UNIVERSITY OF TROMSØ UIT

FACULTY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGENEERING AND SAFETY

Seismic Surveys in Ice-Covered Waters

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TEK-3900 Master’s Thesis in Technology and safety in the High North
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Master's Thesis

Title	**Delivered**
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Abstract

The master's thesis 'Seismic surveys in ice-covered waters' describes several methods within the maritime seismic industry to acquire data concerning the Earth's strata. It is the objective of this thesis to present a viable solution enabling the seismic industry to perform surveys in ice influenced waters.

The hardware conducted for conventional seismic surveys are introduced and explained. Arctic area and ice issues in regards to marine seismic surveys are investigated. A suitable theoretical solution to the issues discussed is described and argued.

Development and description of Submergible Depth Controlled Bodies (SDCBs) are presented. Dynamic finite element model - 3D simulations are conducted with the software package OrcaFlex 3D. The simulations evaluate the characteristics of the SDCBs in regards to response time.

Results of the simulations imply that the SDCBs will have the desired effect and the response times for vertical effect of the configuration. The overall conclusion presents a theoretical solution for a seismic capable system able to operate within ice-influenced waters.

Keywords	**Supervisor**
• **Advanced marine seismic surveys**	Professor Dr.ing. Egil Pedersen, University of Tromsø
• **FEM simulation- OrcaFlex 3D**	
• **Foil shape, lift and drag**	
• **Depth controlled seismic hardware**	

Master Project

Academic Year 2013

For

Jørgen Sørensen Klavenes

‘SEISMIC SURVEYS IN ICE-COVERED WATERS’

The Arctic region has produced indications of a significant quantity of exploitable hydrocarbons within this region. The oil and gas industry are currently increasing activity in the Arctic, as a result need for sustainable and safe solution for hydrocarbon exploration and monitoring under Arctic conditions are requested.

Today’s marine seismic industry relies on in-sea towed equipment for acquisition of the Earth`s strata information. Dependent on the configuration and mode of seismic Hardware, the in-sea equipment is located both on and below the surface. At the present there are no suitable solutions to eliminate the surface equipment, allowing the surveys to be carried out in ice-influenced waters. Given the current ice situation within the Arctic region, the season for seismic surveys is limited. Separated from the obvious ice problems, issues such as; polar lows, high wind speed, sea currents, ice accumulation challenges, extreme temperature variations, daylight issues and visibility contributes to a complex situation for the accomplishment of Arctic marine seismic surveys in ice covered waters.

The option of depth controlled seismic equipment is required, without compromising the spread, integrity or effectiveness of the equipment. This scenario presents a complex and vast challenge.

The master’s thesis shall investigate several aspects of importance for marine seismic surveying in ice-covered waters, with emphasis on the technical solution. The work shall include, but is not limited to, the following:

- An introduction to the area of interest; Arctic and the climatically challenges coherent with this area.
- An introduction to seismic operations and data acquisition.
- An important element in this project is to ensure the auteurs’ academic comprehension development within the scientific field of hydrodynamics. The thesis will contain a segments describing the Finite Element Model (FEM) and the software package OrcaFlex 3D.
- Description of solutions for development of hardware suitable for marine seismic operations in ice covered waters.
- Case study of an appropriate vessel and cable system to investigate and analyse the characteristics on equipment with submersible capabilities;
    - Modelling and simulation of a possible solution to the challenges described in this thesis (performed by the software package OrcaFlex

for 3D time-domain dynamic analysis of flexible marine vessel – cable systems).

- Utilize the simulated results in order to;
  - Identify type of wing section for the Submergible Depth Controlled Bodies.

In the master's project thesis the candidate shall present his/her personal contribution to the resolution of problem within the scope of the thesis work. Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction. The candidate should utilize the existing possibilities for obtaining relevant literature.

The manuscript should be typed single-sided in Times New Roman font style. Every sheet shall be numbered and arranged according to: Title and subtitle (if desired), the text defining the scope, abstract, acknowledgements (if any), nomenclature and conventions (if any), contents, main body of thesis (suitably divided in numbered main chapters with titles, numbered sub-paragraphs for which further headings are optional), conclusions with recommendations for further work, references and appendices (if appropriate). All figures, tables and equations shall be numerated.

The thesis should be organized in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be written as concisely as possible, but not at the expense of clarity. Descriptive or explanatory passages, necessary as information but which tend to break up the flow of the text, should be put into appendices. Units and symbols should conform to the recommendations contained in the International System of Units (SI). The project thesis should in general not exceed 100 pages.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The project thesis shall be submitted in two bound volumes, signed by the candidate, and as an electronic file.

Supervisor : Professor. Dr. Ing. Egil Pedersen
Start : 01.01.2013
Deadline : 01.06.2013

Tromsø, 01st September 2012

Professor Dr. Ing. Egil Pedersen
(Supervisor)

Preface

I would like to acknowledge my teaching supervisor, Professor. Dr. Ing. Egil Pedersen, University of Tromsø. For the time and dedication he has devoted in regards to this project. My wife Gunhild and my daughter Astrid deserve to be recognised for being patient, supportive and a constant source of inspiration.

Other people that have contributed to this thesis with censorship, critical questions and evaluation are: Solveig Johansson, Kathe Beate Klavenes and Ivar Klavenes.

Asbjørn Eirik Risholm Haukebø contributed with computer hardware, knowledge and much appreciated critical questioning throughout the duration of this project.

I would also like to express my regards to my brother, Torstein Sørensen, for convincing me to pursuit an engineering education six years ago.

To the reader of this thesis: Reading materials and suitable literature regarding the marine seismic industry and the different aspects of the seismic acquisition are scares. Relative information are kept in-house by the seismic companies, and/or presented in articles with a high academic level.

I therefore hope this thesis can enlighten both present marine seismic industry and the investigations into the subject of advanced Arctic marine seismic operations regarding operations in ice covered waters.

University of Tromsø, 1 June 2013.

Jørgen Sørensen Klavenes

Definitions, Abbreviation and Notations

Definition in alphabetical order:

Aboard:	within the structure of the ship.
Acquisition:	the act of acquiring: to locate and hold (a desired object) in a detector.*[1]
Anthropometric:	the study of human body measurements especially on a comparative basis.*
Autumnal:	the season between summer and winter comprising in the northern hemisphere usually the months of September, October, and November or as reckoned astronomically extending from the September equinox to the December solstice -called also _fall._*
Availability:	the quality or state of being available: having a beneficial effect.*
Azimuth Angle:	an arc of the horizon measured between a fixed point (as true north) and the vertical circle passing through the centre of an object usually in astronomy and navigation clockwise from the north point through 360 degrees.*
Basin:	an enclosed or partly enclosed water area.*
Brine:	water saturated or strongly impregnated with common salt.*
Buoy:	body with god buoyancy characteristics.*
Buoyancy:	the power of a fluid to exert an upward force on a body placed in fluid; also**:** the upward force exerted.*
Cable Junction:	intersection with two or more lines.
Cariolis effect:	the effect of deflection as a result of the Earth's rotation.
Circum Polar:	continually visible above the horizon.*
Client:	buyer of seismic data.

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[1] All text marked * is collected and displayed without modification from Merriam-Webster (2013) online dictionary.

Configuration:	refferd to the number shape and characteristics of the seismic in-sea hardware.
Convection:	the circulatory motion that occurs in a fluid at a nonuniform temperature owing to the variation of its density and the action of gravity.*
Dead reckoning:	the determination without the aid of celestial observations of the position of a ship or aircraft from the record of the courses sailed or flown, the distance made, and the known or estimated drift.*
Density:	the quantity per unit volume, unit area, or unit length: as: the mass of a substance per unit volume.*
Erosion:	the gradual destruction of something by natural forces (such as water, wind, or ice).*
Equinox:	either of the two times each year (as about March 21 and September 23) when the sun crosses the equator and day and night are everywhere on earth of approximately equal length.*
Frazil crystals:	small ice crystal, first stage of transition from liquid to solid substance.
Hydrocarbon resources:	an organic compound containing only carbon and hydrogen and often occurring in petroleum, natural gas, coal, and bitumens.*
In-Sea equipment/hardware:	refers to the equipment and hardware towed after the vessel, all lines and cables behind the stern of the ship are classified as ‘in-sea’.
Ideal Fluid:	An ideal fluid is a fluid with no friction, it is inviscid (viscosity is zero) (Finnmore and Franzini, 2002).
Lookout:	one engaged in keeping watch: watchman.*
Maintainability:	to keep in an existing state (as of repair, efficiency, or validity): preserve from failure or decline.*
Mode:	refers to the azimuth angle or the dimensions involved in the survey.
Moon-pool:	a hull design detail allowing for direct access to the surrounding waters.

Northern regions:	In this thesis the Northern regions is defined as the areas within the Polar circle on the northern hemisphere.
Open water:	there is no ice on the surface.
Reliability:	the quality or state of being reliable: suitable or fit to be relied on: dependable.*
Salinity:	is the saltiness or dissolved salt content.
Shot Point:	the position of the seismic source when the airguns are discharged.
Supportability:	to hold up or serve as a foundation or prop for.*
Surface:	the exterior or upper boundary of an object or body.*
Strata:	a region of the sea or atmosphere that is analogous to a stratum of the earth.*
Topography:	the configuration of a surface including its relief and the position of its natural and man-made features.*
Transverse pull:	force inflicted on the configuration by the deflectors orthogonally to the average movement of the ship.
Vernal:	of, relating to, or occurring in the spring.*
Vessel:	refferd to the seismic ship.
Wastage zone:	the zone where glaciers produce ice flows.

