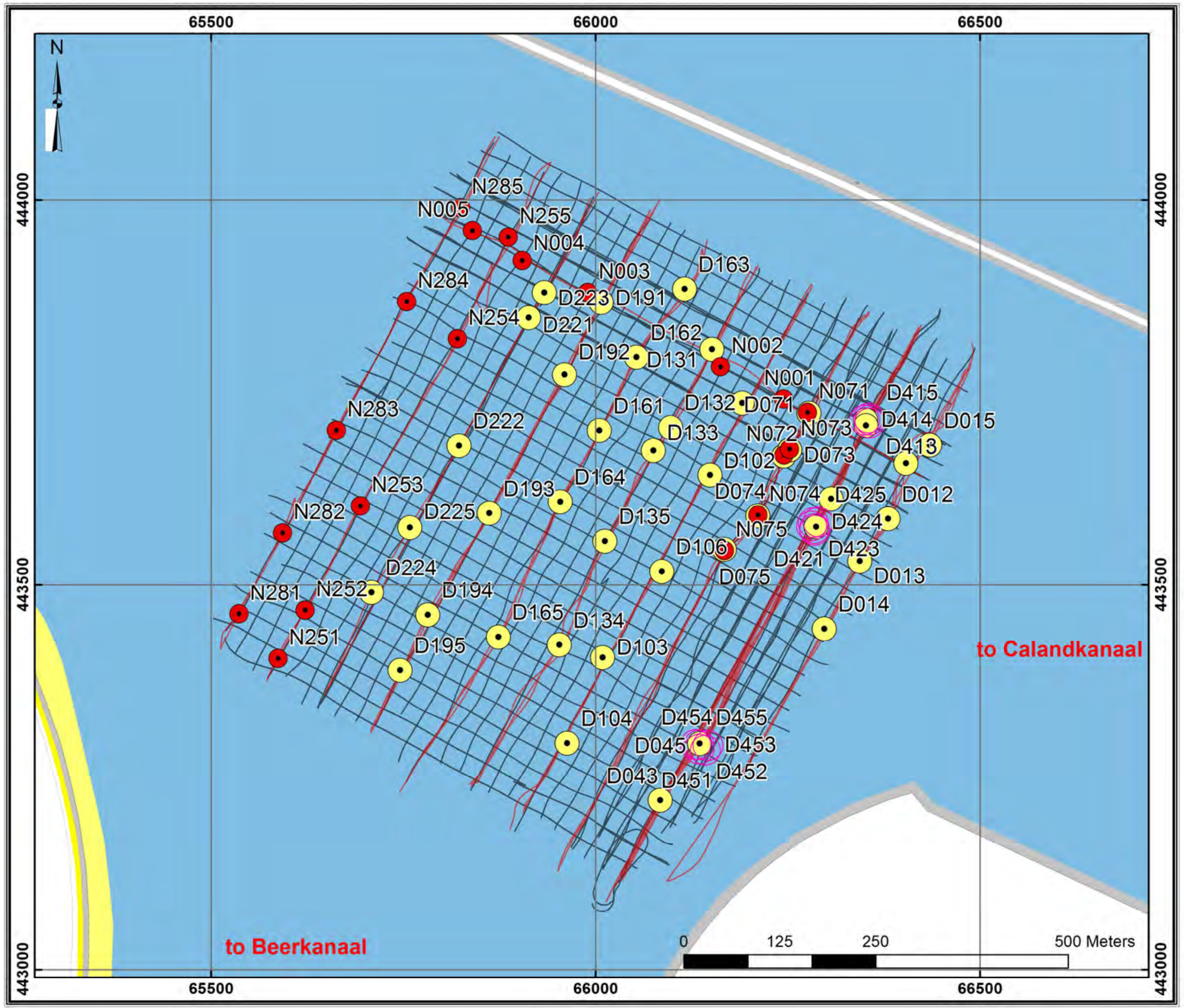

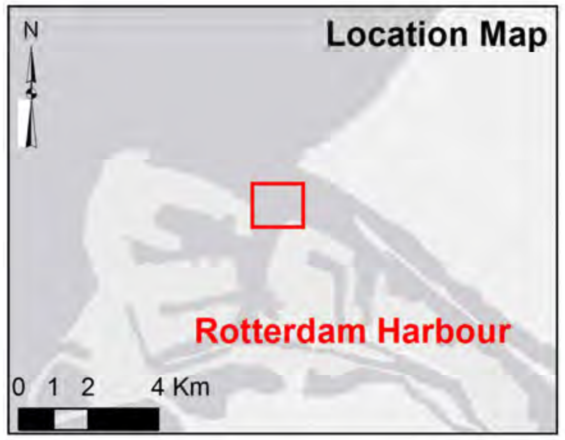

Legend

Measurement instrument

- D - D2Art
- N - Navitracker
- DC - D2Art clusters
- Calibration-lines
- SILAS-lines

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Distance to calibration line

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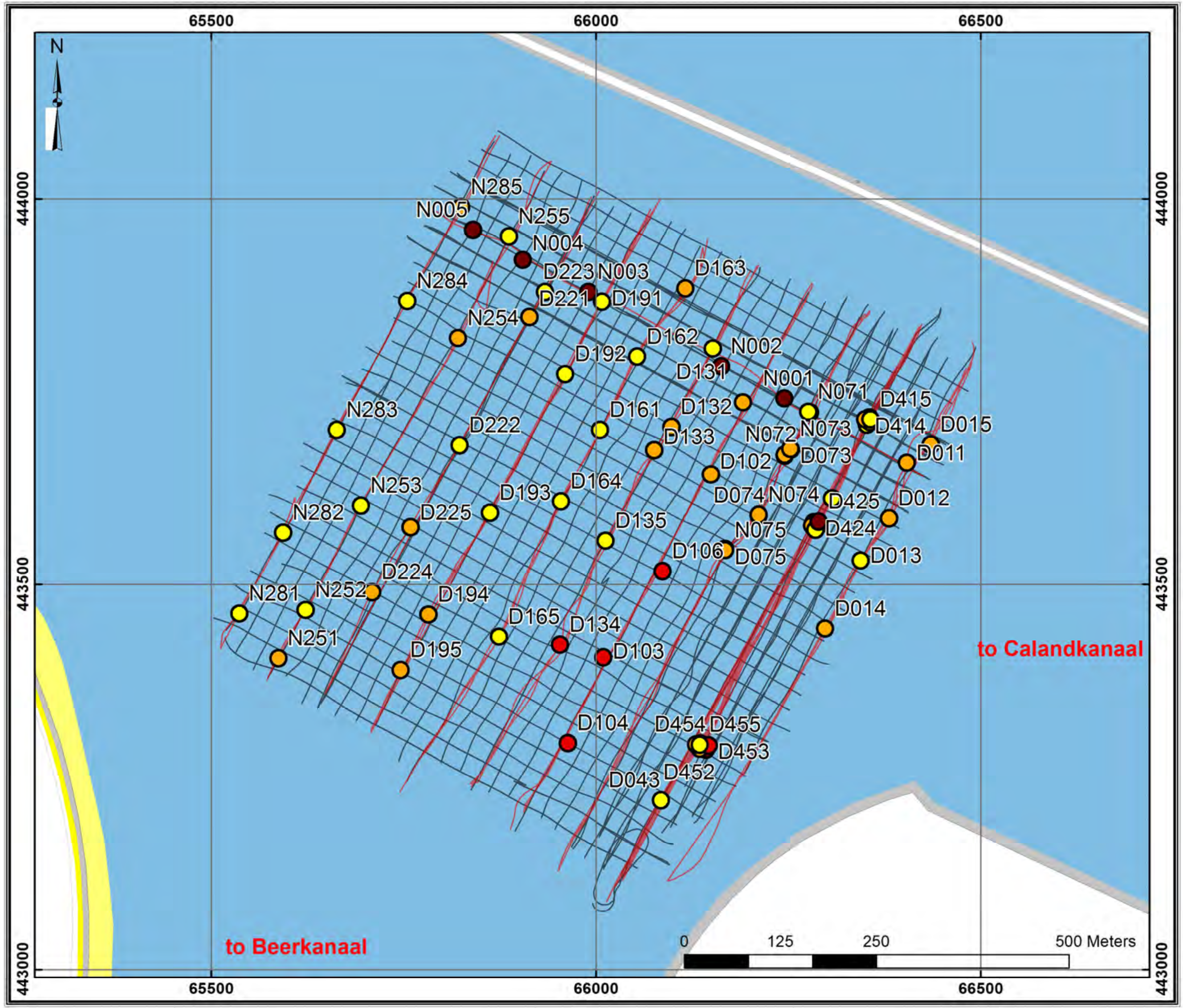

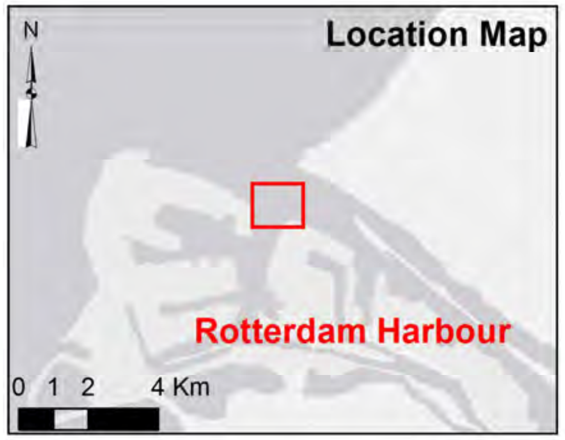

Legend

Distance to calibration line (m)

- < 1.0
- < 5.0
- < 10.0
- > 10.0
- Calibration-lines
- SILAS-lines

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Locations used for the basic calibration

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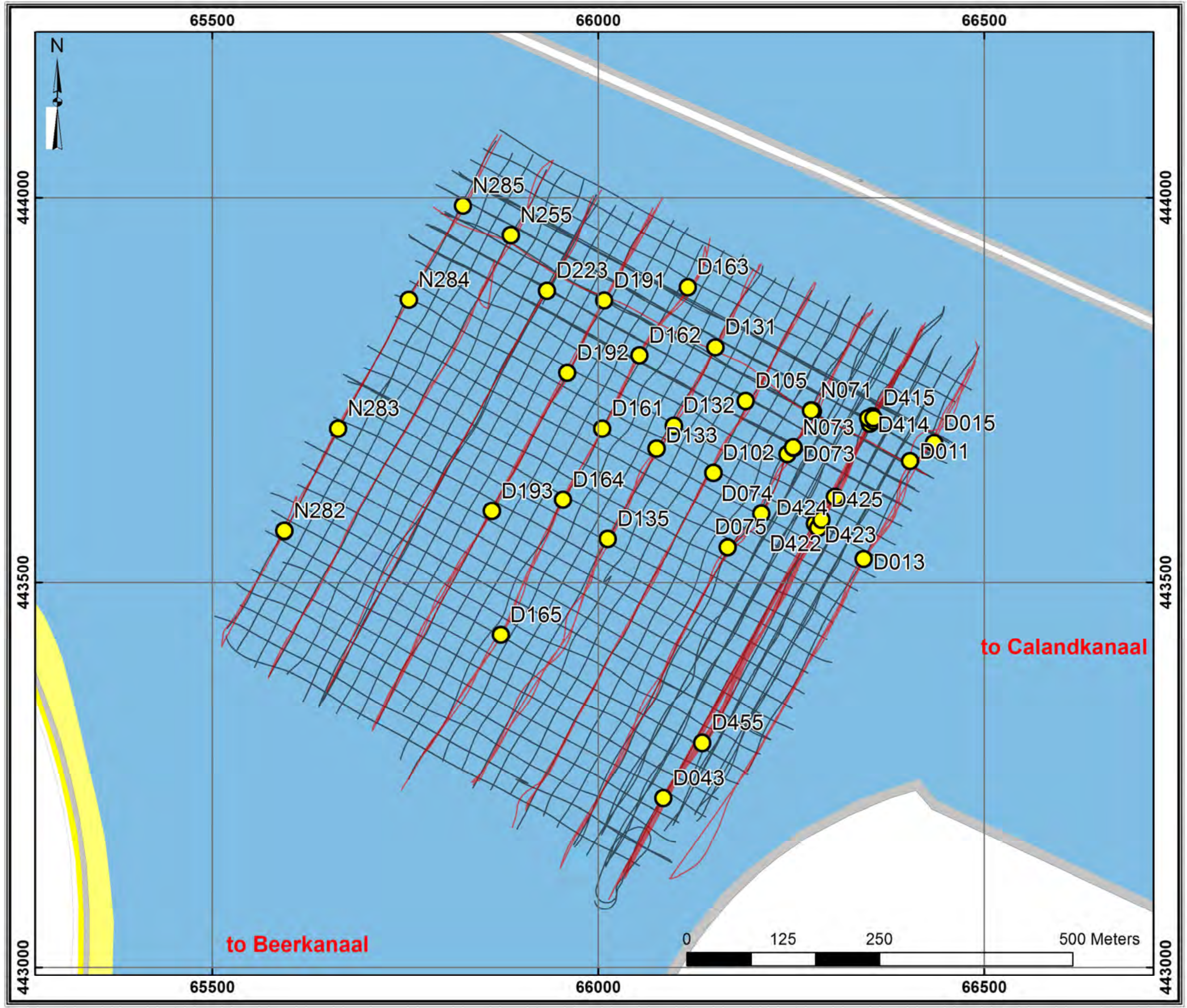

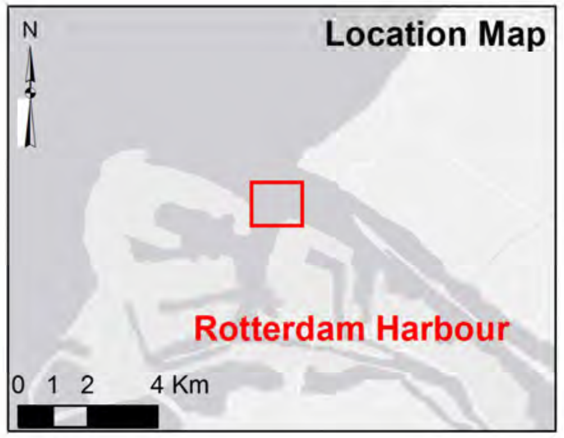

Legend
- Density measurement
- Calibration-lines
- SILAS-lines

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Locations used for r40 reflector

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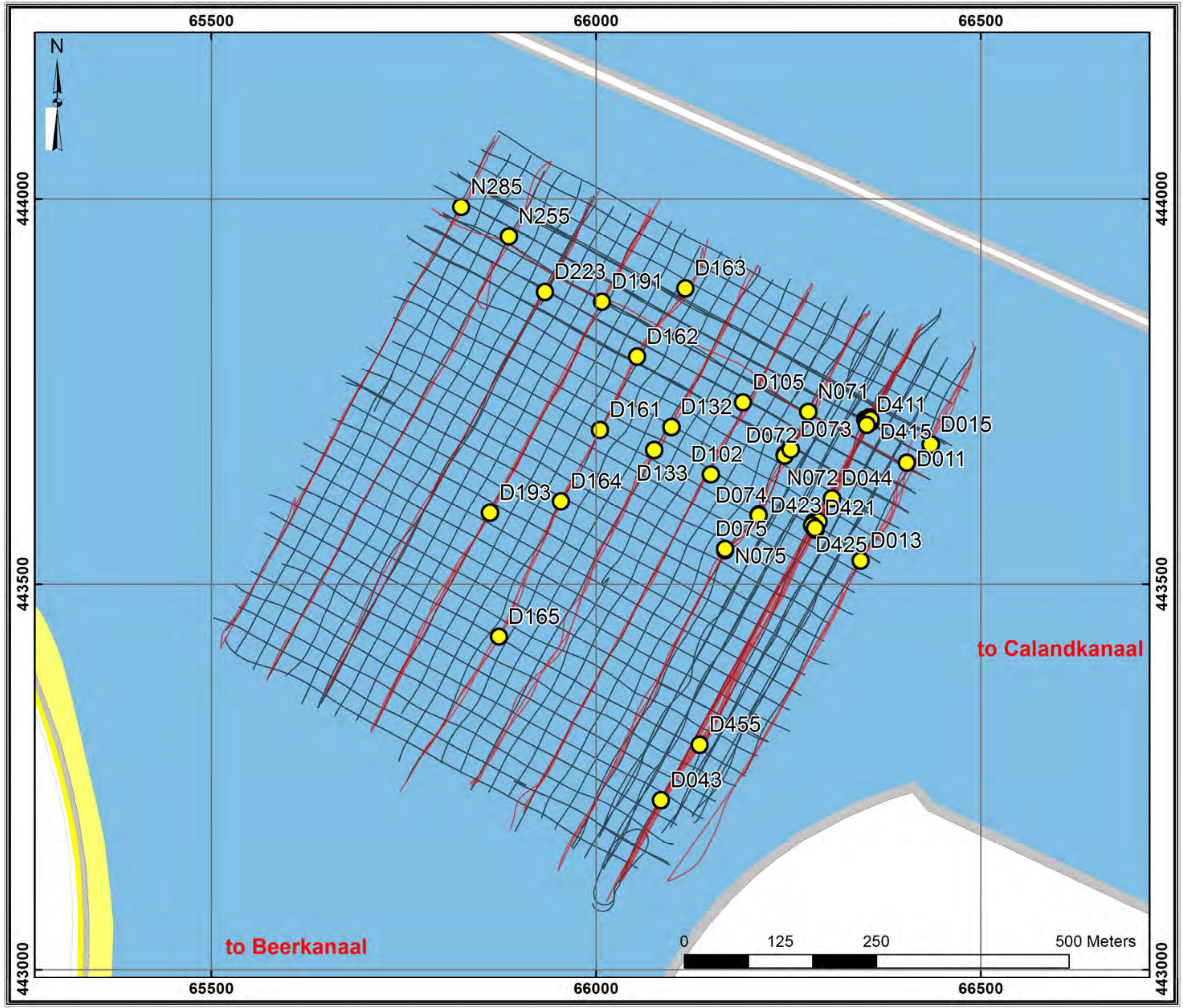

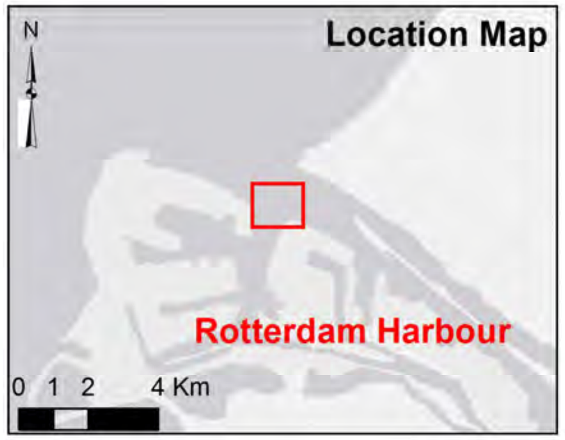

Legend

- Density measurement
- Calibration-lines
- SILAS-lines

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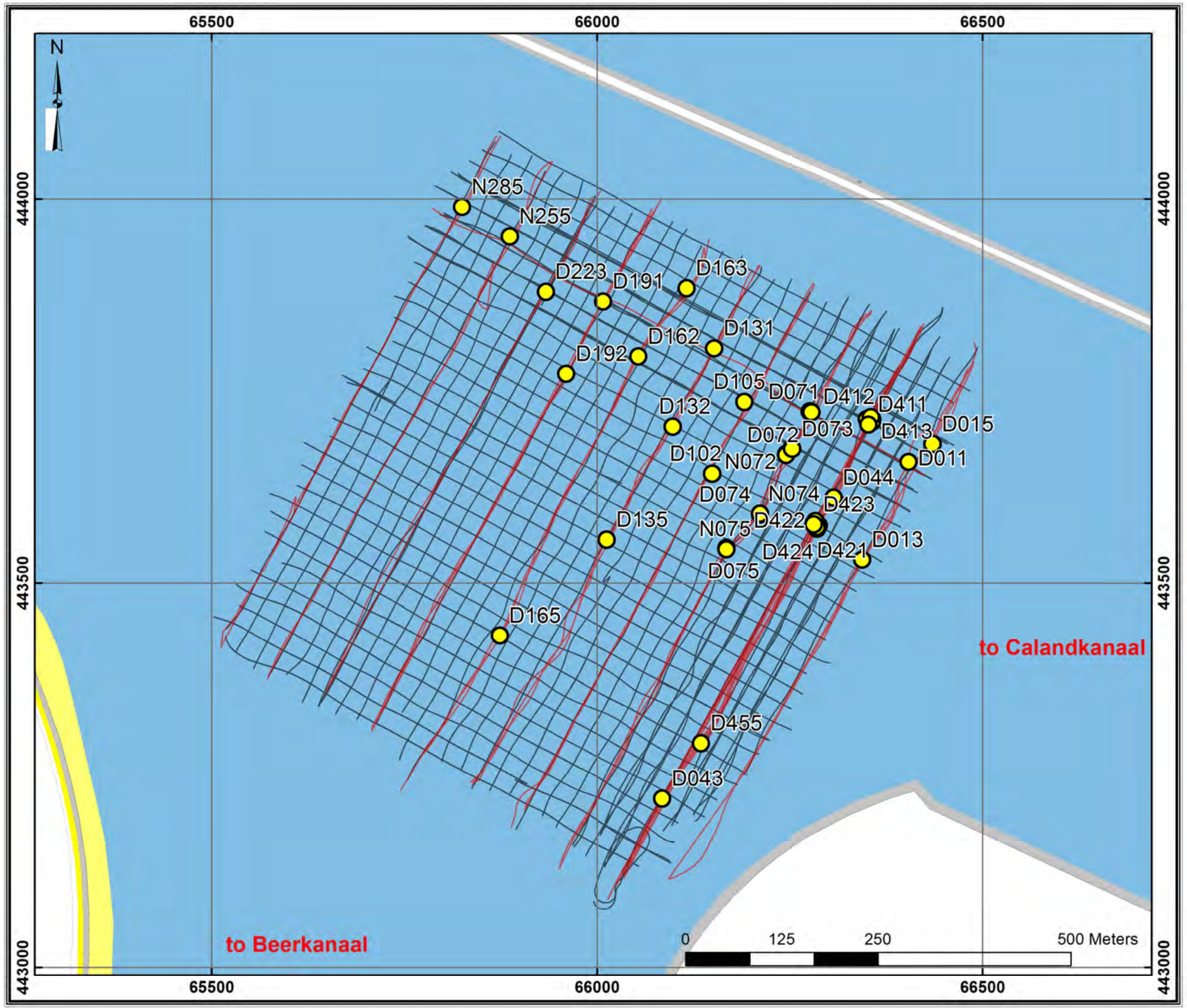
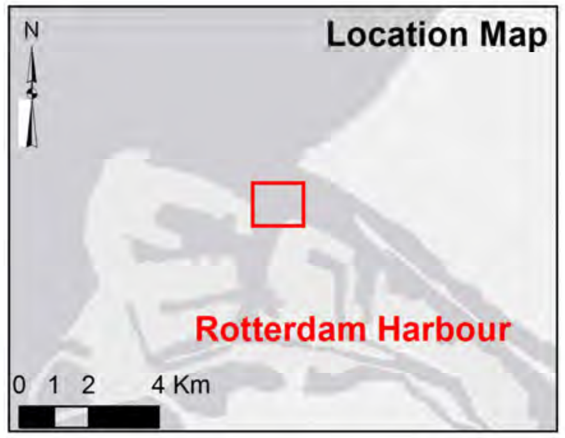
Locations used for r40b reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

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Locations used for r40c reflector

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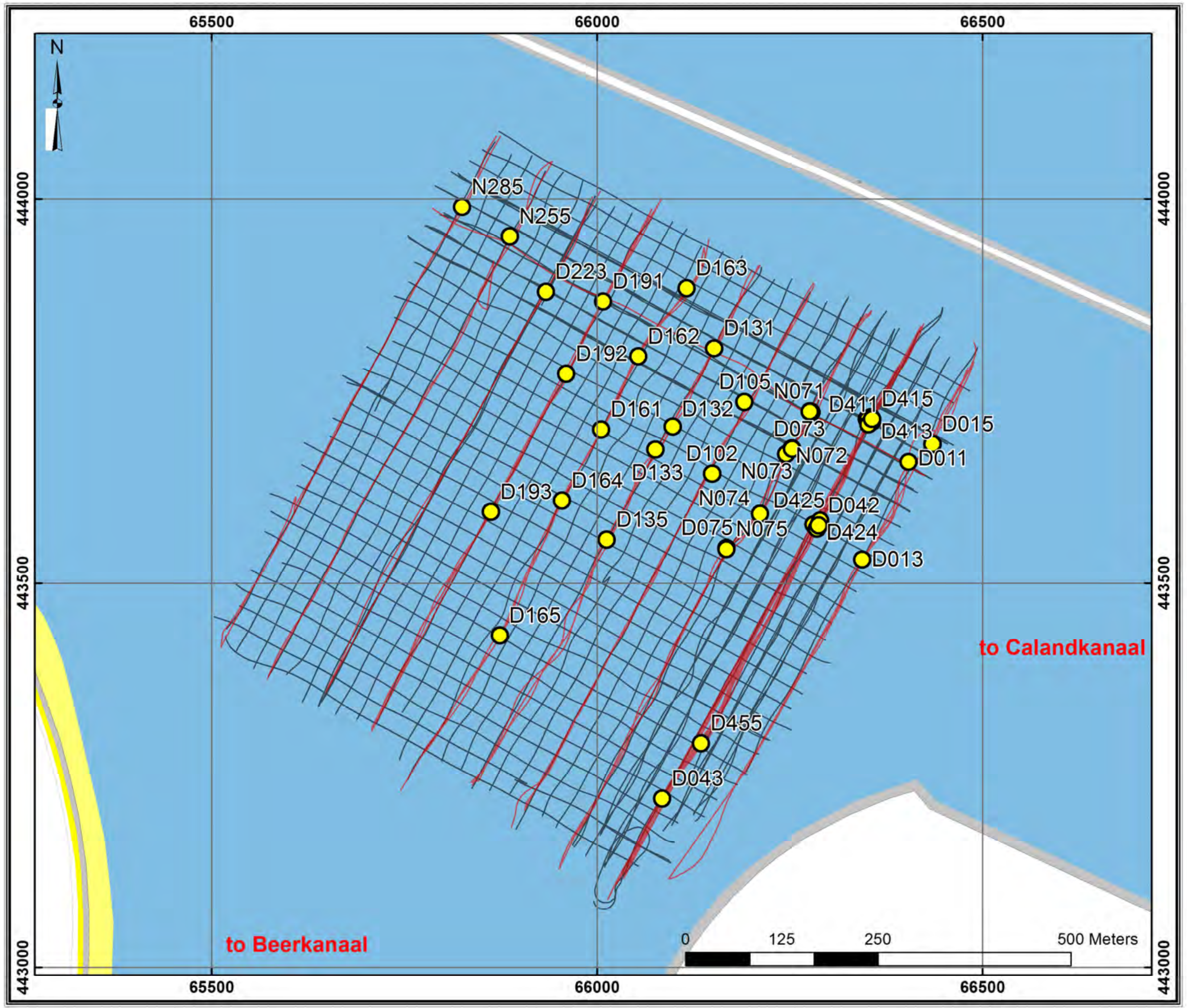

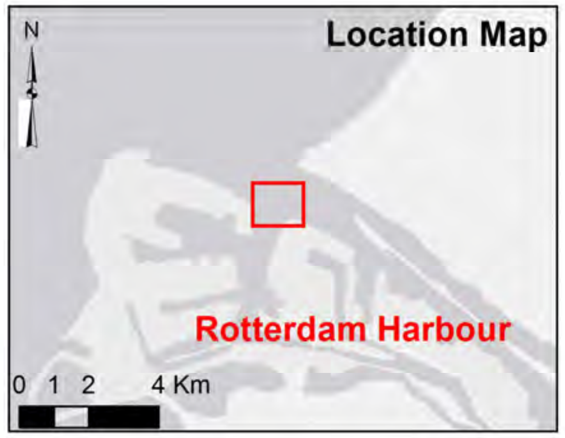

Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

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Locations used for r40d reflector

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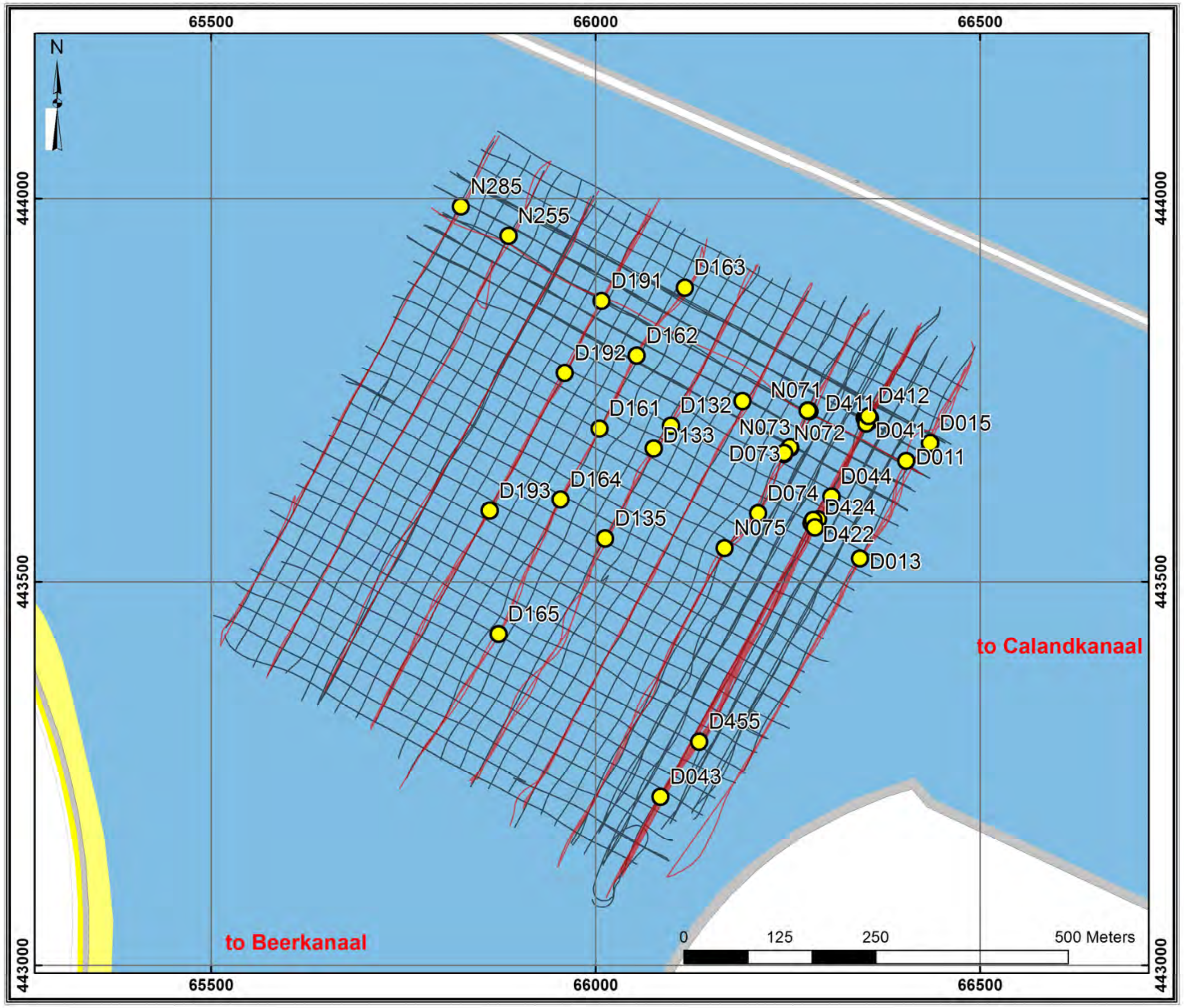

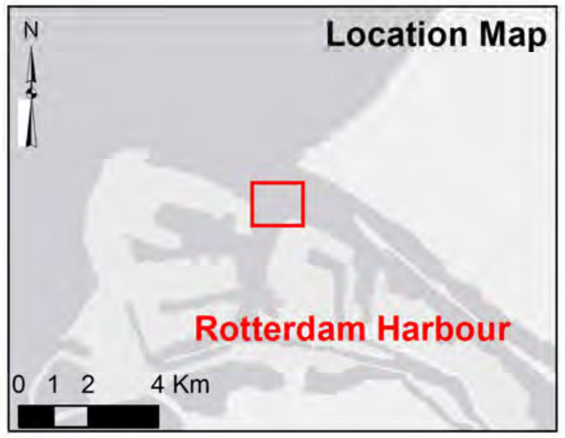

Legend

- Density measurement
- Calibration-lines
- SILAS-lines

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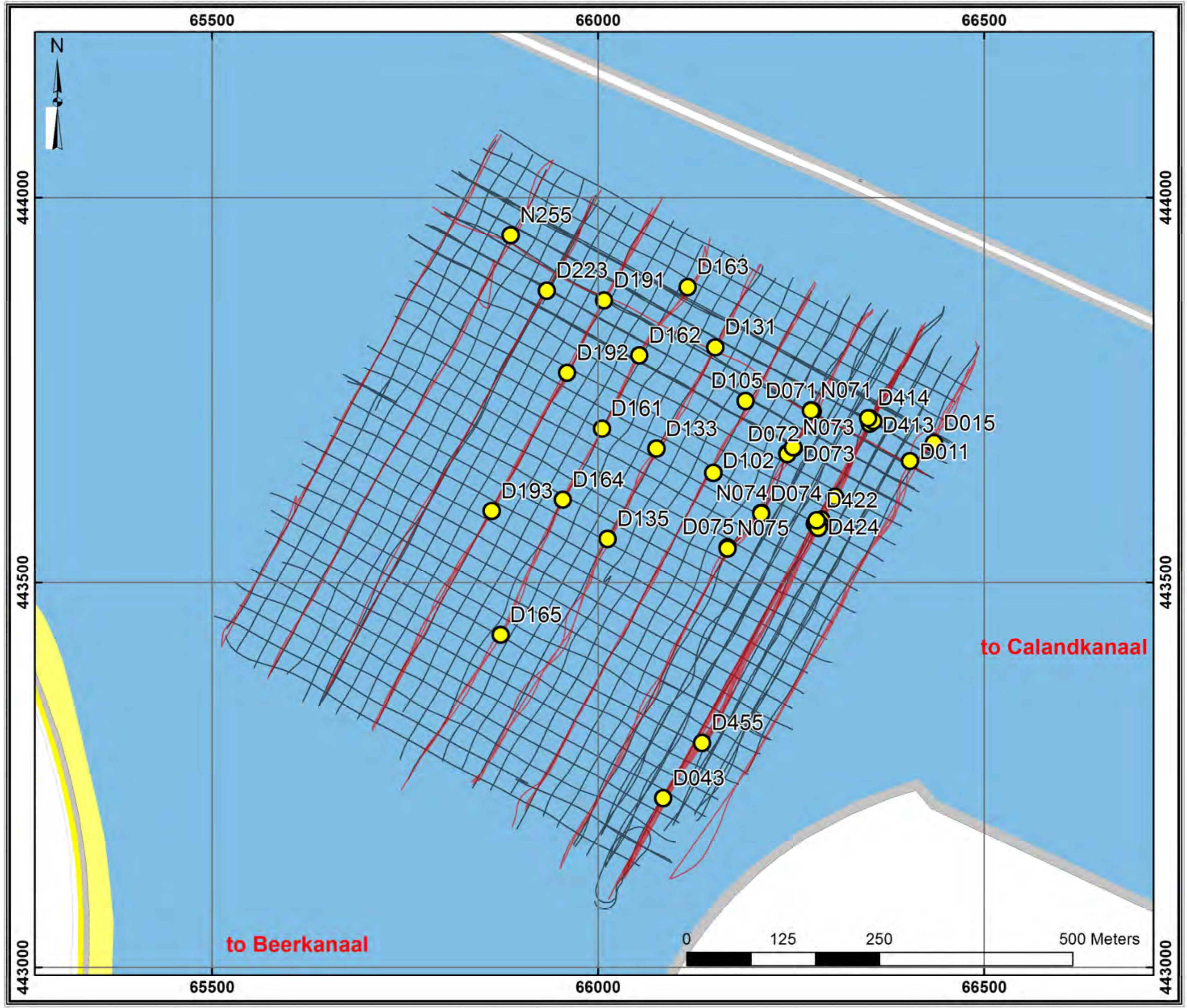
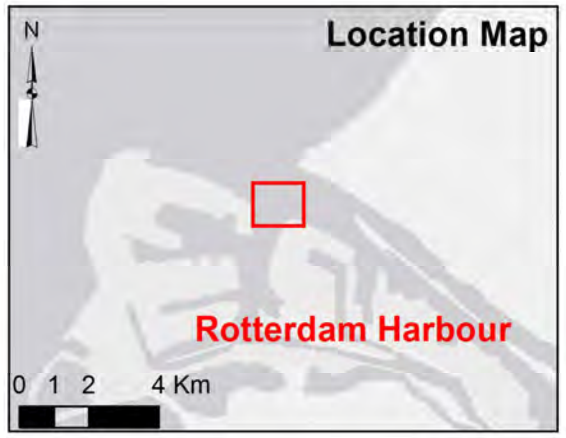
Locations used for r40e reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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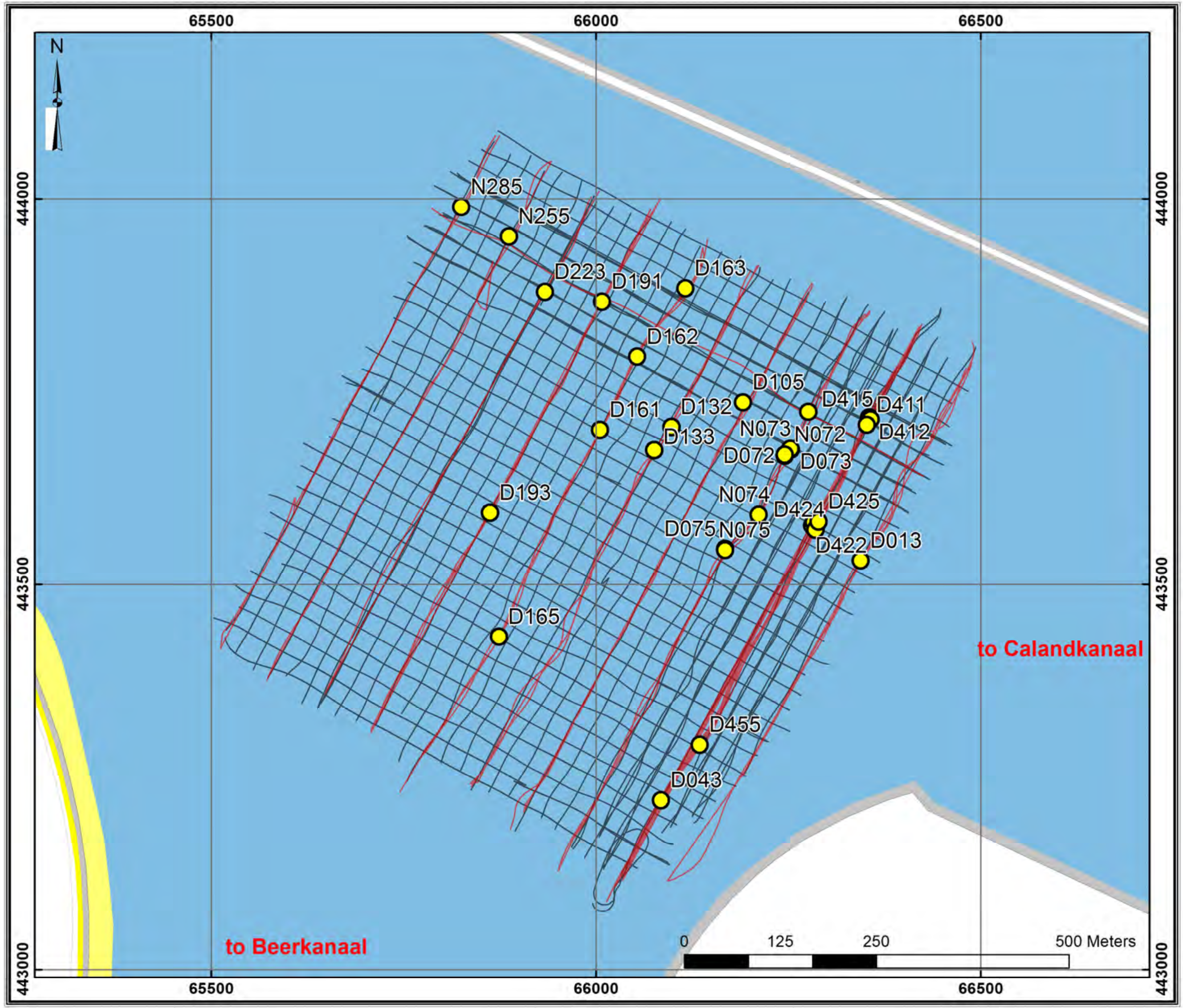
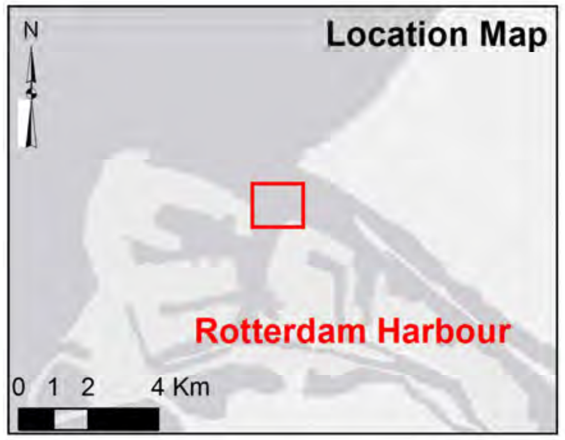
Locations used for r30 reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

