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Sub report 2
Overview of measuring instruments and analysis of measurement campaign 3, with regard to density instruments

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Sub report 2: Overview of measuring instruments and analysis of measurement campaign 3 with regard to density instruments

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Abstract

As part of the optimisation of the follow-up of dredging works, the Department of Mobility and Public Works, Maritime Access division, has purchased a number of density-related measuring instruments. These instruments represent the various measuring principles available on the market for the measurement of in-situ density of (dredged) mud: **“With which density instrument (or combination of instruments), with which accuracy and with which repeatability can we measure the dredging mud in a practical way?”.** In addition to density, measuring devices were also purchased to chart the strength of the mud.

A number of campaigns were carried out in Zeebrugge to test the feasibility of deploying a number of instruments. This feasibility consists of: user-friendliness (manipulability: safety, lateral and temporal application, data acquisition, data processing,...) and the accuracy, the resolution and the repeatability of the measurements.

During the first two campaigns, the focus was on mobilisation (connecting the periphery, adjusting the setup), demobilisation, manipulability, safety and the possibility of combining the various instruments. The integration of external parameters, data acquisition and data flow were also tested and fine-tuned.

A third measurement campaign focused on the repeatability, resolution and accuracy of the recorded data for density. For accuracy, a sampling that represents the ground truth is required. However, due to failure of the sampling equipment, this could not be done in-situ. As an alternative, a validation measurement was organised at Flanders Hydraulics Research where mud with known densities was measured.

The results of these measurements and a theoretical description of the measuring instruments considered are discussed in the following report.

Contents

List of tables

List of figures

1 Introduction

Within the framework of optimising the dredging works, the Department of Mobility and Public Works, Maritime Access division (abbreviation “aMT”), has purchased a number of density-related measuring instruments. These instruments represent the different measurement principles available on the market for measuring the in-situ density of dredging mud. With this purchase and the testing of the instruments, aMT tries to answer following management question: **“With which density instrument (or combination of instruments), with which accuracy and with which repeatability can we measure the dredging mud in a feasible way”.** Besides density, measuring devices were also purchased to map the (shear) resistance of the mud and to take mud samples.

A number of campaigns were carried out in Zeebrugge to test the feasibility of deploying a number of instruments. This feasibility consists of: user-friendliness (manipulability: safety, lateral and temporal application, data capture, data processing,...), the accuracy, the resolution and the repeatability of the measurements.

In this report, a detailed description of the measuring instruments is given (chapter 2.1.2), both with regard to the theoretical background and an overview of the practical ease of use of the instruments. All instruments purchased by aMT are discussed, both the instruments for measuring density and the instruments for measuring strength (transitions) in mud.

On the other hand, an extensive analysis of the third measurement campaign in Zeebrugge is also presented. In this campaign, carried out in the period April - May 2018 and described in chapter 4, three measuring devices were used, namely the Admodus USP (chapter 2.1), the DensX (chapter 2.2) and the Rheotune (chapter 2.5). The measurement results of these devices were also validated at Flanders Hydraulics Research, as described in chapter 3. An overview of the processing of the measurements, focusing on the repeatability of the measurements, is given in chapter 5.

2 Overview of the measuring instruments

In this chapter the various instruments purchased by the Department of Mobility and Public Works, Maritime Access division (abbreviation: “aMT”) are discussed. These instruments were developed for measuring the density (Admodus USP, DensX, Rheotune) and for measuring the strength of the mud, the rheology (Graviprobe, Rheocable, Rheotune). One device was developed for taking mud samples, namely the mud sampler. In the considered measuring campaign the focus was set on the instruments for density measurement, i.e. the Admodus USP (section 2.1), the DensX (section 2.2) and the Rheotune (section 2.5). An overview of the characteristics of all instruments is given in section 2.7.

2.1 Admodus USP

2.1.1 Introduction

The "Admodus USP pro" is a measuring device developed by Synergetik for measuring mud density (https://admodus.de/en/products/usp-pro/), based on an acoustic measuring principle. The technical information shown below is taken from the manual of the device (Synergetik, 2016).

A picture of the Admodus USP is shown in Figure 1. The Admodus USP is about 0.93 m high and 0.55 m wide. Together with the wings, which are detachable, the instrument weighs 35.8 kg. The main characteristics of the Admodus are shown in Table 1.

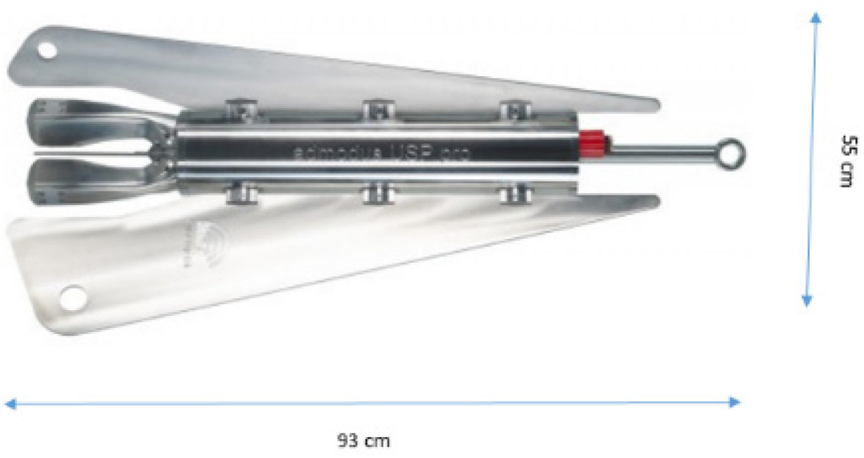


Figure 1 – Picture of the Admodus USP (Geo-matching, 2018)

The Admodus USP is used to measure a depth profile for the following parameters: density, temperature, sound velocity and acoustic attenuation, depending on the frequency. Using the pressure sensor and 3D accelerometer, the following parameters are also recorded during probe lowering: depth, rate of descent and slope angle. The Admodus USP can be connected to an external GPS, thus saving the exact geographical position.

Table 1 – Table of main characteristics of Admodus USP, as presented by the manufacturer (Synergetik, 2016). The third column shows the specifications in units, used in the measurement campaign

Model	Admodus USP	
Weight	35.8 kg (with wing) 28.4 kg (without wing)	
Dimensions	93 cm x 55 cm (wing) 93 cm x 18 cm (without wing)	
Maximum depth	40 m	
Internal/external sampling rate	4 kHz / 50 Hz	
Density: resolution/ accuracy	0.001 g/cm³ / ± 0.005 g/cm³	
Vertical resolution	< 1 cm (vertical speed: < 0.5 m/s)	
Pressure: range	0 tot 5 bar	0 – 50 m
Pressure: Resolution/accuracy	0.001 bar / ± 0.0015 bar	0.01 m / ± 0.015 m
Temperature: Resolution/accuracy	0.1°C / ± 0.15°C	

2.1.2 Operating principle

The Admodus USP Pro is an acoustic instrument, with an operating frequency of 2MHz. The Admodus USP Pro measures three ultrasonic parameters:

- Acoustic impedance of the medium (Z_{med} [Pa.s/m³])
- Speed of sound within the medium (c_{med} [m/s])
- Ultrasonic transmission characteristics of the medium, attenuation

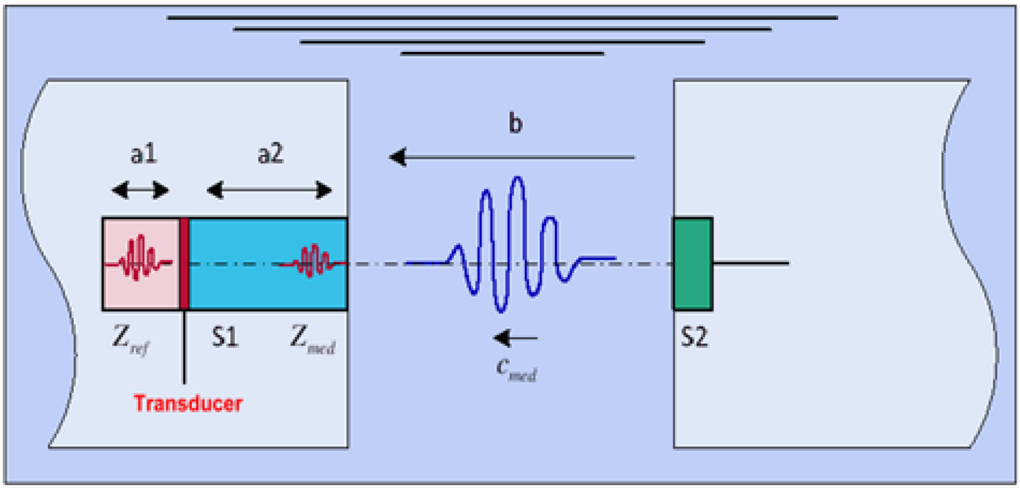


Figure 2 – Operating principle of the Admodus USP (from Claeys et al., 2013; Greiser et al., 2009)

An (ultra)sound wave is emitted by the transducer of the left sensor, indicated in Figure 2. The emitted sound waves propagate in both directions (a1 and a2) and are reflected at both ends of the sensors. The amplitude of the reflected ultrasound wave depends on the acoustic impedanceof the reference medium inside the sensor (Z_{ref}) and outside the sensor (Z_{med}).

The acoustic impedance of the medium (Z_{med}) is calculated using the following equation:

$$Z_{med} = \rho_{sensor}.c_{sensor}.\frac{1+r}{1-r}$$

where r is the reflection coefficient [-], ρ_{sensor} the density of the sensor medium [kg/m^3] and c_{sensor} the speed of sound within the sensor reference medium [m/s].

To measure the value of the reflection coefficient r, it is necessary to record the amplitude of the reflected sound signals, in particular A_{med} and A_{ref} [m]. The reflection coefficient r is calculated using:

$$r = \frac{A_{med}}{A_{ref}}.\frac{-1}{k}$$

with k [-] a sensor specific calibration coefficient, given by the manufacturer.

The sound signals are shown in Figure 3. The x-axis in Figure 3 is the distance (in cm) within the Admodus USP Pro sensor S1 (Figure 2). Additional calculations are done using special algorithms, for the compensation of temperature dependent changes of the sound velocity measured within the reference material. These compensations will influence the values for the amplitudes A_{med} and A_{ref} (described in the German patent DE 101 12 583 C2, issued by Siemens AG on 27 March 2003). The determination of the temperature dependent compensation is based on the relationship between the sound velocity and the attenuation of the sensor reference medium. The most accurate density measurements will occur when the temperature of the sensor material is the same as the temperature of the medium to be measured outside the sensor. For measurements in the field the sensors must be "acclimatised" before the measurement starts to ensure that the temperature is the same for both sensors and medium.

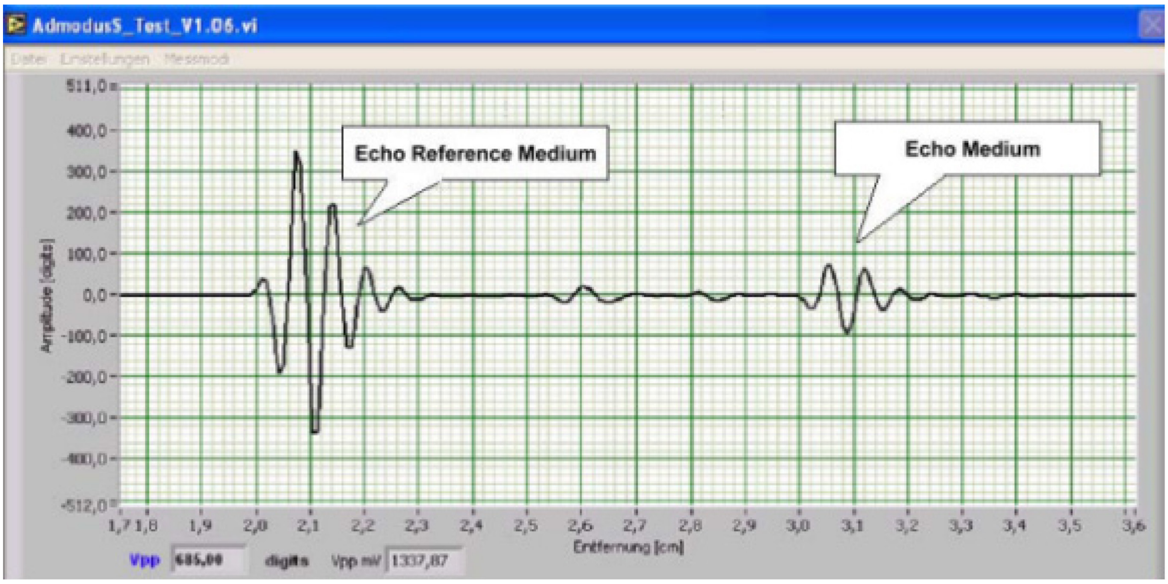


Figure 3 – Reflection of ultrasonic wave signals on the left and right sides of the sensor (Claeys et al., 2013).

The speed of sound within a medium is based on the transmission time of the ultrasound signal emitted by the second sensor (S2) to the receiver of the left sensor (S1). This measurement is corrected by the time taken for the transducer to reach the maximum signal intensity and by subtracting the travel time through the section of the sensor, indicated as a2 in Figure 2.The speed of sound within the medium is found using the following equation:

$$c_{med} = \frac{d_b}{t_b}$$

With t_b [s] the travel time from S1 to S2 and d_b [m] the distance between S1 and S2

The density [kg/m³] of the medium, measured directly on the right side of the impedance sensor, is calculated as:

$$\rho_{med,surface} = \frac{Z_{med}}{c_{med}}$$

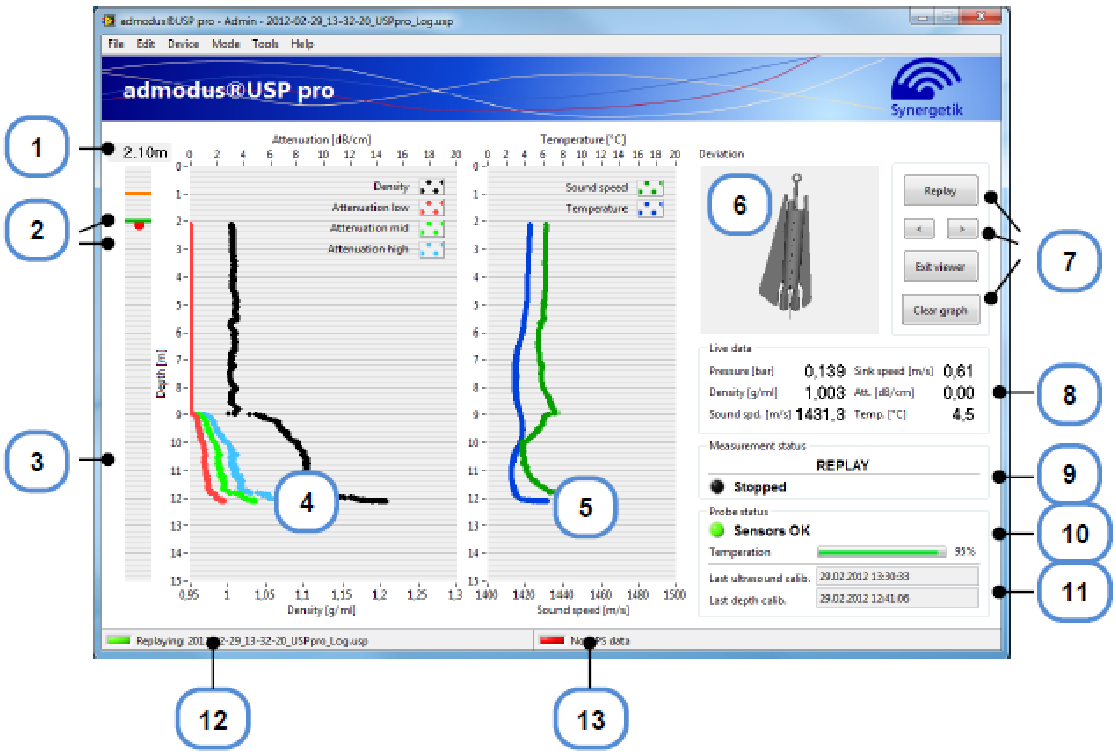
The determination of the density in this way is valid for homogeneous media. For heterogeneous (multiphase) media, this density value will not correspond exactly to the average density of a larger volume of the medium. Therefore a correction factor was determined experimentally. The correction factor is determined on the basis of the changes of the sound waves, emitted by transducer S2, after they have passed the considered medium. In this context, the Admodus output for density is a combination of density values: one value measured directly at the surface of the sensor and a second value (integral density value) more directly linked to the acoustic properties of the volume of the sample penetrated by ultrasound waves.

During a profile measurement, the medium is continuously acoustically scanned by the Admodus USP, resulting in a depth profile measurement of the following variables: density, sound velocity, temperature and acoustic attenuation (depending on the frequency).

2.1.3 Software

Figure 4 shows the graphical user interface of the Admodus USP software, which is available during the measurements. This interface consists of 4 columns. The leftmost column shows the depth location of the sensor. In the second column, a depth profile shows the course of the density and the acoustic attenuation.

In the third column, the course of the temperature and the related sound velocity are shown. In the fourth column, a number of actual measured values are given, as well as the status of the measurement and the measuring device.



1 Current depth of US-transducers Click for depth calibration

2 Marker for automatic-mode

3 Current position of the probe

4 Density- and attenuation graph

5 Temperature- and sound velocity graph

6 3D-orientation of the probe

7 Control elements

8 Realtime data of the probe

9 Measurement procedure and play-back info

10 Sensor status and tempering

11 Time stamp of last calibration

12 Probe connection status, serial number and playback information

Figure 4 – Overview of the graphical user interface of the Admodus USP (from Synergetik, 2016).

2.1.4 Performing measurements

The procedure followed for taking measurements is described below:

1) Setup
The measuring instrument must be connected to a suitable davit via the mounting eyelet. The connecting cable must be secured (with strain relief) in the vicinity of the sensor suspension and guided over a pulley on the crane.

The oil reservoir of the pressure sensor (depth measurement) must be opened with the wrench provided. The cap of the oil reservoir and the sealed pipe of the riser must be clean. After cleaning the oil reservoir, fill it up with sewing machine oil. The riser pipe must be free of air bubbles and completely filled with oil. The blind plug must be removed. The seawater resistant power cable should then be connected to the probe at one end and to the terminal system installed on board at the other end.

The four ultrasonic transducers and the temperature sensor should be carefully cleaned. Due to the temperature sensitivity of the sensors, it is necessary to "acclimatise" the probe before calibrating or taking a measurement. This can be done simply by immersing the probe in water for 5 minutes.

2) Calibration
Before performing measurements, a calibration must be carried out to compensate for any drift of the ultrasonic transducers. The following steps are followed in the calibration process:
   a) Cleaning the sensors
   Before starting the calibration, the four sensors must be cleaned, dirt on these sensors can disturb the calibration.
   b) Salt concentration
   The salinity (expressed in PSU units) must be entered in the software
   c) Immersing the probe in the calibration medium
   The probe must be completely immersed in the medium during calibration. This medium must be clean and clear, particles or air bubbles can disturb the calibration.
   d) Sensor stabilisation
   To obtain a good calibration, the software tests the current sensor values. Only when stable values are reached, the 'Next' button can be used.
   e) Verification of calibration
   If the calibration fails, the last valid calibration is automatically restored.
   f) Completing the calibration
   After calibration, the Admodus USP can be used in water with any salinity. The salinity of the sample to be measured may differ from the salinity of the sample used for calibration.

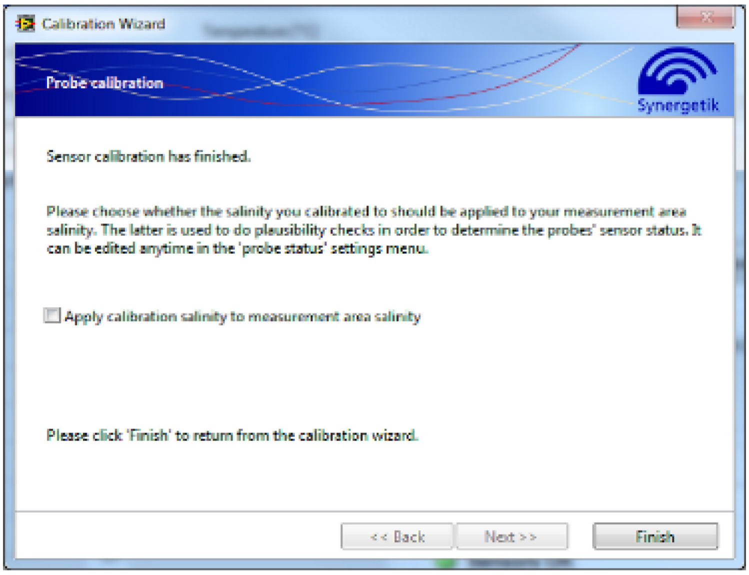


Figure 5 – Calibration interface in the Admodus software (Synergetik, 2016)

3) <u>Performing measurements</u>
   a. The expected values depend on the salinity of the measurement area, which must be set in the configuration menu. An incorrectly entered value may result in the probe not being able to be used for measurement, as the expected sound velocity and density do not coincide with the measured values.
   b. The sensor is lowered at a (variable) speed of the crane/davit
   c. When the cable tension disappears, the probe reaches its deepest point and can be retrieved. The probe can be lowered at a defined speed using the crane/davit. A lowering speed of 0.5 m/s results in a vertical resolution of approximately 1 cm. At lower speeds the probe cannot penetrate the entire mud layer, at higher speeds the probe can be damaged.
   d. Measurements can be started and stopped manually. In "hands-free" automatic mode starting and stopping is performed automatically by the program. In the "hands-free" automatic mode, the sinking velocity and the inclination of the probe are used to stop the measurement automatically.
   e. After stopping the measurement, the probe must be completely pulled out of the water.
   f. The sensors must be cleaned between measurements.
   g. The four ultrasonic transducers, the temperature sensor and the depth sensor must be checked visually. No sediment particles may adhere to the sensors. The riser tube of the pressure sensor must be free of dirt particles.
   h. The depth calibration is relative to the current ambient pressure, so the probe should not be immersed during the verification and calibration of the pressure sensor. The depth calibration should be checked frequently and executed if necessary. Verification is performed by observing the actual pressure value. It must be in the range of ± 0.001 bar (equivalent to ± 1 cm). Calibration is performed by hovering the mouse over the "sensor depth" at the top left of the window. The display then changes to a red coloured "Calib" button with which the calibration can be initiated.
   i. The operating program displays the current status of the sensors in the lower right corner. Once the probe is fully immersed, the actual sensor values are automatically compared with the expected values. As soon as the probe is ready for measurement, the green light is illuminated.

4) After the measurement
To avoid possible short circuits, the electricity is switched off using the on/off switch. The device must be cleaned and the oil reservoir of the depth sensor should be emptied. Before the device is put back into the transport case, check that the device is completely dry. The wings of the device must be removed.

2.1.5 Output

The data recorded during a measurement with Admodus USP pro are saved in a directory defined in the 'settings' menu. The default naming convention of the file is 'YYYY-MM-DD_HH-MM-SS_USPpro_Log', consisting of an ISO format of the date of measurement ('YYYY-MM-DD') and the start time of the measurement ('HH-MM-SS'). Depending on the used option in the 'settings' menu, besides the standard '.USP' binary log file, also a '.csv' file can be exported. An overview of the information that is displayed in such files can be found in Table 2.

Table 2 – Overview of the available information (in '.csv' file format) of an Admodus USP measurement

Label	Description	Unit
Date	Recording date of the measurement point	YYYY-MM-DD
Time	Recording time of the measurement point	HH:MM:SS
Depth	Depth at the density-measurement point	m
SinkSpeed	Sink speed of the probe	m/s
Pressure	Pressure at the level of the pressure sensor	bar
Temp	Medium temperature at the level of the sensor head	°C
TempGrad	Medium temperature gradient at the level of the sensor head	°C/s
SurfDensity	Additional Info: Density measured at the surface of the impedance sensor	g/ml
IntDensity	Mean density of the medium in between the sensor head (displayed density value)	g/ml
MediumSoundspeed	Mean speed of sound in the medium in between the sensor head	m/s
Attenuation	Mean acoustic attenuation in the medium in between the sensor head	dB/cm
Freq0	Frequency at the first node of the frequency-dependent attentuation	kHz
Att0	Attenuation at the first node of the frequency-dependent attentuation	dB/cm
Freq1	Frequency at the second node of the frequency-dependent attentuation	kHz
Att1	Attenuation at the second node of the frequency-dependent attentuation	dB/cm
Freq2	Frequency at the third node of the frequency-dependent attentuation	kHz

Att2	Attenuation at the third node of the frequency-dependent attentuation	dB/cm
Freq3	Frequency at the fourth node of the frequency-dependent attentuation	kHz
Att3	Attenuation at the fourth node of the frequency-dependent attentuation	dB/cm
Freq4	Frequency at the fifth node of the frequency-dependent attentuation	kHz
Att4	Attenuation at the fifth node of the frequency-dependent attentuation	dB/cm
Freq5	Frequency at the sixth node of the frequency-dependent attentuation	kHz
Att5	Attenuation at the sixth node of the frequency-dependent attentuation	dB/cm
Deviation	Imbalance/pitch of the probe	°
RelHum	Relative humidity inside the probe (leakage detection)	RH (%)
DepthCalibDate	Date of the latest pressure sensor calibration	YYYY-MM-DD
DepthCalibTime	Time the latest pressure sensor calibration	HH:MM:SS
UltrasoundCalibDate	Date of the latest ultrasound sensor calibration	YYYY-MM-DD
UltrasoundCalibTime	Time of the latest ultrasound sensor calibration	HH:MM:SS
Zone	Zone of the GPS position (relevant for UTM datum)	-
Easting	East coordinate of the GPS position	m
Northing	North coordinate of the GPS position	m
GPSString	Raw data string of the GPS receiver (NMEA GPGGA)	-
QualityE1	Echosounder signal quality of the first echo of the imported depth data	-
DepthE1	Echosounder depth of the first echo of the imported depth data	m
QualityE2	Echosounder signal quality of the second echo of the imported depth data	-
DepthE2	Echosounder depth of the first second of the imported depth data	m
DepthString	Raw data string of the imported Echosounder data (Echotrac DBT)	-

2.2 DensX

2.2.1 Introduction

The DensX device is a measuring device developed by dotOcean (dotOcean, 2018), for the measurement of mud densities. The DensX is the successor to the Navitracker. This device, also for measuring the density of a medium, worked with the same measuring principle as the DensX (Vandecasteele, 2012), but used a different type of source.

The DensX, shown in Figure 6, is used to perform density profiling. During the lowering of the probe a depth profile is measured of the following parameters: density, speed of the winch, torque of the winch and slope of the DensX.

The measured data is displayed in real time in the display module (PC) and saved for later use.

Figure 6 – Picture of the DensX device (dotOcean (2018))

Figure 6 shows an illustration of the DensX. This device has a height of approx. 80 cm and is approx. 35 cm wide. The weight of the DensX probe is 70 kg. Table 3 lists the technical specifications as communicated by the manufacturer (dotOcean, 2018).

Table 3 – Technical specifications of the DensX (DensX, 2018) as presented by the manufacturer (kolom 2). The third column shows the specifications in units, used in the measurement campaign

Model	DensX	
Type	DX-01003	
Weight	70 kg	
Dimensions	70x34x13 (WxHxD in cm)	
Density: range	1 – 1.5 kg/l	
Density: accuracy	-2.5 +2.5 ‰	± 0.003 g/cm³ (@ 1.2 g/cm³)
Pressure: range	0 – 3.5 bar	0 - 35 m (H_2O)
Pressure: resolution	0.00014 bar	0.0014 m (H_2O)
Depth: accuracy	± 1.5 %	± 0.15 m (@ 10 m)
Activation depth	5 m	
Stability	< 0.1 % (5 – 40 °C)	
Radiation	1 µSv/h (distance < 10 cm)	
X-ray voltage	< 30 kV	
Power	< 20 Watt	

2.2.2 Operating principle

The operating principle of the DensX is based on the transmission of X-rays. In the DensX, an X-ray source and detector are present, more specifically in the "legs" of the DensX. The X-ray source is marked with an X-ray logo (as shown in Figure 6). The photons, emitted by the X-ray source, interact with the electrons of the medium along their path. The higher the density of the medium, the higher the number of electrons present. Only the photons captured by the detector, more precise the crystal NaI(Tl), are recorded. The signals received by the detector decrease according to an exponential function as the number of electrons present increases.

The relationship between the density of the considered medium *d* [kg/m³] and the value of the signal measured by the detector is:

$$d = Kd_0 + Kd_1\left(\frac{Nc}{N_0} - 1\right) + Kd_2Ln\left(\frac{Nc}{N_0}\right)$$

where *d* is the density of the medium [g/cm³], N_0 is the measured signal by the detector in clear water and $K\,d_0$, $K\,d_1$ and $K\,d_2$ are the calibration coefficients for the DensX.

The first term considered in the previous equation, $K\,d_0$, is related to salinity, the second term considered $Kd_1\left(\frac{Nc}{N_0} - 1\right)$ is related to the scattering of the DensX. The latter term is equated to zero for the DensX (verbal communication, dotOcean). The third term $Kd_2Ln\left(\frac{Nc}{N_0}\right)$ is used for the transmission of the DensX.

The latter term is determined using mud from the location to be studied (verbal communication with dotOcean). Additionally, an extra correction term can be used in case of decreasing source strength. The calibration coefficients are specific to the device and to the type of medium and are provided by the manufacturer. These values are stored in a calibration file and loaded into the software. The device should be checked before each measuring campaign to ensure proper functioning and accurate calibration.

The drift of the X-ray source is monitored by placing metal plates of known composition and thickness. Deviations from the expected transmission of the X-rays through these plates indicate the drift. In the software, the DensX can be compensated for this drift. A regular check must be done by qualified personnel. During this operation, some of the safety measures are bridged and carried out in the air, without the water above. The company dotOcean is involved in such operations. Radiation measurements were also carried out by Controlatom in the vicinity of the device during the calibration mentioned above. Calibration is also carried out in containers filled with the medium to be measured (mud); here too the safety measures are overridden and handling is only carried out by qualified personnel wearing the necessary PPE and a dosimeter. Measurements were also carried out by Controlatom and the safety perimeter was determined during the measurement.

2.2.3 Software

The software allows to switch the DensX device on and off, and can be further used to store and process the data and control the winch. The calibration settings are stored separately and must be available on the PC used.

The software is project-based. A project is stored in a custom file format and can be opened easily. The settings are stored in the software. The directory in which the project is opened is used as a 'temp' directory. Therefore it is not possible to use other directories.

The recommended system requirements are:

- +2 Ghz quad core CPU
- 6 GB RAM
- 100 GB free space on hard drive
- Windows 7 of Windows 8
- Minimal screen resolution: 1600x900

The DensX system uses an IPv4 network range (from 192.46.111.1 to 192.46.111.254). To connect the computer to the DensX, the user must set a fixed network IP address in Microsoft Windows.

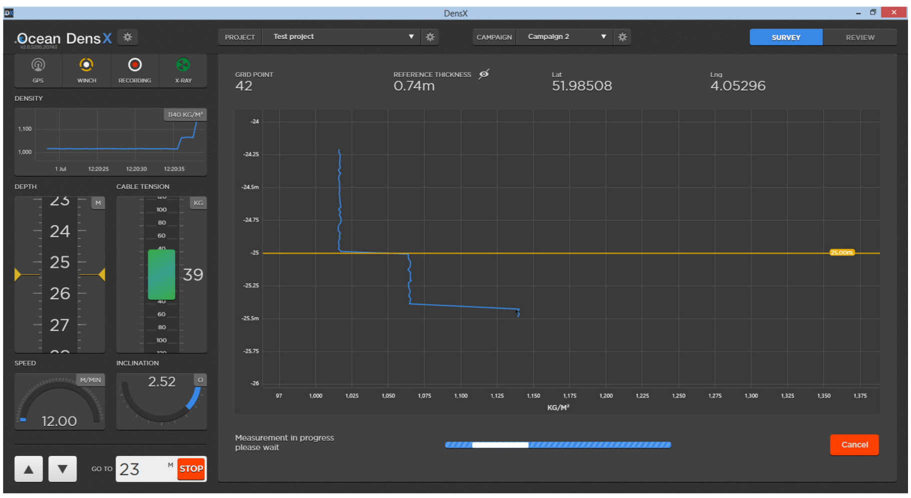


Figure 7 – Main window of the DensX software (DensX, 2018)

When the DensX software is opened, the main page appears, as shown in Figure 7. It consists of two columns. The second column contains the name and location (lat and lon) of the measurement point, next to a graph with the density profile. A more detailed overview of the left column, the control panel, is shown in Figure 8.

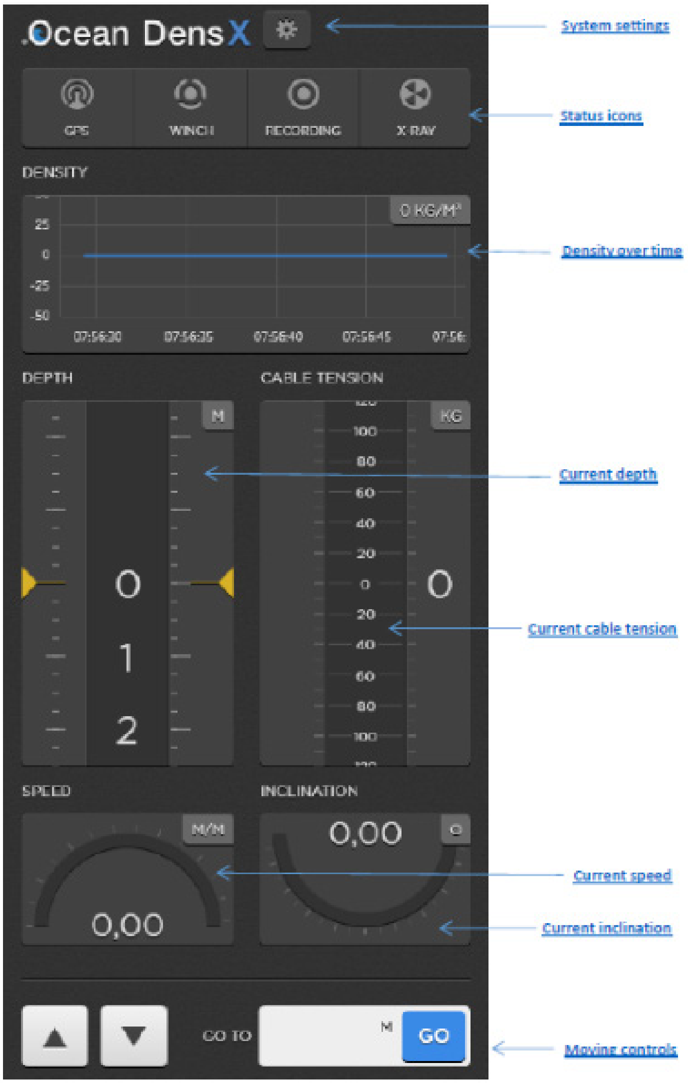


Figure 8 – Detailed view of the control panel in the DensX software (DensX, 2018).

The following options (see Figure 8) can be selected or read in the different areas of the control panel:

- In the system settings, the following options can be selected:
  - DensX configuration window:
    - IP address of the connected device
    - Options that can be set:
      - Minimum and maximum permitted cable lengths
      - Minimum and maximum permissible cable tension
      - Maximum permitted inclination
  - GPS configuration: display of the serial COM port settings and status of the GPS.

    - Single-beam configuration: display of the serial COM port settings and the status of the single-beam
    - The external port is a serial output with the current depth and density. The external configuration displays the COM-port settings.
    - The calibration settings are used for a proper calibration of the device.
    - There are two different log files in the software. The system log file tracks every change in the software and stores every action in the software. The calibration log file stores all calibration actions.
  - Icons, showing the GPS connection status, connection of the winch, the X-ray status and the data recording status to save the results.
  - Chart of density [kg/m^3] as a function of time
  - Current depth [m] and cable tension [kg] during the measurements
  - Current speed [m/min] and inclination [degrees] during the measurements. The DensX can tilt in two directions, only the maximum value is displayed.
  - Moving control to move the DensX up or down

Before starting a new measurement, there is the option of creating a new project or opening an existing project. The list of options that can be changed in a project are (see also manual): maximum inclination DensX (10°), top mud threshold (1.05 g/cm^3), target density (1.20 g/cm^3), minimum sequential values (3 times), minimum cable tension (20 kg), calibration target (-), coordinate system (ETRS89), interpolation settings (interpolation grid cell size is 5m), quality settings (with standards) and project specific changes. The values in brackets represent the settings during the measurement campaign.

There are templates for these project specifications, with certain predefined options. In a certain project, a 'survey map' can also be loaded, a grid with measurement positions, where density profiles can be taken. When the position of the ship is close to a grid point, the screen to start a new measurement can appear automatically. A grid point can also be selected manually.

2.2.4 Performing measurements

The procedure followed for taking measurements is shown below:

1. <u>Setup</u>
   The terminal of the data cable must be connected to the top of the DensX. The tube for the pressure measurement should be filled with fresh water. After filling, the lower screw must be closed. It is important to avoid air bubbles in the tube.

2. <u>Calibration</u>
   The DensX must be calibrated with mud from the measurement location at a frequency of at least once a year (dotOcean, 2018). A regular calibration of the source with copper elements is also recommended. The DensX is then placed in the calibration system and copper plates are inserted between the measuring legs. It is useful to monitor an offset of the X-ray source over time.

   For calibration, the system must be set up and the following steps must be followed:
   a) Set the winch to 'START' mode
   b) DensX is in the calibration unit and the calibration unit is closed
   c) The key of the control unit is inserted and in position “1”,
   d) The software is running in calibration X-ray sensor

3. Performing measurements
    - Instructions for starting a measurement:
        - Start winch to enable the winch and the DensX
        - Set winch local to manually move the winch with the remote control
        - Put the DensX in the water with the remote control to a depth of (at least) 5 m
        - Activate the X-Ray source of the DensX with the key
        - The winch can be set to 'PC mode' so that the winch is controlled using the software
    - Starting the measurement
      When the measurement window is open, a new measurement can be started and a profile taken. The speed of the winch is controlled by the software. When a complete profile has been measured, three options can be selected: save, restart or cancel the measurement.
    - Instructions for stopping a measurement:
        - Set winch local to manually, move the winch with the remote control
        - Deactivate the X-ray on the DensX with the key of the control-command unit
        - Put the DensX on deck with the remote control
        - Clean the DensX with fresh water
        - Stop winch to disable the winch and the DensX
    - Profiles:
      It is possible to review and edit the depth profiles after the measurements.

2.2.5 Output

The data saved during a measurement with the DensX device are stored in a directory that is determined in the 'settings' menu. The selected profiles can be exported in a '.csv' file. An example of such a file is shown in Table 4. In this file, the name of the profile measurement, the date and time of the measurement itself, the density, the measurement position (latitude and longitude) and the sb_high (210 kHz) and sb_low (33 kHz) parameters are displayed. These last two parameters are variables obtained from the single beam measurement.