Abbreviation in alphabetical order:

AUV:	Autonomous Underwater Vehicles
DGPS:	Differential Global Positioning System
ECDIS:	Electronic Chard Display and Information System
E.G:	For Example
FAZ:	Full Azimuth Angle
FEM:	Finite Element Model
GNSS:	Global Navigation Satellite System
ISO:	International Organization for Standardization

INS:	Integrated Navigation System
MAZ:	Multi Azimuth Angle
MIZ:	Marginal Ice Zone
MSO:	Marine Seismic Operation
NAZ:	Narrow Azimuth Angle
OB:	Ocean Bottom
OBC:	Ocean Bottom Cable
OBN:	Ocean Bottom Node
O&G:	Oil and Gas (implies Oil and Gas Industry)
RAMS:	Reliability Availability Maintainability Supportability
RAZ:	Rich Azimuth Angle
ROV:	Remote Operated Vehicle
UAV:	Unmanned Aerial Vehicle
ULS:	Upward-Looking Sonar
SAR:	Synthetic Aperture Radar
SDCB:	Submergible Depth Controlled Body
SSAS:	Sercel Sentinel Active Section

Notations

α -	Angle	[°]
M -	Momentum	$[Nm]$
l -	Length	$[m]$
F -	Force	$[N]$
a -	*Acceleration*	$\left[{}^{m}/_{s^2}\right]$
u -	*Velocity*	$[{}^{m}/_{s}]$

C_m -	*Mass coefficient*	$[-]$
V -	*Volume*	$[m^3]$
A -	*Area*	$[m^2]$
ρ -	*Density*	$\left[{}^{kg}/_{m^3}\right]$
L -	*Lift force*	$[N]$
C_l -	Lift *coefficient*	$[-]$
D -	*Drag force*	$[N]$
C_d-	*Drag coefficient*	$[-]$
te -	*Tonnes*	[kg x10^3]
T-	Degrees	[° C]
p-	*Pressure*	$\left[{}^{N}/_{m^2}\right]$

Contents

1 Introduction

1.1 Background and Motivation

The search for exploitable hydrocarbon resources is increasing in the Arctic region. At the present, equipment used for seismic surveys are not constructed with regards to Arctic conditions. Presently there is no solution to safely accomplish seismic surveys in- or near -ice.

The Oil and Gas (O&G) industry are increasing their activity in the northern regions. New technology opens possibilities for extractions of hydrocarbon resources from wells located in deeper waters within higher latitudes. This implies that new markets are opening for seismic surveys in ice-covered waters. Currently the only option to extract information regarding the Earth's strata in the Arctic areas is to utilize the narrow window, when ice distribution is at the seasonal minimum. Areas covered by multiyear ice for whole seasons are inaccessible for seismic survey vessels. Relative small volumes of ice pose a significant threat to the integrity of the hardware, vessel and crew.

The decision to investigate marine seismic operations in ice-covered waters was influenced by the possibility of a career within the seismic industry after the completion of the authors' current education. The motivation for this project is based upon the satisfaction of creating a plausible sustainable solution to overcome some of the issues described and discussed in this thesis. The acquirement of academic skills, knowledge and theory through this project will give the author and the reader of this thesis an introduction into the seismic industry.

Future involvement of the seismic industry in the Arctic region is imminent. To be able to research and influence the future of the seismic industry is a strong source of motivation and inspiration.

The outcome of this project will be a step in the right direction considering Marine Seismic Operations (MSOs) in ice-covered waters with regards to equipment integrity, safety and sustainability of Arctic MSOs.

This thesis represents the last stage in the authors' current 'master of technology' education. Earlier academic educational achievements by the author are a bachelor degree in nautical sciences.

1.2 Target Group

This thesis is intended for anyone who has an interest in the maritime seismic industry. Above all, this thesis is indicated for the authors' teaching supervisor and the external examiner. They will evaluate the project based on this thesis and the cohesive presentation/exam.

Anyone who has an interest in the seismic industries and its future in Arctic region might find this thesis relevant and informative. Other, lower level, master's students might find this project thesis to be inspirational. Chapter six will include a section of ‘recommendations for future work’, which could encourage other students to base their master’s projects on issues regarding seismic industry.

It is the authors’ intention to produce an independent thesis. There are no assumptions made for the readers to possess any knowledge considering the seismic industry.

1.3 Previous Work

Previous work has resulted in the article; ‘Ice impact on towed seismic in-sea hardware’. The article was the foundation for a presentation and oral exam during the second semester of 2012. The article discussed the topic of a collision between a superwide and multiple ice flows ranging from 3.000 te to 30.000 te. The discussion was founded upon analyses conducted with OrcaFlex 3D software package. Results of the analysis in the article proved that also minor ice flows will have devastating effect on in-sea hardware, and a negative effect on MSOs. The conclusion of the article stated that it would be unwise to utilize present-day (2012) equipment in open waters where the possibility of ice might occur (Klavenes, 2012).

Parallel to the production of the article (Klavenes, 2012), a mandatory project: ‘Specialization Course in Technology and Safety’ (Tek 3004) was accomplished. The learning intentions concerning the project were described as:

“The goal is to give the students knowledge of the research methodology of engineering, the ability to carry out scientific work and skills in presenting the results in an academic thesis” (UiT, 2011 p. 19).

Accomplishment of Tek 3004 gave an introduction to the seismic survey hardware, in-sea equipment and a short introductory to the software (OrcaFlex 3D). OrcaFlex were utilized to conduct the simulation, which the analysis were based upon. The project produced several plausible solutions for seismic surveys in ice-covered waters. Two plausible scenarios described in the project were to utilize a fully submergible vessel or a vessel with a ‘moon-pool’ (Klavenes, 2013).

The option of utilization of a moon pool involved two scenarios 1) a considerable reconstruction of an existing seismic vessel. 2) The creation of a new concept for seismic acquisition ships.

A submergible vessel involves the utilization of a typhoon class submarine. This option involves a crew with special skills, which renders the solution unsuitable. At the present both scenarios are unsuitable. Nevertheless, the idea of eliminating the surface equipment which was a common factor for the described alternatives provides a contributing factor for this project.

To prepare for this master’s project a wide range of articles were investigated during development of the article “Ice impact on towed seismic in-sea hardware” (Klavenes, 2012), and for the development of the specialization project (Tek-3004). The topics of the articles were related to ice monitoring, 2D seismic expeditions within the Arctic Circle, ice detection, ice impact, deep water Arctic development, ice friction, ice loads and more. Information considering seismic hardware and software was mainly researched online. Theoretical knowledge needed to perform analysis were required using the manual (OrcaFlex, 2013) for OrcaFlex 3D. The literature studies were accompanied by teaching session covering multiple topics instructed by the teaching supervisor.

1.4 Present Work

This master's thesis is the final step in the authors' current education. After delivery of this thesis the author will present the project in an open lecture followed by an oral examination and discussion. The thesis hand-in deadline is 1st June 2013. Presentation and examination date is 20th June 2013. This thesis has close ties to the previous work. Nevertheless, the master's thesis is to be perceived as an independent project.

The on-going work will allow the author to gather and utilize the knowledge acquired during the past six years of academic engineering education.

It is the author's goal to educate the reader to the level where he/she understands the principal proceedings of a seismic operation and key-issues connected to seismic surveys in ice-influenced waters. The literature review has not discovered suitable alternatives to the solution presented in this thesis.

The main research declaration is:

"This thesis will describe whether there is a viable solution to enable marine seismic operations in ice-covered waters, with as little modifications to the equipment and hardware as possible."

To investigate the possibilities of seismic exploration in ice-influenced waters the use of OrcaFlex 3D is crucial. The scenario to be analysed in this thesis is: To eliminate all equipment located on the surface. The new equipment developed for the intention of depth controlled configurations will be the subject of the OrcaFlex simulations and analysis.

Limitations

To limit the extent of the thesis, the following limitations are inflicted on the project.

- *Positioning of the submergible equipment*

The positioning of the streamers will distort the precision of the position by removing the surface equipment containing positioning receivers (GPS). This thesis will provide an alternative for the positioning of submerged hardware. However, the solution might not be suitable for operational standards in the Arctic.

- *Depth controlled deflectors*

The solution for vertical controlled deflectors[2] will be implemented but not investigated in this thesis. Technical solution regarding the infliction of vertical force for the adjustment of deflector depth will not be subject for the simulations. The simulations will assume that the deflectors can move vertically in the water column.

- *Deployment issues regarding the equipment (open water)*

The most vulnerable part of the MSO will be the launching and recovery of the equipment. Therefore is it assumed that the launch and recovery of the equipment is performed in open waters.

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[2] Explained in section 2.3.4

- *Development of the Crane Units*

The effect of crane Units will be simulated with a simplified arrangement. Mechanical details and development of the crane units is not a subject regarding the simulations.

1.5 Organisation of the Thesis

The thesis follows a logical index. Chapter one contains the introduction to this thesis and predetermined sections appropriate for a master's thesis.

Chapter two gives the reader an introduction to the different aspects of the seismic operations. The different modes and general difference of the seismic hardware configurations are explained. Fundamental systems, principal workings and the acquisition of seismic data are described. Equipment and hardware are introduced within two main categories; aboard- and in-sea –hardware/equipment. The aboard computer system is superficially introduced.