Author:	**Project manager:**
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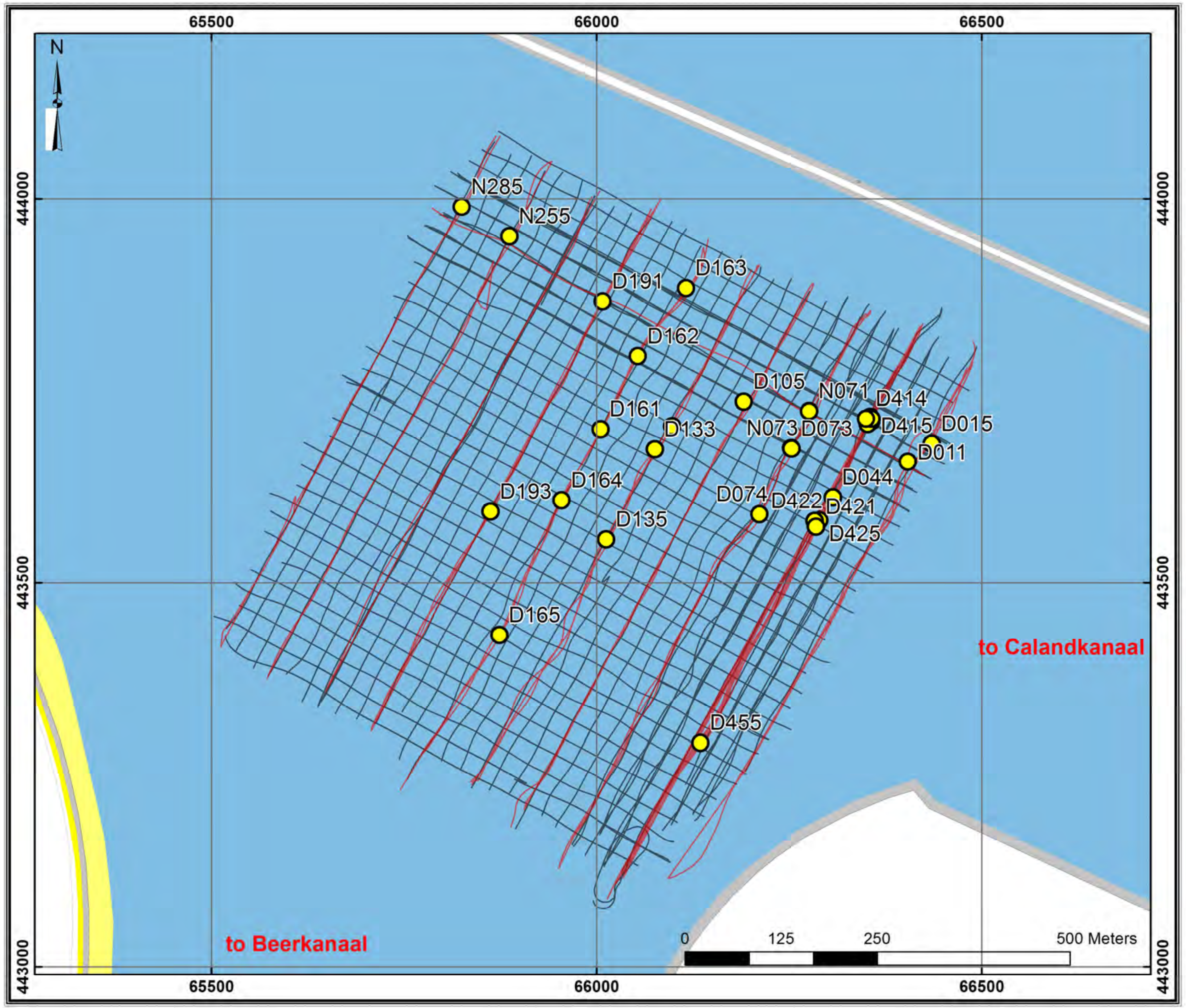
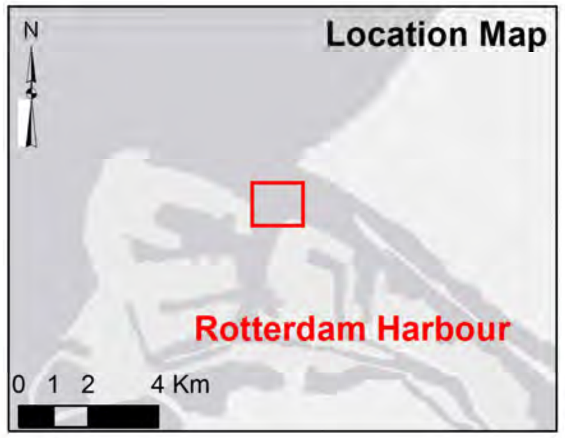
Locations used for r30b reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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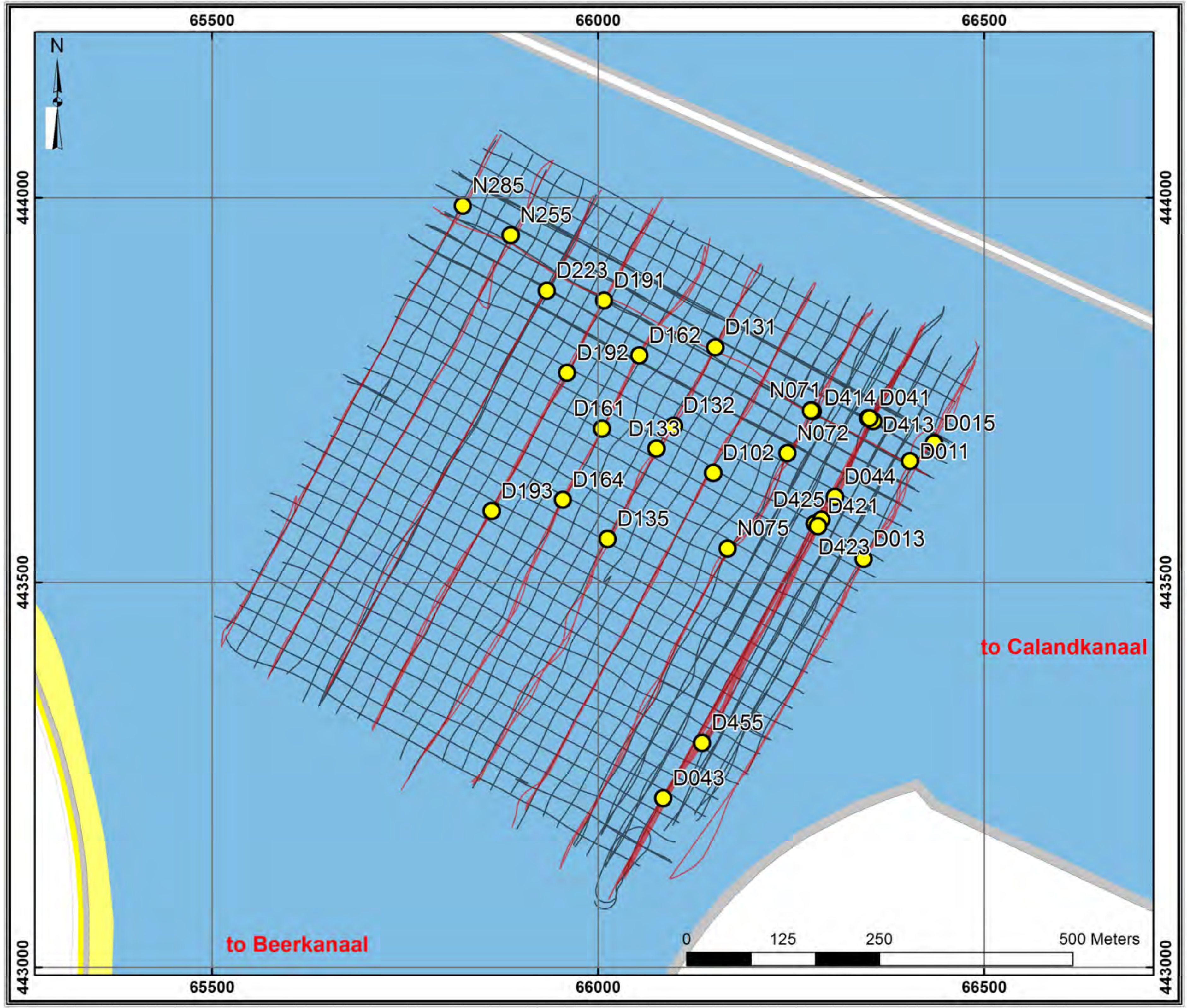
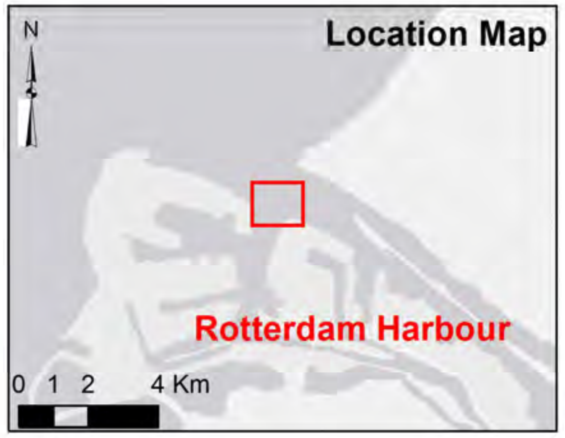
Locations used for r30c reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

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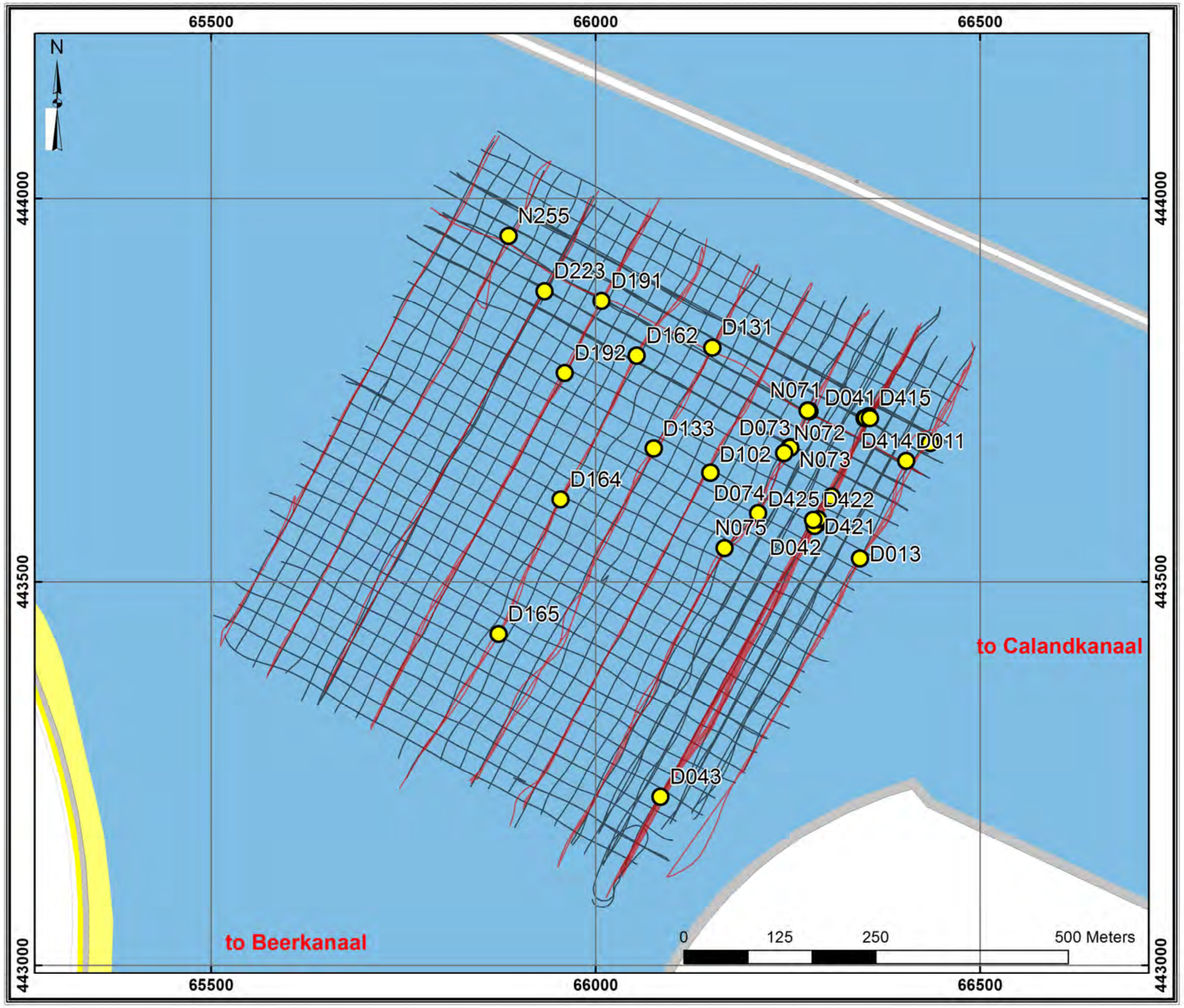
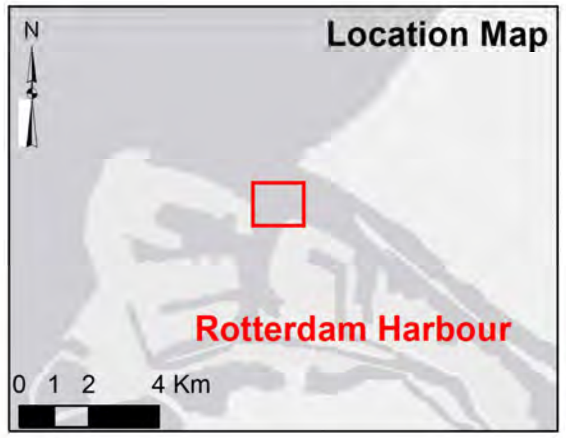
Locations used for r30d reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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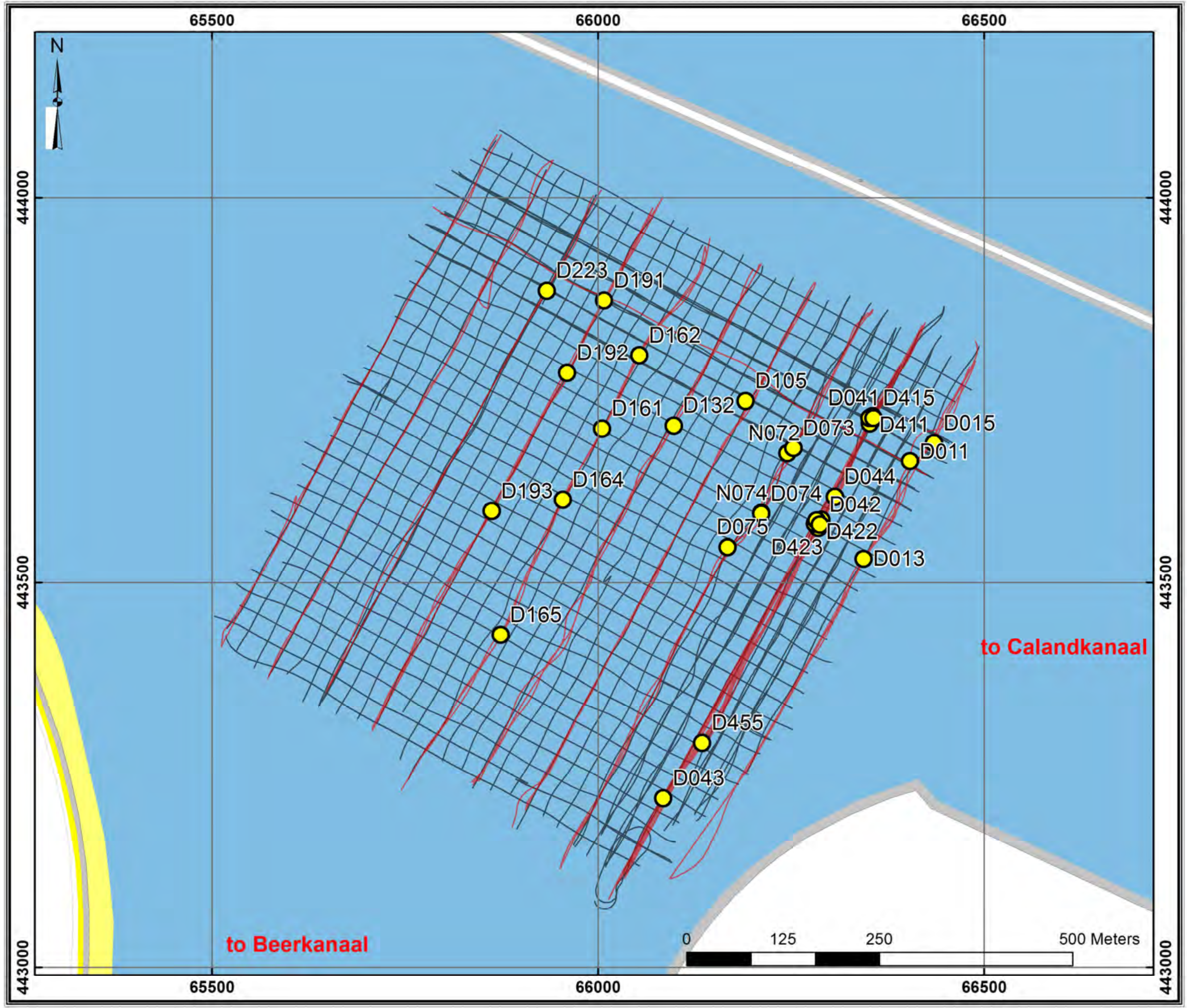
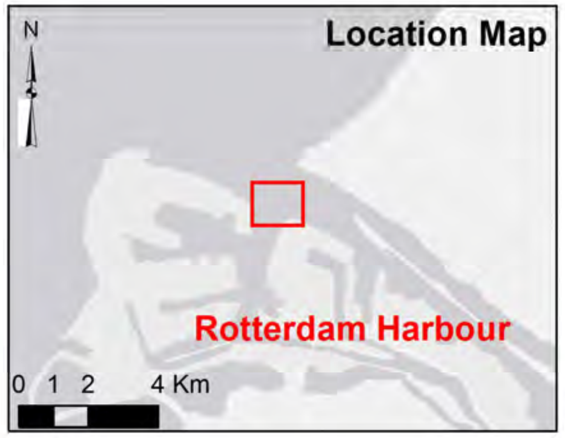
Locations used for r30e reflector

project nr: 1207624





Legend

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Contractor:

Rijkswaterstaat

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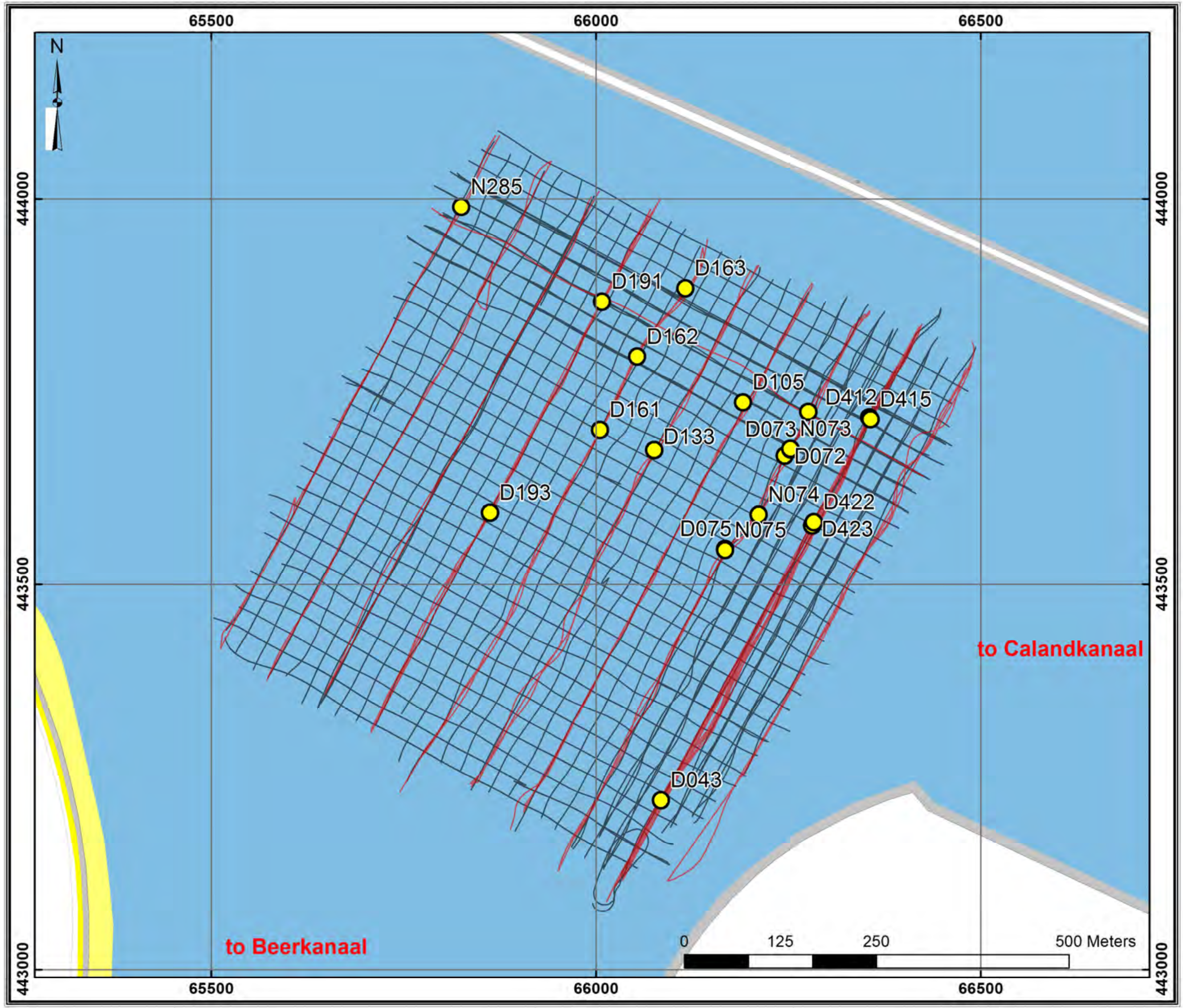
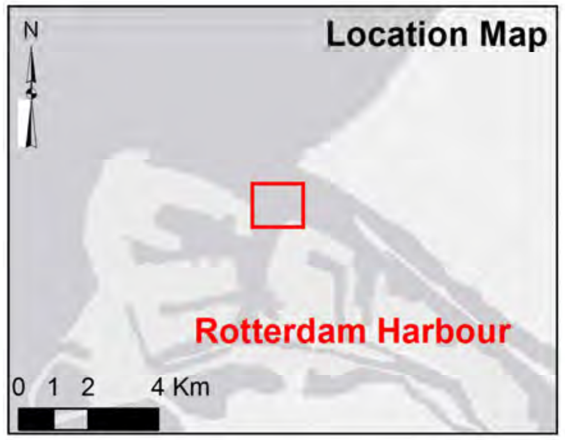
Locations used for r20 reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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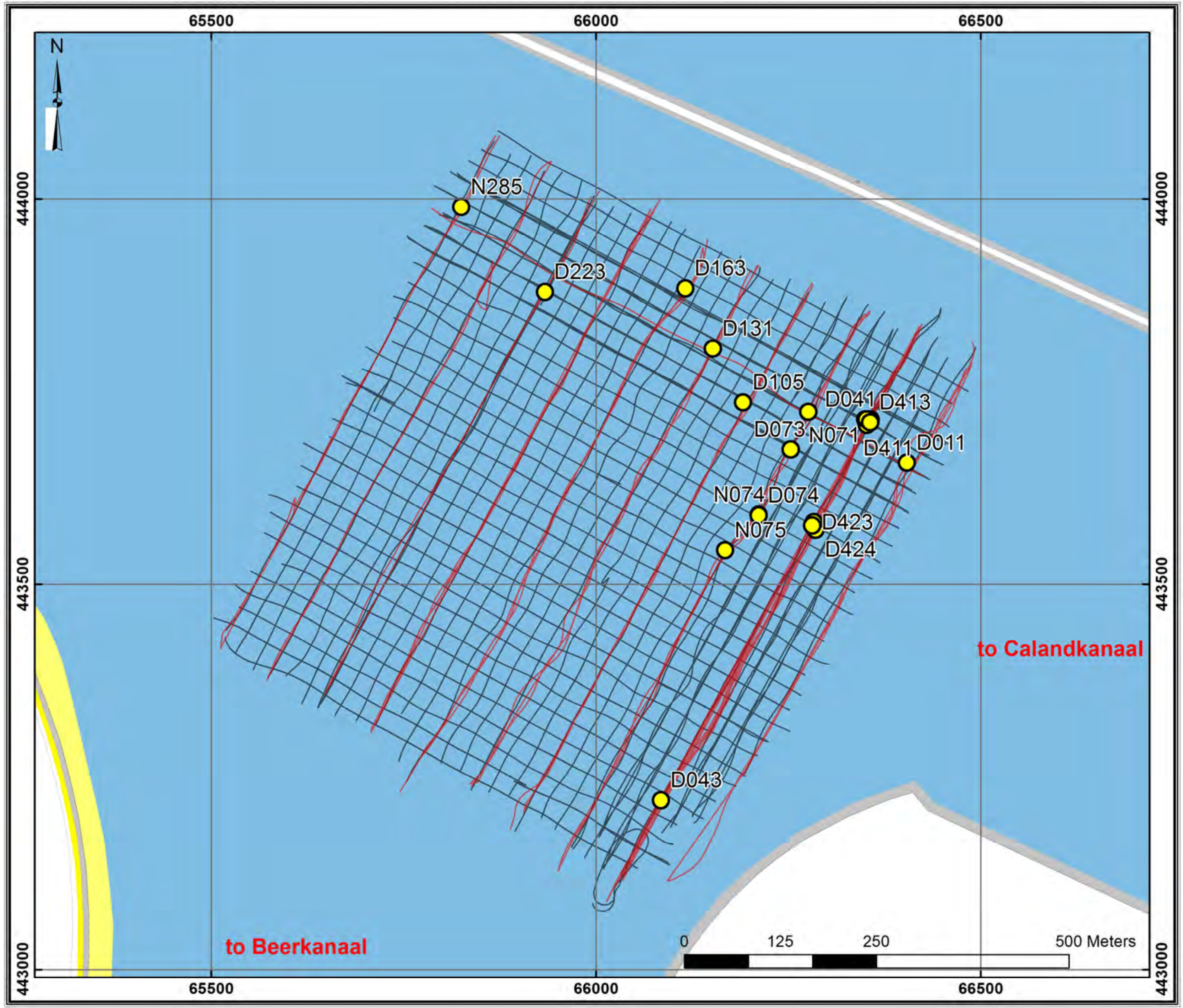
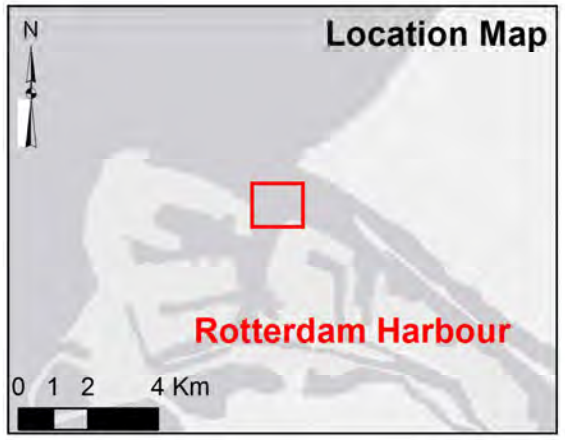
Locations used for r20b reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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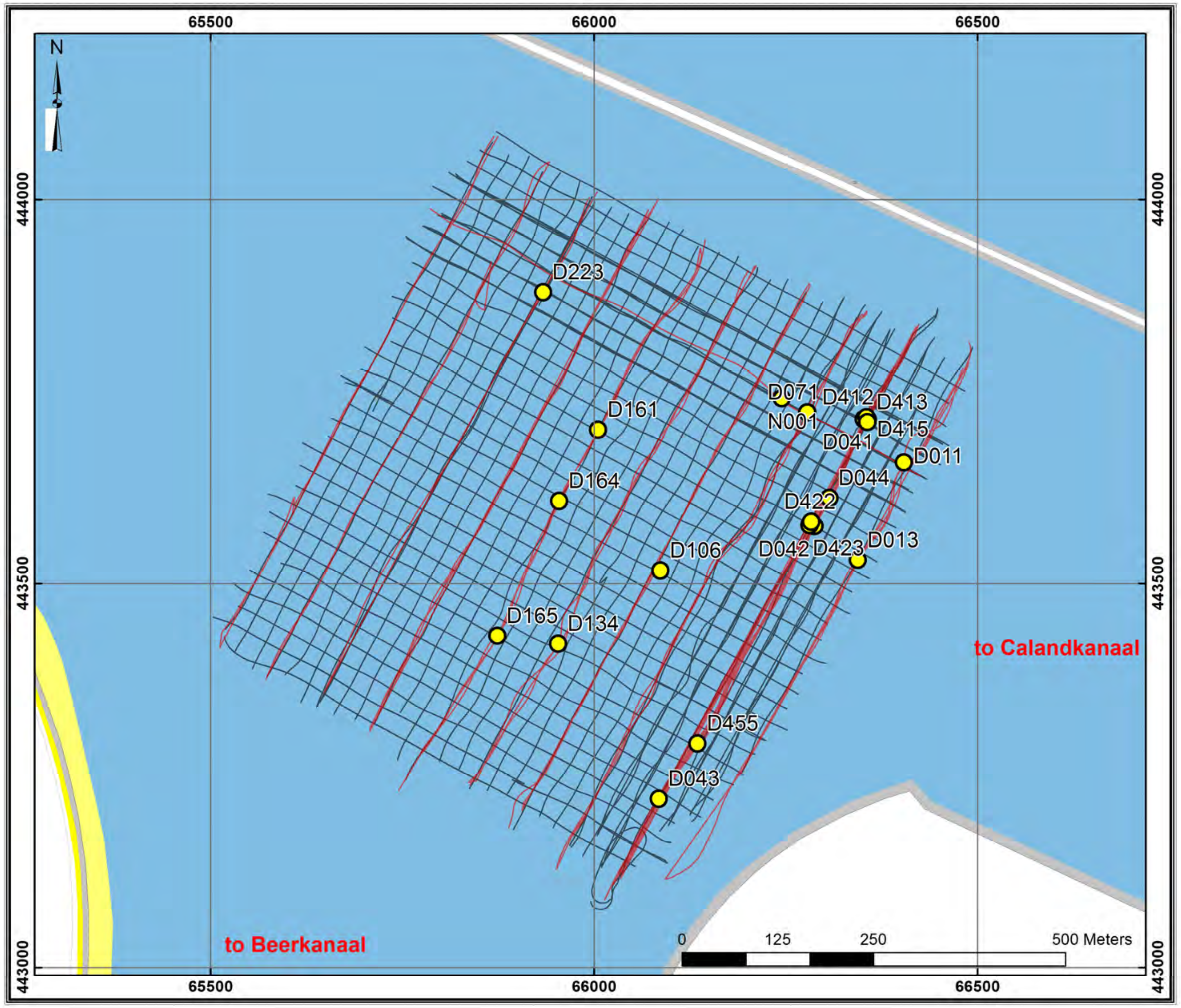
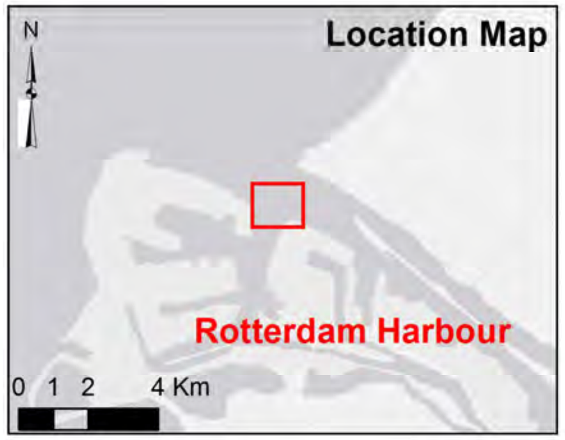
Locations used for r20c reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

Author:	Project manager:
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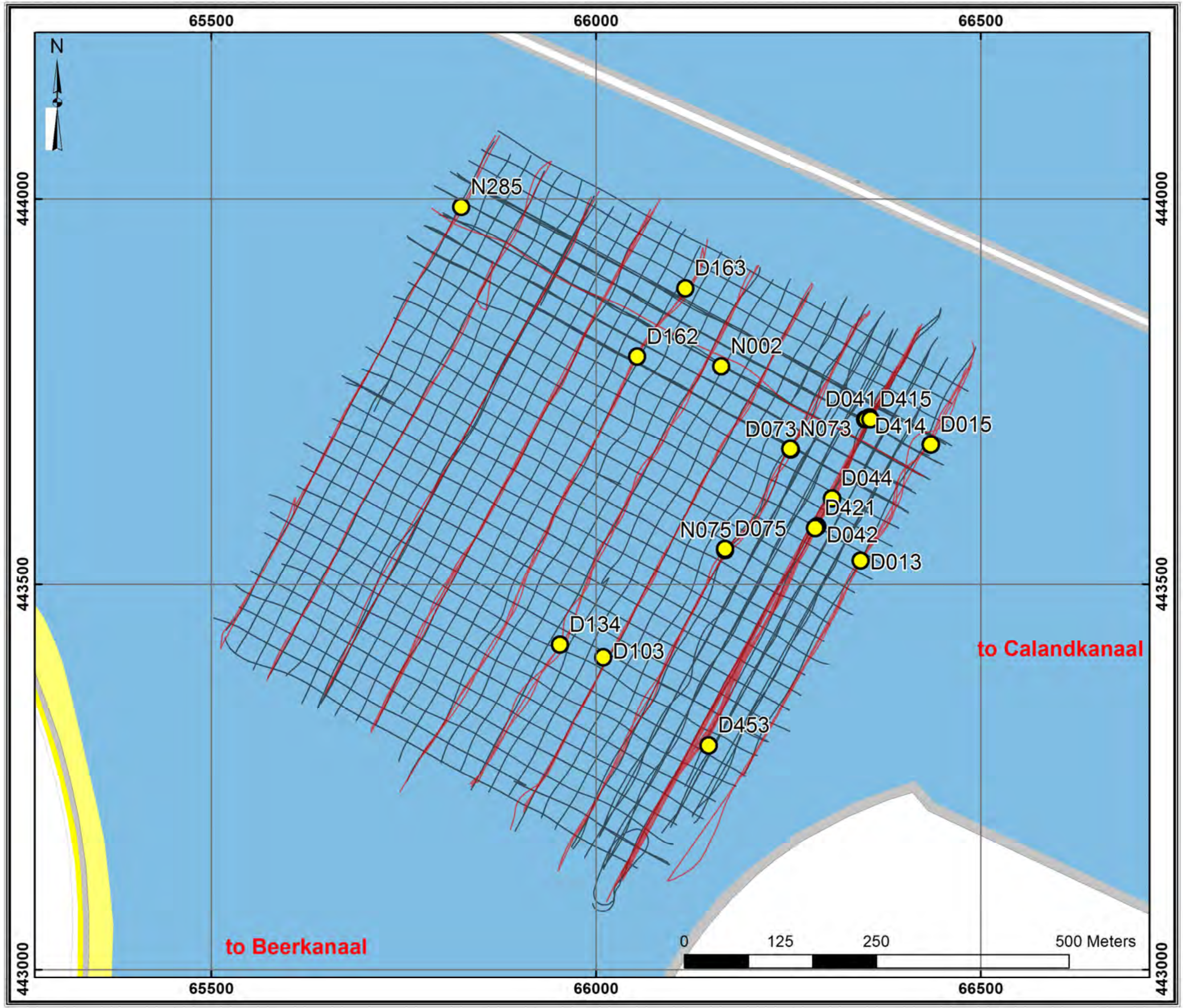
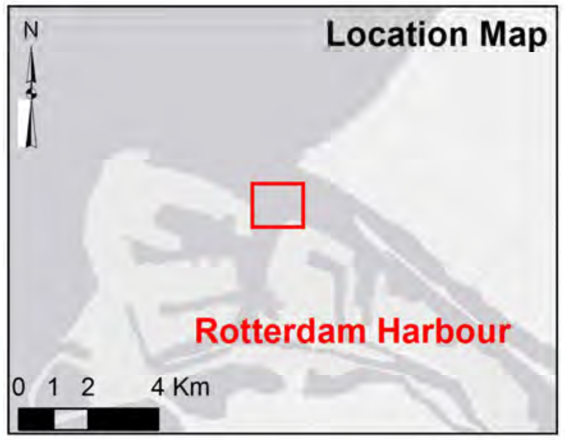
Locations used for r20d reflector

project nr: 1207624





Legend

- Density measurement
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- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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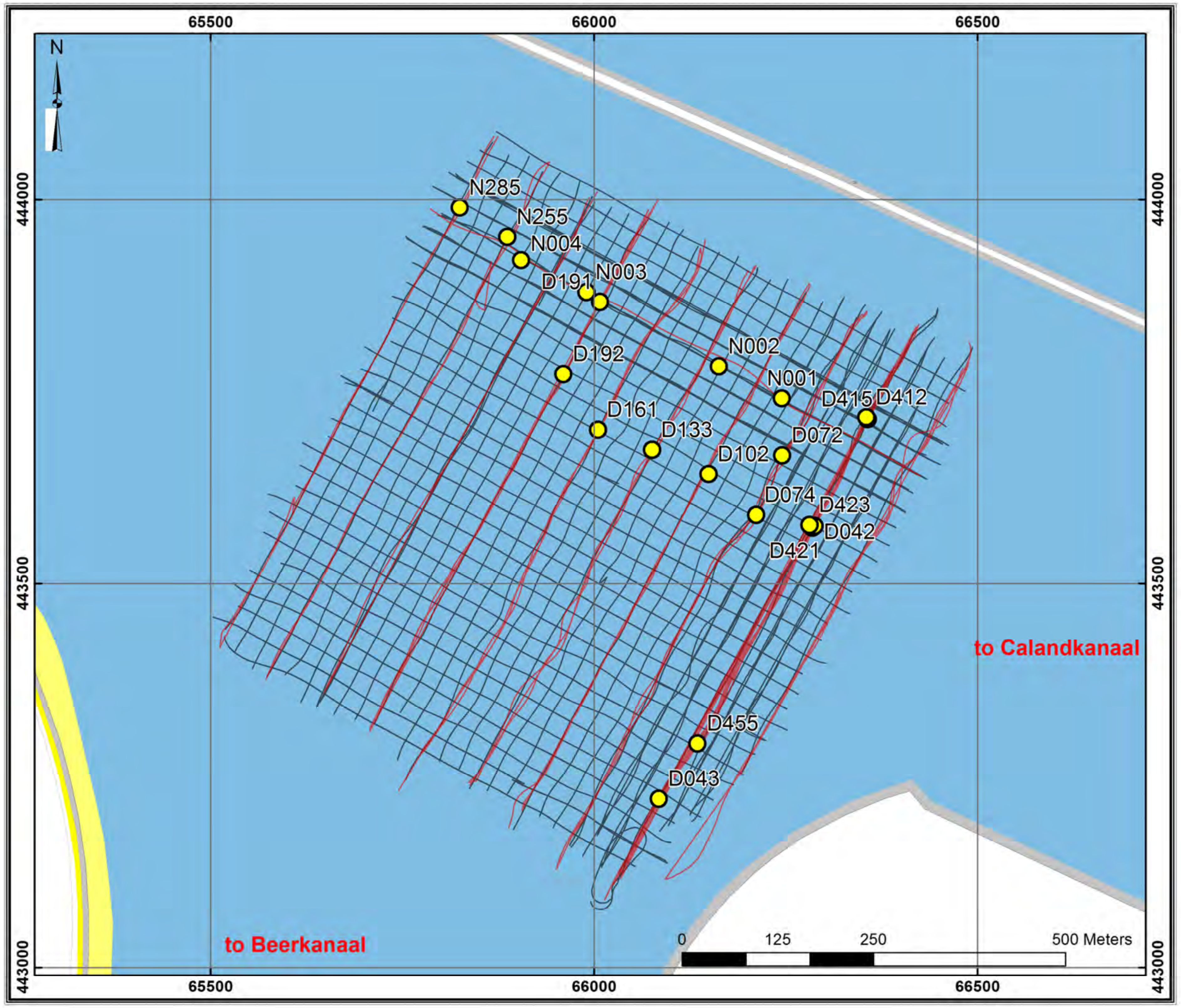
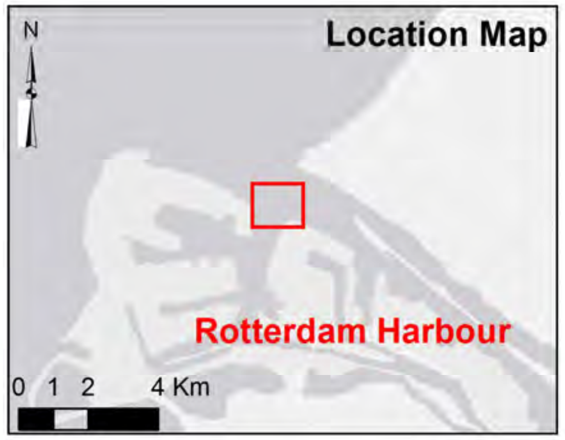
Locations used for r20e reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
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Contractor:

Rijkswaterstaat

Map information:

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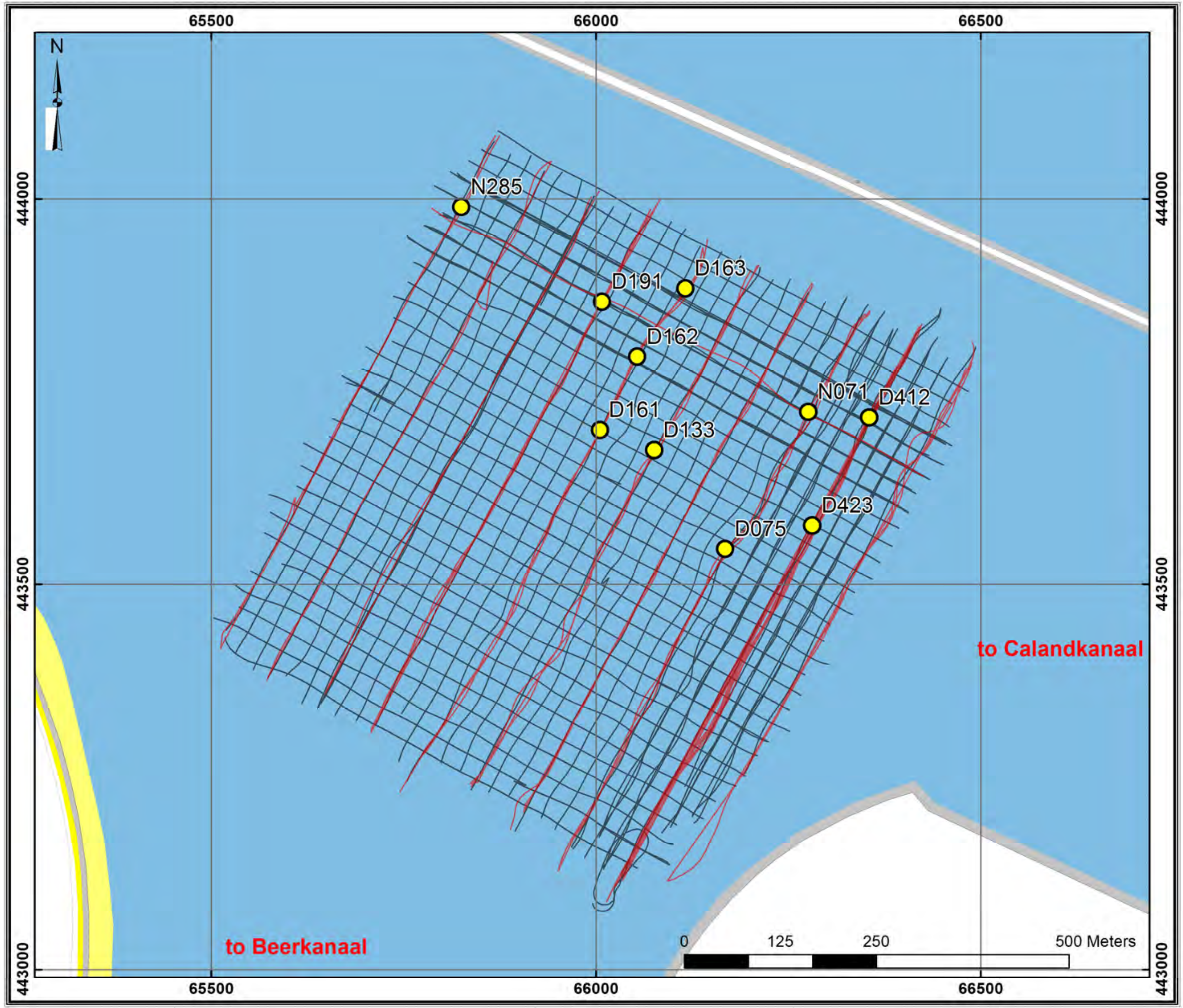
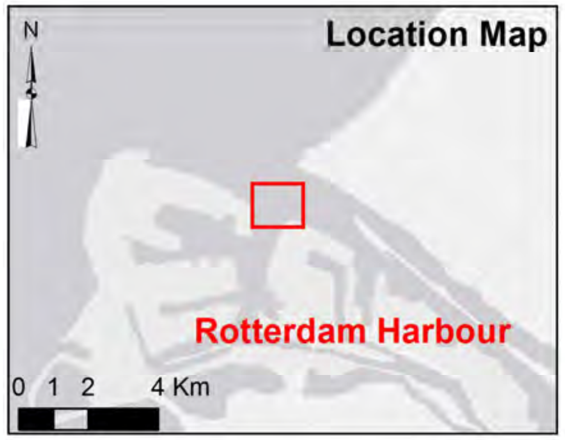
Locations used for r10 reflector

project nr: 1207624





Legend

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Contractor:

Rijkswaterstaat

Map information:

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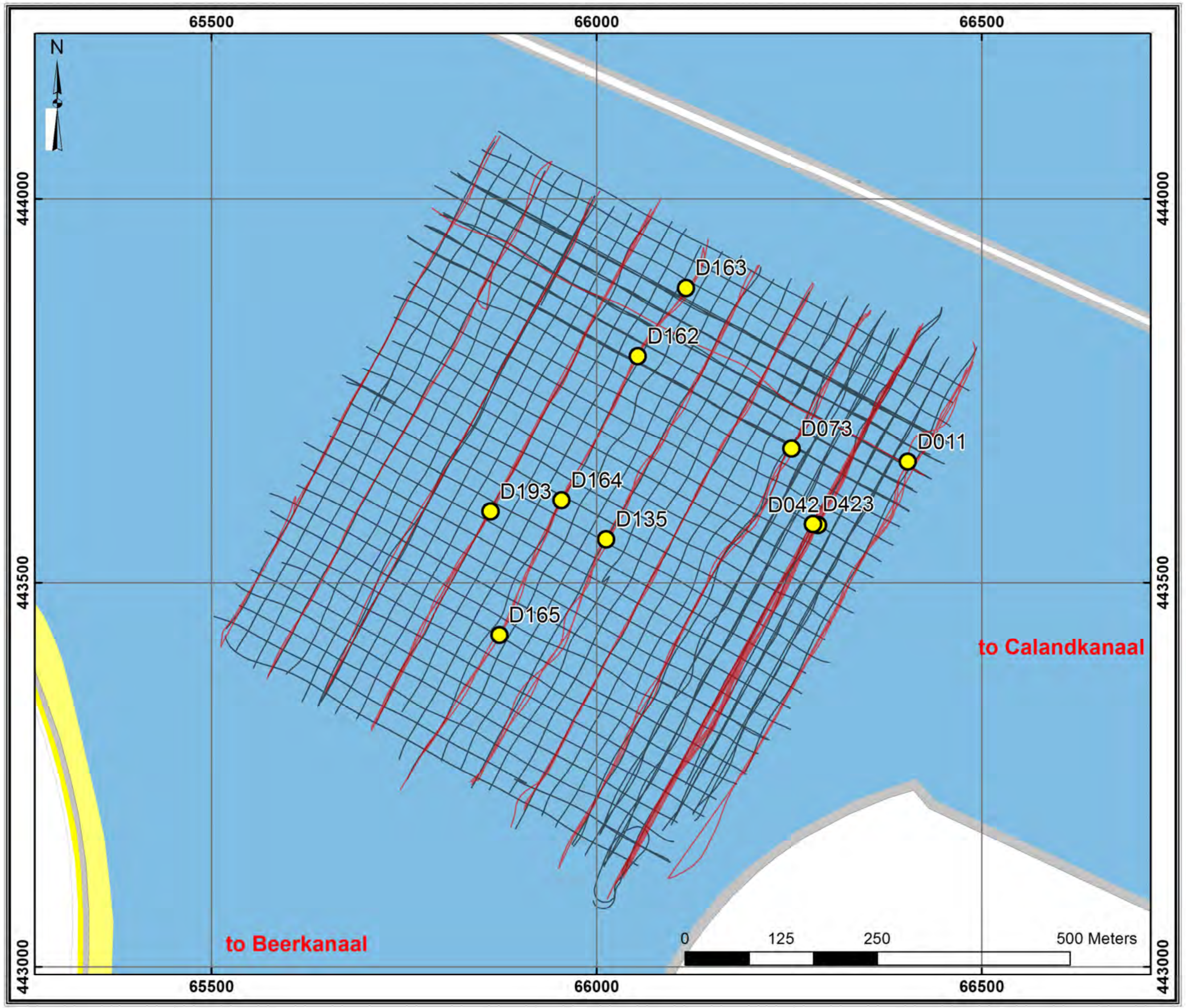
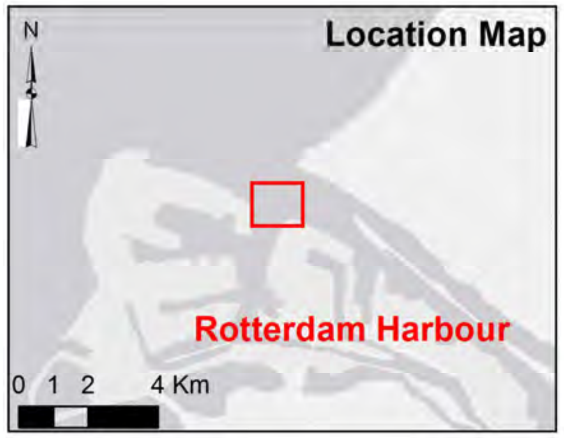
Locations used for r10b reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

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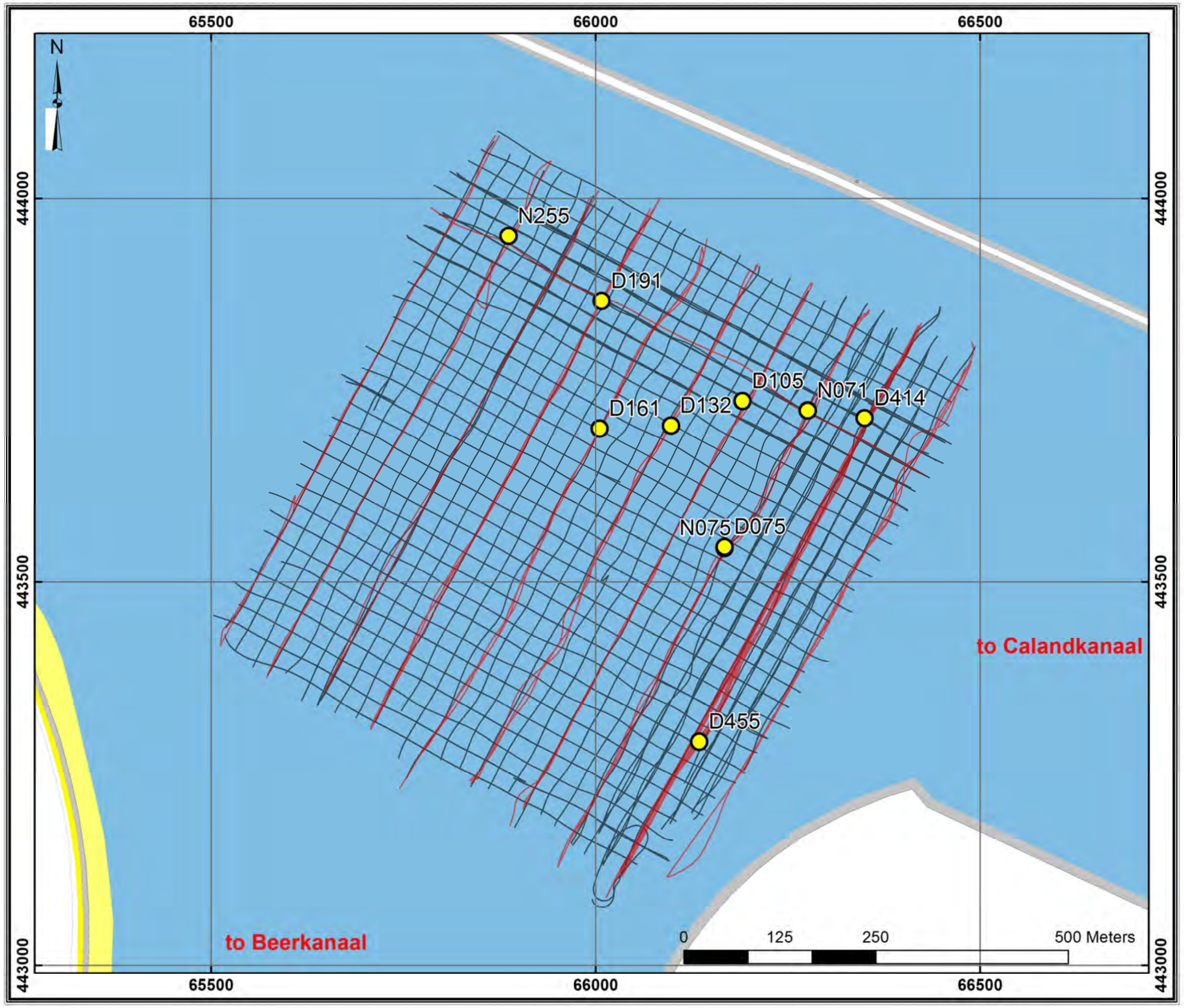
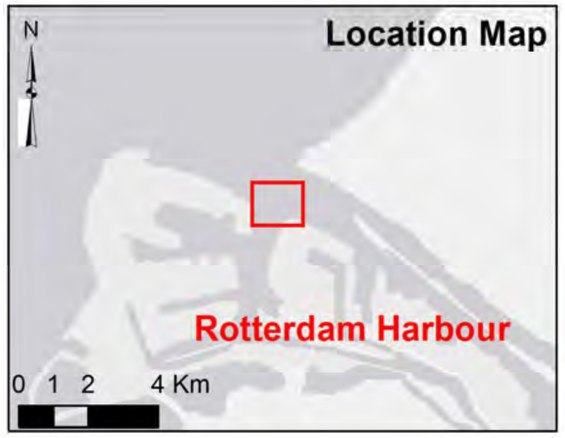
Locations used for r10c reflector

project nr: 1207624





Legend

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Contractor:

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Locations used for r10d reflector

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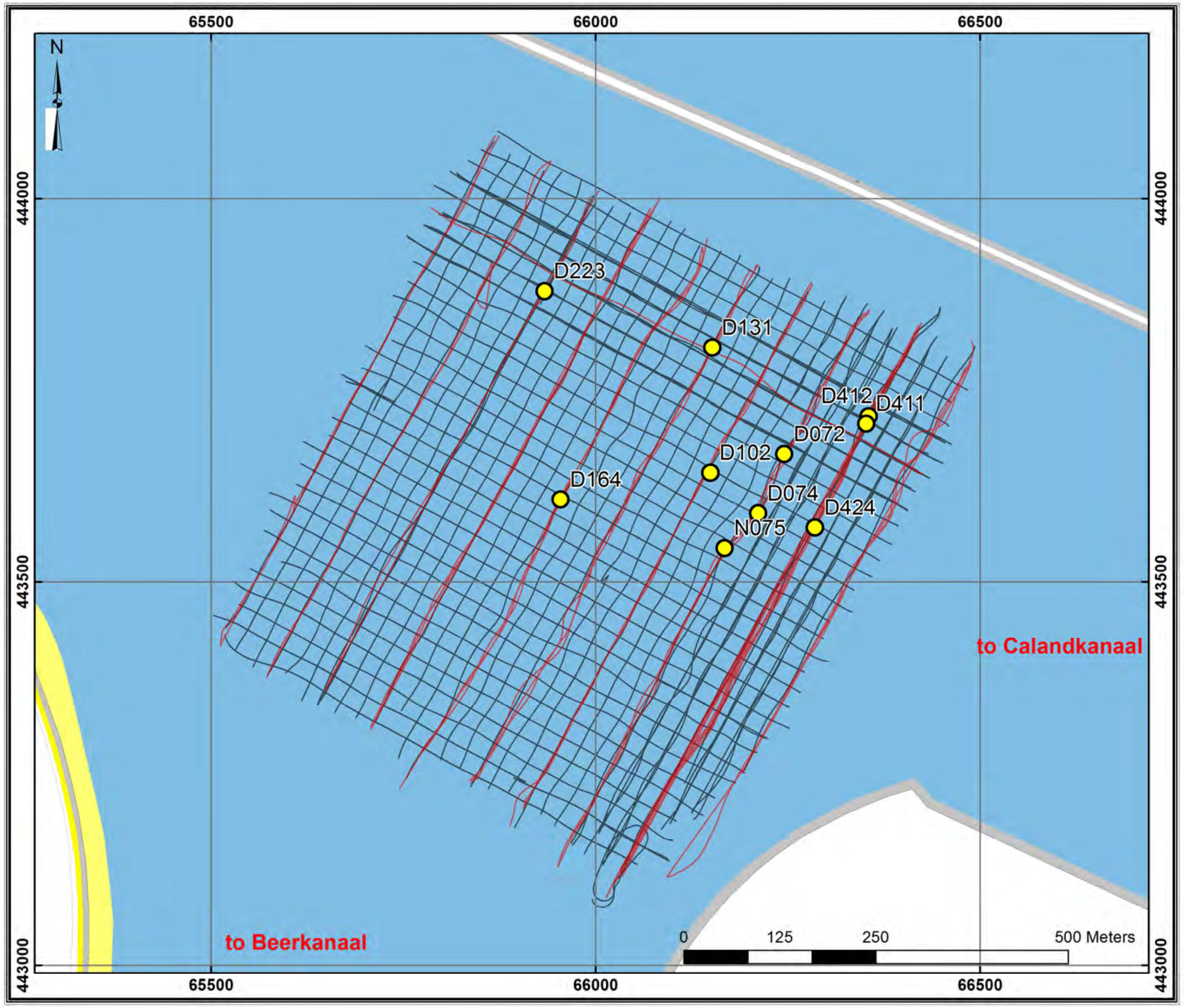

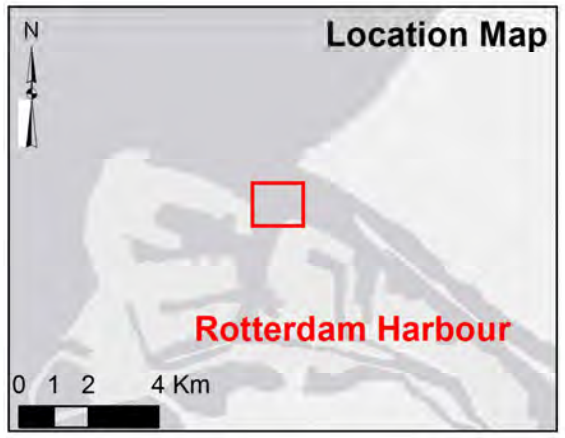

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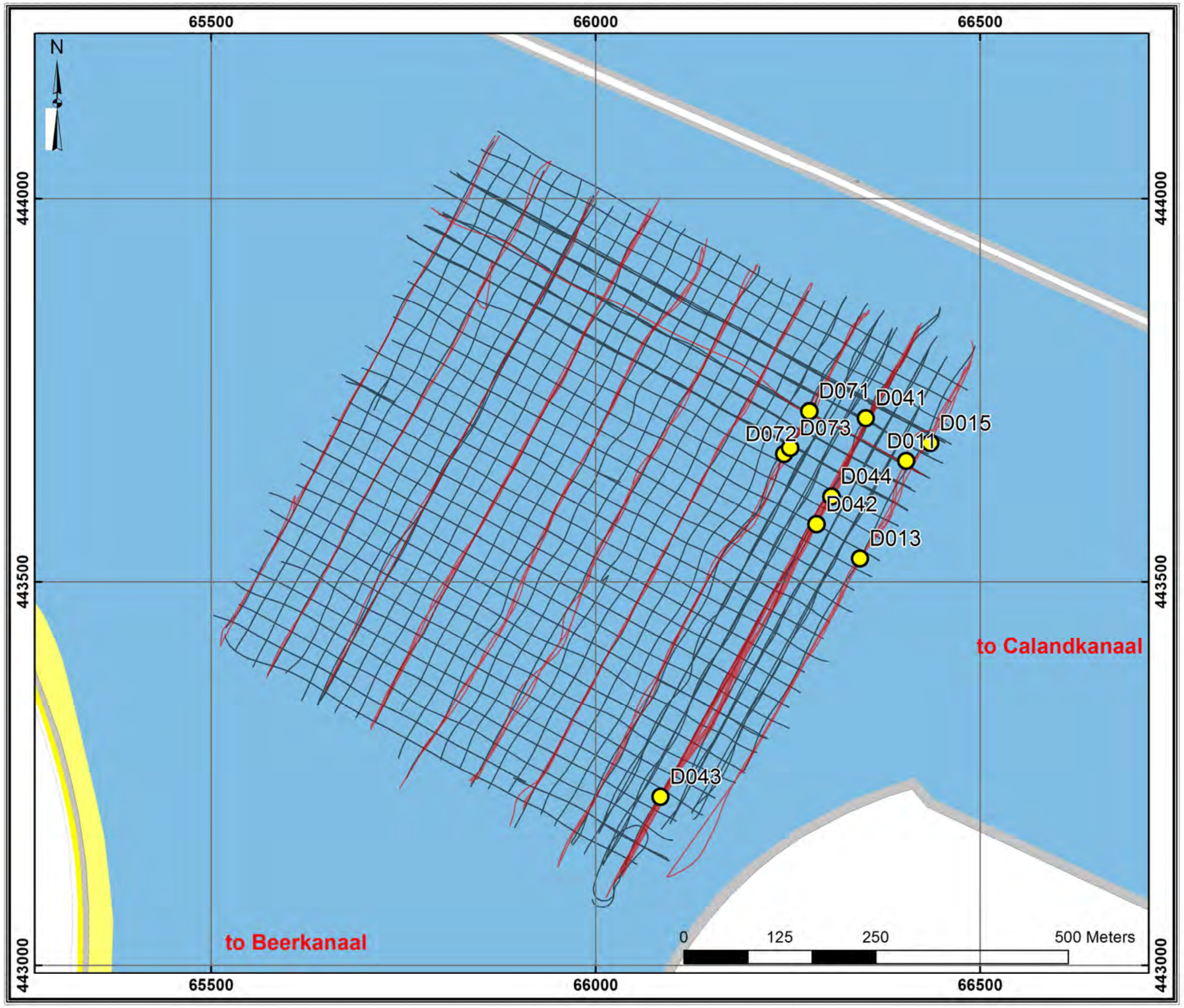
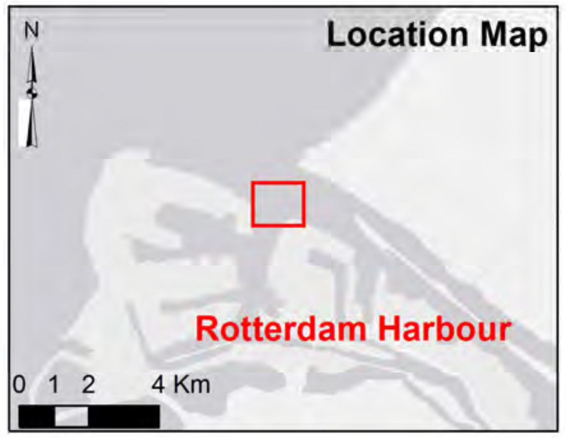
Locations used for r10e reflector

project nr: 1207624





Legend

- Density measurement
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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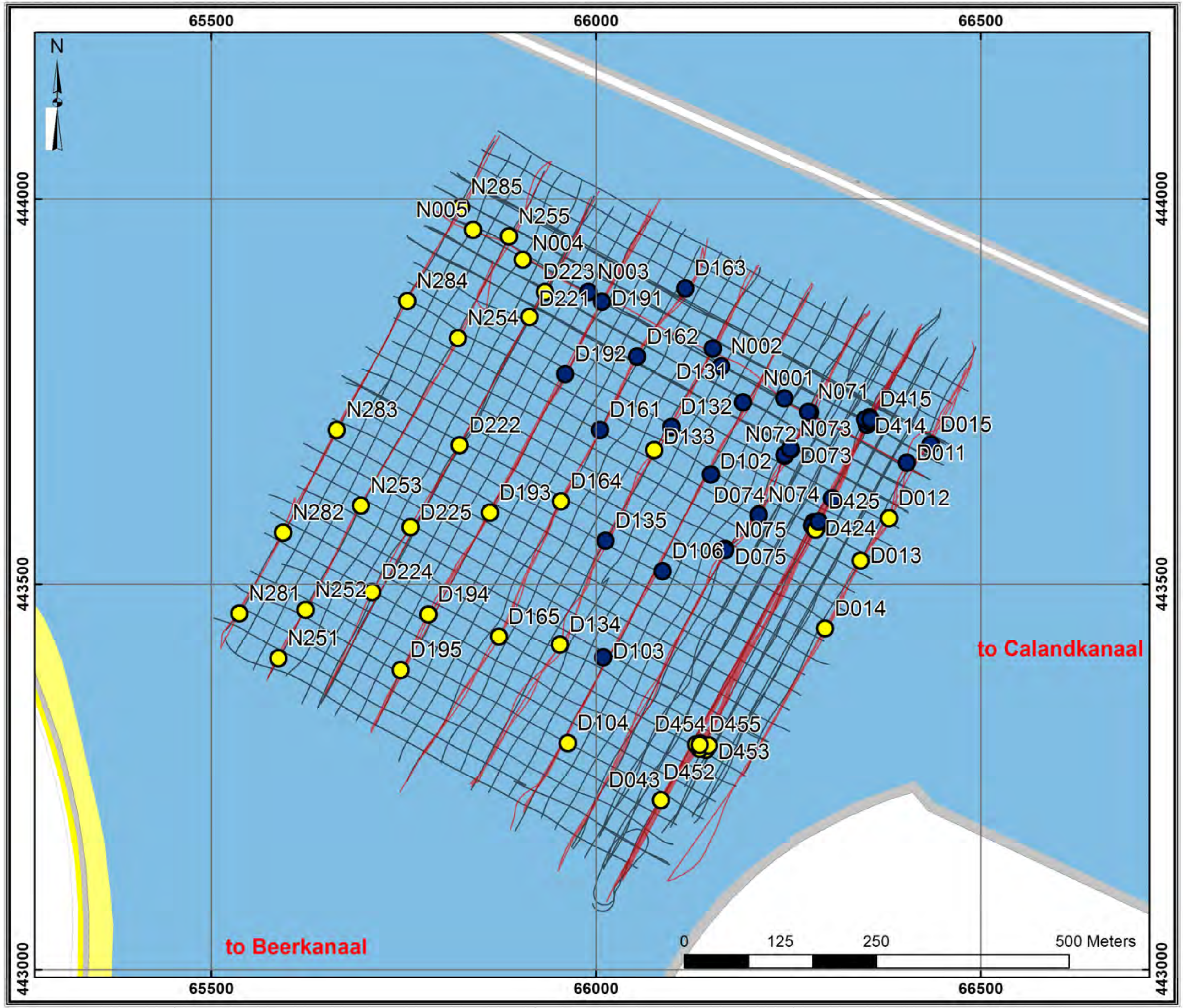
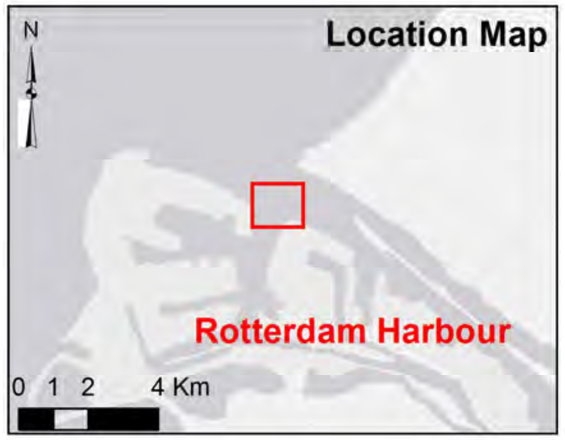
Thick and thin locations

project nr: 1207624





Legend

Thickness L2-L1 (m)

- < 0.5
- > 0.5
- Calibration-lines
- SILAS-lines

Contractor:

Rijkswaterstaat

Map information:

Projection: Rijksdriehoek stelsel (RD New)

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B Explanation of calibration algorithm of SILAS

The explanation of the calibration algorithm is taken from the Stema report "Reactie op rapport Deltares "Assessment Silas Systeem"", by drs. C.J. Werner, date 07-03-2012. This report is written in Dutch.

Kalibratie algoritme

Voor de relatie tussen een gereflecteerd akoestisch signaal en invallend akoestisch signaal geldt:

[4] $R_{12} = A_r/A_i$

Hierin is:
R_{12} = Reflectiecoëfficiënt van desbetreffende reflectie
A_r= Amplitude van gereflecteerde golf
A_i=Amplitude van invallende golf

De formule die de relatie beschrijft tussen de reflectiecoëfficiënt en de impedantie is:

[5] $R_{12}= (\rho_2 v_2- \rho_1 v_1)/ (\rho_2 v_2+\rho_1 v_1)$

Hiervoor is gebruikt dat $A_{i=}A_r+A_{t,}E_{\ i=}E_r+E_{t,}$ $E= A^2\rho v$

Hierin is:
R_{12}= Reflectiecoëfficiënt van desbetreffende reflectie
ρ_1= dichtheid van materie boven het reflecterend oppervlak
ρ_2= dichtheid van materie onder het reflecterend oppervlak
v_1= voortplantingssnelheid van p-golven boven het reflecterend oppervlak
v_2= voortplantingssnelheid van p-golven onder het reflecterend oppervlak
E_i=Energie invallende golf
E_r=Energie gereflecteerde golf
E_t= Energie doorgelaten golf
A_t=Amplitude van doorgelaten golf ("Transmitted" golf)

Voor de transmissie coëfficiënt (de hoeveelheid doorgelaten signaal) geldt:
[6]$T_{12}=2\ \rho_1\ v_1/(\ \rho_2\ v_2+\ \rho_1\ v_1)$

Aangezien de energie van een signaal dus kan worden beschreven door de volgende formule:

[7] $E=A^2\ \rho v$

kan men schrijven:

[8] $E_r /E_i = R_{12}^2$

R_{12}^2 kan nu worden berekend worden uit vergelijking [4]. Hierin staat de amplitude van de gereflecteerde golf A_r. Deze wordt geregistreerd door het akoestische systeem.

De werkwijze van Silas is nu als volgt:
Op ieder calibratie punt waar een dichtheidspuntmeting van is, wordt in Silas uit de akoestiek E_r als functie van de tijd berekend uit het kwadraat van de gereflecteerde amplitude (ook wel intensiteit genoemd).

Vervolgens wordt bij verschillende E_i een uniek verticaal profiel berekend van de R_{12t} versus tijd middels vergelijking [8]. Hierbij wordt uit de Intensiteit op tijdstip t omgerekend naar R_{12t} en beschouwd als een nieuwe reflectiecoëfficiënt. Uit R_{12t} wordt van boven naar beneden de dichtheid berekend volgens vergelijking [5]. Hierbij wordt de snelheid in slib constant verondersteld. Het aldus ontstane dichtheidsprofiel wordt omgezet naar diepte middels de geluidsnelheid in water en de geluidsnelheid in het slib.
Door nu voor alle puntmetingen de energie van het invallend signaal (E_i) te variëren krijgt men een ander synthetisch dichtheidsprofiel per puntmeting.
Door deze variatie automatisch uit te voeren, zal er een waarde voor de energie van het invallend signaal (E_i) zijn, waarbij de ligging van het dichtheidsniveau volgens de puntmetingen het minst afwijkt van het synthetische dichtheidsprofiel volgens de akoestiek. Dit is de uiteindelijke kalibratieuitkomst: de waarde van de zogenaamde “Arrival power” zoals deze in de Silas software wordt genoemd.

Bij de berekening van de “Arrival power” wordt dus niet 1 frequentie beschouwd, maar de intensiteit van het volledige invallende signaal (bij 24 kHz een signaal met een bandbreedte tussen 15 kHz en ca. 34 kHz). De energie van het invallende signaal is het signaal, vlak voordat het aankomt bij de eerste significante dichtheidsovergang (afhankelijk van gebied een dichtheidsovergang op een dichtheid tussen c.a. 1020 en 1050 g./l.) .

Kalibratie procedure

De koppeling van het akoestische signaal aan de puntmetingen gebeurd in Silas na de opname, dus tijdens de processing.

De stapsgewijze omschrijving van het algoritme voor het koppelen van het akoestische signaal aan de puntmetingen is als volgt:

1) Bepaling van significante dichtheidsovergangen in de puntmetingen. Afhankelijk van het gebied ziet men de eerste significante dichtheidsovergang optreden bij een dichtheid tussen resp. 1020 g./l. en 1050 g./l.
2) Vergelijking van de verticale ligging van de eerste significante overgang in de puntmetingen met de verticale ligging van de eerste significante reflectie in de akoestiek.
3) Koppeling van de eerste significante overgang van de puntmeting naar de eerste significante reflectie in de akoestiek.
4) Automatische constructie van synthetisch dichtheidsprofiel in akoestiek ter plaatse van iedere puntmeting op basis van invallend akoestisch vermogen en berekening van impedanties uit reflectie-intensiteiten, met constante geluidssnelheid in water, zie boven..
5) IJking: automatische variatie van invallend akoestisch vermogen (iteratie) totdat sprake is van kleinste gemiddelde afwijking tussen alle synthetische dichtheidsprofielen en ligging niveau (1200 g./l.) volgens puntmetingen. Er wordt dus uiteindelijk 1 invallend akoestisch vermogen voor een deelgebied bepaald.

6) Opslaan invallend akoestisch vermogen in kalibratiebestand, en berekening van het 1200 g./l. niveau op basis van het gekalibreerde akoestische vermogen.
7) Het kalibratiebestand kan in het gebied langere tijd worden gebruikt.
8) Op basis van regelmatige ijking zal ervaring moeten worden opgedaan over de geldigheidsduur van een kalibratiebestand.

C Stema report on calibration options

Answers to additional questions about Silas

Date: 27-02-2013
By: Drs. C.J. Werner

Stema Systems	
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Answers to additional questions about Silas

Table of contents

1 Introduction

This document describes the answers to additional questions from Deltares about the Silas system. These questions were posed in relation to the Silas assessment study for the Maasmond area.
In general 3 topics are presented:

1) Description of the calibration methods, advantages and disadvantages (chapter 2).
2) Preferred methods to be used in the Maasmond area (chapter 3)
3) Information about silt sound velocity as applied in Silas (chapter 4).

2 Silas density Calibration methods

2.1 Cumulative method-no vertical corrections model

This model uses the density information of the exported density level depths resulting from geophysical ground truth point measurements (e.g.D2Art). Three levels should be exported (1050 g./l. level (lutocline), a 1200 g./l. level (level of interest) and a 1300 g./l. level (could be any density level).
This procedure will assume that the location of the 1050 g./l. level and the top of the fluid sediment (first significant reflector) in the seismics coincide. In case there is a difference between these two the entire ground truth data will be shifted vertically until the 1050 g./l. level matches with the autotraced (and edited) first seismic reflector location.

Subsequently, the Silas program will calibrate the seismics to selected ground truth density level (preferably the exported 1200 g,./l. level) using an iterative method (fig.1). At all point measurement locations an average synthetic density profile is constructed which results from one assumed arrival power and registered reflected power which is for all locations identical[1]. Subsequently the arrival power is changed for all locations iteratively and the arrival power is found which gives the best fit between synthetic density level and geophysical point density level [2].

[1] The calculation is based on standard acoustical laws which relate seismic arrival signal power and reflected power to the physical properties of the sediment [McGee, 1992], which can be described by the impedance, see formula (1).

$$\text{Impedance}=\rho * v \quad (1)$$

in which:
ρ = density of sediment layer in kg./l.
v= propagation velocity of p-waves in sediment in meters/second. This velocity is assumed constant

[2] For time depth conversion of the synthetic density profiles a constant velocity of sound in the silt layer is used, which can be varied by user.

This arrival power is the result of the calibration and will give a best fit calibration for the area. Finally, using this calibration for all seismic data synthetic density profiles and locations of calibrated density level can be calculated.

Advantage: the method results in one calibration for all points. Possible errors due to mismatch, positioning errors and errors in the geophysical point measurements are averaged out.

Disadvantage: possible spatial calibration variations due to different seabed composition, and related variations in attenuation, sound speed are not taken into account.
In order to account for these influences one could use the combination of the cumulative method with the vertical corrections model.

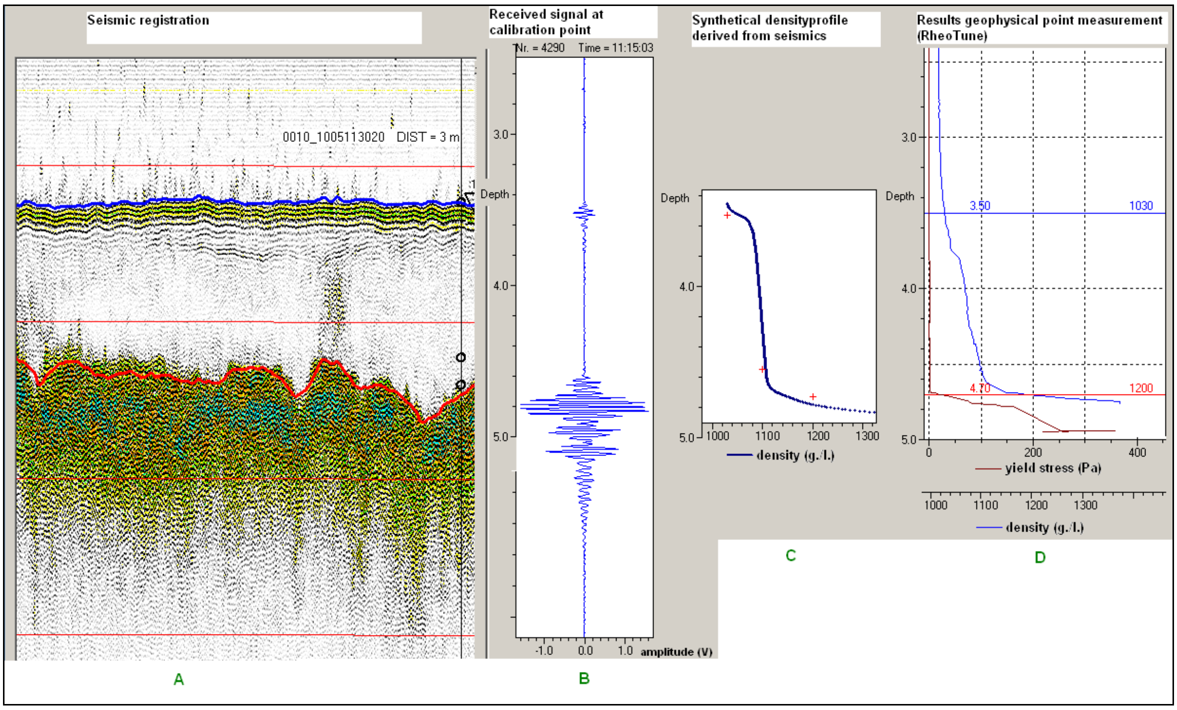


Fig.1 Procedure of cumulative density calibration of high resolution seismics as applied by Silas. A=Seismic registration, B= Received signal at calibration point, C= Synthetic density profile derived from seismics at calibration point, D= Results geophysical point measurement .

2.2 Cumulative method-vertical corrections model

This method is identical to the method described in paragraph 2.1, but in addition after the resulting estimate of the arrival power all vertical differences between synthetic and true density level are calculated. Subsequently these vertical differences are modeled using an inverse distance (power 1) kriging method.
Finally, using this calibration for all seismic data synthetic density profiles can be calculated and subsequently the vertical difference model is applied.

Advantage: This method accounts for possible compositional variations, and related variations in attenuation and sound speed.

Disadvantage: The method assumes that all geophysical point measurement used for calibration do not have errors and represent the situation at the seismic line even if there is a distance between point measurement and seismic. Another disadvantage is that currently this method can only be used with offline data. However, future implementation of this method for real time data is relatively simple.

2.3 Gradient method

This method uses the ratio of the depth of selected density level (e.g. 1200 g./l. level) below the lutocline (e.g. below 1050 g./l. level) with respect to the depth below first reflector of an autotraced reflector. For each geophysical point measurement this ratio is determined. Subsequently, the software will make a model of these ratios based on kriging (inverse distance to power 1).
Subsequently, the software will apply these ratios to all seismic which consist of the indicated lutocline and autotraced reflector to calculate the location of the selected density level.

Advantage: This method does not account for variations in the seismic arrival power. The method also produces accurate results in areas where density gradients are not acoustically detectable.

Disadvantages: The method does not use all seismic information, because reflected signal power between the first reflector and deeper reflector is not used. Only the additional use of the signal power at the lutocline is optional. Moreover an additional autotracing of a deeper reflector is required and the selection of this reflector is highly subjective.

3 Advised calibration method for Maasmond area

In general the cumulative method (without or with vertical corrections model) is to be preferred above the gradient model.
The gradient model is not preferred for following reasons:
-The gradient model adds an extra error source (additional autotracing of deeper reflector)
-The choice of this deeper reflector is highly subjective
-Not all seismic data between first reflector and density level is used.

The choice between the cumulative method with- and without vertical corrections depends on:
-The number and spacing of available geophysical point measurements.
If only a low amount of point measurements is available or if these are not equally spaced, the cumulative method without vertical corrections model is to be preferred
If there are many geophysical point measurements for calibration, the vertical corrections method could be preferred.

-The quality of the point measurements. If the quality of the geophysical point measurements is not optimal the cumulative method without vertical corrections model is to be preferred.

Though above statements can be a general guidance, it is preferred to use the acquired test data to select best cumulative method.
In order to do so, it is recommended to execute following procedure:

1) Verify the Silas calibration (arrival power) of two consecutive days.
2) If these are the same within 10 percent, apply a density calibration using 50 % of the point density measurements of both days for cumulative method without vertical corrections.
3) If these are the same within 10 percent, apply a density calibration using 50 % of the point density measurements of both days for cumulative method with vertical corrections.
4) Compare the differences at the other 50 % of the point measurement locations and compare both methods.
5) Probably one could repeat this for other parts of the data set.

4 P-wave sound velocity in Silt

4.1 Method and background for used velocity in Silas

Silas applies a silt velocity which is constant and app. 35 m/sec higher than measured average velocity in the water column.

These values were based on literature.
In general at the water silt interface (lutocline) one could expect a decreasing speed of sound with increasing amount of concentration of suspended particles, up to 0.28 % concentration [Larry Buchanan,2005]. If the relative strength of the material increases the sound velocity is expected to increase. Above source suggests this happens at densities above 1200 g./l. The theoretical sound velocity in fluid saturated sediments can also be found using formulas shown by [Ballard, Mc Gee and Leist, 1993]

However some Admodus in-situ velocity measurements [Wurpts, Greiser] indicate that velocity in the harbor of Bremen starts to increase above a density of about 1050 g./l. from 1434 m/sec to 1446 m/sec. (velocity in water: 1434 m./sec).

The Corps of Engineers [Mc Gee,Ballard, Caulfield 1995] indicate that in silty clay with a density of 1460 g./l. an in-situ velocity of 1552 m/sec was measured and a velocity of 1544 m/sec could be deduced for a density of 1230 g./l.