Table 4 – Output of a DensX measurement, in '.csv' format

Name	Date	Depth	Density	Latitude	Longitude	sb_high	sb_low
18	2017.07.05 13:55:09.012	-9.00407	1025.722	51.35316	3.197122	17.31	
18	2017.07.05 13:55:09.015	-9.0071	1025.787	51.35316	3.197122	17.31	
18	2017.07.05 13:55:09.020	-9.00473	1025.84	51.35316	3.197122	17.31	
18	2017.07.05 13:55:09.028	-9.00401	1025.828	51.35316	3.197122	17.31	
…	…	…	…	…	…	…	…

2.3 Graviprobe

2.3.1 Introduction

The GraviProbe is an instrument for measuring rheological and density profiles, manufactured by dotOcean (dotOcean, 2015). It is primarily used to perform strength measurements. The GraviProbe is used as a free-fall instrument and analyses the sediment layers by penetrating the sediment itself. Under its own weight, it accelerates and penetrates fluid- and consolidated mud layers.

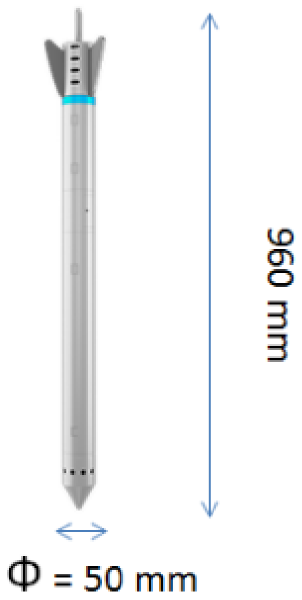


Figure 9 – Illustration of the Graviprobe, with its dimensions (dotOcean, 2015)

Figure 9 shows an illustration of the GraviProbe with the dimensions of the instrument. The device is approx. 1 m high and has a diameter of 50 mm. The GraviProbe weights approximately 8 kg. The technical specifications of the GraviProbe (dotOcean, 2015; Claeys, 2013) are listed in Table 5.

Table 5 – Technical specifications of the Graviprobe, as presented by the manufacturer (dotOcean, 2015). The third column shows the specifications in units, used in the measurement campaign.

Model	GP-R-01	
Weight	8 kg	
Dimensions	Ø 50 mm – length: 900 mm	
Depth: Range	0 – 3.5 (or 10 bar)	0 – 35 (100 m) H_2O
Depth: accuracy	± 1.5% accuracy	± 0.015 m (@10 m)
Penetration resistance: range	0 – 100000 Pa	
Penetration resistance: accuracy	1 %	
Shear strength: range	0 – 10000 Pa	
Shear strength: accuracy	1 %	
Maximum Impact	0 – 70 G	

2.3.2 Operating principle

The GraviProbe is a free-fall measuring instrument that monitors the sediment layers by penetrating them. The measuring device accelerates, after release, under its own weight and penetrates into the fluid and consolidated silt layers. The rheological properties of these layers determine the dynamic behaviour of the device, which is recorded. The data obtained from the built-in accelerometers, inclinometers and pressure sensors is used as input into a dynamic model that determines the rheological parameters (depth, undrained shear stress and viscosity) of the mud being penetrated (dotOcean, 2015).

The GraviProbe measures its own acceleration (via accelerometers) and pressure in the head of the tail. Based on the acceleration and pressure, the different sediment layers can be distinguished from each other. An example of the raw data obtained by the GraviProbe is shown in Figure 12, in which the acceleration and velocity are shown in the water column and then the fluid sediment layer.

The density can be determined by the pore (head) and depth (tail) pressure, which is monitored during the measurement. The point at which the curves (over the depth) of the pore pressure and pressure differ from the hydrostatic pressure, indicates the location of the top of the fluid mud layer. The difference between these curves is a measure for the density of the mud, so the density of the fluid mud can be calculated from the pressure measurements. Density is not delivered as a measurement result.

The various forces on the GraviProbe and related losses are calculated to determine the shear strength. Dissipation due to friction on the sleeve is a basis for determining shear strength. Figure 10 shows the forces on the GraviProbe, during a measurement.

An important condition for carrying out a reliable measurement is the fact that the GraviProbe must reach its limit velocity before it enters the silt layer. The GraviProbe can therefore only be used when the depth of the water column is sufficient to meet this condition. This limit or end velocity is necessary to obtain stable, controlled initial measuring conditions before penetration into the silt layers.

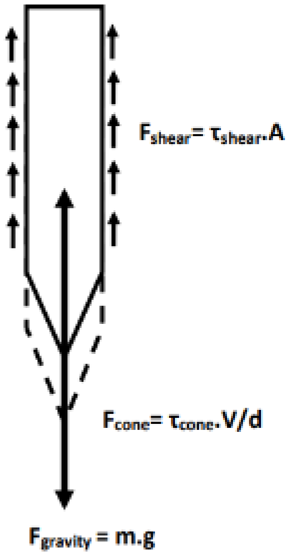


Figure 10 – Operating principle of the Graviprobe.The forces that occur during the falling of the instrument, i.e. during the measurement, are shown (gravity, shear stress and cone resistance).

2.3.3 Software

The GraviProbe works with the GraviProbe v2.0 software. Figure 11 shows a screenshot of this software. In this main window there are 2 submenus, namely "survey" and "process".

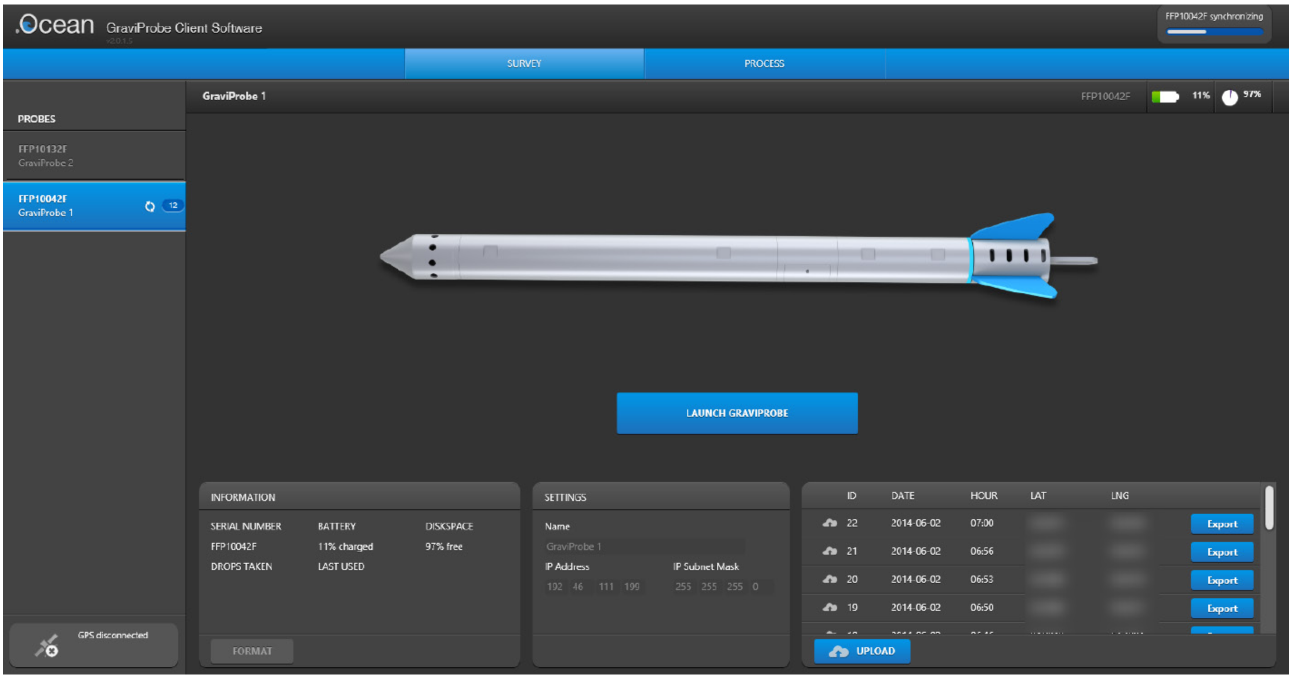


Figure 11 – Main window of the GraviProbe software (from dotOcean, 2015)

When the GraviProbe is connected to the software, the battery status can be checked in the lower left corner (see Figure 11), and the profile measurements stored on the internal memory can be exported in the lower right corner. The number of profile measurements present on the internal memory can be seen in the left column, next to the probe number itself.

Via the "process" tab, the data can be viewed, as shown in Figure 12. A list of all profile measurements on this measurement day is shown in the list below. The results of a selected profile measurements are shown in 4 separate figures. In particular the variation of the acceleration, the velocity, the shear strength and the cone resistance with depth are visualised. It is also possible to edit the measurement, e.g. to adjust the starting point of the profile measurements.

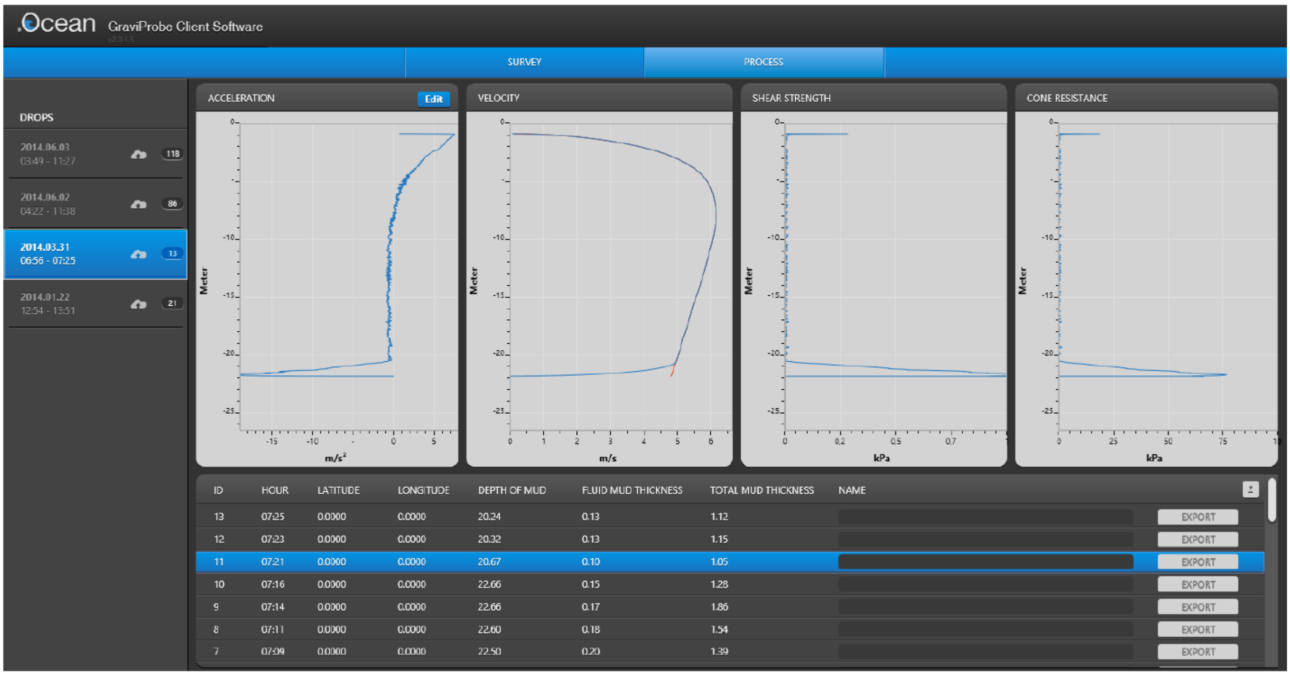


Figure 12 – Main window of the GraviProbe software - "process" tab (from dotOcean, 2015)

To perform a measurement, select the "Launch Graviprobe" button in the start page (Figure 11). When the LED-lights on the GraviProbe are blinking, the device is ready for use.

2.3.4 Performing measurements

An instructional video on mounting the GraviProbe can be found on Youtube (https://www.youtube.com/watch?v=Y1gSLm6ytWQ (dotOcean, 2015). The following steps are required to assemble the probe:

1. The ON-Connector (with the red tip) must be placed over the pins at the tail of the GraviProbe. When the LED's are blue, the device has booted.
2. Assemble the GraviProbe:
    a. Slide the small cylinder over the device
    b. Assemble the fins and place them on the GraviProbe
    c. Slide the large cylinder over the fins and the device
    d. Screw the lifting eye into the back of the unit and fasten the bolt with the M17 screw
    e. Screw the desired tip onto the front of the GraviProbe
3. Put the rope through the eye of the weight and connect the rope to the lifting eye of the GraviProbe

4. Attach the rope (with a length of approximately 2 times the expected depth) to the boat's davit

5. The GraviProbe must be connected to the software, the "launch Graviprobe" must be pressed and the LED lights blink approximately every 3 seconds. On more recent models the result of the profile measurement can be loaded directly.

The measurement itself can be done by following the steps below:

1. Lower the weight: the weight should be lowered to a depth approximately equal to the measuring depth (see Figure 13).

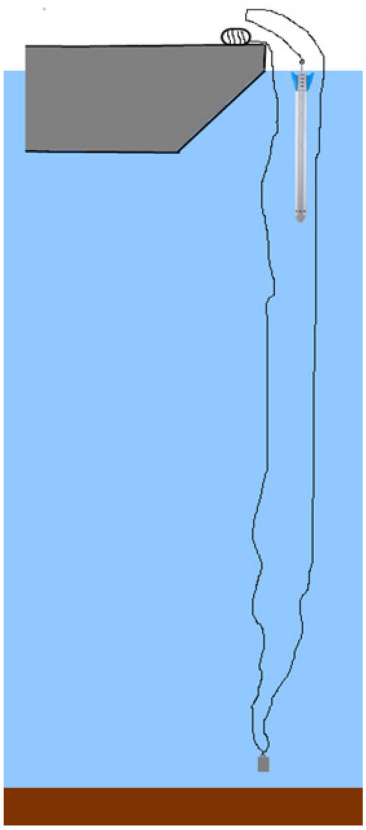


Figure 13 – Lowering the weight and the GraviProbe

2. Lower the GraviProbe: Lower the probe until the tail fins are just beneath the surface of the water. Hold for a few seconds to stabilise the sensors (see Figure 13).

3. Release the GraviProbe: try to avoid any upward and downward movement of the rope and the probe.

4. Wait a few seconds while the probe measures: during free-fall in the water and slowing down in the silt layers.

5. Pull up the probe and the weight.

The duration of the measuring cycle is ± 30 seconds, depending on the depth. It is recommended to place the measuring device on the deck when manoeuvring the vessel (to avoid damage and loss).

2.3.5 Output

The selected profiles can be exported in a '.csv' file. An example of such a file is shown in Figure 14. The naming convention for these files is a time stamp, in this project "Y.M.D_H.M.S". In this file the depth is given, the acceleration and velocity of the device, a simulated velocity, and the dynamic undrained shear strength and penetration resistance of the cone.

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Depth (m.)	Depth Tide corrected (m.)	Accelerations (m/s²)	Velocity (m/s)	Simulated Velocity (m/s)	Dynamic undrained shear strength (kPa)	Cone penetration resistance(kPa)
-0,86	-0,86	4,621888898	0,019964243	1,099839483	0	0
-0,87	-0,87	9,949423444	1,686677251	1,405527325	-6,154844115	-423,4532751
-0,88	-0,88	6,672981901	1,737518891	1,561645283	0,856141605	58,90254242
-0,89	-0,89	7,400791447	1,774830407	1,684385758	0,791683523	54,46782636
-0,9	-0,9	9,962139091	1,821399701	1,788081308	0,5703091	39,23726611
-0,91	-0,91	6,27995625	1,868636058	1,879826167	0,417345704	28,71338445
-0,92	-0,92	8,642191373	1,902037398	1,962097679	0,459816545	31,6353783
-0,93	-0,93	9,860733948	1,952330184	2,039340132	0,374727244	25,78123436
-0,94	-0,94	9,761756114	2,002333866	2,111688759	0,332041301	22,8444415
-0,95	-0,95	9,283863919	2,050439951	2,179269436	0,29723131	20,44951416
-0,96	-0,96	9,931183065	2,095860796	2,242199056	0,267398418	18,39701115
-0,97	-0,97	9,924690407	2,141868583	2,300585855	0,24682026	16,9812339
-0,98	-0,98	9,928180536	2,187896475	2,356517434	0,245048202	16,85931629

Figure 14 – Output of a Graviprobe measurement, in '.csv' format

2.4 Rheocable

2.4.1 Introduction

The Rheocable is a measuring instrument developed by THV Nautic (THV, 2014). The Rheocable consists of a pressure sensor that is dragged over the bottom, followed by an array of resistance measurements, to ensure that the pressure sensor does not float above the bottom. Both the pressure sensor and the resistance measurement cable are pulled by the survey vessel via a power cable with CTD's (conductivity - temperature - depth) measuring devices. A picture of the Rheocable and rheoset (computer and interface) are shown in Figure 15. The dragging of the cable is shown in Figure 18.

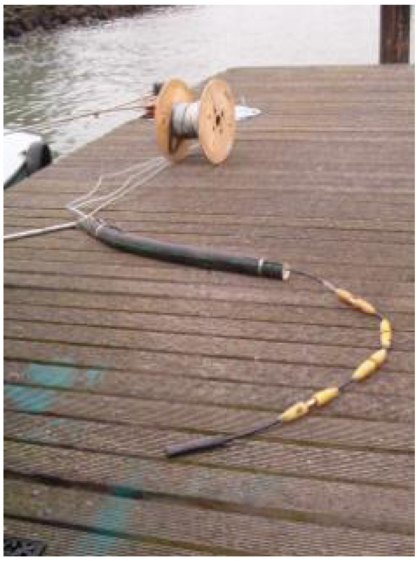


Figure 15 – Picture of the Rheocable. On the left: Rheocable, right: computer and interface (from THV, 2014; Claeys et al., 2014)

The Rheocable consists of the following elements (THV, 2014):

- steel-sheathed power cable with the following connectors: resistance cable with 4 electrodes and a connector for the pressure sensor on the "seabed side" and a connector for connecting the modules on the ship side.
- connection between the steel-sheathed power cable and the rheoset unit
- pressure sensor ATM/N 24 mm 4 bar, precision: 0.1% (over the full range)
- watertight cylinder with the pressure sensor
- 2 vent pipes
- 2 sets of lead weights
- rubber hose 1.5 m long
- Steel handle to drag the cable behind an inspection vessel
- CTD diver and holder in stainless steel

Cable length	3 * expected depth	
Weight	20 kg (for 20 m) (MDCE, 2014)	
Sampling frequency	1 Hz (depth) 50 Hz (resistance)	
Depth: range & accuracy	0 – 4 bar / 0.1%	0 – 40 m / ± 0.001 m

2.4.2 Operating principle

The Rheocable method involves dragging an object through the mud, attached to the survey vessel. The working principle described here is based on the description in Druyts et al. (2012). With the Rheocable, a pressure sensor is attached to the tow rope, next to the lead weight, behind which a short resistivity cable (with resistance measurements) is attached. This resistivity cable serves to check whether the pressure sensor is located in the solid (consolidated) mud or in the fluid mud. If the cable is situated on this consolidated mud layer, characteristic resistance values for consolidated mud are measured. When the cable is located above the fluid/solid mud transition, resistance values are observed that are characteristic of fluid mud or seawater (Druyts et al., 2012).

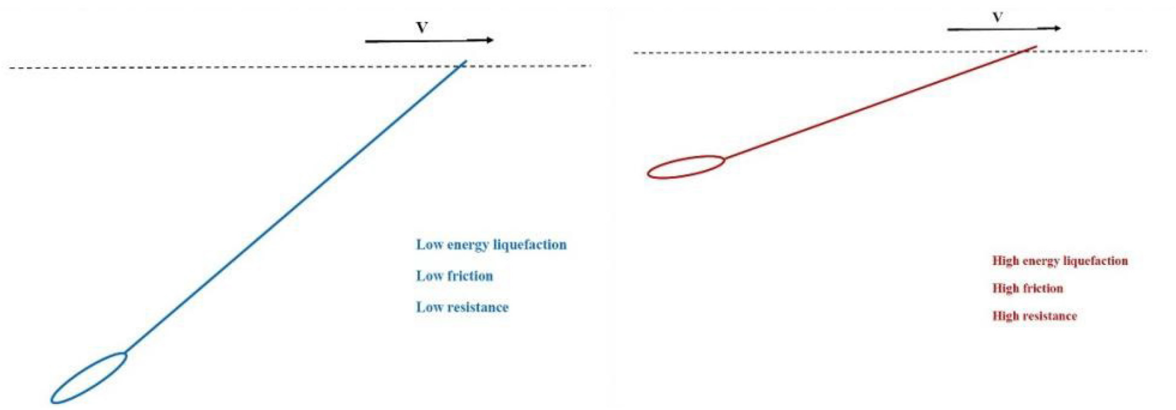


Figure 16 – Illustration of the position of a dragged object in 2 different media (from Druyts et al., 2012)

If a random object is dragged with a velocity *v*, this object will occupy a low position in a medium with low viscosity, as shown in Figure 16 (left). The resistance and consequently the drag force are low. With the same action in a medium with high viscosity (Figure 16, right), the object will be in a higher position. Due to a higher yield stress, the resistance will be higher and consequently the drag force larger. When there are two layers, assuming that the two layers are respectively the fluid mud and the consolidated mud, the dividing line between the two is called the "Rheological transition" (see Figure 17).

Assuming that the towing speed is between a minimum and maximum speed, the object (Rheocable) will position itself on this dividing line. The fluid and consolidated mud have different, characteristic electrical resistance values. By adding the resistivity cable, these resistance values are measured, and it can be checked whether the Rheocable is in contact with the consolidated mud, i.e. that it is not floating (Druyts et al., 2012). The maximum speed of the vessel depends on the water depth, cable length, cable weight and thickness of the fluid mud layer. A normal speed of 4 to 5 knots is assumed (MDCE, 2015). The depth position of the cable is measured by measuring the hydrostatic pressure.

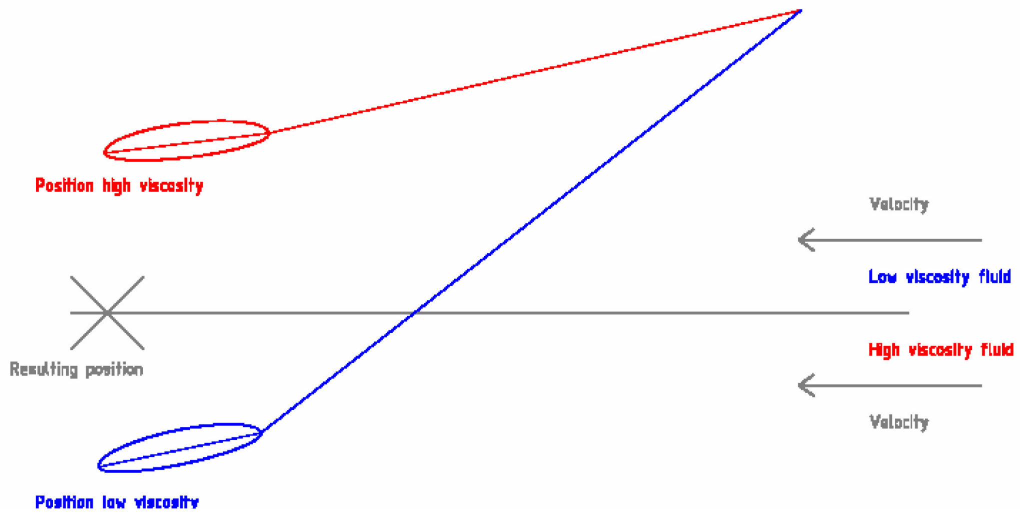


Figure 17 – Illustration of the Rheocable's operating principle (from Druyts et al., 2012)

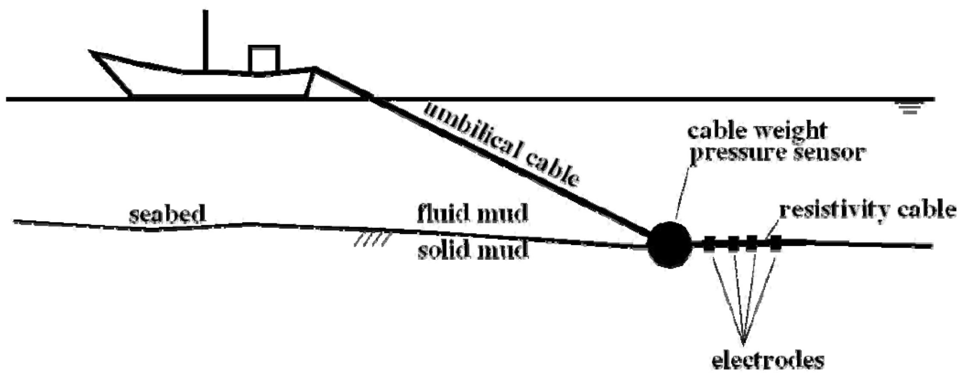


Figure 18 – Dragging the Rheocable (from THV, 2014)

2.4.3 Software

To read out the data from the divers, the “diver-office” software is used, published by van Essen instruments (https://www.vanessen.com/products/software/diver-office/). This software will not be discussed here.

Rheonavigator2 is the data acquisition software supplied with the Rheocable, which is used to control the Rheocable. A GPS and echosounder can be connected to the computer via separate serial ports. A Rheoset, either with SCXI-1600 or "CompaqDaq technology", must be connected via USB port.

The following conventions and formats are used in the Rheonavigator software:

1. Database

A data file contains coordinate information of data points, in the following format:

- No: number of measurement
- X-coordinate
- Y-coordinate
- Data - value
- String (optional): text

2. Line file

A line file is a special data file, where the data points have values with a specific meaning:

- 0: beginning of a new line
- -1: end of a closed line. The line is closed for the last data point with a point number equal to "0"
- Any other value: no meaning

Three Tabs can be selected in the Rheonavigator2 software. A first Tab contains the settings and values for the positioning, a second contains parameters for the Rheocable and a third relates to navigation and data collection.

The “*positioning tab*” contains parameters such as cable length, distance between ship's stern and GPS location, height of the stern above sea level, for properly determining the position of the cable. These parameters are stored in a "ctd-gps.par" file.

The "*Rheocable tab*” is used to define the settings of the Rheoset unit. Both "CompaqDaq" and "SCXI-1600" hardware is accepted. As long as the assigned device (as found in "Measurement & Automation") or hardware type is incorrect, the screen colour turns red and the system cannot work (see Figure 19). If the connection parameters are set correctly, the system can be tested by pressing "A/D" to check the voltage of the four channels and to select the “Current” box and change the polarity.

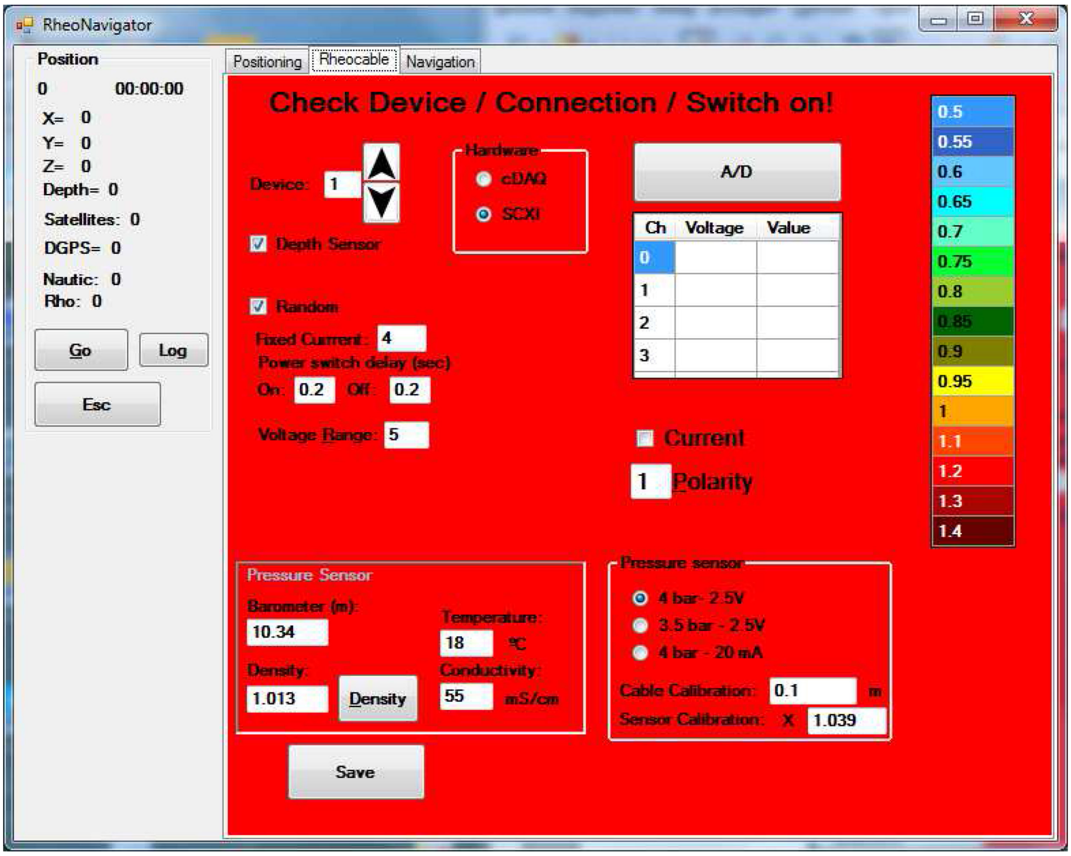


Figure 19 – Screenshot of the Rheonavigator2 software, in particular the "Rheocable" tab (from THV, 2014)

When working with the Rheocable, the depth sensor check box should be controlled. For test purposes, random data can be generated by selecting the "Random" check box. The injected fixed current can be specified as well as the required delay of the current switch and the voltage range. Pressure values can be converted to depths after entering the barometric pressure and the density of water (this can be calculated after measuring the water temperature and conductivity) and pressing the "Density" button.

A calibration factor for the sensor and a cable calibration can be entered as indicated, as well as the type of pressure sensor. Under normal circumstances the calibration factor is equal to 1. For 2.5V sensors the cable calibration is 0.1 m for an 80 m long standard cable. For 20 mA pressure sensors the cable calibration is 0 m.

Finally, the “*Navigation tab*” is used to monitor the position, together with the (nautical) depth. Data is finally entered into a file with following format:

N X Y P Time Rho HF LF

With:

- N: integer
- X: easting
- Y: northing
- P: Pressure sensor (in m)
- Time: “uu: mm: ss” based on the GPS time
- Rho: resistance value measured by the Rheocable
- LF: depth echosounder (low frequency)
- HF: Depth echosounder (high frequency)

The programme "NauticDepthEdit" is used for editing nautical depth information. The input file is a file with the same format as the output file described above. An overview of the GUI of the program is shown in Figure 20. In this program the data can be loaded, viewed, edited (removing outliers, smoothing). After processing, the data can be saved in the same format as the output of the Rheonavigator software (".raw" extension). Additionally, the data of the Rheocable itself (".NAUT") and of the SB 33 kHz and 210 kHz can be stored separately (extensions (".LOWF" and ".HIGHF")).

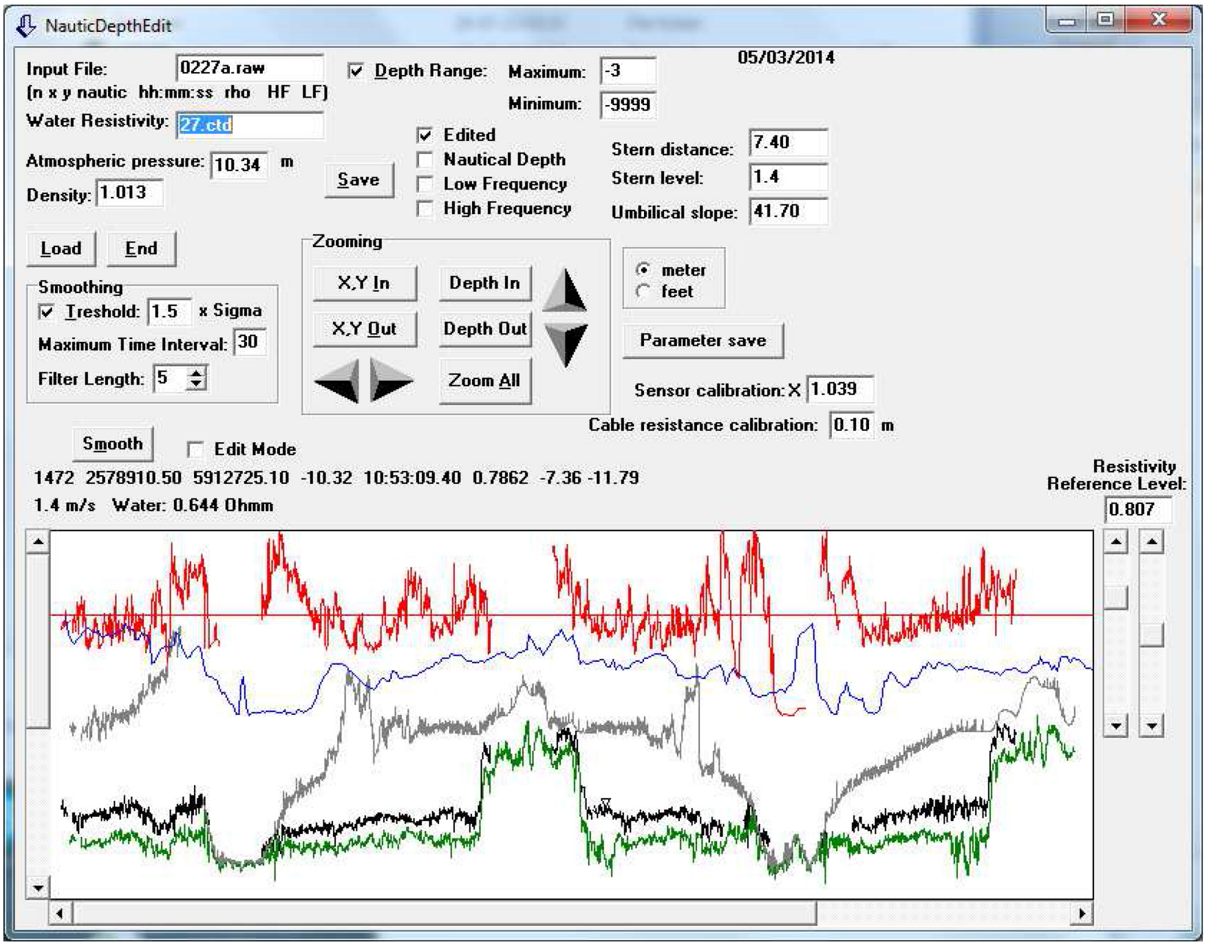


Figure 20 – Interface of the NauticDepthEdit processing software

2.4.4 Performing measurements

Steps to prepare the Rheoset unit and the computer before starting measurements (THV, 2014):

1. Start the computer before connecting the GPS and/or echosounder signals
2. Install NIDAQ software 'Measurement & Automation' according to NI instructions
3. Connect the Rheoset unit to a USB port and switch on the Rheoset unit
4. Open Measurement & Automation, click 'Devices and Interfaces' and check if the Rheoset unit is detected as an NI SCXI-1000 unit or an NI cDAQ-9174 unit. If a SCXI-1000 unit is detected, click 'Configure' and set the gain for all channels to a value of 1
5. Install Rheonavigator2, SetDirectory and Diver-Office software according to the instructions.
6. Define a working directory (with at least one file in it) using SetDirectory
7. Start the Rheonavigator2 programme and go to the tab "Rheocable".
8. Select cDAQ or SCXI hardware according to the situation. The standard is cDAQ (recent technology)
9. Select the correct device number from 'Measurement & Automation' or with 'try & error' until the Rheoset is recognised by the software and the red colour of the menu disappears
10. Check communication with the Rheoset by clicking on the 'Current' and / or 'Polarity' checkboxes and listen for the relay clicking in the Rheoset unit
11. Connect the Rheocable to the Rheoset unit
12. Enter the correct barometric pressure using the Baro Diver and calculate the water density based on the water temperature and conductivity values of the CTD diver.

13. Click on the 'A / D' command button to check the voltages measured along the 4 channels numbered 0 to 3. Channel 0 shows the voltage measured on the resistor cable while channel 3 shows the results of the pressure sensor.
14. A suitable value for the fixed current can be selected by hanging the resistor cable overboard and adjusting the current limiting knob until an acceptable voltage level is reached. It is recommended that the voltage is set not higher than approx. 30 V for the constant current source.
15. Go to the Positioning tab and connect USB-to-serial devices if necessary.
16. Connect GPS and echosounder cables to the serial ports of the computer. The 12 VDC power supply (banana plugs) can be used to power the GPS
17. The 'Comport' button tells you which baud rate and parity to use for receiving GPS and echo sounder information and which port is linked to the GPS and/or echo sounder. If depths are already corrected for transducer and sound speed, the corresponding values for offset and speed should be '0' and '1500'.
18. Appropriate values for the level of the ship's stern and so on must be selected in order to correctly visualise the position of the pressure sensor on the navigation tab.
19. Once you have selected the correct parameters, you can test communication with the hydrographic system by clicking "Go" and checking the values for East, North and Depth. At the same time, the computer is synchronised with the GPS time
20. Program the CTD diver and Baro diver using Diver-Office. Ensure that these are synchronised with the computer time
21. If necessary, a sensor calibration factor can be defined by measuring and comparing the barometric pressure with the pressure directly connected to the Rheoset unit. The calibration factor is normally equal to "1". It is appropriate to check this factor when changing the sensor.
22. Perform cable calibration by comparing the depth value obtained while connecting the pressure sensor first directly to the Rheoset unit and then to the cable connector. For 2.5 V pressure sensors this shift is about 0.1 m for a standard 80 m Rheocable while it is 0 m for 20 mA pressure sensors
23. Before lowering the Rheocable to the sea bed, the air vents must be rinsed with water until all air bubbles have disappeared.

2.4.5 Output

The Rheocable measurements result in a file with the following information:

N X Y P Time Rho HF LF

Met:

- N: integer
- X: easting
- Y: northing
- P: pressure sensor (in m)
- Time: “uu: mm: ss” based on the GPS time
- Rho: resistance value measured by the Rheocable
- LF: Depth echosounder (low frequency)
- HF: Depth echosounder (high frequency)

2.5 Rheotune

2.5.1 Introduction

The Rheotune is a device, based on vibrating fork technology, to measure density by analysing its vibrations in the mud (Stema, 2017). The Rheotune is a variant of the Densitune Silt Density probe (Stema, 2017).

The Rheotune, developed by Stema, is used to measure the density and rheological characteristics of the surrounding medium. The response of the produced vibration from one tuning fork to the other tuning fork (both frequency and amplitude) is determined by the rheological characteristics of this medium. The device is made for measuring vertical density profiles in fluid to semi-solid media such as mud layers.

The measurement data is displayed in real time in the display module (PC) and can be saved for later use.

Figure 21 Picture of the Rheotune (Stema, 2017)

Figure 21 shows a photo of the Rheotune. The device is about 65 cm high and 15 cm wide. The total weight of the Rheotune is about 15 kg. Table 6 shows the technical specifications of the Rheotune.

Table 6 – Technical specifications of the Rheotune, as presented by the manufacturer (Stema, 2017).
The third column shows the specifications in units, used in the measurement campaign.

