RWS UNCLASSIFIED

Shallowest Point Determination with Water Column Imaging

The use of water column imaging for future wreck-like surveys

Datum           7 July 2017
Status          Version 1.5
Colophon

Published by D.H. van der Heide
Information Bachelor thesis
Lay-out Rapport_2010-RWS-UNCLASSIFIED
Datum 7 July 2017
Version number 1.5
MIWB supervisor Ir. R.E van Ree
RWS supervisor Ir. B.C. Dierikx
RWS mentor S. Bicknese

University of applied science NHL University of Applied Science
Institute Maritime Institute Willem Bartentsz
Department Ocean Technology
Preface

This thesis was submitted for the fulfilment of my bachelor degree in Hydrographic surveying of the Maritime Institute Willem Bartentsz, West-Terschelling. The research was conducted for Rijkswaterstaat under the supervision of Ben Dierikx and Simon Bicknese. The data was supplied during the scientific survey with TU Delft and Rijkswaterstaat, whilst the Royal Netherlands Navy conducted the diving operation for the absolute depth comparison.

Any citation regarding this bachelor thesis should appear as follows

Acknowledgements

I would like to express my gratitude to everyone from Rijkswaterstaat and other (international) organisations and companies who made my thesis possible. I would like to thank the following people, organisations and companies in particular:

- My supervisor and mentor from Rijkswaterstaat Ben Dierikx and Simon Bicknese for supervising this project and giving me the opportunity to research and conduct this exciting new survey method. Also for answering all my questions, feedback, and granting me the opportunity to manage my part of the research survey on board of the Arca.

- The Royal Netherlands Navy, the crew of the mv. Nautilus and especially John Loog and Raymon van de Veen, for proving the diving data. Without the diving survey, my thesis would not have been succeeded as it did.

- Mobiel meten department of Rijkswaterstaat and in particular Peter de Boer for helping me to organise my part of research survey of the first case study with the Arca.

- Kongsberg Maritime and particularly Ronald Keesmaat, Kevin Weerman and Sandro Fenech for their advice, recommendations, and answers to all my questions regarding the EM2040c and water column imaging.

- The crew of the Arca, especially Rob Cupedo, Bert van Angeren and Koen Schippers for helping, supporting and supplying me with the water column data of the research survey.

- Nicolàs de Hilster, the survey team of Lex Veltman and the crew of the Octans, for granting and helping me to conduct the second case study during the Oosterom survey.

- QPS and Ron Dekker, for answering my questions, the online support and the opportunity to use their software package Qimera.

- Auke van der Werf, for inspiring and giving me the knowledge regarding water column imaging.

- Tannaz Haji Mohammadloo and Leo Koop of TU Delft, for helping me during those tense hours of the research survey on board of the mv. Arca.

- Rob van Ree and the Ocean Technology department of the MIWB, for the knowledge and inspiration during the four years of the education.

Finally, I want to thank my parents, brothers, friends, and fellow students who always motivated and helped me during my study and work for this bachelor thesis.
Abstract

Currently, the method Water Column Imaging (WCI) is being researched and developed, including for usability for wreck surveys. This method is already commercially utilised by fishermen searching for fish. Basically, the soundings reflected on the fish are shown inside the water column and thus providing a useful tool in this sector. Over the course of time, hydrographic surveyors have started to experiment with this tool, for numerous midwater purposes like detecting the shallowest depth between a geodetic surface and the target. The UKHO and the NOAA have introduced water column imaging in their wreck surveys. Which gives rise to the question if Dutch companies and government organisations should also change to this hydrographic survey/analysis method? Since, the wire sweeping method and the diving operations were still the standard survey type at the time. Therefore, RWS has commissioned the following task: How can water column imaging be an aid for wreck surveys at Rijkswaterstaat?

To answer the subject of this thesis two case studies were conducted, a diving operation by the Royal Netherlands Navy and a comparison between the wire sweeping method and the Water column imaging method. The results showed that wrecks had four returning characteristics:

1. The different slant ranges in one single fan view;
2. The intensity levels of wreck-targets are between -40dB up to and including 13dB;
3. A low amplitude reflection around the sounding at steel (riveted) wreck-like targets;
4. The number of low in amplitude spots below mast-like targets.

With the results from case study 1 at the North Sea, the difference between the diving operation and the WCI method was computed. The outcome showed that the points were within the TVU of the special-order requirements, i.e. within ±0.3m. The average difference between the diver and the shallowest WCI point was 0.041 m. Since, the individual pulses did not vary much from each other, it can also be concluded that the different pulse lengths at -20 meters gave the same results as the pressure sensor of the diving operation.

Another fact was concluded, that the increase of the amount of lines would improve the reliability of the shallowest point(s). Therefore, the optimal survey method should consist out of at least of six lines: were half of the lines in the direction of the wreck and an equal amount in a perpendicular direction. Although these lines are designed for a water column survey, an optimal wreck/target detection survey should include a side scan sonar survey. The line spacing and direction was depending on the water depth and position of the wreck.

Thus, with the outcome of the desk and case studies it was concluded that the water column imaging can aid the wrecks surveys as the primary method for future and current wreck surveys at Rijkswaterstaat. Since, wrecks can be well distinguished from the contamination by sidelobes and/ or other sources of error. Also, the depth variations are within the IHO special order and can therefore be considered as a replacement for wire sweeping methods.
# Table of Content

**Preface**  4  
**Acknowledgements**  5  
**Abstract**  6  
**Table of Figures**  9  
**List of Tables**  11  
**List of Acronyms**  12  
**Table of nomenclature**  13

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Introduction</strong></td>
<td>15</td>
</tr>
<tr>
<td>1.1</td>
<td>Definition of the problem</td>
<td>15</td>
</tr>
<tr>
<td>1.2</td>
<td>Objective</td>
<td>15</td>
</tr>
<tr>
<td>1.3</td>
<td>Scope of work</td>
<td>16</td>
</tr>
<tr>
<td>1.4</td>
<td>What is not included</td>
<td>16</td>
</tr>
<tr>
<td>1.5</td>
<td>Thesis structure</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td><strong>State-of-the-art in wreck survey methods</strong></td>
<td>17</td>
</tr>
<tr>
<td>2.1</td>
<td>Sweeping methods</td>
<td>17</td>
</tr>
<tr>
<td>2.1.1</td>
<td>Fundamentals</td>
<td>17</td>
</tr>
<tr>
<td>2.1.2</td>
<td>Survey procedures</td>
<td>18</td>
</tr>
<tr>
<td>2.1.3</td>
<td>Disadvantages of the sweeping method</td>
<td>19</td>
</tr>
<tr>
<td>2.2</td>
<td>Pressure sensor method</td>
<td>19</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Pros and cons</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td><strong>Midwater surveying</strong></td>
<td>21</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction and terminology</td>
<td>21</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Terminology of the multibeam echosounder</td>
<td>22</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Sound velocity probe</td>
<td>27</td>
</tr>
<tr>
<td>3.2</td>
<td>IHO standards</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td><strong>Midwater target detection</strong></td>
<td>29</td>
</tr>
<tr>
<td>4.1</td>
<td>Water column geometry</td>
<td>29</td>
</tr>
<tr>
<td>4.2</td>
<td>Midwater target detection</td>
<td>32</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Bottom detection methods</td>
<td>32</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Extra and Multi-detections method</td>
<td>34</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Angular and range resolution</td>
<td>35</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Target referencing</td>
<td>38</td>
</tr>
<tr>
<td>4.3</td>
<td>Sources of error</td>
<td>40</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Acoustic dead zones</td>
<td>40</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Sidelobes</td>
<td>41</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Multipath</td>
<td>43</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Interference</td>
<td>44</td>
</tr>
<tr>
<td>4.3.5</td>
<td>Fish detection</td>
<td>44</td>
</tr>
<tr>
<td>4.3.6</td>
<td>Random noise</td>
<td>45</td>
</tr>
<tr>
<td>4.3.7</td>
<td>Error budget</td>
<td>45</td>
</tr>
</tbody>
</table>
5 Case studies and results 46
5.1 Wreck information: SR7285 46
5.2 Wreck information: Boetak 46
5.3 Methodology 47
5.3.1 Filters 50
5.4 Survey results of wreck SR7285: Case study 1 52
5.4.1 Quality check 52
5.4.2 Side scan sonar results 52
5.4.3 Medium CW- short phase ramp 53
5.4.4 Long-CW 57
5.4.5 Medium-CW 61
5.4.6 Royal Netherlands Navy diving operation 66
5.5 Depth comparison 67
5.6 Survey results of the Boetak: Case study 2 69
5.7 Wire sweeping vs WCI74

6 Conclusions and recommendations 76
6.1 Conclusion 76
6.2 Recommendations 78
6.2.1 Recommendations regarding future wreck surveys 78
6.2.2 Recommendations regarding future research 80

7 References 81

Annex A: Sound Velocity Profiles SR7285 84

Annex B: A-priori Calculations 85

Annex C: Side scan sonar images SR7285 88

Annex D: Survey Vessels 90

Annex E: QINSy Controller settings Roompot survey 91
Table of Figures

Figure 1  Swept wreck symbols for nautical chart (sailing almanac).........................17
Figure 2  Barsweep system ((Y) Olsen).......................................................................17
Figure 3  Wire/ bar sweeping setup ((N)Directie_water_en_scheepvaart, 2017)........18
Figure 4  Seabed interaction of a directional piston transducer ((ZC) Weber, 2016) 22
Figure 5  Typical beam pattern of a piston transducer ((ZE) Weber, 2016).............23
Figure 6  Dual head configuration sonar (Kongsberg)................................................24
Figure 7  Visualisation beam spacing ((O) Fenech, 2016)............................................26
Figure 8  Nearfield focusing ((Q) Hughes_Clarke, 2016)..........................................27
Figure 9  Single fan view of HD147 ((ZF) Werf, 2010)..............................................29
Figure 10 Common time series of data from HD147 ((ZF) Werf, 2010)....................30
Figure 11 Stacked fan view of HD147 ((ZF) Werf, 2010)..........................................30
Figure 12 Point cloud bathymetry by the MBES (HD147)........................................31
Figure 13 Point cloud WCI spot selection (HD147)....................................................31
Figure 14 Bathymetric image (HD147)....................................................................31
Figure 15 Amplitude detection of HD147.................................................................33
Figure 16 MBES Split-Beam processing ((ZC) Weber, 2016)......................................33
Figure 17 Zero crossing ((ZC) Weber, 2016)..............................................................34
Figure 18 Angular and range resolution....................................................................35
Figure 19 Range resolution of the nadir relative to the water depth (based on the EM2040c) 36
Figure 20 Refracting errors in the water column ((J) Beaudoin, 2010).......................38
Figure 21 Right handed coordinate system ((S) J.E. Hughes_Clarke, 2006)............39
Figure 22 Acoustic dead zones nadir angle beams ((ZD) Weber, 2016).....................40
Figure 23 Acoustic dead zones oblique angle beams ((ZD) Weber, 2016)..................40
Figure 24 Sidelobes contamination in the water column single fan view (HD147) 41
Figure 25 Ghost of wreck SR7285 (case study 1)......................................................42
Figure 26 Multipath ((S) J.E. Hughes_Clarke, 2006)...................................................43
Figure 27 Miss tracking by multipath ((ZF) Werf, 2010).............................................43
Figure 28 Passive sonar image (case study 1).............................................................44
Figure 29 Fish detection stacked fan view (case study 1)..........................................44
Figure 30 Random noise (case study 1).................................................................45
Figure 31 Side scan sonar image from wreck SR7285 ((M)Directie_Noordzee, 1988) 46
Figure 32 Boetak Side Scan Sonar image of the Boetak............................................47
Figure 33 Line scheme of the case studies.................................................................48
Figure 34 Kongsberg Filter and Gains ((E) Kongsberg_Maritime, 2013).....................50
Figure 35 Side Scan Sonar image of wreck SR7285....................................................52
Figure 36 Medium CW, Short phase ramp - survey tracks........................................53
Figure 37 Outer beams Medium-CW-Short phase ramp........................................53
Figure 38 Stacked fan view Medium-CW, Short phase ramp.....................................54
Figure 39 Cross check - Medium CW, short phase ramp..........................................54
Figure 40 Group A – Tracks – Medium CW, Short Phase ramp...............................55
Figure 41 Group A – Point Cloud – Medium CW, Short Phase ramp..........................55
Figure 42 Group B – Point Cloud – Medium CW, Short Phase ramp.........................55
Figure 43 Group B – Tracks – Medium CW, Short Phase ramp....................................55
Figure 44 Group C – Tracks – Medium CW, Short Phase ramp...................................55
Figure 45 Group C – Point Cloud – Medium CW, Short Phase ramp..........................55
Figure 46 S-Curve Medium-CW-Short phase ramp Group C (grid 0.01 x 0.01 m) 56
Figure 47 Long CW - survey tracks...........................................................................57
Figure 48  Stacked fan view Long-CW ................................................................. 57
Figure 49  Cross check Long-CW ..................................................................... 58
Figure 50  Group A – Tracks – Long CW .......................................................... 58
Figure 51  Group A – Point Cloud – Long CW .................................................... 58
Figure 52  Group B – Point Cloud – Long CW .................................................... 59
Figure 53  Group B – Tracks – Long CW ............................................................ 59
Figure 54  Group C – Point Cloud – Long CW .................................................... 59
Figure 55  Group C – Tracks – Long CW ............................................................ 59
Figure 56  S-Curve Long CW Group C (grid 0.01 x 0.01 m) ............................... 60
Figure 57  Medium CW - survey tracks ............................................................. 61
Figure 58  Stacked fan view Medium-CW .......................................................... 62
Figure 59  Cross check – Medium CW .............................................................. 62
Figure 60  Group A – Point Cloud – Medium-CW ............................................. 63
Figure 61  Group A – Tracks – Medium-CW ...................................................... 63
Figure 62  Group B – Point Cloud – Medium-CW ............................................. 63
Figure 63  Group B – Tracks – Medium-CW ...................................................... 63
Figure 64  Group C – Tracks – Medium-CW ...................................................... 64
Figure 65  Group C – Point Cloud – Medium-CW ............................................. 64
Figure 66  Group D – Tracks – Medium-CW ...................................................... 64
Figure 67  Group D – Point Cloud – Medium-CW ............................................. 64
Figure 68  Group E – Point Cloud – Medium-CW ............................................. 64
Figure 69  Group E – Tracks – Medium-CW ...................................................... 64
Figure 70  S-Curve Medium-CW Group E (grid 0.01 x 0.01 m) .......................... 65
Figure 71  Plane view Short and Very Short CW pulses .................................... 69
Figure 72  Point cloud Short CW ..................................................................... 70
Figure 73  Point cloud Very Short CW ............................................................. 70
Figure 74  Short CW wreck characteristics ....................................................... 71
Figure 75  Adjusted single fan view ................................................................. 71
Figure 76  Colour range setup of the single fan plot .......................................... 72
Figure 77  Low reflections around the sounding ............................................... 72
Figure 78  Mast-like target HD147 .................................................................. 73
Figure 79  Mast-like target Boetak ................................................................. 73
Figure 80  Plan view target survey ................................................................. 74
Figure 81  Cross check target survey ............................................................... 74
Figure 82  AMUST: 14μ – Very Short CW ....................................................... 85
Figure 83  AMUST: 27 μs – Short CW ............................................................... 85
Figure 84  AMUST: 54 μs – Medium CW ......................................................... 86
Figure 85  AMUST: 135 μs – Long CW ............................................................. 86
Figure 86  AMUST: 324 μs – Very Long CW .................................................. 87
Figure 87  AMUST: 918 μs – Extra Long CW .................................................. 87
Figure 88  Survey vessel mv. Arca – case study 1 ............................................. 90
Figure 89  Survey vessel mv. Octans – case study 2 (Vesseltracker.com) ........... 90
List of Tables