Because the Silas density level calculation module was meant for calculation of various density levels (densities ranging between 1000-1500 g./l.) these (varying) results lead to the assumption to keep the general silt velocity app. 35 m/sec higher than determined velocity in water.

Since The D2 art profiles taken in the Maasmond generally indicate a density exceeding 1050 g./l. for the entire profile it seems valid to use a sound velocity in silt which is app. 5 m/sec higher than at the base of the water column.
It is not clear if the sound velocity profiles executed in the Maasmond do penetrate the lutocline. The velocity graphs show that in most occasions the first reflector is reached and penetrated by the velocity sensor. This is in contradiction with what was initially observed in some of the cast-away data. The profiles "All SVP graph" indicated that almost no or no significant velocity change occurs at the lutocline or in the fluid mud

until end of penetration. This supports the above recommendation to estimate silt sound velocity to be 5m/sec higher than at the base of the water column.

4.2 Errors resulting from velocity estimate

Assume Silas applied a velocity of 1505 m/sec while the true velocity was 1475 m/sec. If the thickness of the layer with density < 1200 g./l. was app. 2 m thick this would give the following differences:

Thickness fluid mud (density <1200 g./l.) Silt Velocity 1505 m/sec	Thickness fluid mud (density <1200 g./l.) Silt Velocity 1475 m/sec
2.04 m	2.00 m

This means the velocity estimation error could result in a systematic mismatch error between seismic and ground truth data of 4 cm.
However, since the seismic (Silas) data are matched to the vertical scale of the geophysical point measurements there is no apparent vertical error expected at calibration points.

4.3 Recommendations for application of silt velocity

It is recommended to use a sound velocity in silt which is app. 5 m/sec higher than average at the base of the water column. It is possible to set this velocity artificially in Silas using the velocity settings at the “depth settings” entry. This should be set 35 m./sec lower than the Silt velocity to be applied, so 30 m/sec higher than average velocity at the base of the water column.
Finally re-perform the density calibration and after this, re-enter the correct depth settings for average speed of sound in the water at the Silas “depth settings” entry. Please keep a backup of the initial project.

5 References

1. Robert F. Ballard, R.G. Mc Gee, Leist, *Dredging research,-Technical notes* (US Army Engineers Waterways Experiment Station, July 1993)
2. L. Buchanan, *Surveying in fluid mud* (Hydro International Volume 9, Number 6, 2005).
3. R.G. Mc Gee, and Robert F. Ballard, David Caulfield, *A technique to assess the characteristics of bottom and subbottom marine sediments* (Dredging Research program Technical report DRP 95-3, 1995).
4. R.G. Mc Gee, and Robert F. Ballard, *An Acoustic impedance method for subbottom material characterization* (Hydraulic Engineering sessions at water forum, 1992).
5. R.Wurpt, N. Greiser, *Baggerungen und wirtschaftlichen Nutzung des Baggermaterials* (Messtechnik und Baggertechnologie fur ein Kosten sparendes Sedimentmanagement met Hilfe der Flieszfahigkeit der Baggergutes).

D Overview of calibration results

Appendix D - Overview of calibrations

	Name of calibration	First test	08-Jan	09-Jan	10-Jan	14-Jan	15-Jan	16-Jan	17-Jan	ALL	Basic set > 0.25 m	Thick	Thin
	Number of calibration points	50	5	15	10	10		10 (ARCA)		75	55	38	37
	Number of USED calibration points		5	12	9	9		10 (ARCA)		75	45	31	32
	Density level	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	no calibration performed	1.2 kg/L	no calibration performed	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L
	Cumulative model	x	x	x	x	x		x		x	x	x	x
	Cumulative model with vertical corrections	x								x	x	x	x
	Gradient model	x											
Cumulative	Arr. Power (V)	700.42	915.77	758.93	1020.67	1029.18		970.17		688.74	915.70	915.41	627.42
	Average density errors (g/l)	-11	-27	5	-6	-5		0		-25	-25	-28	-29
	Average vertical errors (cm)	0	0	0	0	0		0		0	0	0	0
	Standard Deviation (cm)	26	35	32	24	24		12		30	29	32	18
Cumulative with vertical corrections	Arr. Power (V)	702.15								688.74	915.76	915.82	647.66
	Average density errors (g/l)	-11								-25	-25	-28	-23
	Average vertical errors (cm)	0								0	0	0	0
	Standard Deviation (cm)	26								30	29	32	18
Gradient	Arr. Power (V)	not specified											
	Average density errors (g/l)												
	Average vertical errors (cm)												
	Standard Deviation (cm)												

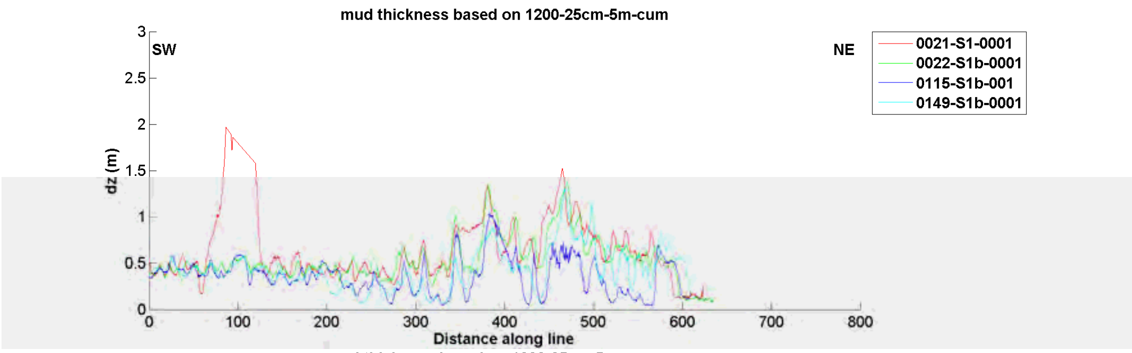
	Name of calibration	Random 40	Random 40b	Random 40c	Random 40d	Random 40e	Random 30	Random 30b	Random 30c	Random 30d	Random 30e	Random 20	Random 20b
	Number of calibration points	40	40	40	40	40	30	30	30	30	30	20	20
	Number of USED calibration points	40	40	40	40	40	30	30	30	30	30	20	20
	Density level	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L
	Cumulative model	x	x	x	x	x	x	x	x	x	x	x	x
	Cumulative model with vertical corrections	x					x					x	
	Gradient model												
Cumulative	Arr. Power (V)	891.48	1015.74	1043.76	1057.77	1043.76	915.77	1057.77	896.65	879.49	903.71	943.58	834.03
	Average density errors (g/l)	-17	-30	-20	-25	-27	-10	-20	-16	-30	-21	-9	-18
	Average vertical errors (cm)	0	0	0	0	0	0	0	0	0	0	0	0
	Standard Deviation (cm)	26	32	30	27	32	26	25	23	26	31	27	28
Cumulative with vertical corrections	Arr. Power (V)	891.54					915.82					943.69	
	Average density errors (g/l)	-17					-10					-9	
	Average vertical errors (cm)	0					0					0	
	Standard Deviation (cm)	26					26					27	

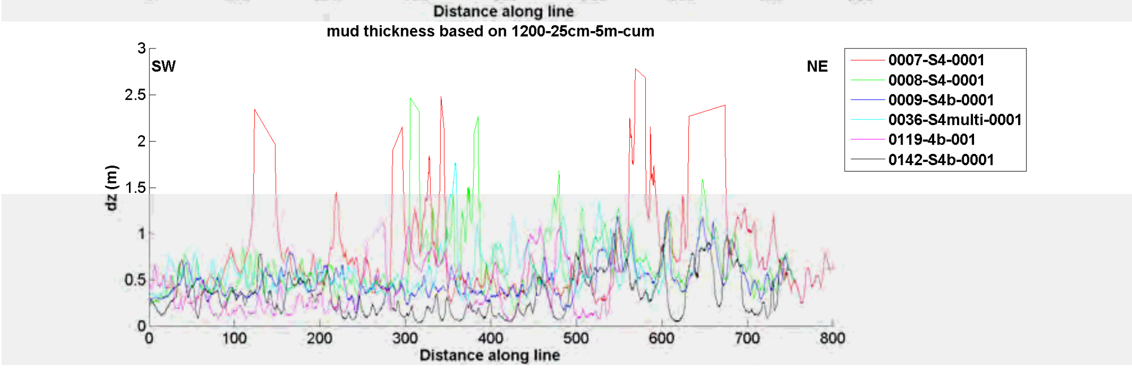
	Name of calibration	Random 20c	Random 20d	Random 20e	Random 10	Random 10b	Random 10c	Random 10d	Random 10e	Level 1.15	Level 1.16	Level 1.17	Level 1.18
	Number of calibration points	20	20	20	10	10	10	10	10	75	75	75	75
	Number of USED calibration points	20	20	20	10	10	10	10	10	64	64	64	64
	Density level	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.2 kg/L	1.15 kg/L	1.16 kg/L	1.17 kg/L	1.18 kg/L
	Cumulative model	x	x	x	x	x	x	x	x	x	x	x	x
	Cumulative model with vertical corrections				x					x	x	x	x
	Gradient model												
Cumulative	Arr. Power (V)	909.77	1024.90	1061.13	1093.76	1209.77	1049.02	870.41	861.95	492.46	632.98	723.83	776.72
	Average density errors (g/l)	-24	-40	-38	-8	-24	6	-14	-44	-15	-2	0	-5
	Average vertical errors (cm)	0	0	0	0	0	0	0	0	0	0	0	0
	Standard Deviation (cm)	28	32	32	20	29	19	23	31	15	26	27	28
Cumulative with vertical corrections	Arr. Power (V)				1093.76					507.03	633.01	723.83	770.65
	Average density errors (g/l)				-8					-12	-2	0	-6
	Average vertical errors (cm)				0					0	0	0	0
	Standard Deviation (cm)				20					15	26	27	28

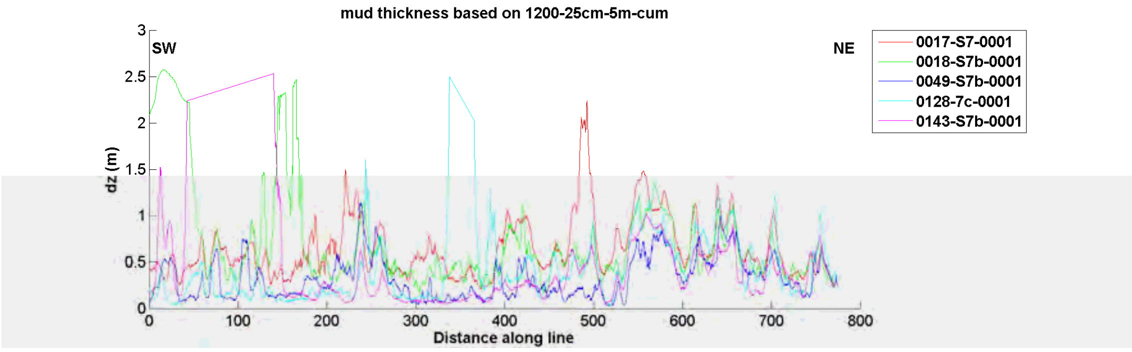
	Name of calibration	Level 1.19	Level 1.20	Level 1.21	Level 1.22	Level 1.23	Level 1.24	Level 1.25	Basic set>0.25 m_LATER	Basic set>0.25 m_MUCH LATER
	Number of calibration points	75	75	75	75	75	75	75	55	55
	Number of USED calibration points	64	64	64	64	64	64	64	44	44
	Density level	1.19 kg/L	1.20 kg/L	1.21 kg/L	1.22 kg/L	1.23 kg/L	1.24 kg/L	1.25 kg/L	1.2 kg/L	1.2 kg/L
	Cumulative model	x	x	x	x	x	x	x	x	x
	Cumulative model with vertical corrections	x	x	x	x	x	x	x		x
	Gradient model									
Cumulative	Arr. Power (V)	824.84	837.82	863.50	885.55	903.71	903.71	879.49	1172.99	1209.03
	Average density errors (g/l)	-13	-15	-18	-24	-27	-25	-36	-10	-13
	Average vertical errors (cm)	0	0	0	0	0	0	0	0	0
	Standard Deviation (cm)	27	28	28	28	29	29	30	26	30
Cumulative with vertical corrections	Arr. Power (V)	824.84	837.82	870.30	885.55	903.71	903.71	879.49		1209.03
	Average density errors (g/l)	-13	-15	-17	-24	-27	-30	-36		-13
	Average vertical errors (cm)	0	0	0	0	0	0	0		0
	Standard Deviation (cm)	27	28	28	28	29	29	30		30

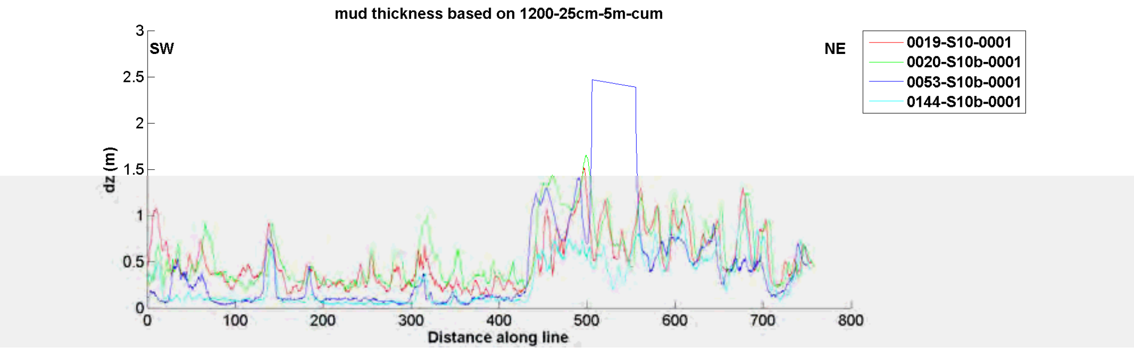
E Figures of multiple measured lines

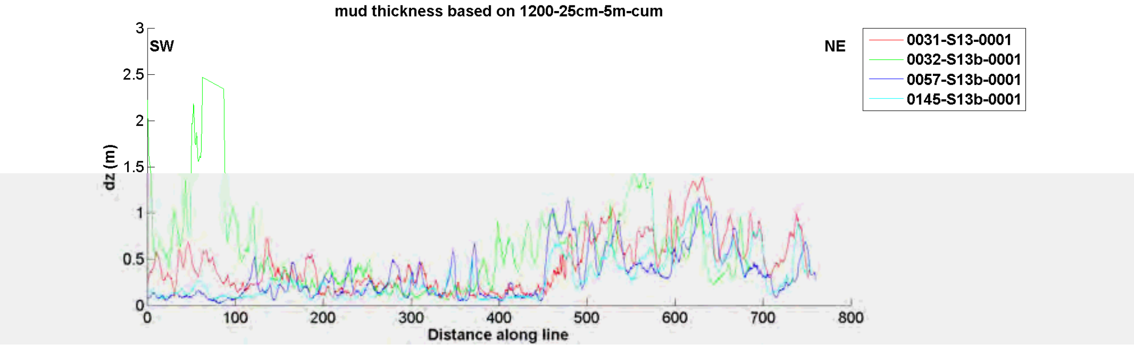
The figures in this appendix show the mud thickness (dz) as a function of distance along the line for the lines that have been measured multiple times with standard vessel speed of 2 m/s. The parts of the lines with no SILAS data can be recognized by the sudden jump to high thickness, e.g. around 100 m distance along the line for the figure below. The standard calibration (1200_25cm_5m_cum) has been used.

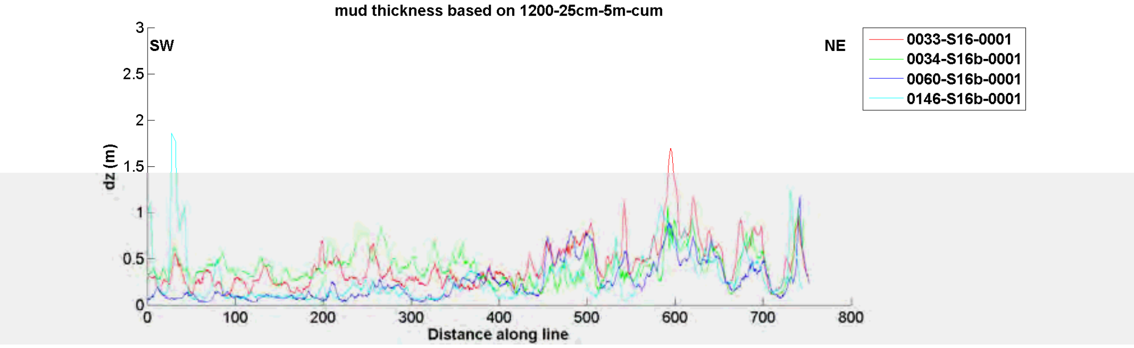


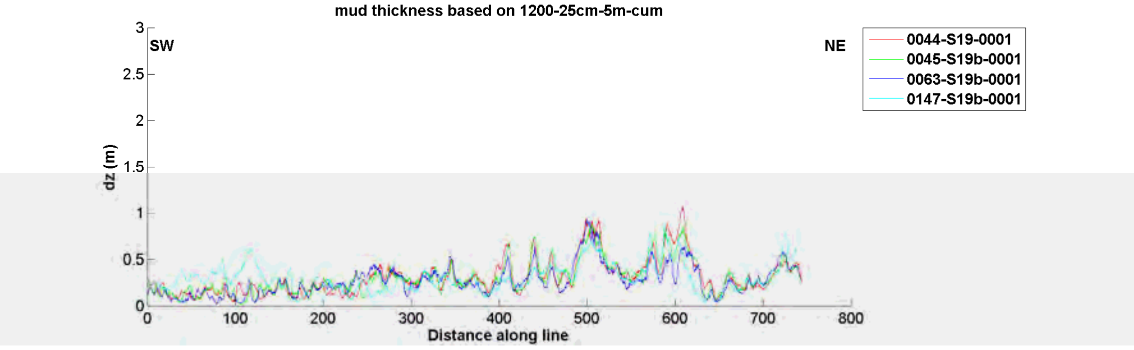


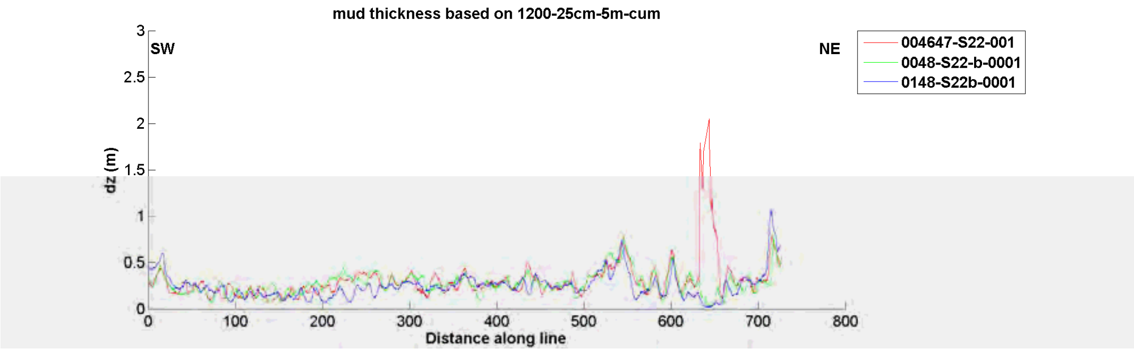


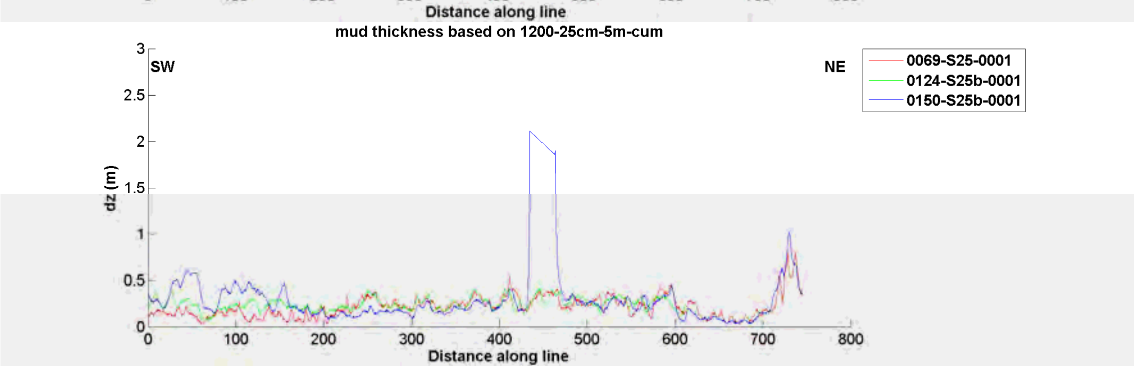

mud thickness based on 1200-25cm-5m-cum
SW
NE
0019-S10-0001
0020-S10b-0001
0053-S10b-0001
0144-S10b-0001
dz (m)
Distance along line

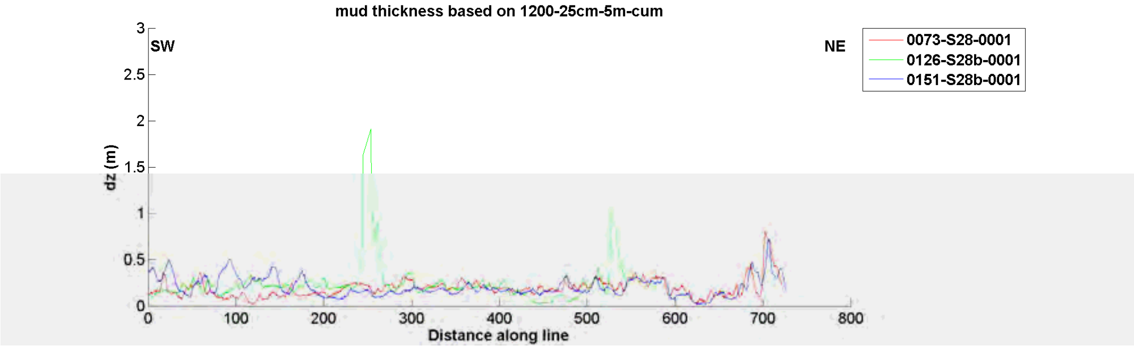

mud thickness based on 1200-25cm-5m-cum
SW
NE
0031-S13-0001
0032-S13b-0001
0057-S13b-0001
0145-S13b-0001
dz (m)
Distance along line


mud thickness based on 1200-25cm-5m-cum
SW
NE
0033-S16-0001
0034-S16b-0001
0060-S16b-0001
0146-S16b-0001
dz (m)
Distance along line


mud thickness based on 1200-25cm-5m-cum
SW
NE
0044-S19-0001
0045-S19b-0001
0063-S19b-0001
0147-S19b-0001
dz (m)
Distance along line

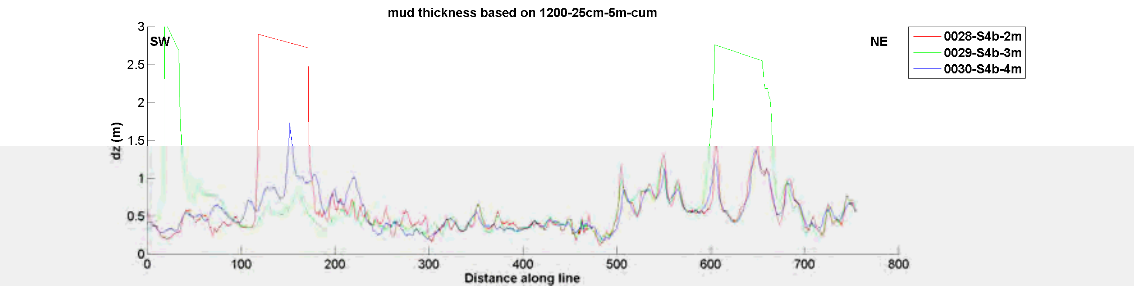

mud thickness based on 1200-25cm-5m-cum
SW
NE
004647-S22-001
0048-S22-b-0001
0148-S22b-0001
dz (m)
Distance along line

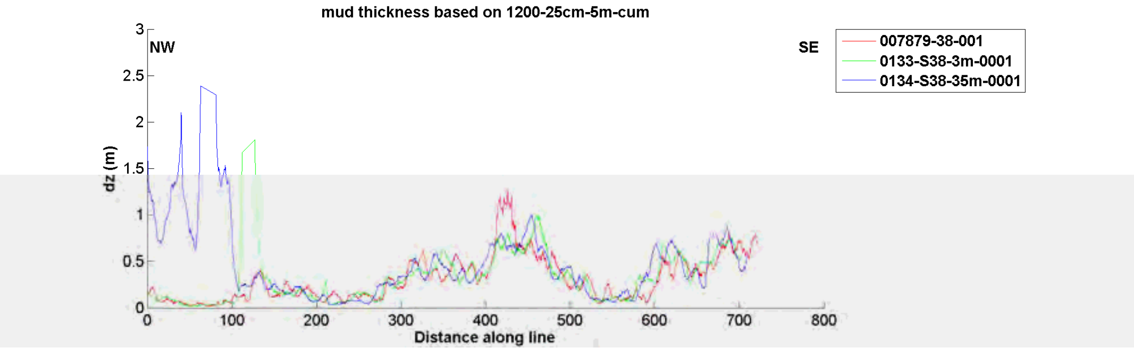

mud thickness based on 1200-25cm-5m-cum
SW
NE
0069-S25-0001
0124-S25b-0001
0150-S25b-0001
dz (m)
Distance along line

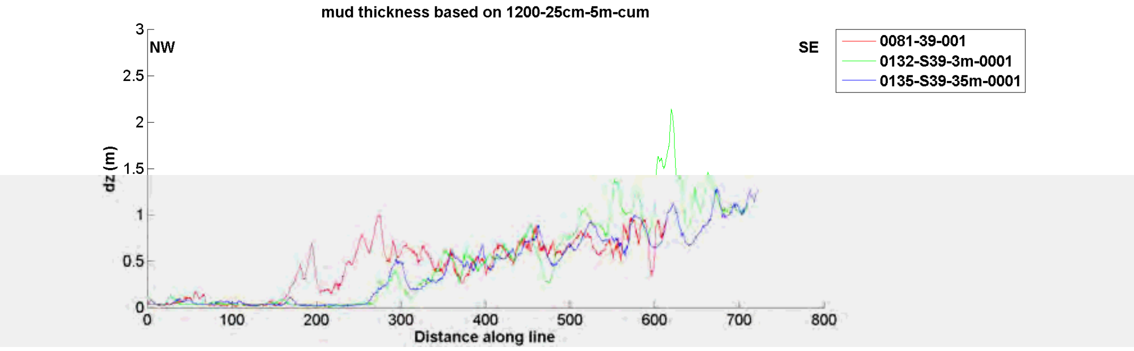

mud thickness based on 1200-25cm-5m-cum
SW
NE
0073-S28-0001
0126-S28b-0001
0151-S28b-0001
dz (m)
Distance along line

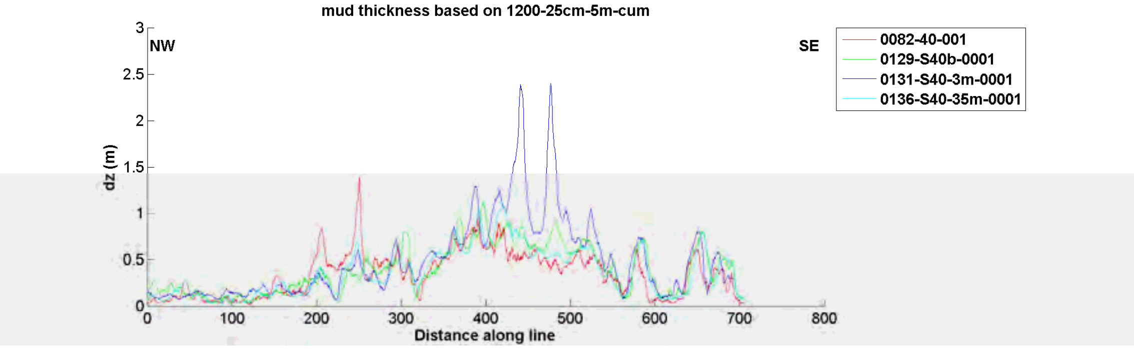
F Figures of different vessel speeds

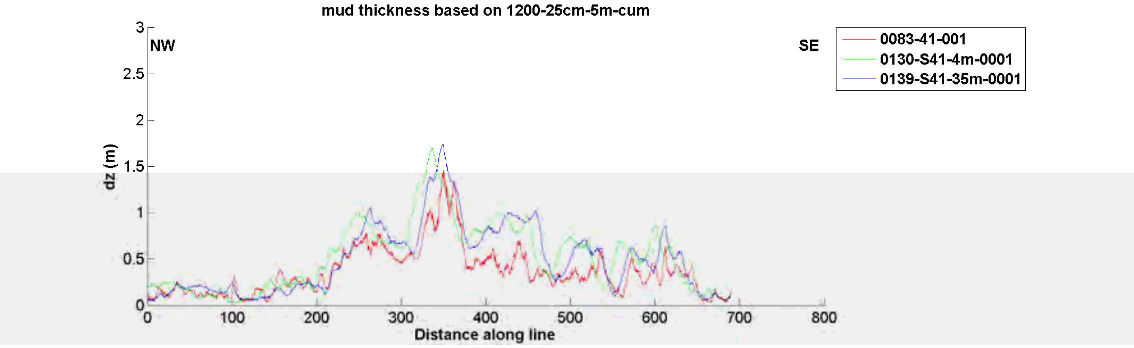
The figures in this appendix show the mud thickness (dz) as a function of distance along the line for the lines that have been measured multiple times with different speeds. The parts of the lines with no SILAS data can be recognised by the sudden jump to high thickness, e.g. between 100 and 200 m distance along the line for the figure below. The standard calibration (1200_25cm_5m_cum) has been used. From top to bottom, lines S4, 38, 39, 40, 41 and 42 are shown. In the legend, the speed is indicated: 2m indicates a speed of 2 m/s, etc; 35m indicates a speed of 3.5 m/s (no dots in filename allowed).

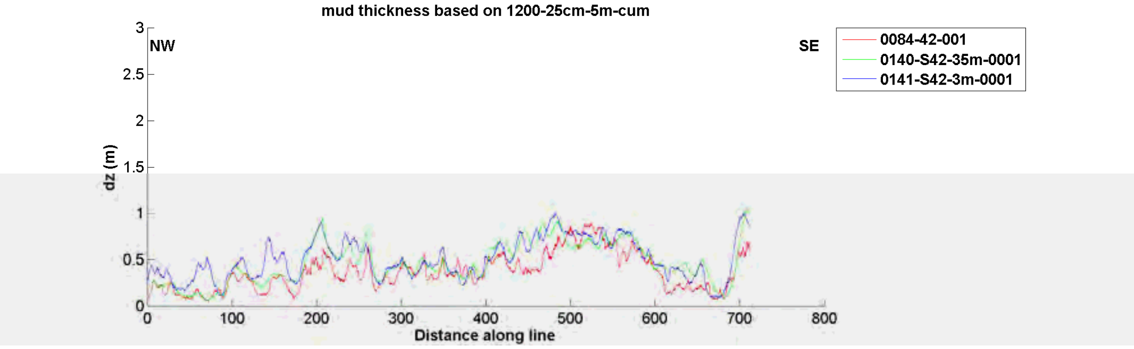




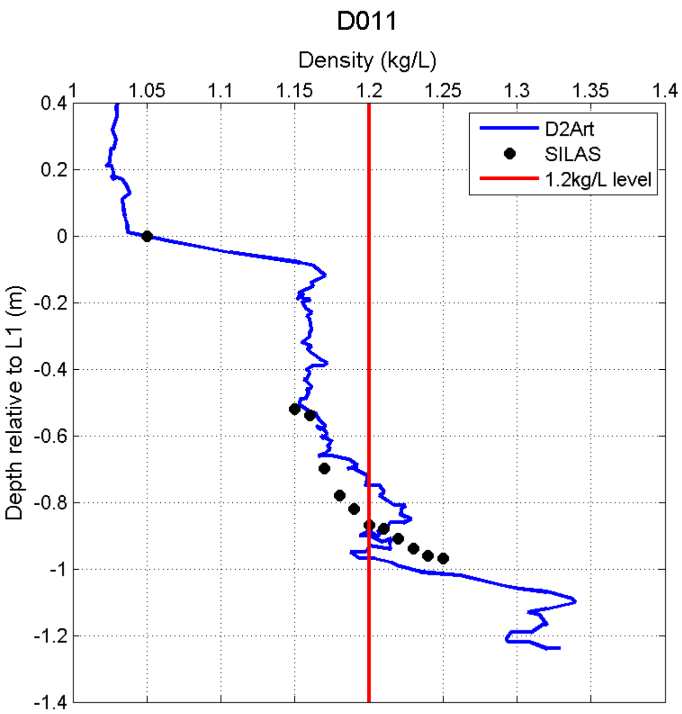


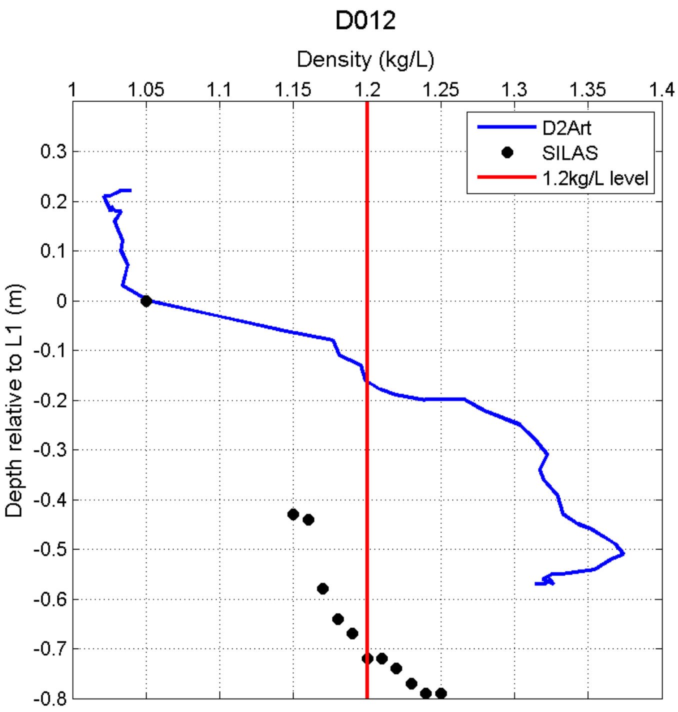

mud thickness based on 1200-25cm-5m-cum
NW
SE
0082-40-001
0129-S40b-0001
0131-S40-3m-0001
0136-S40-35m-0001
dz (m)
Distance along line

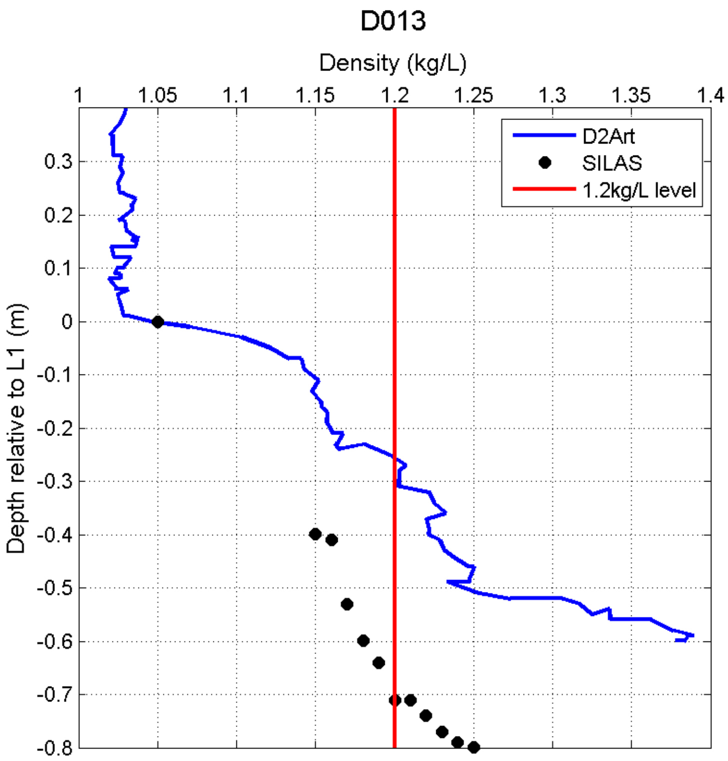

mud thickness based on 1200-25cm-5m-cum
NW
SE
0083-41-001
0130-S41-4m-0001
0139-S41-35m-0001
dz (m)
Distance along line

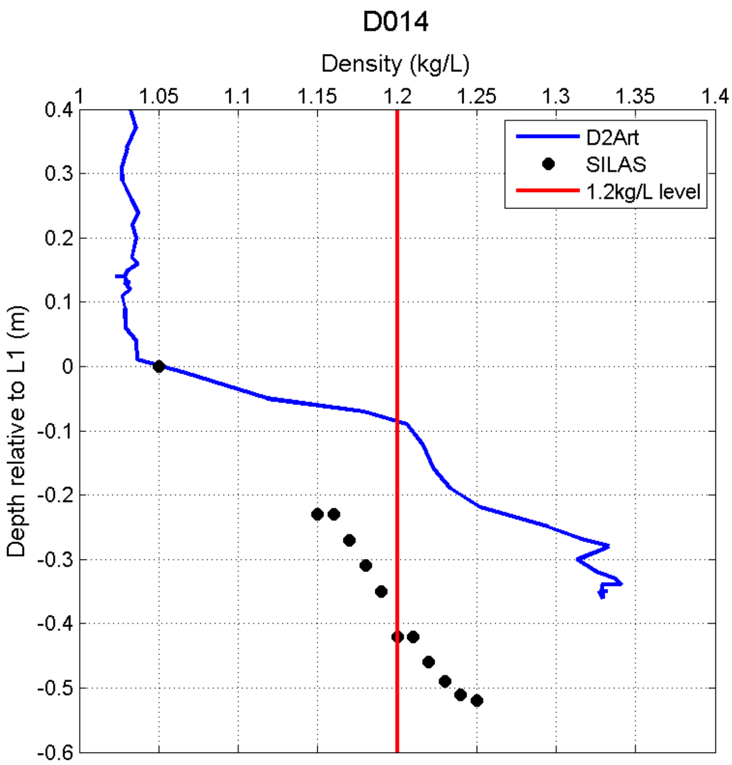

mud thickness based on 1200-25cm-5m-cum
NW
SE
0084-42-001
0140-S42-35m-0001
0141-S42-3m-0001
dz (m)
Distance along line

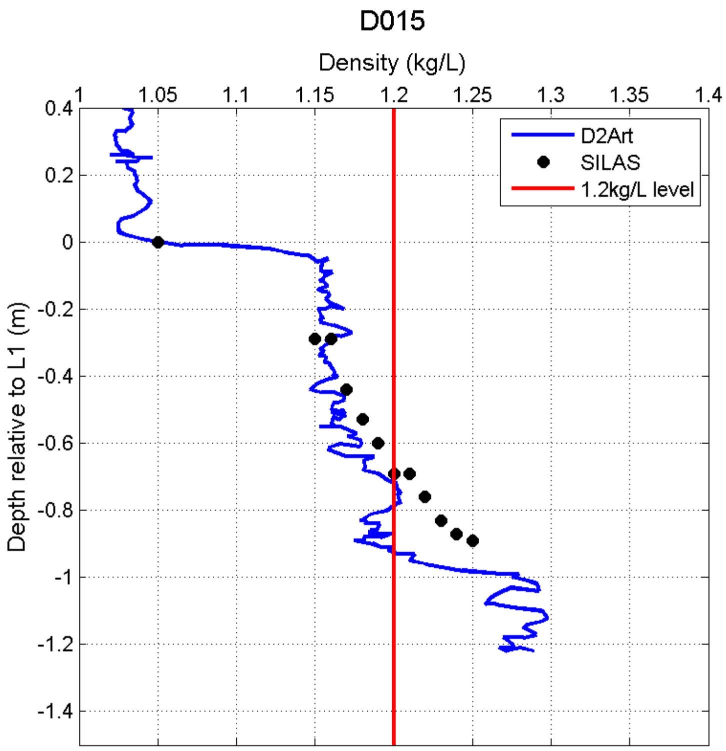
G Measured and reconstructed density profiles