Dimensions	650 mm x 150 mm Ø	
Weight	15 Kg	
Density: range	1000-1800 g/l 800 – 1500 g/l (if Bingham yield stress < 1kPa)	1.00 – 1.80 g/cm³
Density: accuracy	<1% (Newtonian fluids)	± 0.012 g/cm³
Density: resolution	1 g/l	0.001 g/cm³
Viscosity: range	0-600 Pa s	
Viscosity: resolution	1 Pa.s	
Yield stress: range	0 – 500 Pa	
Yield stress: resolution & accuracy	1 Pa – ca 5 %	
Depth: Range	Vl0-60 m	
Depth: accuracy	< 0.15%	± 0.015 m (@ 10 m)
Temperature: range	0-60° C	
Update rate	20 Hz	
Inclination	2 inclinometers	
Housing	Stainless steel	
Power	110-220 VAC, 35 W	
Output	Ethernet UDP	

2.5.2 Operating principle

The operating principle of the Rheotune is based on the tuning fork principle to measure densities. The induced harmonic oscillation in the in-situ material, caused by the tuning fork, is related to the density, resistance and viscosity of the mud.

The tuning fork is forced at an adjustable frequency by a piezoelectric element located at the base of the tuning fork, while the change of this signal through the medium to be measured is measured by another piezoelectric element in the device. The frequency ω imposed by the device is adjusted so that a certain phase difference between the imposed frequency and the point displacement of the tuning fork is obtained

(Groposo, 2014). Based on the results of Allwright (2002), the movement of the point can be represented as a forced oscillator with a frequency ω:

$$F = -M_0\omega^2 x - \rho V_0\omega^2 x + B_0 i\omega x + (1-\alpha)(i\omega)^{3/2}\sqrt{\mu\rho}A_0 x + K_0 x + \alpha A_0 k x \,.$$

with *F* the amplitude of the external force (F exp($i\omega t$)); *x* the complex amplitude of the detected displacement x exp($i\omega t$), where i is an imaginary value and t [s] is the time; M_0, V_0, B_0, K_0 and A_0 correspond to the mass [kg], the volume [m³], the damping [N s/m], the elasticity [kg/s²] and the surface [m²] of the tuning fork; ρ, μ and *k* represent the density [kg/m³], the viscosity and the elasticity of the mud; α is a parameter with a value between 0 and 1, and characterises the behaviour of the mud. If α = 0, the mud behaves like a viscous fluid, a value of α = 1 indicates an elastic characteristic of the mud. A value between 0 and 1 reflects a partly viscous and partly elastic behaviour of the mud.

As mentioned, it is possible to adjust the frequency of the imposed oscillation to a value ω_B, so that the oscillation is in phase with the viscous damping of the mud. This gives the following equations for, respectively, the frequency ω_B and the modulus of displacement A_B= |x/F| of the tuning fork (Valentina Groposo, 2014).

$$\omega_B = \frac{B_0 + \sqrt{B_0^2 + 4(M_0+\rho V_0)(K_0+\alpha k A_0)}}{2(M_0+\rho V_0)},$$

$$A_B = \left[\sqrt{2}B_0\omega_B + (1-\alpha)\omega_B^{3/2}\sqrt{\mu\rho}A_0\right]^{-1}$$

From the above equation it can be seen that ω_B depends on the elastic response of the mud through the term $\alpha k\, A_0$. The modulus A_B depends on the viscosity of the mud, the density and the elasticity. The latter is evident explicit through the presence of the factors ρ, μ and α in the equation, and implicit through ω_B.

2.5.3 Software

A data acquisition and data processing software was developed by Stema (Stema, 2017). The parameters recorded in the application are depth, time, temperature, shear strength and density. In Figure 22 the GUI of this Rheotune software is shown.

The interface of the software consists of a number of blocks. On the left, a depth profile of the density, strain and viscosity can be displayed. On the top right are two blocks, which respectively contain the metadata of the measurement (date, time, location, filename) and an overview of previous measurements. At the bottom right the data are displayed in the form of a table or data sheet. For each new measurement, a new file is created, with a specific naming convention.

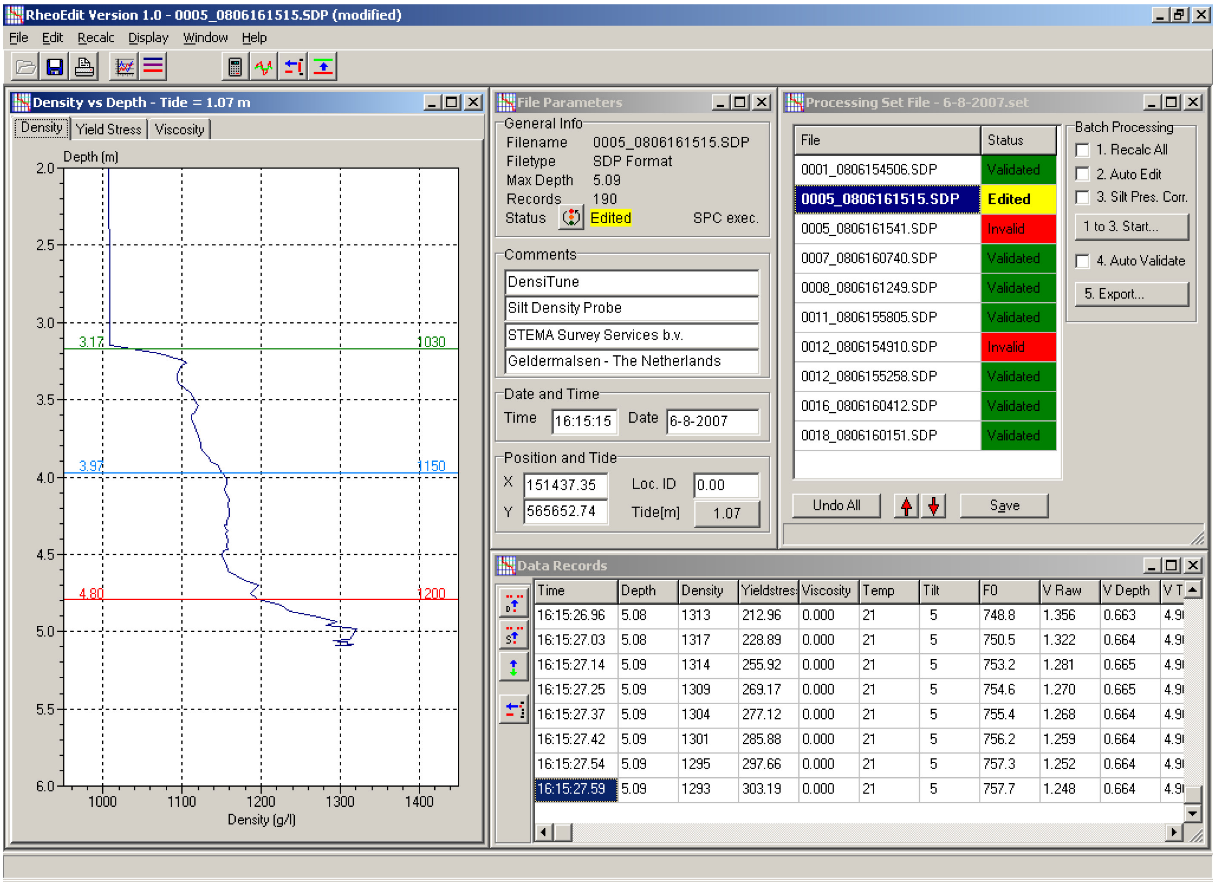


Figure 22 – Main window of the Rheotune software (Claeys S, 2009)

2.5.4 Performing measurements

The procedure for performing the measurements is shown below:

1) Setup

   The cable from the crane or davit must be connected to the top of the Rheotune using the fixing eye.

2) Calibration

   The Rheotune can be calibrated with mud from the location where the measurements are taken. In this way more accurate measurements can be obtained (Stema, 2017). In general, measurements are performed with a universal calibration formula.

3) Performing measurements

   - Instructions to start a measurement:
     - Place the Rheotune in the water using a crane or davit
     - Start the measurements in the software
   - Software:

     When the software has been opened, the main window as shown in Figure 22 appears.
   - Instructions to stop a measurement:
     - Check cable until device reaches bottom and loses tension.
     - Stop the measurement in the software
     - Pull the Rheotune back up using the crane
     - Clean the Rheotune with water, so that the mud between the tuning fork is completely rinsed away

2.5.5 Output

The data that are recorded during the measurements with the Rheotune, are stored in a directory defined in the 'settings' menu. The profiles selected in the table can be exported in a file with a '.sdp' extension. An example of such a file is shown in Table 7.

Table 7 – Overview of the data collected by a Rheotune measurement

```
YAV 1

CM1 Rheotune

CM2 Silt Density Probe

CM3 Vlaamse Hydrografie

CM4 Oostende

LIM 2.85 18.00

DAT  38742.11  0  3.01  1017   0.000  12.1   4.2   732.37   0.00   732.37  7.926  0.630  3.011  5.034  5.367

DAT  38742.54  0  3.20  1017   0.000  12.1   3.3   732.33   0.00   732.33  7.933  0.665  3.011  5.073  5.318

DAT  38742.54  0  3.20  1017   0.000  12.1   3.3   732.33   0.00   732.33  7.933  0.665  3.011  5.073  5.318

DAT  38742.55  0  3.20  1017   0.000  12.1   3.3   732.33   0.00   732.33  7.933  0.665  3.011  5.073  5.318

DAT  38742.55  0  3.20  1017   0.000  12.1   3.3   732.33   0.00   732.33  7.933  0.665  3.011  5.073  5.318

...
```

2.6 Slibsampler

2.6.1 Introduction

The SMPL-002 Beeker sampler is a remotely operated instrument to take mud samples, using a specially designed sampling tube. This tube is fitted with measuring points, every 50 mm, including a sediment core sampler (type beeker) with integrated opening for penetration of the mud layers and a reservoir for bellows to hold the sample. This device can be remotely operated and is designed for a maximum water depth of 50 m. The sampler is combined on board with a LIER-036 winch system (Seatec, 2015).

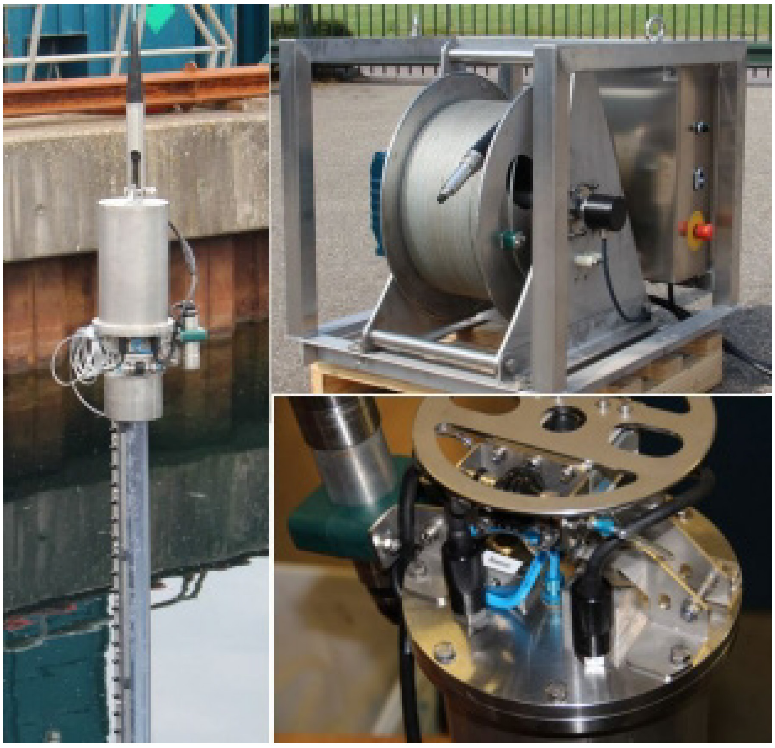


Figure 23 – Picture of the mud sampler (bottom left and right) and winch (top right) (Seatec, 2015)

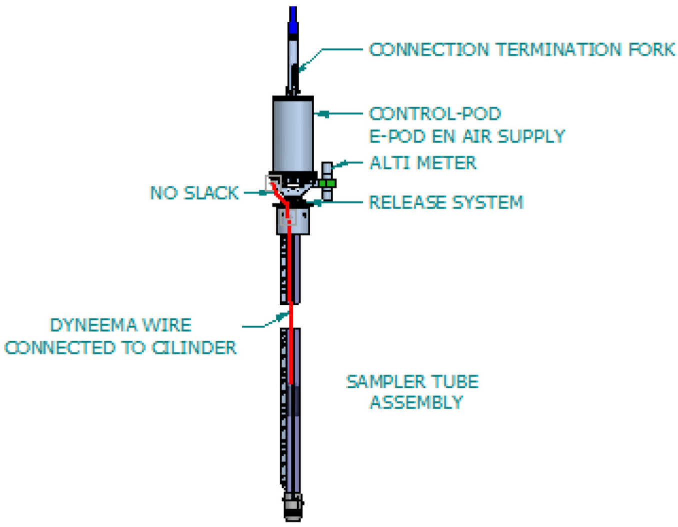


Figure 24 – Illustration of the mud sampler, with indication of the different components (from Seatec, 2015)

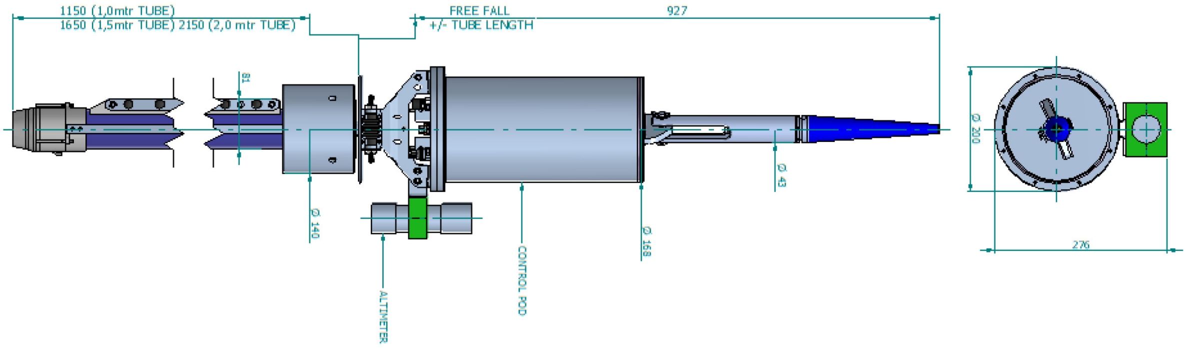


Figure 25 – Illustration with the dimensions of the mud sampler (from Seatec, 2015).

"*Mud sampler pod*":

- Material: AISI 316L cylinder
- Depth range: max. 50 m
- Weight: approx. 25 kg
- Air connection: 531664 KS2-CN-4-S fitting for refilling
- Electrical connection: Seacon MCBH-8M / SS
- Overpressure protection: integrated pressure relief valve
- Integrated sensors: altimeter 0-15 m range Pitch & Roll sensor
- External cycles: 4-5 release cycles with full air tanks (8 bar)

"*Mud sampler tube*"

- PVC pipe with specially made openings every 50 mm, equipped with Beeker-sample cutting head

The SMPL-002 system consists of a Windows-based control computer with preinstalled mud sampler software. The RS232 communication interface runs through the LIER-036 winch system to the mud sampler. The mud sampler consists of a "control unit" equipped with both electronics and pneumatics, from which the sampler tube is operated.

2.6.2 Software

The software used to perform measurements with the mud sampler is the SMPL-001 software (Seatec, 2015). Before starting the software, make sure that the slibsampler is connected and the winch is switched on.

1. Start the SMPL-001 software. The software starts scanning the serial port and shows the result on a pop-up window. Close this window when the operation is finished.
2. The main window is now displayed (Figure 26). This screen has the following features:
   - Button "Release Sampler Unit"
   - Button "Close Sampler Orifice"
   - Display of air pressure, altimeter, roll and pitch

Figure 26 – Main window of the SMPL-001 software (from Seatec, 2015)

The settings screen (Figure 27) can be accessed by clicking on the "Settings" tab from the main window. In this tab, the parameters of the sensors are entered, as well as the OK thresholds for the different signals. Once the data has been entered, click on "Save changes" to write the settings to the file "epod.ini". During start-up, the SMPL-001 software reads these settings from the file "epod.ini", which is located in the program directory.

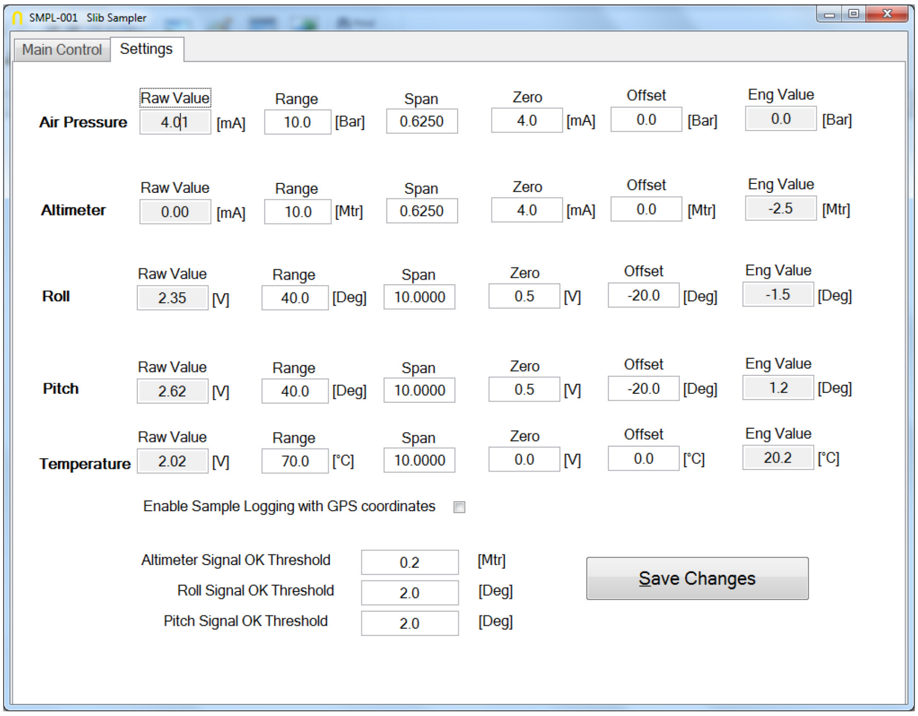


Figure 27 – Settings of the SMPL-001 software (from Seatec, 2015)

3. When the "Release sampler unit" checkbox is set, the mud sampler is released in free fall until the cable is tensioned. On the main window a light indicates whether this function is active. By pressing the button again, this release system can be deactivated. The cylinder remains engaged until the reset valve is used to release the accumulated air pressure. When the "Enable Sample Logging" checkbox is set, the current GPS location is recorded together with the sample number.

4. The winch can be used to bring up the sample. The indicator on the screen shows when the "close sampler orifice" is active. Press the button again to deactivate the function. The opening is closed by inflating a bellow

When the mud sampler is hanging straight down, the indicators on the main window light up green to indicate that the sampler is ready to be released. The threshold values for the indicators can be set in the 'Settings' tab.

The altimeter shows the distance between the mud sampler and the mud bottom. In the "Settings" tab the zero value of the altimeter offset can be adjusted. The indicator of the pressure shows the actual pressure of the pneumatics in the "control pad".

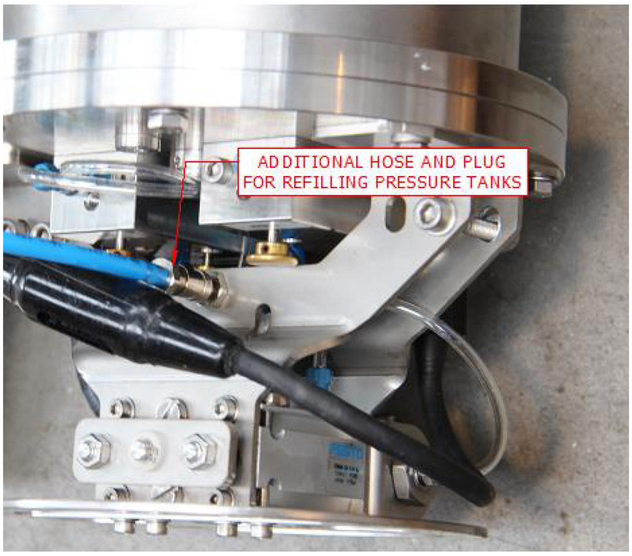


Figure 28 – Picture of the plug for refilling the pressure tank

2.6.3 Performing measurements

The following preparations must be performed in order to take mud samples with the measuring instrument:

1. Connecting all required cables:
   - sampling device connected to main umbilical (termination fork)
   - communication cable between winch and PC (COM3)
   - Survey string cable (if applicable)
   - Power supply cables (for PC and winch)
2. Ensure that the termination fork is attached to the "pad-eye" on the "control pod" (Figure 29)
3. Install the cable between fork termination and the "control pod" (Figure 29)
4. Check that the bleed plug (A) is closed (Figure 30)

5. Turn on both the winch and the control PC and start the sampler software (SMPL-001)
6. Check all sensor values in the software (altimeter, pitch and roll, air pressure).
7. Fill the air reservoir with air to a maximum pressure of 8 bar
8. Ensure that the sampler tube's air hose is connected to the 'control pod' (Figure 31)
9. Ensure that the opening of the sampler tube (orifice) is vacuumed, using the vacuum pump:
    - Connect the vacuum pump to the connection for the vacuum pump (Figure 31)
    - Start the vacuum pump and simultaneously press the reset valve (O) until the opening of the sampler tube is completely vacuumed
    - Remove the pump and release the reset valve (O). Make sure that the piston in the tube is in its lowest position (Figure 32), the supplied rod can be used for this purpose
    - Ensure that all measuring points on the sampler tube are closed
10. Fasten the sample tube to the "sample pod":
    - Click on the "release sampler unit" button in the software. This will open the locking mechanism on the "sample pod"
    - Click again on the " release sampler unit " button to deactivate the function
    - Insert the upper end of the tube (Figure 34) into the entrance of the locking mechanism (Figure 33).
    - Press the button of the release valve of the release system (R) to close the locking mechanism (Figure 31 and Figure 33). The tube is now locked under the “sample pod”.
    - Connect the carabiner (which is connected to the piston via an aramid cable (Figure 34)) to the fixing bolt on the "sampler pod", which is illustrated in Figure 33.
    - The measuring device is now ready to take samples

Figure 29 – Photo of the connection on the termination fork

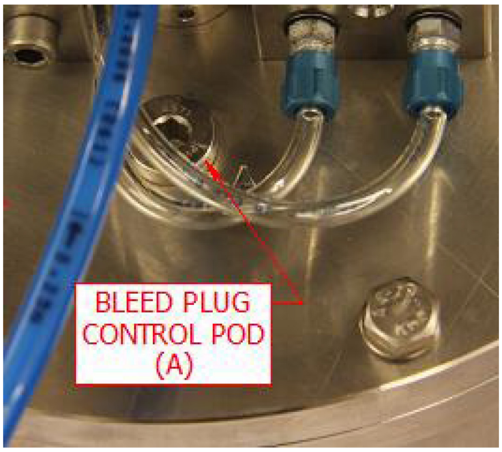


Figure 30 – Photo of the bleed plug on the “control pod”.

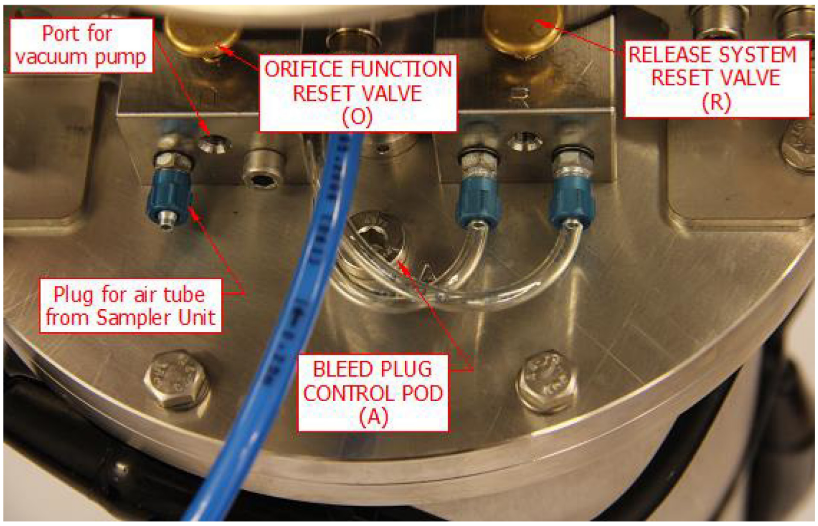


Figure 31 – Photo of the top of the "control pod" connections

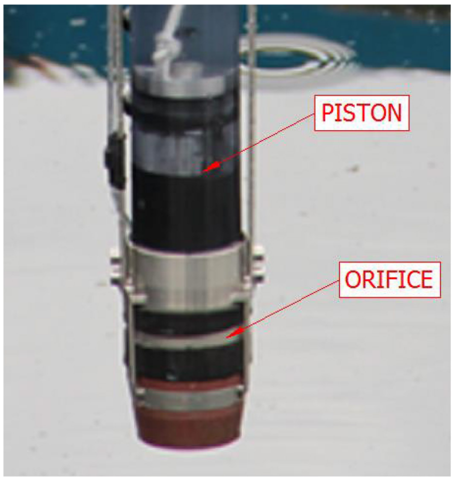


Figure 32 – Photo of the sample tube with the piston and opening with bellow

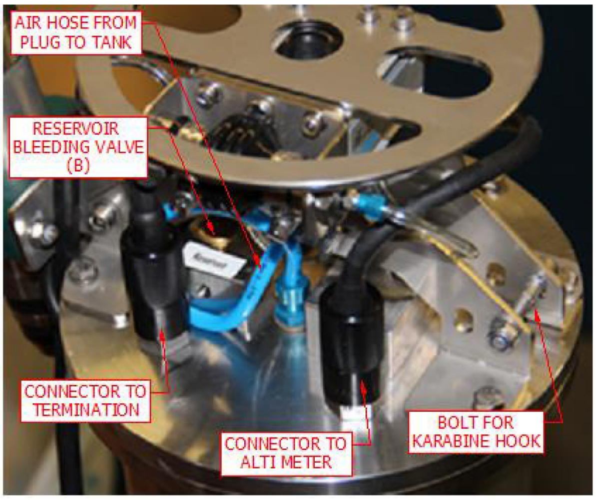


Figure 33 – Photo of the bottom of the "control pod" connection, with locking mechanism for attaching the sampling tube

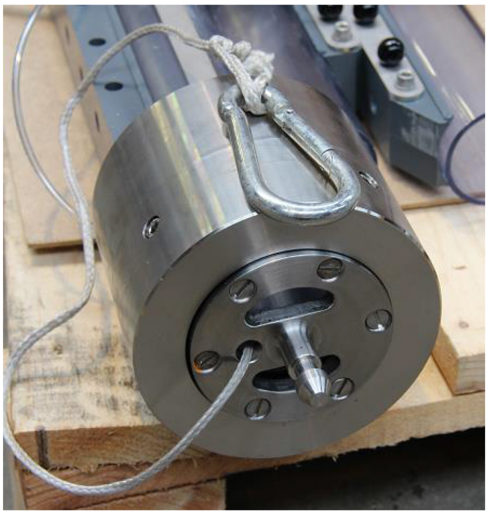


Figure 34 – Photo of the top of the sample tube (point of connection with the "sample pod")

After the preparations, taking a sample with the mud sampler can be summarised as follows:

1. Ensure that the complete system is configured: the mud sampler is connected and the winch is engaged

2. Start the SMPL-001 software and the main window will be displayed (Figure 26)

3. Place the device overboard and lower it into the water.

4 When the "Release sample button" is pressed, the mud sampler is released and is in free fall until the cable is tensioned. An indicator on the display shows when this function is active. The same button must be pressed again to deactivate this "release system"; this prevents the magnets from heating up. The cylinder remains engaged until the reset valve is used to release the accumulated air pressure. When the "Enable Sample Logging" checkbox is activated, the actual GPS location is recorded together with the sample number.

5. Press the "close sampler orifice" button. The opening at the end (bottom) of the sampler tube is closed so that the mud sample is secured.

The removal of the sample on board can be performed according to the following steps.:

1. The winch is used to lift the device to the top. An indicator on the screen shows when the "release sample unit" function is activated. Press the button again to deactivate the function. The opening is closed by inflating a bellow

2. After the sample has been pulled back on deck, it is still attached to a cable.

3. Open the "Sampler Tube Unit" from the top.

4. The cylinder and vent are still activated. Press the orifice opening valve (O) and release the system reset valve on the control pod to reduce the air pressure (Figure 28). Repeat if necessary.

5. The pressure on the control pod should be adjusted regularly (every 4-5 cycles).

2.7 Summary

2.7.1 Overview of the technical specifications

Density devices

An overview of the operating principles and technical specifications of the three measuring instruments that measure density and whose results are discussed in this report, namely Admodus, DensX and Rheotune, is given in Table 8. It is clear from this table that the range of densities that can be measured by the various instruments, as specified by the manufacturer, is more than sufficient for the applications described here. Maximum measured densities of approx. 1.3 g/cm³ are expected and measured. The given resolution of the density measurement is high for all measuring devices, with 3 digits after the comma, which is more than sufficient for our applications. It must be mentioned, however, that for the Rheotune this accuracy is given with the statement that it is valid for Newtonian fluids. For non-Newtonian fluids, such as mud, no separate accuracy is given. The density measurement of the Rheotune is derived from a resistance measurement. For both the DensX and the Admodus the density measurement is a direct measurement of the instrument. The depth range of the instruments is also clearly sufficient for the applications tested in this report, where maximum values around 20 m were recorded. The specified depth accuracy of this measurement is clearly lower for the DensX than for the other devices.

Table 8 – Summary table of the technical specifications (given by the suppliers) of the measuring instruments under consideration

	Unit	Admodus	DensX	Rheotune
Operating principle		Acoustic	Transmission of X-rays	Tuning fork
Weight	kg	35,8 (with wings)	70	15
Sample frequency	1/s	50	10	20
Density: range	g/cm³	1.00-1.50	1.00-1.50	1.00-1.80
Density: accuracy	g/cm³ (@1,2)	± 0.005	± 0.003	± 0.001
Depth: range	m	0 - 40	0 - 35 of 100	0 – 60
Depth: accuracy	m (@10 m)	± 0.015	± 0.15	± 0.015

Table 9 gives an overview of the theoretical advantages and disadvantages of the different measurement techniques.

Table 9 – Overview of theoretical advantages and disadvantages of the different density devices

	Advantage	Disadvantage
Admodus USP	– Direct density measurement	– Light device: (more) difficult to profile in more consolidated mud. But could be made heavier.
DensX	– Direct density measurement – Large measuring volume	– Radioactive source (with loss of radiation value with time) – Influence of certain elements (e.g.) heavy metals in mud, depending on the type of mud – Inspection (of Controlatom) required
Rheotune	– Measuring technique used in multiple disciplines	– Accuracy only given for Newtonian fluids – No direct density measurement – Light device: (more) difficult to profile in more consolidated mud

Rheology devices

Table 10 (Table 10) gives an overview of the working principles and the technical specifications of the measuring instruments able to measure the strength properties of the mud. The analysis of the results of these instruments is not discussed in this report. In general, comparing the rheological characterisation is difficult, because different measuring principles will lead to different results and a clear reference measurement is not available. At the Flanders Hydraulics Research, a measurement protocol is used for the analysis of sub-samples, which can be used as a reference.

Table 10 – Summary table of the technical specifications (given by the suppliers) of the measuring instruments under consideration

	Unit	Graviprobe	Rheocable	Rheotune
Operating principle		Free fall	Dragging cable	Tuning fork
Weight	kg	8	20 kg (per 20 m)	15
Sample frequency	1/s		1	20
Depth: range	m	0 – 35	0 – 40	0 – 60
Depth: accuracy	m (@10 m)	± 0.015	± 0.001	± 0.015

The Rheotune and the GraviProbe measure a profile, while the Rheocable does not measure a profile but determines the depth position of the "rheological transition". It is unclear which position this device will assume when there is no clear transition in strength of the mud. This assumption, of a clear direct transition ("the rheological transition"), has not been proven and is for the time being not followed by the Flanders Hydraulics Research.

Moreover, it can be expected that also the shape and aerodynamics of the cable can have an influence on the measurement. Also the speed of movement of Rheocable in the mud could influence the behaviour of the cable and the changing of the behaviour of the mud (dynamic viscosity) itself. Also, no physical parameter (except pressure (depth)) is measured, so that the comparison with a strength value, e.g. from a rheological standard measurement, is not possible. For the GraviProbe and Rheotune it can be checked whether there is a predictable relation between the measured values and standardised rheological measurements, on collected (sub)samples.

2.7.2 Post-processing

At the end of a measurement day during the measurement campaign, the raw data are copied from the computer onto an external hard disk.

Afterwards, an Excel file per day and per device is created. In this post-processing step, the data are taken from the raw data file, without any smoothing or adjustments to the data. Each data sheet in the Excel file corresponds to one measurement profile. In each data sheet, the following data are listed: measuring position, date, time, depth, density, shear strength (if measured), measurement with echosounder (210 kHz and 33 kHz), tide, depth at which the 1.2 g/cm³ is reached. This last value, the depth at which a density of 1.2 g/cm³ is reached, is calculated with Excel as the first depth value at which the density exceeds the limit of 1.2 g/cm³. These data are made available by the Hydrographic Service on a common data disk.

The Excel files are read in with R scripts. With the help of R scripts, several files are created per measurement. In each file, the time, depth and density are displayed. Figures are also created in which the depth is shown in relation to the density, as shown in Figure 35.

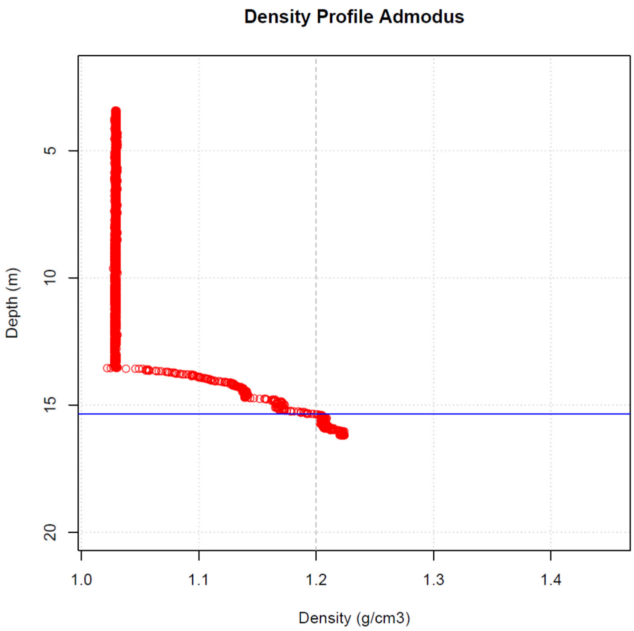


Figure 35 – Density profile measured with the Admodus (profile 1, 27-06-2017)

3 Validation of the instruments on lab scale

A validation of the measuring instruments was carried out at Flanders Hydraulics Research. For such a validation, the density of a mud sample is analysed with the measuring instruments employed in the field. At the same time the density is measured with a pycnometer and an Anton Paar density meter DMA 500. These measurements are considered reference measurements for density. One validation was carried out with mud from Deurganckdok (port of Antwerp), a second validation was carried out with mud from the port of Zeebrugge. For both validations no additional calibration steps were carried out, i.e. the settings of the instrument, as used in the measurement campaign, were used.

3.1 Measurement setup

3.1.1 Setup

In a first validation step, a smaller container was used (Figure 36). This was sufficient as only smaller instruments (Rheotune and Admodus) were used. Moreover, the work could be done faster and the required amount of mud material was smaller. Because of the DensX, in the second validation campaign work was carried out in a larger container, namely the IBC, so that the device could be completely immersed in the mud. DotOcean stated (personal communication) that only the legs of the DensX had to be immersed in the mud, which means that a smaller container can be used for this instrument in the future.

Figure 36 – Mixing of the samples for the first validation

3.1.2 Measuring devices

In addition to the measuring instruments used in-situ (see Chapter 2 for their description), the pycnometer and the Anton Paar density meter were used during validation.

Pycnometer

A pycnometer is an ISO standardised cylinder with a cover (fitted with a hole), manufactured in stainless steel (Figure 37). The pycnometer is first filled with mud. When placing the lid on top, the excess mass runs out through the opening in the lid. This excess mass should be removed from the cylinder and the lid cleaned before weighing. The contents of this cylinder are a fixed volume of 50 ml, with a tolerance of 0.1 %. When the volume of the fluid is known, the density can be deduced after measuring the weight. The weight is determined with a Mettler Toledo XP204 scale.

Anton Paar densimeter

The Anton Paar DMA 500 densimeter was also used during the validation measurement. A mud sample is injected into the densimeter by means of a syringe. With the help of a screen it is possible to check in detail if no air bubbles or impurities influence the measurements (see Figure 37).

Figure 37 - Picture of the pycnometer (left) and the Anton Paar densimeter (right)

3.1.3 Salinity

Salinity was measured using a YSI multi-parameter probe.

3.1.4 Particle size distribution

On all samples a particle size distribution was performed with the Mastersizer 2000. A d50 of 8 - 9 µm was observed for Zeebrugge, with a fraction < 2 µm of about 10% and a fraction between 2 µm and 63 µm of about 80%. For Deurganckdok the particle size distribution is almost identical.

3.1.5 Organic material

The organic content is measured using a Prepash 229. The organic content is determined on the basis of the difference in weight of a sample, which is heated from 110° to 550° C. Using the following equation (Borovec, 1996), this difference in weight is converted into an organic carbon content (OC):

$$OC = 0.0902 + (0.465 * ((M_{110} - M_{550})/M_{110}) * 100)$$

For the Zeebrugge mud an organic carbon content of 7.0 ± 0.3 % was determined.

3.2 Results 1: mud from Deurganckdok

For the first validation, mud was taken in Deurganckdok (Antwerp) on 2 different locations. An overview of the test results is shown in Table 11 for the first mud sample and in Table 12 for the second mud sample. For the first mud sample a range was tested of about 1.25 g/cm³ to about 1.11 g/cm³. For the second mud sample the initial density was lower, and consequently the range of the validation test was from ca. 1.20 g/cm³ to 1.1 g/cm³. For the first sample 10 densities were tested, for the second sample 7. As mentioned above, only Admodus and Rheotune were used in this validation test.

Table 11 – Summary of the results of density measurements using the different measuring devices, for mud sample 1. The values in the table are expressed in g/cm³.

Target	**1.11**	**1.12**	**1.13**	**1.15**	**1.17**	**1.19**	**1.20**	**1.23**	**1.24**	**1.25**
Pycnometer	1.117	1.126	1.142	1.158	1.176	1.187	1.209	1.231	1.243	1.252
Anton Paar	1.115 ±0.001	1.121 ±0.002	1.137 ±0.001	1.155 ±0.002	1.172 ±0.001	1.192 ±0.001	1.208 ±0.001	1.230 ±0.001	1.235 ±0.003	1.256 ±0.002
Rheotune	1.118 ±0.004	1.126 ±0.005	1.142 ±0.001	1.150 ±0.001	1.172 ±0.003	1.182 ±0.007	1.183 ±0.007	1.180 ±0.001	1.212 ±0.003	1.323 ±0.006
Admodus	1.125 ±0.001	1.135 ±0.001	1.126 ±0.001	1.148 ±0.001	1.157 ±0.001	1.180 ±0.001	1.195 ±0.001	1.217 ±0.001	1.248 ±0.001	1.242 ±0.001

Table 12 – Summary of the results of density measurements using the different measuring devices, for mud sample 2. The values in the table are expressed in g/cm³.