Chapter three focus on the challenges MSOs are subjected to. An introduction to the Arctic and current challenges regarding technology, navigation, and human interactions are presented. Challenges described are thereafter presented with possible solutions at a later stage in the chapter. Some of the results described are based on technology developed but not yet implemented in hardware and systems used in the seismic industry.

Chapter four gives an introduction to some of the theory OrcaFlex 3D software calculations are based upon. To give the reader an overview of the theory involved in the simulations the FEM is presented. Simulations of the configuration based upon the solutions described in the former chapter provide data which are analysed in the following section of chapter four. The last section of the chapter contains the result from the simulations conducted with OrcaFlex 3D.

Chapter five contains the discussion based upon the issues described in chapter two, three and four. The authors' aim is to clarify the results from the analytical data acquired in the former chapter. Issues and solutions described in chapter 3 have positive and negative aspects. For the purpose of making an informed and correct conclusion the solution-topics in chapter three are discussed. Evaluations of the simulation results are conducted and trends in the data are discussed. Some of the theory introduced in chapter four is used to determine the characteristics of the implemented new equipment for the configuration.

Chapter six contains the concluding remarks regarding the overall outcome of the simulation. A section is dedicated to future work, containing issues in need of enquiry with future projects. Challenges yet to be solved may be suitable for other master's student's projects.

1.6 Contribution of the Thesis

The authors’ intention is to describe the seismic operations, equipment, and illustrate the need for new and improved seismic in-sea hardware. With a new perspective on Arctic seismic exploration a plausible solution will be presented in this thesis. Recapitulating, this project has made the following basic contributions.

- An introduction to seismic operations, equipment and issues regarding seismic surveys.
- Description of new seismic surveys hardware in ice-cowered waters.
- Introduction to OrcaFlex software package.
- Introduction to the Arctic and ice within the Arctic.
- Introduction to the FEM.
- Introduction Foil Theory
- Introduction to hydrodynamic theory.
- Plausible contribution to a safer MSO in ice-cowered waters.

2 Marine Seismic Operations

2.1 The Seismic Acquisition

There are several different approaches to conduct data acquisitions of the Earth's strata. The main focus in this thesis is aimed at three dimensional (3D) surveys. Seismic survey acquisitions involve the use of towed streamer cables. MSOs can be performed with the following methods of acquirement: two dimensional- (2D), 3D- and four dimensional- (4D) -surveys. These are the most common methods of seismic acquisition. Azimuth angle(s)[3] may be varied to suit customer's specification in regards to density of the data and the definition.

The principle of a marine seismic data acquisition involves a seismic source and a receiving streamer cable. The source produces a signal which propagates through the water column. As the signal reaches the different layers of the Earth's strata some of the signal is reflected due to changes in density-characteristics of the layers. The 'echo' from the signal is registered by hydrophones located in the streamer cable. Signals are then transmitted and processed with the acquisition computer system. Figure 1 shows the principle of seismic data acquisition.

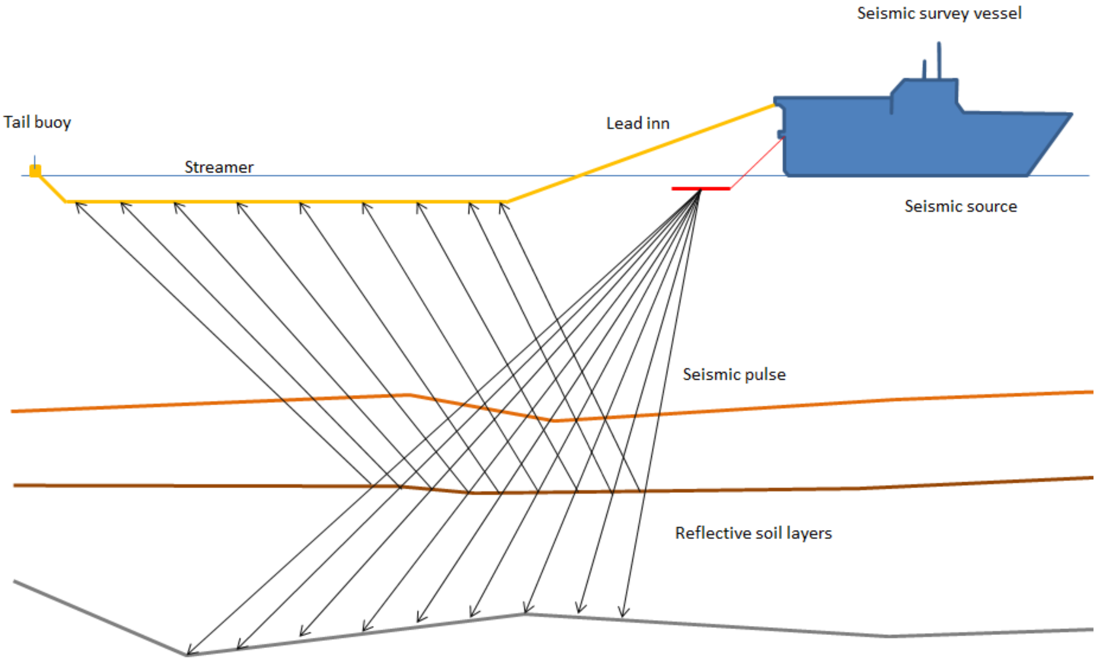

Figure 1: Seismic survey principle, the pulse is reflected in the strata and recorded by the streamer.

Procedures involved in search for information of the Earth's strata are complex and comprehensive. Each of the systems involved are not complicated, but the large number of equipment and systems involved in the process results in an overall high level of complexity.

During a seismic acquisition involving towed hardware the speed of the vessel is critical. The vessels and towed convoy relative motion to the surrounding water keeps

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[3] Azimuth angle are defined in section 2.1.4

the hardware in a constant position (relative to the vessel). Hardware towed behind the vessel is flexible and dependent on the velocity difference relative to the surrounding sea water, to avoid structural collapse. To maintain the in-sea hardware workboats and maintenance crew will conduct maintenance operations while the hardware is deployed.

A configuration used in today's seismic industry represent values equivalent to the vessel towing the hardware. Companies with sufficient resources will design and develop their own streamer cables. In this process the cost regarding development and production are high. Cost associated to the vulnerability of the equipment and lost production has resulted in rigours procedures considering the safety of the equipment.

2.1.1 Two Dimensional Surveys

Product of a 2D survey is a cross-section of the 'line' investigated. A line is one of the pre-planned tracks that the vessel will follow during a seismic survey. The lines form a predetermined plan to execute the survey as efficient as possible. 2D seismic vessels use one streamer cable, towed after the vessel to gather seismic data. The seismic source is also towed behind the vessel and the source configuration is separated with the use of deflectors. This version of seismic investigations is primarily used for the preliminary enquiries of an area. Figure 2 shows the result of a two dimensional seismic survey.

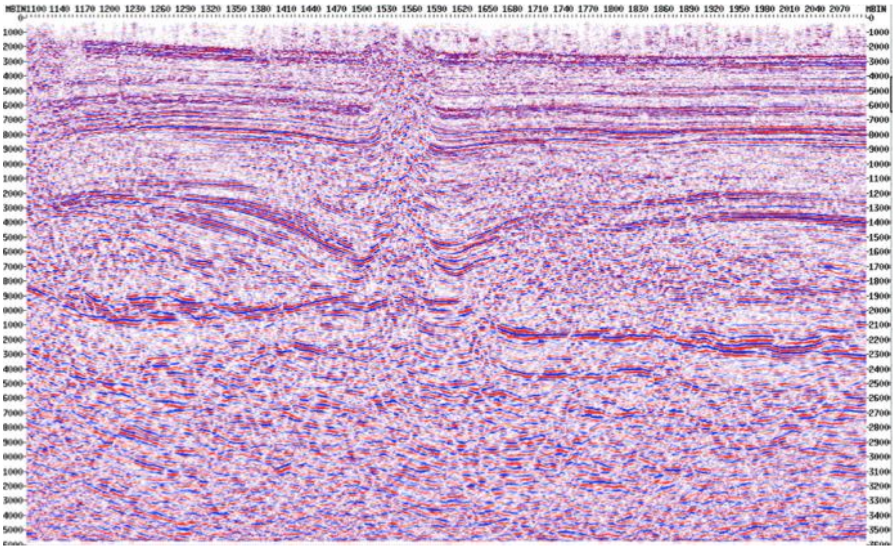

Figure 2: Illustration of a two dimensional seismic survey.

As we can see from Figure 2, the result is displayed along two axes, thereof the name 'Two dimensional seismic survey'. The axis on the left displays the depth of the reflected pulls. This axis is a function of discharge of the seismic source until the hydrophones detect the echo, corrected for density-, salinity- and pressure -variation in the water column. The horizontal axis refers to the pulse fired at a given position (shot point). The product of this survey method is a cross section of the Earth's strata.

2.1.2 Three Dimensional Surveys

3D seismic explorations involve a third axis compared to 2D surveys. This implies that the amount of streamer cables towed behind the vessel is increased. Presently the 3D seismic operations compose the largest part of the global seismic market. In 2012 the amount of km investigated in Norwegian territorial waters using 3D seismic surveys was just above 2.000.000 km. Compared to less than 125.000 km using 2D acquisition (Oljedirektoratet, 2012).