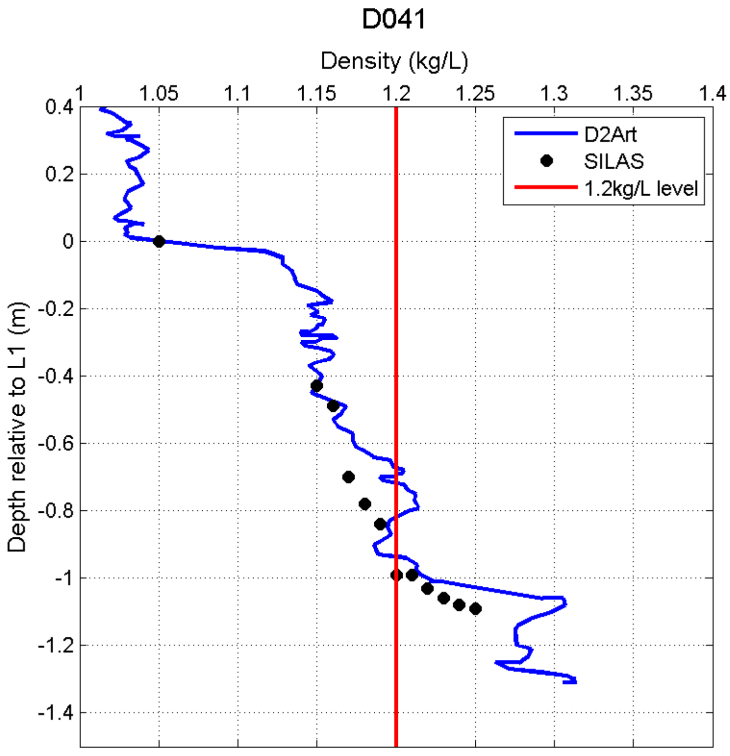


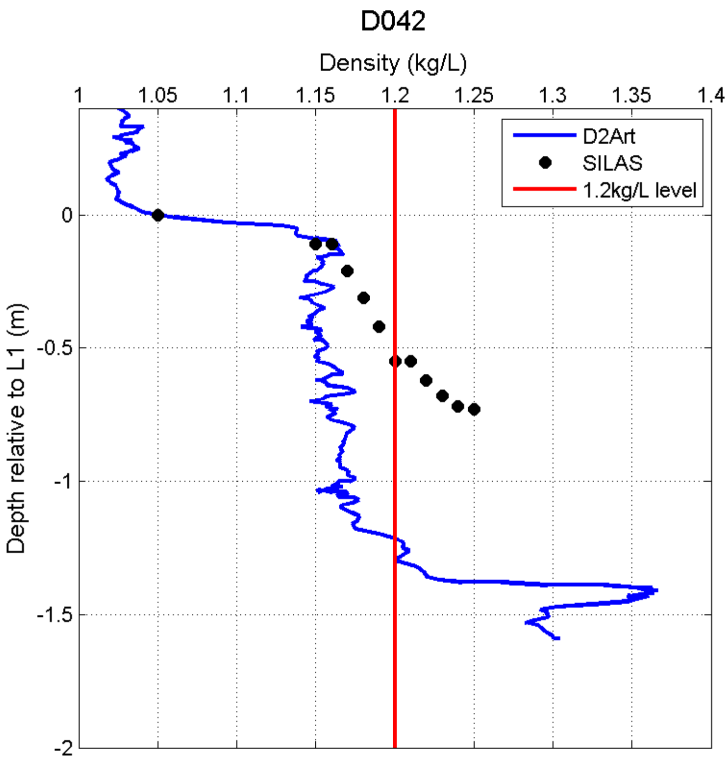


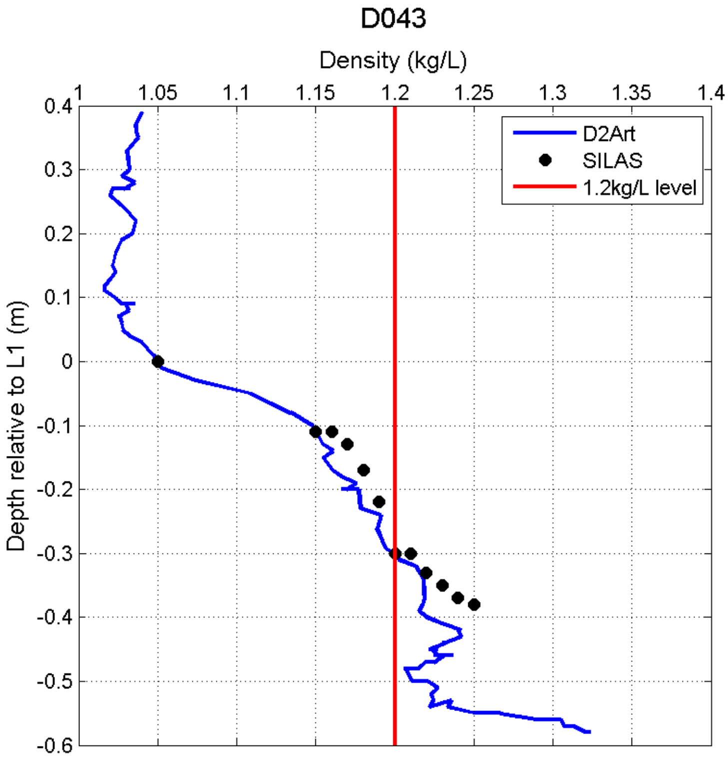

D013
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
D2Art
SILAS
1.2kg/L level

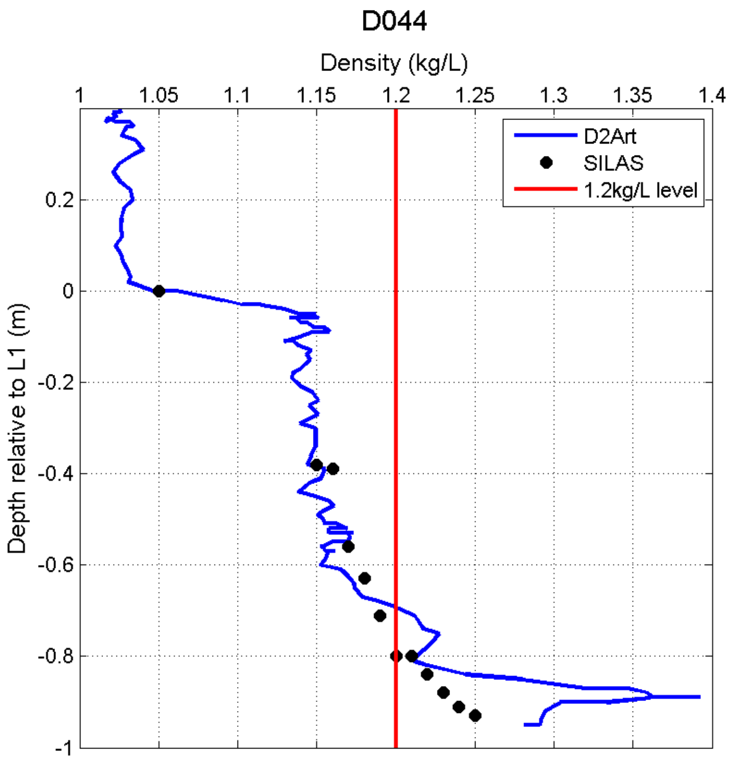

D014
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
D2Art
SILAS
1.2kg/L level

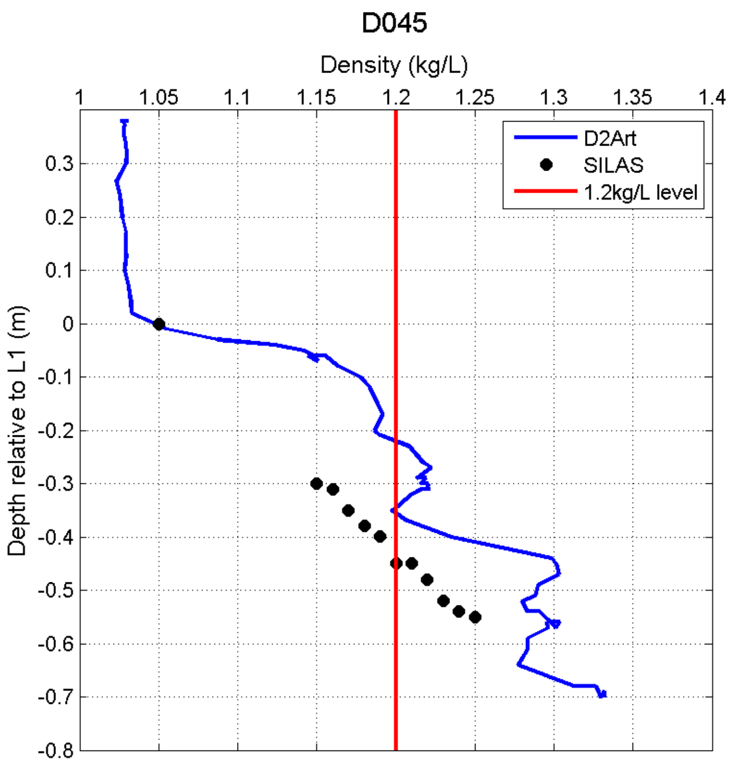

D015
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

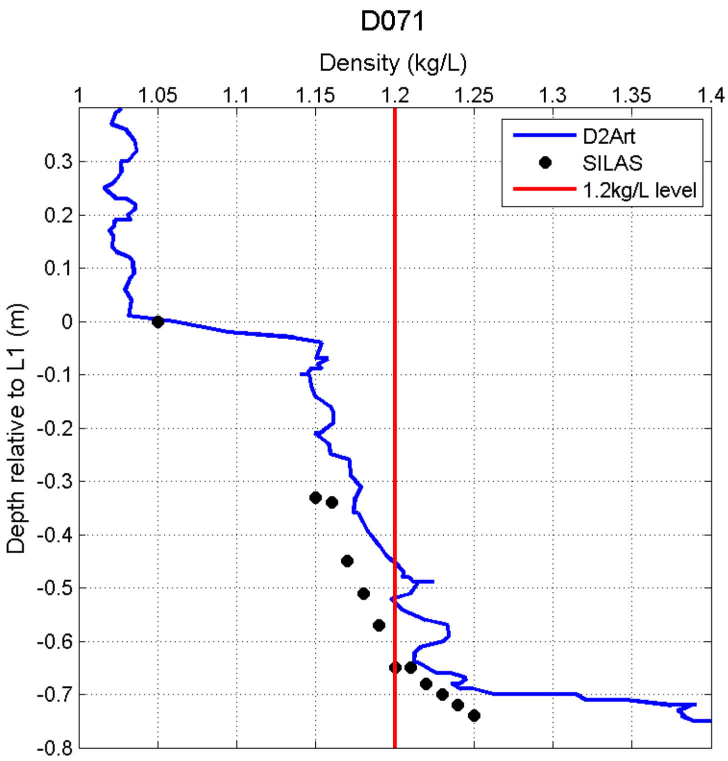

D041
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

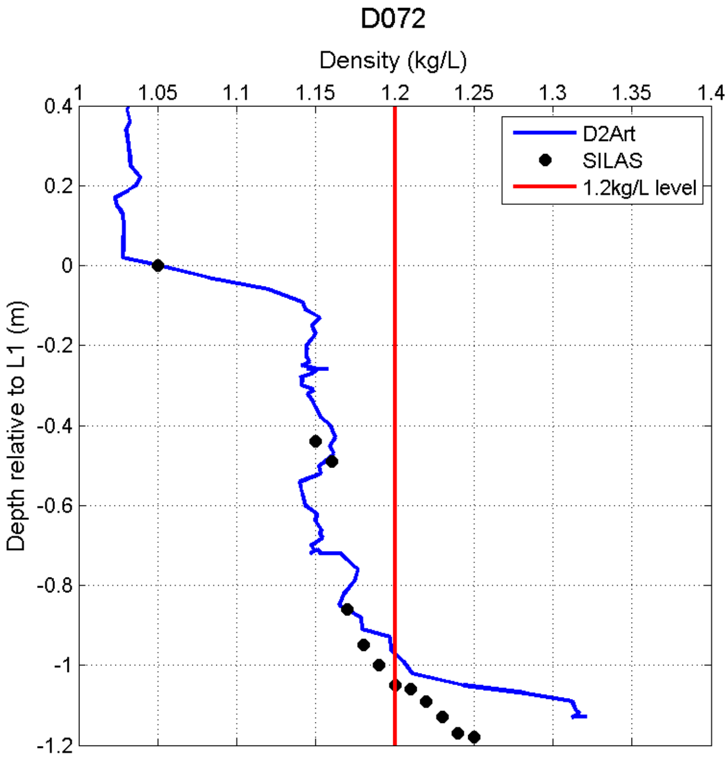

D042
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0
-0.5
-1
-1.5
-2
D2Art
SILAS
1.2kg/L level

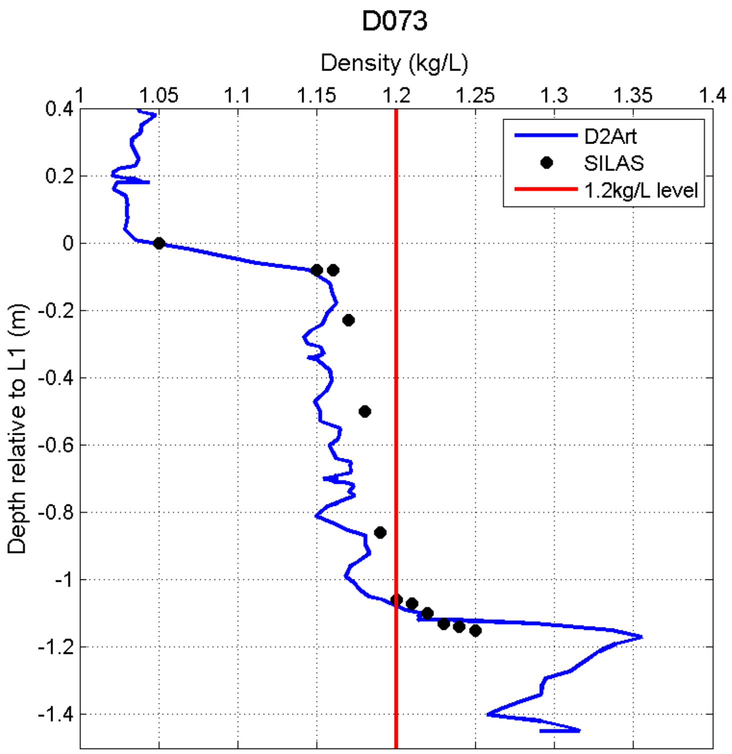

D043
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
D2Art
SILAS
1.2kg/L level

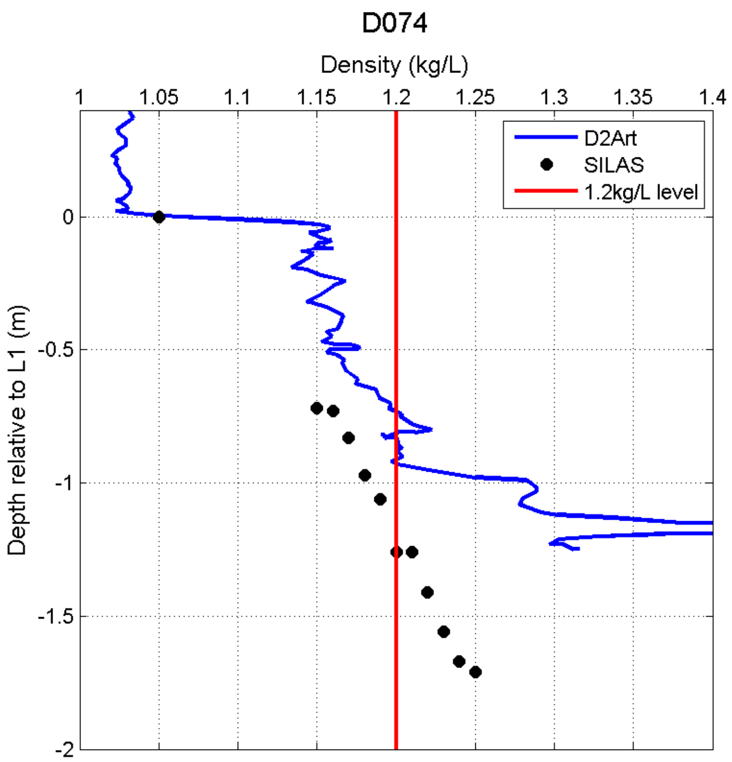

D044
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
D2Art
SILAS
1.2kg/L level
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Depth relative to L1 (m)

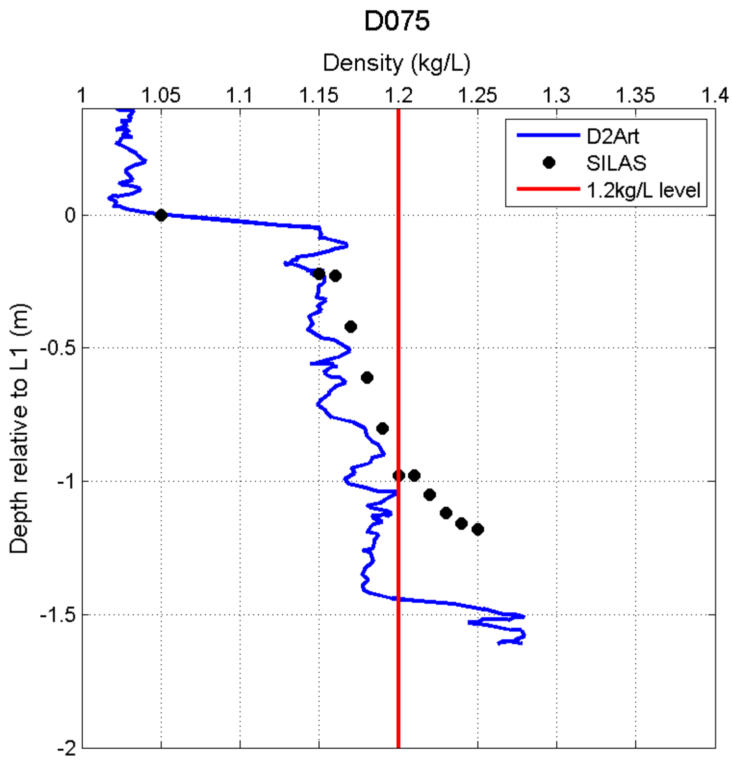

D045
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
D2Art
SILAS
1.2kg/L level
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
Depth relative to L1 (m)

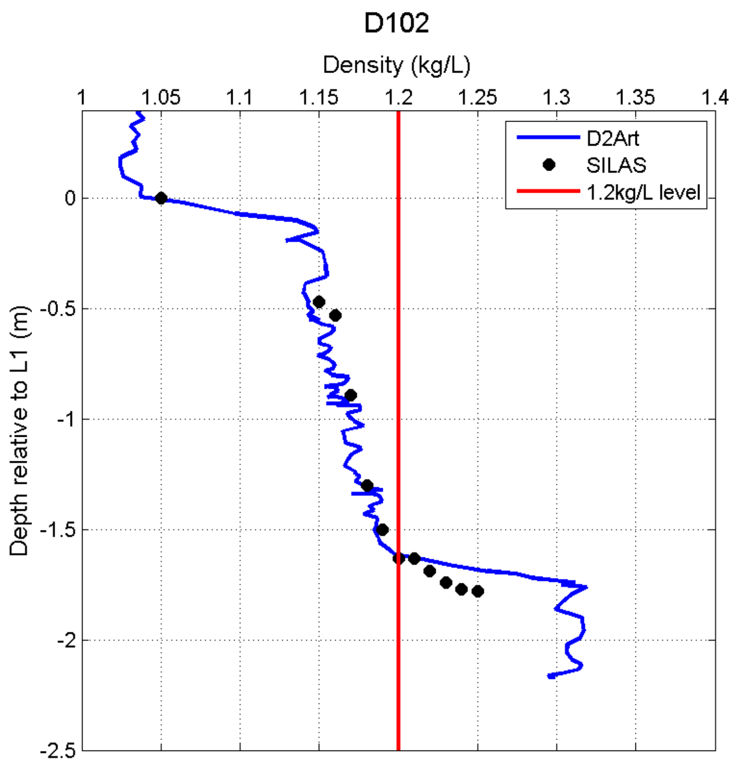

D071
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

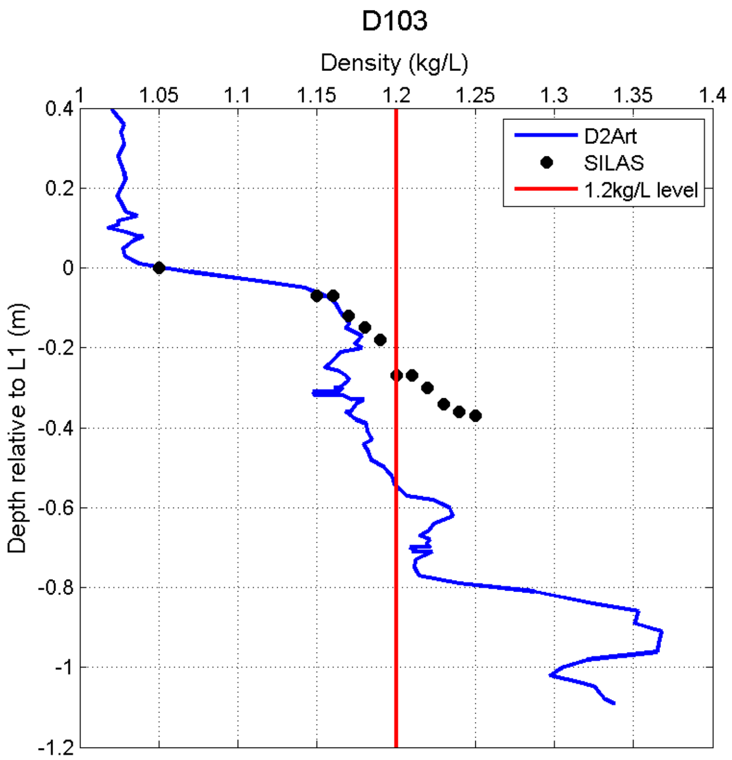

D072
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

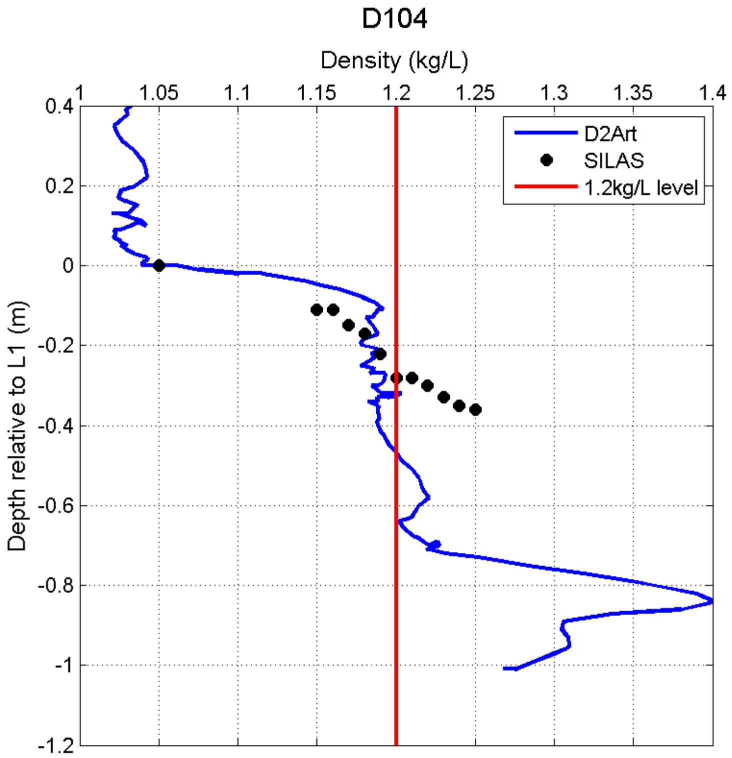

D073
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

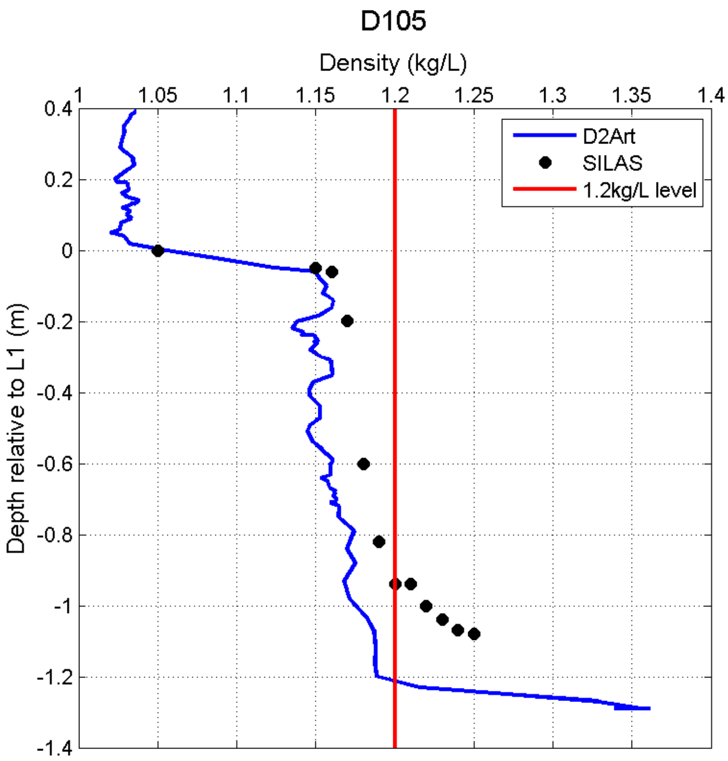

D074
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

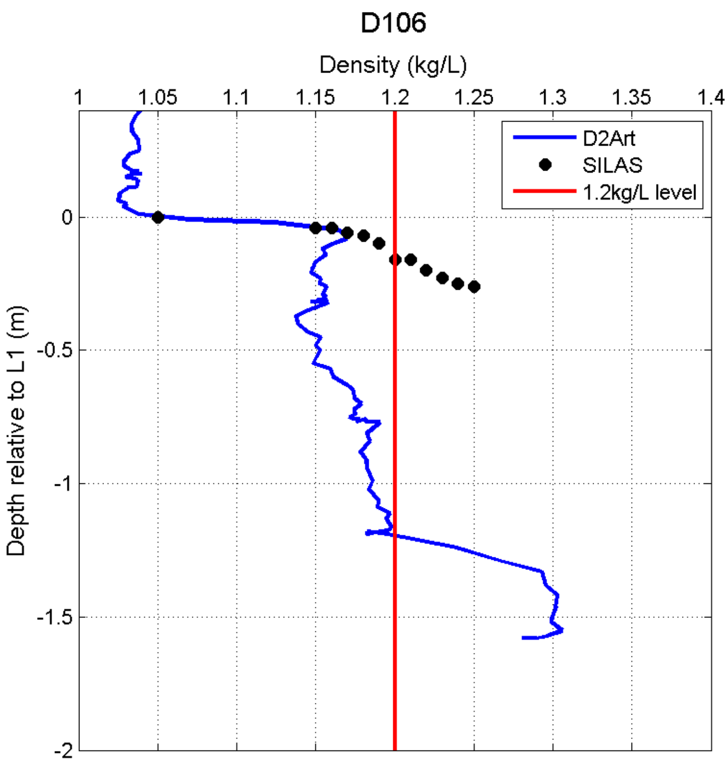

D075
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0
-0.5
-1
-1.5
-2
D2Art
SILAS
1.2kg/L level

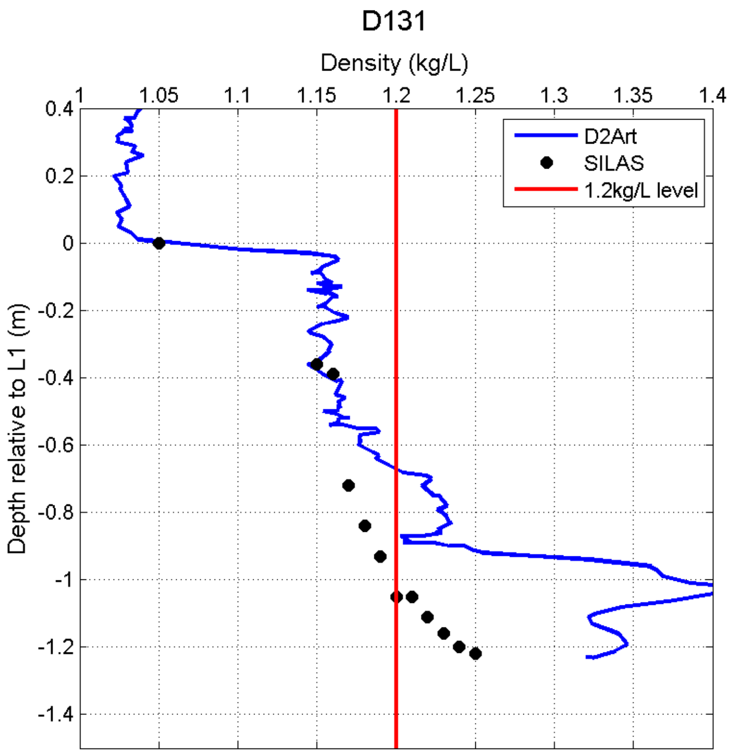

D102
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0
-0.5
-1
-1.5
-2
-2.5
D2Art
SILAS
1.2kg/L level