Table 1  IHO uncertainty requirements  28
Table 2  Pulse lengths EM2040c  37
Table 3  Results A-priori calculations of the EM2040c  37
Table 4  Runtime parameters survey of SR7285  49
Table 5  Used positioning stations  49
Table 6  Patch test results of the Arca  52
Table 7  Results Medium CW, Short Phase ramp  56
Table 8  Results Long-CW  61
Table 9  Results Medium-CW  66
Table 10  Shallowest depth comparison  68
Table 11  Wire sweeping vs WCI  75
List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMUST</td>
<td>A-priori Multibeam Uncertainty Simulation Tool</td>
</tr>
<tr>
<td>AR</td>
<td>Angular Resolution</td>
</tr>
<tr>
<td>BW</td>
<td>Beam Width</td>
</tr>
<tr>
<td>COG</td>
<td>Course over ground</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous wave</td>
</tr>
<tr>
<td>Fig</td>
<td>Figure</td>
</tr>
<tr>
<td>IHO</td>
<td>International Hydrographic Organisation</td>
</tr>
<tr>
<td>LAT</td>
<td>Lowest astronomical tide</td>
</tr>
<tr>
<td>MBES</td>
<td>Multibeam echosounder</td>
</tr>
<tr>
<td>MSL</td>
<td>Mean Sea level</td>
</tr>
<tr>
<td>MSR</td>
<td>Minimum Slant Range</td>
</tr>
<tr>
<td>mv</td>
<td>motor vessel</td>
</tr>
<tr>
<td>NAP</td>
<td>Normaal Amsterdam Peil</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>PL</td>
<td>Pulse length</td>
</tr>
<tr>
<td>PS</td>
<td>Portside</td>
</tr>
<tr>
<td>QINSy</td>
<td>Quality Integrated Navigation System</td>
</tr>
<tr>
<td>QPS</td>
<td>Quality processing software</td>
</tr>
<tr>
<td>RR</td>
<td>Range Resolution</td>
</tr>
<tr>
<td>RTK</td>
<td>Real Time Kinetic</td>
</tr>
<tr>
<td>RWS</td>
<td>Rijkswaterstaat</td>
</tr>
<tr>
<td>SB</td>
<td>Starboard</td>
</tr>
<tr>
<td>SIS</td>
<td>Seafloor Information System</td>
</tr>
<tr>
<td>SNR</td>
<td>Single-to-noise ratio</td>
</tr>
<tr>
<td>SSS</td>
<td>Side Scan Sonar</td>
</tr>
<tr>
<td>SV</td>
<td>Sound Velocity</td>
</tr>
<tr>
<td>SVP</td>
<td>Sound Velocity Profile</td>
</tr>
<tr>
<td>SVS</td>
<td>Sound Velocity Sensor</td>
</tr>
<tr>
<td>THU</td>
<td>Total horizontal uncertainty</td>
</tr>
<tr>
<td>TVU</td>
<td>Total vertical uncertainty</td>
</tr>
<tr>
<td>UKHO</td>
<td>United Kingdom Hydrographic Office</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
</tr>
<tr>
<td>WCD</td>
<td>Water Column Data</td>
</tr>
<tr>
<td>WCI</td>
<td>Water column imaging</td>
</tr>
</tbody>
</table>
## Table of nomenclature

<table>
<thead>
<tr>
<th>Name/meaning</th>
<th>Symbol</th>
<th>Unit</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portion of the uncertainty of TVU</td>
<td>a</td>
<td>Meter</td>
<td>m</td>
</tr>
<tr>
<td>Coefficient of the portion of the uncertainty of TVU</td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed of sound</td>
<td>c</td>
<td>Meter per second</td>
<td>m/s</td>
</tr>
<tr>
<td>Water depth</td>
<td>D</td>
<td>Meter</td>
<td>m</td>
</tr>
<tr>
<td>Sound pressure level</td>
<td>SPL</td>
<td>Decibel</td>
<td>dB</td>
</tr>
<tr>
<td>Transducer length</td>
<td>L</td>
<td>Meter</td>
<td>m</td>
</tr>
<tr>
<td>Pressure</td>
<td>P</td>
<td>Pascal</td>
<td>Pa</td>
</tr>
<tr>
<td>Range</td>
<td>R</td>
<td>Meter</td>
<td>m</td>
</tr>
<tr>
<td>Range future on the transducer</td>
<td>R’</td>
<td>Meter</td>
<td>m</td>
</tr>
<tr>
<td>Time</td>
<td>t</td>
<td>Seconds</td>
<td>s</td>
</tr>
<tr>
<td>Steer angle</td>
<td>Θ</td>
<td>Degrees</td>
<td>°</td>
</tr>
<tr>
<td>Beam width of the transducer in the along-track direction</td>
<td>θ_T</td>
<td>Degrees</td>
<td>°</td>
</tr>
<tr>
<td>Pulse length</td>
<td>λ</td>
<td>Meter</td>
<td>m</td>
</tr>
</tbody>
</table>
1 Introduction

1.1 Definition of the problem
A part of wreck surveying includes finding the shallowest point or depth, which could endanger the marine traffic near that location. Nowadays, the wrecks and objects of importance for Rijkswaterstaat (RWS) are surveyed with sweeping tools or diver operations. These surveys are rather time consuming and at a high safety risk.

Currently the method Water Column Imaging (WCI) is being researched and developed, including for usability of wreck surveys. The method is already commercially utilised by fishermen in search for fish at sea. Basically, the soundings reflected on the fish are shown inside the water column view and thus prove to be a useful tool in this sector. Over the course of time, hydrographic surveyors, companies and organisations have started to experiment with this method for numerous midwater purposes (like detecting the shallowest depth between a geodetic surface and the target). The UKHO and the NOAA have also introduced water column imaging to their current wreck surveys. Which gives rise to the question if Dutch companies and government organisations should also change to this new hydrographic tool? Now Rijkswaterstaat (RWS) and the Royal Dutch Navy are responsible for finding those wrecks on the North Sea and determining if they will be a danger to the maritime traffic. Therefore, RWS has commissioned a task to research the use water column imaging method.

1.2 Objective
The objective is to answer the research question defined by Rijkswaterstaat:

How can water column imaging be an aid for wreck surveys at Rijkswaterstaat?

For answering this question, the subject was divided into four sub questions, which are addressed during the case studies:
- What are the characteristics of a typical wreck in the water column?
- What are the differences between the near absolute and determined shallowest depth?
- What is the optimal survey method for wreck surveys?
- Can water column imaging be a replacement for wire sweeping or diver surveys?

Prior to the case studies, the following sub-question regarding state-of-the-art wreck survey methods are discussed:
- What are the current wreck survey methods?
- What are the pros and cons for using the current methods?

For analysing the use of the water column imaging method for wreck surveys, the following sub questions are addressed:
- What is the IHO standard and accuracy levels for wreck surveys using water column imaging?
- What are the sources of error in the water column?
- What are the ideal sectors in a dual head multibeam survey at Rijkswaterstaat?
1.3 Scope of work
The different sub-questions were answered prior to the case study, which forms the backbone of the literature study of this bachelor thesis. The first four different sections will be answered with the results of the case studies. Case study 1 will contain a survey of a wreck for the coast of Scheveningen at the North Sea, surveyed with different settings. The second case study includes a survey of the Boetak, for determining the characteristics of midwater wreck-like targets. The geodetic reference frame used for this bachelor thesis was the ETRS89 UTM zone 31 with a height reference to the Lowest Astronomical Tide (LAT2006). The analysis of case studies was analysed using the software package from QPS: Qimera (version 1.5).

1.4 What is not included
Water column imaging (WCI) can be applied in a great field of applications. Nonetheless this bachelor thesis will only focus on the application of detection of the shallowest point(s) of wreck-like targets. Hence, this thesis shall not address the level of detail of which the target can be determined. Also, the complete background theory behind the operation of multibeam and single beam echosounders will not be addressed, only the terminology of essence for midwater target detection surveys.

1.5 Thesis structure
Chapters 2 up to and including 4 focuses on the desk studies regarding the state-of-the-art wreck survey methods, midwater surveying and target detection methods. Whilst Chapter 5 addresses the case study (1) of wrecks: SR7285, the Boetak and NCN1653. Finally, in Chapter 6 the conclusion and recommendations are given on the subject.
2 State-of-the-art in wreck survey methods

Common practise for establishing the shallowest depth on a wreck consists of a wire or bar sweeping system and/or diver operations in combination with multibeam surveys. This chapter introduces sweeping methods (§2.1) and pressure sensor based diving operations (§2.2), focusing at the pros and cons.

2.1 Sweeping methods

The current method at RWS for measuring the least depth of wrecks is the sweeping method. The common symbol for representing these least depths is given in Figure 1.

![Figure 1 Swept wreck symbols for nautical chart (sailing almanac)](image)

This method is straightforward and not as complex as for instance a midwater echosounder survey (see §3.0 and §4.0). This subparagraph will discuss the principle of the wire and bar sweeping methods and the survey procedures for achieving a depth.

2.1.1 Fundamentals

Whilst processing echosounder data of a midwater target, difficulties arise in interpreting the data. For example, when a mast is pinged by a multibeam echosounder (MBES), only a few returns can be seen. Are these just anomalies or a real mast? The latter real mast could be a danger to certain vessels. The state-of-the-art solution, is sweeping these pings with a bar or wire ((N)Directie_water_en_scheepvaart, 2017). The difference between the wire method and bar method is the use of a wire or a bar at fixed length, respectively. An example of the use of the bar method, is depicted in Fig.2

![Figure 2 Barsweep system ((Y) Olsen)](image)
According to the Swedish Maritime Administration, the pros for using a sweeping system are ([Z]Swedish_Maritime_Administration):

1) it is a mechanical system instead of an electronic system;
2) it verifies MBES-results;
3) it can be used alongside bathymetric data of the echosounder;

Note that the Swedish Maritime Administration prefers not to use these sweeping methods for determining the shallowest depth of wrecks. The method is only utilised for clearing an area to a certain depth (K. Logdberg, private communications).

2.1.2 Survey procedures
The procedures of wire and bar sweeping methods are essentially the same, although deviations per company or organisation exist. First, the wire or the bar is swept through the water column at the minimum water depth to search for a “hit”. Then the wire or the bar is lowered until the first hit is logged. This marks the shallowest depth of the area.

The cable is marked by yellow (1m interval) and black (10 m interval) tape, therefore an operator measures the water depth by matching the latter amount of tape to the sea level. The accuracy levels of the bar sweeping method is typically 0.25 m under ideal circumstances ([Y] Olsen).

A whole survey procedure could well take about 6 hours.

Fig. 3 shows a schematic view of the bar/wire sweeping tool, with details of the mv. Arca.

\[
\text{Least depth} = \text{Waterline} + (\text{Wire length} - \text{load height})[m]
\]

Whilst C of Figure 3 determines the waterline.
The waterline is for the mv. Arca equal to 8.59 m and the load height at 039. Thus, the least water depth would be 28.20 meters, when the bar hits object/seabed at 10 meters.

2.1.3 Disadvantages of the sweeping method
Besides the long survey and mobilisation times, disadvantages of the wire and bar sweeping methods include:

- Errors related to visual examination;
- Sensitivity for sea current deviations;
- The need for knowledge of the target.