By utilizing more than one streamer the information collected from a single shot point can produce three dimensional data of the strata. Figure 3 shows an illustration of the Earth's strata. In Figure 3 parallel lines represent the width of the 3D configuration and as we can see the 3D model of the different layers underneath the seabed. Figure 3 is not representative for actual seismic data, but a principal illustration of 3D strata modelling.

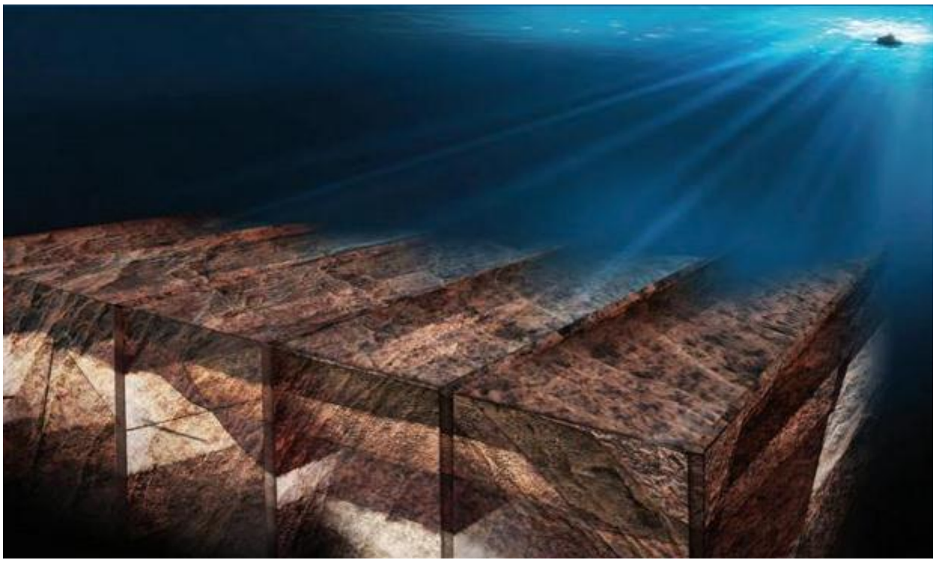

Figure 3: Three dimensional model of the Earth's strata.

Within the 3D concept of seismic surveying the configuration must be met by the client-specifications. Petroleum Geological Services has developed ships capable of towing up to 24 individual streamers at once (PGS, 2013). The definition of the acquired data is closely regarded to the amount of streamers. As the succession of streamers rise, the density of the data increases. Streamer separation control is a key factor to high definition configurations.

2.1.3 Four Dimensions Surveys

4D seismic data acquisition involves multiple surveys conducted over the same area with the same operational inputs. The changes in the strata will appear when the different surveys are compared, giving the data model its fourth dimension, time. This technique is used for reservoir monitoring. Data acquired using these time-laps method can produce probability models for how the reservoir will develop and behave in regards to production of the reservoirs.

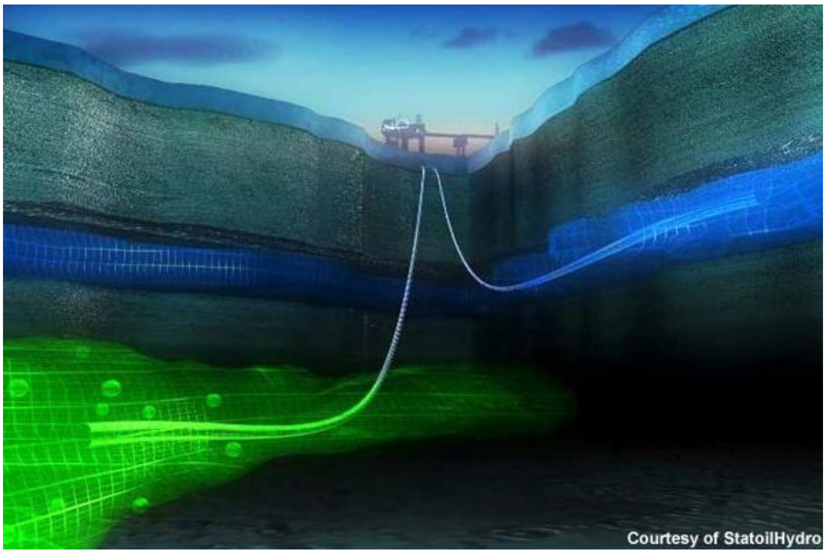

Figure 4: Illustration of multiple reservoirs, a potential client for four dimensional seismic surveys.

When conducting seismic surveys intended for 4D mode, the positioning of the hardware is crucial. Figure 4 shows a projection of a plausible subject for 4D seismic surveys. 4D seismic surveys are the most detail and resource demanding modus. Over the last decade time laps monitoring of oil reservoirs has increased in magnitude.

2.1.4 Introduction to Different Azimuth Angle Modes

The angle formed when the pulse travels down and is reflected in the Earth’s strata is known as the azimuth angle. Ordinary three dimensions acquisition is a Narrow Azimuth (NAZ) survey. Table one describes other modes of strata exploration, involving one or more seismic vessels.

Table 1: Description of different azimuth angles used during seismic surveys.

Mode	Abbreviation	Description
Normal Azimuth	NAZ	Considered the ‘normal’ angle, sources are towed behind the vessel.
Multi Azimuth	MAZ	Two or more vessels are involved in the survey, providing seismic pulses from multiple angles.
Wide-angle Azimuth	WAZ	Involves one tow-vessel and one vessel who provide the seismic source. By regulating the distance between the source and the streamer-configuration, the azimuth angle can be adjusted.
Rich Azimuth	RAZ	The combination of MAZ and WAZ produces rich azimuth angles.
Full Azimuth	FAZ	Involves full coverage of all azimuth angles, using several seismic sources.

(Long, 2010)

Full Azimuth angle (FAZ) is when full coverage of all the angles is provided with multiple seismic sources, shown in Figure 5.

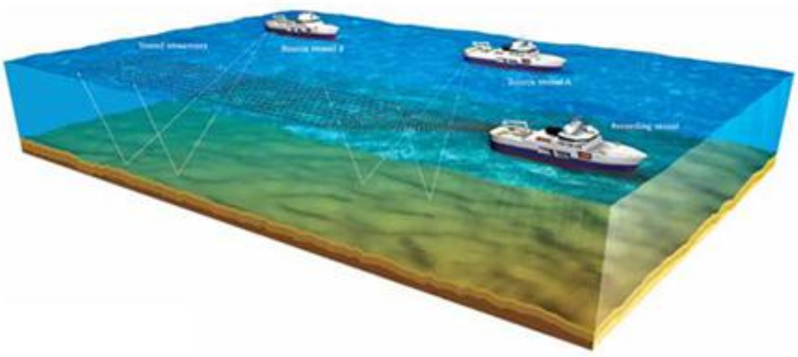

Figure 5: Wide Azimuth three dimensional seismic Survey

For the purpose of clarity, Figure 6 gives an illustration of the MAZ, WAZ and RAZ modes. The advantage of multiple seismic sources is the increased level of coverage and detail acquired from the strata.

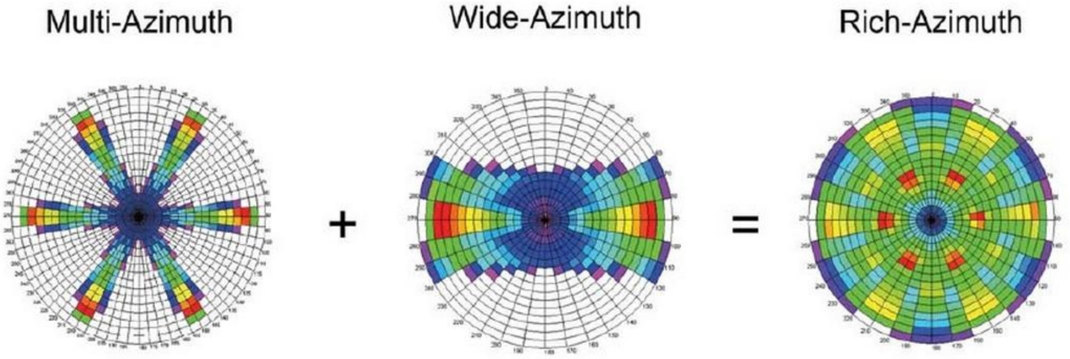

Figure 6: Rich-Azimuth data are composed of several seismic surveys.

2.1.5 Crew

Aboard a seismic vessel several types of specialized professions are represented. Figure 7 shows a hierarchical system aboard in regards to the maritime operation of the vessel. The crew setup might differ from ship to ship and company to company Figure 7 is only an illustrative example, and it must be stressed that other groups of personnel are included in maritime operations.