Target	**1.1**	**1.12**	**1.13**	**1.15**	**1.17**	**1.19**	**1.20**
Pycnometer	1.100	1.120	1.134	1.153	1.173	1.189	1.207
Anton Paar	1.105 ±0.001	1.118 ±0.001	1.134 ±0.001	1.153 ±0.001	1.172 ±0.002	1.190 ±0.002	1.214 ±0.001
Rheotune	1.108 ±0.001	1.124 ±0.001	1.135 ±0.001	1.140 ±0.001	1.174 ±0.002	1.176 ±0.002	1.222 ±0.02
Admodus	1.108 ±0.001	1.122 ±0.001	1.139 ±0.001	1.148 ±0.001	1.168 ±0.002	1.192 ±0.002	1.222 ±0.002

Figure 38 and Figure 39 give an overview of the results for the two mud samples. Figure 38 shows that the measurements of the different devices agree well, from a density of 1.1 g/cm³ to a density of about 1.19 g/cm³. For the measurement range from 1.20 to 1.25 g/cm³ the measurements with the Rheotune are strongly deviant (below) the reference measurement of the pycnometer. For the highest density, about 1.25 g/cm³, the Rheotune overestimates the density. For the dilution series of sludge sample 2, shown in Figure 39, the agreement between the different measuring devices seems to be larger. In the second sample series, no densities higher than 1.2 g/cm³ were measured, as the sample taken had an initial density of 1.2 g/cm³.

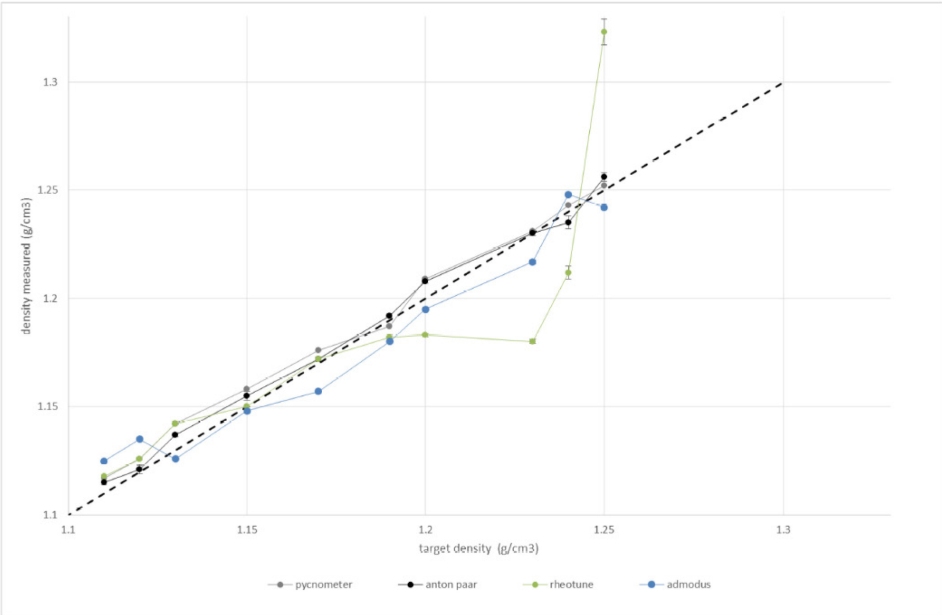


Figure 38 – Measured density with Admodus, Rheotune, Anton Paar densimeter and pycnometer for mud sample 1 from Deurganckdok and 10 dilutions

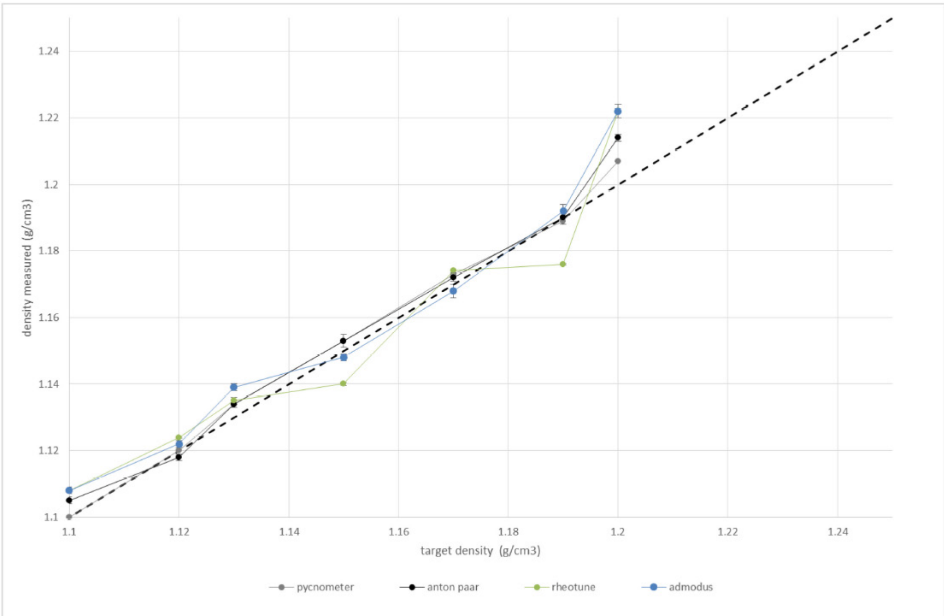


Figure 39 – Measured density with Admodus, Rheotune, Anton Paar densimeter and pycnometer for sludge sample 2 from Deurganckdok and 7 dilutions.

3.3 Results 2: mud from Zeebrugge

For the second validation, mud was taken from the port of Zeebrugge using of a dredger. An overview of the test results is shown in Table 13. A range was tested from about 1.22 g/cm³ to about 1.11 g/cm³. For the highest density, two measurements were carried out, one before homogenisation with the mixer (indicated as “not mixed” in Table 13), and one after mixing the initial mud mixture. For the lowest density, it was tested whether there was a difference between a measurement in which the measuring device was moved during the tests (standard) or simply remained still in the container. In total, 4 different densities were measured.

Table 13 – Overview of the results of density measurements using the different measuring instruments, for the Zeebrugge mud. The values in the table are expressed in g/cm³.

Target	1.11 (still)	1.11	1.16	1.21	1.22	1.22 (not mixed)
Pycnometer		1.115 ±0.003	1.164 ±0.001	1.212 ±0.002	1.231 ±0.003	1.229 ±0.003
Anton Paar		1.106 ±0.001	1.159 ±0.002	1.209 ±0.006	1.229 ±0.006	1.231 ±0.002
Rheotune		1.138 ±0.001	1.182 ±0.002	1.191 ±0.005	1.208 ±0.03	1.208 ±0.007
Admodus	1.125 ±0.003	1.120 ±0.006	1.148 ±0.005	1.194 ±0.001	1.217 ±0.001	1.222 ±0.003
DensX	1.113 ±0.001	1.11 ±0.001	1.155 ±0.001	1.197 ±0.002	1.216 ±0.002	1.218 ±0.002

Figure 40 shows the results of the validation measurement. For the Admodus the measurement of the last density is slightly higher than the reference measurements, for the higher densities slightly lower. This underestimation is at most approx. 0.02 g/cm³. For the DensX, the measurements are slightly closer to the reference measurement, but the difference increases as the densities become higher. The Rheotune generally shows the highest deviations. At the lower densities there is an overestimation of the measurements, at the higher densities an underestimation. The deviations during these validation measurements are larger than for the previous measurements (section 3.2).

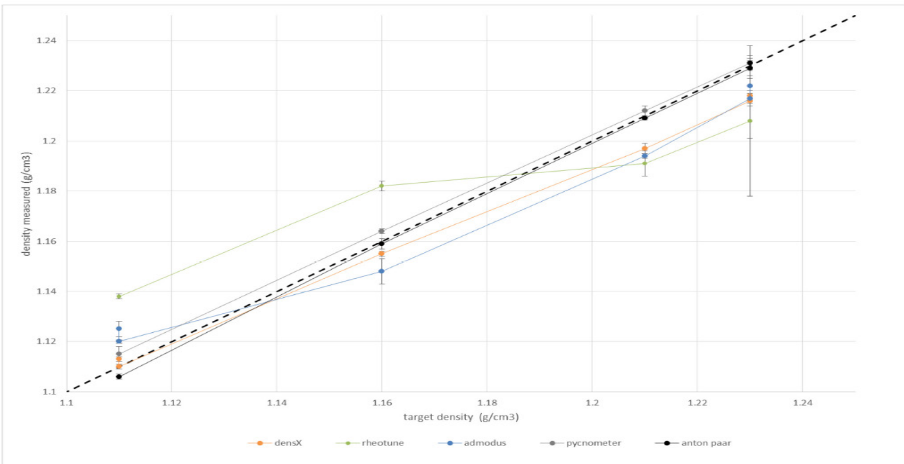


Figure 40 – Measured density with DensX, Admodus, Rheotune, Anton Paar densimeter and Pycnometer for mud sample from Zeebrugge and 4 dilutions.

3.4 Results: overview

Figure 41 and Figure 42 give an overview of the results of the different validation measurements at Flanders Hydraulics Research. Figure 41 shows the absolute differences compared to a reference measurement, where the pycnometer measurements were considered as reference. It is clear that the Anton Paar density measurement is always within 0.01 g/cm³ of these values. No major deviations can be seen for both larger and smaller density values. However, it looks like the density values are in general slightly underestimated. For the DensX, the deviations compared to the reference are between 0.01 and 0.02 g/cm³, whereby rather an underestimation of the density is observed. For the Rheotune, the differences seem to be the largest, considered over all validation measurements. However, no unambiguous determination of under or overestimation can be made. For the Admodus the differences are varying positive and negative and limited to a maximum of 0.02 g/cm³ difference with the pycnometer values. No relationship between the error and density value could be established.

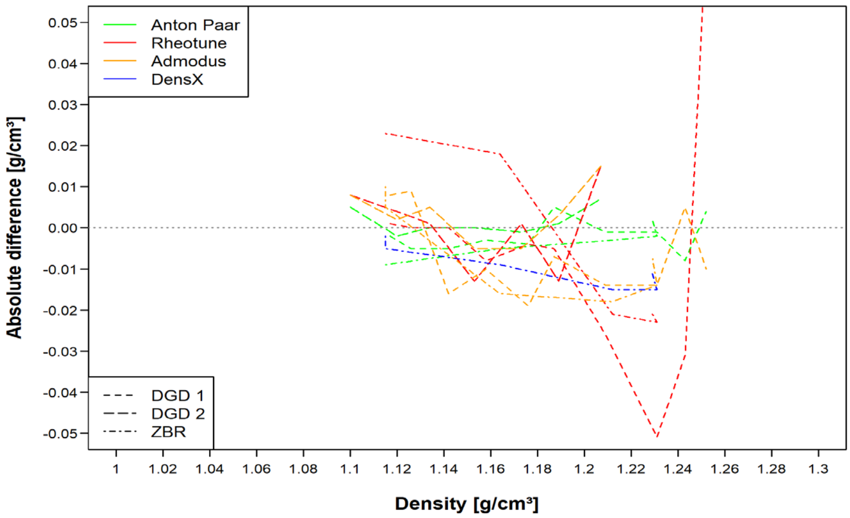


Figure 41 – Overview of the absolute difference between the measuring devices and the pycnometer. The different validation measurements are indicated with a different line types.

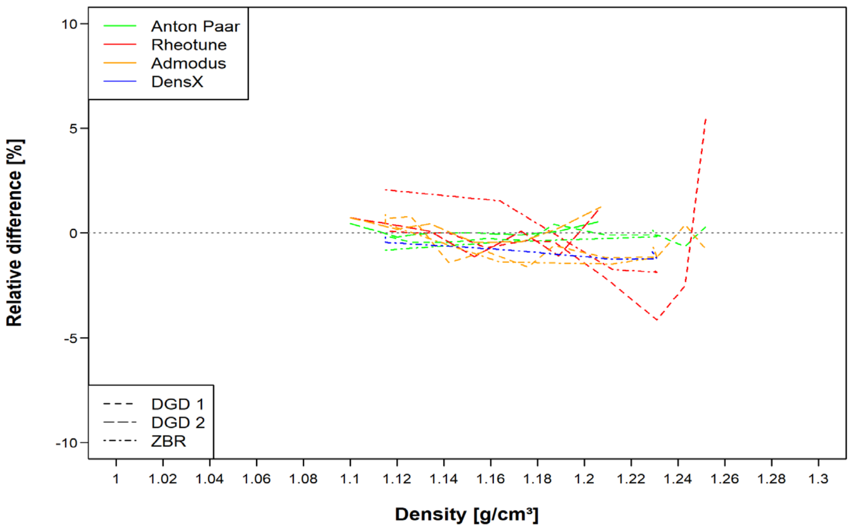


Figure 42 – Overview of the relative difference between the measuring devices and the pycnometer. The different validation measurements are indicated with a different line types.

4 Measurement campaign 3

4.1 Introduction

A third in-situ measurement campaign was performed from 16 April 2018 to 5 May 2018. An overview of the measurement campaign is shown in Figure 43. During this measurement campaign three measuring devices were used, namely those developed for measuring density: the Admodus, DensX and Rheotune. During one day (23/04) Geo-XYZ also measured with their Rheotune. The other instruments, discussed in chapter 2, were tested in other measurement campaigns and are also discussed here with respect to their practical operation. However, the results of the measurements are not discussed in this report.

	11/apr	12/apr	13/apr	14/apr	15/apr	16/apr	17/apr	18/apr	19/apr	20/apr	21/apr	22/apr
Slibsampler						0						
Admodus	v	v	v				v	v	v			
DensX	v	v	v				v	v	v			
Rheotune								v	v			
GeoXYZ												

	23/apr	24/apr	25/apr	26/apr	27/apr	28/apr	29/apr	30/apr	1/mei	2/mei	3/mei	4/mei
Slibsampler			0									
Admodus	v			v	v					v	v	
DensX	v	v		v	v					v	v	
Rheotune	v									v	v	
GeoXYZ	v											

Figure 43 – Overview of the measurement programme during the in-situ measurement campaign April - May 2018.

For the mud sampler (Slibsampler), a device for the direct taking of mud samples, a training day was planned on 16/04, but during the measurement campaign no successful samples were taken with this device.

The DensX was used every day on board, with a total of 12 measuring days. The Admodus was not used for several days, due to a technical defect with the data cable. For the Rheotune there was also a technical defect with the transducer, but these defects could be remedied quickly. In total, these measuring instruments were used for 11 and 5 days respectively.

Over the entire measurement campaign, there is therefore 1 day on which measurements are available from all 4 different instruments. For 6 days measurement results are available from Admodus and DensX together, for 4 additional days the Rheotune was also available.

4.2 Location

The measurement campaign was performed in the port of Zeebrugge. The port of Zeebrugge is divided into a number of sections. The most important sections, during the measuring campaign, are the Albert II dock (A2), Zwaaiplaats 1 (Z1), Zwaaiplaats 2 (Z2) and CDNB . These zones, and their associated sampling locations, are shown on a map in Figure 44. An outline of each zone is shown in Appendix.

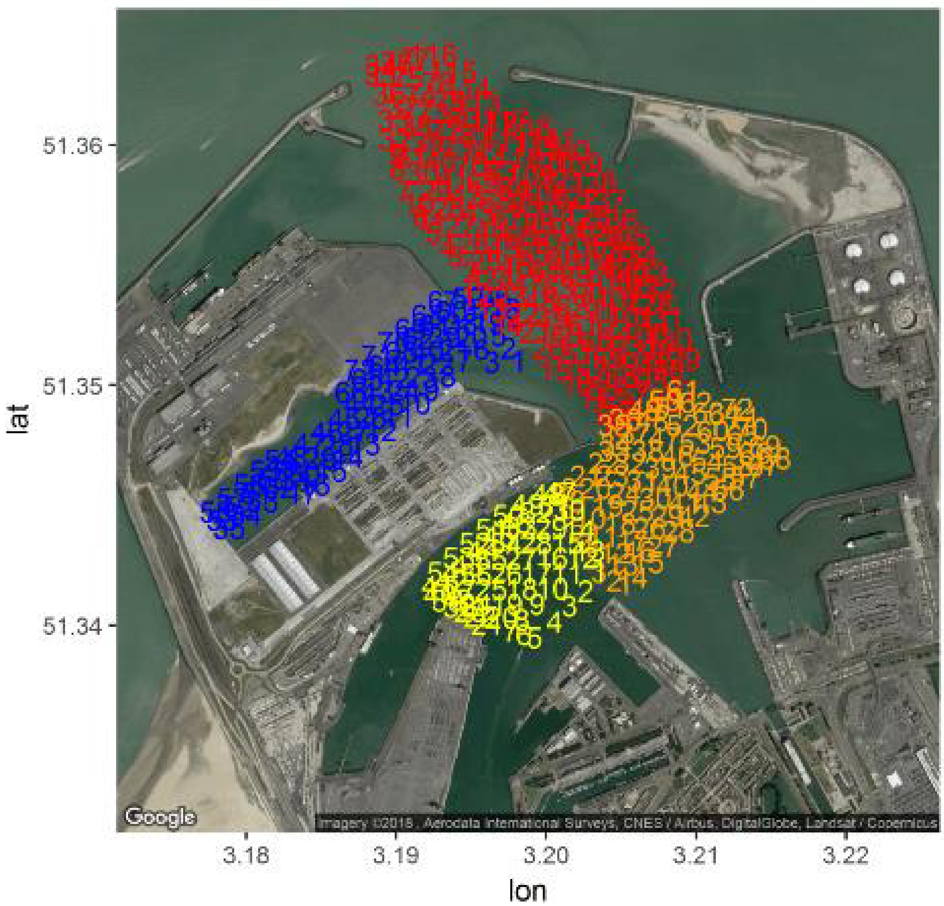


Figure 44 – Overview of the port of Zeebrugge, with profile measurment locations in CDNB (red), Albert-II dock (blue), ZP1 (yellow) and ZP2 (orange).

An overview of the bathymetric survey is shown in Figure 45. A detail of the different zones of the survey (Albert II dock, CDNB and Z1 and Z2) can be found in Appendix 0, in particular Figure 87 to Figure 90.

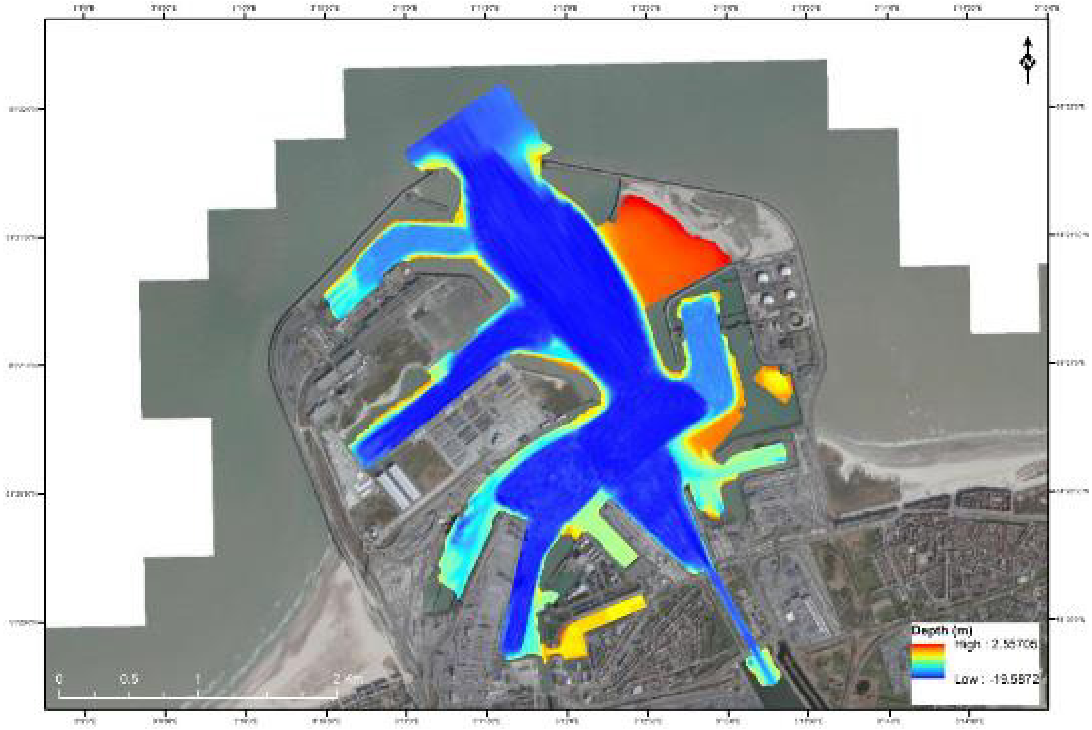


Figure 45 – Overview of bathymetric survey in the port of Zeebrugge, measured with an echo sounder.

4.3 Meteorological conditions and tides

4.3.1 Tide

Figure 46 shows the tide during the measurement campaign, measured at the Leopold II dam. Measurements are available every 5 minutes. The data were obtained via the website of Meetnet Vlaamse Banken. The days on which measurements were taken during the campaign are indicated with a grey background.

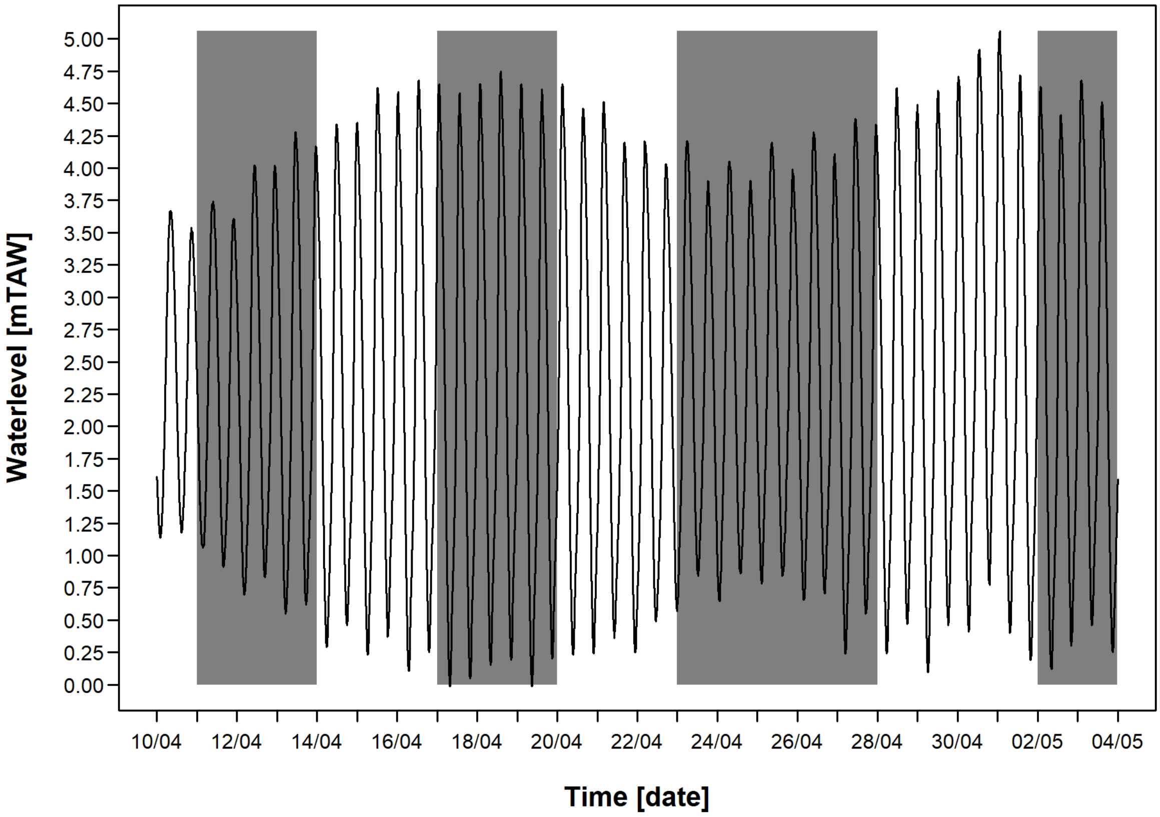


Figure 46 – Tides at Leopold-II dam in Zeebrugge, during the measurement campaign.
The grey background indicates the days where measurements were performed.

The maximum water level during the measuring campaign is 4.75 m TAW, the minimum water level -0.01 m TAW. Table 14 gives an overview of the average high and low water levels on the measuring days, as well as the average tidal difference. It can be seen that the day with the lowest average high waters, highest low waters and smallest tide difference is the first measuring day, i.e. 11/04. The day with the highest average tidal difference and lowest low water is 17/04. The average highest high water is 18/04. The largest tide differences are observed in week 2 and 4 of the measurement campaign, the smallest differences in the first and third week.

Table 14 – Overview of the tide, wind and waves during the measurement campaign. For wind and waves, the average values were calculated between 8 a.m. and 5 p.m., approximately corresponding to the time of the real measurements.

	Tide			**Wind**		**Waves**	
	[m TAW]			[m/s]		[cm]	
	HW	LW	GTV	Gem	Max	$H_{1/3}$	H_{max}
11/04	3.67	0.98	2.69	2.30	2.84	31.46	40.12
12/04	4.02	0.76	3.25	4.77	5.89	35.75	45.58
13/04	4.22	0.58	3.64	3.50	4.25	26.06	33.22
17/04	4.61	0.02	4.59	6.53	8.98	10.76	13.71
18/04	4.70	0.17	4.53	3.05	4.00	13.02	16.60
19/04	4.63	0.09	4.53	2.74	4.18	11.43	14.58
23/04	4.05	0.84	3.22	8.51	10.03	16.58	21.14
24/04	3.97	0.75	3.22	9.39	11.16	20.69	26.38
25/04	4.09	0.81	3.29	10.06	11.96	26.87	34.26
26/04	4.19	0.68	3.51	11.88	13.96	31.18	39.75
27/04	4.36	0.39	3.97	3.33	5.43	16.79	21.41
02/05	4.52	0.21	4.31	9.39	13.63	14.67	18.70
03/05	4.59	0.35	4.24	2.62	3.34	18.70	23.84

4.3.2 Wind

Figure 47 shows an overview of the average wind speed and maximum wind speed during the measuring campaign. The time resolution of the data is 10 minutes. The data are measured at the measuring location 'Zeebrugge Dam instrumentation' and were obtained via the website of 'Meetnet Vlaamse Banken'. The days on which the measurements were taken are indicated with a grey background. The wind speeds during the measuring days were generally not very high. In Table 14 an overview is given of the average wind speed per measuring day (between 8 and 17 h) and the average maximum wind speeds. The maximum average wind speed were measured on 26/04, the minimum average speed on 11/04. The wind data was included in the report to assign possible drift in horizontal position to wind speed and wind direction.

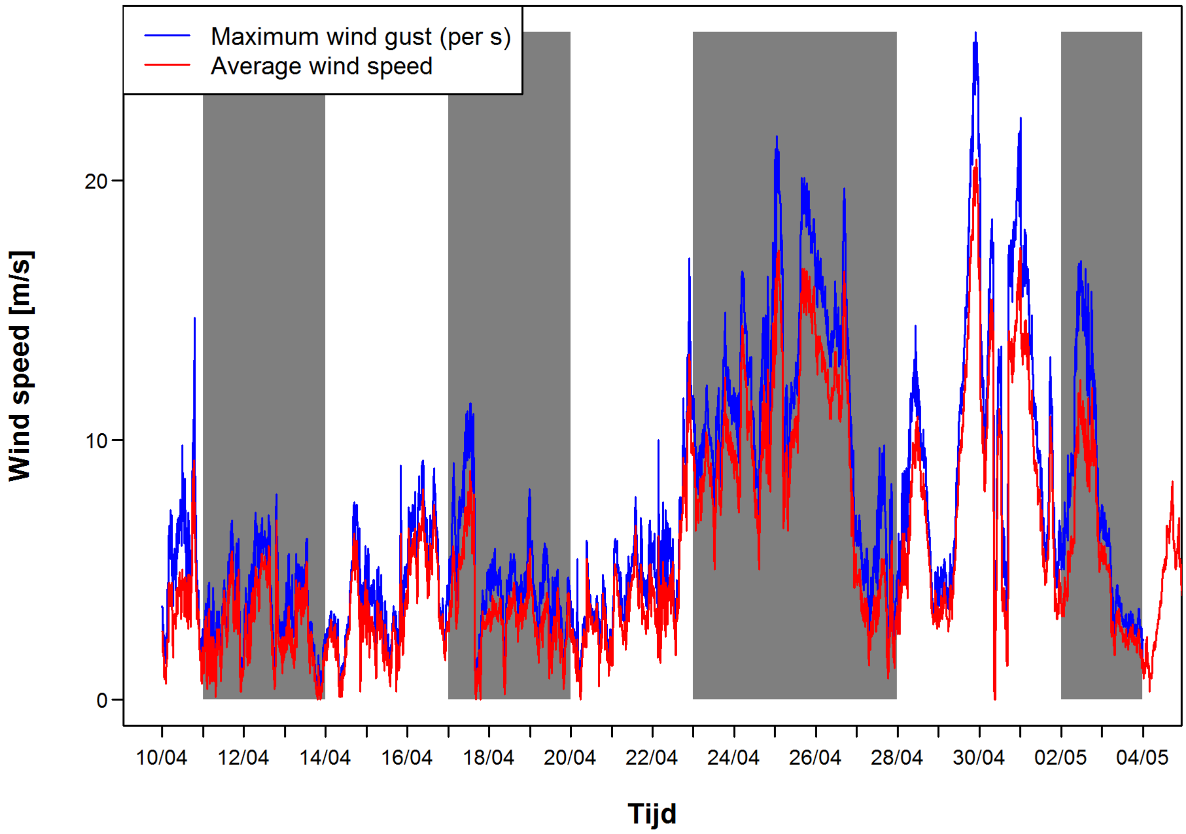


Figure 47 – Overview of the measured wind speed (average and maximum wind speed [m/s]) during the measuring campaign at Zeebrugge Dam instrumentation.

4.3.3 Waves

Figure 48 shows the course of the wave heights at measuring station 'Zeebrugge Zandopvangkade'. The data were obtained through the website of Meetnet Vlaamse Banken. In the figure respectively the average wave height of the 10% highest waves, the significant wave height $H_{1/3}$ (the average of the 33% highest waves) and the average height of waves with a wave period longer than 10 s are shown. For these measurements, one measurement per half hour is available. It is clear from the graph that the wave climate during the measurements was moderate. A maximum average significant wave height of approximately 35 cm was recorded 12/04 (see Table 14). A lowest significant wave height of 11 cm was recorded on 17/04. The wave data was included in the report in order to assign possible inaccuracies in vertical position (depth) to wave movements.

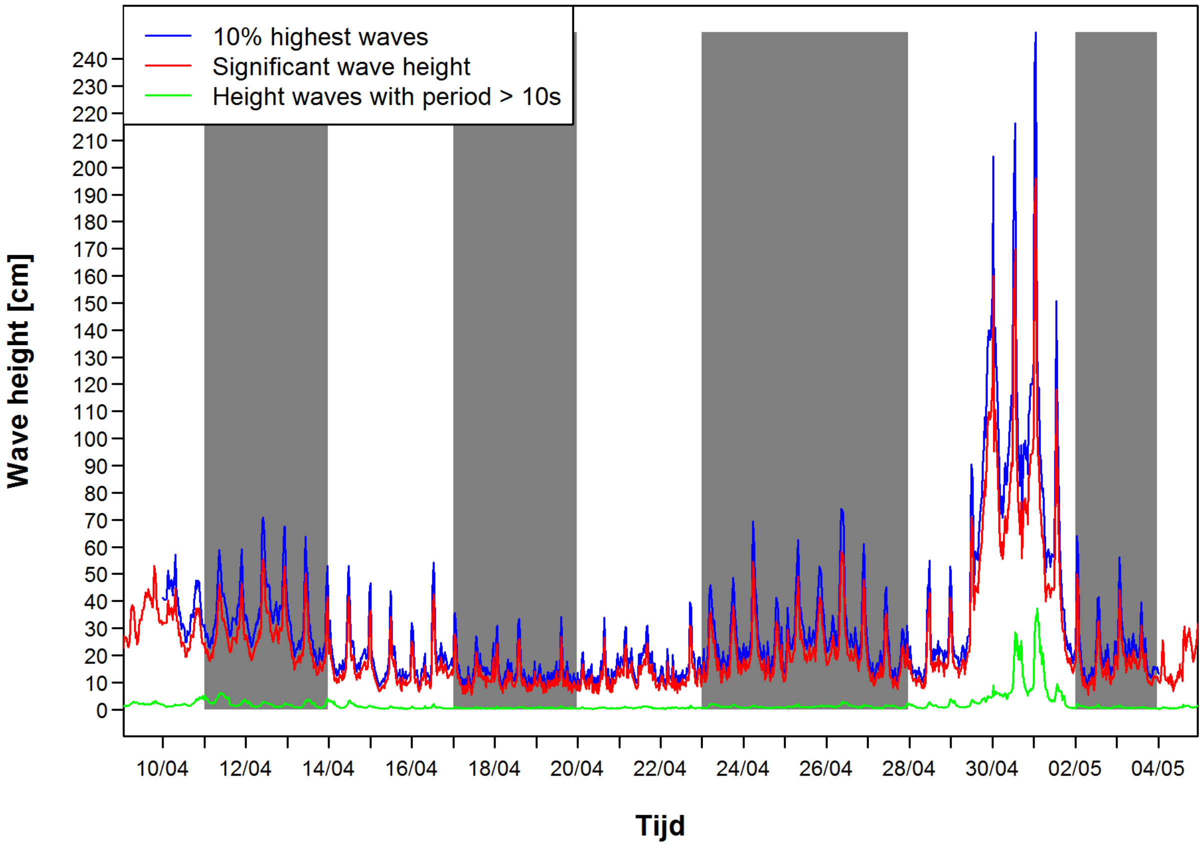


Figure 48 – Overview of the measured wave heights during the measurement campaign, near Zeebrugge Zandopvangkade

4.4 Measurements with in-situ density measuring instruments

4.4.1 Echo sounding

During the measurement campaigns, the 33 kHz and 210 kHz values were noted for each measurement location. In order to get a good estimate of the sound speed, daily salinity measurements were performed at the start of the measurements.

4.4.2 Admodus

Calibration

The pressure sensor is cleaned and the oil is replaced every time (day) the measurements begin. It is important to thoroughly remove the impurities that can accumulate here, so that the sensor delivers correct depth measurements. During a measurement day it is regularly checked that the indicated pressure shows "0" when the instrument is brought just above the surface of the water.

Starting the measurements, the Admodus was always calibrated using distilled water or seawater. The salinity of the distilled water is well known (PSU = 0), this PSU value must be entered in the software. Using seawater for calibration, the salinity (which also determines the density of the seawater) must be measured. This was done using a multi-parameter probe from the Hydrography Service and entered into the software.

Handling

During the measurement campaigns, the device was brought aside the vessel using a davit. When the device is lowered to measure a profile, a new measurement is automatically started in the software. This software is easy to use.

After each profile measurement, the device was always raised to the top to verify that there was no mud between the sensors. This check is very important to ensure the accuracy of the results. In case mud is sticking to the sensors, they are cleaned with a water jet. Also, when the sensor is above water, the zero pressure measurement can be verified and, if necessary, reset to avoid a pressure drop during the measuring day.

During a measurement day, a defect in the data cable was detected in the Admodus. Thanks to the quick response of the manufacturer, it was possible to measure again with the Admodus after only one measurement day. This quick delivery and good training give a positive impression about the support of the supplier. Due to the fact that there is no automatic winch, three people are needed for the operation (winch, data cable and survey pc).

4.4.3 DensX

Calibration

The depth sensor of the DensX is recalibrated daily before the measurements. The sensor is calibrated at a depth of 5 metres. This depth was indicated on the data cable, and in the software the value is adjusted manually. As an extra validation of the depth measurement, the results of the depth sensor are also checked at a depth of 10 metres.

The density sensor of the DensX must not be calibrated every day. The calibration of the density sensor was performed with copper plates always at the start of a new measurement campaign. This calibration checks whether the strength of the radioactive source has remained the same, to ensure that the original calibration curve can be maintained. A calibration with mud from the port of Zeebrugge was performed on 04/07/2017.

It is recommended to perform a new calibration when measuring at a different location or when the previous calibration was a long time ago.

Handling

The DensX was used both on board and in the lab. In lab conditions, the device is clearly larger than the other devices, which means that larger containers are required for measurements with the DensX at full immersion. This means that more mud is needed to perform a validation, and consequently the operations take more time (mud dilution, mixing, ...). During validation in the laboratory (see chapter 3) dotOcean explained that during calibration/validation only the legs of the device must be immersed. This partially compensates for the need for large containers.

The main obstacle to carrying out these calibration measurements is the lack of a separate data cable and key. There is currently only one data cable and key, but they are permanently mounted with the winch on board of the vessel “Pierre Petit”. This means dotOcean must always be present with the cable and key, which makes the measurements expensive, less flexible and more difficult to schedule. Furthermore, the support and accessibility of dotOcean is restricted. Additional safety regulations, according to fixed rules, were applied for the handling of a radioactive source when performing the tests, but this did not cause any further difficulties in performing the validation measurements.

On board, the device was frequently used. The device is suitable to perform profile measurements. It takes a little more time to perform one measurement profile compared to the other instruments, but this cannot be considered a hindrance. With an average number of 54 profile measurements per day, the speed seems sufficient for performing measurements. It takes about three minutes to perform one measurement, of course depending on the total depth. Due to the larger weight of the DensX, it is mounted at the crane of the vessel “Pierre Petit”. The required infrastructure (crane) on a measuring ship for the use of the DensX is larger than for the other instruments, but once present, it cannot be considered a nuisance.

It is especially while moving between different measurement positions that the DensX is a less practical/handy instrument. It is therefore a difficult device for the skipper to work with. There are two particular safety restrictions in the use of the device. Firstly, there must be at least 5 m of water above the device, and secondly, there is a maximum permitted tensile strength of the cable. If any of these restrictions is not met, the instrument is turned off automatically. Due to the minimum water depth of 5 m, a lot of cable has to be given, which always means a risk regarding the propeller when moving. The restriction of the force on the cable means that only slow sailing between the measurement locations is possible. Switching off the device between measuring locations, to avoid these restrictions, is not an option, as it requires about 5 minutes for the radioactive source to restart. In cases of strong currents or in bad weather (when more power is needed to move the boat or even to keep it on the measurement location) measuring with the DensX does not seem possible. This was not a problem for this measurement campaign, as the conditions of waves and wind (sections 4.3.2 and 4.3.3) were favourable.

In addition to these restrictions, a control measurement must be carried out regularly by Controlatom. Also the decay of the source must be checked regularly (by means of the above mentioned adjustment). Furthermore, a separate calibration function per location (mud type) must be entered into the device. The support of the supplier for the execution of the calibration is inadequate (late, unclear or no communication), which further limits the usability of the device.

Finally, when using the device, take care to clean the pressure sensor and the device sufficiently (by spraying with water), as dirt can easily accumulate there.

4.4.4 Rheotune

GeoXYZ

The Rheotune measurements of GeoXYZ were performed with an automatic controlled winch, in contrast to our own measurements which were manually controlled with the winch of the davit. The speed of lowering the device during the measurement is higher.

Calibration

Each day a measurement is performed, the pressure sensor of the Rheotune is calibrated again. This is done based on a two-point calibration, whereby the device is calibrated at a depth of 2 and 10 m.

The density sensor of the Rheotune doesn't required a daily calibration. A calibration of the Rheotune (Flemish Hydrography) was performed using kaolinite, so no mud of the local measurement location was used. A final calibration was performed by Stema in January 2018. The data of this calibration are shown in Appendix.