The aspect of visual examination, causes operator specific scatter in the results. This uncertainty becomes especially important for shallow water. Secondly, “absolute” depth measurement is suspected to have unknown uncertainties caused by current deviations within the sea layers. It is clear that current flows will bend the wire significantly, therefore changing the vertical and horizontal position in an unknown direction. Finally, major errors could be introduced by unknown details of the target.

2.2 Pressure sensor method

The second method for measuring the shallowest depth between a target and a geodetic surface is based on pressure sensors installed by divers. This method is closest to absolute depth, which is a clear advantage for validation of new methods for shallowest depth surveys.

The diving spots can be identified during multibeam echosounder (MBES) or side scan sonar (SSS) survey which is used for the required information, prior to the dive. The acquired information includes:

- The geodetic position of the point(s) or midwater target;
- The heading of the midwater target;
- The water depth of the area.

With the information, the diver can dive to the pre-selected points. However, determining the absolute depth takes a few more steps. Firstly, the period at which pressure sensor is positioned at the shallowest depth. This ‘period’ is depending on the state of the sea, for instance, a period of 4 minutes is generally chosen for correcting pressure variations by long surface waves ((ZB) Veen, 2017). Secondly, the atmospheric pressure is determined for correcting the water pressure. Since, the sensor determines total pressure including atmospheric pressure over the sea.

Thirdly, common practice showed that additional dives are required, for filtering out any miss dive too the shallowest depth of the midwater target. Since, the visual range in the sea is limited in certain region like for instance the North Sea. Therefore, the target could easily be mistaken for its shallowest point.

By following these steps, the depth relative to MSL can be determined. For the conversion to the lowest astronomical tide (LAT), the depth needs to be corrected for the tide. The Royal Netherlands Navy utilises four options: Real Time Kinetic (RTK)/Netpos corrections, Premo, predicted tide and measured tide with nearby tide stations.
2.2.1 **Pros and cons**

Like wire sweeping the diving operation has some disadvantages, although slimmer than the latter method. As mentioned in the previous section, the weather is playing a vital part in the operation. Not only is the air pressuring influencing the determination of the pressure at mean sea level (MSL) but also sever surface waves. This introduces an average water pressure, having a ‘possible’ small random error. Furthermore, the associated risks for the diver are substantial and diving depths are restricted to 25 meters. Nonetheless this operation is considered to be the closed to an absolute depth, due to the resolution of the pressure sensors\(^1\): 1 Pa ((ZG) SAIV A/S). Therefore, the method was ideal for validating the water column imaging tool regarding the shallowest depth determination.

\(^1\) 1 Bar = 100 kPa
3 Midwater surveying

This chapter introduces hydrographic midwater surveying, a new method for RWS when determining the shallowest point(s) of wreck-like targets. It addresses the terminology of systems (§3.1) which are used for midwater surveys and the accuracy levels (§3.2).

3.1 Introduction and terminology

Midwater surveying is basically searching for objects inside the water column instead of searching for targets at the seabed. During the swath sonar training of 2016 in Den Helder, hydrographic midwater surveying was divided into five categories ((ZD) Weber, 2016):

1) Target detection
   "We are interested simply in the existence of some phenomenon in the water column that may trigger further action." ((ZD) Weber, 2016, p. 6)
2) Target tracking
   "We are interested in following a moving target." ((ZD) Weber, 2016, p. 6)
3) Target morphology
   "We are interested in aggregating our target detections in order to learn about the form and spatial features of some entity (...)." ((ZD) Weber, 2016, p. 6)
4) Target strength
   "We use target strength in order to help with aspects of target classification." ((ZD) Weber, 2016, p. 6)
5) Volume scattering strength
   "(...) used in order to help determine the number density of target, or can be integrated to estimate the total number of targets." ((ZD) Weber, 2016, p. 6)

For common midwater wreck detections categories 1, 3 and 4 are applicable. Since a wreck-like target is detected (an action in required), the shallowest depth needs to be determined (target morphology) and be separated from other midwater targets.

The following sub paragraphs address the multibeam system terminology of the latter categories.
3.1.1 Terminology of the multibeam echosounder

The Multibeam echosounder (MBES) and the Singlebeam echosounder (SBES) have both the ability to detect wreck-like targets at midwater. Basically, the systems are using acoustic pulses to measure the distance between the transducer and the seabed. By measuring the time (s), and knowing the velocity (m/s) and the angle of reception (°), the depth can be determined using the following equation.

\[
D = \frac{1}{2} t \cdot c \cdot \cos(\theta) \text{ (m)}
\]

(2)

Where "D" represents the water depth, "t" the time and "c" the speed of sound through water and \( \theta \) is the angle of reception.

For this bachelor thesis, the Kongsberg EM2040c MBES was used. Henceforth only the terminology of the MBES shall be addressed.

Transmit and receive arrays

The transmit and receive arrays are the elements generating and processing the outgoing and incoming acoustic pulses. The number and configuration of these arrays are in relation with the resolution of the data, where the length of the array influences the angular resolution. For example, when the size of the transmit array increases in wavelength (the standard expression of length of an array), the beam will be much narrower and therefore have a better angular resolution (ZE Weber, 2016). A narrow beam will result in a higher angular resolution relative to a small array configuration (§4.2.3).

There are different kinds of configurations for a MBES transducer, for instance: Omnidirectional, directional piston transducer, continuous line array (ZE Weber, 2016). Where the EM2040c could be defined as: a directional piston transducer.

Piston Transducer

The directional piston transducer has a circular shape which vibrates in the piston mode ((ZE Weber, 2016). In Figure 4 is shown how this configuration interacts with the seabed.

![Figure 4 Seabed interaction of a directional piston transducer (ZC Weber, 2016)](image)

The touchdown point (marked by the black arrow) will propagate over the seafloor away from the initial nadir point. Still this propagation will be partly suppressed
since this is emitted by side lobes generated by the main lobe (ZE Weber, 2016). Those directional characteristics can be defined as follows

- The beam pattern is $20 \log(D)$, with $D$ as the water depth in meters. The left side of Fig. 5 shows that the main lob will have its peak around 0 degrees and devolving side lobes beside him.

- The beam pattern polar plot given in the right side of Fig. 5, shows that the main beam will be the strongest around zero degrees. Whilst the side lobes are generated at a lower power and angle.

The 3 dB points are depicted on the edges of the main lobe of Fig. 5. This figure gives a typical view of the beam at the nadir angle.

Interestingly, regarding midwater surveys is the fact that the sidelobes represent the areas with some ambiguity in resolving the angle to an object. If the piston transducer is uniformly weighted, the sidelobes are just 17 dB lower than the main lobe (ZE Weber, 2016).
**Dual head RWS standard configuration**

The EM2040c is equipped with two transducer heads, making it a dual head echosounder. This doubles the original footprint, whilst surveying the same amount of lines. Both transducers were mounted at the survey vessels under a ±40° angle, where the overlap between the beams are at the nadir of the vessel. Figure 6 shows a systematic configuration of a dual swath, with a beam angle of 60 degrees at each head (§5.4.3).

Theoretically speaking, the characteristics\(^2\) at a water depth of 20 meter are:

- Dead zone is at a depth of ±1.30 meter;
- Dual beam overlap is 6.5 meter;
- Total footprint is 70 meters;
- The blue lines depict the inner beams at 40° away from the vessels nadir.

The characteristics are depending on the frequency, which ranges from 200 to 400 kHz. Starting from 320 kHz the dual beam overlap shall decline to a rate at which the overlap will be zero. Since the frequency influences the opening angle of the EM2040c.

The EM2040c is also equipped with the option 'dual swath’. This gives the opportunity to generate more pings in the along-track direction than a standard MBES. Basically, the MBES will transit a swath steered a bit forward and backwards, whilst the swath itself is divided in different sectors. The deviation between these sectors are unique transmit frequencies in each sector. In the centre sector of the swath are commonly the highest frequencies used, due to the attenuation coefficient ((Q) Hughes_Clarke, 2016). The more sectors generated, the higher the along-track resolution ((Q) Hughes_Clarke, 2016). Note, that the dual swath option will limit the use of smaller CW-pulses.

---

\(^2\) Calculations made by Kongsberg Maritime Holland
**Beam steering**

The advantage of the MBES over the SBES is by mathematically receiving more beams, away from the nadir. Nonetheless, the returning pulse shall be out of phase when receiving this on a fixed array, resulting in a noisy outcome. This is prevented by use of “virtual arrays” (Hughes Clarke, 2016). By virtually shifting the arrays in desired angles (which is achieved by changing the incoming pulses in time/phase), the results can be corrected and used for hydrographic midwater surveys.

However, these beam steering techniques with the virtual arrays, have some important disadvantages:

- When steering away from the nadir, the beam will increase in width by \( \cos(\theta) \):

\[
\theta_{\text{radians}} = \frac{0.889}{L \cos(\theta)}
\]  

(3)

Thus, by increasing \( \theta \) the steered angle will be increasing in width \( \lambda \).

- When steering away from the nadir, the beam will take a conic form;
- The beam angle is strongly depending on the sound velocity.

Thus, the beams can be steered away from the nadir, creating a bigger footprint. Yet, at the cost of resolution, because this will be lower in the outer beams than near nadir. This can be solved by surveying multiple lines with an overlap in the outer beams, creating a redundancy in these regions with lower angular resolution.

**Beam spacing**

Whilst working with beam steering, the steering mode needs to be selected. There are three options to steer the beams and creating an overlap with the individual beams and determining the across-track resolution:

- Equiangular: The beam spacing is determined by the angle distance. Therefore, the footprint will have a high angular resolution near the nadir, but will be relatively lower in the outer beams ([Fenech, 2016]).
- Equidistant: The beam spacing is determined by the distance, which will have a constant resolution over the whole footprint.
- High Density: The beam angles are changed, so that an equal set of soundings are displayed at every distance. To achieve this, more soundings are generated per beam ([Fenech, 2016])

In Figure 7 the three spacing methods are depicted, where every colour represents a returning pulse.

\(^1\) John E. Hughes Clarke Multibeam_MBC_2016
Nearfield focusing

The EM2040c can measure objects with nearfield focusing at the transmitter and receiver arrays. This means that objects close to the transducer can be detected. One of the options to achieve this is dynamic focusing ((ZF) Werf, 2010). The dynamic focusing makes also use of the latter addressed virtual arrays. Those arrays are generated by adding time shifts, making them lay on an arc of a circle matching the radius of curvature from the incoming sphere of energy ((ZE) Weber, 2016). Thus, when a mast is located close to the transducer, the virtual array is shifted in time to match the reflected energy.

The opposite of the near field is the far field. In between these fields is an area where the intensity oscillates, the Fresnel zone ((ZF) Werf, 2010). The distance of the Fresnel zone and therefore the distance between the far field and near field can be determined using the following rule of thumb

\[
\text{Fresnel zone} \approx \frac{L^2}{4a} \quad ((V) \text{ Lurton, 2002})
\]  

Where \(L\) is the length of the transducer and the \(\lambda\) is the wave length in meters.

When the object is located within the far field, the path differences are relatively small in comparison with the wavelength, and all the point sources that make up our transducer will add constructively ((ZE) Weber, 2016). Fig. 8 and Eq. 5 illustrate this principle, whilst Equation 5 is

\[
R' - R \ll \lambda \quad \text{(5)}
\]

Where
- \(R\) is the range;
- \(R'\) is the range further on the transducer, which is calculated with

\[
R' = \sqrt{R^2 + a^2} \quad \text{(6)}
\]

\(a\) is the distance between \(R\) and \(R'\) on the transducer.
Note that the equation will only be valid when $a$ is rather small or $R$ is rather large.

### 3.1.2 Sound velocity probe

The sound velocity (SV) is determined with a sound velocity probe (SVP). This probe determines the pressure (for depth), conductivity, temperature, and the sound velocity (when the probe is equipped with a SV-sensor) at a selected time interval when launched in the water. When the SV-sensor is not present, the sound velocity is then calculated by use of Del Grosso’s or Chen and Millero equation. With the calculated/measured sound velocity, the depth can be determined for each beam or pulse. The sound velocity is also used for the beam steering (transmit and receive), dynamic focusing of the virtual arrays and raytracing. To check if the sound velocity is still up-to-date, the profile is compared with the sound velocity sensor (SVS) on the EM2040c.
3.2 IHO standards

The NOAA specified a feature on the seabed or partly in the water column as follows:

“A feature can be any anthropogenic or natural object that may merit individual cartographic representation (e.g. rocks, wrecks, obstructions).”

The accuracy levels for such a feature differ for every situation. The IHO as specified two uncertainty orders applicable for thesis:

1) Special order
2) Order 1a

These two orders were chosen, because this thesis focuses on feature detection and those orders were considered acceptable for determining the shallowest depth at sea. Orders NL A and B were not studied, since the wrecks of the case studies were located at sea (the Waddenzee and the North Sea). Also, past research showed that only a few of the results were outside order 1a. Whilst of the data sets from the case study matched the requirements of the special order (see Annex B and §5.5).

Both orders address the total horizontal uncertainty (THU) and the total vertical uncertainty (TVU).

The maximum allowable TVU for midwater surveys is determined with at least 95% of all soundings. The uncertainty level is calculated using the following equation

\[ TVU = \pm \sqrt{a^2 + (b \cdot D)^2} \]  

(7)

Where:

- \( a \) represents that portion of the uncertainty that does not vary with depth;
- \( b \) is a coefficient which represents that portion of the uncertainty that varies with depth;
- \( D \) is the water depth;
- \( b \cdot D \) represents that portion of the uncertainty varying with depth;

Table 1 gives the IHO orders, with the uncertainty levels, factors used for the calculation and the THU.