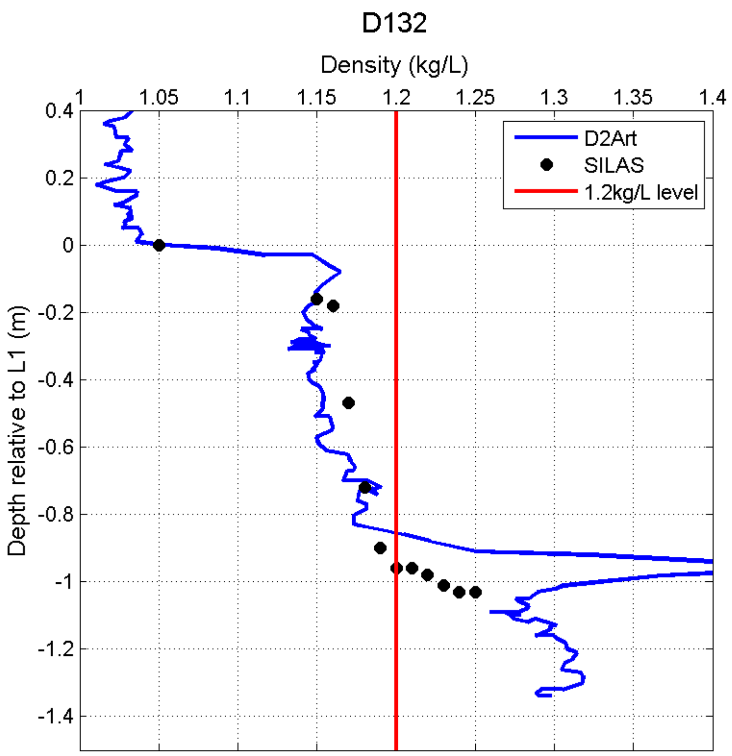

D103
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

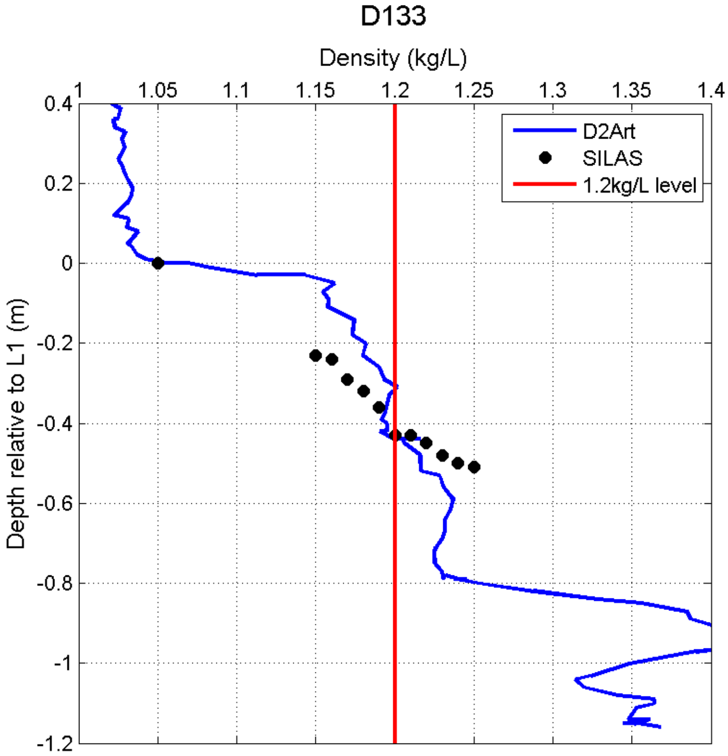

D104
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

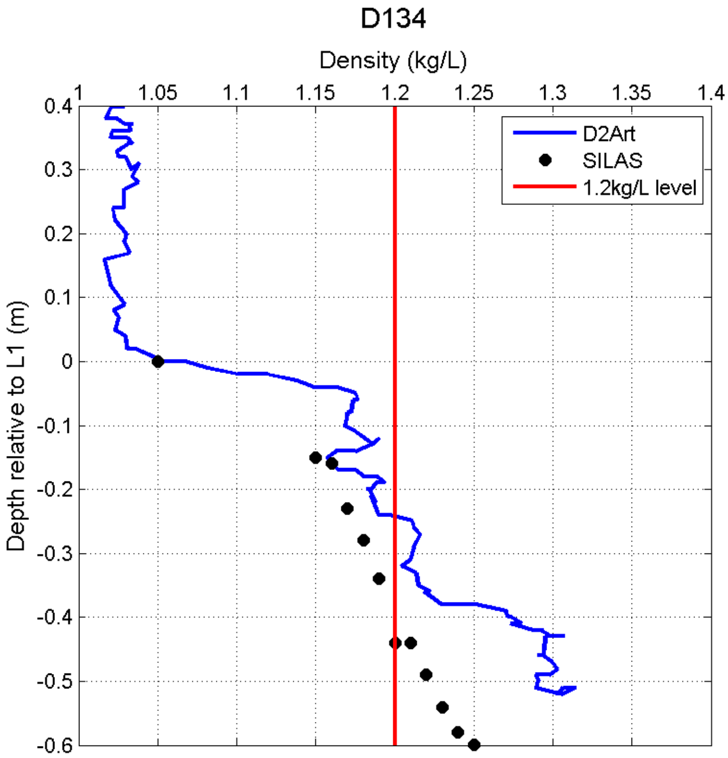

D105
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

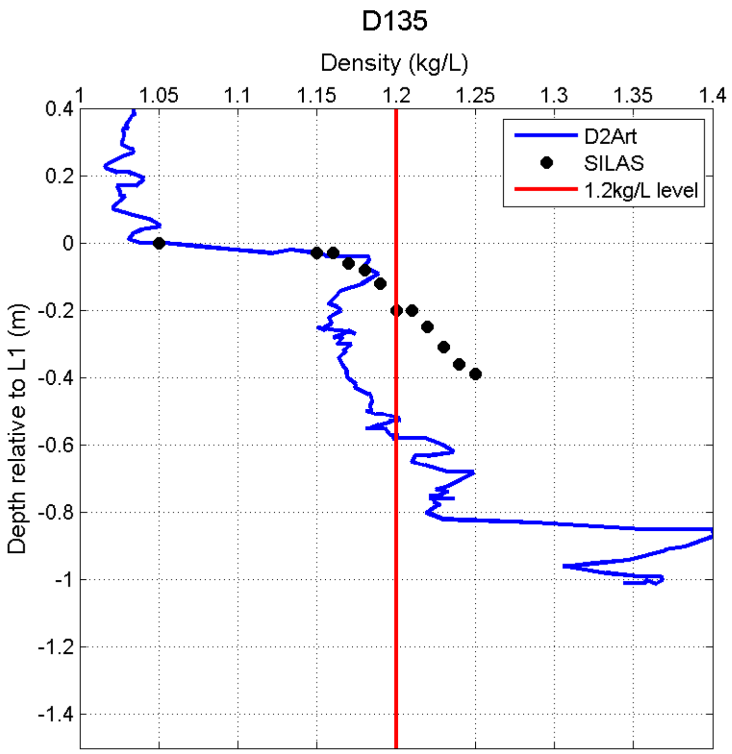

D106
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

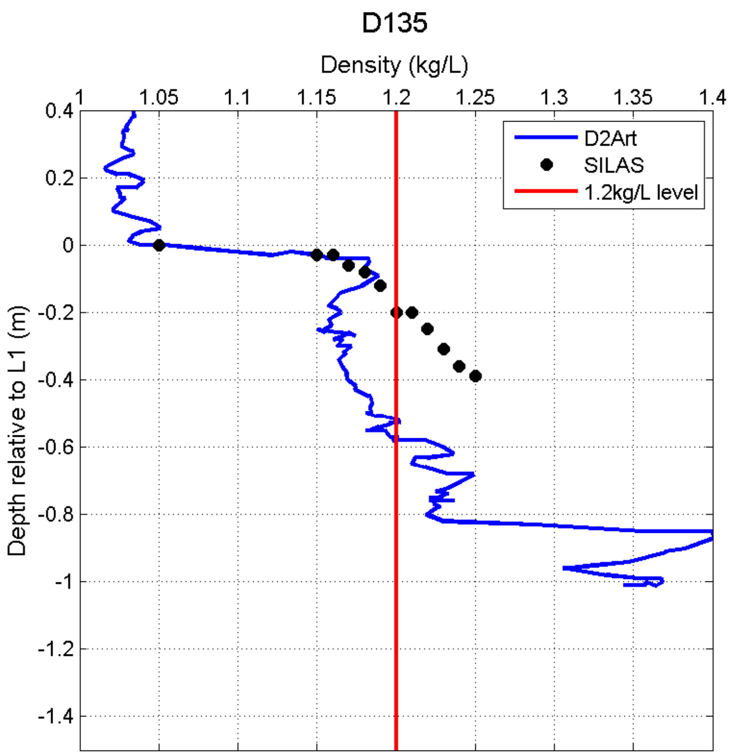

D131
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

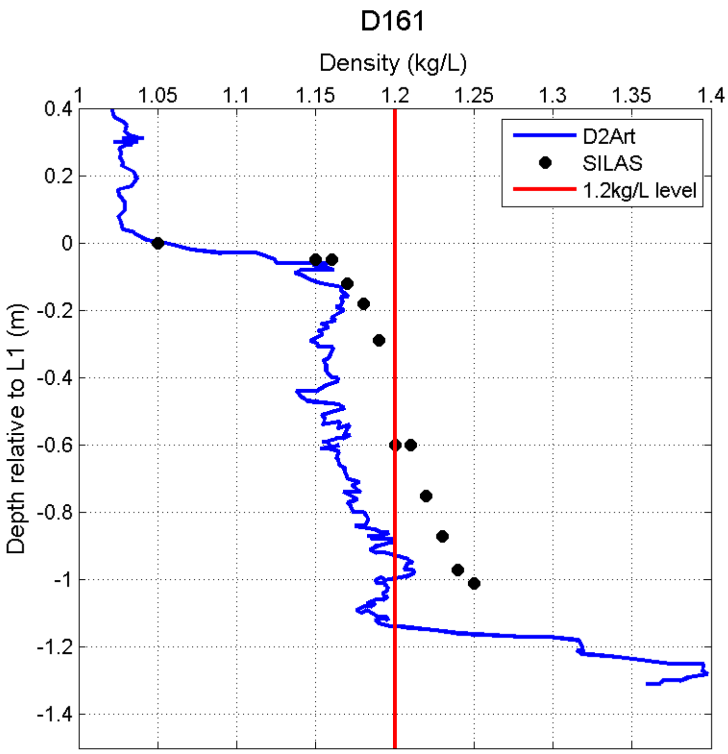

D132
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

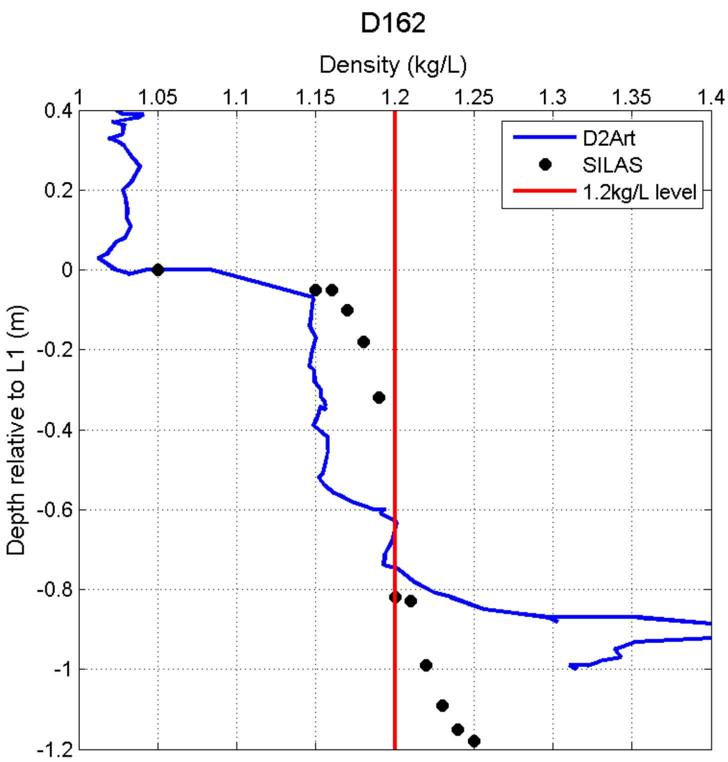

D133
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

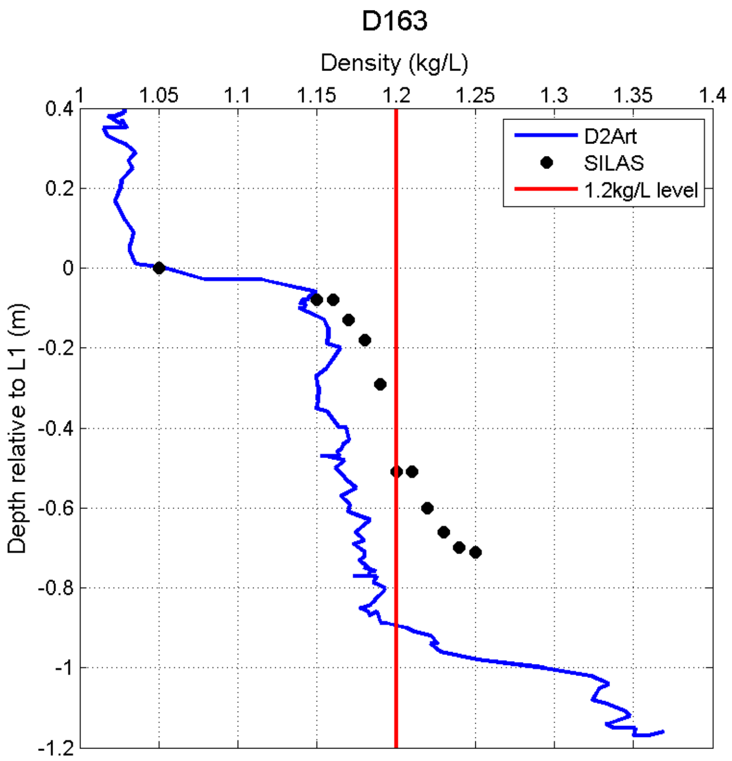

D134
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level


D135
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

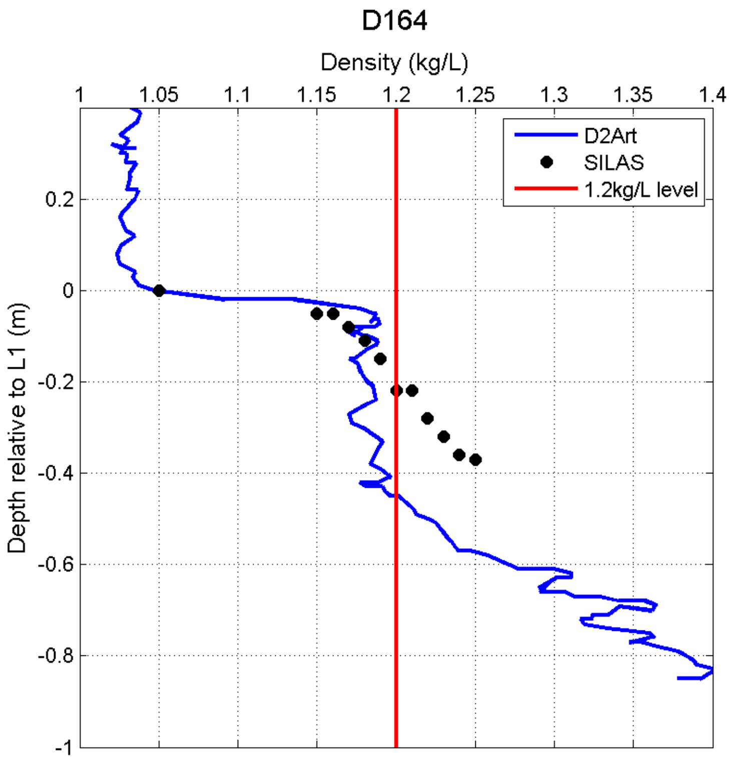

D135
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level


D161
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

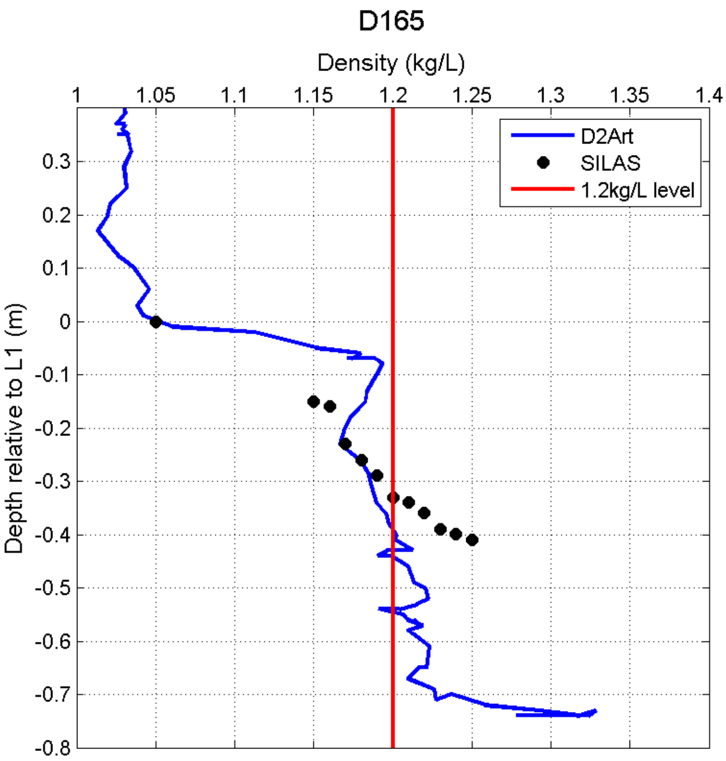

D162
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

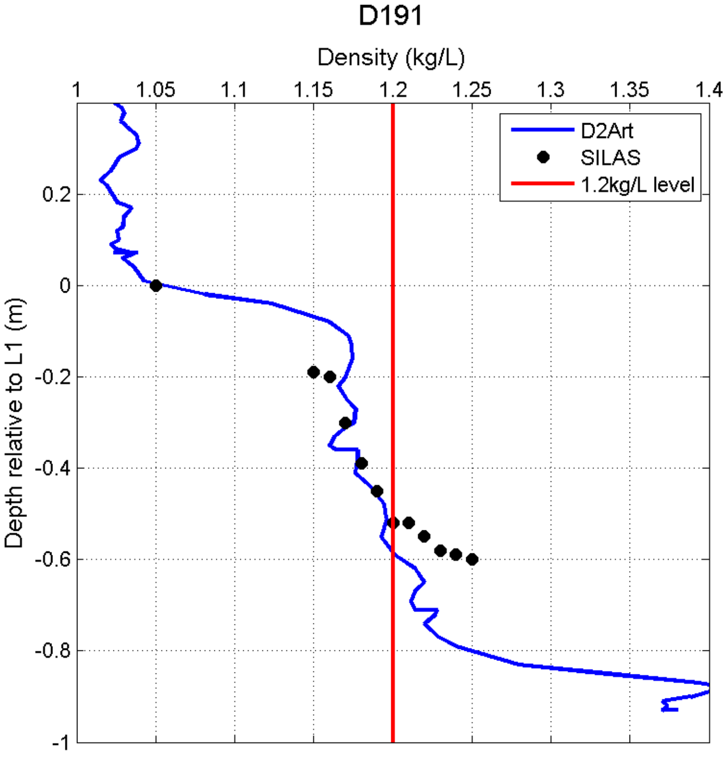


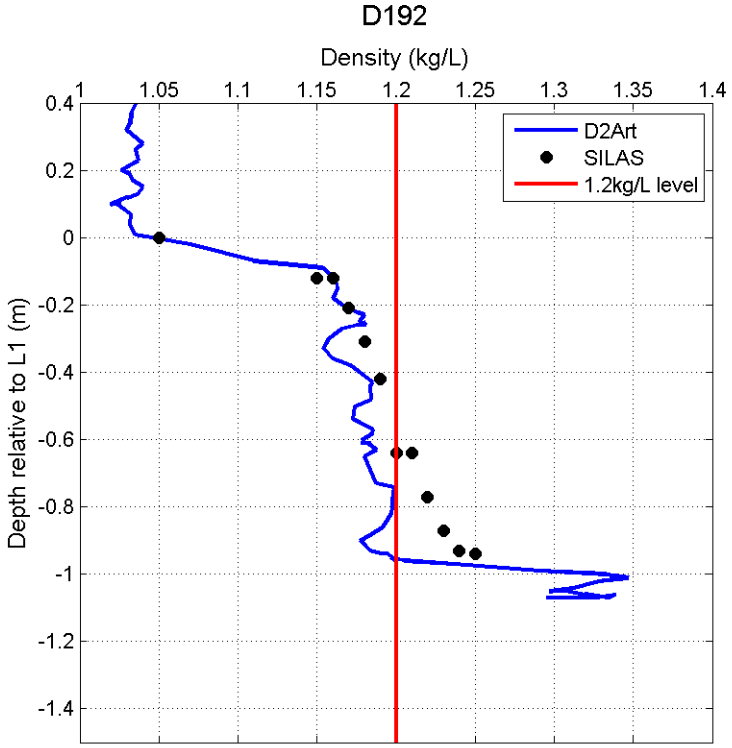
D163
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

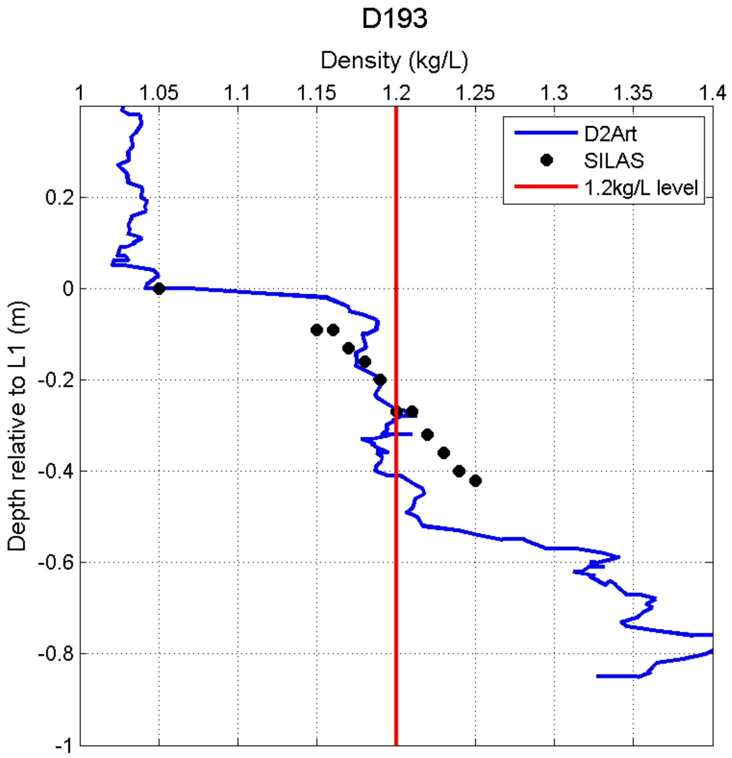


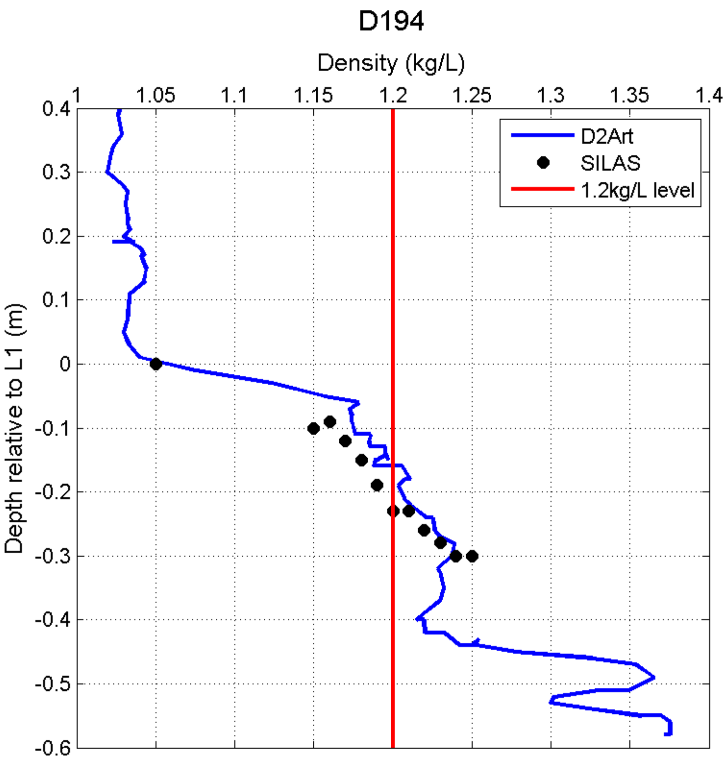
D164
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

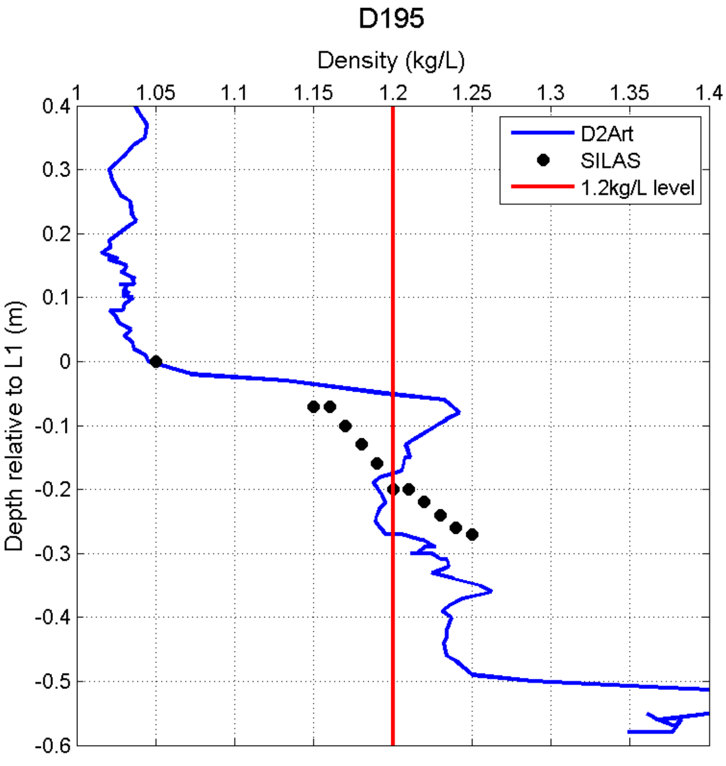

D165
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
D2Art
SILAS
1.2kg/L level

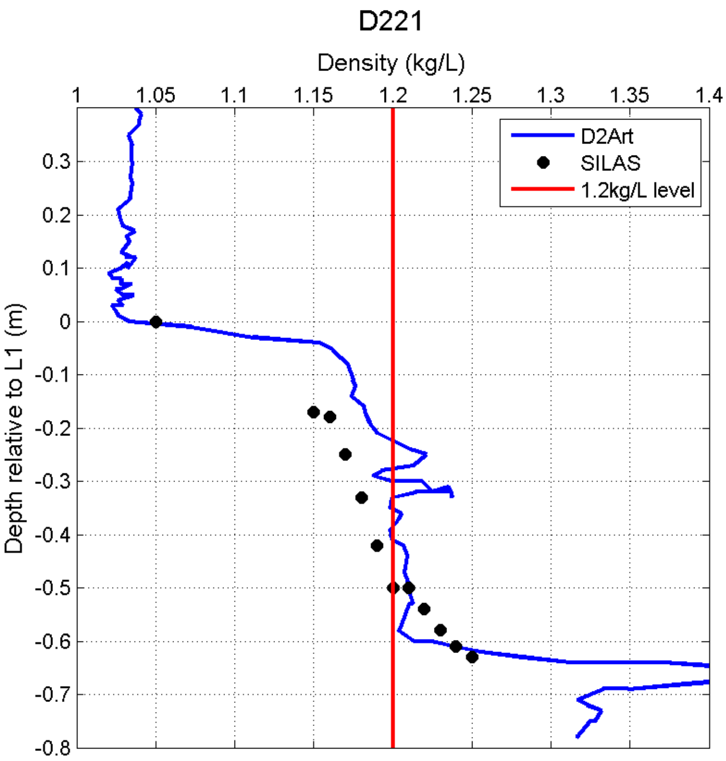

D191
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
D2Art
SILAS
1.2kg/L level


D192
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

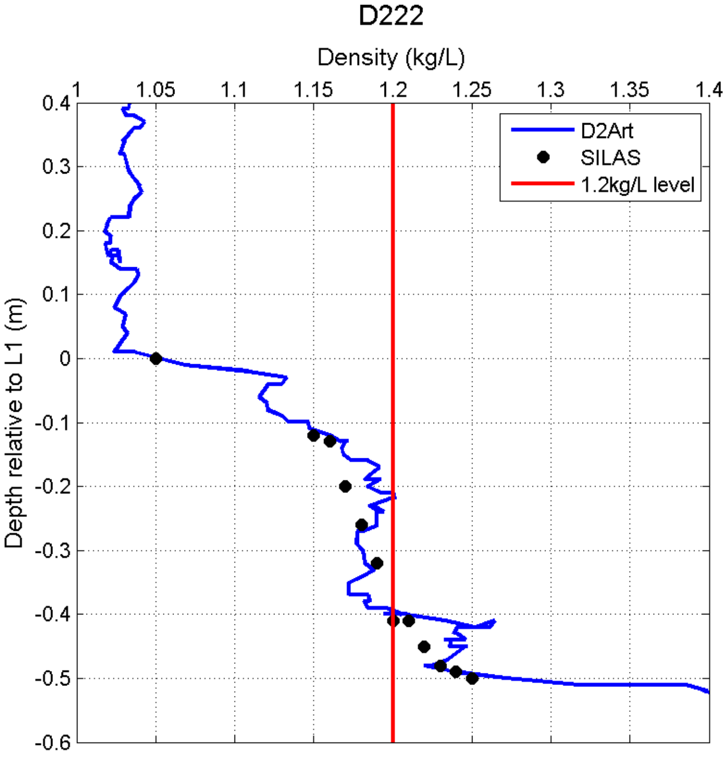

D193
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level


D194
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

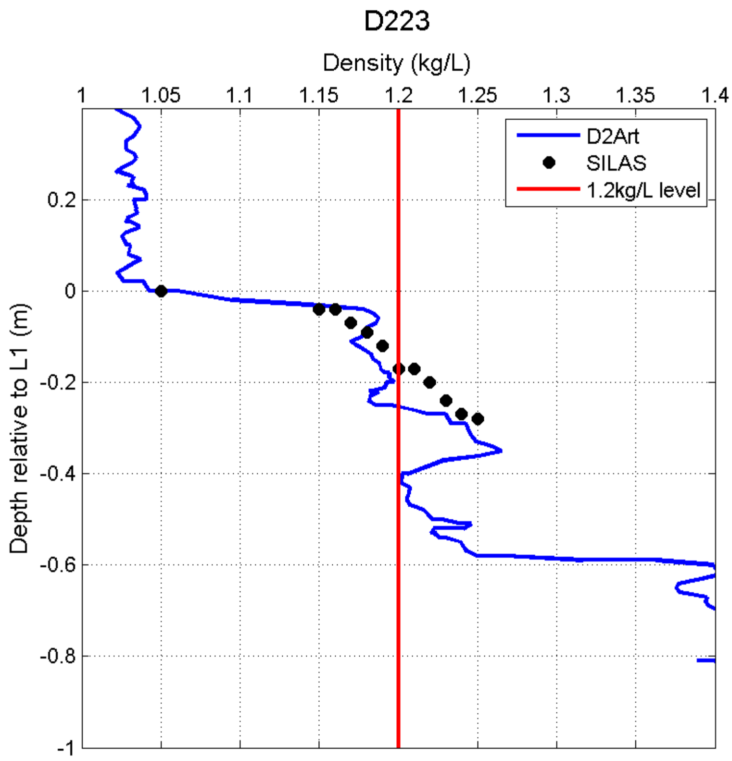

D195
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

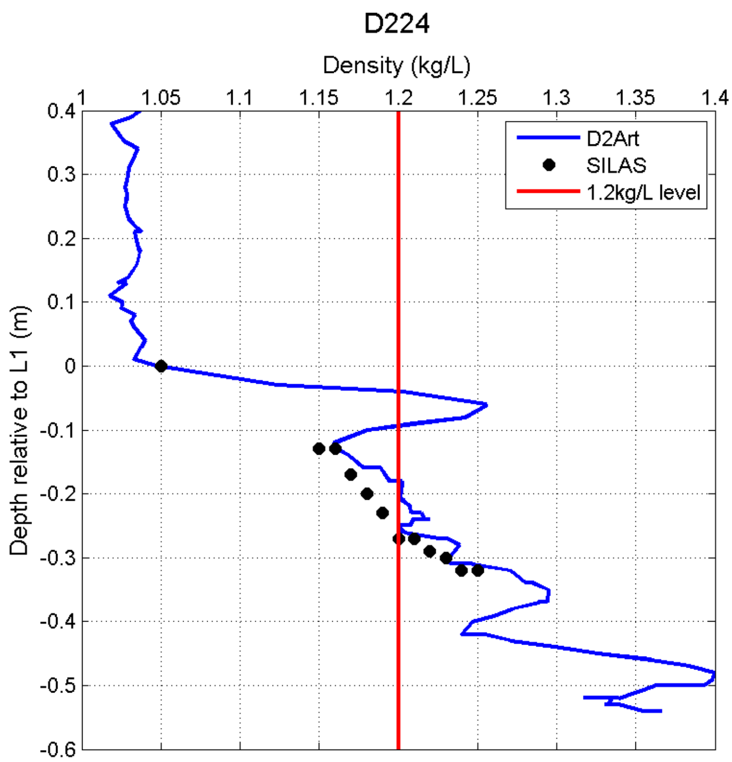


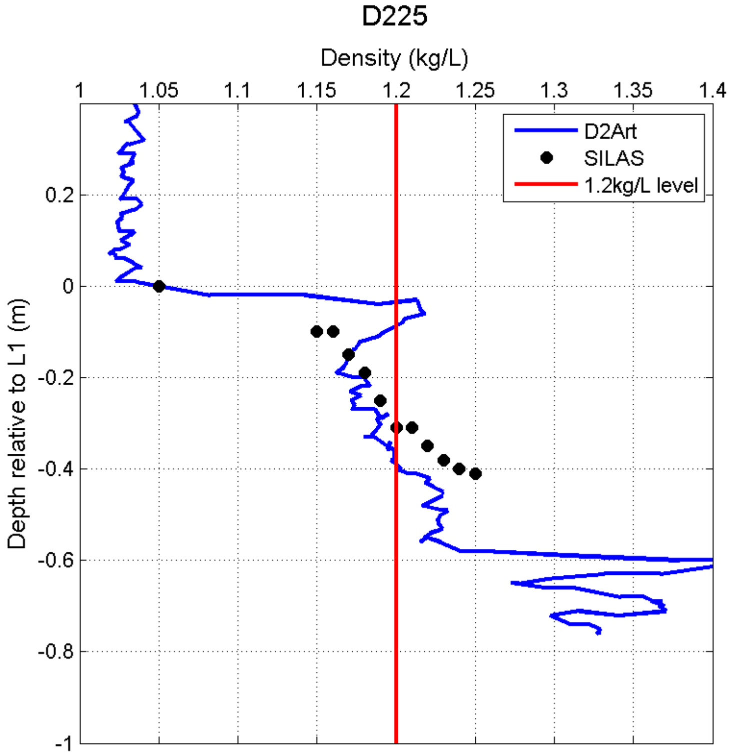
D221
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
D2Art
SILAS
1.2kg/L level

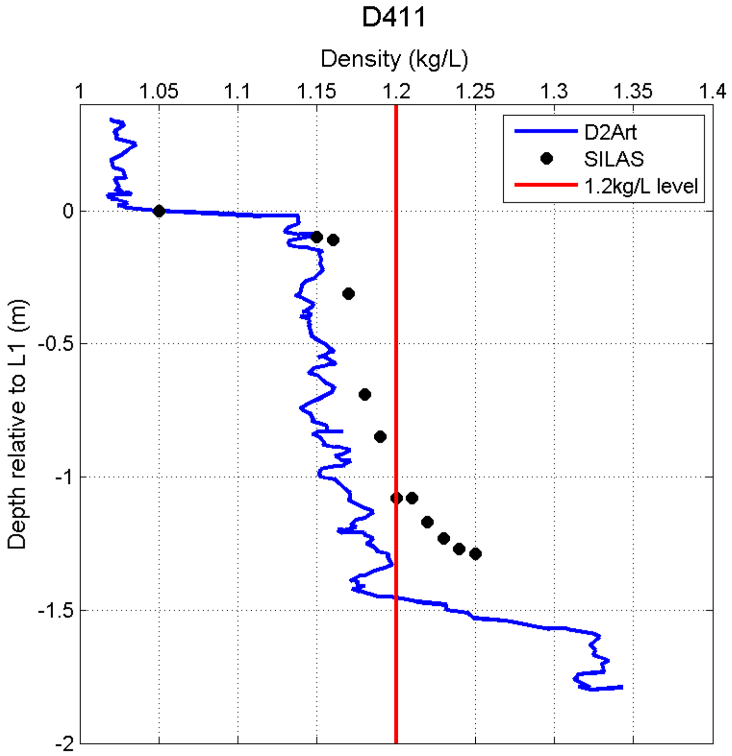


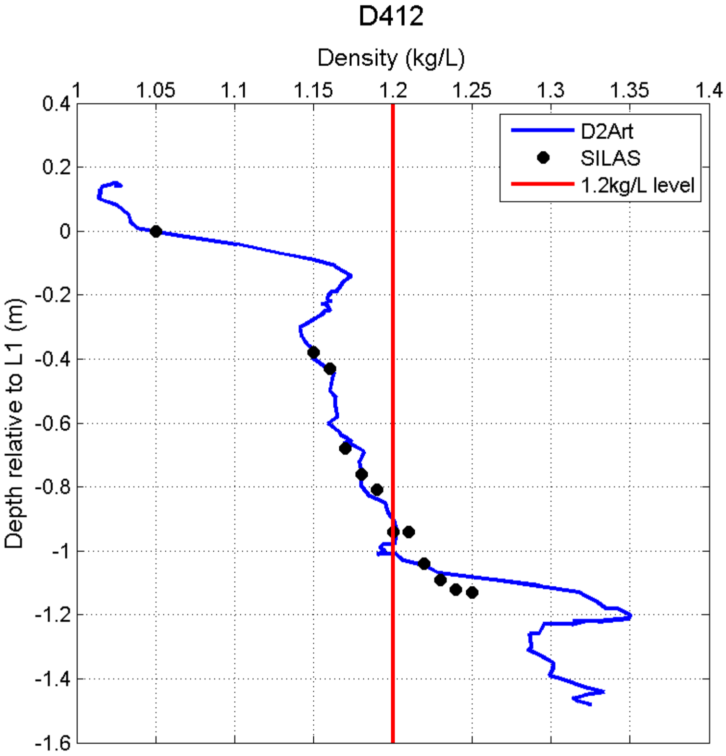
D222
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
D2Art
SILAS
1.2kg/L level

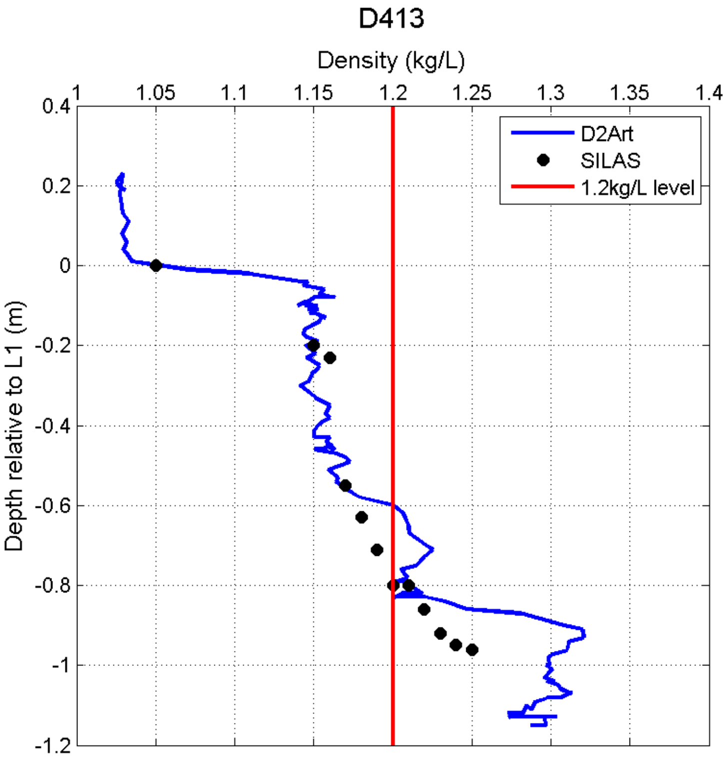

D223
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
D2Art
SILAS
1.2kg/L level

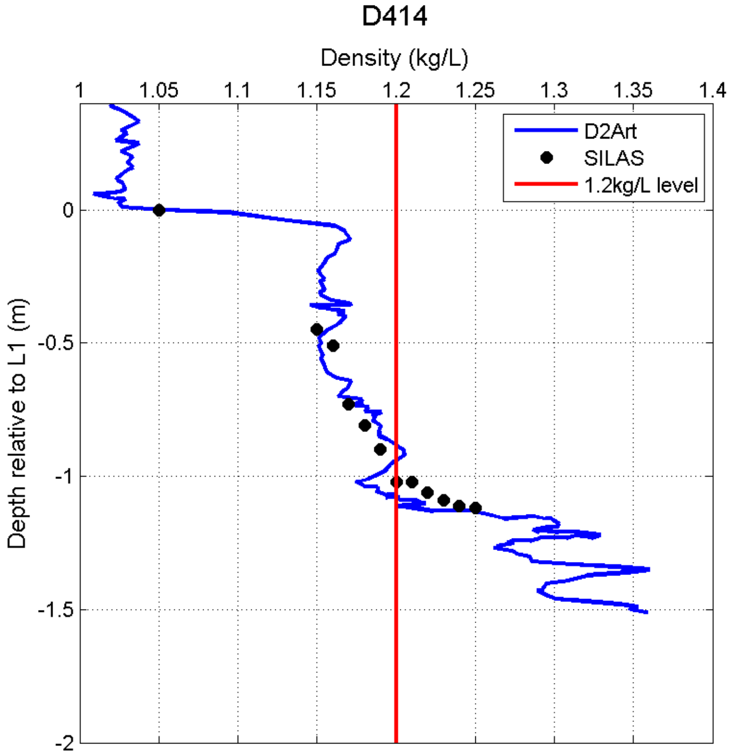

D224
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
D2Art
SILAS
1.2kg/L level