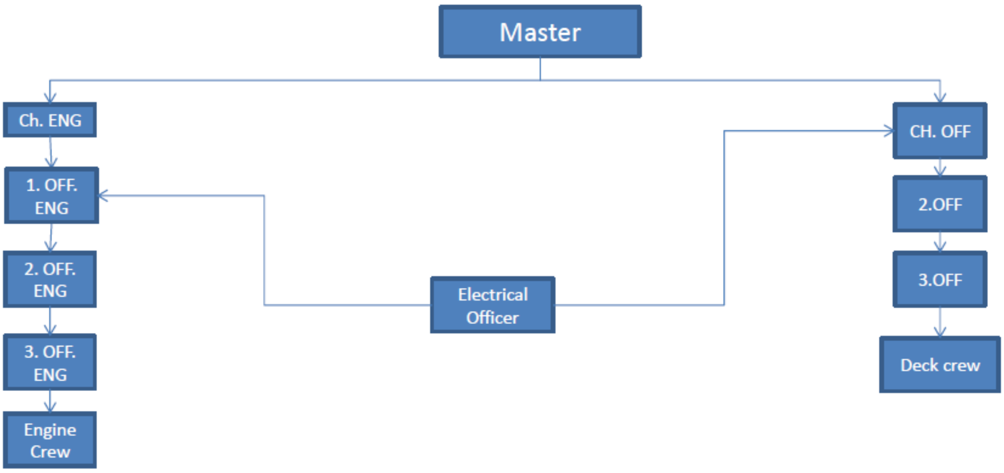

Figure 7: Maritime Crew aboard a seismic vessel might have a structure like this.

The seismic crew has a similar hierarchical system compared to the maritime crew, see Figure 8. Party Chief has the ultimate responsibility for the operation. Chief Navigator (Ch.NAV) is responsible for planning and execution of operations. Chief Observers (Ch.OBS) has the responsibilities for the operational state of the streamers, and the maintenance coherent with this hardware. Chief Mechanic (Ch.MEC) has responsibilities for the aboard equipment such as the compressors, winches, cranes etc. Chief Mechanics also has the responsibilities for the seismic source. Chief Processor (Ch. PROC) leads the work of integrity assessments regarding the information assembled from the seismic process. Quality controls of the data also fall under the Ch. Processors area of expertise. To grant the respective crews access to the in-sea hardware, workboats are used with dedicated workboat drivers, for the purposes of maintenance.

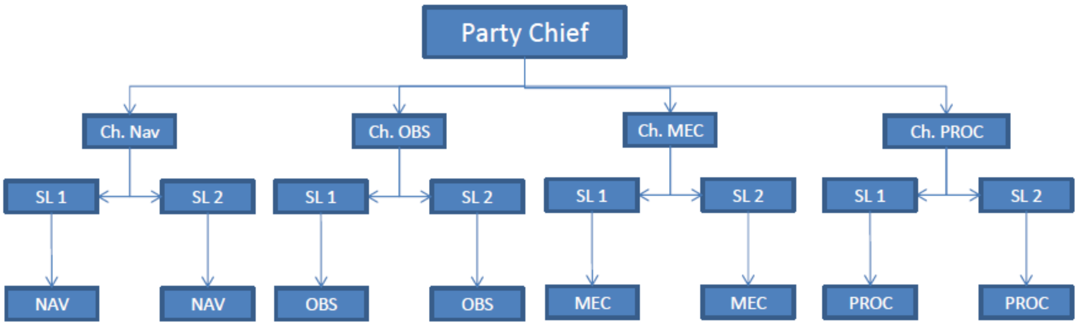

Figure 8: Seismic Crews can be organized like this.

Crew structure-differences might vary dependent on the particular vessel and company. Customer specification, regional and national demands can require specialist to accompany the crew during surveys. The porpoise is to monitor and oversee the operation.

Within the industry standard procedure is to operate with 12 hours shifts lead by the Shift Leaders (SL)[4]. The standard seismic industry norm in regards to crew-deployment is a one to one ratio with a five week interval.

2.2 Marine Seismic Hardware

Hardware used for seismic offshore operations can be divided into two main categories: in-sea- and aboard -hardware. When the ship is in transit and in a non-operational modus, the in-sea hardware is stowed aboard the ship. At the start of an MSO the ship will deploy the in-sea hardware form the ships stern and the deflectors from the ships sides.

The reference ship chosen for this thesis is designed with two dedicated decks that are utilized during an MSO. Figure 9 shows the in-sea hardware and the ship, viewed from below the surface. Displayed is an eight streamer hardware configuration. The seismic source is deployed from the gun deck. From the streamer deck, located above the gun deck, the seismic streamers are launched. All coherent equipment connected to the seismic acquisition hardware is deployed from this location, except the deflectors and superwides.

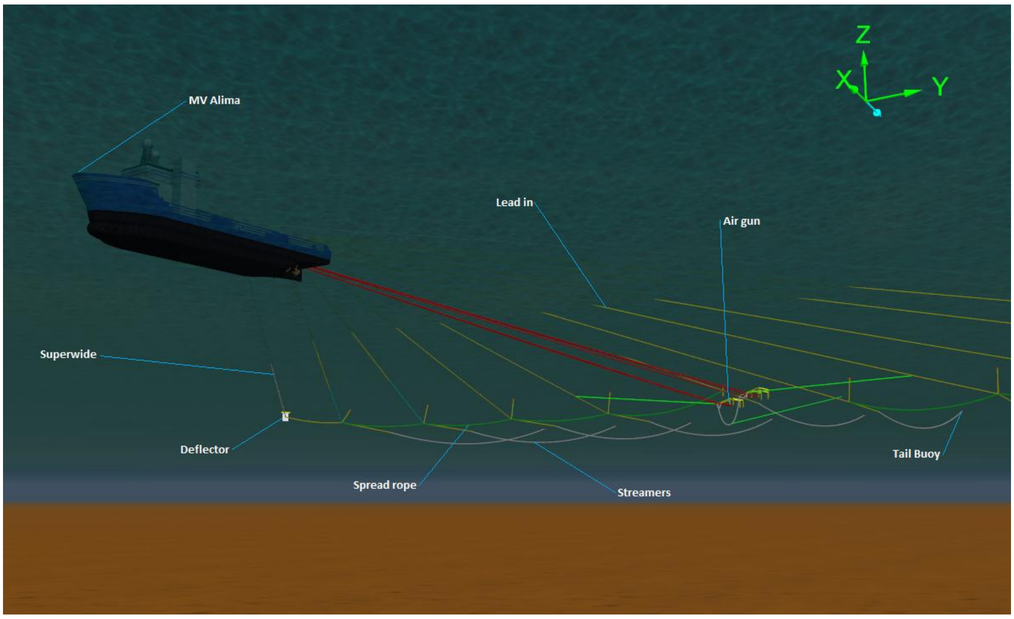

Figure 9: In-sea hardware viewed from bellow.

2.2.1 Polarcus Alima

The reference ship used for this thesis is ‘Polarcus Alima’. She was launched in 2011, and she is described as an ultramodern 12-streamer 3D/4D seismic vessel. The vessel has a diesel-electric propulsion system and a maximum speed of 15 knots. Normal operational speed is 4.5 knots (2.315m/s), which is a standard operational speed.

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[4] The Ch. position might also be SL during one of the shifts.

Reasons for choosing this ship as a reference include the ICE-1A- and WINTERIZED –classes obtained by this vessel. Another reason is that Polarcus Alima is a relative new and ultra-modern 3D/4D seismic vessel. These attributes gives the ship the capability to operate in Arctic conditions. The table below contains details concerning the ship. Some of the equipment located on the ship is presented in the following sections. Figure 10 shows Polarcus Alima in transit (Polarcus, 2012).

Table 2: Polarcus Alima system overview.

System	Details
The seismic sources	Bolt 1500-LL/1900_LLXT dual sources
Marine Compressor	3 x LMF Compressors
Streamers	12
Streamer Type	Sercel Sentinel solid streamers
Acquisition System	Sercel Seal Marine Data Acquisition System
Navigation System	ION Orca
Streamer positioning	ION DigiBird depth controllers and DigiRANGE acoustics
Source Controller	Seamap GunLink 4000 fully distributed digital gun controller

(Polarcus 2012)

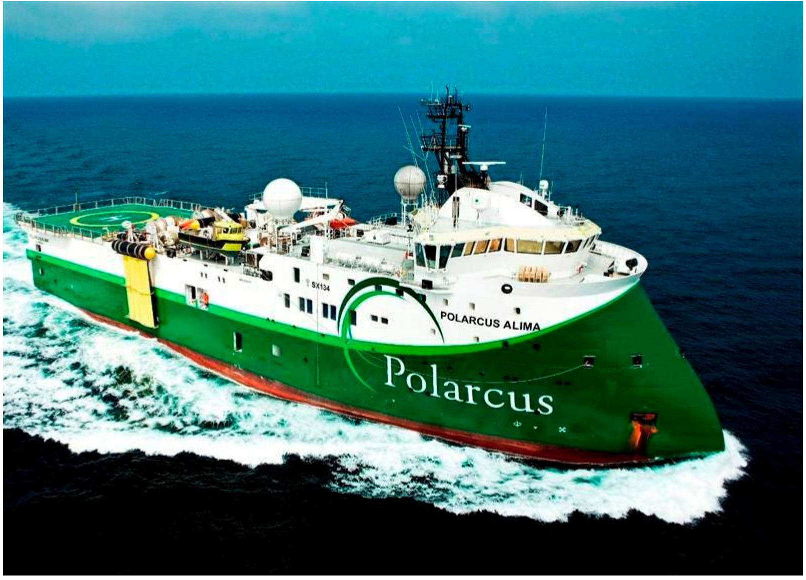

Figure 10: Polarcus Alima in transit.

2.3 In-Sea Hardware

The systems required to investigate the Earth’s strata is complex and contains too many elements to describe in details in this thesis. During the following sections the most relevant in-sea hardware and coherent systems are described.