<table>
<thead>
<tr>
<th>Order</th>
<th>THU (m)</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special</td>
<td>2</td>
<td>0.25</td>
<td>0.0075</td>
</tr>
<tr>
<td>1a</td>
<td>5 + 5% of depth</td>
<td>0.013</td>
<td>0.075</td>
</tr>
</tbody>
</table>
Chapter 4 focuses on detection of midwater targets by addressing the water column geometry (§4.1), midwater target detection (§4.2), extra detections (§4.2.2), resolutions of the EM2040c with different continue waves (§4.2.3) and the sources of error (§4.3).

4.1 Water column geometry

The method water column imaging with the MBES is logging all the detections regarding of the bottom between the transducer and the seabed, instead of only saving the computed seabed from the bottom detections (§4.2.1).

When working with water column data (WCD), different plot options are available Qimera and Fledermaus. The three views/plot options of interest are:

1. Single fan view [1];
2. Common time series plot [2];
3. Stacked fan view [3].

The Single fan view [1] is depicted in Fig. 9 and shows of the wreck HD147 with a mast-like target.

This single fan view shows an across-track profile relative to the depth and can be seen as the standard view of the WCI. The red spots in this view, represents the peak return or heights value in amplitude. The green colour indicates the lower amplitudes and the possible existence of a mast-like target and/or sidelobes (§4.3.2). The minimum slant range (MSR) is shown with the light blue colour, which gives the lowest in amplitude returns. The yellow colours depict the amplitude levels higher than sidelobes, yet lower than the mean detection. This view was commonly used in the analysis of the case study, by manually selecting the spots corresponding to the wreck-like midwater target.
The single fan view is based on two factors, the colour scale picked by the user and the common time series plot. In Fig. 10 an example is given of such a plot. Note that this was made with FM Midwater from Fledermaus – QPS, since the version of Qimera did not support this utility at that time.

![Figure 10 Common time series of data from HD147 (ZF Werf, 2010)](image)

This figure shows amplitudes (dB) relative to the range. The red circle in the plot, represents the range at which the bottom detection algorithm computes the seabed (§4.2.1.). Beside the circle, depicts the red arrow the minimum slant range which marks the first side lobe. Yet, for other cases the arrow could indicate the existence of a possible target in midwater like a mast. Therefore, the operator can be more confident in selecting the shallowest point(s).

The third plot is a stacked plot, where an example is shown in Fig. 11. This stacked fan portrays a wreck-like target with a possible mast.

![Figure 11 Stacked fan view of HD147 (ZF Werf, 2010)](image)

This stacked plot shows all the single pan plots of a pre-selected processing area, whilst using only one line at the time. Therefore, the different sorts of targets (wrecks, masts, and containers), can be easily distinguished. For instance, Fig. 9 depicts a possible mast-like target, but not as distinctive as in Fig. 11.
By selecting those spots of interest in the single pan plots (or stacked view) a 3D point cloud can be produced. The point cloud of wreck HD147 is illustrated in Figure 13. Whilst Figure 12 shows the product of the bathymetric survey, build without the influence of the water column spot sections.

Striking is the detail of the mast-like target by water column spot selection, in comparison with the bathymetry of the MBES. Nonetheless the variation of the shallowest point is 0.20m. Yet, most bathymetry generated points clouds needs some validation for spikes and random noise. Therefore, when a filter (manually and/or mathematically) is applied over the MBES data, the mast could completely vanish (like in Figure 14) or the shallowest depth is displayed at a deeper depth. For that reason, the water column spot selecting was considered the main detecting method in the case studies of Chapter 5.
4.2 **Midwater target detection**

To detect and establish the shallowest point of a midwater target whilst using the EM2040c MBES, the following aspects are of importance:

- The bottom detection methods;
- Extra detections;
- The angular and range resolution;
- Target referencing.

These aspects influence the presentation of the results and the judgement of the operator whilst selecting the spots in the single pan plots.

4.2.1 **Bottom detection methods**

The fundamental principle of using a MBES is detecting the sea bottom, by use of bottom detection algorithms. Nonetheless, detecting a target above the seabed could cause complications. For instance, the algorithm could filter these detections altogether, therefore giving a misleading image of the surface (see Figures 12, 13 and 14). These filters are basically thresholds, where only the bottom amplitudes shall remain. This results in an unwanted side-effect for target detection. The bottom detection or target detection are based on the following two principles: amplitude and phase detection \((ZC)\ Weber, 2016\).

**Amplitude detection**

Amplitude detection is defined by selecting the highest amplitude of the returning signal as bottom detection. This amplitude shall be decreased, since it will be influenced by i.e. seabed absorption and scattering. Also, amplitudes of sidelobes are registered, influencing the detection method and therefore the bottom determination. The influences of side lobes on the seabed is addressed in §4.3.2. Nevertheless, these returns always appear to be lower than the bottom \((ZF) Werf, 2010\).

The IHO specifies three methods where the amplitude detection is used \((B) IHO, 2011\):

1) "Leading Edge of the reflected signal", by setting a threshold and picking a range to where this will be first crossed. This method can only work with the nadir beam, since the returns at an incident greater than 0 will not have a sharp edge to set a threshold;
2) "Maximum amplitude of the reflected signal", where the bottom is defined, by the time of the strongest "peak" return (maximum backscatter strength amplitude);
3) "Centre of mass of the reflected signal", where the centre of mass (the weighted mean time) is computed. The samples used are within 10 dB \((X) Nilsen, 2007\) of the maximum amplitude.

On the other hand, the amplitude detection does also imply a filter/threshold at -80 dB, where most of the time a lot of noise is registered \((ZC) Weber, 2016\).

In Figure 15, the total result is given of all latter water column geometry options, to illustrate how amplitude detection looks at a pre-selected angle.
Note that the lines are for illustration purpose, not placed at the desired angle line in green. Eye-catching is the main peak (blue arrow) and the ("possible") side lobe peak in front (orange arrow). Since, the side lobe peak indicates a wreck or even a mast-like object. Figures 10 and 15 depicts the situation why this bottom detection method is commonly used for inner and nadir beams. Yet, when the beams are steered, the peak value will be hard to distinguish due to the side lob interference. Therefore, the next bottom detection method is needed to distinguish the bottom or midwater targets from noise and sidelobes contamination.

**Phase detection**

This detection method utilises the receiver array differently, since it is divided into two sub-apertures ((ZC) Weber, 2016). This principle is illustrated in Figure 16, where the term Split-Beam processing is introduced.

The figure depicts two beams, which receive a pulse from the same place but at a different time. In general, this shift in time can be determined whilst pointing the beam in the same direction resulting in an overlap. Hence, the return is out of phase and can be measured ((ZC) Weber, 2016). Also, when displaying the phase (in radians) relative to the range (in meters), a phase ramp can be seen. The phase ramp marks the zero crossing or the point of which the two beams are in phase. This crossing indicates the depth range.
To illustrate the phase ramp, Figure 17 is given, whilst steered at an angle of 40° and using a single head MBES.

![Figure 17 Zero crossing (ZC Weber, 2016)](image)

Note that this method cannot work, whilst the beam is near a nadir angle for a single head MBES. Since both sub-apertures will overlap each other through the whole water column, making it hard to determine the zero crossing of the phase. Using the phase ramp method, away from the nadir beams, does also have some uncertainties. These can be divided into three categories:

- **Signal-to-noise ratio (SNR),** where Figure 17 showed a relative high SNR, noise can influence the ability to disguise the phase ramp and therefore the bottom detection.
- **Baseline decorrelation,** "(...) the region corresponding to the main beam is returning a very distorted and noisy time series of phase differences." (ZC Weber, 2016, p. 21).
- **The shifting footprint effect,** which was proposed by Lurton in 2000, basically the two footprints are decreasing while the steering angle increases.

Therefore, to achieve the detection of a wreck (or the bottom for that matter), both methods are usually being used and compared. Where the amplitude detection is normally conducted first for determine for where the bottom should be, followed by the phase detection.

### Extra and Multi-detections method

The water column imaging tool logged far more data for only one or three soundings needed to determine the shallowest depth. Since the WCI method logs the complete water column between the vessel and the seabed. To limit these data files, multibeam manufactures introduced a new mathematical filter/method technique:

- **Extra Detections – Kongsberg Maritime**
- **Multi-Detections – Teledyne**

Essentially these detection filters the return of each beam for multiple detections along the receive beam axis in a fixed amplitude threshold, instead of collecting all the data (K Christoffersen). Consequently, when the amplitude is above the set threshold the echo will be defined as candidate, which will then be tested by the other bottom detection algorithms (private conversation K.E. Nilsen). Consequently, unnecessary data will be filter out, leaving the desired points of the midwater target. Although, setting a wrong threshold could filter soundings of that corresponds with the target. Therefore experienced knowledge is needed of this utility, before using it.

The differences between the Extra- and Multi-detections are the limitations of the quantity of allowable depths (L Damstra, 2016). The Extra Detections can divide the total water column in 7 classes, where Multi-Detection defines this in 5 classes.
For example, the Extra Detection can have class 1 to be 10 to 30% of the total water depth, class 2 30-60% and class 3 65-70% of the depth and so on (private conversation K.E. Nilsen). For each class the amplitude threshold, quality threshold and SNR limit can be set by the operator. The selection of the different classes depends on the type of target, target dimensions, complicity of the target construction and target height ([L] Damstra, 2016). Class 4 has shown the best results during the trials of latter research by Fugro B.V.

4.2.3 Angular and range resolution

For detecting an object, the angular and range resolution is directly related to the capability of detecting targets midwater. Figure 18 portrays how both resolutions are defined.

The distance between E and F is the angular resolution (AR) and the distance between range A and B, C and D are the range resolution (RR). *Note that these values are for illustration and do not represent the actual AR and RR of the EM2040c.*

**Angular resolution**

The angular resolution is the angular distance between the edges of the beam. When detecting a mast at a high resolution, the distance between the edges needs to be as small as possible. Giving a high AR will result in a better chance of detecting mast and/or wreck. For this thesis, the AR was set at 1° by 1°, which was the optimal resolution for the EM2040c.
Range resolution

The definition of the resolution in the range is the length of one pulse (shown in Figure 18). Consequently, when the range resolution decreases, the pulse length (between A & B of Fig.18) increases. This will result in a high SNR, but at a cost of detailed information of the target. Therefore, the RR should be high enough for detecting targets, whilst the SNR is relatively high. The resolution is strongly depending on the selected pulse length. To roughly calculate for the range resolution, the following equation can be used:

\[
\delta y = \frac{D}{\cos^2(\theta)} \theta_T
\]  

(8)

Where:
- \(D\) is the water depth;
- \(\theta\) is the steering angle;
- \(\theta_T\) is equal to "beam width of the transducer in the long track direction" (Z.A. T. Haji Mohammadloo, 2016)

To illustrate the range resolution of different steering angles (0, 15, 25, 45 and 60 degrees), the graph in Fig. 19 was made, using equation 8. The water column ranges from 1 to 25 m and the red line is the special-order uncertainty. Note that these are a-priori calculations and the figure is based on a commonly used single head MBES.

![Range resolution trough the watercolumn](image)

Figure 19: Range resolution of the nadir relative to the water depth (based on the EM2040c)

What strikes, is the range resolution increases linear relative to the water depth. Also, at a steered angle of 60 degrees away from the nadir, the range resolution decreases in such way that the resolution is expected to be a 0.64 m. Though, the inner angels remain below 0.2 m, making them acceptable for target detection when using a single head.
For this thesis, the Kongsberg EM2040c was equipped with a dual head configuration and was utilising different continues waves (CW) during the case study. In Table 2 the CW pulses are shown in microseconds and their corresponding names ((E) Kongsberg_Maritime, 2013).

<table>
<thead>
<tr>
<th>Pulse length (μs)</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Very Short CW</td>
</tr>
<tr>
<td>27</td>
<td>Short CW</td>
</tr>
<tr>
<td>54</td>
<td>Medium CW</td>
</tr>
<tr>
<td>135</td>
<td>Long CW</td>
</tr>
<tr>
<td>324</td>
<td>Very Long CW</td>
</tr>
<tr>
<td>918</td>
<td>Extra-long CW</td>
</tr>
</tbody>
</table>

The last two pulse lengths are used in relatively deeper waters than the wrecks of the case study with a considerable lower angular and range resolution. These, a-priori calculations, were determined by use of the latest version of AMUST (version 2.02 2016). The following additional settings were used for making the a-priori calculations:

- Sound velocity: 1481 m/s (Annex A)
- Openings angle: 60˚ (§5.4)
- Survey speed: 5 knots (§5.4)
- Water depth: 24 m (§5.1)
- Positioning: Marinestar-HP Fugro (§5.4)

The results are shown in Table 3, with the corresponding IHO order, the valid beams, and the total horizontal uncertainty.

<table>
<thead>
<tr>
<th>Name</th>
<th>TVU</th>
<th>Valid beams [°]</th>
<th>THU [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Short CW</td>
<td>Special order</td>
<td>0 - 65</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Short CW</td>
<td>Special order</td>
<td>0 - 64</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Medium CW</td>
<td>Special order</td>
<td>0 - 63</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Long CW</td>
<td>Special order</td>
<td>0 - 63</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Very Long CW</td>
<td>Special order</td>
<td>39 – 62</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Extra Long CW</td>
<td>Order 1a</td>
<td>37 - 70</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

The very short, short, medium, and long CW pulse lengths had the same a-priori results. Giving that all four could prove useful, whilst surveying with the inner beams. The opposite occurs, when using the very long and extra-long CW pulses. The very long CW could only work with valid beams steered at a minimum of 37 degrees, but loses the order when the beams were steered at a lower angle. The same holds for the extra-long CW pulse but instead of Special order, Order 1a was valid in the same region. Taken this into account, only these four categories of Table 2 were considered useful for the case study. The a-priori calculations of each individual CW pulse can be found in Annex B.
Effective beam width
The EM2040c is operating using an effective beam width, which is basically the width of the beam pattern at -3dB of the energy (integral) of the beam. For the EM2040c the Hammings shading is used, therefore when 35.4% of the normal pulse is just for the effective pulse ((I) Kongsberg Maritime AS, 2016). For instant, the Very-Short CW had a length of 37 μs, when applying the hamming’s shading the pulse length is 14 μs.