Handling

During the measurement campaigns, the device was brought aside the vessel using a davit and lowered manually. When lowering the device, a new measurement is started manually in the software. After profiling, the device was always raised to the top to check for the accumulation of mud in between the tuning fork. In most cases, the tuning fork has to be cleaned with a water hose from on board, to remove the remaining mud material. During the measurement campaign there was a problem with the interface box, which is needed for supplying and data transfer. As no solution was found by the producer, a new interface box was ordered and collected from the producer.

4.4.5 Rheocable

Calibration

Before the measurements can be started, the density must be calculated in the software, based on the data of the CTD diver. A calibration value for the sensor (default value 1) and a calibration value for the cable must be entered in the software.

Handling

The Rheocable is not an easy device to handle. Because of the long cable (3 times the length of the expected depth) dragging behind the ship, manoeuvring the survey vessel is difficult. This makes the application of such a measurement in a port, with many ship movements, almost impossible. In addition, the cable must be pulled in manually, which requires hard work. The software used to operate the device is unclear and difficult to use. The software was installed on the PC by the supplier, which also makes it difficult to transfer. Furthermore, adjustments were made during start-up, which calls the maturity into question.

4.4.6 GraviProbe

Calibration

The GraviProbe does not require calibration before measurements.

Handling

The GraviProbe is a very handy, light and mobile device. It is easy to use. The duration of a measurement is short, as such a large number of measurements can be taken in a short time. The device must be put overboard manually. Furthermore, sufficient cable must be winched, with a weight low in the water, whereby good communication with the skipper is required to avoid to lose the device and to avoid cable in the propellers. The biggest disadvantage of the actual (purchased) version of the device is the fact that the data can only be read afterwards, and that possible malfunctions can only be noticed at a late stage. In recent versions of the device, this seems to be solved by a wireless communication of the device with a tablet/laptop.

The device provides a lot of data for many parameters (see above). However, these parameters cannot yet be unambiguously related to the in-situ structure of the mud. Relating them is a future challenge.

4.4.7 Slibsampler

Handling

The slibsampler is only suitable for use when the weather conditions are good, flow is limited and when the vessel is stationary. The vacuum pumps supplied are of poor quality and therefore cannot be used on board. A good compressor can solve this problem. The connection between the "control pad" and the sampling tube is made with a simple rope, which is considered not sufficient. Breakage of this one rope would result in the loss of the sampling tube with Beeker cutting head. The sampling tubes, with holes every 5 cm, hardly close off, so that a large part of the sample already empties out during the raising process and a correct determination of the depth of the water-mud transition is not possible with these tubes. Moreover, many tubes already show cracks. It is possible to work with a closed tube, but detaching the tube from the device is not easy on board, so this does not offer a solution from a practical point of view. Tubes that can be sampled directly (for density measurements) are necessary in combination with this device. Collecting mud samples for rheological measurements (where the tube must be removed and subsamples are taken) is not practical with this device.

4.4.8 Handling of the devices

Table 15 gives an overview of the assessment of the handling of the different devices, the theoretical consideration of the devices is given in Table 9.

Table 15 – Overview of practical issues related to the handling of the different devices, both advantages (left) and disadvantages (right)

	Advantage	**Disadvantage**
Admodus USP	– lightweight – Software easy to use – Sturdy transport case – Good support from the manufacturer – Deployable anywhere	– 3 men needed for operation – Adhesion of mud, impurities on sensor can disturb measurement
DensX	– Robust – No on-board calibration required	– Radioactive source – no separate data cable for lab validation

	– Automatic winch – 1 person sufficient during measurement – 1 cable (data/supply + drag)	– long start-up time of the device – Winch not easily movable, therefore the measurement is ship-dependent – reduced survey speed – no case, difficult to move – restricted manoeuvring possibilities during measurement (speed restriction) – Only to be used in good conditions (weather, flow) – Not usable in shallow water – little support from the manufacturer
Rheotune	– lightweight – Easy to use (software) – Sturdy transport case – Deployable anywhere	– 3 men needed for operation – Sticking of mud between the tuning fork, impurities on sensor can disturb measurement
GraviProbe	– lightweight – Quick measurement – No calibration required – Sturdy transport case – Deployable anywhere	– Manual lifting in & out of water – Measurement results only visible after reading/post-processing of the data
Rheocable	– None	– Non-visible cable behind ship restricts manoeuvrability and is therefore dangerous to shipping – Bringing cable on board heavy work – Software not user-friendly – Difficult handling – Only to be used in good conditions (weather/currents)
Slibsampler		– Only to be used in good conditions (weather/flow) – No pressure sensor for depth measurement (only distance to bottom is measured) – Sampling tubes leaky and fragile – Rope for connecting sampling tube and "control pad" (too) fragile

5 Data analysis

5.1 Introduction

This chapter discusses the results of the three density measurement instruments: Admodus, DensX, Rheotune, which are described in chapter 5.3. The differences and similarities in the results obtained with the different instruments are evaluated. At each measuring location, at least 2 vertical profiles were taken, with the same measuring device. In this way, the robustness, accuracy and repeatability of the measurement results were checked.

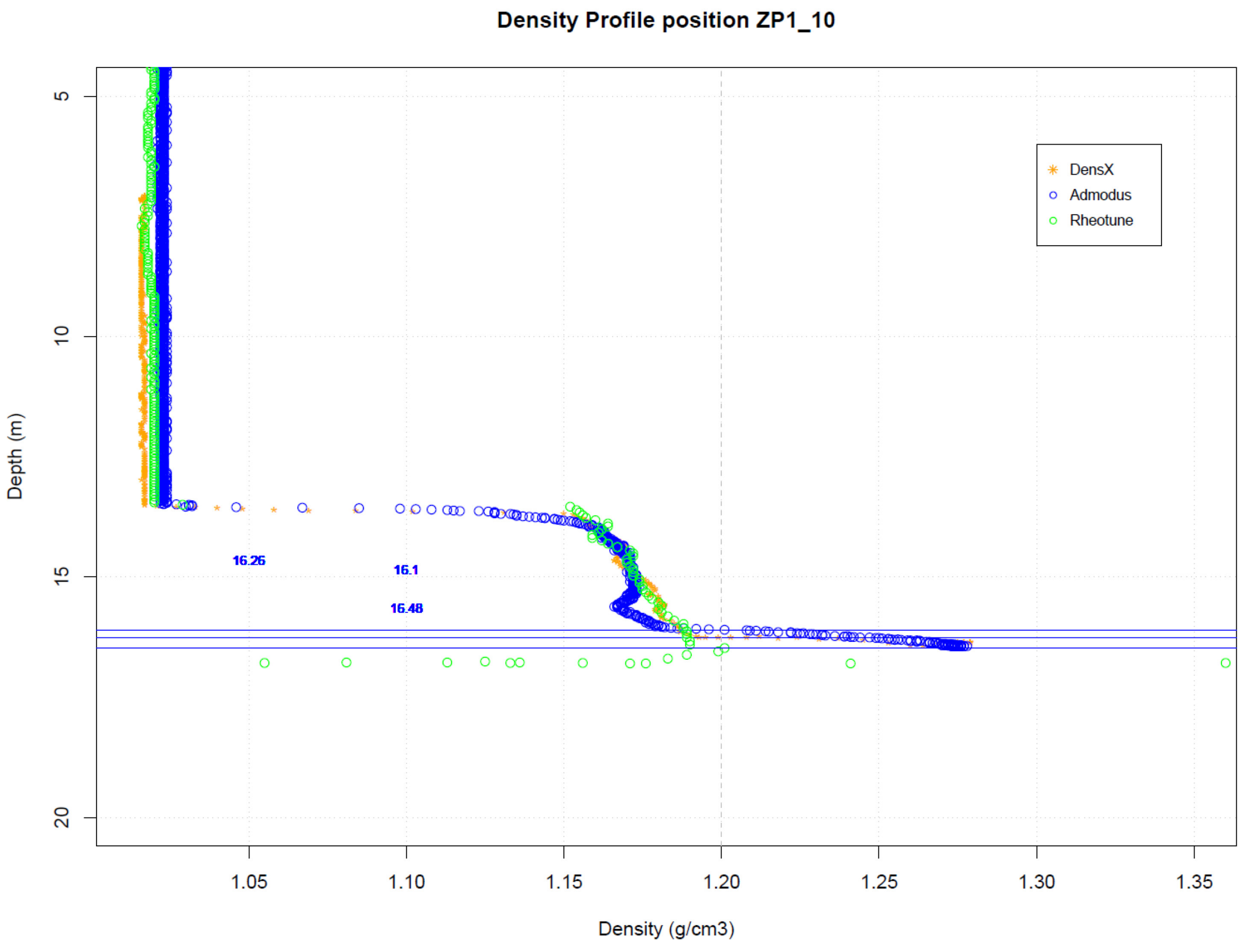


Figure 49 – Density profile at measurement site ZP1_10 (X=514133.384 m, Y=5688153.302 m) measured with the DensX, Admodus USP and Rheotune. The x-axis shows the density (g/cm³), the y-axis the depth in m LAT (m).

Figure 49 shows the density profiles at measurement position ZP1_10 (X=514133.384 m, Y=5688153.302 m), measured with the different devices. The actual location of the measurement is respectively (X=514131.36 m, Y=5688154.58 m) for the DensX, (X=514144.03 m, Y=5688165.13 m) for the Admodus and (X=514133.38 m, Y=5688153.30 m) for the Rheotune. This is respectively at 2.4 m; 16 m and 0.004 m from the theoretical measurement location. In Figure 49, as for each density profile in this report, the y-axis reflects the depth in m LAT and the x-axis the density in g/cm³. An orange symbol stands for DensX, blue for Admodus and green for Rheotune.

Figure 50 shows the density profile measured in A2 point 27 with the Admodus USP. As explained in Figure 49, the y-axis represents depth in m LAT and the x-axis represents density in g/cm³. The profile starts with a quasi-vertical line, representing the (almost) constant density of the water column. At a certain depth, the slope of this vertical line varies significantly. The devices begins to penetrate the mud layer and higher densities are observed. The depth of deflection corresponds to the position of the top mud. The devices continue to descend, reaching higher densities, until it cannot descend any further. At this point the measurement stops and the device is brought back up again. The blue horizontal line, shown in Figure 50, indicates the depth at which a density of 1.20 g/cm³ is reached.

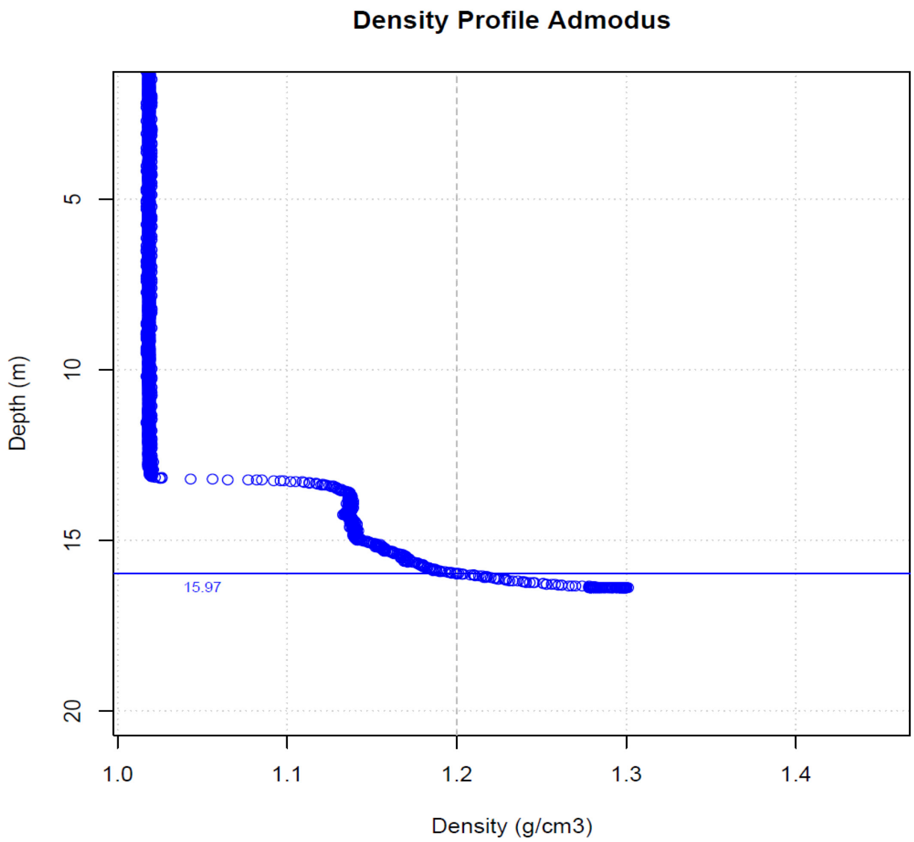


Figure 50 – Typical density profile (measured with Admodus at location A2 point 27).

Figure 51 shows a typical density profile, which was measured at location A2_27 with the Admodus. At every location the profile was measured twice with the Admodus (indicated in Figure 51 with ° and * symbol). In Figure 51 the parameters used in the analysis are outlined, these are:

- <u>water density</u>: The average density measured in the water column. This value is calculated from the data in the profile.
- <u>position of 1,2 g/cm³</u> : is the depth at which the density of 1.2 g/cm³ is reached for the first time. This value is taken from the post-processing by Flemish Hydrography.
- <u>Thickness of mud layer</u>: this is the distance from the top mud (visual through the inflection point in the density profile) to the depth of 1.2 g/cm³.
- <u>210 KHz depth</u>: the depth at which the 210 KHz is reflected, this value being given by the echo sounding. This depth is the top of the mud (the end of the water column).
- <u>Δ 1.2</u>: is the absolute difference between the 1.2 g/cm³ depth measurements made at the same point by the same instrument (as shown in Figure 51)
- <u>Δ Thickness of mud layer</u> is the absolute difference between the thickness of the mud layer of the different profiles at the same point and measured with the same measuring device (see Figure 51)

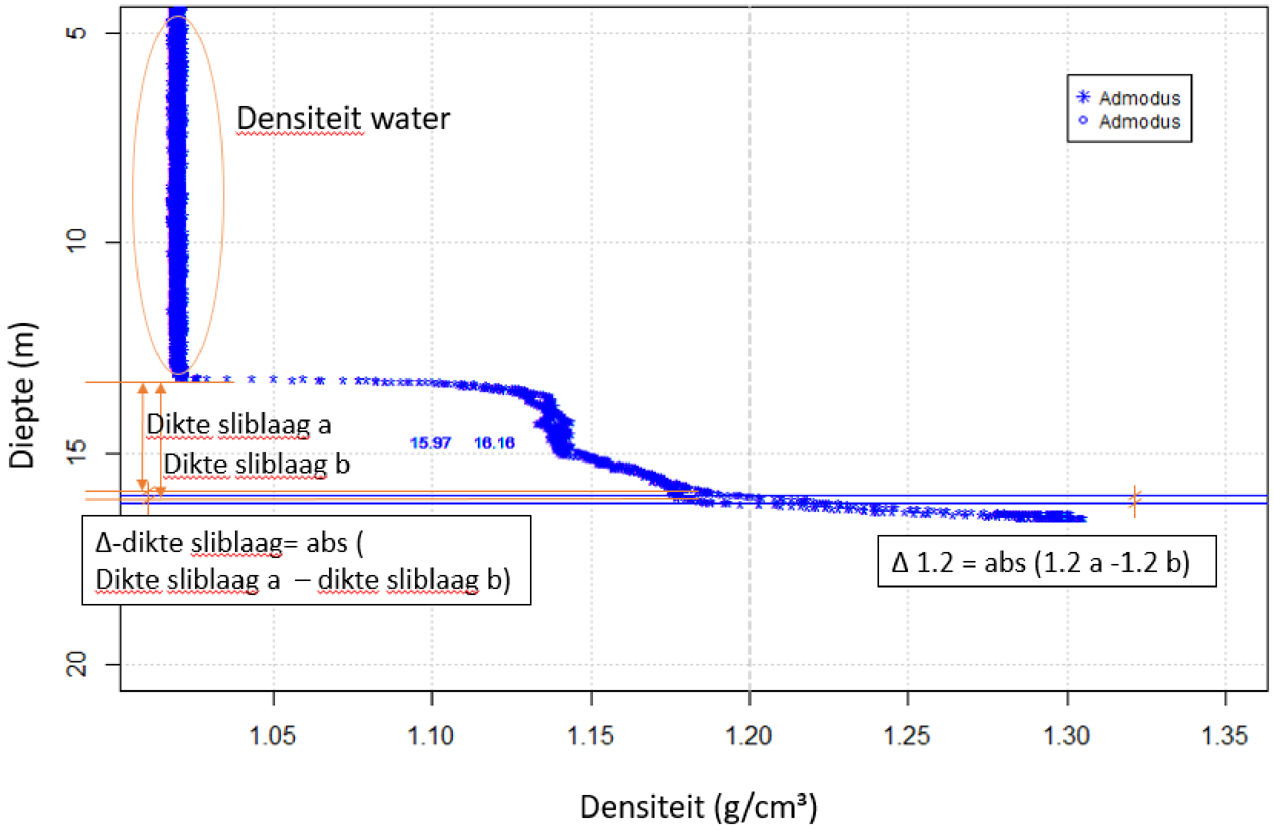


Figure 51 – Typical density profile, measured here at location A2_72 with the Admodus.
The different parameters (ρwater, Δ1.2 and Δthickness of the mud layer) used in the analysis are indicated.

5.2 Measurement variability

5.2.1 Water density

A first analysis on the measurement results is a detailed analysis of the measured water density, by the different devices. A visual and manual analysis of the density data in the water column is made to determine the average density of the water column in each measuring location and each measuring point of the campaign. From this average water density of each profile, the average water density per position (a profile is measured at least twice per instrument) is calculated. Figure 52 shows the average water density of all locations where density was measured during the campaign. 23% of the measurements are above the average density of 1.021 g/cm^3. The maximum average value obtained from the measurements is 1.029 g/cm^3, 10% of the measurements have a value below 1.021 g/cm^3, with a minimum value of 1.015 g/cm^3.

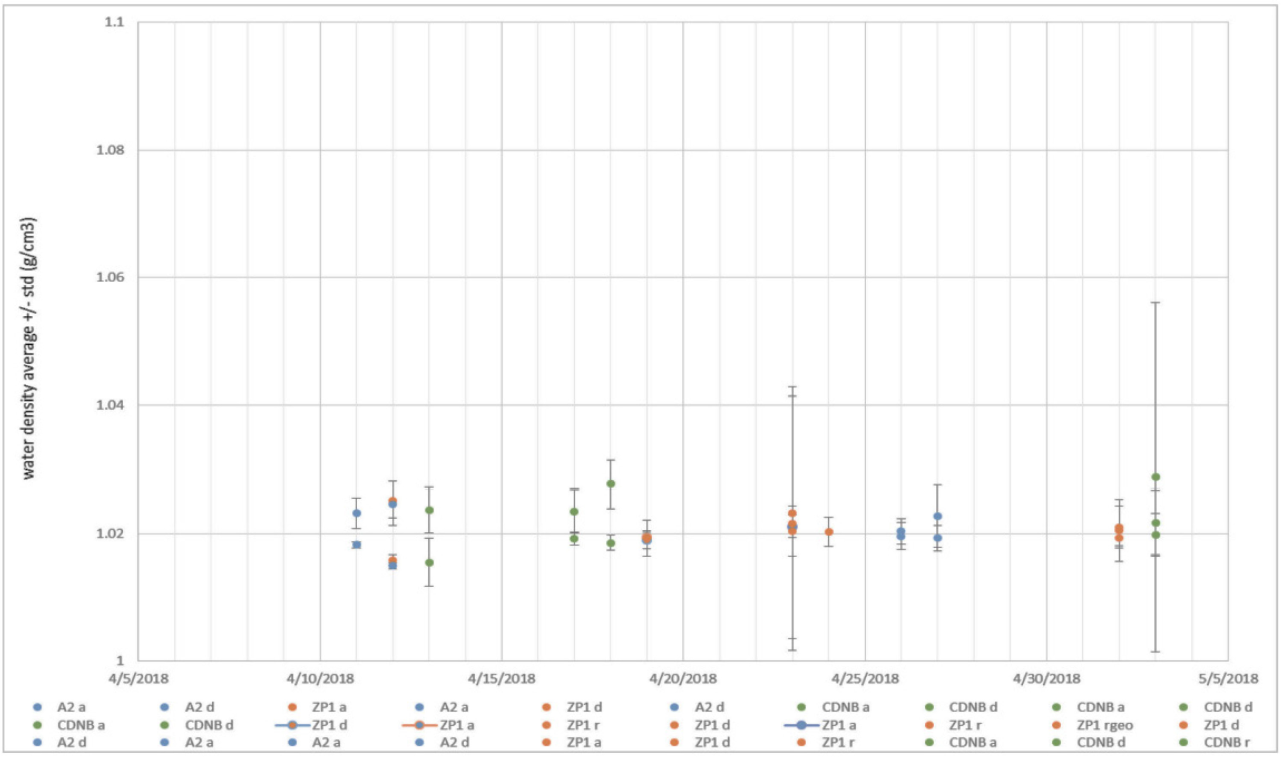


Figure 52 – Average water density with standard deviation for all measurement locations and all devices.

Admodus

Figure 53 shows the average water density measured with Admodus during the measurement campaign at the different locations. From 11-04-2018 to 16-04-2018 the average water density is 1.016 g/cm³, during these days the calibration of the devices on board was performed using distilled water. From 17-04-2018 the calibration of Admodus was performed with local sea water. In the case where distilled water is used as calibration fluid, the density is slightly lower than expected, especially 12 & 13 - 4, but the difference is limited to approx. 0.003 g/cm³. The variation on the data is smaller for Admodus than for the other two devices. There are some profiles where the water density is clearly higher, close to 1.04 g/cm³. These profiles are studied in more detail below.

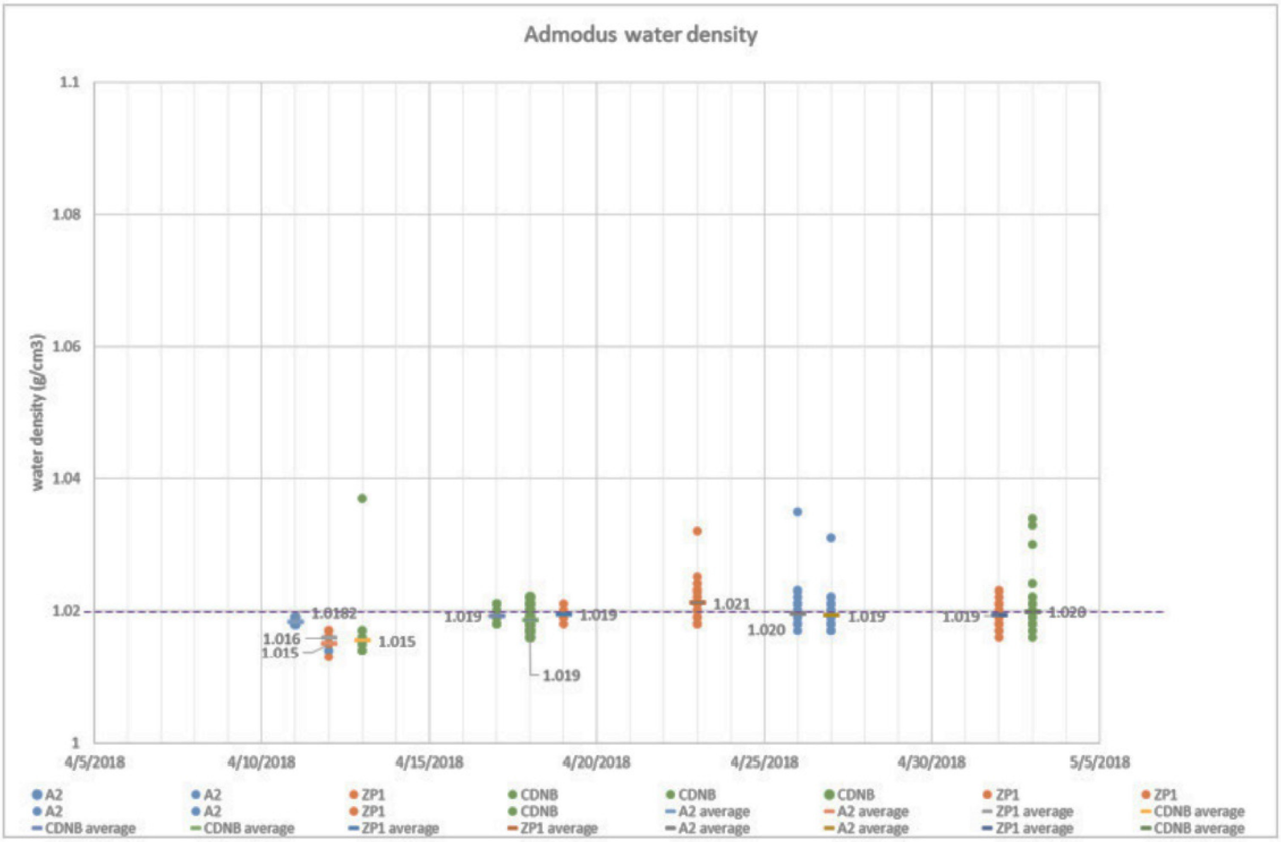


Figure 53 – Average water density measured with Admodus during the measurement campaign, for the different lcoations.

Figure 54 shows the density profiles of measurements where a higher than expected density was observed in the water column. The measurements cannot be related to a specific location, because this deviating values were found in CDNB (profiles 1, 5, 6), Albert II dock (profiles 3 and 4) and Zwaaiplaats I (profile 2). In most cases (Figure 54), the density profile shows higher values in the upper part and, after a sudden change, this value falls back to lower (and expected) values. This pattern can be recognised in profiles 1, 3 and 5. Presumably in these cases there is still sediment sticking to the sensors, which is removed by the downward movement of the instrument, causing the measurement values to fall back to more realistic values. In profile 2 this is less evident, the (automatic) measurement seems to have started later here, but there is still a suspicion of the same behaviour. For profiles 4 and 6 no such change can be observed, the profile shows high density values but otherwise appears normal. Possible causes cited by Synergetik, the manufacturer of Admodus, are dirt on the sensor (mud particles) or air bubbles stuck to the sensor. It is possible, that in these cases (profile 4 and 6) the bubbles and mud particles were not removed by the downward movement of the device and therefore no change could be detected.

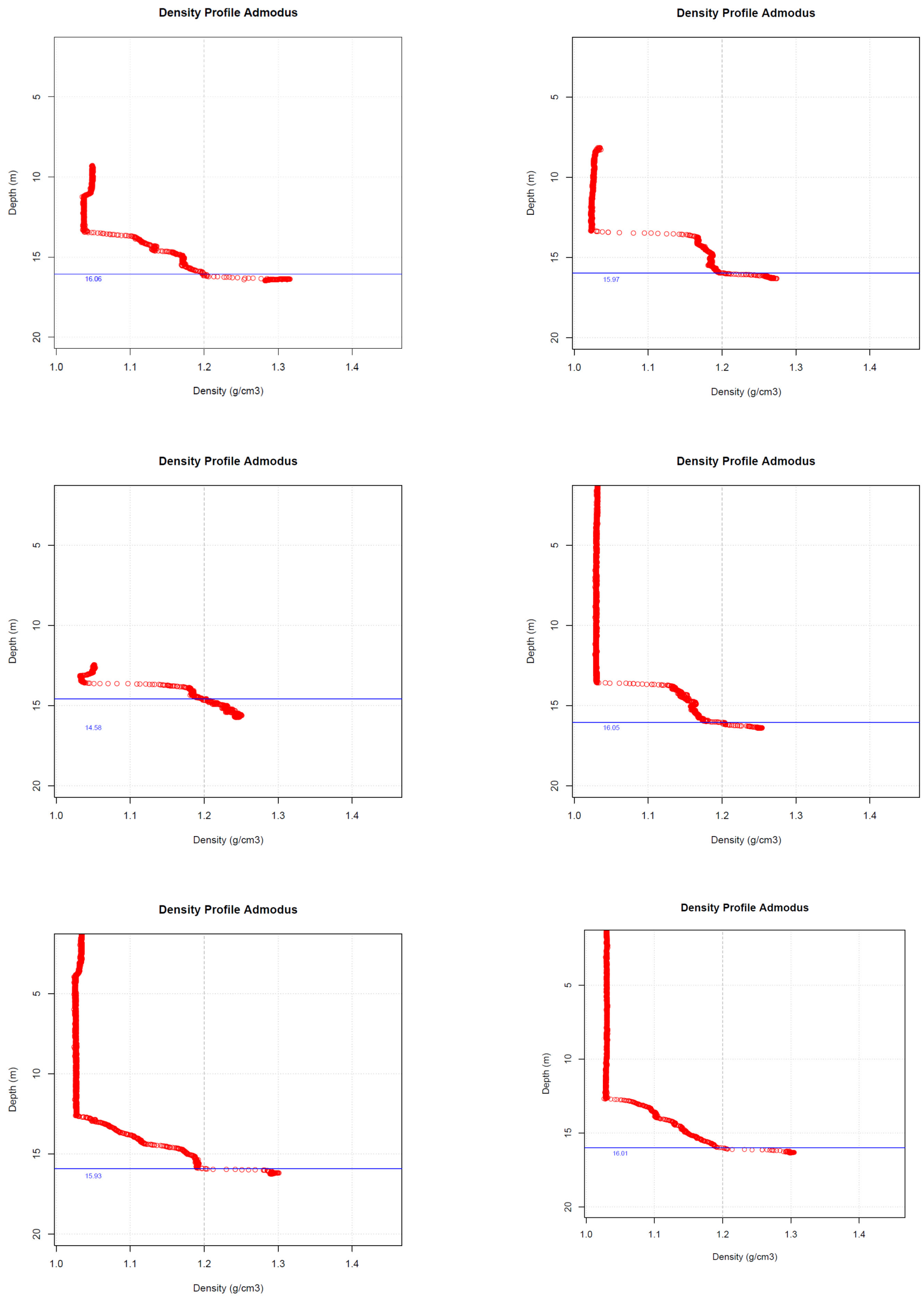


Figure 54 – Density profiles in which high water density was measured.
The following average densities were measured respectively:
1.037 g/cm³, 1.032 g/cm, 1.035 g/cm³, 1.031 g/cm³. 1.034 g/cm³ en 103 g/cm³.

DensX

Figure 55 shows the average water density at each position measured with the DensX during the measurement campaign. The average water density measured with the DensX is slightly higher than for Admodus measurements. The values of the water density measured with the DensX show a variation of 1.014 to 1.046 g/cm³. There are some profiles where the water density is around 1.040 g/cm³, these profiles are shown in Figure 56. In none of these profiles a clear bend or error can be noticed. In a number of examples, such as profiles 3, 4 and 6, the variations in the measurement do seem to be larger than average with the DensX.

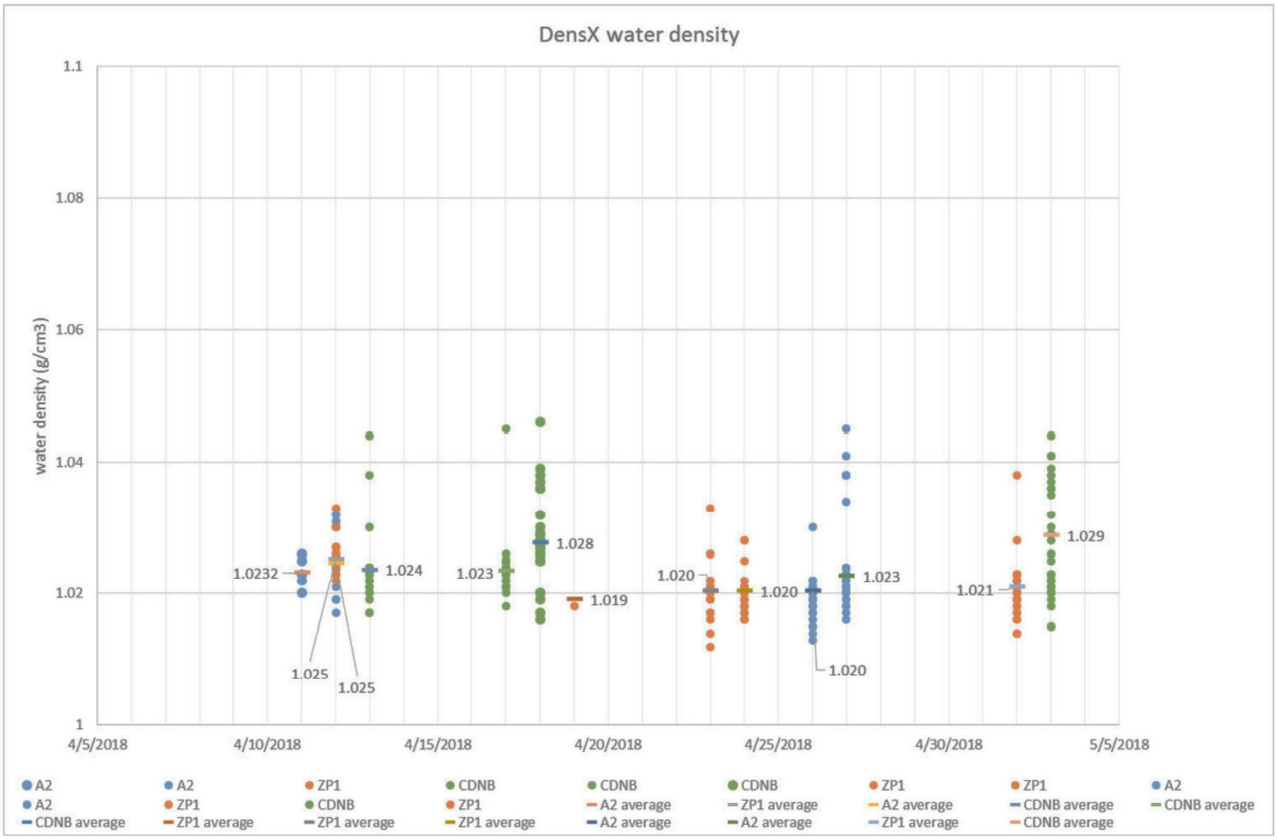


Figure 55 – Average water density measured with the DensX during the measurement campaign, for the different locations.

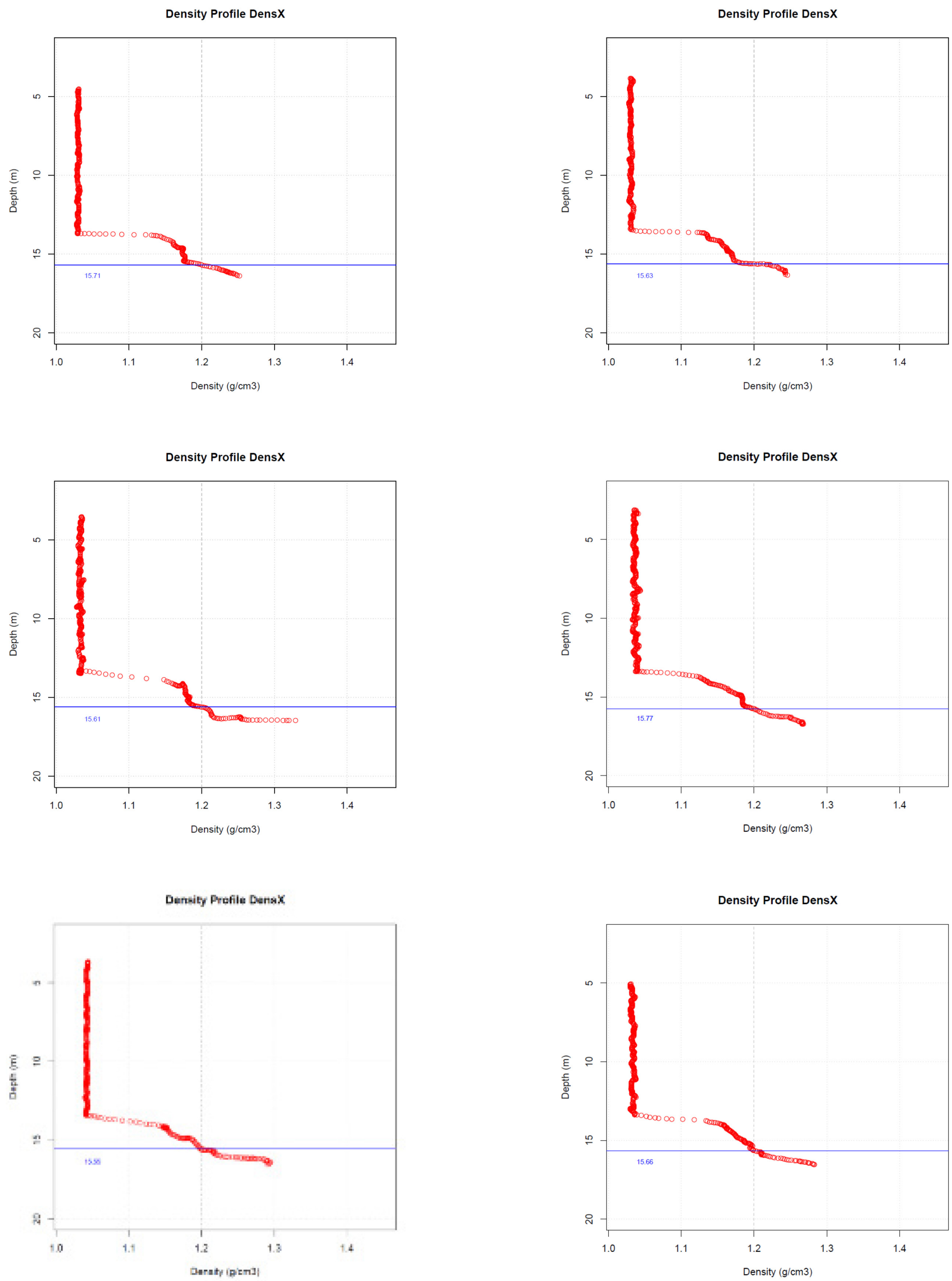


Figure 56 – Density profiles, measured with the DensX, in which a high water density was measured.
The following densities were measured respectively:
1.03 g/cm³; 1.032 g/cm; 1.033 g/cm³; 1.038 g/cm³; 1.044 g/cm³ en 1.03 g/cm³.

Rheotune

Figure 57 shows the average water density for each position measured during the measurement campaign with the Rheotune. In Figure 58 this is also shown for the Rheotune, but measured by GeoXYZ on 23/04/2018. The average water density measured with the Rheotune per location corresponds well to the actual water density value of 1.021 g/cm³. With a few exceptions, the variation on the results measured by Flemish Hydrography is small, the measurements measured by GeoXYZ show a large(er) variation. The values of the water density measured by Rheotune (Flemish Hydrography) vary between 1.012 and 1.081 g/cm³, whereby around 1.08 g/cm³ two clear outliers can be observed. A number of examples of measuring points where the water density is higher than 1.03 g/cm³ are shown in more detail in Figure 59 and Figure 60 respectively. In Figure 59, despite the (too) high measured water density, no evidently "wrong" profiles can be seen. In example 1 the measured value seems very constant, for the other profiles there is a little higher variation on the measured data. Figure 60 shows the measurements of GeoXYZ. Very clear deviations from a normal density measurement can be seen here. In two cases, there is a sudden change of the measurement value in the graph, which slowly decreases with depth (examples 1 and 3). In the other examples, the measured density is much too high and seems to decrease slowly with depth, most significantly in example 6. These profiles were probably carried out with a device that was not cleaned properly, causing mud stick between the tuning fork.