2.3.1 Seismic Source

The airguns release a short and powerful pulse. The reflection or echo reflected in the Earth’s strata is recorded by the seismic streamers. Figure 11 shows the hardware which is referred to as the ‘gun-arrays’. The gun-arrays are constructed with a frame connected to an elongated flotation element. Airguns are located underneath the frame. In Figure 11 there are several double and some single airguns, which combined gives the pulse the correct signature as specified by the client.

Deployment of the gun-arrays is conducted with cranes located overhead on the gun deck. The control of discharge and air supply is delivered to the gun-arrays with flexible cables named ‘umbilical cords’. Dependent on the configuration of the hardware and mode of seismic surveys conducted, multiple gun-arrays may be used. Separations of the gun-arrays are kept constant with sliding ropes connected to the nearest lead-inns. One rope is connected to each side, see Figure 17: Centre of the Towed (page 21).

Figure 11: Seismic Source in stand by position on the gun deck.

2.3.2 Streamer Cable

A representative streamer cable is the ‘Sercel Sentinel streamer cable’. The streamer contains several different sections. Figure 13 shows a standard example for a Sercel Sentinel streamer cable.

Two important sensors connected to the workings of the streamer cable are the hydrophones and the vertical velocity sensors imbedded in the cable. The hydrophones detect the change in pressure and the velocity sensor will record the speed of the pulse, see Figure 12.

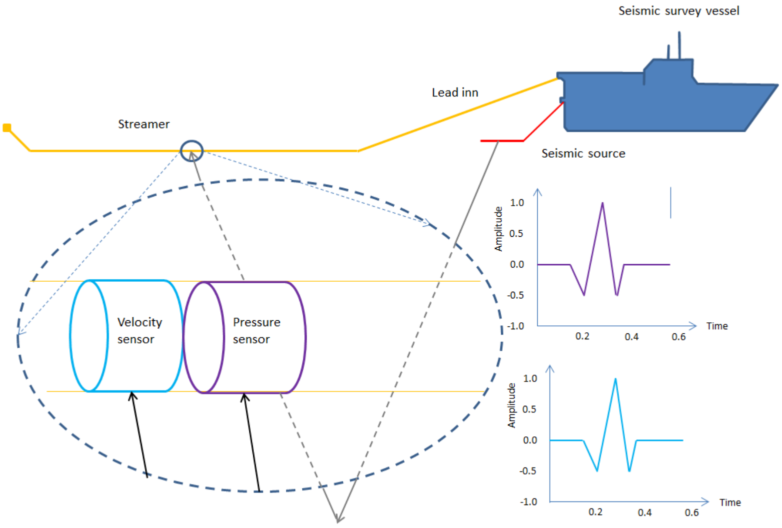

Figure 12: Streamer Sensors and pulse recordings

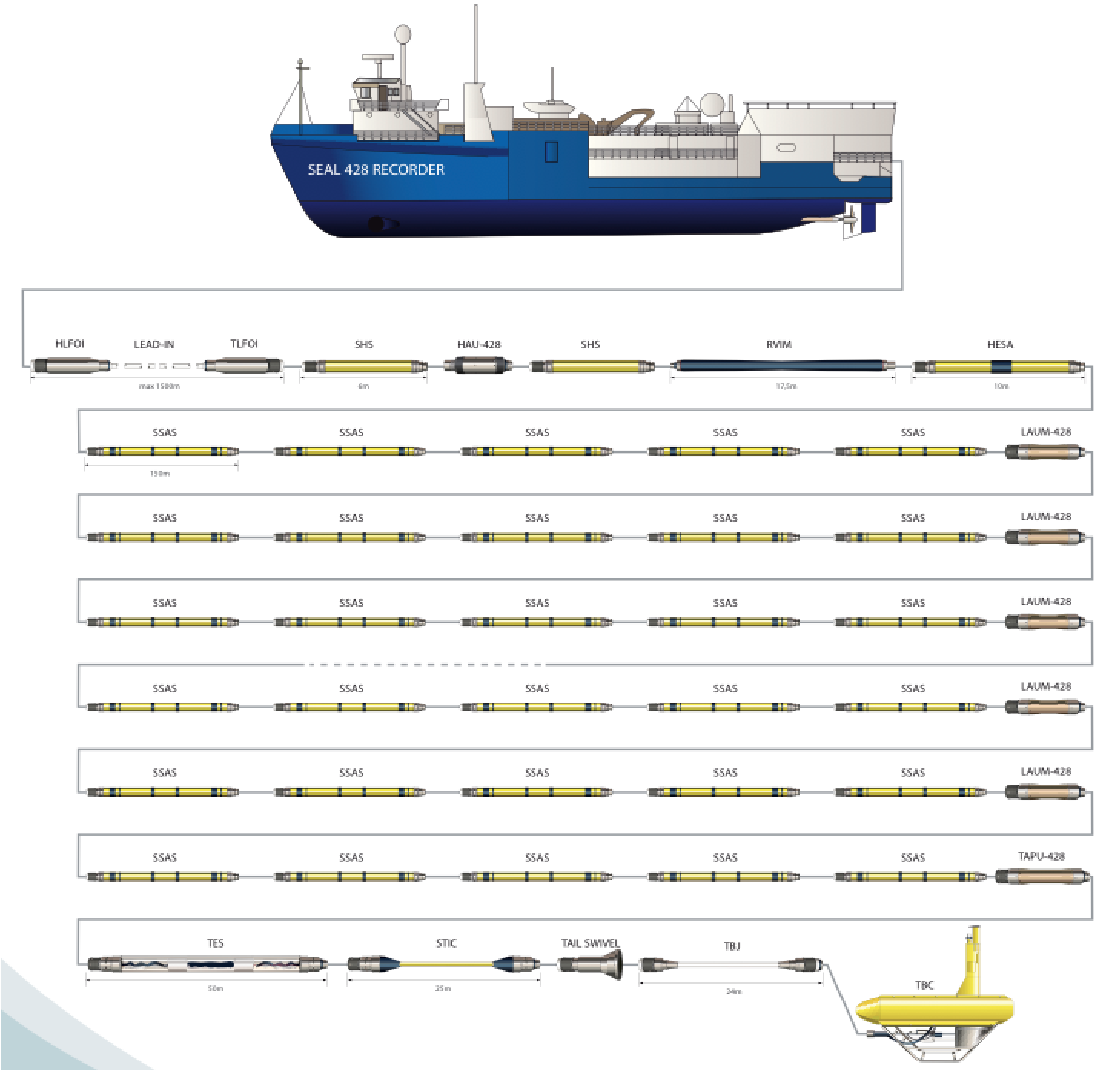

Figure 13: Example of elements and structure of a Sercel Sentinel streamer cable.

Figure 13: are only an example and variation to the streamer configuration is common. Specification from the client defines what kind and how many active sections are included in the streamer.

Elements displayed in Figure 13 are designed for different purposes. Main sections of the cable are the Sercel Sentinel Active Section (SSAS). SSAS are 150m long and contain sensors described in Figure 12: Streamer Sensors. Appendix 1 (page *i*) provide more information on the streamer elements shown in Figure 13.

2.3.3 Lateral and Depth Control Units

When the streamer cable is deployed the sections for lateral and depth control units (also referred to as 'birds') are fitted in-between the other sections. The birds are inserted with an interval of 300 meters. When the body of the birds has passed through the last roller on the streamer deck, the snap-on/snap-off wings[5] can be

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[5] Snap-on/snap-off wings are one option. Birds with fixed wings are also a possibility.

attached. As Figure 14 shows, the units are fitted with three wings. By rotating the wings, the birds can inflict horizontal and vertical movement onto the streamer cables. Forces generated by the wings also allows for rotation of the streamers.

Birds are controlled as group or individually, which allows for independent control of each streamer and to some extent each section of the streamer cable. By controlling the position of each of the streamer sections (located every 300 meters). The streamers can be towed with less separation, without the risk of entanglement. Short distance between the streamers allows for higher definitions surveys. The birds also widen the operational window during challenging stream conditions (Kongsberg, 2009)[6].

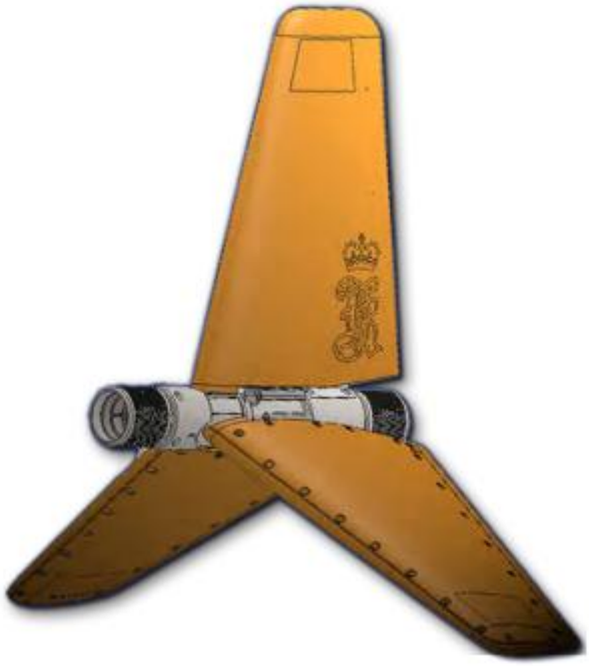

Figure 14: Depth and lateral control unit. Design by Kongsberg.