4.2.4 Target referencing
When analysing the WCD in the plots shown in Figures 9 to 11 of §4.1, the extracted data is in a raw state. This basically means that the depth value cannot yet be placed in a geodetic reference frame or nautical chart for that matter. The depth needs to be referenced to place them in a reference frame, with use of these three factors ((I) Beaudoin, 2010):

- Depression angle;
- Azimuth;
- Sound speed;

The depression angle and the azimuth are needed to determine the position of the receiving pulse. The sound speed is not only needed to calculate the water depth by use of equation 2, but also for ray-tracing (the travel path of the pulse). The water column consists of several layers, with changing temperature, pressure and conductively. Therefore, influencing the velocity at which the pulse propagates through the water column. This change in velocity causes the path being refracted by the law of refraction ((P) Hughes_Clarke, 2016). When a sound profile has been taken, these values can be determined and thus the reference position of the depth value.

Refraction uncertainties
Using incorrect values for determining/calculating the sound velocity or take a fixed value throughout the water column, introduces a vertical and a horizontal uncertainty in the position of the pulse ((I) Beaudoin, 2010). In Fig. 20 illustrates the uncertainty and the consequences of wrongly implementing the refraction.

Figure 20 Refracting errors in the water column ((I) Beaudoin, 2010)

The red lines in the figure indicate the wrongly implemented sound velocity, whilst the green lines represent the proper velocity. Hence the smile and frown terms, mentioned in the two polar plots, are the errors which will arise when targets are near the surface or at a considerable depth. The right-side of the figure shows the resulting error of the bottom detection, where around mid-water/mid-depth the errors are almost cancelled out. For instance, when a target is in one of the other categories, the pulse could be deeper or shallower than the real presentation.
This is shown in the left side of the Figure 20, since the green “real” bottom is presented lower at the smile artefact and higher at the frown.

4.2.4.1. Referencing

When the depth reference value (relative to the vessel) has been calculated, the coordinates should be transferred to a local plane. The local plane/coordinates system used for this thesis is a right-handed system shown in Fig. 21.

![Right handed coordinate system](image)

Figure 21 Right handed coordinate system ((S) J.E. Hughes_Clarke, 2006)

Hence, the roll is positive to starboard, the pitch is positive up the yaw is positive to starboard. Taking this into consideration, the coordinates can be recalculated into the desired reference frame. The frame used for this bachelor thesis was the **ETRS89 UTM zone 31** with a height reference to the **Lowest Astronomical Tide (LAT2006)**.
4.3 Sources of error

When detecting objects inside the water column, several sources could interfere with the results. The following sources of error can be identified: Acoustic dead zones (§4.3.1), Sidelobes (§4.3.2), Multipath (§4.3.3), Miss-tracking (§4.3.4), Interference (§4.3.5), Fish detection (§4.3.6) and Random noise (§4.3.7).

4.3.1 Acoustic dead zones

One of the sources of errors is the acoustic dead zones. These dead zones are located where the bottom power will over class the target in water column (ZD Weber, 2016). These zones behave differently when steering the beams away from the nadir or at the nadir. The size of the acoustic dead zone depends on the pulse length, the beam width, and the steering angle (ZD Weber, 2016). Resulting, an increase in pulse lengths and beam width will increase the acoustic dead zone. Whilst looking at the steering angle the nadir and oblique beams show different situations. In Fig. 22 the nadir beam is illustrated over a flat seabed.

![Figure 22 Acoustic dead zones nadir angle beams (ZD Weber, 2016)](image)

Here the centre pulse interacts with the seabed, showing an increase in amplitude and therefore assumed to be the bottom. Therefore, the edges of the beam, shown in red, will be marked as sidelobes. Still, this is relatively small when compared to the beams steered under an oblique angle. The zones at these angels will be larger in relation to the inner angels. Figure 23 gives an example of the acoustic dead zones generated by oblique beams.

![Figure 23 Acoustic dead zones oblique angle beams (ZD Weber, 2016)](image)
As shown due to the increase of incidence, the dead zone is bigger than the preceding zone of Figure 22. Therefore, when a target is located inside these zones, it disappears in the long trail behind the first return. A solution for this error would be to use beams close to the nadir and/or in the regions where the beams overlap (e.g. dual head MBES). Lowering the chances of that a filter cleans the target.

### 4.3.2 Sidelobes

There are two categories, of which the sidelobes can contaminate the soundings: the receiver and ghost-like sidelobes ((ZF) Werf, 2010).

**Receiver sidelobes**

A side effect of working with underwater acoustic is the existence of side lobes, especially when working with steered beams ((Q) Hughes.Clarke, 2016). The first arrival of the side lobes can be defined as the minimum slant range, by the arc of apparent solutions at the common range. The reason the MSR is lower at the nadir and overlapping beams, is because the side lobe backscatter strength increase while steering away from the nadir. The arc of the MSR increases when a stronger echo returns from the seabed, making it difficult to distinguish any mast-like target near de MSR ((ZF) Werf, 2010). To minimize the chances of contamination by the receiver sidelobes, the targets should be near or inside the minimum slant range ((ZF) Werf, 2010). Illustrated in Figure 24 are: the minimum slant range (the multiple green spot area) [1], the side lobe contamination of the data (the area bounded by the red lines) [2] and the side lobes generate near the wreck (the green spots underneath the wreck-like target) [3].

![Figure 24 Sidelobes contamination in the water column single fan view (HD147)](image)

When working with a mast-like target, coherent side lobes are generated depicted by [2]. These echoes are the vertical green stripes/lines in the water column ((ZF) Werf, 2010).

Another resolution for anticipating the side lobe errors/contamination is suppression by use of thresholds. Which are set at the corresponding side lobe amplitudes, generally -20dB which corresponds with the assumption of §3.1.1. Therefore, a part of the data shall be filtered leaving only the data from the main beam. Note that any target with low backscatter strength, could be filtered out even mast-like targets.
**Ghost-like sidelobes**

The ghost-like sidelobes are generated by the fact that those lobes will be transited in a front and behind the main lobe ((ZF) Werf, 2010). To the illustration of these ghost-like sidelobes, a single fan view was made of SR7285 (case study 1) in Figure 25.

![Figure 25 Ghost of wreck SR7285 (case study 1)](image)

This figure shows an (red encircled) possible wreck-like target, where the first hit is logged with lower amplitudes. This indicates the existence of ghost-like sidelobes. Nonetheless, these sidelobes will always appear at lower amplitudes than the actual depth amplitude. This gives the user a helpful analysis tool, since these echoes shows some detail and the location of the wreck-like target. Yet when wrongly interpreted, the user could identify these spots already as the wreck-like target introducing an error in the 3D point visualisation. Therefore, the amplitude levels should be check prior to the spot selection.
4.3.3 *Multipath*

The multipath could occur when detecting targets in midwater, in areas with existence of for instance quays, canyons or wreck-like targets. Basically errors concerning multipath are being introduced when the return of a pulse is reflected on targets or anomalies prior to the seabed ((T) Kuus). The effect of this source on the data is that the bottom is presented deeper than the actual bottom. In Figure 26 an example is shown of bottom miss-tracking in a flooded canyon ((S) J.E. Hughes_Clarke, 2006).

![Figure 26: Multipath](image)

Here the bottom is miss-tracked and a will be presented deeper than intended. When working with midwater targets, the bottom could easily miss tracked by the multipath error. Yet, with proper examination of the operator, these sources can be detected without using any filter.

Miss-tracking can also occur when a mast-like target is detected, but is defined as sidelobes. Since the pulse will propagate trough the water column, and hits the seabed resulting the algorithm to choose the highest return as bottom ((ZF) Werf, 2010)

In Figure 27 an example is shown, of how this error is manifested in the data at selected ranges.

![Figure 27: Miss tracking by multipath](image)

The echo at the selected range is just a few dB lower than the bottom detection, yet the first selected range represents a mast-like object. This will not be collected whilst using regular bottom detection methods. A solution for this error is the Extra-detection and WCI method. Therefore an incomplete occlusion can be prevented, by detecting or selecting multiple spots per beam.
4.3.4 Interference

Detecting targets requires sensitive tools, even when diminishing the number of filters. Therefore, a reflection of, for instance a SBES, could easily be picked up in the water column geometry and contaminated the results. This would make it hard to interpret the data and locate the height of the object in the water column. Still shutting down the single beam during the survey, would not solve all the problems concerning interference. The thruster wash from vessels and sea waves can cause interference in the water column. Figure 28 illustrates how a single beam and thruster wash interferes when using water column imaging.

![Figure 28 Passive sonar image (case study 1)](image1)

The contamination is clearly shown (the stripes and red encircled 'possible' thruster wash) and therefore advised not to use any acoustic equipment other than the MBES, during water column imaging surveys.

4.3.5 Fish detection

One of the fundamental error sources, while detecting midwater targets are fish and bubbles. Since the multibeam will also detect this as mid water targets. The instrument/method was and still is used for fishery purposes ((U) L. Mayer, 2002) and therefore ideal for getting a reflection in the water column. Theoretically speaking this will not cause any problems for a common MBES survey. Though for target detection it is important to be aware of this source, as the fish can intervene with the determination of the shallowest point(s). In Figure 29 an example is given of how fish contaminates (red encircled) the imagery of the water column.

![Figure 29 Fish detection stacked fan view (case study 1)](image2)

The fish can be found at the higher levels in the stacked view. Still in this example, the mast-like target was not present, but could be disguised by the present fish.
4.3.6 Random noise

The last noticeable source is the noise error. Here the noise is a summary name of all different types of external errors having an impact on the survey, but not as severe as the previous ones. This noise can be seen in the water column as miss tracks or false soundings and are most of the time hard to interpret. Nevertheless, this source can be determined using a stacked view, by the green colour inside MSR. In Figure 30 an example is shown in which the sounding cannot be classified as a depth sounding but also would not fit in the previous specified classes of error sources. For this bachelor thesis, these soundings will be classified as random noise.

![Figure 30 Random noise (case study 1)](image)

4.3.7 Error budget

To determine the vertical and horizontal accuracy of the measurement, the error budget or summaries of the whole measurement should be calculated. This has been conducted as follows:

\[ WCD_{\text{uncertainty}} = zPosition_{\text{uncertainty}} + Equipment_{\text{uncertainty}} \]  

(9)

Where:
1) \( zPosition_{\text{uncertainty}} \): The uncertainty in which i.e. the tide or GNSS
z-correction is applied to the data;
2) \( Equipment_{\text{uncertainty}} \): The random uncertainty of the used equipment;
3) \( WCD_{\text{uncertainty}} \): The uncertainty of the Water Column Data.

Yet, a fixed uncertainty value is hard to determine for the WCD, due variation of the environment, shape of the target and to the influence of the validation of the operator. Since every individual operator validates the data differently, a random error is introduced when selecting the shallowest points. Nevertheless, the error can be corrected by a second opinion from other surveyors/processors.

For this thesis the uncertainty of the WCD was determined by use of the cross check utility of Qimera. Therefore the individual datasets would be statistically analysed and checked if the order requirement was achieved.
5 Case studies and results

This chapter will address the two case studies on the 30th of March 2017 (§5.4) and on the 10th of May 2017 (§5.6). The methodology of those case studies is addressed in §5.3. The focus of §5.4.6 is the diving operation conducted by the Royal Netherlands Navy and §5.6 gives the comparison between the WCI and the diving results. The focus of Subchapter §5.8 is the final check between the wire sweeping tool and the WCD. Whilst the information leading up to the survey and case studies are given in §5.1 and §5.2.

5.1 Wreck information: SR7285

For the case study, SR7285 has been selected as a relatively unknown wreck. This wreck lies at location 52.1421861N; 3.90553E (UTM ETRS89 zone 31N). The information about the target was limited. The only information available was a relatively old survey report conducted by Rijkswaterstaat from 4th of May 1988. This report shows that the survey was conducted using a side scan sonar and an echosounder (probably single beam). In Figure 31 is the wreck shown on the side scan images.

![Side scan sonar image from wreck SR7285 (M)Directie_Noordzee, 1988)](#)

The assumption based on this data was made that the vessel was a metal (probably) fishing vessel. Therefore this target was ideal for a comparison between the WCI and diving method.

5.2 Wreck information: Boetak

The wreck Boetak was selected for the second case study and is located near the coast of Terschelling. The vessel sunk in 1945 and is a riveted steel tow vessel (private conversation Hilde Dieren, 2017). The location of the vessel is 53;21.20N; 005;14.95E (WGS84). Due to the vessels, long dimensions (length of 85m and a width of 10 m), and the vessel is ideal for this case study. The wreck is shown in Figure 32 on the side scan images, made during the Oosterom survey of the 11th of May 2017.
Consequently, this target is ideal for determining wreck-like target characteristics and comparing bathymetric data with user picks from the water column imaging.

### 5.3 Methodology

The case studies consist out of 5 different surveys. The case studies address the determination shallowest depth, whilst the second case study also in classifying wreck-like characteristics. These surveys can be distinguished by the runtime parameters. Since every survey will have a different setup. These setups can be disguised by the lines, logging data, runtime parameters, position stations and filters.