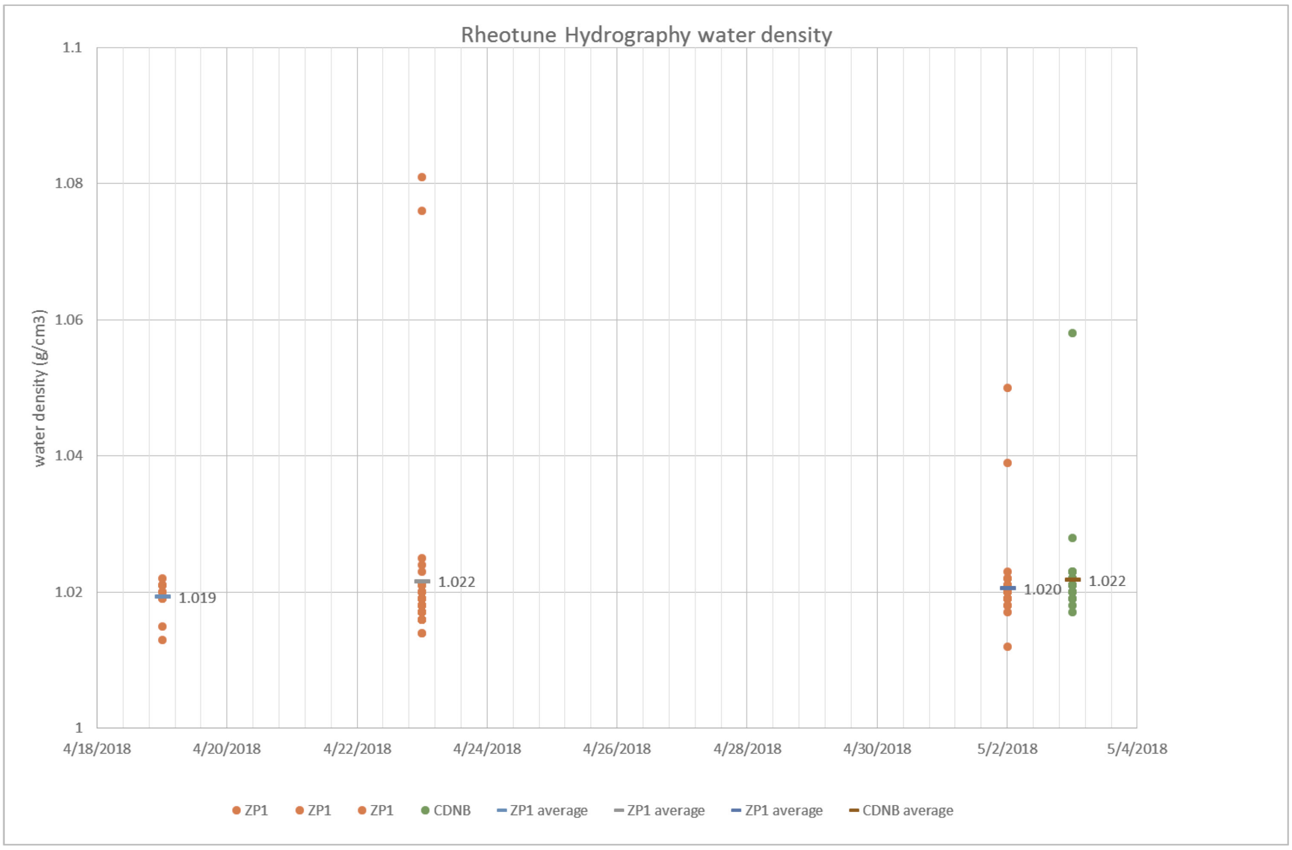


Figure 57 – Average water density measured with the Rheotune (Flemish Hydrography) during the measurement campaign, for the different locations.

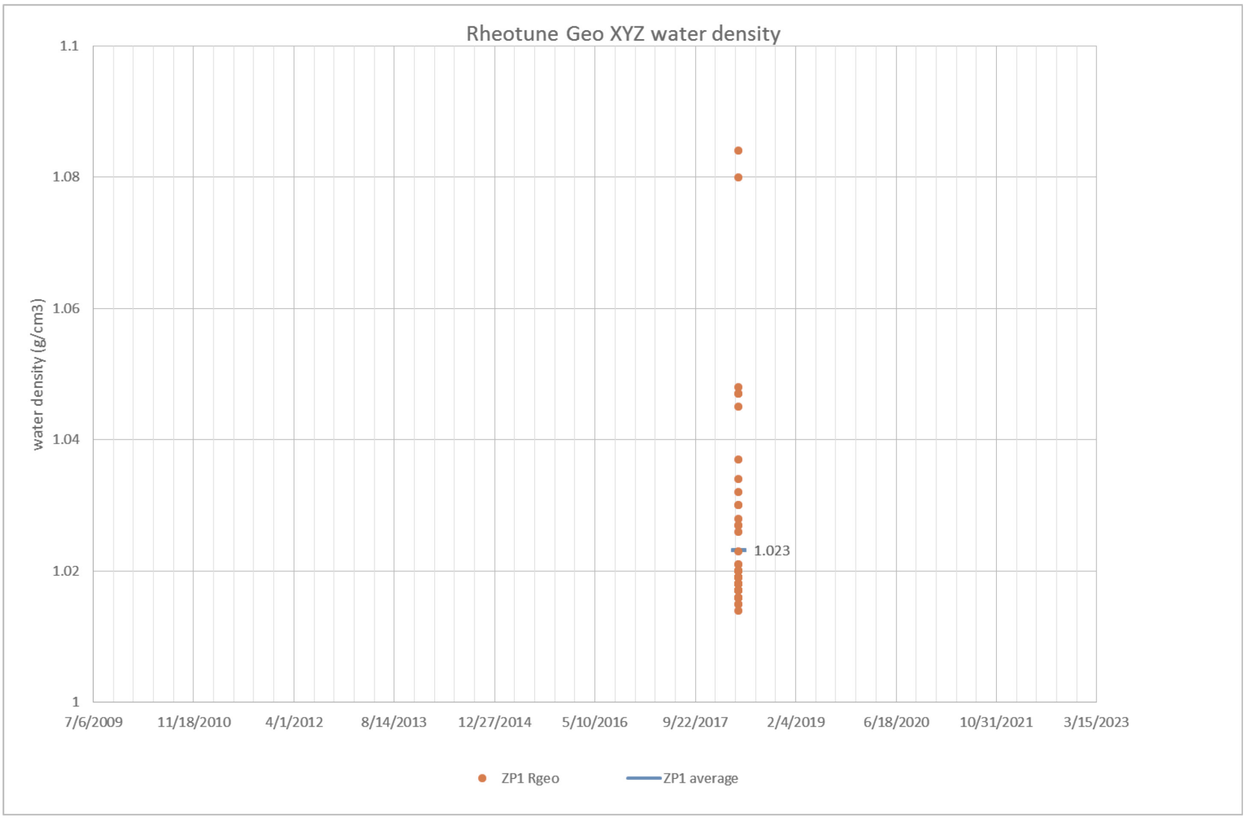


Figure 58 – Average water density measured with the Rheotune (GeoXYZ) during the measurement campaign, in ZP1

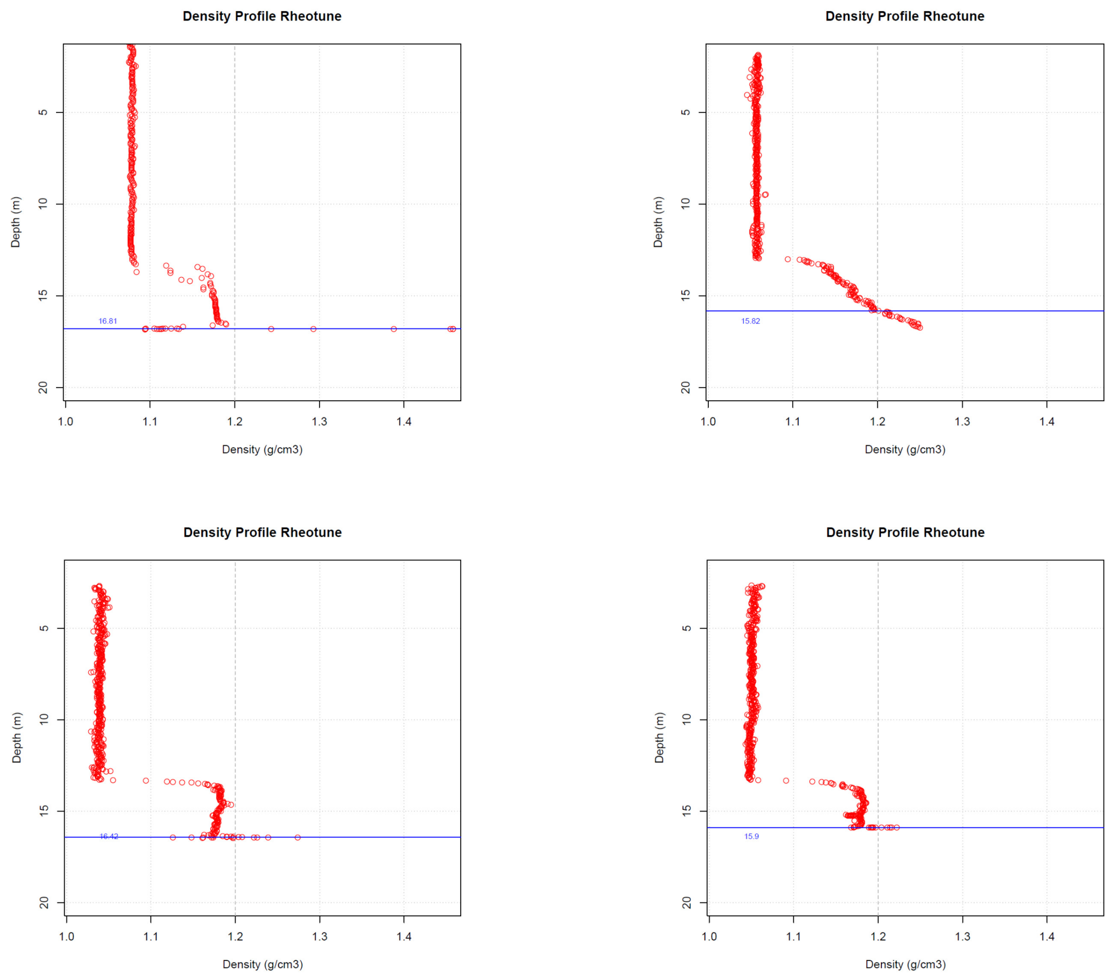


Figure 59 – Density profiles, measured with the Rheotune (Flemish Hydrography), in which a high water densities were measured. The following densities were measured respectively: 1.081 g/cm³; 1.058 g/cm; 1.039 g/cm³; 1.05 g/cm³.

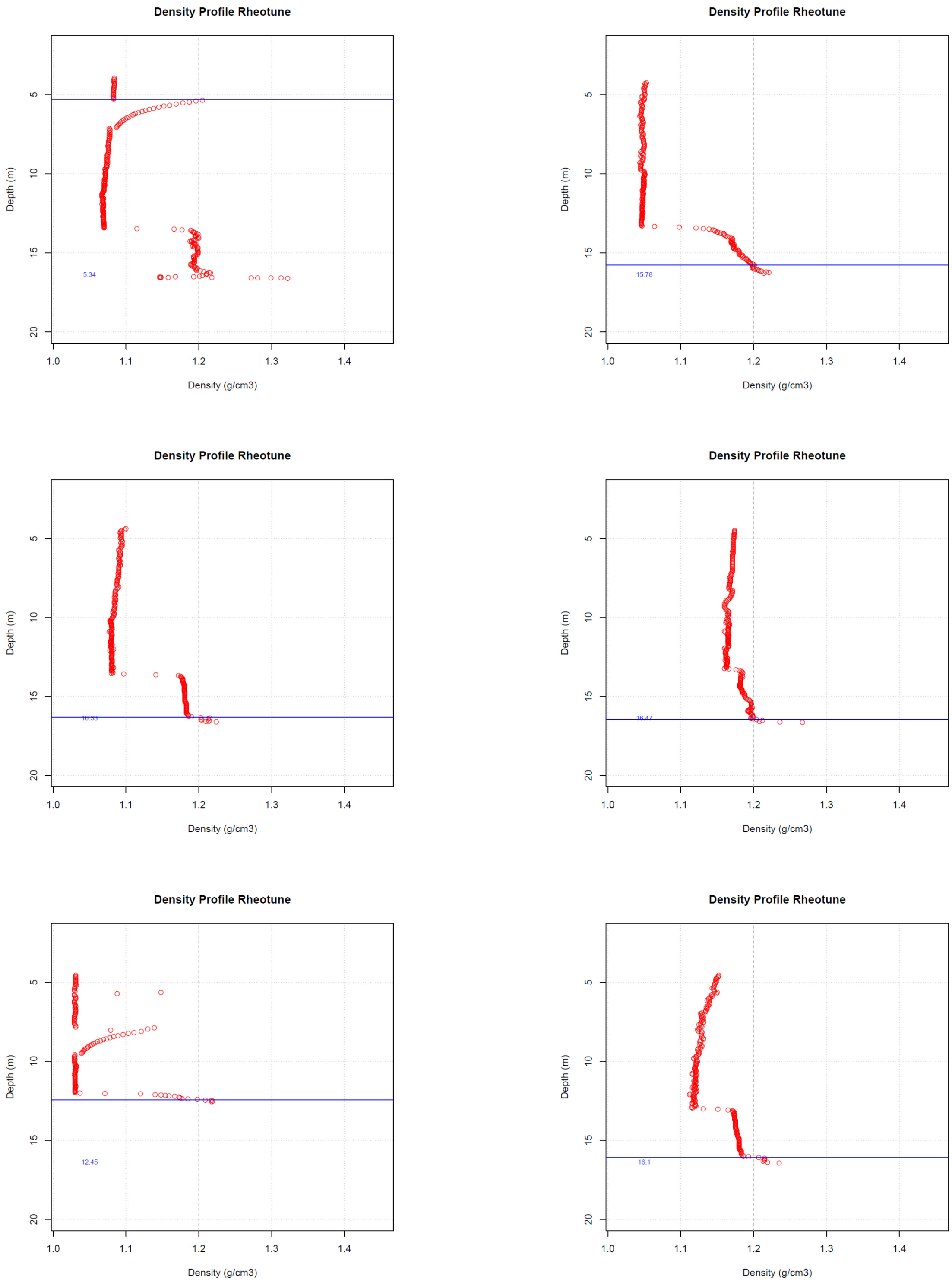


Figure 60 – Density profiles, measured with the Rheotune (GeoXYZ), in which a high water density was measured. Respectively, the following densities were measured:
1.084 g/cm³; 1.047 g/cm; 1.08 g/cm³; 1.163 g/cm³; 1.03 g/cm³ en 1.145 g/cm³.

5.2.2 Water - mud transition

In the different density profiles, the top of the mud layer can be noticed when the curve starts to deviate, as shown in Figure 50. In the echo sound measurements, the 210 kHz is considered to be the reflected at the water - mud transition. In Figure 61 a relationship is shown between both measurements. On the x-axis is always the 210 kHz measurement and on the y-axis the transition from water to mud, which was determined on the basis of the density profile. In general, it is evident that the most measurements are close to the 1:1 line. However on 17/04 there seems to be a larger deviation for the DensX measurements, albeit that a clear cause could not be detected.

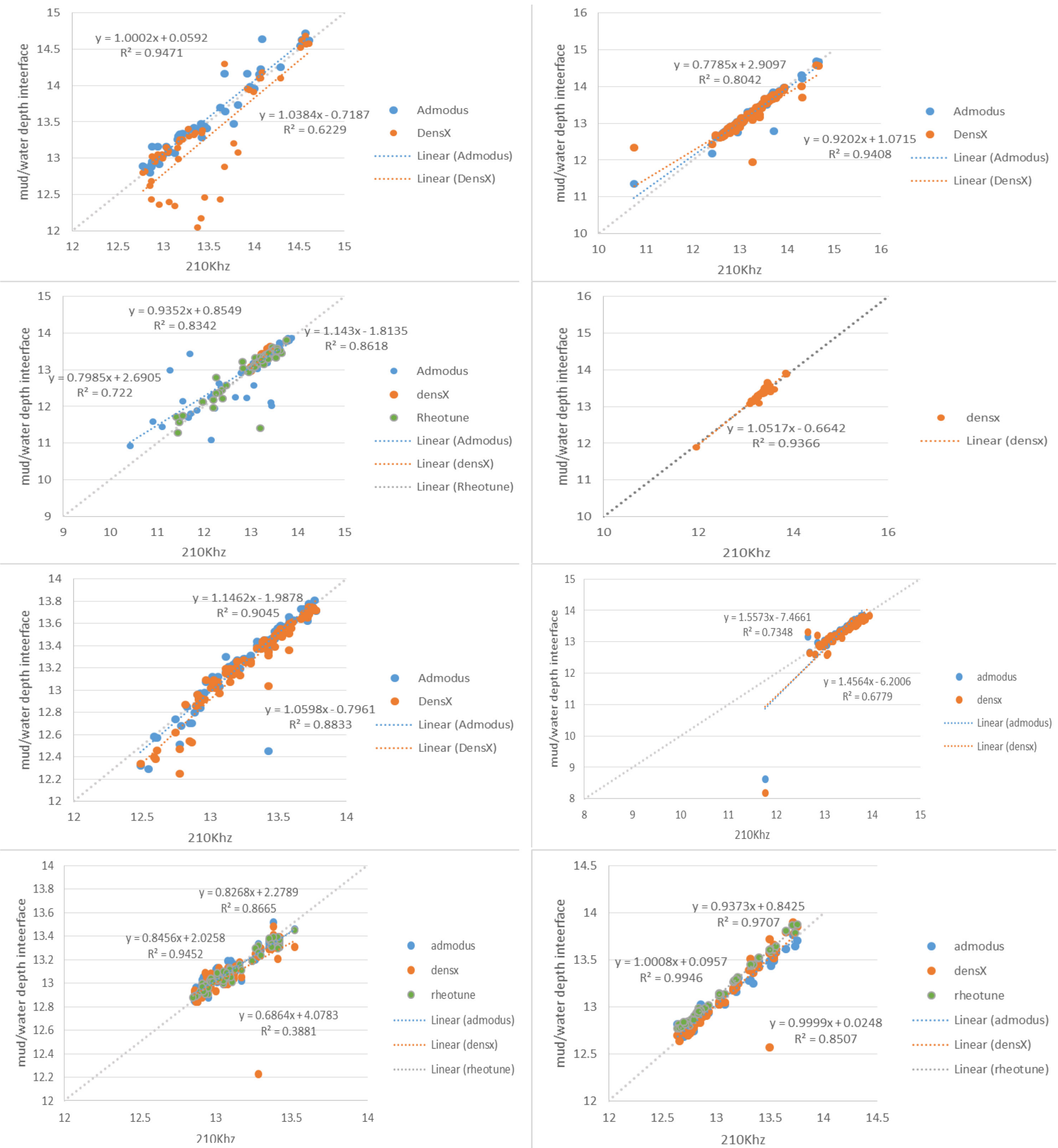


Figure 61 – Relation between the mud - water transition measured with the density measurement devices and the location of the 210 kHz reflection, for each measuring day from left to right. 17/04; 18/04; 23/04; 24/04; 26/04; 27/04; 2/05 en 3/05.

5.2.3 Mud density

The data which was recorded by the three measurement devices during the measurement campaign were examined in detail. The parameters investigated are defined in section 5.1. In the following section, the analysis will focus on the relationship between the parameters of each measurement devices separately.

Admodus

The first parameter examined is the Δ 1.2, which was defined in section 5.1 (Figure 51), and is the absolute difference between the depth measurements of 1.20 g/cm³ for the same measuring location with the same instrument. In Figure 62 the Δ 1.2 (m) parameter is shown for all locations and all measuring days of the campaign, measured with the Admodus. In this figure it can be seen that the difference between two (or more) consecutive measurements can be very large, as well the variation of this difference. No clear locations or days can be distinguished where the variation is significantly smaller. The exception is measurement day 1, 11/05, when the ship was moored at the quay. The maximum deviation measured is approx. 2.2 m. In about 4% of the measuring locations, the difference between two measurements is greater than 1 m, in about 15% of the measurements, the difference is greater than 0.5 m.

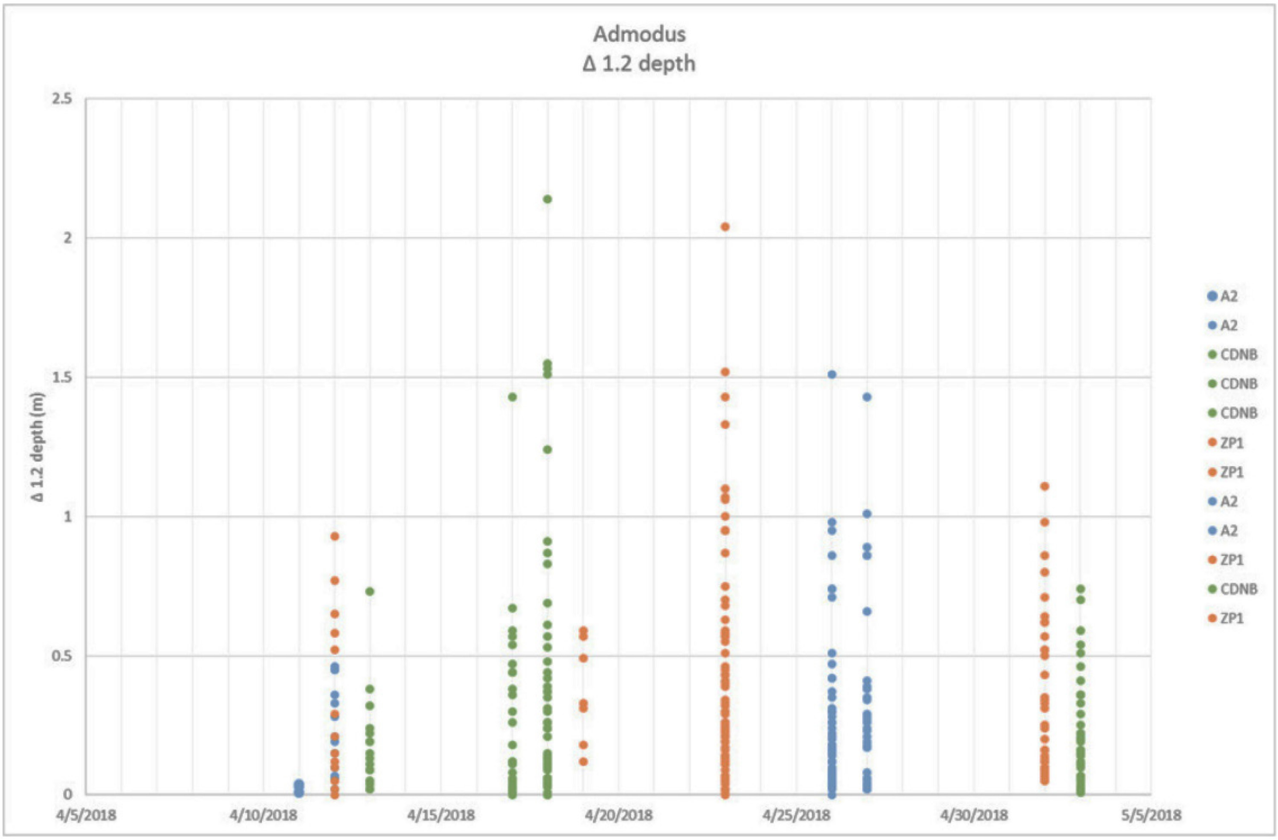


Figure 62 – Δ 1.2 for all measurement locations and measurement days of the measurement campaign measured with the Admodus USP.

In Figure 63 a number of examples of profiles are shown in which the depth difference of the 1.20 g/cm³ boundary between the two repetitions is larger than 0.8 m. Various causes for the differences can be derived. In example 1 and 3 clear differences can be observed, which are caused by the sudden jump of the density values, shortly after the measurement instrument has penetrated into the mud. After this, the density values decrease and the two curves are very similar. The position where the curve intersects with the 1.20 g/cm³ for the second time, however, is very similar between the two curves. In example 4, the depth at which the density starts to deviate is clearly different, and so is the result. This is due to the location of the measuring point, close to a slope, and the slight shift in position of the measuring vessel. For the selection of the correct (most representative) profile, the depth measurement with the 210 kHz can be used here, depending on the knowledge of the terrain of the operator/worker. In examples 5, 6 and also 2, no clear fault profile can be distinguished. Both curves show a logical course, but still result in a large difference in the measured location of the 1.2 g/cm³, of > 0.8 m. Examples 5 and 6 are profiles in ZP1, where dredge marks remain more present. This could be a cause of the deviation at higher densities, and consequently the position of the 1.20 g/cm³ depth.

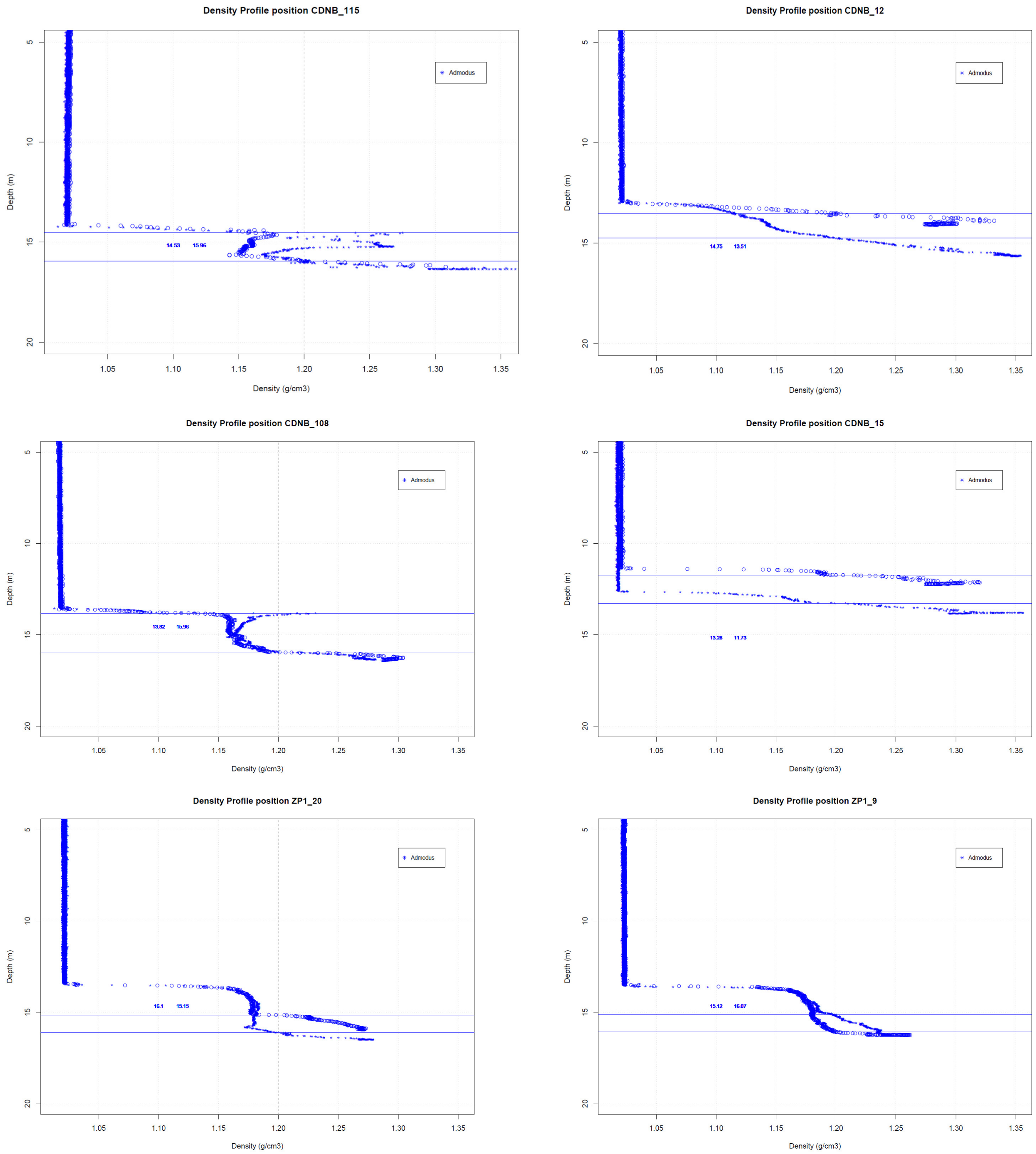


Figure 63 – Examples of measurements with the Admodus, where Δ 1.2 (m) is greater than 0.8 m.

In addition to this general description of the measurements, the geographical distribution of the measurements was also examined. For this purpose, a number of measuring points ("transects") were selected in the different regions in which measurements were performed. An overview of the transects is shown in Figure 64. Measurements were taken in Albert II dock, on 26 and 27 April (Figure 64 top, left and right respectively), in CDNB (Figure 64, bottom left) on 3/05/2018 and ZP1 (Figure 64, bottom right) on 2/05/2018.

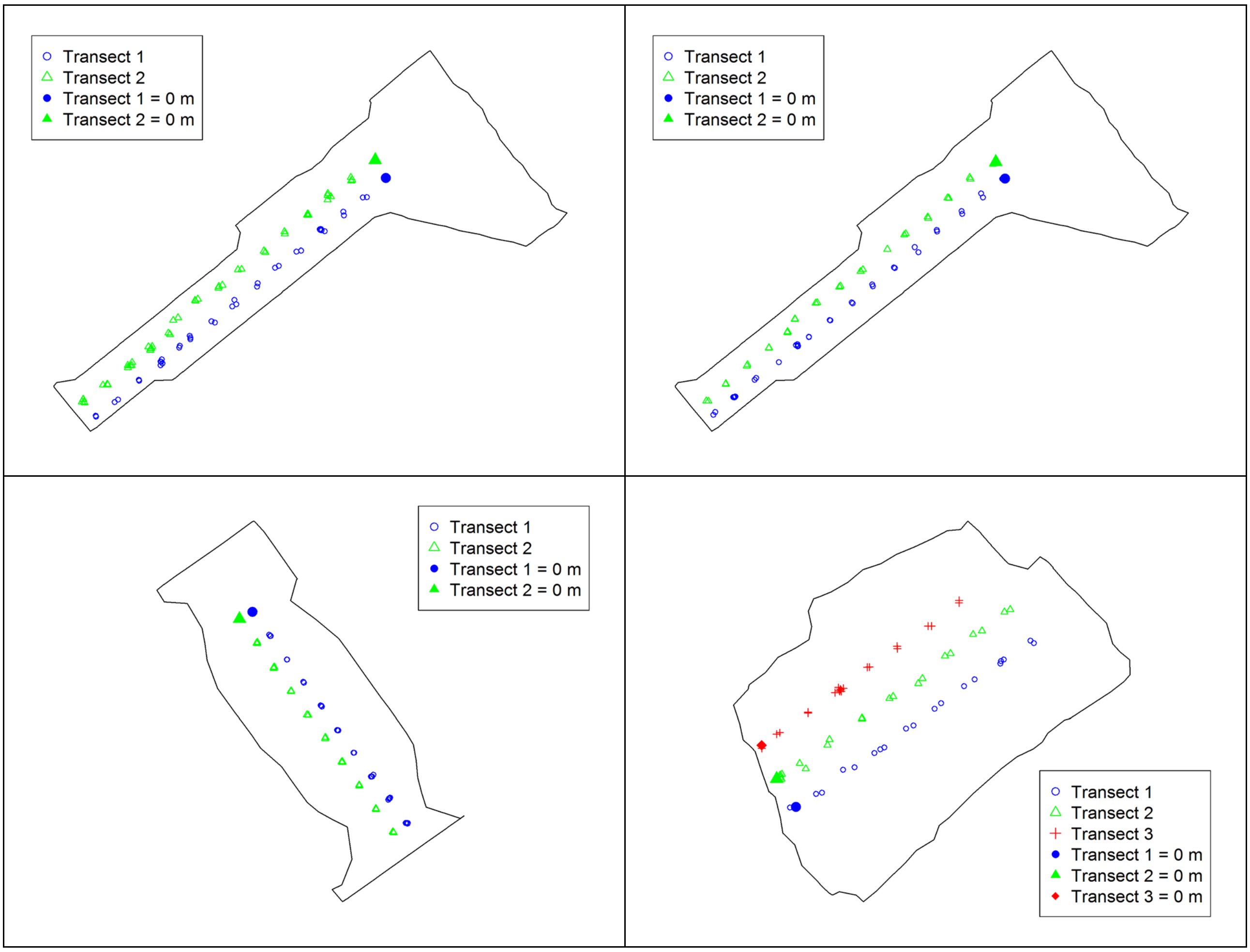


Figure 64 – Overview of the examined transects, with the exact location of the measuring points for the Admodus.
Above are the measurements in A2 dock on 26 and 27/04 (left and right)
and below left CDNB (3/05) and below right ZP1 (2/05)

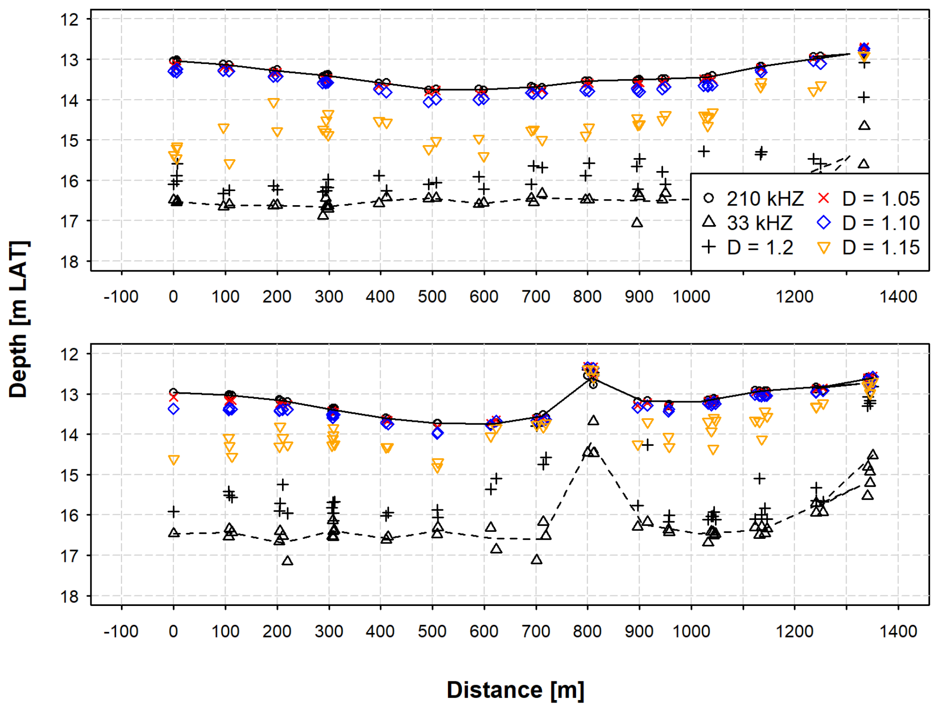


Figure 65 – Course of 33 and 210 kHz and densities 1.05; 1.10; 1.15;1.20 along two transects in A2 dock (see Figure 64) on 26/04/2018 measured with the Admodus

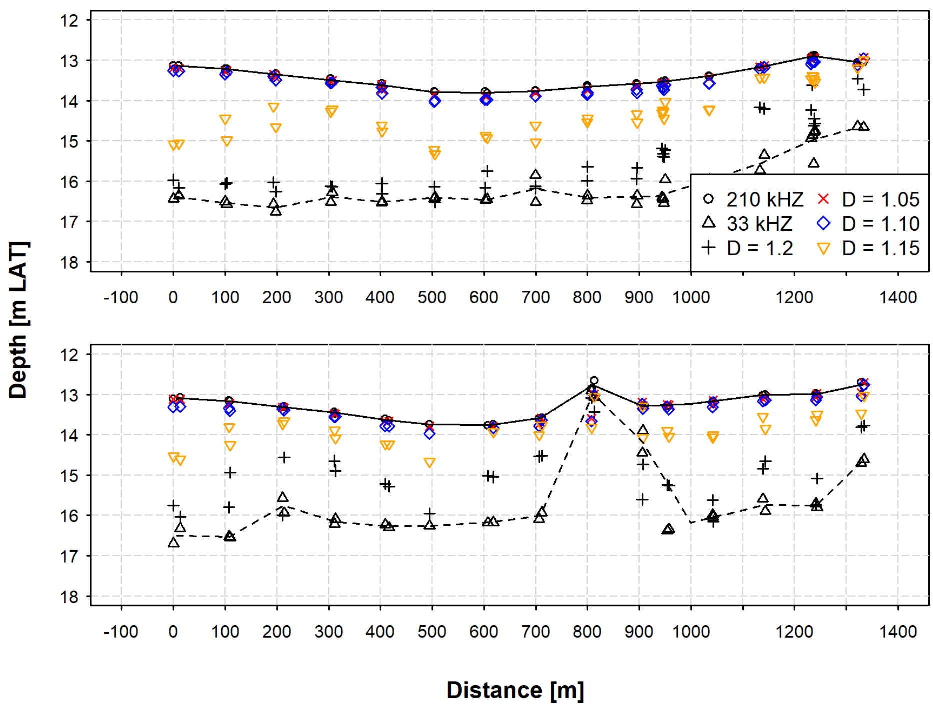


Figure 66 – Course of 33 and 210 kHz and densities 1.05; 1.10; 1.15;1.20 along two transects in A2 dock (see Figure 64) on 27/04/2018 measured with the Admodus

Figure 65 and Figure 66 show the Admodus measurements in the transects of the A2. It is evident that there is one measurement that strongly deviates from the other measurements in transect 2, this measurement corresponds to the place where the dock becomes slightly narrower (northern part with sandy slope) and there is a more gradual transition to the deep parts (see Appendix, Figure 87). The average difference, along respectively path (transect) 1 and 2, between the 210 kHz measurements is respectively 0.02 and 0.05 m (the maximum difference is respectively 8 and 29 cm, the minimum 0 cm). For the 33 kHz measurements the differences are larger, with an average deviation of 0.18 m and 0.29 m (with maximum differences of 0.81 m and 0.95 m). For the Δ1.2, the average difference is 0.26 m for both transects, with maximum differences of about 0.98 m and 1.51 m. Similar differences are measured on the same transects, but on 27/04/2018. A summary is shown in Table 16.