2.3.4 Deflectors

The purpose of the deflectors is to apply the transverse forces needed to separate the flexible cables towed in the configuration. The size of the deflector is related to the configuration of the towed hardware. Quantity and length of the streamers are key-factors to choose what sized deflector is needed.

The construction of a deflector consists of a frame, fitted with an elongated flotation buoy. The flotation devices ensures positive bouncy at all times. There are possibilities for assembling radar reflectors and visual units on top of the flotation buoy.

Foils are mounted to the frame in a relationship to each other. The different foils are mounted with different relative angles of attack[7]. Accordingly the close proximity of the foils gives favourable lift characteristics and lift to drag ratio. The foils own

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[6] Note: eBirds are described here, while the digiBirds are normally used with the Sercel Sentinel streamer cable. The eBirds represent newer technology and this is the reason for describing the eBird hardware.

[7] Angle of attack is described in section 4.1.3 Hydrodynamic loads.

angles of attack are fixed in relationship to each other. The combined (average) angle of attack can be adjusted with changes applied to the lines in the connection ropes between the deflector and the superwide. Multiple connections points are located on the deflector to ensure even lode distribution.

Configurations might occur where the deflector is towed directly by the lever arm, causing the use of the superwide to be eliminated. Configuration dependent on this setup will typically contain fewer streamers, than conventional configurations. Given the increased tension inflicted on the leaver arm and lead-in by the deflector.

The adjustment of the deflectors' angle of attack must be predetermined to the operation. Adjustment of the angle assumes the retrieval of the in-sea hardware and a delay in production.

Figure 15 shows the shape and dimensions of a Barovan 48, which is produced by Baro. This deflector model is one of the paramount deflectors in the seismic industry today (Baro, 2013).

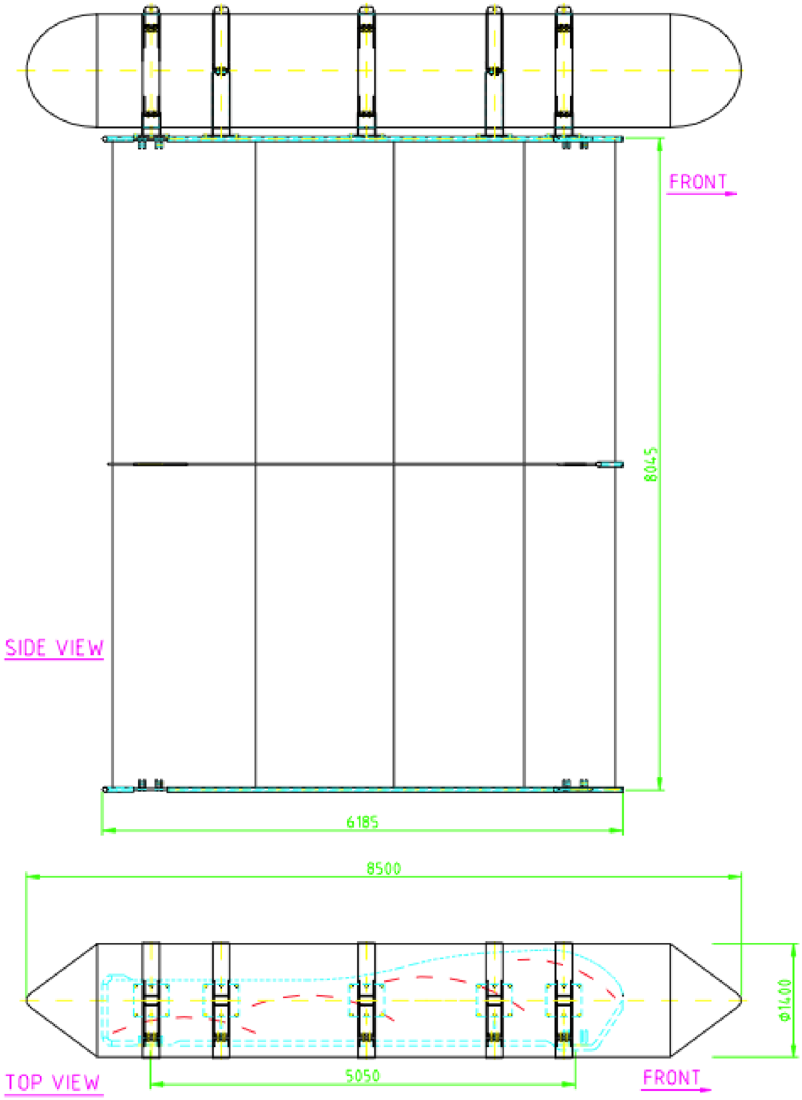

Figure 15: Top- and side –view schematics of a Barovan 48 deflector.

2.3.5 Tail Buoy

The tail buoys are located at the end of each streamer cable. Tail buoys are equipped with a Global Network Satellite System (GNSS) –antennas for the purpose of determining the position. A power generator located underneath the buoy supply the power needed for operational tasks. On top of the buoys radar reflectors units are located for easy identification and positioning purposes.

If a streamer cable should become detached, the buoy remains at the surface and the backup battery will keep the positioning process intact. Real-time positioning update eases the retrieval of the lost equipment (PartnerPlast, 2011).

2.3.6 Connection Cables and Farings

Superwide

The superwide is the link between the deflector's fixture and the winch located on the top deck of the ship. From the winch, the rope is guided through a tackle. The tackle reduces friction forces that otherwise would cause the superwide to be damaged. Superwide ropes' used for MSOs are made from special fibres (Dynema, 2012), which absorb friction forces poorly (Mørenot, 2012).

Cable Junction

In the transition from lead-in to streamer cable several joining elements are connected. Figure 16 shows the details of the junction located with streamer number eight (numbered from starboard to port). The lever arm is connected to the deflector and conveys the transverse force generated by the deflector to the configuration. To guarantee that the streamers are at a constant level of separation the spread ropes are connected to the intersection between the lead-in and the streamer cable.

Main purpose of the surface buoy connected to the junction point is to provide position data to the aboard positioning system. In addition to keep the first section of the streamer at the chosen depth (given by the length of the rope). Figure 16 illustrate the junction point containing the lead-in, streamer, spread rope, surface buoy distance rope and lever arm. The deflector and superwide are also displayed in Figure 16.

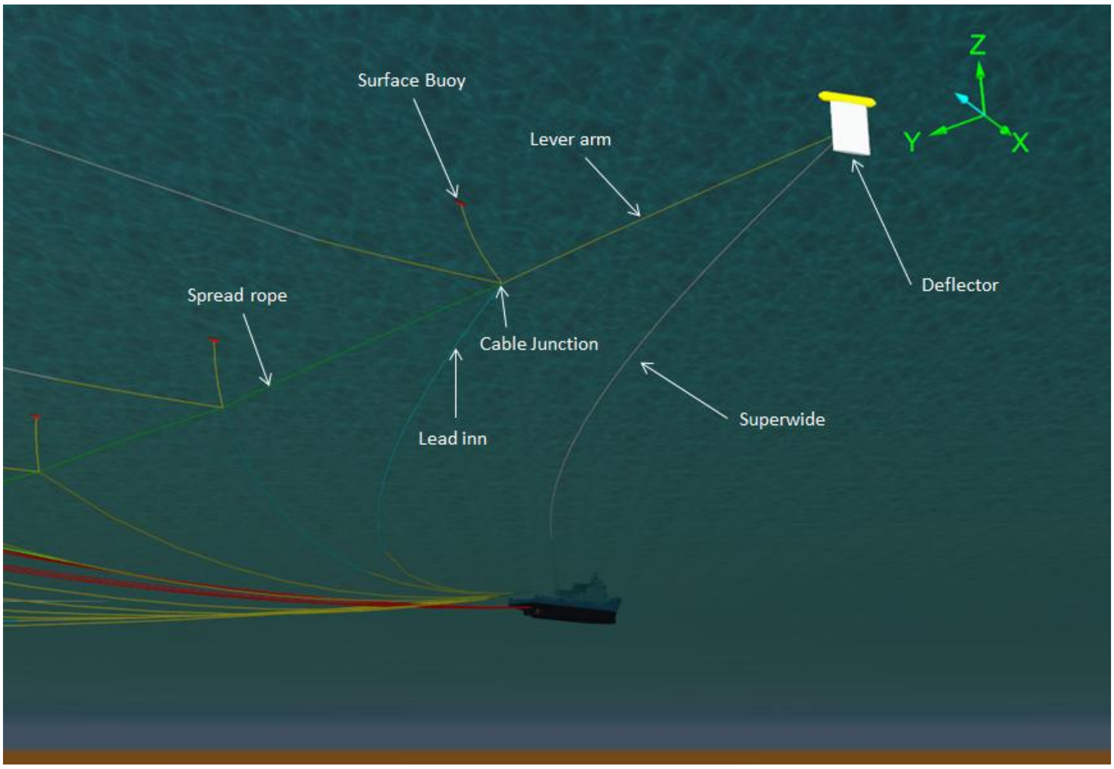

Figure 16: Overview of cables and equipment present in a configuration.

Figure 17 shows details of the centre section of the configuration (the same configuration as Figure 16). The gun-arrays umbilical lines are connected to the lead-inns with sliding ropes. The sliding rope-ends connected to the lead-inns are fitted with rollers allowing the rope to slide freely along the lead-in, resulting in the spreading of the gun-arrays.