**Selecting lines**

For detecting targets the following aspects were taken into consideration:

- Inner beams close to the nadir and the overlap sector should use;
- Line spacing should allow the inner beams of both heads of the EM2040c to detect the target;
- The directions should be parallel and perpendicular with the direction of the target.

In Figure 33 is the line plan is given with a rectangular area, where the wreck is located in the centre. Note that the plan was both intended to be used for SR7285 and the Boetak and based on the intended depth and direction of the wrecks.
The line spacing is chosen for each survey as:

a. Lines 01 and 06 on top of the wreck;
b. Lines 02, 03, 07 and 08 with a spacing of 15m relative to [a];
c. Lines 04, 05, 09 and 10 with a spacing of 25m relative to [b].

Subgroup [a] uses the overlap sections of the EM2040c, by directly sailing over the wreck. For subgroup [b] the nadir beams of both heads were used, in subgroup [c] the least acceptable beam geometry was tested. The sailing directions were the same, except for subgroup [a]. Nonetheless, when the data of [c] proves to be unusable the line shall be discarded and only line sets [a] and [b] will be used.

Lines 05 and 04 could in this case also be used for a reconnaissance survey of the wreck SR7285. The sonar of the mv. Arca is the Klein 5000 and could be deployed in near the lines.

**Required data**

The data formats used for these surveys are the Kongsberg .all file. This is a Kongsberg format, including all the raw data. The water column data will be included in the .all format and can be found under the extension .wci. This includes water column and extra detections, logged by the EM2040c ((H) Kongsberg_Maritime, 2016).

The firmware of the EM2040c was 1.5.0, the QINSy software was 1.4.8.1. and the SIS was 4.3.2.
Runtime parameters
In Table 4 the different runtime parameters are given, with the date, target, pulse length, bandwidth, angular sector and change in filters. The frequency was originally intended to be at 400 kHz, but during the pre-tested while sailing to site the overlap between the two heads could not be achieved. Therefore, the frequency was changed until the overlap was acceptable to be used. The latter frequency is given in Table 4.

Table 4 Runtime parameters survey of SR7285

<table>
<thead>
<tr>
<th>Date</th>
<th>Object</th>
<th>PL (µs)</th>
<th>BW (kHz)</th>
<th>Angular sector (degrees)</th>
<th>Filters</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-3-2017</td>
<td>SR7285</td>
<td>50</td>
<td>320</td>
<td>65</td>
<td>Phase ramp: Short</td>
</tr>
<tr>
<td>30-3-2017</td>
<td>SR7285</td>
<td>100</td>
<td>320</td>
<td>65</td>
<td>Phase ramp: Normal</td>
</tr>
<tr>
<td>30-3-2017</td>
<td>SR7285</td>
<td>50</td>
<td>320</td>
<td>65</td>
<td>Phase ramp: Normal</td>
</tr>
<tr>
<td>10-5-2017</td>
<td>Boetak</td>
<td>27</td>
<td>320</td>
<td>65</td>
<td>Phase ramp: Normal</td>
</tr>
<tr>
<td>10-5-2017</td>
<td>Boetak</td>
<td>14</td>
<td>320</td>
<td>65</td>
<td>Phase ramp: Normal</td>
</tr>
</tbody>
</table>

Note that only the phase ramp was changed during the case study, the other filters were kept on the following settings:

- Slope: OFF
- Aeration: OFF
- Interference: OFF
- Penetration: OFF
- Range gate size: LARGE
- Spike filter strength: OFF
- Special amp. Detect: OFF
- TVG: ON

Positioning
The tide stations and GPS equipment utilised for the case study were selected afterwards. The stations where:

Table 5 Used positions stations

<table>
<thead>
<tr>
<th>Station</th>
<th>Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheveningen (LAT)</td>
<td>SR7285</td>
</tr>
<tr>
<td>06-GPS</td>
<td>Boetak</td>
</tr>
</tbody>
</table>

The data for the tide for the first survey was collected by RWS at an interval of 10 minutes.
5.3.1 Filters

The following four filters were of importance during the case study:

- Penetration;
- Range gate;
- Spike filter strength;
- Phase ramp;

The other settings were not being used during the survey and were switched off.

Penetration filter

The penetration filter is used to minimize the possibility of tracking detections in lower sediment layers in the seabed. The main features for this filter are:

- Uses the same frequency for port and starboard sectors;
- Priorities the first instead of the strongest echo from the central beams.

Whilst the last feature could provide promising imagines, it was advised to shut off (O) Fenech, 2016. For this reason, the filter was left off during both case studies.

Range gate filter

The range gate filter is specified for determining the size of the bottom detection window. The limits of the range gate were defined by the information of previous returning pulses. In Figure 34, an example is given of how the filter operates.

As shown, three options are available for this filter: small (Rmin), normal (black line), and large (Rmax). The large range setting is advised to use when surveying depths varying more than 10% of the total water depth (A) Kongsberg_Maritime, 2013). The side effect of using a large range gate is the increase of noise in the data. A small rage gate will have the opposite effect, less noise but also a decrease in bottom detection. For these case studies, the range gate is set on large, since the wreck could be changing largely in depth relative to the total water depth.
**Spike filter strength**

This filter chooses the rate of samples filtered out of the total data set ((E) Kongsberg_Maritime, 2013). The filter has four options which can be selected: OFF, WEAK, MEDIUM and STRONG. For target detection, the option “OFF” was advised, since soundings of any target could be a deviation from a smooth bottom.

**Phase ramp**

The phase ramp was defined in §4.2.1. as the bottom detection slope in the phase detection method. Basically, this filter sets how much samples are being used for the detection of each depth ((A) Kongsberg_Maritime, 2013). There are three options for choosing the right phase ramp: SHORT, NORMAL and LONG. The SHORT option will give a better detection (higher resolution) but will introduce more noise as it takes more samples in consideration. The opposite can be chosen with the LONG setting, as this will reduce the noise but at the cost of seabed/target resolution. The NORMAL has a bit off both, having a reasonable good resolution relative to the SHORT option and a limited amount of noise contamination in the data. For this case study, the SHORT and NORMAL option were studied. The LONG option was invalid for this type of survey, due to the decrease in resolution.

**Tracking mode**

The last option for improving the water column data is the detector mode of the EM2040c. There are four modes:

1) Normal, is a based on a standard detector mode with an improved multipath rejection filter. The mode assumes a contiguous bottom ((C) Kongsberg_Maritime, 2013). Still detecting mast-like target is less likely, due to the ping-to-ping filter. As this filter would keep track of the bottom, but will see a mast as a spike or side lobe.

2) Minimum depth, which detects the shallowest depth no matter what. This makes it ideal for midwater target detection.

3) Tracking, practically the same as the minimum depth mode, but with a weak filter. Therefore, fish and possible objects could be filter out of the data. Also, this mode will track any targets or sudden changes regarding the water depth.

4) Waterway, gives a better bottom detection between e.g. walls and seafloors. Working at the same principle as the tracking mode.

For detecting targets on the seabed, such as wrecks like the Boetak and SR7285, the mode, minimum depth, was advised ((O) Fenech, 2016). Since the analysis of the all target detection surveys required unfiltered data.
5.4 Survey results of wreck SR7285: Case study 1

5.4.1 Quality check
To guarantee the quality set in §3.3, a patch test was conducted. To gain survey time, the location was altered so that the survey could continue. Instead of utilising the slope on the far end of the survey area, the wreck proved to be valid. The test was conducted during the Medium-CW survey. The results are given in Table 6.

<table>
<thead>
<tr>
<th>#</th>
<th>Head 1 (PS)</th>
<th>Head 2 (SB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
<td>39.850</td>
<td>-39.420</td>
</tr>
<tr>
<td>Pitch</td>
<td>-0.589</td>
<td>-0.040</td>
</tr>
<tr>
<td>Yaw</td>
<td>0.190</td>
<td>-0.330</td>
</tr>
</tbody>
</table>

The Z-check/validation of the Arca were valid till 28th of June 2017 and therefore considered acceptable. For the final check of the area, a historic site check (20/12/2016) was conducted. This dataset was logged using the Netpos position corrections and therefore suitable for a quick Z-check. The data was not matching the historic since, the draft needed to be corrected since the .all files were not adjusted it. The correct draft was 5.3 m relative to the centre of gravity (COG).

The average sound velocity during the survey was stable around 1481.5 m/s, indicating a stable water column. The complete profiles were used for the raytracing and are included in Annex A.

5.4.2 Side scan sonar results
In addition to the water column survey, the side scan sonar (SSS) survey was performed during the last survey. The SSS survey included three lines, all parallel to the wreck. The results are included in Annex B. One of these results is shown in Figure 35. The three locations, which could have the least depth, were marked with a red circle.

Figure 35 Side Scan Sonar image of wreck SR7285

Also, the total length of the wreck could be determined, which was 42 meters.
5.4.3 Medium CW– short phase ramp

The first survey used the Medium CW pulse, with a short phase ramp filter. The line scheme is depicted in Figure 36.

![Medium CW, Short phase ramp - survey tracks](image1)

A total of six lines were utilised for analysing the first survey, with the following name code: line0002; line0003; line0004; line0005; line0007; line0010. The missing lines (0006, 0008, 0009) could not be used, since the outer angles (±65°) did not hit the wreck and/or could not be distinguished from the effects described in §4.3. The maximum distance between the lines and the target was ±38 m. In Figure 37 the situation is shown, of the beams which did not reach the wreck.

![Outer beams Medium-CW-Short phase ramp](image2)
For verifying, if any mast-like target was located within the minimum slant range, a stacked fan view was made of line 0003. The situations are depicted in Fig. 38, where the red colour represents the highest return in amplitude and blue the lowest.

The figure shows three possible features given in Figure 38, which could have the shallowest point(s). Yet, a distinctive mast-like target was not detected in the several across-track stacked plots. Therefore, the assumption was made that the features, given in SSS image of the Figures 35 and the stacked fan of Figure 38, were the shallowest depth.

The last step prior to analysing the dataset, was the estimation of the IHO order regarding the TVU addressed in §3.2 and Annex B. In Fig. 39 are the results depicted of the cross check, which shows a scatterplot with the depth bias relative to the beam angle. The yellow dotted line represents the IHO special order, whilst the blue line shows the mean bias with the pink standard deviation envelope.

The average depth bias is based on the difference between the different lines. Where the scattering between -45° to 45° of the pink standard deviation envelope was within the special order. Since the mean difference was ±0 m and the average standard deviation was 0.0378 m, so the data was accepted to be processed and used in the analysis.
**Analysis**

To compare and determine the optimal surveying method, three line groups were made:

A. Across-track: Line0003 & 0006  
B. Along-track: Line0002; 0007;0010  
C. All lines: Line0002;0003;0006;0007;0010

The maximum distance between outer line0007 and the target was ±22 m. Therefore, the overlap and inner beams would be hitting the target adequately. For this analysis, the main and extra-detections were used to determine the shallowest point(s). In Figures 40 to 45 are the groups shown with the corresponding 3D view. In this 3D view the aft of the vessel is shown ((ZB) Veen, 2017) with the two other shallow targets of the Figure 35.

- **Group A**
  
  ![Figure 41 Group A – Point Cloud – Medium CW, Short Phase ramp](Image)

- **Group B**
  
  ![Figure 43 Group B – Point Cloud – Medium CW, Short Phase ramp](Image)

- **Group C**
  
  ![Figure 45 Group C – Point Cloud – Medium CW, Short Phase ramp](Image)
After the point cloud analysis, the aft wreck was considered to be the shallowest. The shallowest depths of the aft from the line groups were determined by creating S-curve graphs. These graphs gave the amount of points which established the shallowest depth. The S-curve of the last group is depicted in Fig.46.

![S-Curve Medium-CW-Short phase ramp Group C (grid 0.01 x 0.01 m)](image)

The results of the three line groups are given in Table 6. In the table are the shallowest depths and the amount of points shown.

<table>
<thead>
<tr>
<th>Lines</th>
<th>Depth</th>
<th>Point(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-20.075</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>-20.175</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>-20.075</td>
<td>1</td>
</tr>
</tbody>
</table>

The outcome showed: that an increase of lines resulted in a shallower depth whilst analysing it in a 0.01x 0.01 grid. Yet, the change was not significantly (only 0.10 meter). So indicating that there was no correlation between using only across or along track lines for these lines groups.

The deviation between the multibeam data and the water column data was established by using a very weak spline filter over the shallowest multibeam data. Since a filter/manually point cleaning were needed, the comparison with bathymetric data was discarded.
5.4.4 *Long-CW*

For the Long-CW survey, the outer most lines proposed in the survey plan (§5.3) were unreliable and therefore not surveyed. The lines for the Long-CW survey are depicted in Figure 47.

![Figure 47 Long CW - survey tracks](image)

The line numbers were: 0031, 0032, 0033, 0034, 0035 and 0036.

To illustrate the target whilst using the Long-CW pulses, a stacked view was made of line 0036 depicted in Figure 48. The colour scale was based on the backscatter strength of the signals, which were: -63dB to 22dB. Therefore, a more distinct view of the target could be made.

![Figure 48 Stacked fan view Long-CW](image)

Noticeable in comparison with Fig. 38, was the degradation of resolution of the vessel and the amount of noise in the water column. Nevertheless, the aft of the vessel can still be considered as a representation of the shallowest depth.
The statistical analysis of the Long-CW data set is shown in Fig. 49. The figure shows the scatterplot of the data distribution, where the depth bias is relative to the beam angles. The yellow dotted lines show the IHO standard levels.