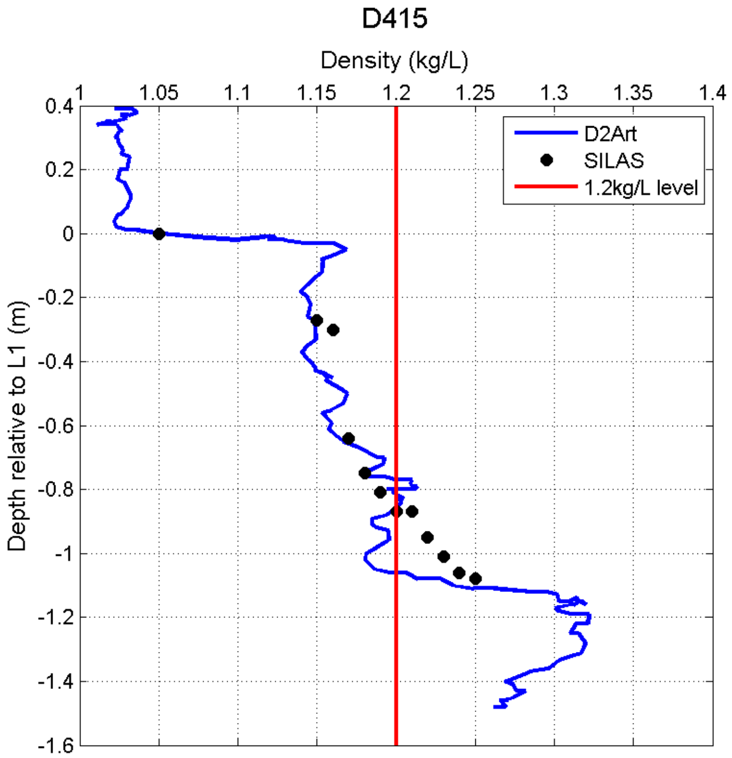

D225
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

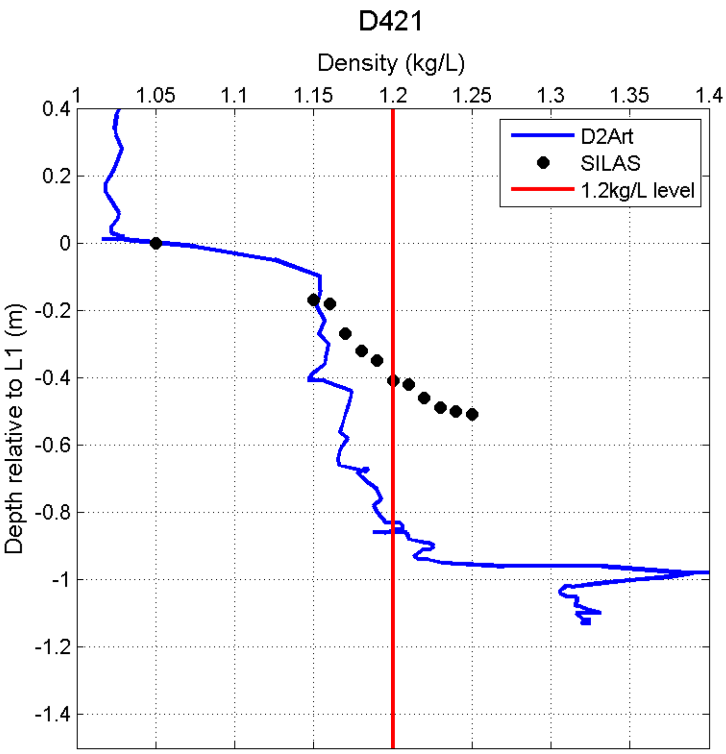

D411
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

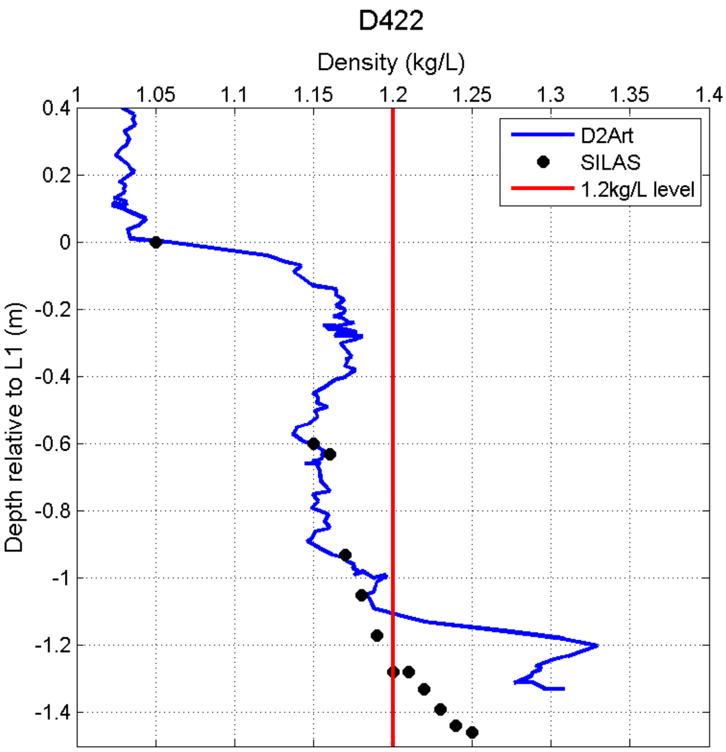

D412
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

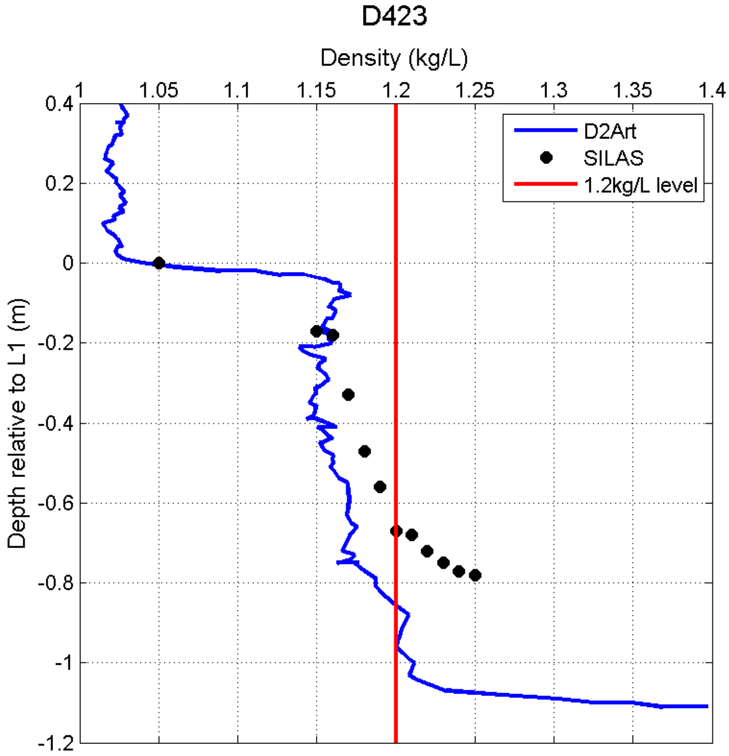

D413
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

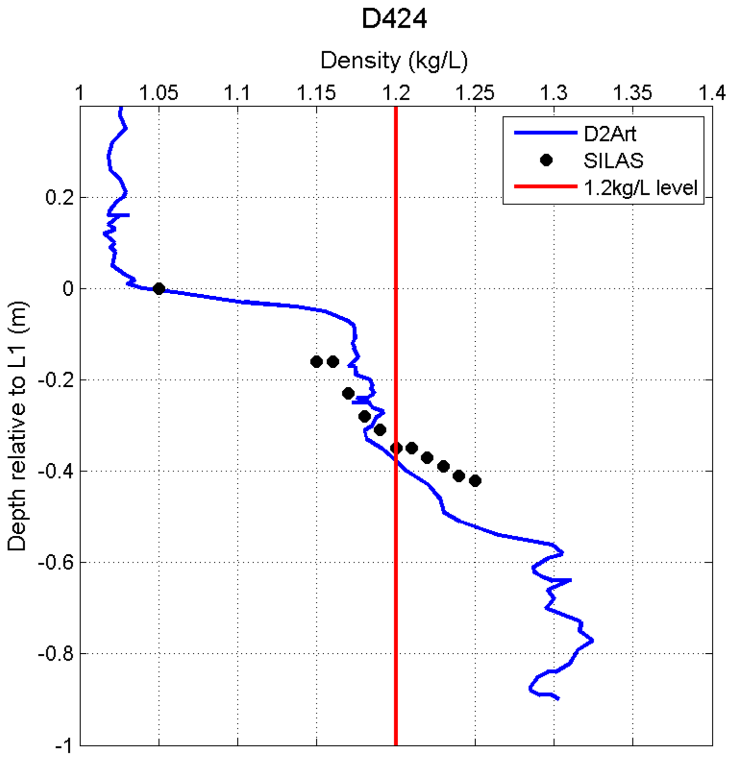

D414
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

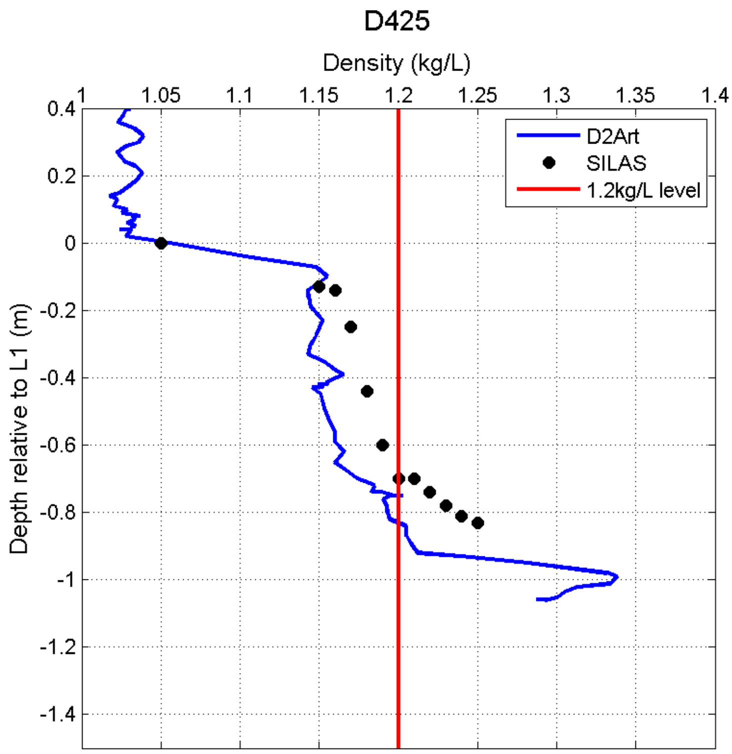

D415
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

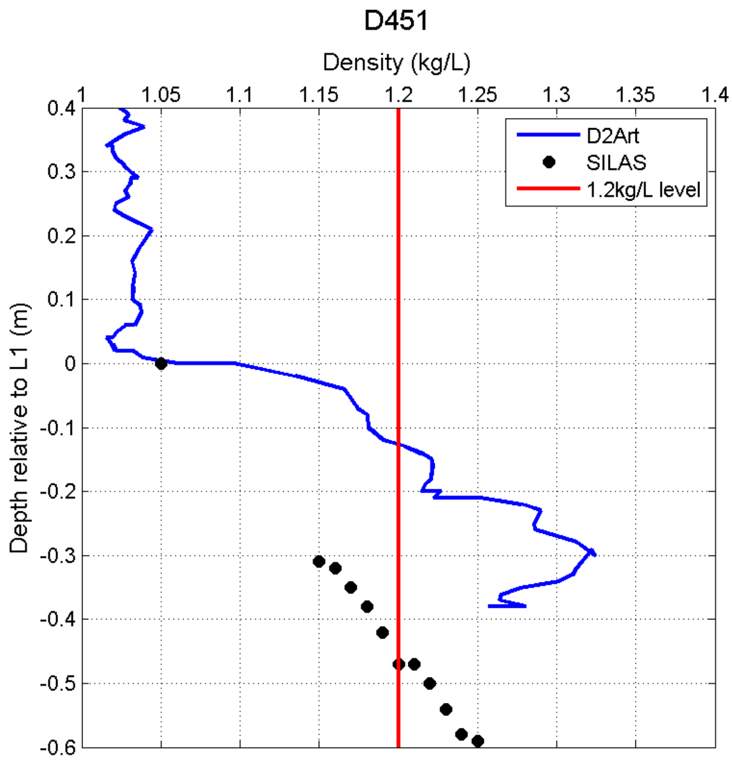

D421
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

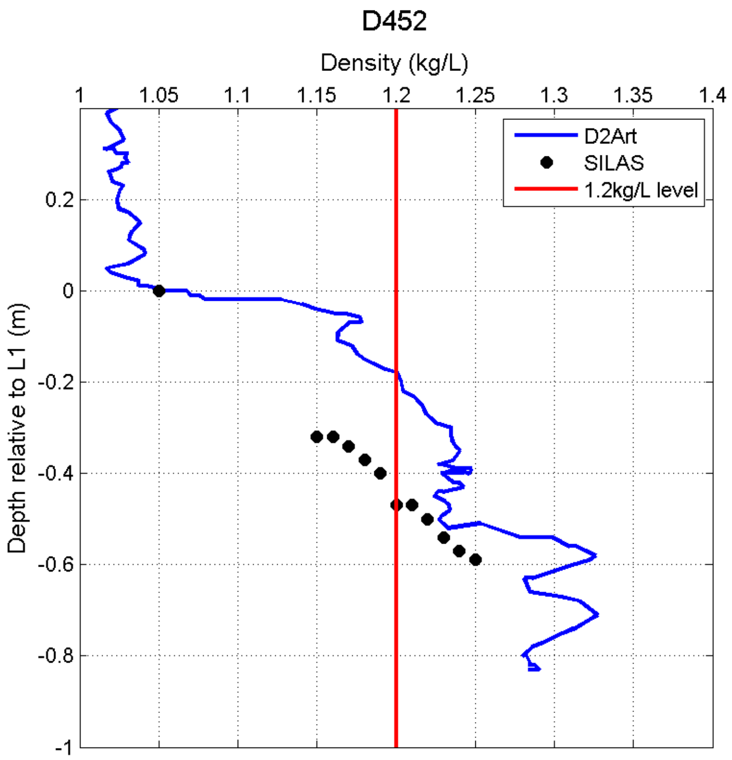

D422
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

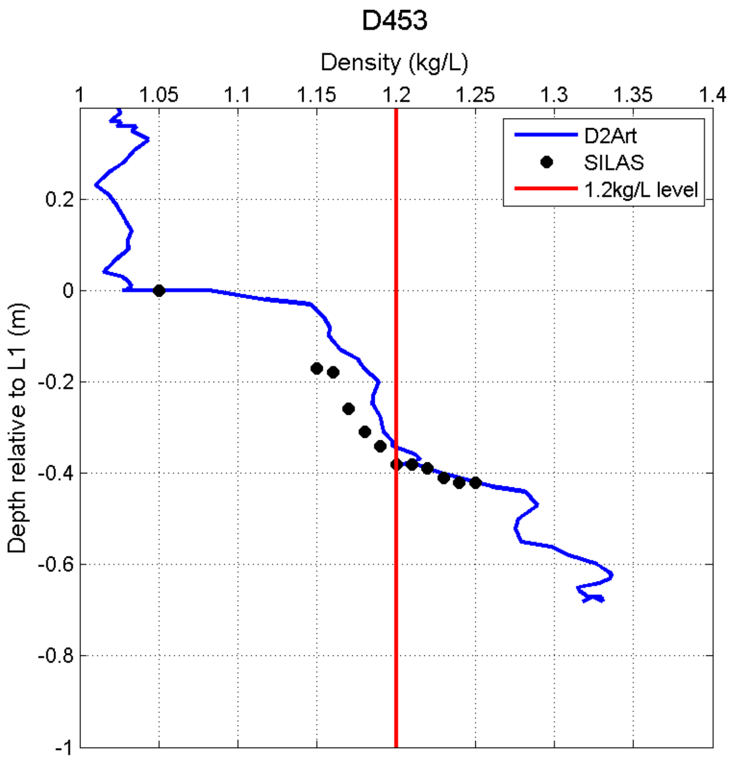

D423
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

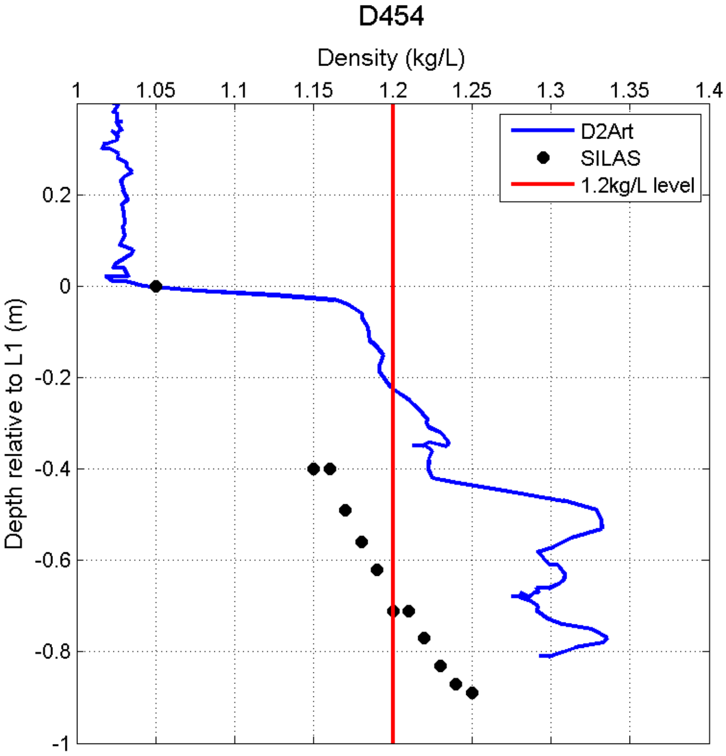

D424
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

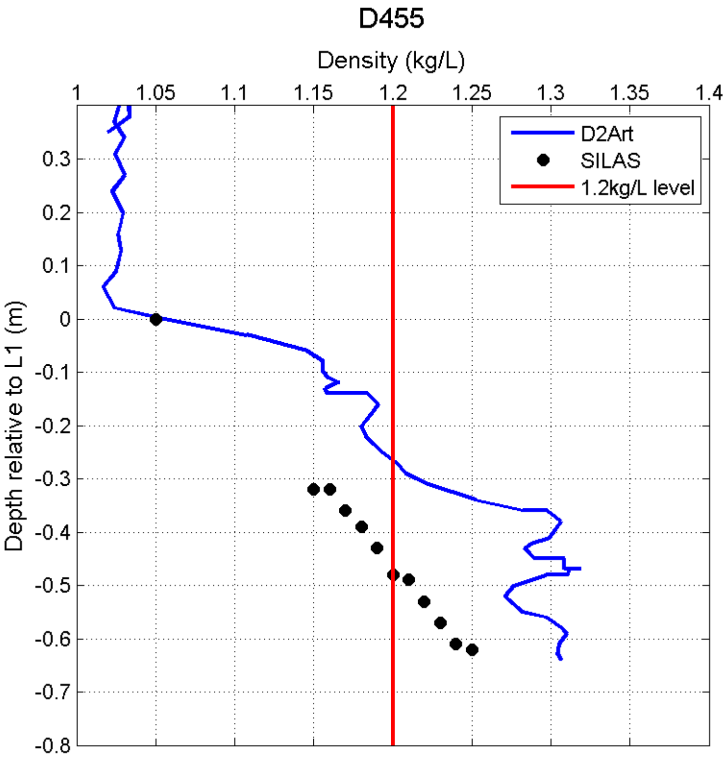

D425
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

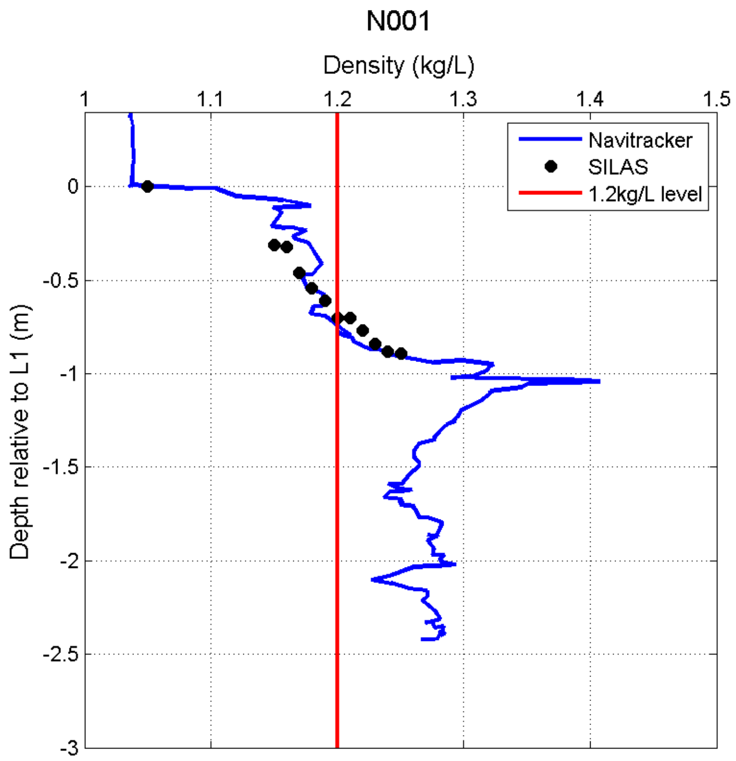

D451
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

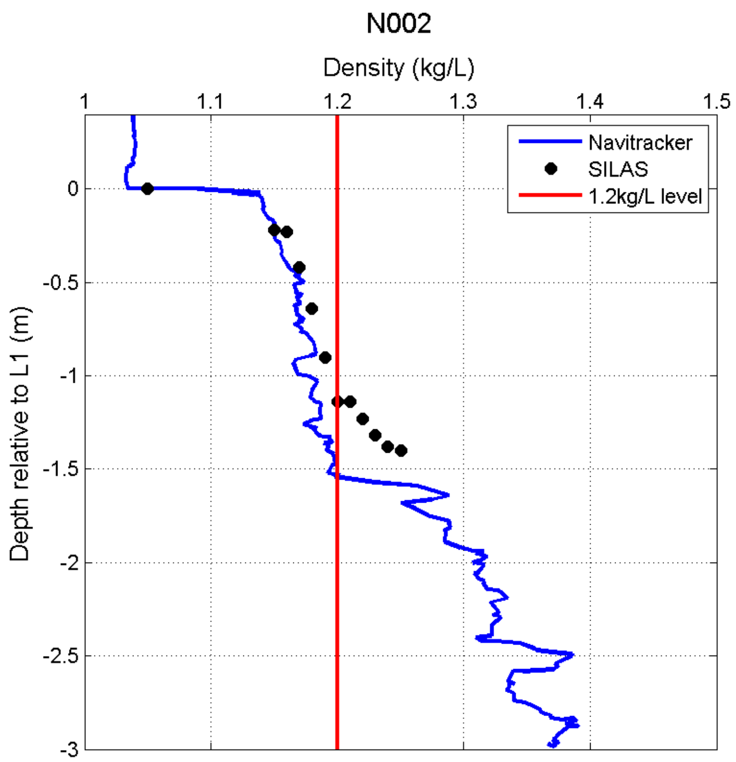

D452
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

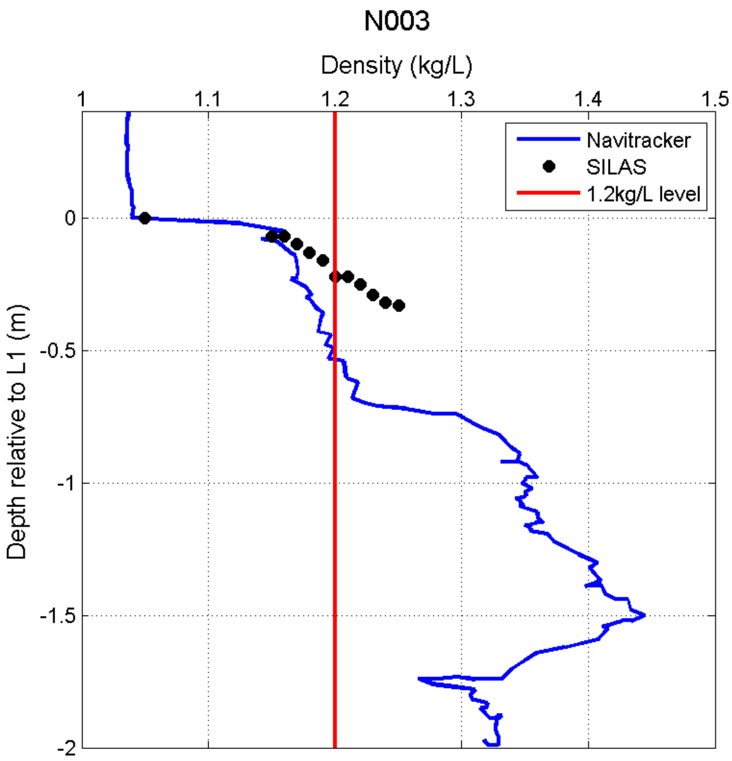

D453
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Depth relative to L1 (m)
D2Art
SILAS
1.2kg/L level

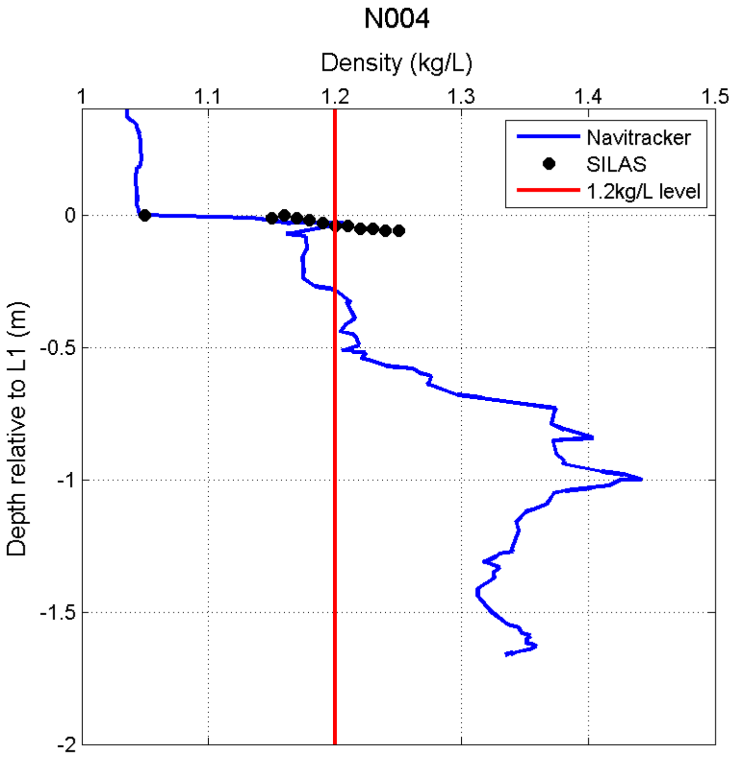

D454
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
D2Art
SILAS
1.2kg/L level

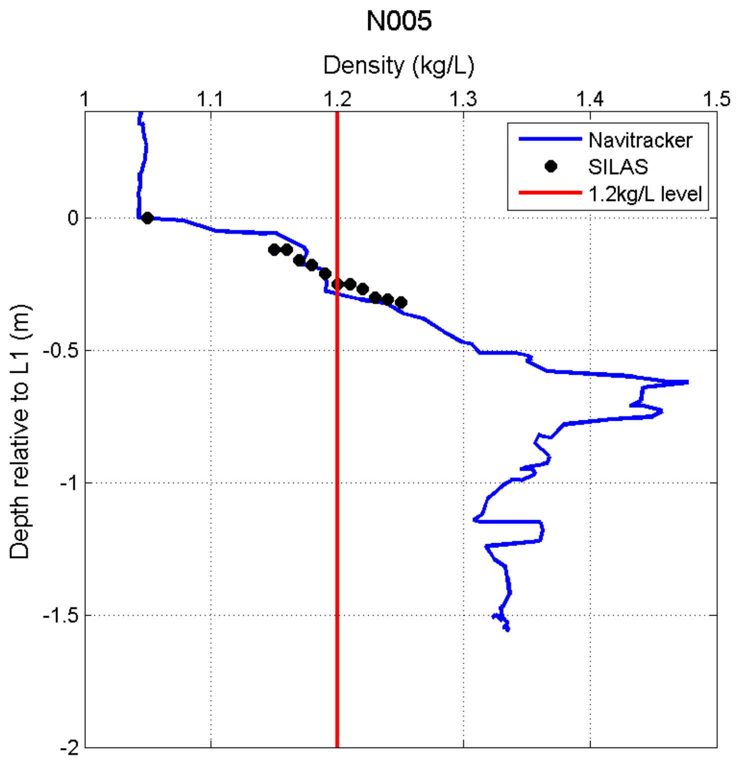

D455
Density (kg/L)
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
Depth relative to L1 (m)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
D2Art
SILAS
1.2kg/L level

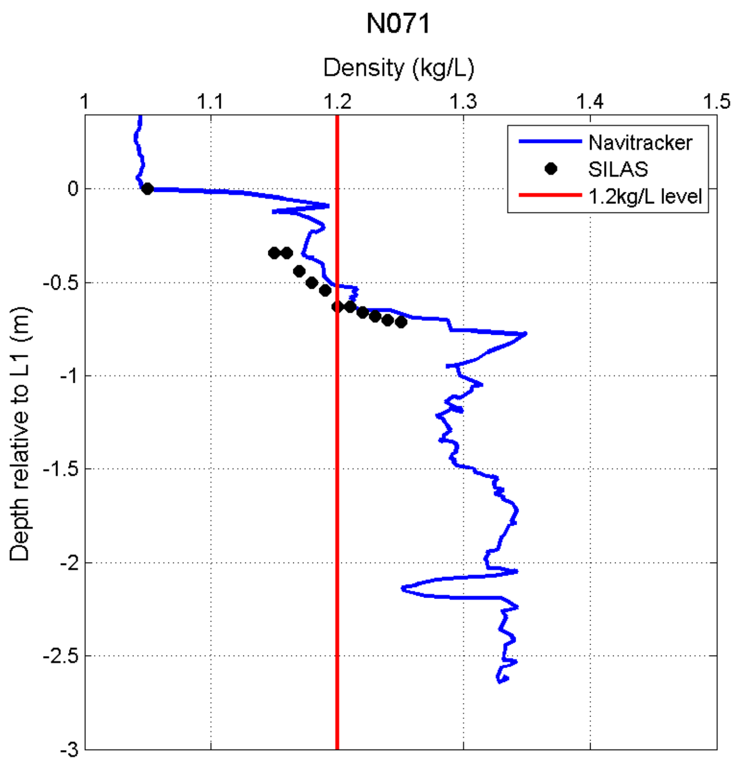

N001
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth relative to L1 (m)

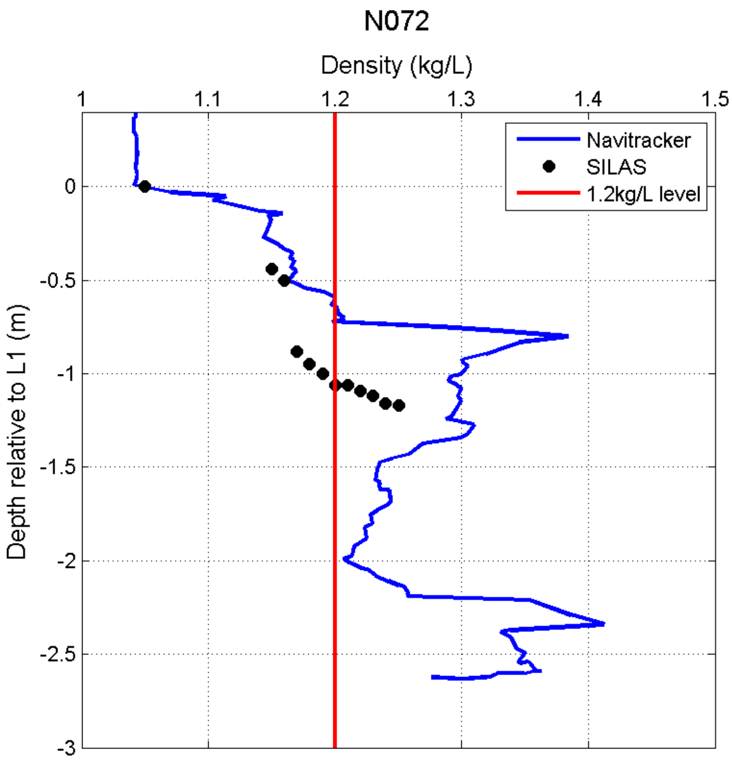

N002
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth relative to L1 (m)

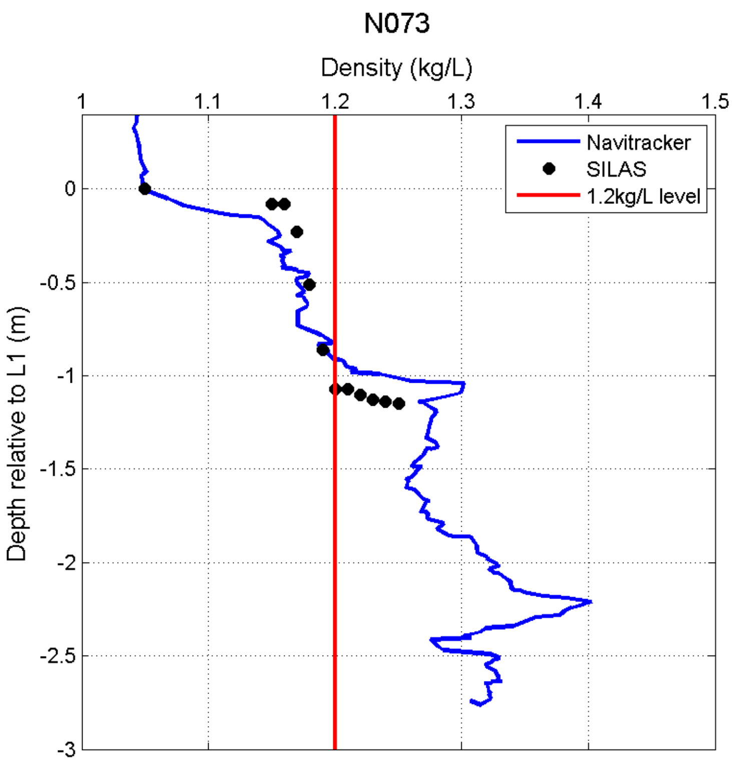

N003
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)
Navitracker
SILAS
1.2kg/L level

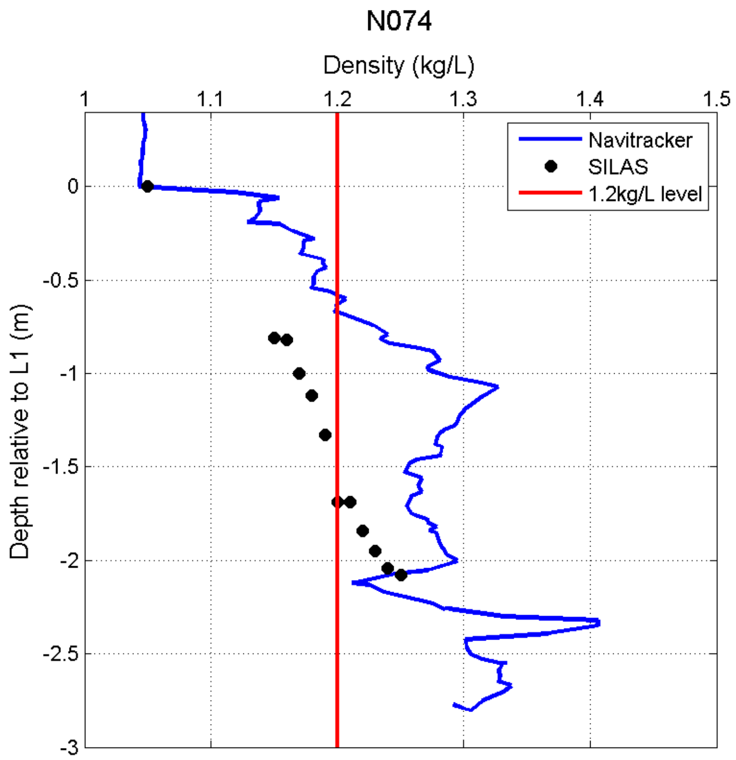

N004
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)
Navitracker
SILAS
1.2kg/L level

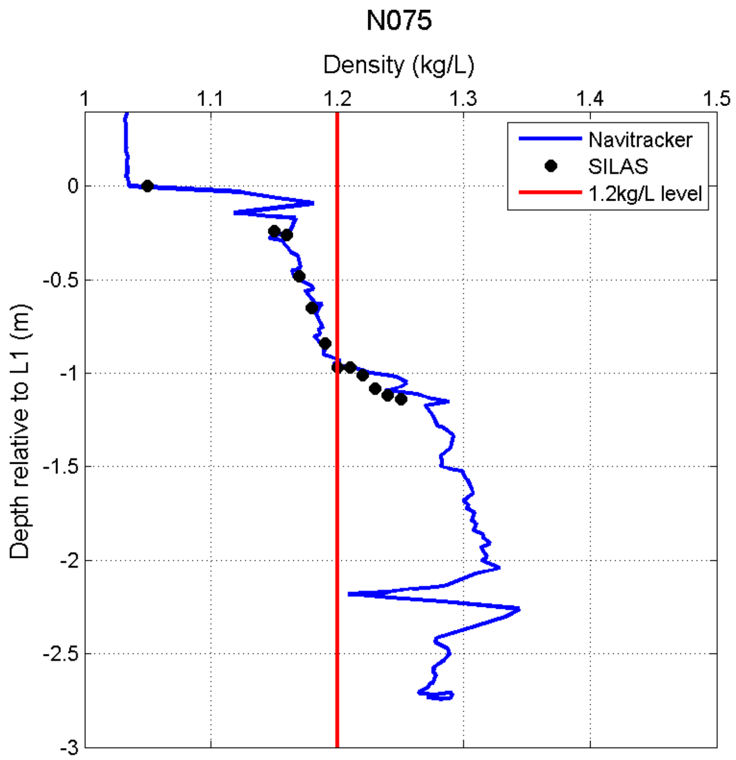

N005
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Depth relative to L1 (m)
0
-0.5
-1
-1.5
-2
Navitracker
SILAS
1.2kg/L level

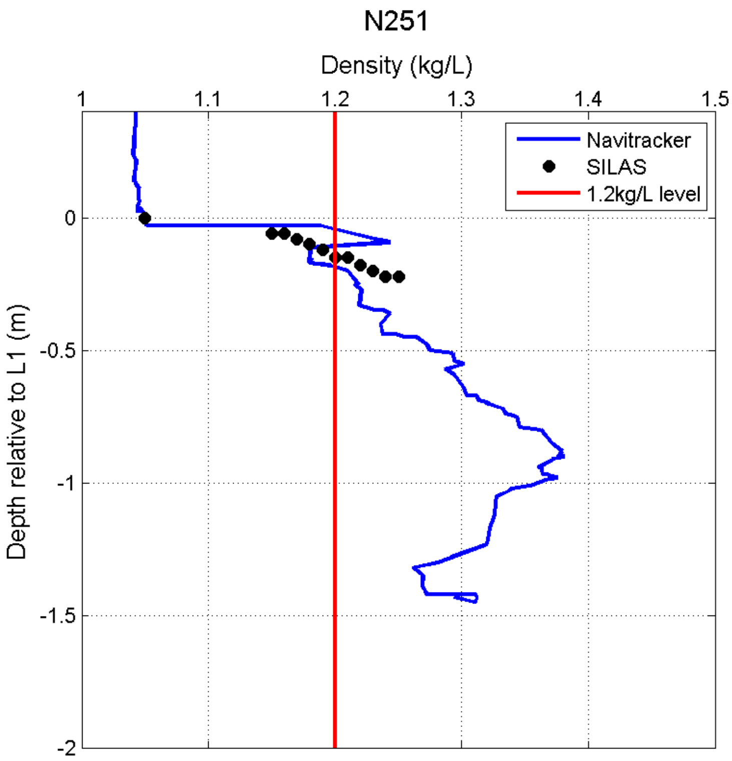

N071
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Depth relative to L1 (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
Navitracker
SILAS
1.2kg/L level

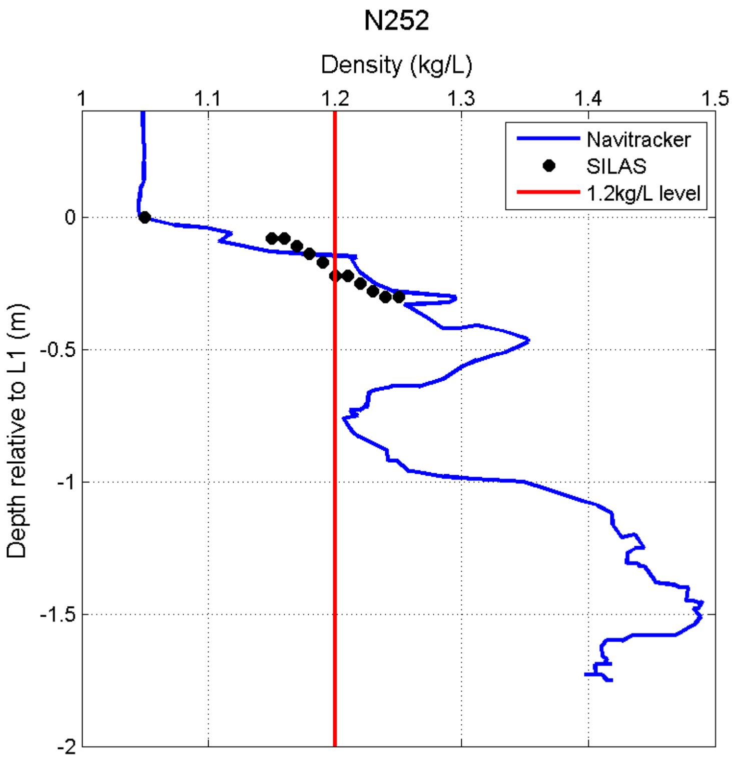

N072
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth relative to L1 (m)

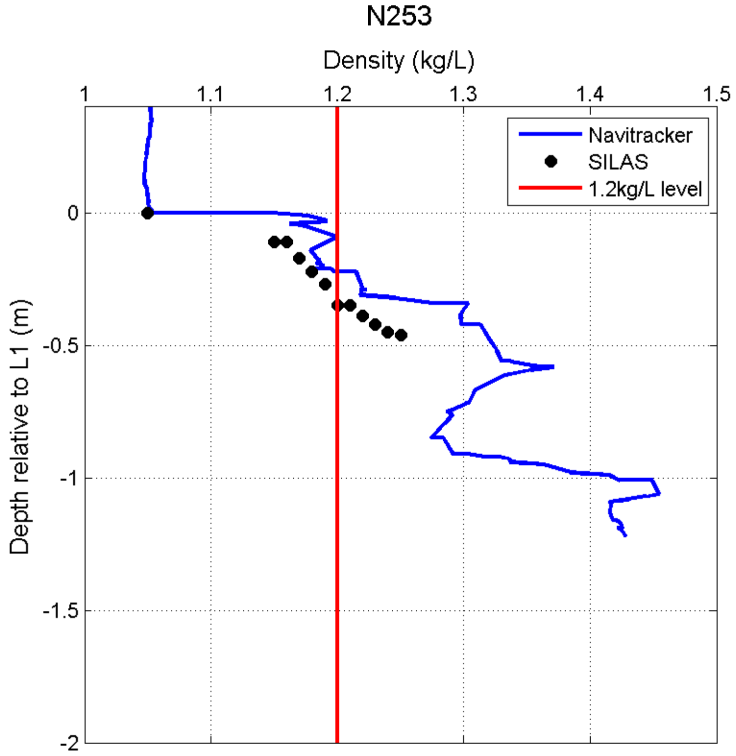

N073
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth relative to L1 (m)

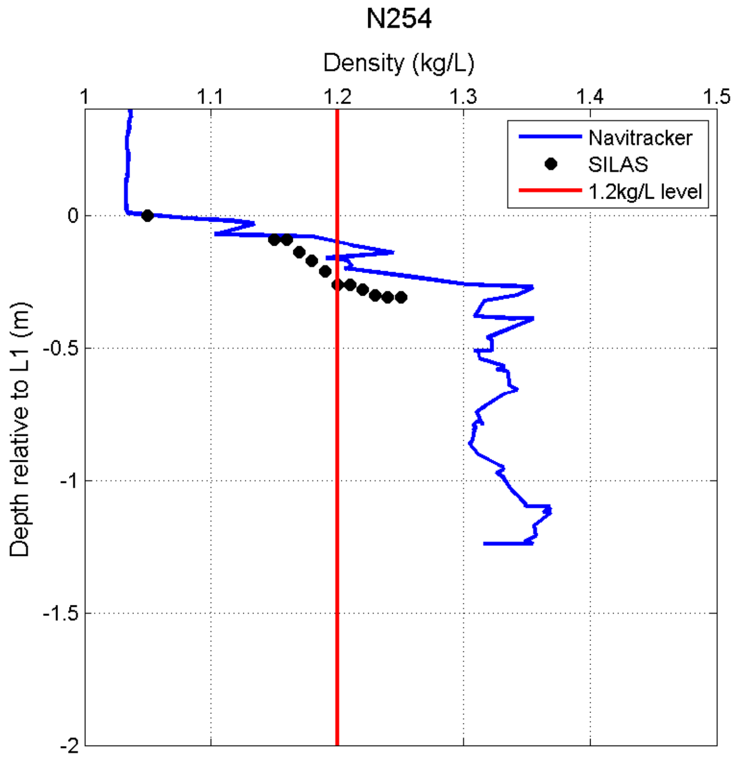

N074
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth relative to L1 (m)

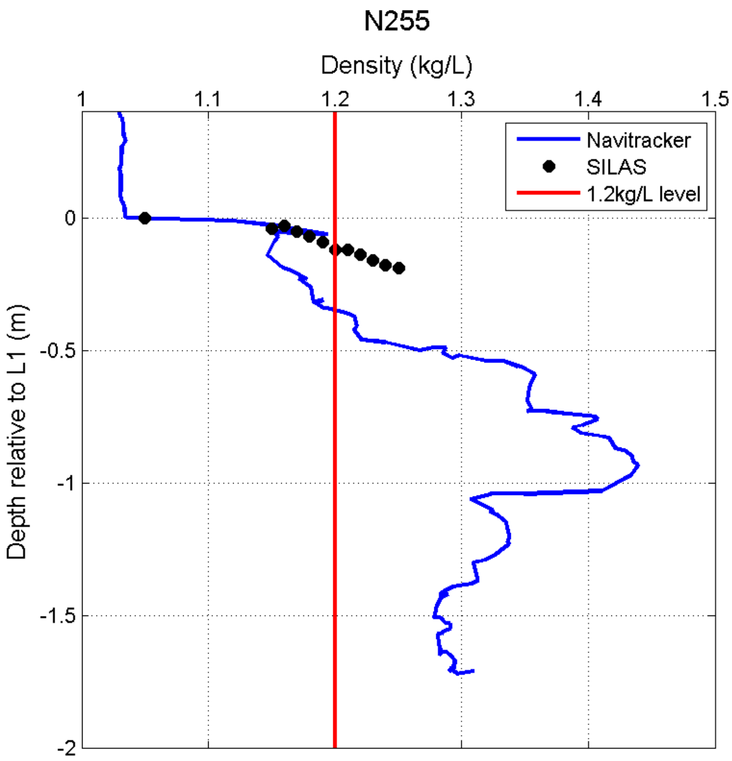

N075
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
-2.5
-3
Depth relative to L1 (m)

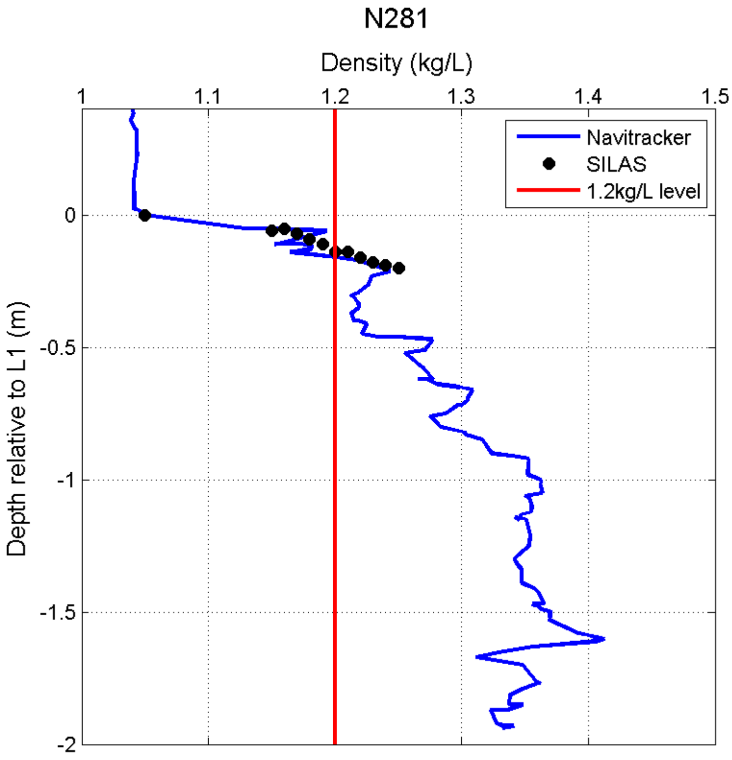

N251
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)

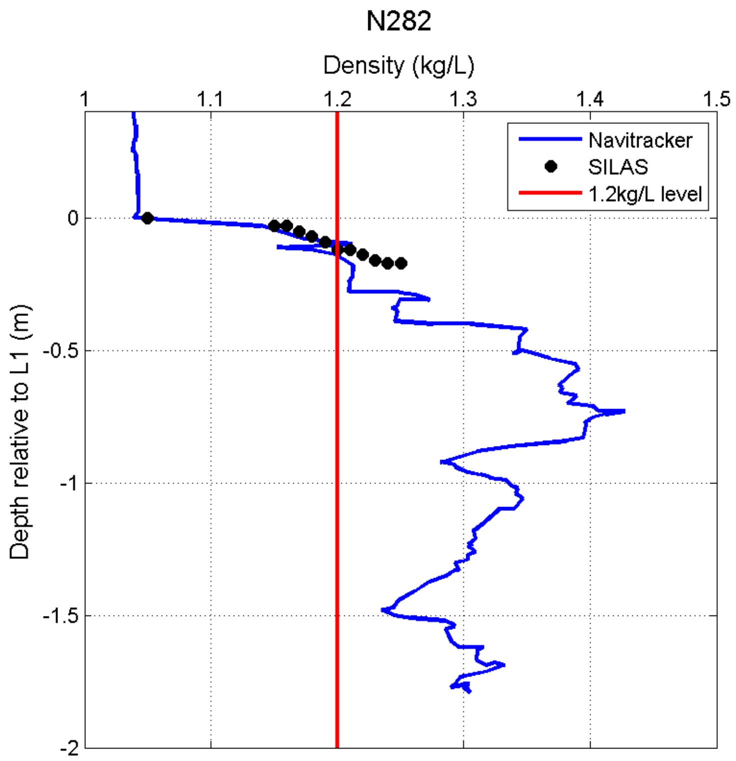

N252
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)

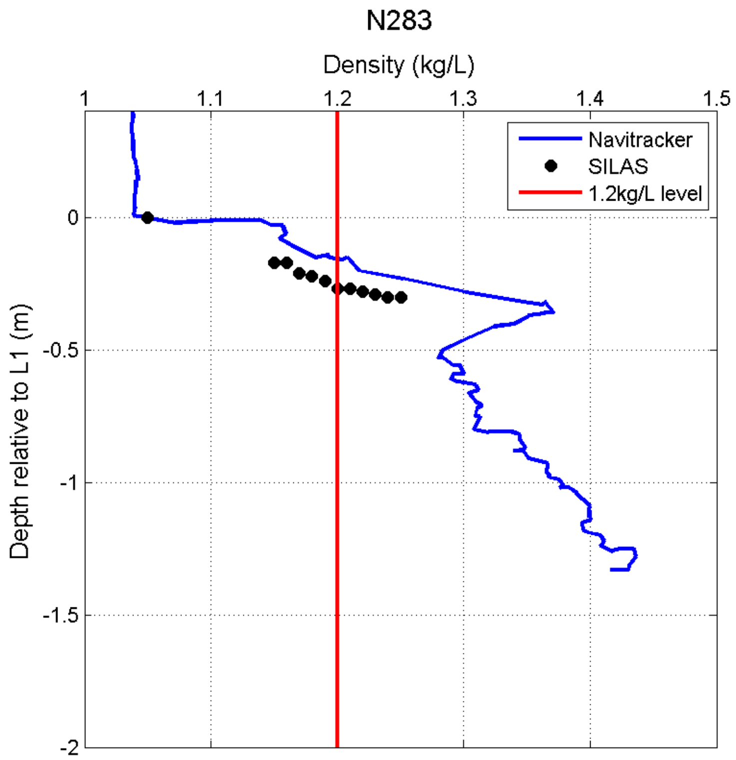

N253
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
Depth relative to L1 (m)
0
-0.5
-1
-1.5
-2

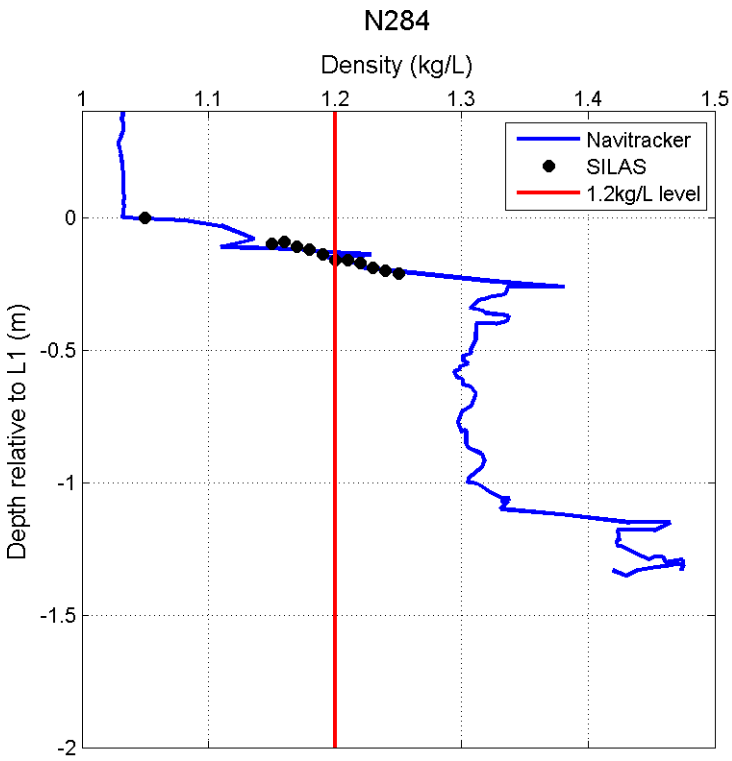

N254
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
Depth relative to L1 (m)
0
-0.5
-1
-1.5
-2

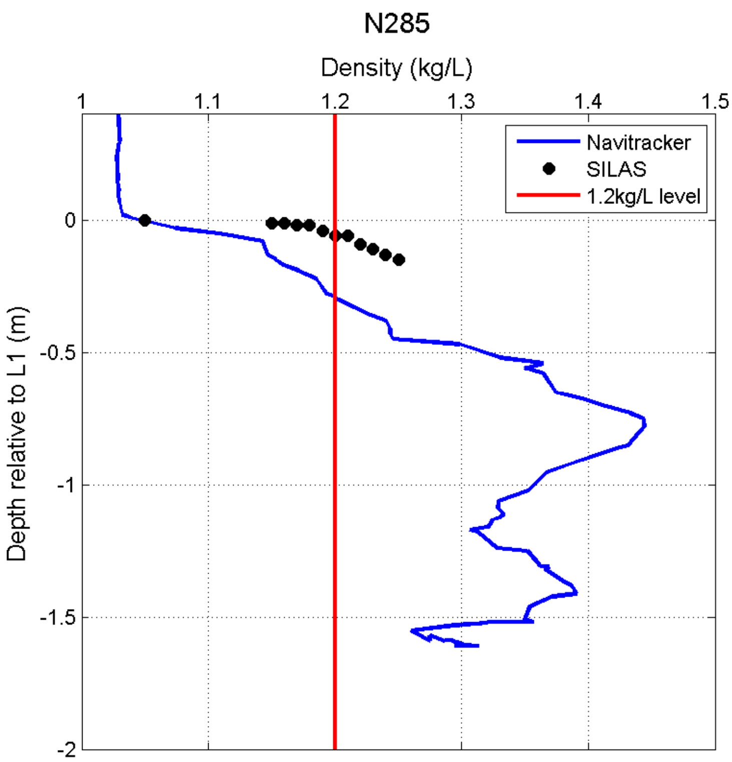

N255
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)


N281
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)


N282
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)


N283
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)


N284
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)


N285
Density (kg/L)
1
1.1
1.2
1.3
1.4
1.5
Navitracker
SILAS
1.2kg/L level
0
-0.5
-1
-1.5
-2
Depth relative to L1 (m)

H Analysis of crossings

In an additional analysis, the crossings of the 1.2 kg/L level (1200_25cm_5m_cum) at the SILAS lines were analysed per day. In this appendix, the maps of the crossings per day are shown, together with the histograms of the differences in 1.2 kg/L level. For the first day, measurements were done at the Maeslantkering (bottom right in the map in Figure H.1) and in the study area (top left in the map). The histogram is from all data of that day. Additionally, explanatory images are shown for the large deviations on days 8, 10 and 15 January 2013.