Table 16 – Summary of mean, maximum and minimum differences for transects 1 and 2 at Albert II Dock measured on 26/04 and 27/04

	day	210 kHz			33 kHz			Δ1,2		
		Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.
T1	26/04	0.03	0.08	0.00	0.18	0.95	0.01	0.26	0.98	0.03
	27/04	0.02	0.07	0.00	0.28	0.81	0.01	0.22	1.01	0.02
T2	26/04	0.06	0.29	0.00	0.29	0.95	0.02	0.27	1.51	0.02
	27/04	0.17	1.43	0.00	0.17	0.59	0.01	0.88	1.43	0.02

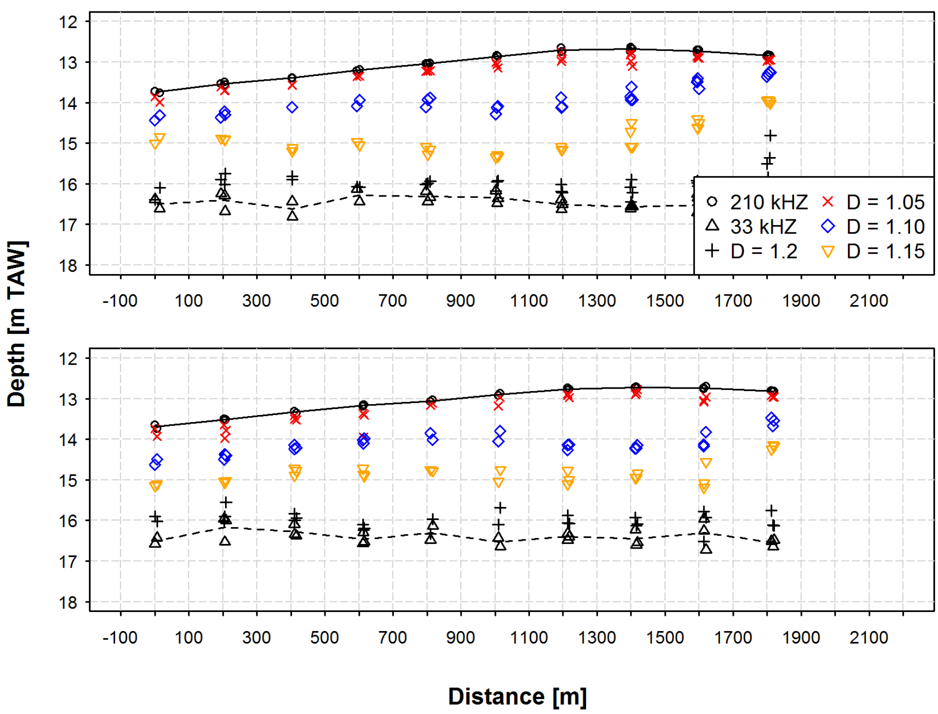


Figure 67 – Course of 33 and 210 kHz and densities 1.05; 1.10; 1.15;1.20 along two transects in CDNB (see Figure 64) on 03/05/2018 measured with the Admodus

Figure 67 shows the location of different mud densities in CDNB, including the 210 and 33 kHz measurements. The structure of the mud layer in this region appears to be consistent across the various measurements. The average difference for the 210 measurements is here 0.04 and 0.03 m respectively, for the 33 kHz the differences are slightly larger around 0.22 m and 0.2 m. The course of the measurements is consistent along the whole transect. There is much more variation in the shape of the different density profiles in ZP1 (see Figure 68), but the repetition of the different measurements seems to be relatively consistent. The geographical distance between the different measurements (repetitions) is larger, as can be seen in Figure 64 (bottom right).

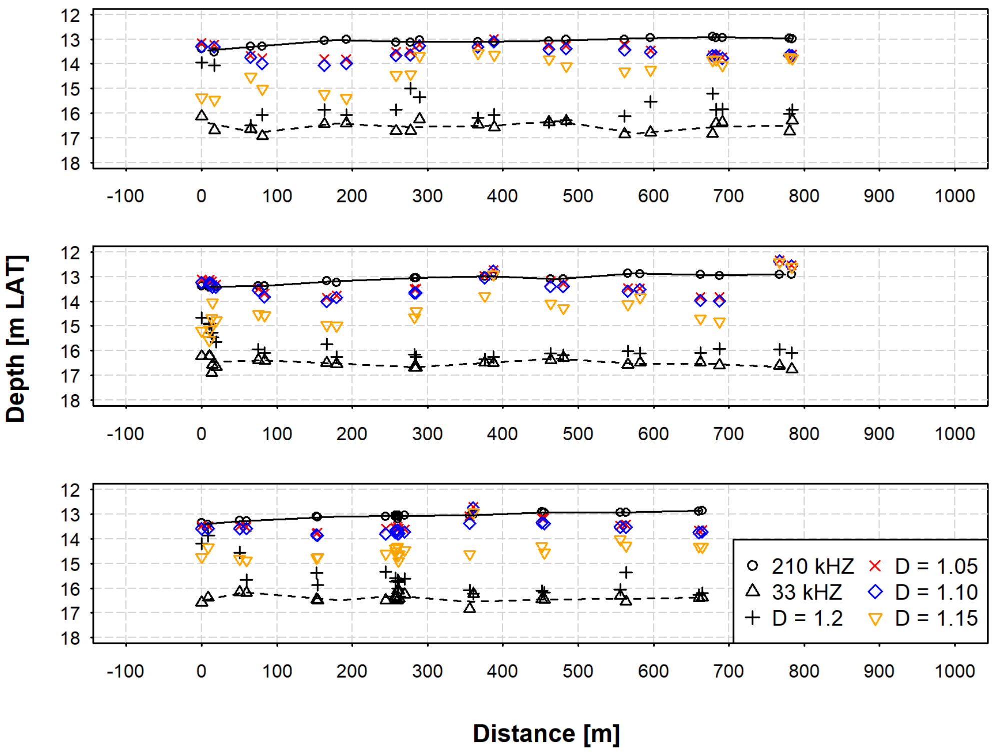


Figure 68 – Course of 33 and 210 kHz and densities 1.05; 1.10; 1.15;1.20 along three transects in ZP1 (see Figure 64) on 02/05/2018 measured with the Admodus

DensX

Figure 69 shows the Δ 1.2 (m) parameter for all locations and all measuring days of the campaign, measured with the DensX device. The maximum measured deviation between two repetitions is approx. 2.2 m. In about 3% of the measuring locations the difference in the 1.2 position is greater than 1 m, in about 13% of the measurements the difference is greater than 0.5 m.

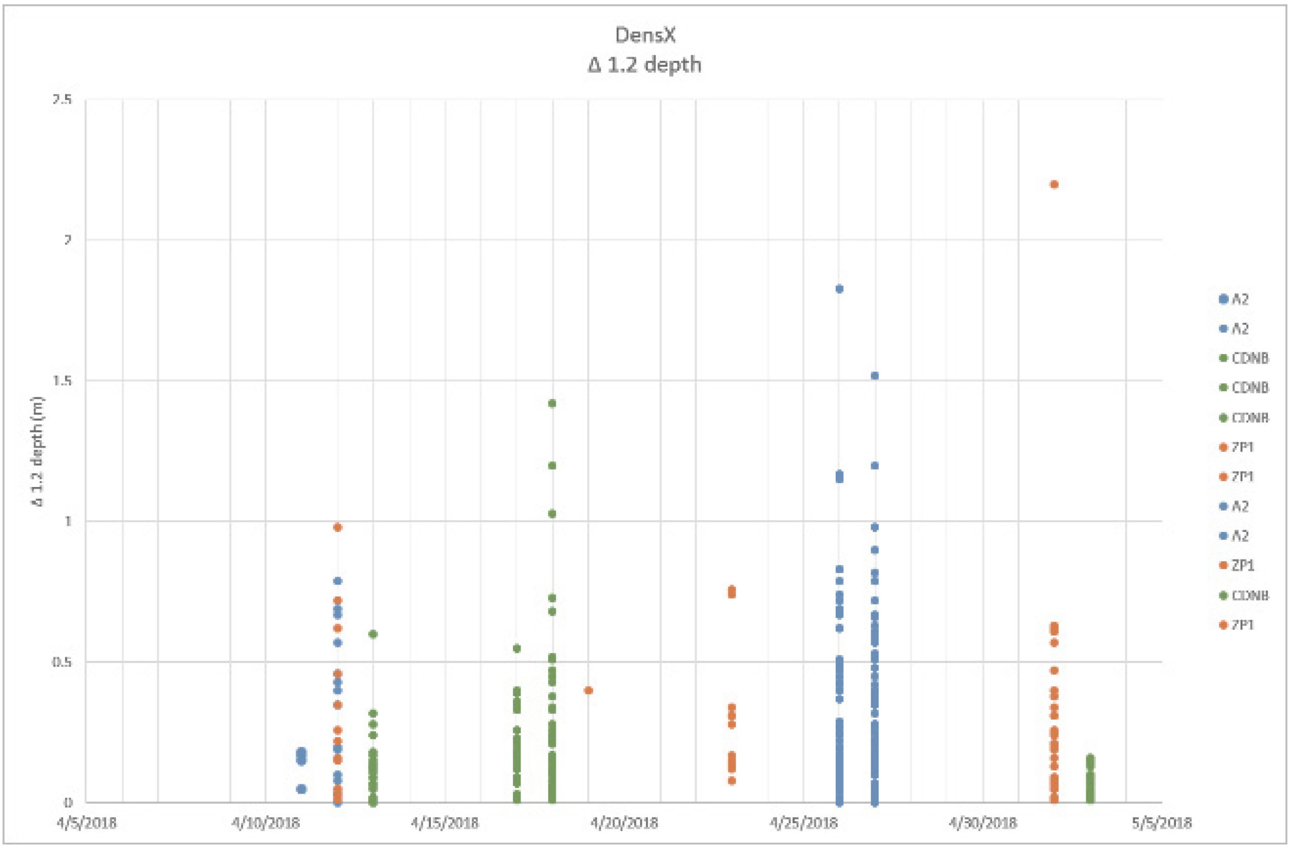


Figure 69 – Δ 1.2 for all measurement locations and measurement days of the measurement campaign measured with the DensX.

Figure 70 shows a number of examples of profiles, measured with the DensX, in which the depth difference between the two measured 1.20 g/cm³ depths is greater than 0.8 m. A number of different causes for the differences can be presented. In examples 1 and 2, the deviation of the densities is evident at a different height. This is probably due to measurements near a slope and slight displacement of the measuring vessel during the measurement. For the selection of the right (most representative) profile, the depth measurement with the 210 kHz can be used here, depending on the field knowledge of the operator/worker. In example 3 and 4, the measured water density is clearly different for the different profiles. The resulting depth of the 1.2 density is also very different. In examples 5 and 6, the measured curves of the different profiles are realistic. However, the measurement of the 1.2 depth is highly variable. For the measurement in ZP1 (example 6) the measurement can be influenced by dredging marks in this zone.

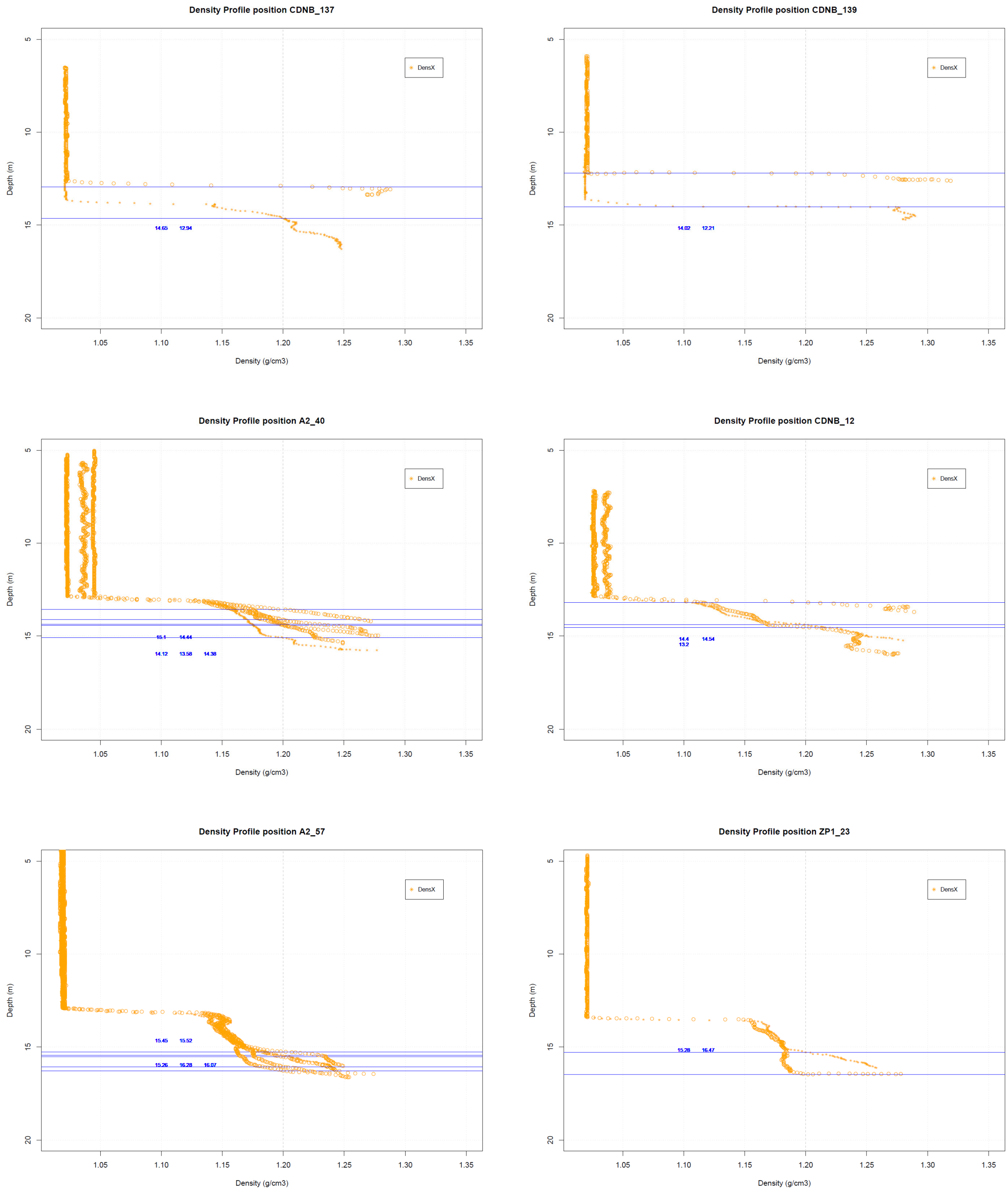


Figure 70 – Examples of measurements with the DensX, where Δ 1,2 (m) is greater than 0.8 m.

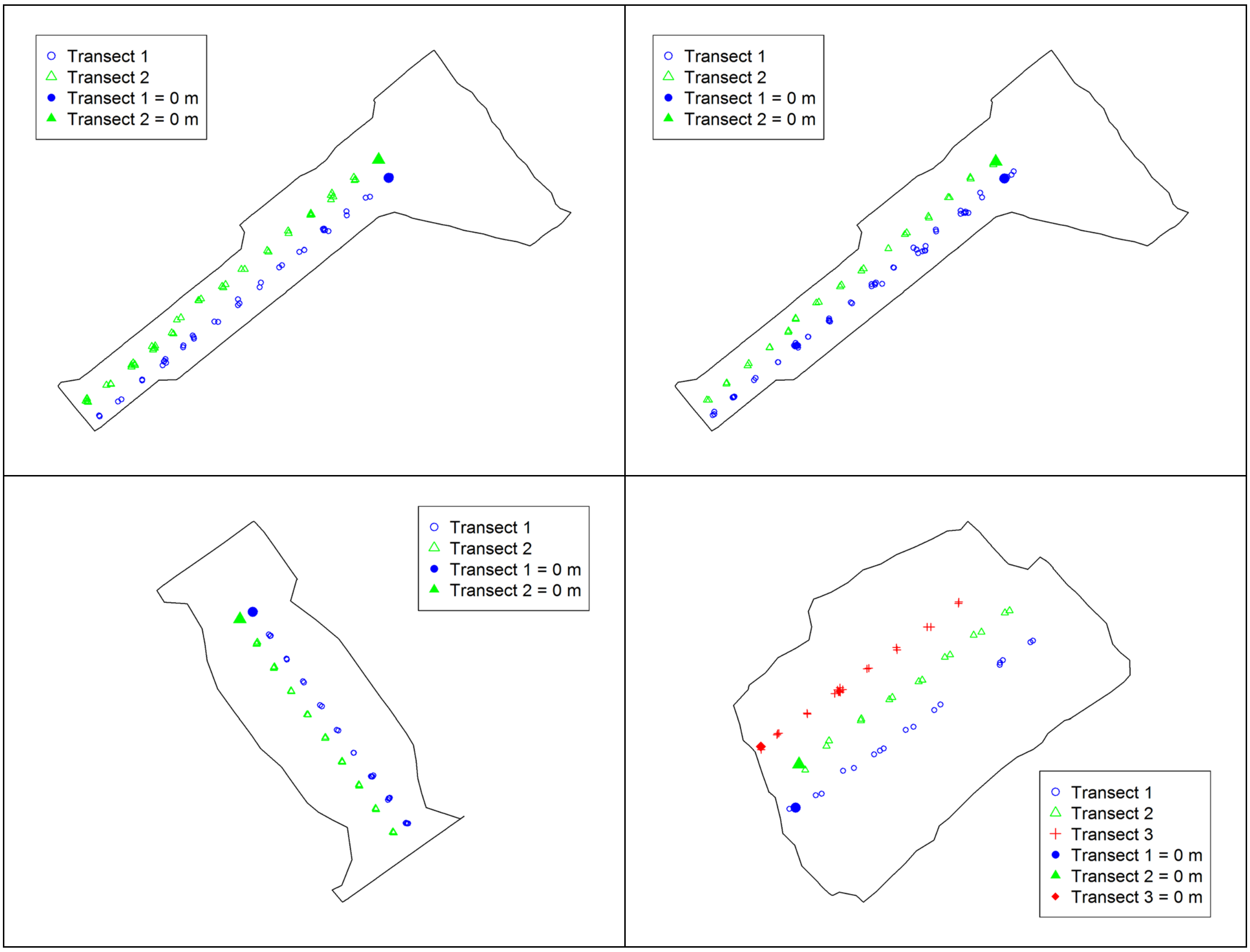


Figure 71 – Overview of the examined transects, with the exact location of the measuring points for the DensX. Above are the measurements in A2 on 26 and 27/04 (left and right) and below left CDNB and right ZP1

Figure 72 and Figure 73 show the measurements with the DensX in the transects of the A2 dock. Also here it is evident that there is one measurement that strongly deviates from the other measurements in transect 2, this measurement corresponds to the place where the dock becomes slightly narrower and there is a more gradual transition to the deep parts (see Appendix, Figure 87). The average difference, along respectively transect 1 and 2, between the 210 kHz measurements is respectively 0.03 and 0.05 m (the maximum difference is respectively 8 and 29 cm, the minimum 0 cm). For the 33 kHz measurements the differences are larger, with an average deviation of 0.18 m and 0.29 m (with maximum differences of 0.81 m and 0.95 m). For the Δ1,2 the average difference is 0.33 and 0.37 m for both transects, with a maximum difference of about 1.17 m and 1.83 m. Similar differences are measured on the same transects, but on 27/04/2018.

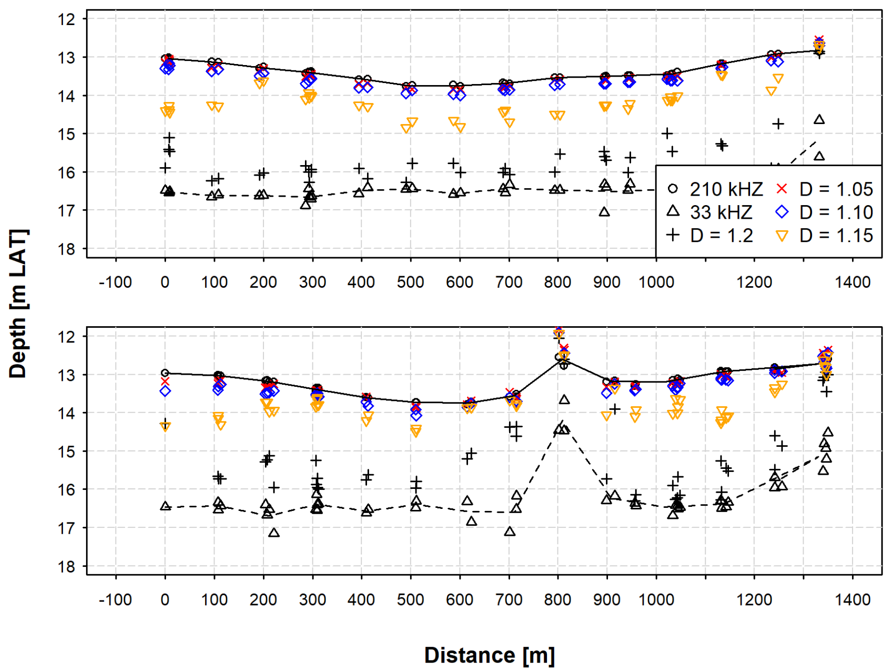


Figure 72 – Course of the 33 and 210 kHZ and densities 1.05; 1.10; 1.15;1.20 along two transects in A2 dock (see Figure 64) on 26/04/2018, measured with the DensX

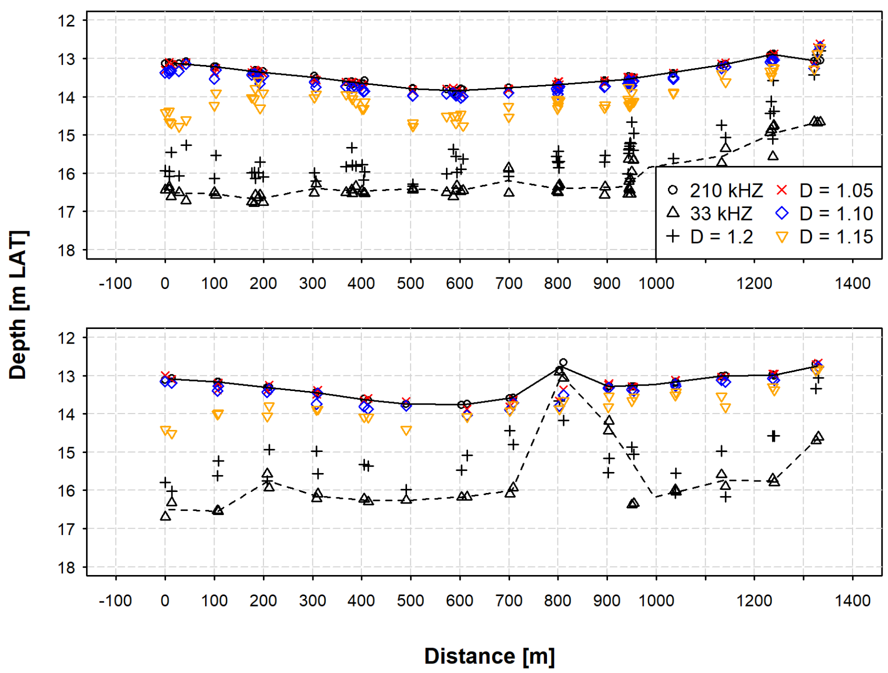


Figure 73 – Course of the 33 and 210 kHZ and densities 1.05; 1.10; 1.15;1.20 along two transects in A2 dock (see Figure 64) on 27/04/2018, measured with the DensX

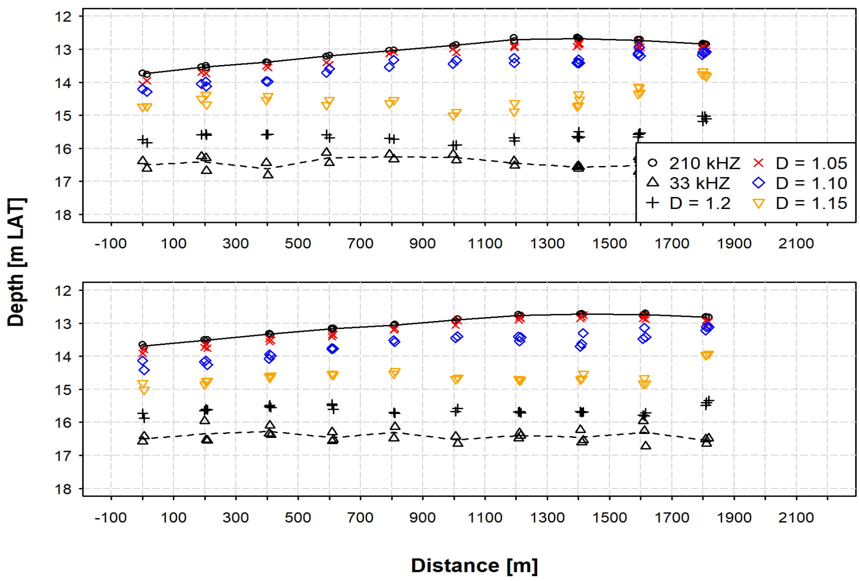


Figure 74 – Course of the 33 and 210 kHz and densities 1.05; 1.10; 1.15;1.20 along two transects in CDNB (see Figure 64) on 03/05/2018, measured with the DensX

Figure 74 shows the position of different mud densities in CDNB, including the 210 and 33 kHz measurements. The structure of the mud layer in this region seems consistent across the different measurements. The average difference for the 210 kHz measurements here is 0.03 m, for the 33 kHz the differences are slightly larger around 0.29 m and 0.2 m. The Δ1.2 is 0.05 and 0.06 m respectively, with a maximum of around 0.15 m for each transect. This is smaller than the variation within the Admodus measurements (approx. 0.20 and 0.25 m). The course of the measurements is consistent along the whole transect. The composition of the different density profiles in ZP1 (see Figure 75) shows much more variation, but the repetition of the different measurements seems to be relatively well in agreement.

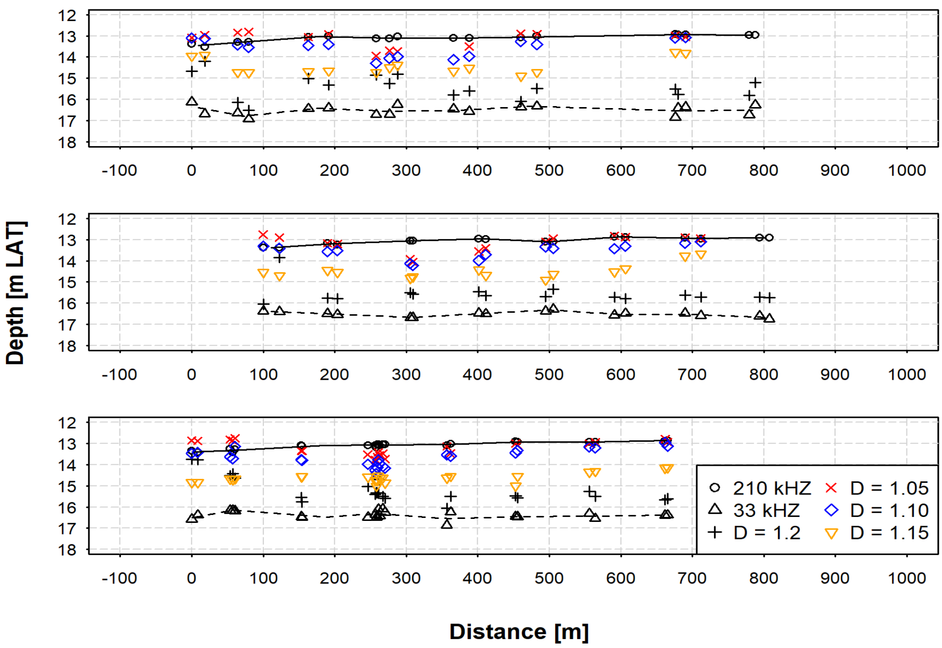


Figure 75 – Course of the 33 and 210 kHZ and densities 1.05; 1.10; 1.15;1.20 along three transects in ZP1 (see Figure 64) on 02/05/2018, measured with the DensX

Rheotune

The first parameter examined is the Δ 1.2, which has already been defined in section 5.1, and is the absolute difference between the depth measurements of 1.2 g/cm³ for the same measuring point with the same measurement instrument. Figure 76 shows the Δ 1.2 (m) parameter for all locations and all measuring days of the campaign with the Rheotune of Flemish Hydrography. In addition, Figure 77 shows the Δ 1.2 for the measurements performed by GeoXYZ. The maximum differences in Figure 76 and Figure 77, respectively measurements, are approx. 2.4 m and 2.1 m. In 12% of the measurement locations the difference between the 1.2 location is larger than 0.5 m, in 9% larger than 1 m. For the measurements of GeoXYZ this is respectively 13% and 10%. In Figure 76 it is evident that the measurements in ZP1 show a larger deviation than the measurements in CDNB.

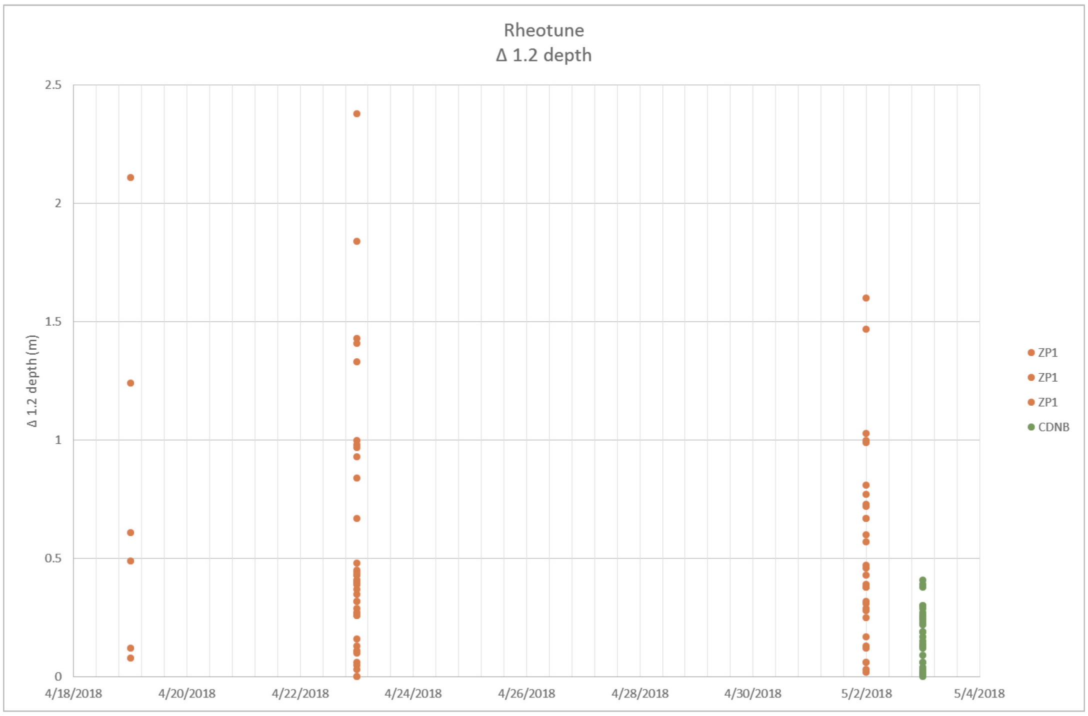


Figure 76 – Δ 1.2 for all measurement locations and measurement days of the measurement campaign, measured with the Rheotune

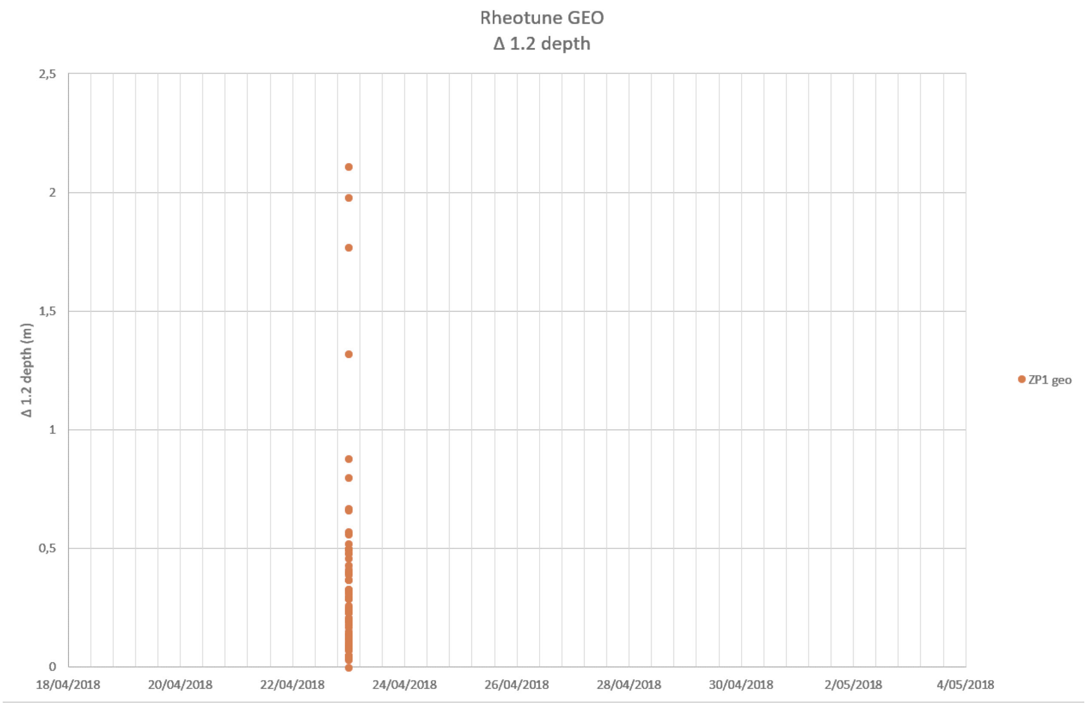


Figure 77 – Δ 1.2 measured by GeoXYZ, with a Rheotune

A number of examples of profiles are shown where the depth difference between the two measured 1.2 values is greater than 0.8 m. These profiles were measured using the Rheotune of Flemish Hydrography. In example 1, the water density between the profiles is very different. The measured depth for the 1.20 g/cm³ also differs strongly for the different measurements, the shift in the measured values in the water column seems to continue in the mud layer. In the other examples, the differences in the 1.2 depths are also large. In general, no clearly incorrect profiles can be found here, although there are several profiles that show a decrease in density with depth. Many profiles have a constant density up to approx. 1.18 g/cm³, after which the density starts to increase strongly (sometimes to higher as well as lower densities), as can be seen for example in examples 2, 3 and 5.

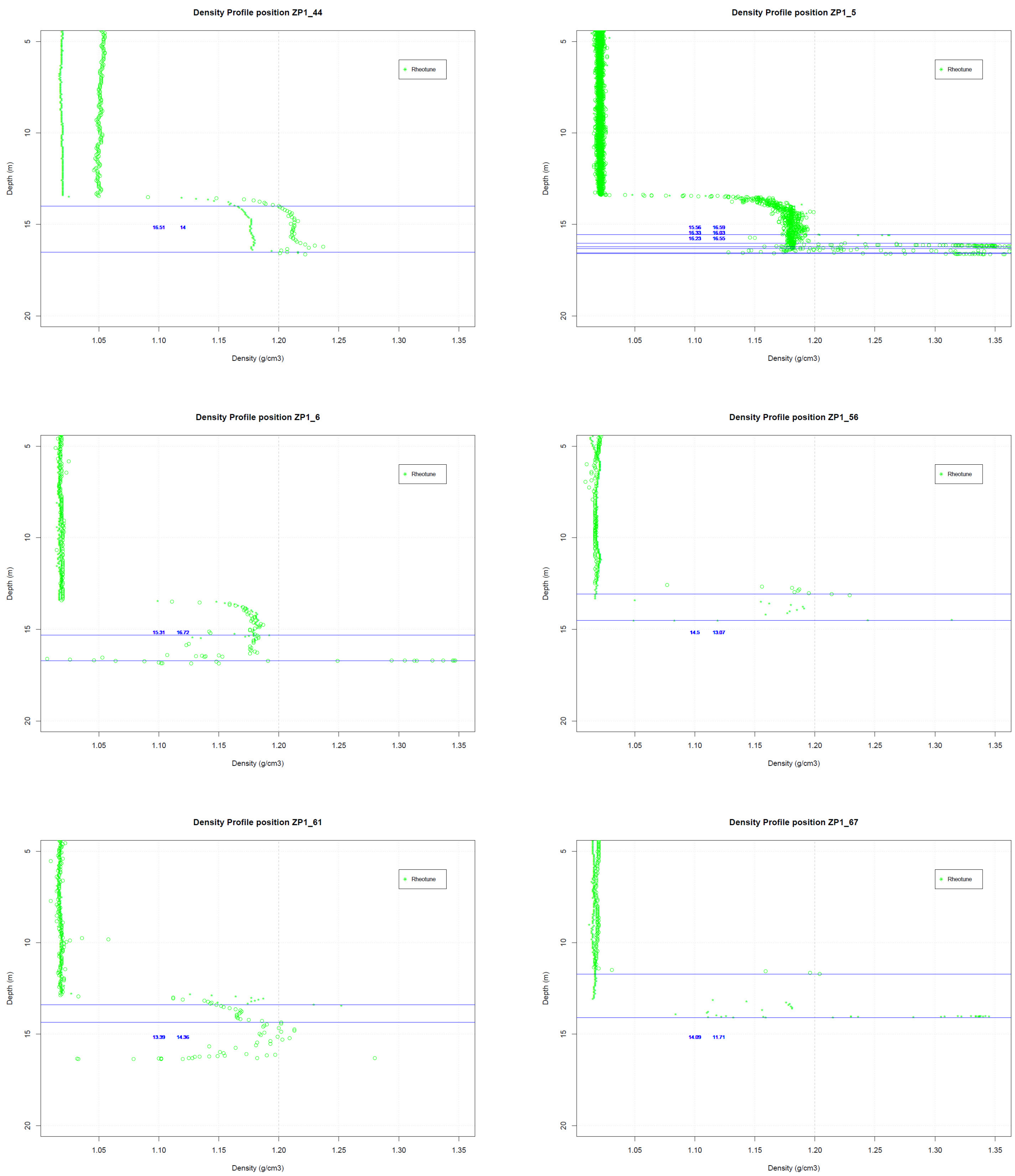


Figure 78 – Examples of measurements with the Rheotune, measured by Flemish Hydrography, where Δ 1.2 (m) is greater than 0.8 m.

Figure 79 shows a number of examples of profiles in which the depth difference between the two measured 1.2 values is greater than 0.8 m. These profiles were measured by GeoXYZ using a Rheotune. In examples 1, 2 and 3, the measured water densities are very different for the measured profiles. The measured depth for the 1.2 also differs strongly for the different measurements, despite the fact that the shape of the curves of the repetitions is similar. By shifting the curves to the left, with a density equal to the difference in water density, the curves seem to agree better and the depth measurement of the 1.20 g/cm³ value also agrees more. In example 4 there is a direct deviation of one profile, which is not necessarily a wrong measurement. In examples 5 and 6, the density of one of the two profiles does not seem to increase with depth (in one case it even decreases), and in the end a very large deviation (outlier) of the density can be observed.