The striking feature of this plot was at the outer beams at -65°. Here the depth bias rises to 17 (m) at this angle, which is caused by the unfiltered soundings. This underlines the fact that the inner beams should be used for analysing the WCD, since the lines were within the IHO special order. With an average depth bias (blue line) of this survey was -0.065 m, with a standard deviation of 0.102 m.

**Analysis**

For the analysis three line groups were made, which could provide the optimal and the most reliable shallowest points of the target. The groups were based on the direction and distance to the aft of the vessel. The groups were:

- **A.** Along-track: Line0031, 0033 and 0035
- **B.** Across-track: Line0032 and 0034
- **C.** All lines: Line0031, 0032, 0033, 0034, 0035 and 0036

For this survey, the maximum distance between the lines and the target was ±11 m. Like the previous survey, the extra detections and main detections were utilised in the production of the 3D point clouds and analysis of the shallowest point(s). In Figures 50 to 55 these plots and the corresponding lines are given.

- **Group A**
The Figures show a detailed aft of the target, whilst using multiple lines in opposite sailing directions. To determine the depths of these three groups, S-curves were made of the different line groups. The S-curve of the last section is given in Figure 56, with the number of cells relative to the water depth.
The graph shows a high density in the lower areas of possibly the front of the target, which was most likely the deck. Whilst the depth decreases, the number of points declined to a minimum after -20.975 m.

The results from the S-Curves of the different groups are given in Table 8, where the shallowest depth in meters with the corresponding number of soundings indicating this depth.

<table>
<thead>
<tr>
<th>Line selections</th>
<th>Depth</th>
<th>Point(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-20.175</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>-20.375</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>-20.175</td>
<td>1</td>
</tr>
</tbody>
</table>

Like Table 7, the results were similar when concerning the amount of survey lines. This benefits the reliability of the depth value, by creating redundancy in the data. The depth values differs only +0.125 m. Yet the amount of points indicating the depth is relatively slim, with 1 point giving the shallowest depth.
5.4.5 *Medium-CW*

The final survey of case study 1 was focused on using Medium-CW pulses. The only difference was the absence of any filters and particularly the phase ramp, which was put back to normal. For this survey, considerable more survey lines were sailed than the previous two. Therefore, a high redundancy in the data over the wreck SR7285 was achieved. The tracks of the survey are shown in Fig. 57.

![Medium CW - survey tracks](image)

The maximum distance between the survey lines and the target was ±27 m, indicates that the inner beams of some of the outer lines did not hit the target.

The following line numbers for the Medium-CW survey were used: line0015, 0017 up to and including line number 0030 (except for 0022 & 0023 for their sailing track instability).

The stacked view was made for the determination of potential mast-like targets and the shallowest depth. For the Medium-CW survey, line0020 was selected which is given in Figure 58.
Like the previous stacked views, Figure 58 showed that the aft of the target would have the shallowest point(s). Note that the green circle above the wreck was most likely fish or air bubbles in the water column, which should therefore not be mistaken for a mast-like target.

Just as for to the previous surveys, a statistical scatter plot was made with the depth bias limit set at the IHO special order TVU requirements. The outcome of the scatterplot is given in Figure 59, where the depth bias is relative to beam angle.

Similar to Figure 49 the beam angle of -65° gave a result outside any IHO order. This, again, recommends the use of the inner beams for water column surveys. Therefore, lines should be planned close to the wreck, which allows the use of the inner beams. The standard deviation envelope stayed within the special-order specifications, i.e. average mean of 0 m and standard deviation of 0.0754 m.
**Analysis**

The analysis was made using five lines groups from the across- and along-track lines, inner lines, and outer lines. These corresponding groups are:

A. Along-track: Line0015;0024;0028
B. Outer angles: Line0017;0021;0025;0026
C. Across-track: Line0018;019;0020;0027;0029;0030
D. Inner angles: line0015;0018 0019; 0020; 0021;0024;0027;0028; 0029
E. All lines: Line0015;0017;0018;0019;0020;0024;0025;0026;0027; 0028; 0029; 0030

The 3D point clouds of the analysis of the Medium-CW survey are given in Figures 61 to 69:

- **Group A**

![Figure 61 Group A – Point Cloud – Medium-CW](image1)

![Figure 60 Group A – Tracks – Medium-CW](image2)

- **Group B**

![Figure 63 Group B – Point Cloud – Medium-CW](image3)

![Figure 62 Group B – Tracks – Medium-CW](image4)
• Group C

![Figure 64 Group C – Tracks – Medium-CW](image1)

![Figure 65 Group C – Point Cloud – Medium-CW](image2)

• Group D

![Figure 66 Group D – Tracks – Medium-CW](image3)

![Figure 67 Group D – Point Cloud – Medium-CW](image4)

• Group E

![Figure 68 Group E – Tracks – Medium-CW](image5)

![Figure 69 Group E – Point Cloud – Medium-CW](image6)

Noteworthy, is the extended part of the vessel of Figures 65, 67 and 69, which were produced by using the across-track lines. Also, this part portrays the complete wreck detected in the water column. To determine the shallowest point(s) of the aft of the target, corresponding S-curves of the front were produced. Figure 70 depicts the curve of the line group E.
The graph shows that the shallowest depth will be between -21 and -20 m of the total water column. These graphs were re-produced for all other the line groups, determining the different shallowest point(s) of the target. In Table 9 the results are given, with the depths and the amount of points representing this.

Table 9  Results Medium-CW

<table>
<thead>
<tr>
<th>Lines section</th>
<th>Depth</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-20.33</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>-20.33</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>-20.25</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>-20.25</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>-20.25</td>
<td>5</td>
</tr>
</tbody>
</table>

With Table 9, it can be concluded that an increase in survey lines provided a shallower depth with a higher point density, which is consistent with the previous results where the difference between [B] and [D] were +0.08 m. Therefore, lines at 25 m to 27 m away from the target resulted in a deeper or less legit depth, than when lines close to the target were used.
5.4.6 Royal Netherlands Navy diving operation

The diving operation was conducted on the 10th of May 2017, by the Royal Netherlands Navy. The divers of the mv. Nautilus was equipped with a SAIV A/S tide recorder Model TD304 (resolution of 1 pa) and dove to the shallowest depth of the wreck. The period the sensor was attached to the shallowest depth was between 3 to 4 minutes. Therefore, the variations caused by surface waves were corrected. The surface start location for the divers was determined by a mobile GNSS receiver. Therefore, the divers could drop the anchor and position a dive line at the pre-selected location.

A total of 2 dives were conducted used to validate the results, which showed that the divers did found the shallowest depth.

The outcome of the diving operation revealed that the shallowest depth of SR7285 was \(-20.18\) m relative to LAT2016.

*The reader is revered to the diving report made by the Royal Netherlands Navy of further details.*
5.5 Depth comparison

To compare the WCD and the results of diving operation, the following equation was utilised

$$\Delta_{\text{depth}} = \text{Diver}_{\text{depth}} - \text{WCD}$$ (9)

Note that a positive value indicates the data of the water column would be deeper than the results of the diver. In Table 10 the line groups are shown with the difference between the shallowest point(s) and the near absolute depth. The determined depth differences are given the following abbreviations:

- Medium-CW with Short phase ramp: M\_SP-line scheme code
- Long-CW: L-line scheme code
- Medium-CW: M-line scheme code

The depths variations were given in meters.

<table>
<thead>
<tr>
<th>Line groups</th>
<th>( \Delta_{\text{depth}} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M SP-A</td>
<td>-0.11</td>
</tr>
<tr>
<td>M SP-B</td>
<td>-0.010</td>
</tr>
<tr>
<td>M SP-C</td>
<td>-0.11</td>
</tr>
<tr>
<td>L-A</td>
<td>-0.010</td>
</tr>
<tr>
<td>L-B</td>
<td>+0.20</td>
</tr>
<tr>
<td>L-C</td>
<td>-0.010</td>
</tr>
<tr>
<td>M-A</td>
<td>+0.17</td>
</tr>
<tr>
<td>M-B</td>
<td>+0.15</td>
</tr>
<tr>
<td>M-C</td>
<td>+0.070</td>
</tr>
<tr>
<td>M-D</td>
<td>+0.070</td>
</tr>
<tr>
<td>M-E</td>
<td>+0.070</td>
</tr>
</tbody>
</table>

The depth differences with the diving operation were within the TVU of the special-order limits (i.e. within ±0.3m), when assuming that is the nearest absolute depth determination. Nonetheless the operator selects the soundings manually, so the amount of hits was expected to be lower than using an algorithm and could explain the differences.

Noteworthy the amount of survey lines improves the variation with almost +0.10 m. Indicating, that at least six lines should be considered for target detection surveys. Another striking feature was the difference in using Medium-CW with and without the phase ramp. The phase ramp gave a shallower result in all the lines relative to the diving results than without. So, a short phase ramp would improve the depth determinations. Yet, additional research will be needed to test this assumption, since only one survey used the short phase ramp.

Concerning the different pulse lengths, the results gave a constant trend: the amount of lines improved the shallowest depth value. Since the average difference of all the survey lines was +0.041 m. However, no correlation could be found between using only along- or across-track direction lines. Since, for instance, the Medium-CW gave two different results, considering the two sailing tracks.
The different pulse lengths at -20 meters gave the same results as the pressure sensor of the diving operation.

When reflecting on previous research on the matter, comparisons gave a similar result. In one of the researches conducted by NOAA, the difference between a diver and the water column imaging was 0.01 m to nothing ((R) K. Wyllie, 2015). This indicates that the method when used properly, would give the same results as wire sweeping systems or diving operations.
5.6 **Survey results of the Boetak: Case study 2**

To examine the Very Short-CW, Short-CW and single swath of the EM2040c, a survey was conducted over the Boetak. The results from the survey addresses:

1) Validation of the latter line plan;
2) Comparison between Short-CW and Very Short-CW pulses;
3) Typical characteristics of wreck-like targets in the water column;
4) Comparison between bathymetric data and WCD.

This survey consisted out of 12 lines using a single swath, with six lines for Short-CW pulses (yellow) and an equal amount for Very Short-CW pulses (white). In Figure 71 the different tracks are depicted in white and yellow.

![Figure 71 Plane view Short and Very Short CW pulses](image)

The figure shows a contradicting view on the tracks than the intended survey plan, specified in §5.3. Yet, the line scheme proved too difficult and dangerous in the area, since Boetak lay too close to a shallow area. The total under keel clearance between the target and the vessel was around 3 meters.

Nevertheless, this situation reflects the climate of every future surveys. Because, not all target detection surveys can be performed with the ideal circumstance like the latter case study. To see if these plans had any influence on the point density or the shallowest depth, point clouds were produced with the water column utility in Qimera, the results are given in Figures 72 and 73.
Remarkable is the amount of points collected over the target in comparison with the latter surveys. This could be explained due to the low water depth and use of smaller pulse lengths. Although, this seems promising, the along-track resolution was considerably less compared to using the dual swath mode. Yet, despite the degradation in along-track resolution, the geometry itself showed far more distinctive features in the water column than during the survey of SR7285. This would be ideal to characterize certain aspects of the wreck-like targets. Even a mast-like target could be present in the encircled area of Figures 72 to 73. The assumption can be made that the not the pulse length but the number of lines, direction and speed influences the results of the water column imaging.

The encircled object of Figure 72 was used for determining the typical characteristics of wrecks-like targets midwater. In Figure 74 is a snapshot showing the first feature of characteristics from the Short-CW pulse over the target.
Fig. 74 portrays three noticeable slant ranges (in red encircled), at different water depths. These three ranges originate from a mast-like target, a target and the seabed. The variations in MSR can be noticed when examining each beam individually.

The top slant range on the left of the Figure 74 was most eye catching feature. This could indicate an object with a high reflection or amplitude level on a shallow depth. However, the other two features are as important as the first one. Since, the features describe a midwater target and knowledge of mast-like target. Thus, the slant ranges give the operator an impression of how the target is distributed in midwater. These features arose each time a wreck-like target was analysed. Yet, further research will be needed to confirm this was a typical characteristic of wrecks in the water column.

The second feature of midwater wreck-like targets was the intensity levels/amplitude thresholds. This threshold can be selected by changing the colour scale of the water column between the two receiving amplitude levels. In Figure 75 and 76 the typical amplitude thresholds are depicted with the corresponding colour range setup.
In Figure 76, the colour range layout is shown corresponding to the single fan view of Figure 75. The typical scale range for such midwater targets is around -40 up to and including 13 dB. This eliminates any unwanted sidelobes and keeps a clear view for the operator for selecting the spots related to the target without picking a wrong shallowest point(s). Note that this utility cannot be used for spot selections in stacked fan views.

The third feature which is a typical characteristic of all the targets (wreck-like or not) in the water column, is the low amplitude reflection around the sounding itself. In Figure 77 an example is shown of the shallowest reflection of the Boetak (see Figure 74 and 75 for the complete view).

The green colour is here -17.14 to -6.61 dB, giving a wide range of possibilities to what the actual depth of this spot is. For this thesis, only the yellow and red spots were considered for the wreck. Whilst the green spots where only pick for the wreck, when a mast-like target was detected (HD147, Boetak).

Another aspect for wreck-like targets was the number of spots with low amplitude below mast-like targets. Figures 78 (HD147) and 79 (Boetak) portrays two example of these 'green' spots.
With the help of stacked views, a mast-like target became visible over the midwater target. However, the results shown in Figures 78 and 79 did not give a distinctive confirmation. Since the green spots were this time part of the complete mast-like target, rather than a sidelobes reflection. Therefore, the suppression tool or a high the threshold range could filter out the details of the mast. Yet, the shallowest depth representation is kept in the single fan views. Although this sounds as an advantage, these spots can also be classified as fish or air bubbles. Henceforth, the operator could be ignored without proper information of the target. Note that the green spots (encircled in orange) in Figure 78 were illustrating examples of errors regarding: occurring sidelobes and/or multipath.