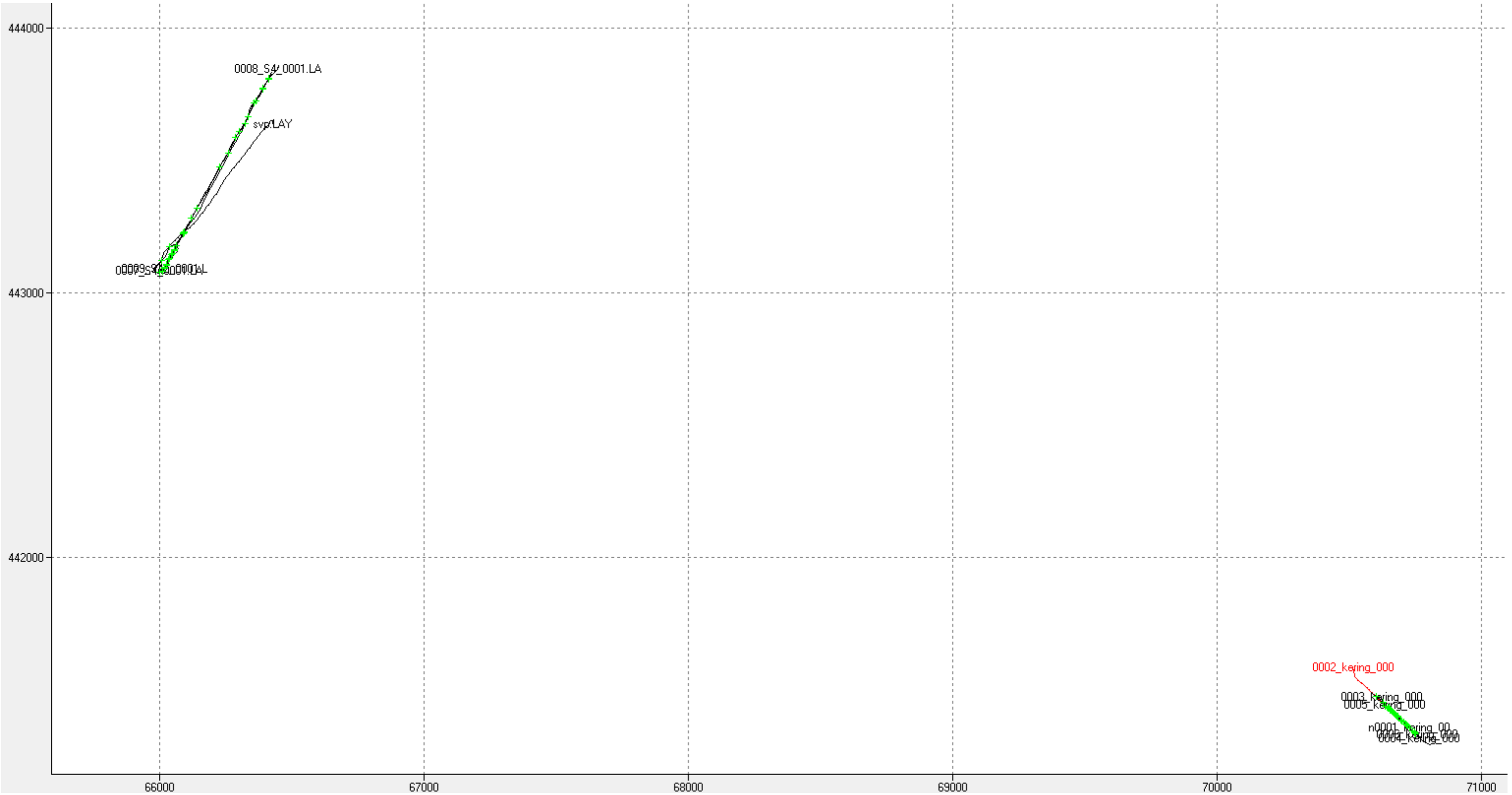
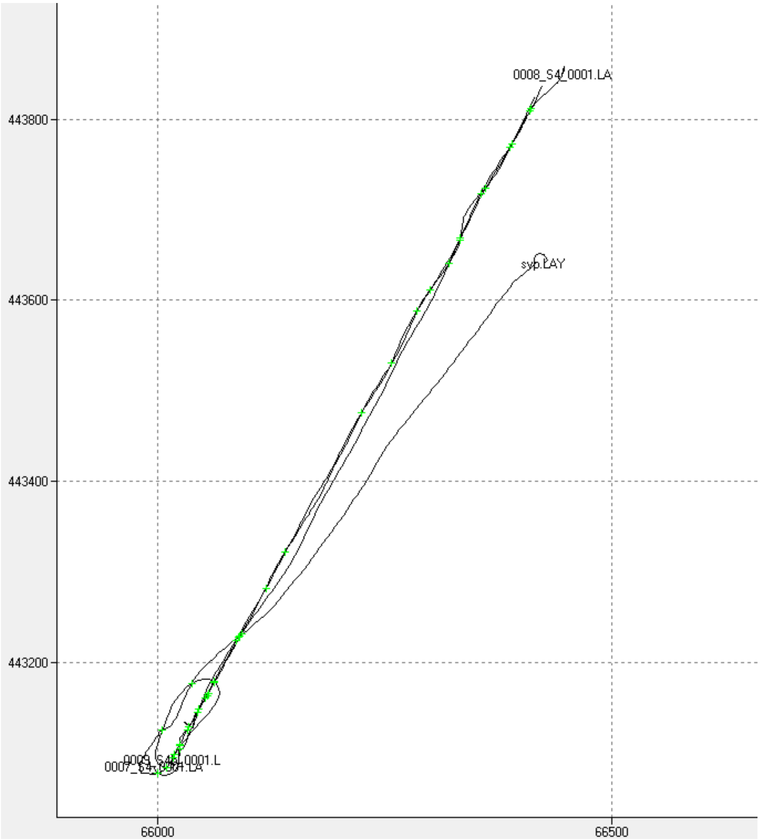


Figure H.1 Map of locations of crossings for 8 January 2013. Crossings are indicated by green dots.



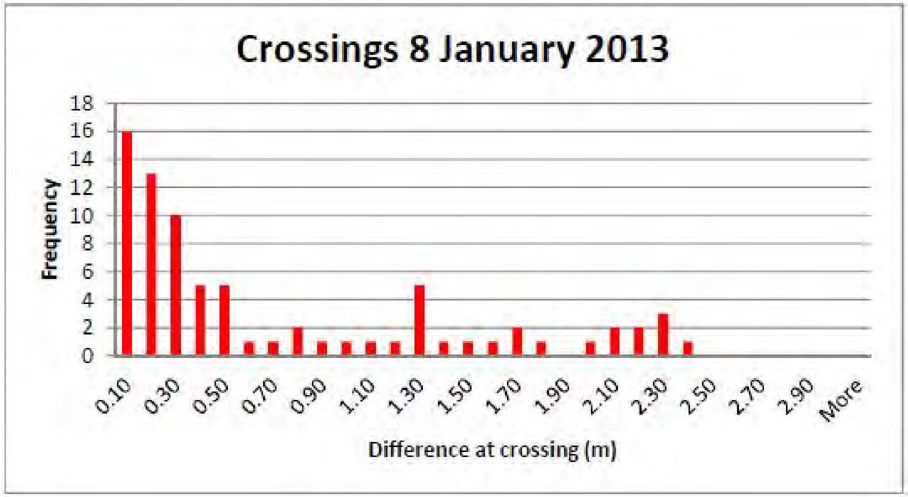
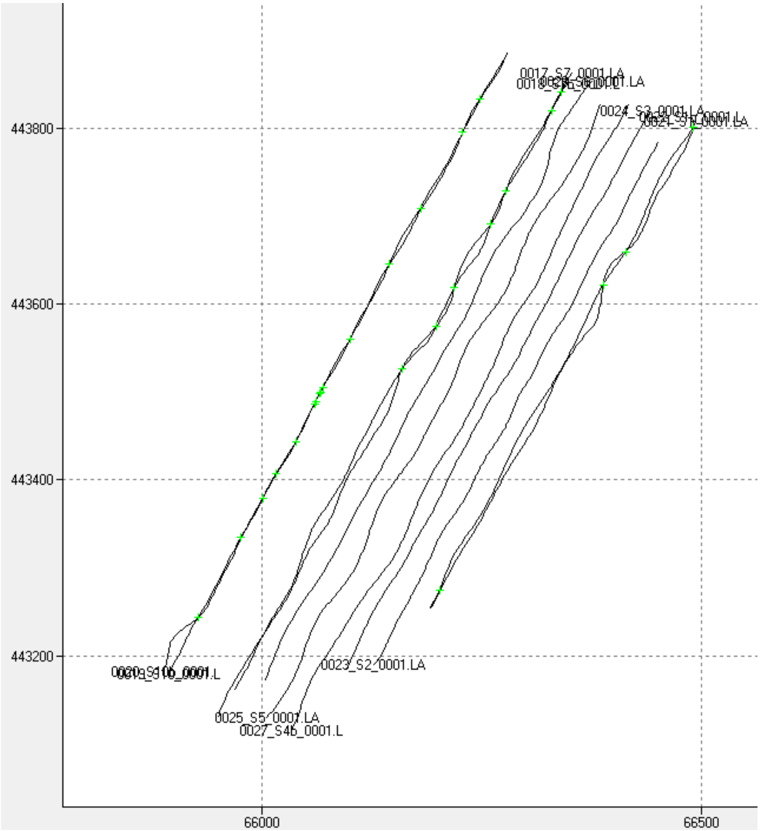


Figure H.2 Left: Map of locations of crossings for 8 January 2013. Crossings are indicated by green dots. Right: histogram of differences in depth of the 1.2 kg/L (1200_25cm_5m_cum) level at the crossings, for all data of that day, both at Maeslantkering and in study area..



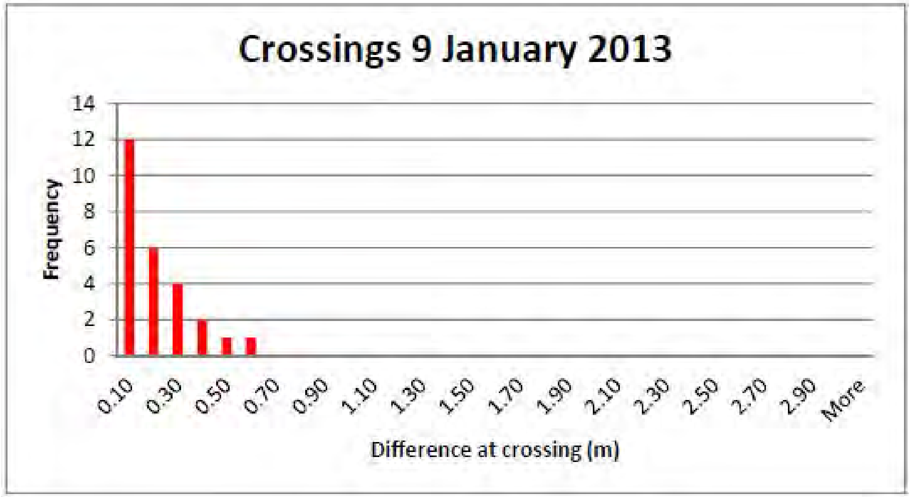
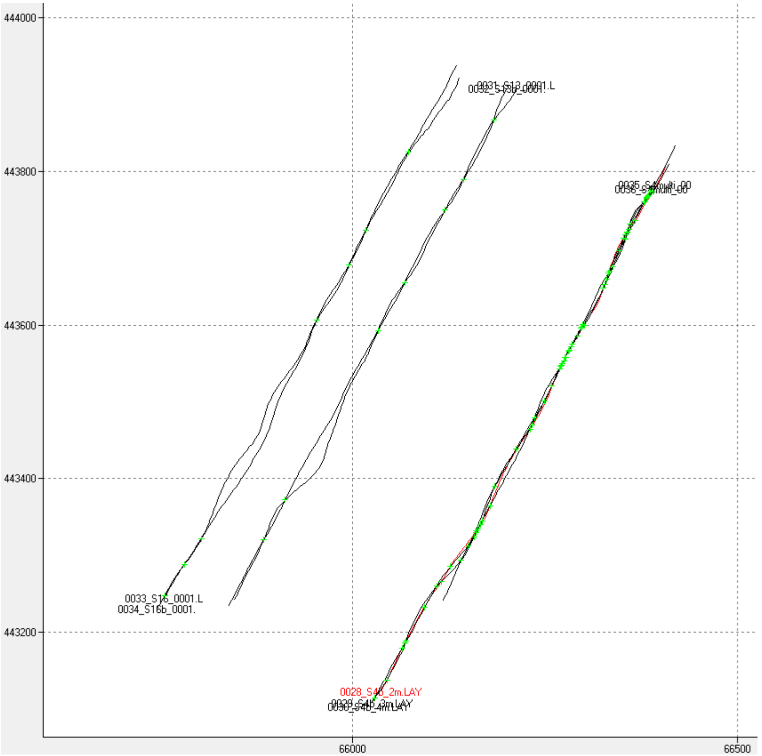


Figure H.3 Left: Map of locations of crossings for 9 January 2013. Crossings are indicated by green dots. Right: histogram of differences in depth of the 1.2 kg/L (1200_25cm_5m_cum) level at the crossings.



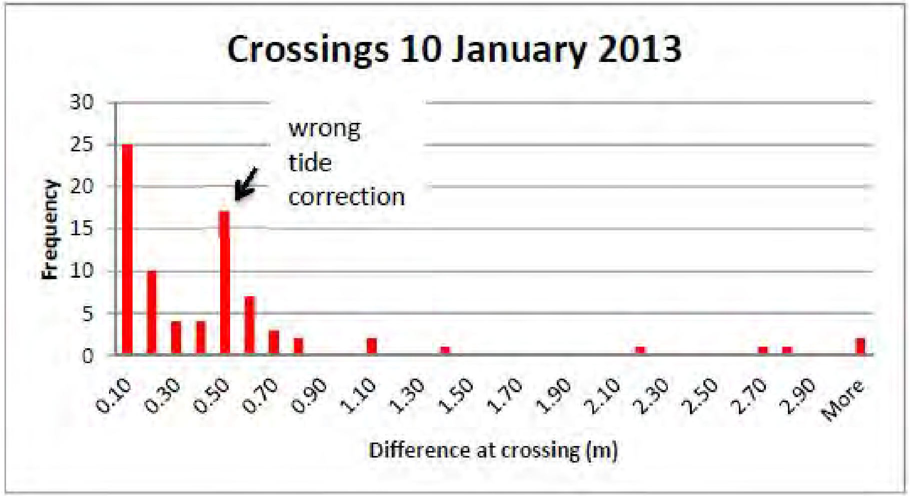
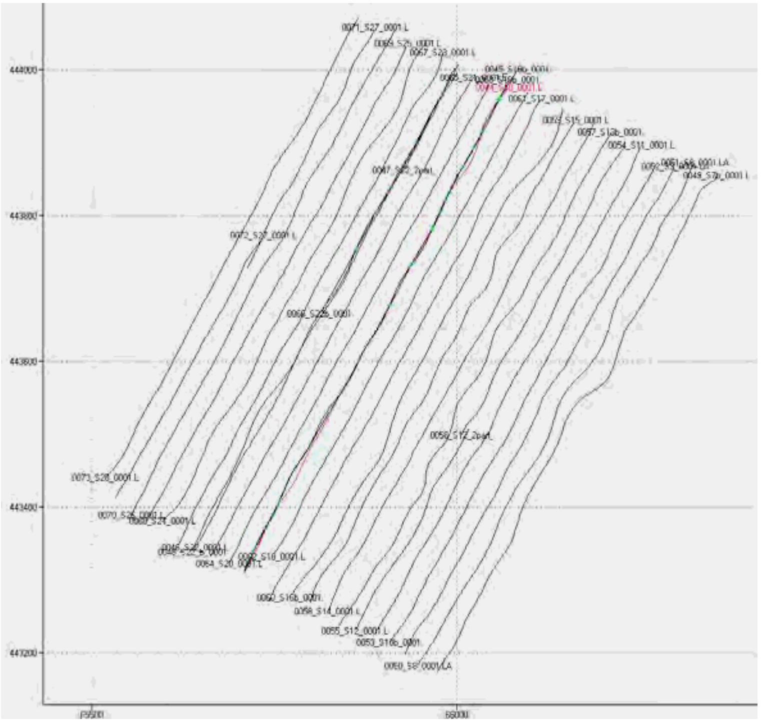


Figure H.4 Left: Map of locations of crossings for 10 January 2013. Crossings are indicated by green dots. Right: histogram of differences in depth of the 1.2 kg/L (1200_25cm_5m_cum) level at the crossings.



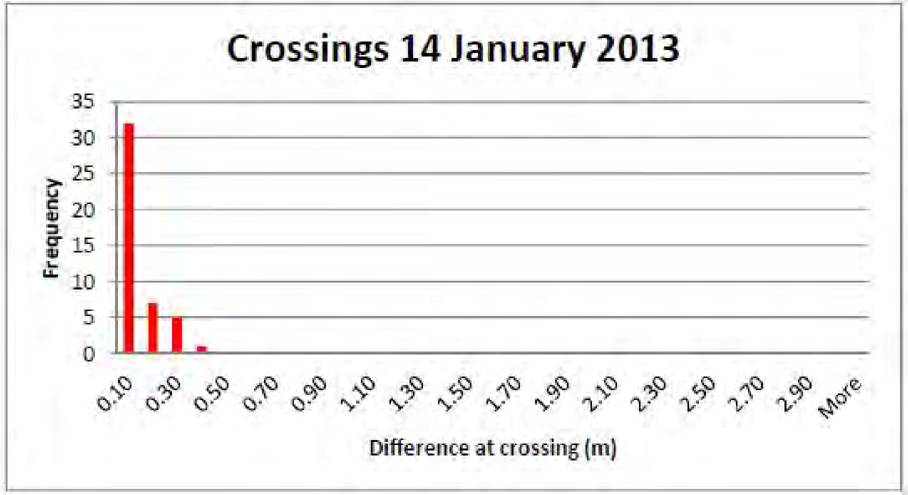
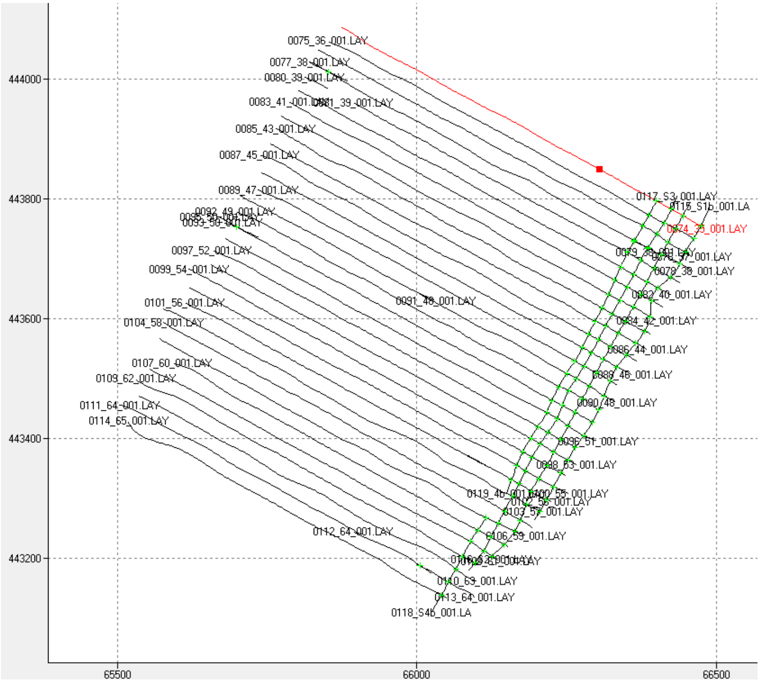


Figure H.5 Left: Map of locations of crossings for 14 January 2013. Crossings are indicated by green dots. Right: histogram of differences in depth of the 1.2 kg/L (1200_25cm_5m_cum) level at the crossings.



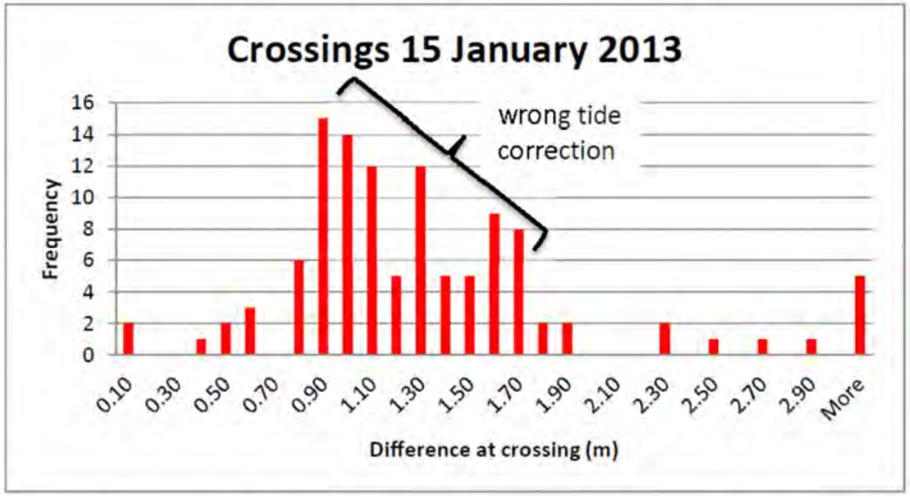
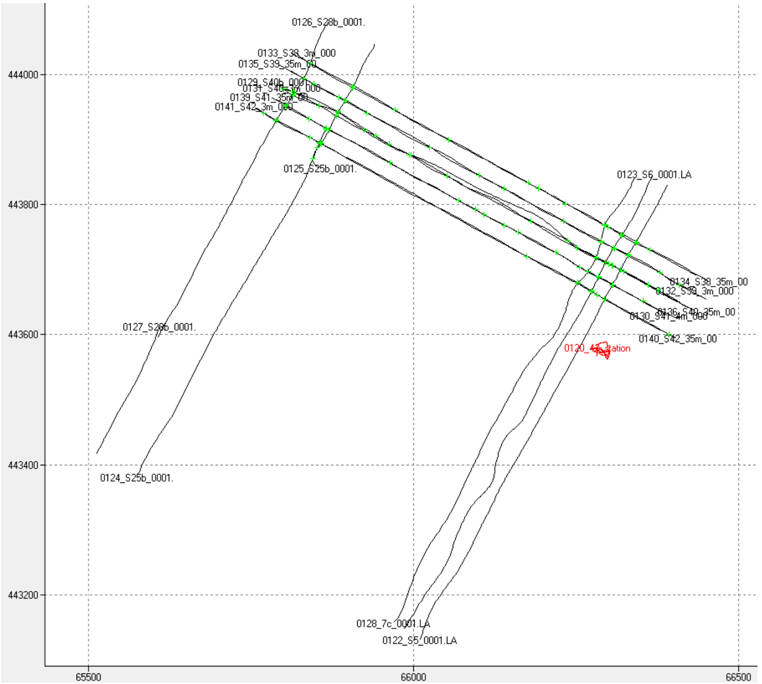


Figure H.6 Left: Map of locations of crossings for 15 January 2013. Crossings are indicated by green dots. Right: histogram of differences in depth of the 1.2 kg/L (1200_25cm_5m_cum) level at the crossings.



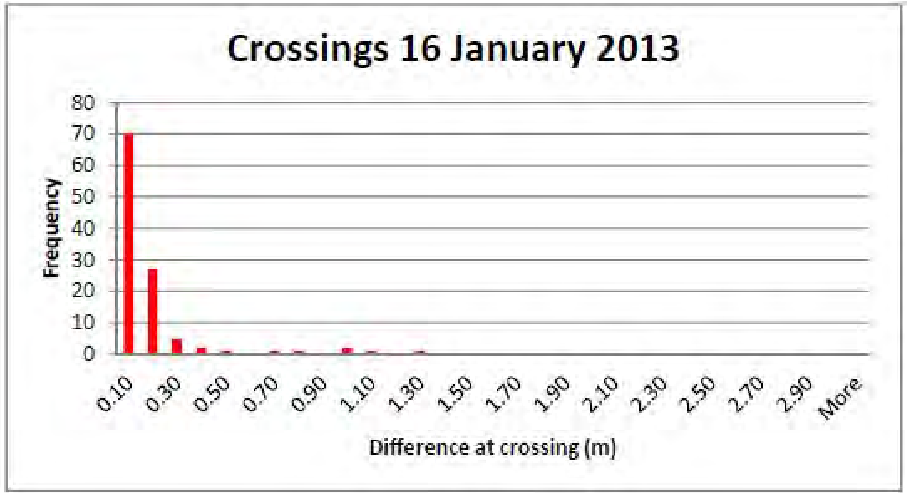
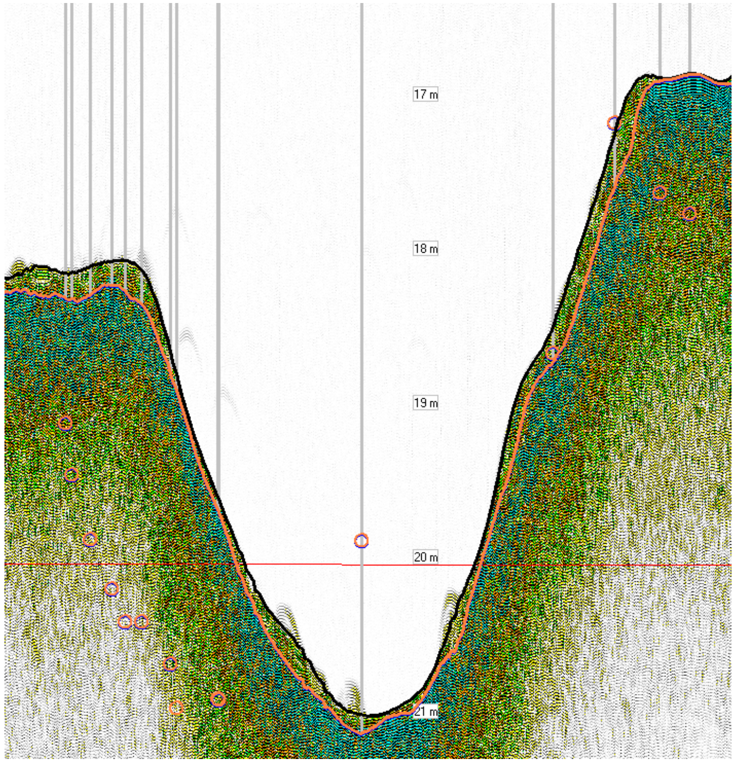


Figure H.7 Left: Map of locations of crossings for 16 January 2013. Crossings are indicated by green dots. Right: histogram of differences in depth of the 1.2 kg/L (1200_25cm_5m_cum) level at the crossings.

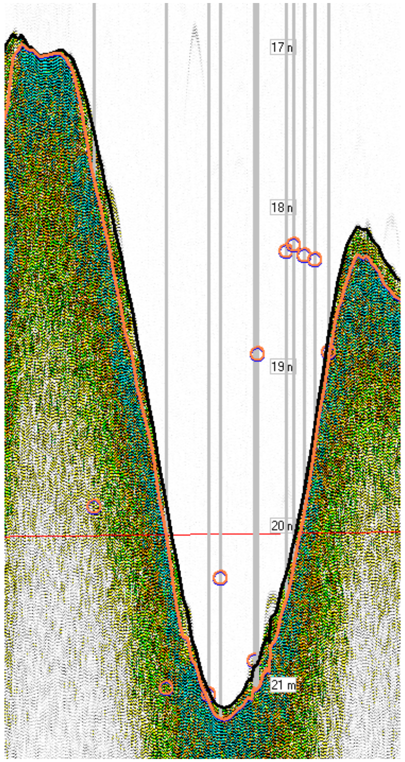
Explanation of large values for 68% and 95% accuracy levels

Day 8 January 2013:

- Due to measurements on slope at Maeslantkering, Figure H.8.
- Possibly, the shift of 1 second was not constant during the day. Measurement speeds were faster on the Maeslantkering than on the SILAS lines.



0005_kering



0006_kering

Figure H.8 Crossings of the 1.2 kg/L level at the Maeslantkering (plateau on the left for 0005_kering). The 1.2 kg/L level (1200_25cm_5m_cum) is represented by the orange line, the crossings are indicated grey lines, the 1.2 kg/L level at the crossing line is indicated by the pink circle. On the slopes, the crossings next to the slope, because of the two opposing measurement directions.

Day 10 January 2013:

- Erroneous tide correction after 13:20 hrs (GMT), see Figure H.9.

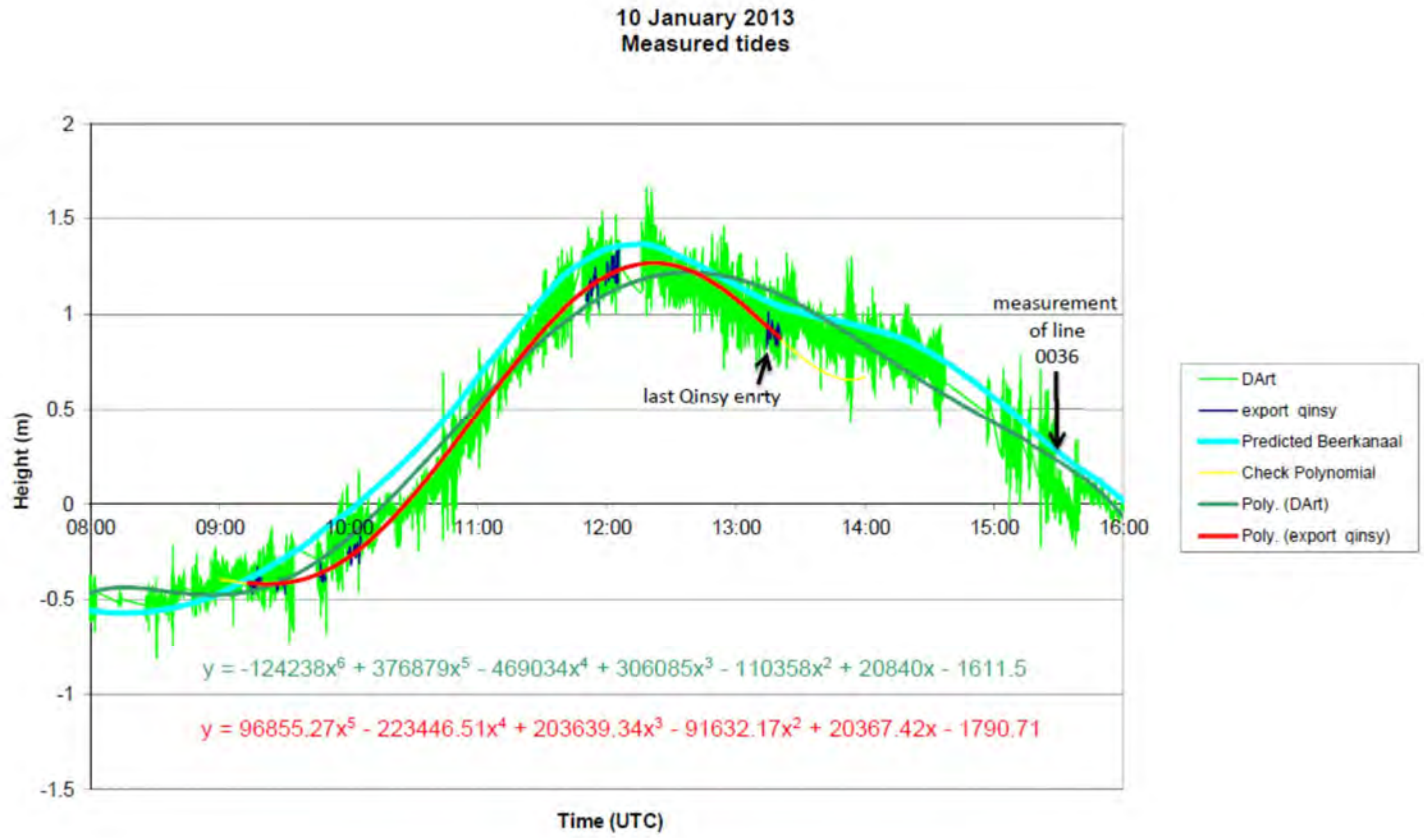


Figure H.9 Tide graphs of 10 January 2013 with last Qinsy entry at 13:30 hrs and measurement of line 0036 at 15:26 hrs.

Day 15 January 2013:

- Erroneous tide correction after 13:57 hrs (GMT), see Figure H.10 and H.11.

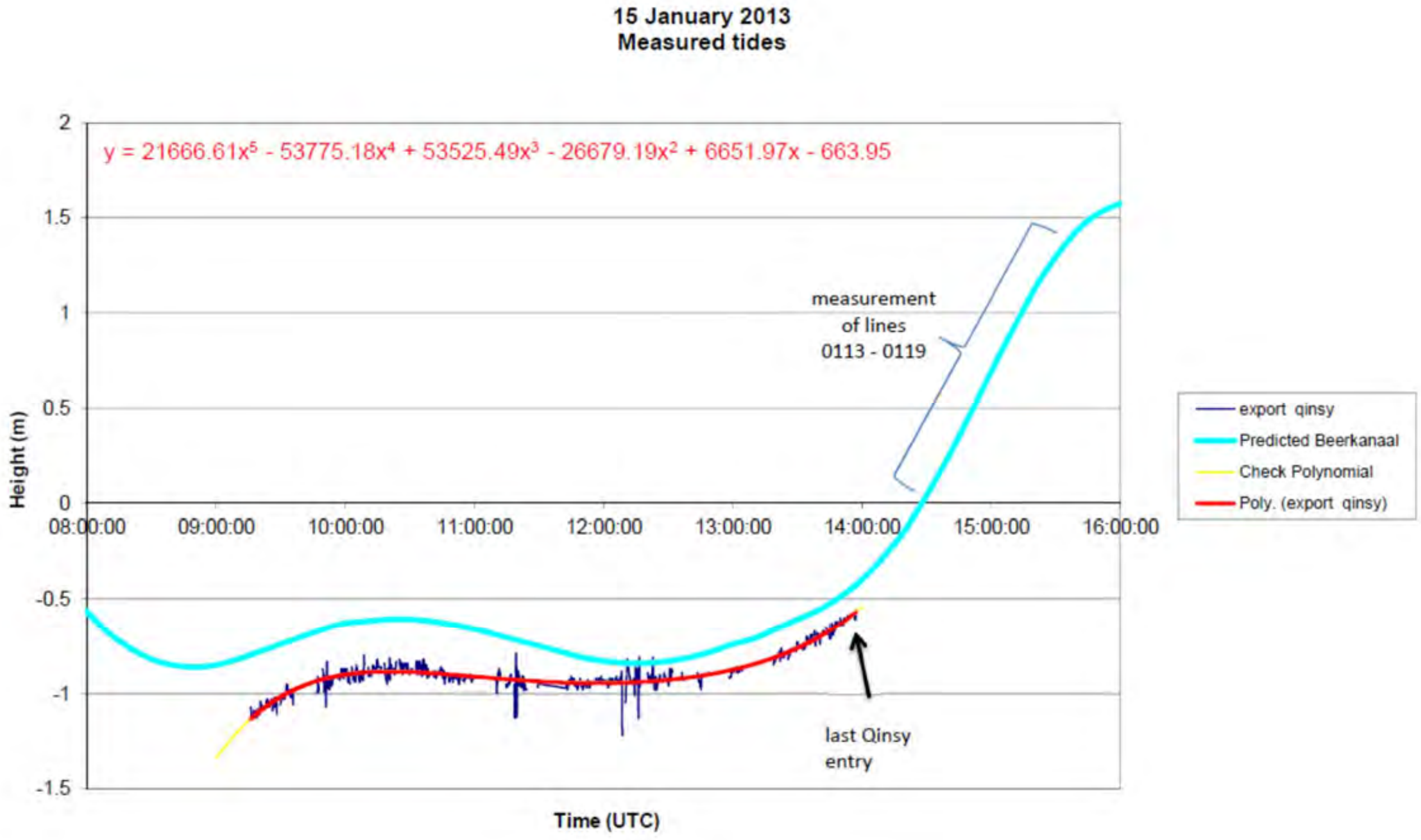


Figure H.10 Tide graphs of 15 January 2013 with latest Qinsy entry at 13:57 hrs and measurement of lines 0113 to 0119 between 14>34 and 15:39 hrs.

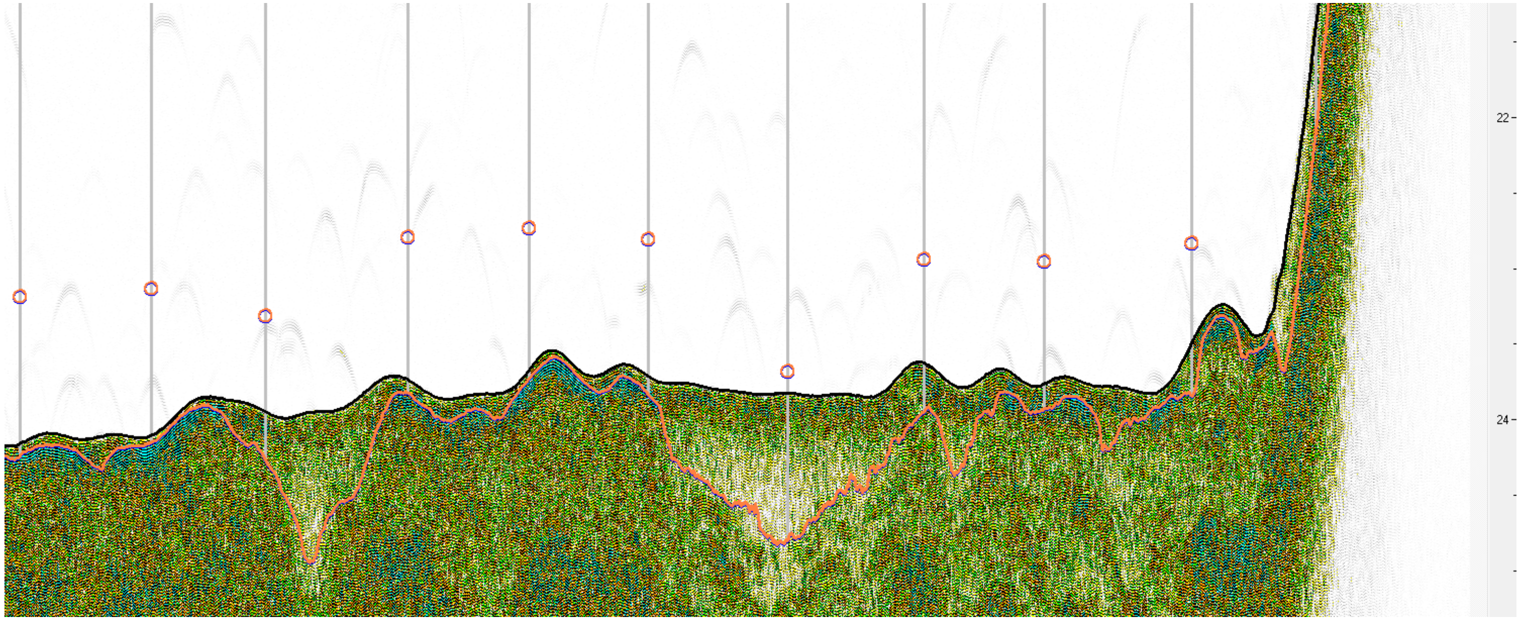


Figure H.11 Example of SILAS line (0016_S2) with 1.2 kg/L level in orange (1200_25cm_5m_cum). The 1.2 kg/L level (1200_25cm_5m_cum) is represented by the orange line, the crossings are indicated grey lines, the 1.2 kg/L level at the crossing line is indicated by the pink circle. The circles follow the orange line, but with a shift caused by the erroneous tide correction for the SILAS line shown in the image (circles are at correct depths).