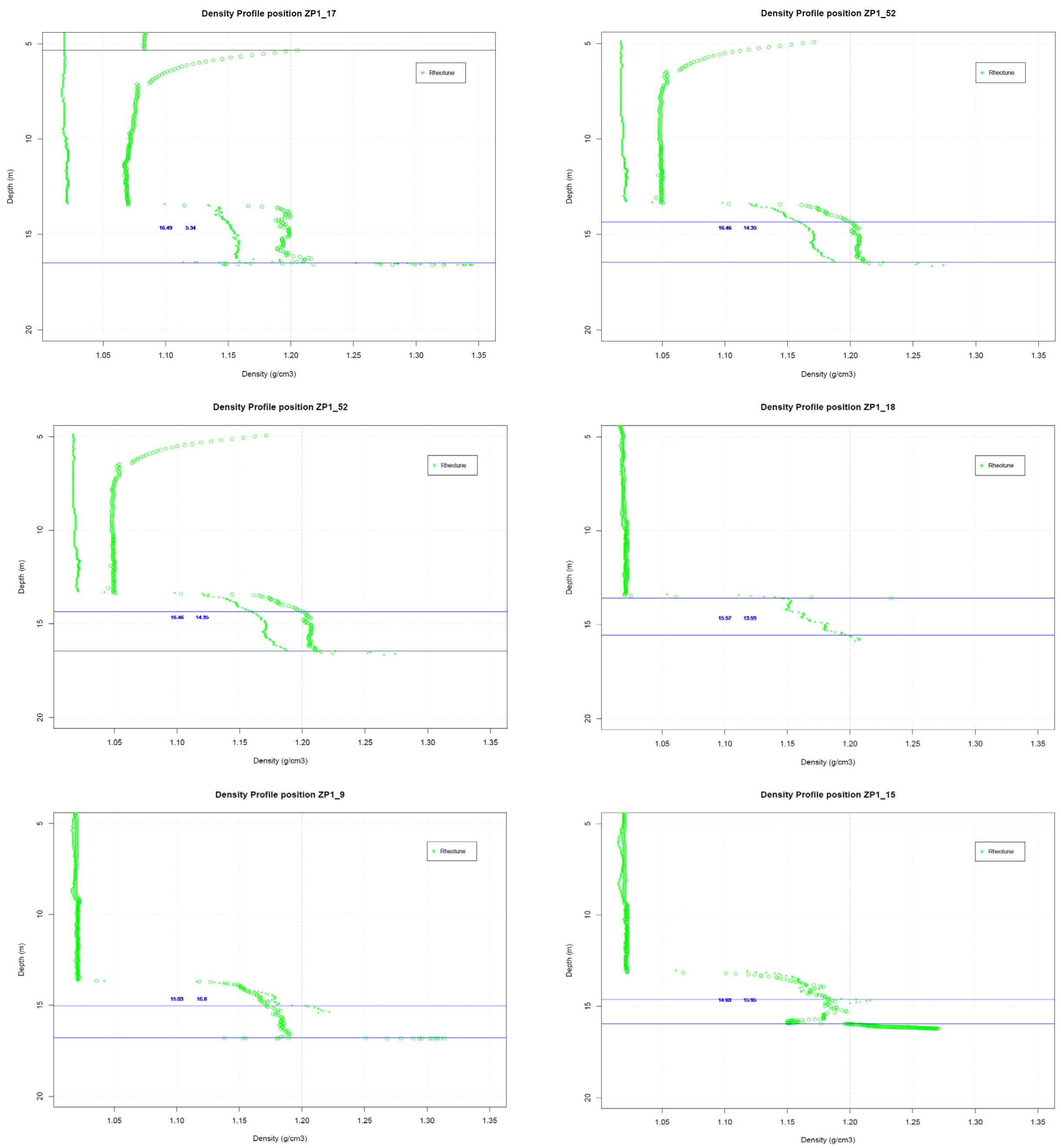


Figure 79 – Examples of measurements with the Rheotune, measured by GeoXYZ, where Δ 1.2 (m) is greater than 0.8 m.

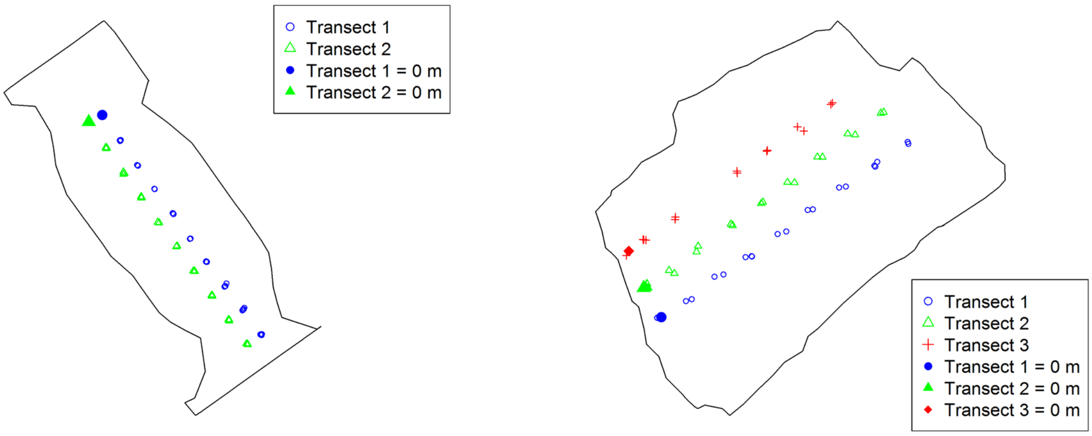


Figure 80 – Overview of the examined transects, with the exact location of the measurement points for the Rheotune. On the left are the measurements in CDNB (03/05/2018), on the right in ZP1 (02/05/2018).

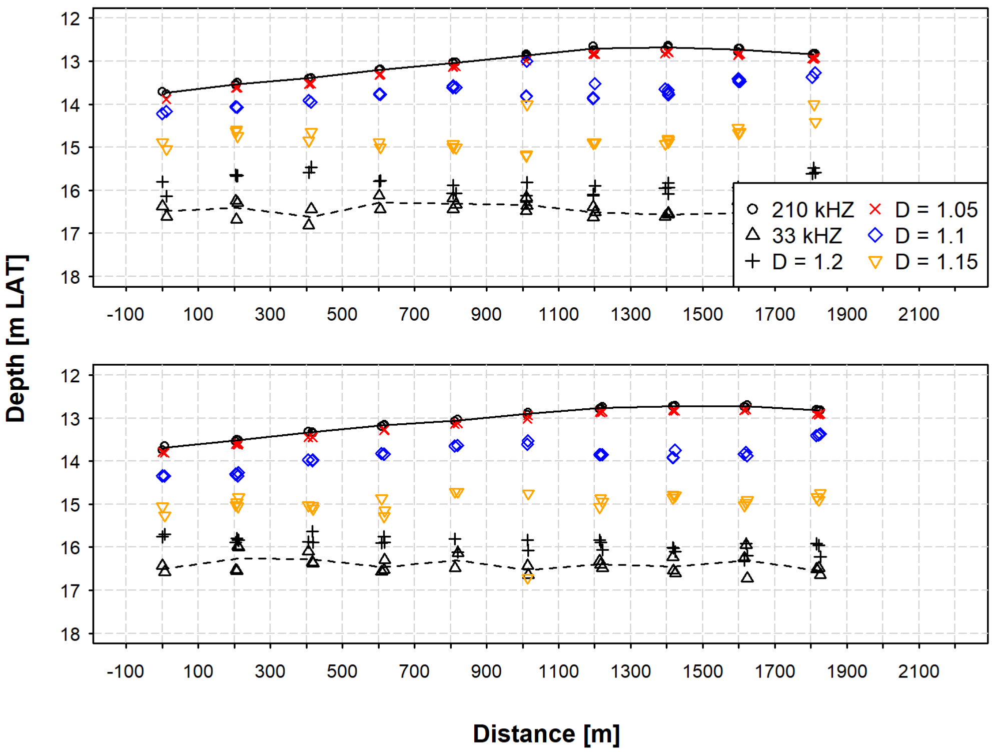


Figure 81 – Course of the 33 and 210 kHz and densities 1.05; 1.10; 1.15;1.20 along two transects in CDNB (see Figure 64) on 03/05/2018, measured with the Rheotune

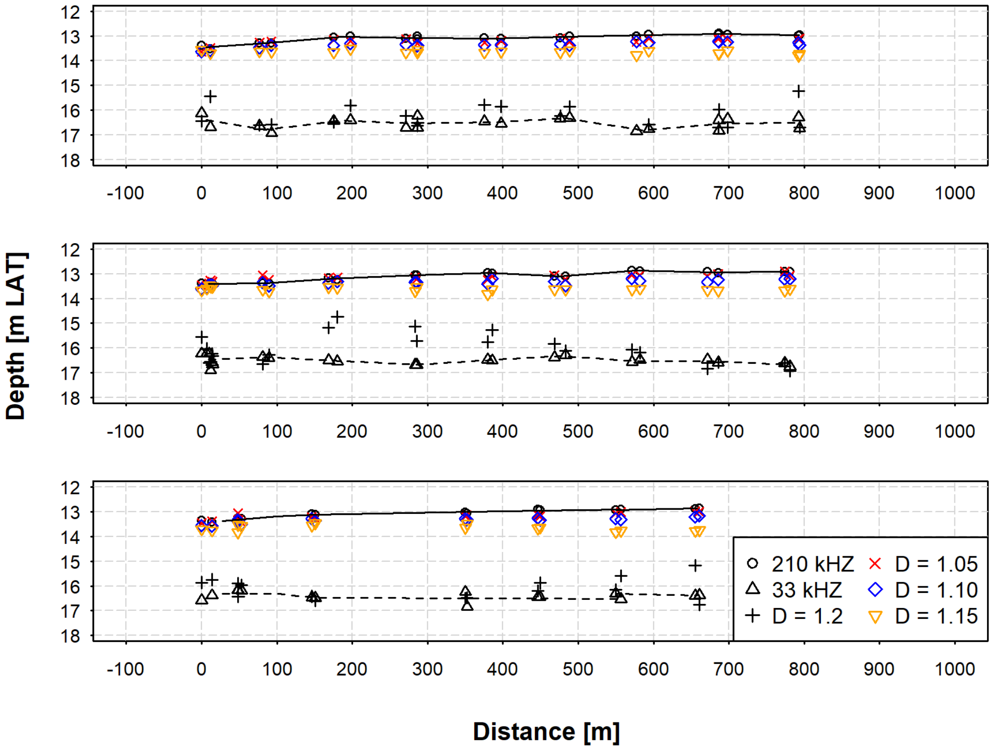


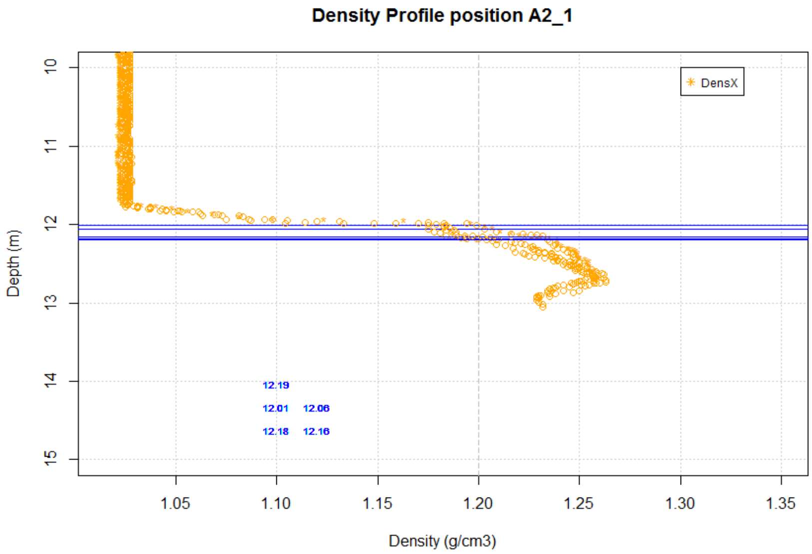
Figure 82 – Course of 33 and 210 kHz and densities 1.05; 1.10; 1.15;1.20 along three transects in ZP1 (see Figure 64) on 02/05/2018 measured with the Rheotune

Figure 81 shows the position of different mud densities in CDNB, with also the measurements of the 210 and 33 kHz. The structure of the mud layer in this region appears to be consistent across the various measurements. The average difference for the 210 kHz measurements is 0.03 m, for the 33 kHz the differences are slightly larger around 0.28 m and 0.20 m. The average difference in the location of the 1.20 g/cm³ is 0.17 and 0.16 m, the maximum differences around 0.40 m. The course of the measurements is consistent along the whole transect. The composition of the different density profiles in ZP1, see Figure 82, is very constant, but the pattern is different from those measured with the other measurement instruments. The average values for Δ1,2 are 0.52 m, 0.35 m and 0.72 m for the different transects respectively.

5.3 Comparison between the measurement instruments

Because an absolute comparison of the measurements is not possible, due to the fact that there was no reference value (no samples were collected during the measurement campaign), this report mainly focuses on the repeatability of the measurements with one particular device.

Figure 83 shows density profiles of a measurement, with the ship moored at the quay, with the DensX and Admodus. For each device five repetitions have been measured. The depth of the 1.20 g/cm³ density, measured with the DensX, lies between 12.01 m TAW and 12.19 m TAW. The Admodus measurements are between 11.89 m TAW and 11.96 m TAW. The Δ1.2 therefore varies between 0.01 and 0.04 m for the Admodus. The Δ1.2 varies between 0.05 and 0.18 m for these measurements with the DensX. The 1.2 g/cm³ position for the DensX is slightly larger than that for the Admodus. The water density measured with the DensX is 1.023 g/cm3 (± 0.001 g/cm3 between measurements), for the Admodus it is 1.018 g/cm3 (± 0.001 g/cm3).



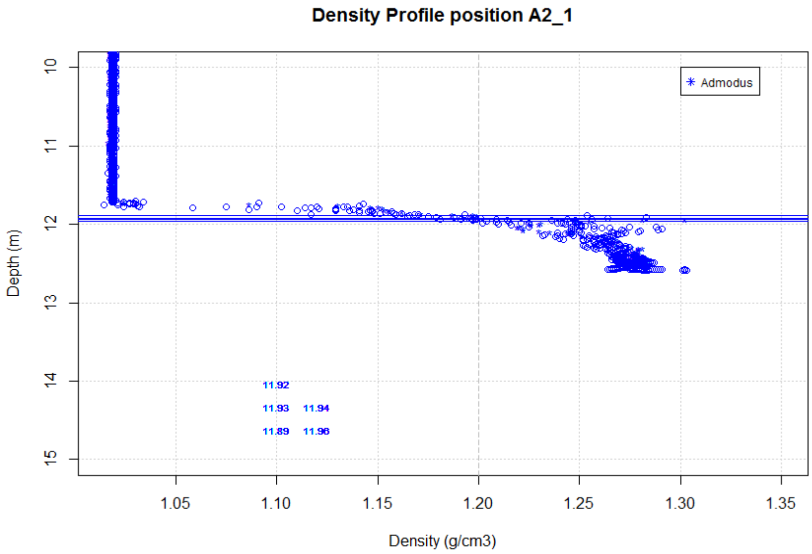


Figure 83 – Density profile measured with the DensX (5 measurements) and the Admodus (5 measurements), with the ship moored at the quay

In the following, additional examples are given of the measurements with the three different instruments together. Some locations were selected. Figure 84 shows the density profile for a location in CDNB (CDNB_58: x= 514276.002; y=5688809.999). This profile was measured three times with each device.

There are a number of measurements, one with the Admodus and one with the DensX that are deviating because the water density along the water column is greater than the actual value of the water density. These two measurements have been removed from the chart and the remaining profiles are shown in Figure 85. A large difference in the depth of the 1.2 g/cm³ is still observed. The largest difference is 0.7 m and this is the difference between the two measurements taken with Admodus and between Admodus and Rheotune.

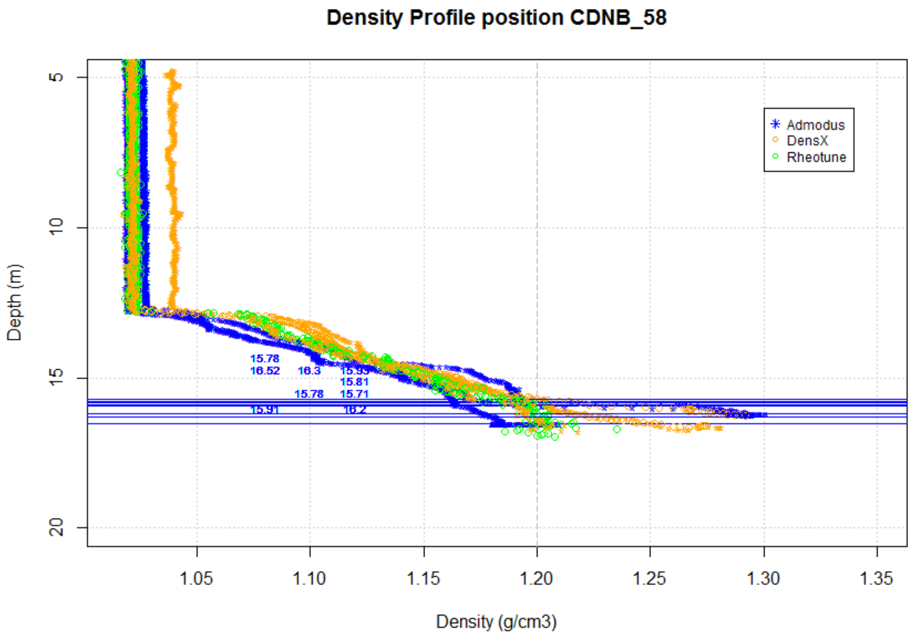


Figure 84 – Density profile measured with the three measurement instruments (position CDNB 58).

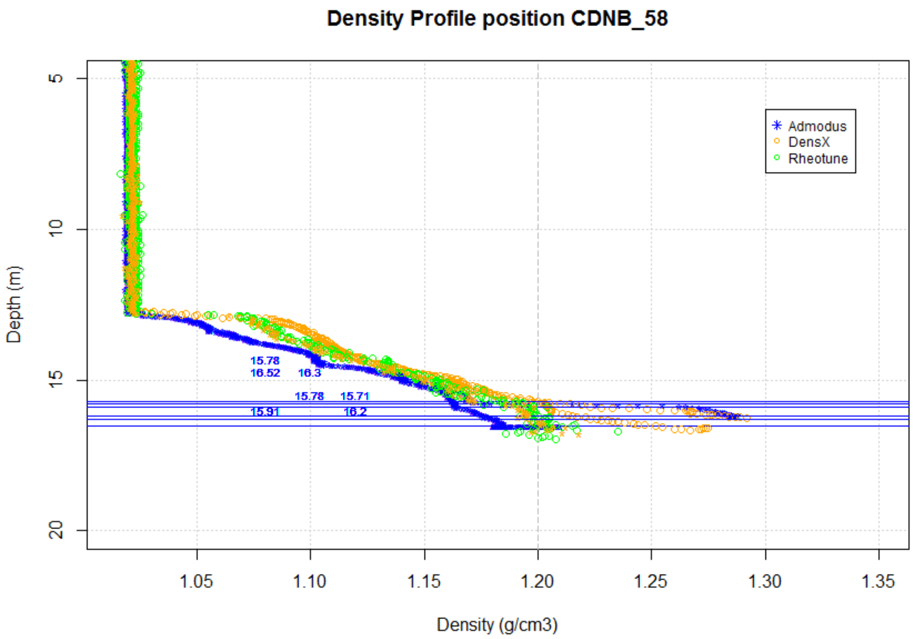


Figure 85 – Density profile measured with the three measuring instruments (position CDNB 58): selection of measuring profiles

Another example is the profile measured on CDNB_62 (X = 514042.998, Y = 5689135.002), the density profile is shown in the figure below. Three measurements are performed with the Admodus and DensX, two measurements with the Rheotune. In this case the profiles measured by the three different devices are more similar to each other and the largest depth difference obtained for the density of 1.20 g/cm³ is only 0.20 m.

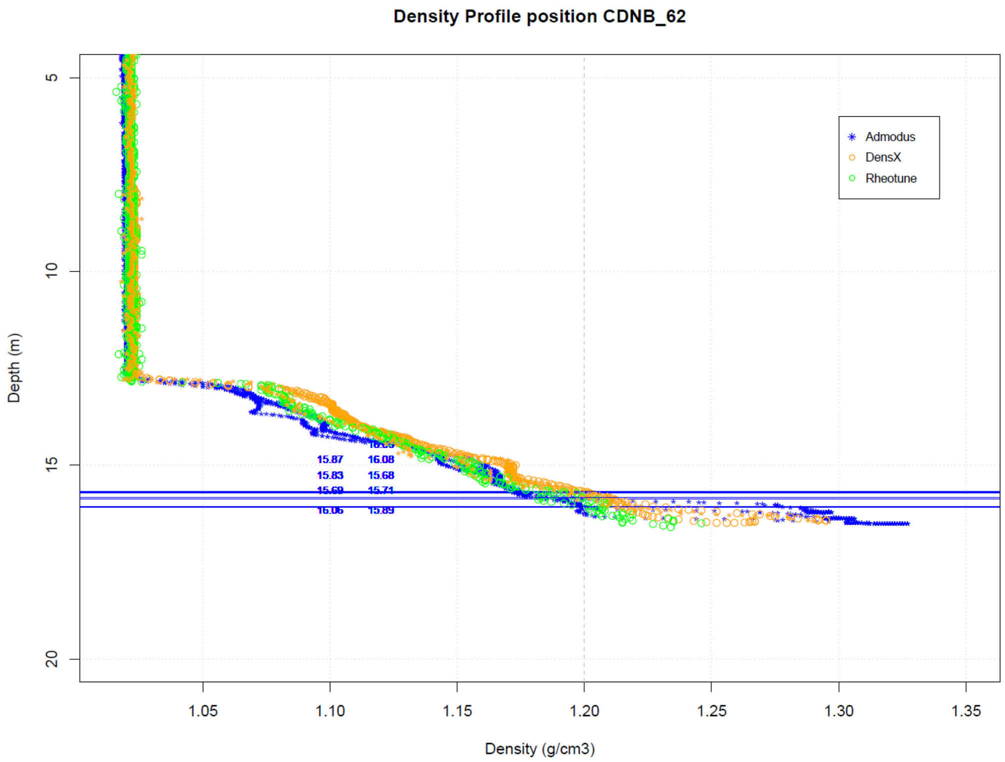


Figure 86 – Density profile measured with the three measuring instruments (position CDNB 62)

6 Conclusions and Recommendations

In this report an overview is given of the operation and use of various measuring instruments purchased by the Department of Mobility and Public Works, Maritime Access division (abbreviation: “aMT”), to measure mud characteristics. In addition, the results of the third measurement campaign are presented, focusing on the measuring instruments suitable to perform density measurements.

In a first part of the report the theoretical basis of several instruments are discussed, in particular the Admodus USP, DensX, Graviprobe, Rheocable, Rheotune and Slibsampler. A theoretical summary of the operation is given in section 2.7, an overview of the practical feasibility in section 4.4.8. The Slibsampler did not give any results so far, as no samples could be retrieved. These samples would also only be useful for comparing density values, as in order to take subsamples the sample tube has to be removed from the slibsampler, which is a cumbersome process. The Rheocable is a very unpractical instrument to work with, almost unworkable in daily practice. Moreover, it is not clear which mud parameter can be measured with it. The Graviprobe is a light device and easy to work with. However, the measurement results cannot be viewed live and the results of the device must be compared with strength measurements of samples under controlled laboratory conditions.

Specifically for the density instruments, all manufacturers emphasise good calibration/adjustment to obtain good and accurate measurements. For the Admodus USP, a number of specific points are mentioned that are important for obtaining good measurements: on the one hand, it is important that the sensor is given some time to adjust to the temperature of the medium and, on the other hand, the sensors must be clean, i.e. free of air bubbles and mud residues. The importance of clean sensors is also emphasised with the Rheotune. With this instrument, mud sticks between the tuning fork after practically every measurement. From a practical point of view, the Admodus and the Rheotune are similar. Both instruments are relatively light and the speed of the measurements during the measuring campaign is similar. This is controlled by the winch speed of the crane/davit. For the DensX, the duration of the measurement itself is not an obstacle, as the speed of the automatic winch is only slightly lower than the winch speed of the davit. However, the start-up of the instrument, in particular the radioactive source, takes a long time. This causes, that the DensX must remain 5 m below the water surface between measurements, and as such during steering the survey vessel. Because there is also an additional safety system on the device whereby the tensile forces must also be limited, it is only possible to move slowly and the manoeuvrability of the survey vessel is limited. This criterion can also cause a problem in case of strong currents.

In this report both own data and data from GeoXYZ were used. No filters or smoothing were applied to our own data, no outliers were removed and all data (profiles) were looked at, without removing certain measurements. Such processing (filtering, outlier removal,..) of the data could probably lead to better results or smaller deviations, but it is important that clear criteria are found for this postprocessing steps, to have a consistent work flow. Also the calculation method to determine the 1.20 g/cm³ depth location, now defined as the first depth where the 1.20 g/cm³ value is exceeded, could be varied to obtain a more robust measurement. In general we can state that the measurements where a large deviation was observed in the 1.2 g/cm³ depth location, could be mainly assigned to the following causes:

a) An aberrant measurement of the water density, which also affects the measurement of the mud layer
b) An unusual depth at which the density increase occurs, due to a displacement of the survey vessel during the measurements itself
c) Outliers in the density measurements, after reaching the mud layer, after which the density value falls back to a smaller value and then (gradually) increases again with increasing depth (examples 1 and 3 Admodus, Figure 63)

d) Sudden outliers in density after constant density measurement (examples 3 and 4 at Rheotune, Figure 78)
e) Conversion of rheological parameters to density

For cases a and b, an incorrect measurement can easily be detected, either by using the known water density or by using the 210 kHz measurement. In the other cases, and also in cases where 2 "visual" normal density profiles are measured, it is more difficult to observe such errors directly during the measurement. Therefore, even in case of operational measurements, it seems appropriate to always measure a location twice, so that an idea of the accuracy of the measurement is obtained.

Both for the validation in laboratory conditions as for the measurements in situ, the measurements with the Rheotune seem to imply larger fluctuations. In the validation measurements in the lab, deviations up to 0.07 g/cm³ were measured for one sample. Especially at higher densities, the deviations in the measurements increase. In-situ the difference in the position of the 1.2 g/cm³ is larger than 1 m in approx. 10 % of the cases. For the DensX and Admodus this is only 3 to 4 %. The number of samples in which the difference is greater than 0.5 m is about the same for all instruments, around 15 %. The measurements taken by GeoXYZ show a significant variation in measuring the water density.

Due to the fact that there are no reference values, no absolute comparison of the performance of the different instruments could be made, as such the evaluation in this report is limited to a relative comparison. For future research, it is advisable to be able to make an absolute comparison as well. For this purpose, there are two possible approaches:

- A mud layer build-up can be simulated in the sediment test tank Flanders Hydraulics Laboratory. In this way, a density structure of the mud can be simulated, whereby the absolute values can be measured.

- On the other hand, a successful in situ sampling technique (e.g. the slibsampler, or other) to take undisturbed mud samples can also be an option

In general, it can be said that large differences in the measurement of the 1.2 g/cm³ position were noticed, even considering measurements with the same measuring instrument. It is interesting to narrow down the possible causes of measurement variations (position of the ship, local variations in the mud layer, etc.), so that a real assessment can be made of the robustness of the measurement of the instruments themselves. In the current measurement campaign, one measurement was done where the ship was moored to the quay. It would be interesting to expand the number of locations where measurements are made this way (with all instruments), as this reduces already some variation in the measurement caused by in-situ phenomena.

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Appendix

Bathymetric recording measurement zones

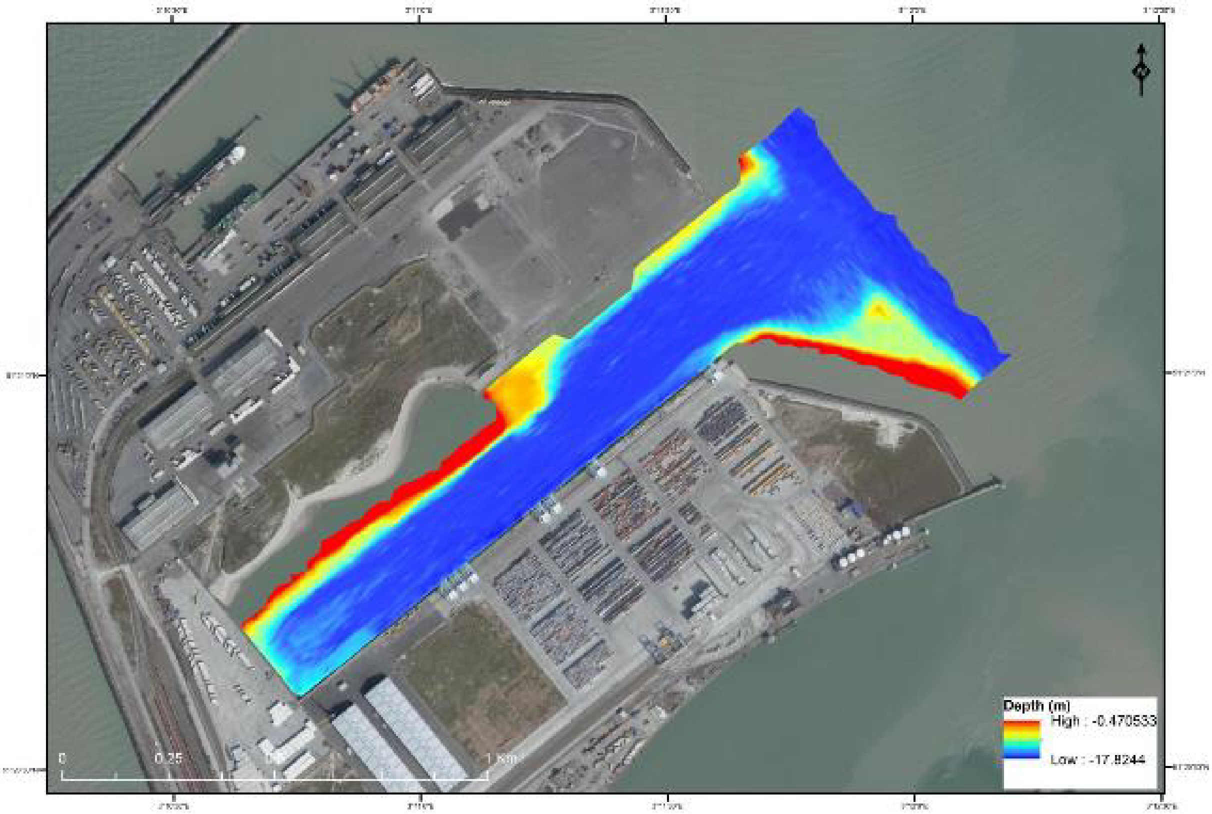

Figure 87 – Bathymetric recording Albert II dock

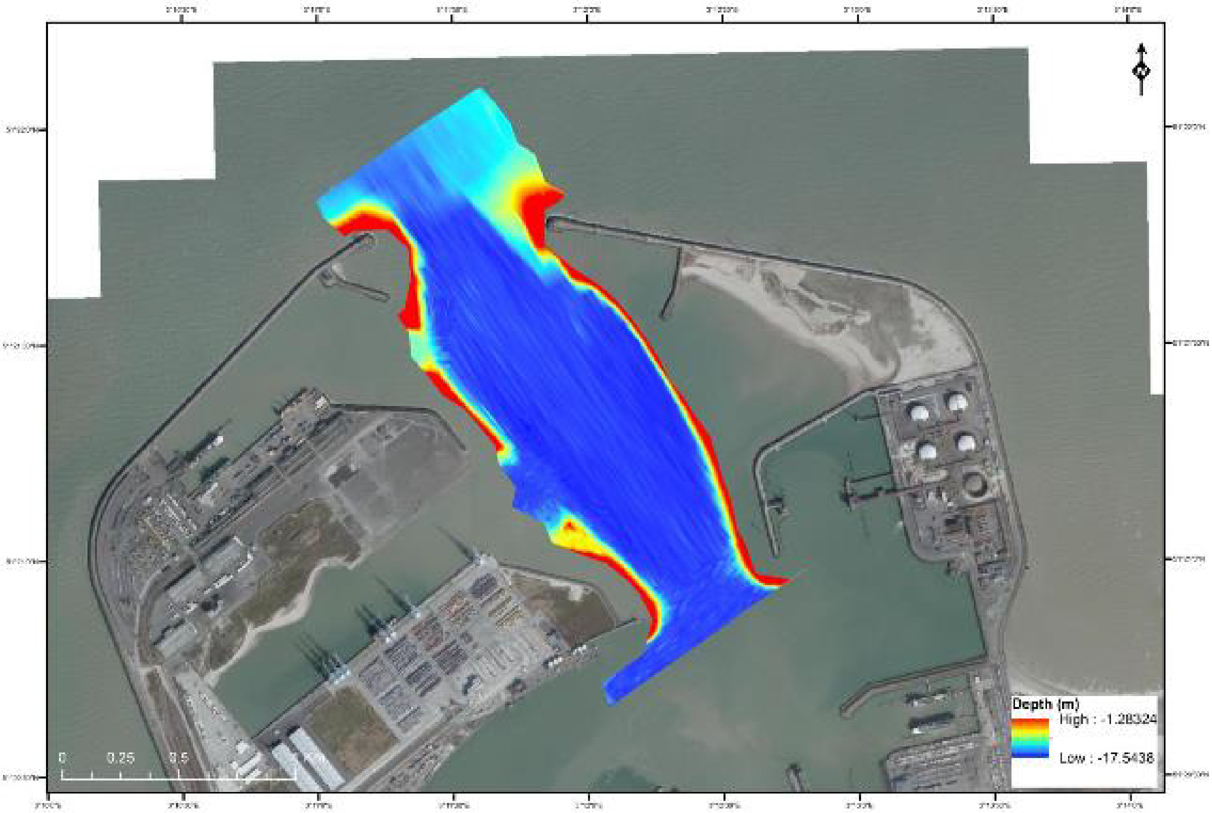

Figure 88 – Bathymetric recording CDNB

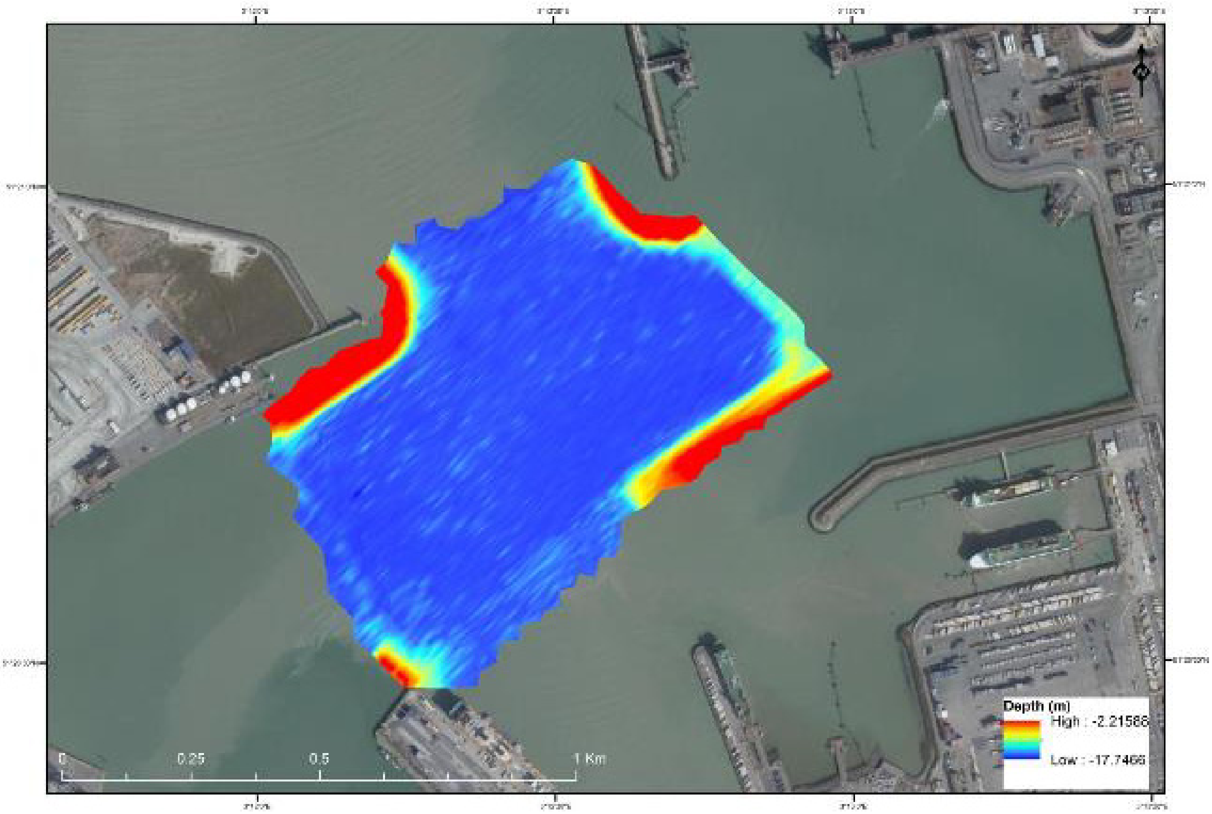

Figure 89 – Bathymetric recording Zwaaiplaats 1 (Z1)

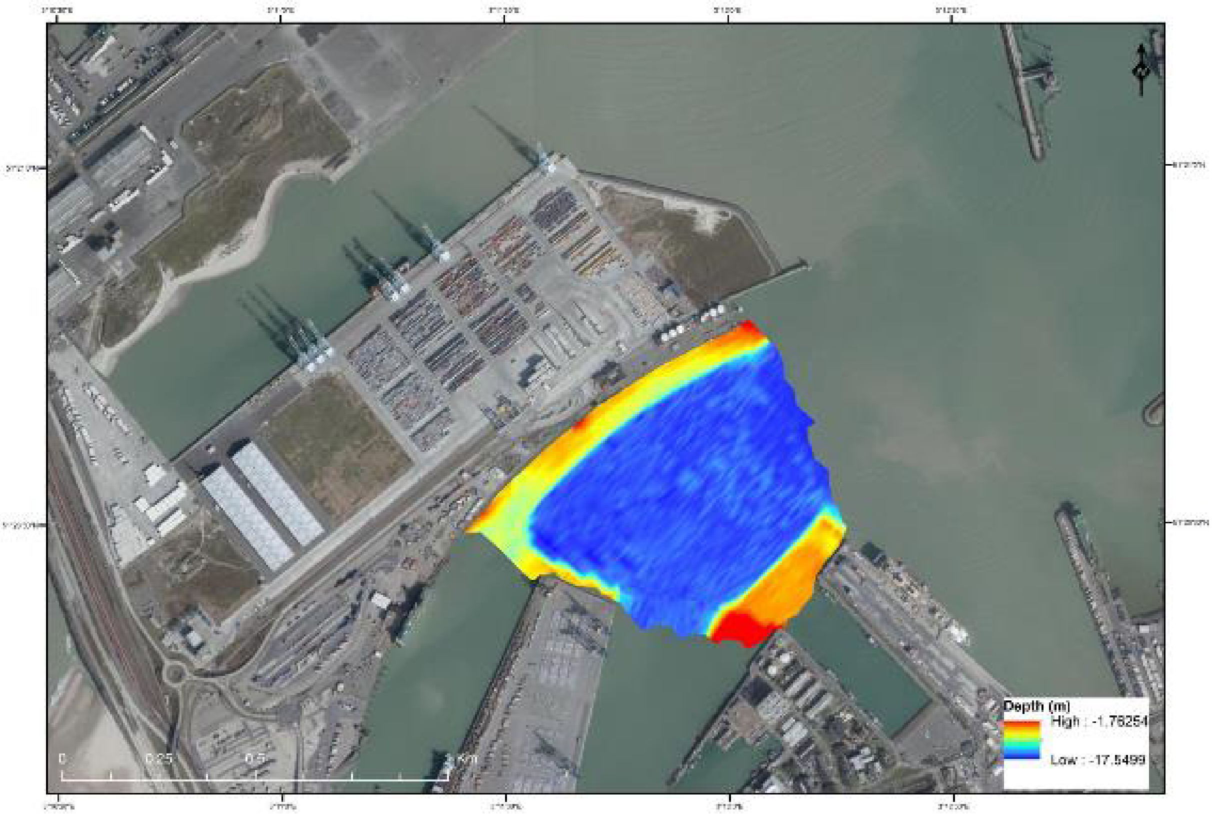

Figure 90 – Bathymetric recording Zwaaiplaats 2 (Z2)

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