Thus, the threshold could help in this case for the determination of the shallowest point(s) but diminishes details of the mast-like targets by filtering wanted green spots.

The last purpose of these survey results was to address the shallowest depth in comparison with historic data. However, due to errors in the draft and position corrections of the GNSS, the results were unacceptable for comparison with the bathymetric data of the Oosterom. Yet the difference between the shallowest points in short and Very Short-CW was - 0.1 m. So, the Short-CW should be giving a shallower depth than Very Short-CW pulses. Still, this is an assumption based on comparing both point clouds without any absolute depth or matching with other bathymetric surfaces.
5.7 Wire sweeping vs WCI
To confirm the conclusions made in §5.5 and §5.6 a wreck survey was conducted with the Roompot over the target NCN1653 on the North Sea near the province Zeeland (The Netherlands). The target was surveyed using automatic settings of the water column imaging and a wire sweeping tool. The settings are given in Annex E of the appendix. The line scheme for this survey is depicted in Figure 80.

![Figure 80 Plan view target survey](image)

The line scheme varies somewhat from the intended survey plan, nevertheless the cross check conducted of the lines gave that the standard envelope was mostly within in IHO Special order (an average standard deviation of 0.152 m). The parts of the envelope outside the level can be explained by the fact, that the data was unfiltered and the huge depth variation relative to the seabed (ΔZ of ±5 m over an area of 4 m in length). Note that the assumptions made by AMUST calculations of Annex B were also valid for this survey. The results are given in Figure 81.

![Figure 81 Cross check target survey](image)

Hence, the water column data can be used for the final check between wire sweeping. The 3D point cloud is added to the annex Roompot, whilst the results of the WCI and the wire sweeping methods are given in Table 11, in meters. For the comparison is the WCD subtracted from the Wire sweeping.

<table>
<thead>
<tr>
<th>Table 11 Wire sweeping vs WCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
</tr>
<tr>
<td>Wire</td>
</tr>
<tr>
<td>WCI</td>
</tr>
<tr>
<td>Comparison</td>
</tr>
</tbody>
</table>
Concluding, the results show little variation between the methods. Therefore, the assumption can be made that using auto setting for pulse section would result in an accurate shallowest depth. Still, the explanation in the variation of shallowest points can be found in several error sources including, the stiffness of the wire, and the low redundancy of the survey and setup parameters which were not perfectly for target detection. Yet, using the recommended line plane and run parameters could give the same or even a better result than the wire sweeping system.
6 Conclusions and recommendations

6.1 Conclusion

With the results from the desk and case studies, the subject and the other sub questions, defined in §1.2, were answered:

- **What are the ideal sectors in a dual head multibeam survey at Rijkswaterstaat?**

The ideal sectors of the MBES utilising dual swath were the most inner beams and the overlapping swath of under the vessel. Yet, the first case study showed that the frequency of the EM2040c influences the overlap of both heads. So, the frequency should be kept around 320 kHz resulting in a sufficient overlap. Also, the different continues waves did not affect the outcome of the water column picks. Hence, the auto pulse mode should be used during future wreck surveys.

- **What are the sources of error in the water column?**

The desk study showed that the sources of error, whilst working with water column data are: Acoustic dead zones, Sidelobes, Multipath, Interference, Fish detections and Random noise. These sources influence the data and the ability of the operator for selecting the corresponding spots of the wreck-like target.

- **What is the IHO standard and accuracy levels for wreck surveys using water column imaging?**

Both the AMUST calculations and the results of the case study showed that, wreck-surveys at the North Sea of -20 meter water depth were within the standards of the IHO special order. Since the inner and nadir beams were mainly used during the analysis and the different cross checks gave that the mean difference and standard deviation was within the 0.3 depth bias. In addition, the data was influenced by the positioning z-corrections (GNSS or tide), uncertainty of the equipment and the validation of the users. Yet, a fixed uncertainty value is difficult to determine for the WCD, due variation of the environment, shape of the target and to the influence of the validation of the operator. Since every individual operator validates the data differently, a random error is introduced. Nonetheless, the error can be corrected by second opinions from other surveyors/processors. Therefore it was concluded that the IHO special order can be required as minimum for wreck-like surveys at the North Sea.

- **What are the characteristics of a typical wreck in the water column?**

The survey conducted in the second case study was focused on determining the characteristics in relation with the SR7285 and the wreck surveyed in previous research. Four returning aspects could be determined, which were:

1. The different slant ranges in one single fan view;
2. The intensity levels of wreck-targets are between -40dB up to and including 13dB;
3. A low amplitude reflection around the sounding at steel (riveted) wreck-like targets;
4. The number of low in amplitude spots below mast-like targets.
What are the differences between the "real" and determined shallowest depth?

With the results from case study 1 at the North Sea, the difference between with the diver survey and the WCI method was computed. The outcome showed that the points were within the TVU of the special-order requirements, i.e. within ±0.3m. The average difference between the diver and the determined shallowest depth was 0.041 m. Since, the individual pulses did not vary much from each other, it can also be concluded that the different pulse lengths at -20 meters gave the same results as the pressure sensor of the diving operation.

What is the optimal survey method for wreck surveys?

The results of the case study from SR7285 and the Boetak showed that the amount of lines would improve the reliability of the shallowest depth. Since a consistent trend was shown with the other surveys when increasing the amount of surveying lines. Nevertheless, no connection could be found between using only along-or across-track direction lines. Also, by only using lines without the overlapping sector of the EM2040c caused a variation of +0.11 m relative to the diving operation. Yet, the difference was within the special-order requirement. Therefore, the optimal survey method should consist out at least of six lines: were half of the lines in the direction of the wreck and an equal amount in a perpendicular direction. Although these lines are designed for a water column survey, an optimal wreck-like target detection surveys should include a side scan sonar survey.

Can water column imaging be a replacement for wire sweeping or diver surveys?

Based on the findings of case study 1, §5.8 and on historic research, the water column tool could serve as a replacement for the wire sweeping tool. Since the results of the Roompot survey gave a difference of -0.10 m and historic research data 0.01 m. Considering that the average difference was 0.041 m, it can be assumed that wire sweeping and/or diving operations would give the same result as the water column imaging tool.

How can water column imaging be an aid for wreck surveys at Rijkswaterstaat?

With the results of the desk and case studies it can be concluded that the water column imaging is able to aid the wrecks surveys as primary method for future and current wreck surveys at Rijkswaterstaat. Since, wrecks can be well distinguished from the contamination by sidelobes and/or other sources of error. Also, the depth variations are within the IHO special order and can therefore be considered as a replacement for wire sweeping methods.
6.2 Recommendations

For future midwater detection surveys, it is advised to use the following setup, which was based on the results of this bachelor thesis.

6.2.1 Recommendations regarding future wreck surveys

Proposed setting and survey guidelines

Pulse length
Based on the conclusions, the automatic CW pulse length option should be used. Yet, the higher pulses lengths are limited due to the recommended dual swath option. Therefore, more hits on the target can be guaranteed at an increased along-track resolution.

Use of filters
For the midwater target detection surveys, it is recommended to use as little filters as possible. The few filters/options which should be considered are:

- The phase ramp: normal
- The spike filters off and
- Range gate: large.
- Detection mode: Minimum depth
- Beam spacing: Equiangular

The phase ramp is advised to remain on normal, yet further research will be needed to confirm the results of §5.5

Use of Extra Detections or water column imaging
Since this research did not focus on finding the difference between extra detections and the water column imaging results, it is recommended to only use WCD. Further research will be needed to confirm if the method of only using extra detections would prove useful for target detection surveys.

Line scheme
Depending on the water depth and the direction of the target, the line scheme should be consisting of at least six lines:

- Three lines in an along direction of the target;
- Three lines in an across direction of the target.

Whilst one of each line section, should have an opposite heading. Therefore, the inner beams (the cross section of both heads) and the overlap of the individual heads would log the shallowest point(s) of the target. Also, any errors relating to the mounting errors could be localised.

Distance to wreck
The maximum distance of the wreck-like target depends on the water depth and the mounting angle of the EM2040c. For instance, the mounting angle is 39° and the water depth is 20 m, the maximum distance would be: ±24 m.
Survey speed
The survey speed of the vessel is recommended not to be faster than 5 knots over ground. Even when the dual swath option is used, this will result in a higher along-track resolution.

Reconnaissance survey
Like the case studies, a reconnaissance survey is required. Since, this can be used for visualisation of the location of the shallowest depth of the target. Therefore, a solid line scheme can be made, optimised for the target at hand.

Side scan sonar survey
A side scan sonar survey is required, which should be used to get a more detailed view of the target.

Proposed workflow
To analysing the water column data the following workflow in Qimera is proposed:

1. Bathymetric data should be checked by the cross-check utility for the spreading of the data;
2. Stacked plots should be analysed of the across track lines for mast-like targets and/or the location of the shallowest point(s) of the target;
3. The spots representing the shallowest depth of the target should be selected in every line, in the singe pan views;
4. The selected data should be checked in the 3D analyser for any possible side lobe selection;
5. The data should be flagged and exported to a ascii file, where the shallowest point(s) can be analysed in the QINSy processing manager;
6. The minimum of the data, computed by the statistical analysis, will represent the shallowest depth of the target. Yet, a second analysis would be needed to confirm the results.

For the optimisation of the workflow it is recommended to introduce the possibility of analysing multiple lines at once. With the latter suggestion, a 4D stacked view could be created, showing if the green cloud of spots (like in Figure 58) is fishes or something else.
6.2.2 Recommendations regarding future research

The following recommendations were made for future research on the subject:

- It is recommended to validate the steps of the workflow with ‘new’ and/or wooden wrecks. Since the recommended workflow and runtime parameters were based on steel/riveted wrecks-like targets.
- The options of extra detections for this kind of shallowest point(s) determination, since the runtime parameters were used incorrectly and considered not valid during the case studies.
- Surveying with different kind of weather types and survey environments like seasonal or tidal changes.
- To validate if the wreck-like characteristics arise, when analysing ‘new’ and/or wooden wreck-like targets.
- The use of FM pulses instead of CW pulses, for the determination of the shallowest point.
- The validation of the IHO Special order standard, for wrecks with mast-like targets.
- A new chart symbol for depths determined using the water column imaging method.
7

References

References


### Table of references in the text

<table>
<thead>
<tr>
<th>Reference code</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>50, 51</td>
</tr>
<tr>
<td>B</td>
<td>32</td>
</tr>
<tr>
<td>C</td>
<td>51</td>
</tr>
<tr>
<td>D</td>
<td>§3.1.1</td>
</tr>
<tr>
<td>E</td>
<td>37, 50</td>
</tr>
<tr>
<td>F</td>
<td>34</td>
</tr>
<tr>
<td>G</td>
<td>25</td>
</tr>
<tr>
<td>H</td>
<td>48</td>
</tr>
<tr>
<td>I</td>
<td>38</td>
</tr>
<tr>
<td>J</td>
<td>38</td>
</tr>
<tr>
<td>K</td>
<td>33</td>
</tr>
<tr>
<td>L</td>
<td>33</td>
</tr>
<tr>
<td>M</td>
<td>46</td>
</tr>
<tr>
<td>N</td>
<td>50</td>
</tr>
<tr>
<td>O</td>
<td>25, 51</td>
</tr>
<tr>
<td>P</td>
<td>38</td>
</tr>
<tr>
<td>Q</td>
<td>24, 26, 41</td>
</tr>
<tr>
<td>R</td>
<td>43</td>
</tr>
<tr>
<td>S</td>
<td>69</td>
</tr>
<tr>
<td>T</td>
<td>43</td>
</tr>
<tr>
<td>U</td>
<td>44</td>
</tr>
<tr>
<td>V</td>
<td>17, 18, 26</td>
</tr>
<tr>
<td>W</td>
<td>Used for inspirational purposes</td>
</tr>
<tr>
<td>X</td>
<td>32</td>
</tr>
<tr>
<td>Y</td>
<td>18</td>
</tr>
<tr>
<td>Z</td>
<td>18</td>
</tr>
<tr>
<td>ZA</td>
<td>36</td>
</tr>
<tr>
<td>ZB</td>
<td>19, 55, 67</td>
</tr>
<tr>
<td>ZC</td>
<td>22, 32, 33, 34</td>
</tr>
<tr>
<td>ZD</td>
<td>21, 40</td>
</tr>
<tr>
<td>ZE</td>
<td>22, 23, 25</td>
</tr>
<tr>
<td>ZF</td>
<td>20</td>
</tr>
<tr>
<td>ZG</td>
<td>25, 32, 41, 42</td>
</tr>
</tbody>
</table>
Annex A: Sound Velocity Profiles SR7285
Annex B: A-priori Calculations

Figure 82 AMUST: 14μ – Very Short CW

Figure 83 AMUST: 27 μs – Short CW
Figure 84 AMUST: 54 μs – Medium CW

Figure 85 AMUST: 135 μs – Long CW
Figure 86: AMUST: 324 μs – Very Long CW

Figure 87: AMUST: 918 μs – Extra Long CW
Annex C: Side scan sonar images SR7285
Annex D: Survey Vessels

Figure 88 Survey vessel mv. Arca – case study 1

Figure 89 Survey vessel mv. Octans – case study 2 (Vesseltracker.com)
Annex E: QINSy Controller settings Roompot survey