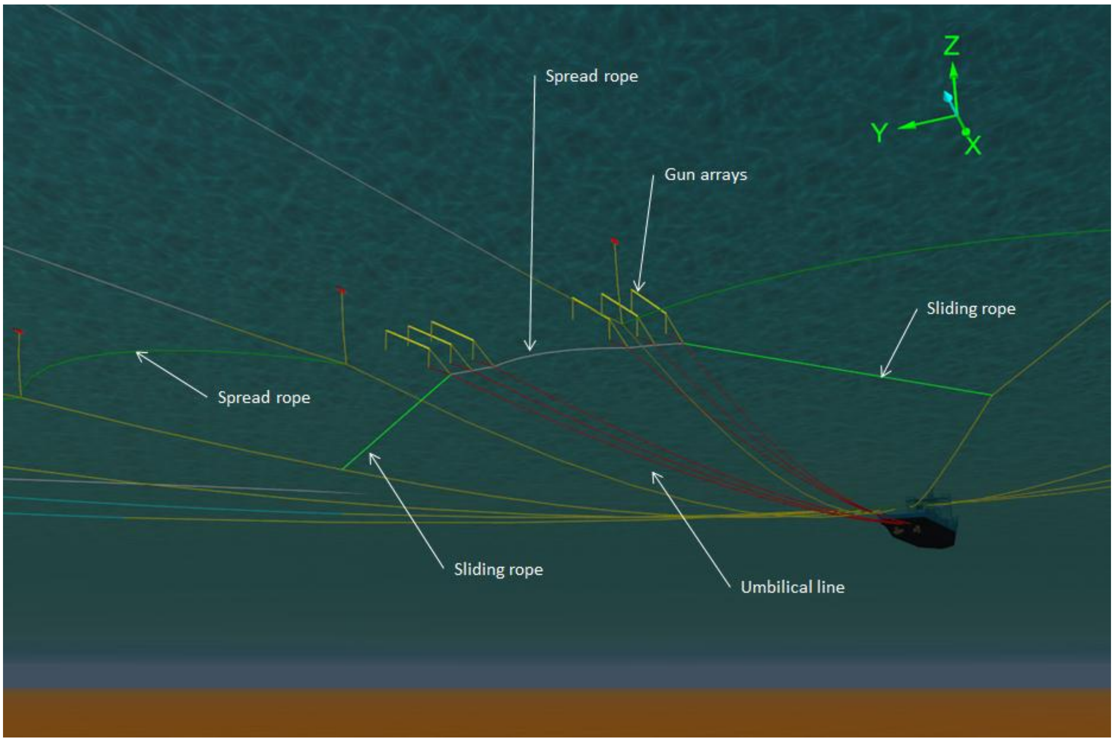

Figure 17: Centre of the Towed configuration with details.

Fairings

To reduce the drag forces inflicted on the configuration as a result of the forward relative movement of the vessel with the towed configuration. Ropes with a considerable angle to the direction defined by the movement of relative flow are fitted with fairings. The spread ropes are oriented orthogonally to the direction of the flow. This results in a large drag force, causing the spreader rope to deflect. By fitting a symmetrical foil shape to the rope, the drag forces and deflection (of the rope) are reduced. Figure 18 shows the difference between a two dimensional cylindrical object with and without fairings. The fairings results in differences between thicknesses of the turbulent flow-layers behind the two shapes (Pedersen, 2013).

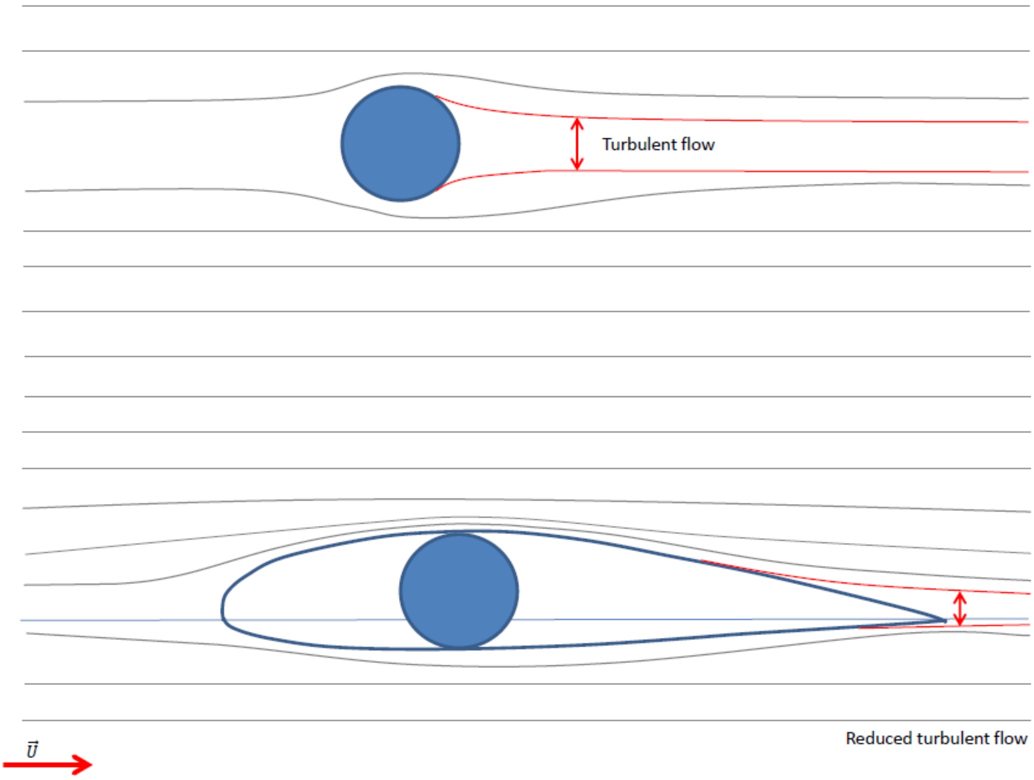

Figure 18: Cylindrical shape in laminar flow, with ant without fairing. The reduction in turbulent flow is illustrated.

Fairings are fitted to all lines in the configuration where a possibility of drag coefficient[8] reduction is present. The spread ropes are fitted with hard fairings mounted with spacer's in-between. This permits the spread rope do deflect without interlocking the fairing elements to each other. Hairy- and ribbon –fairings are fitted to the lead-inns and superwide. These fairings are flexible and will assume a foil shape when submerged in a flow.

The angle of attack fluctuates along the cables, particularly along the led-inns. Figure 19 shows the correlation between three different fairing types. Given that the vessel holds a constant speed and the read body is equal for all cables in Figure 19. The effect of the different fairings corresponds to the inclination of the cables. The point of the illustration is to visualize the effect of the drag coefficient.

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[8] The drag coefficient is introduced in equation 3, and explained in section 4.1.4

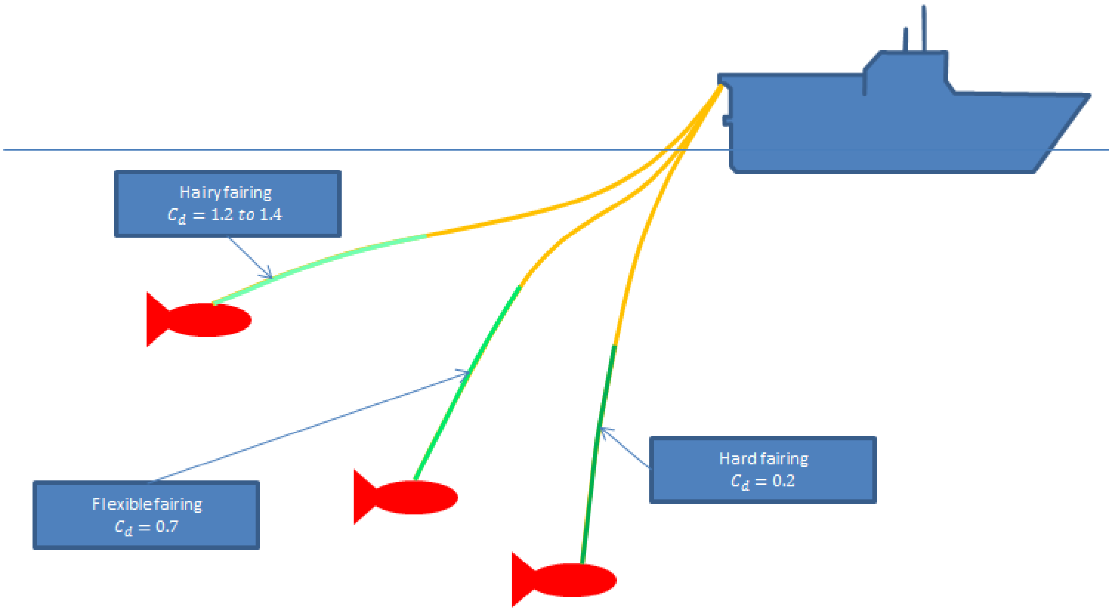


Figure 19: Different effects of fairings and drag coefficients.

2.4 Aboard Systems and equipment

2.4.1 Control Room

The control room is located aboard the ship. From this location there are several operations conducted simultaneously. This location can be perceived as the heart of the MSO. All systems regarding MSOs are controlled and/or monitored from this location. Figure 20 shows the inside of the control room aboard a Polarcus vessel.

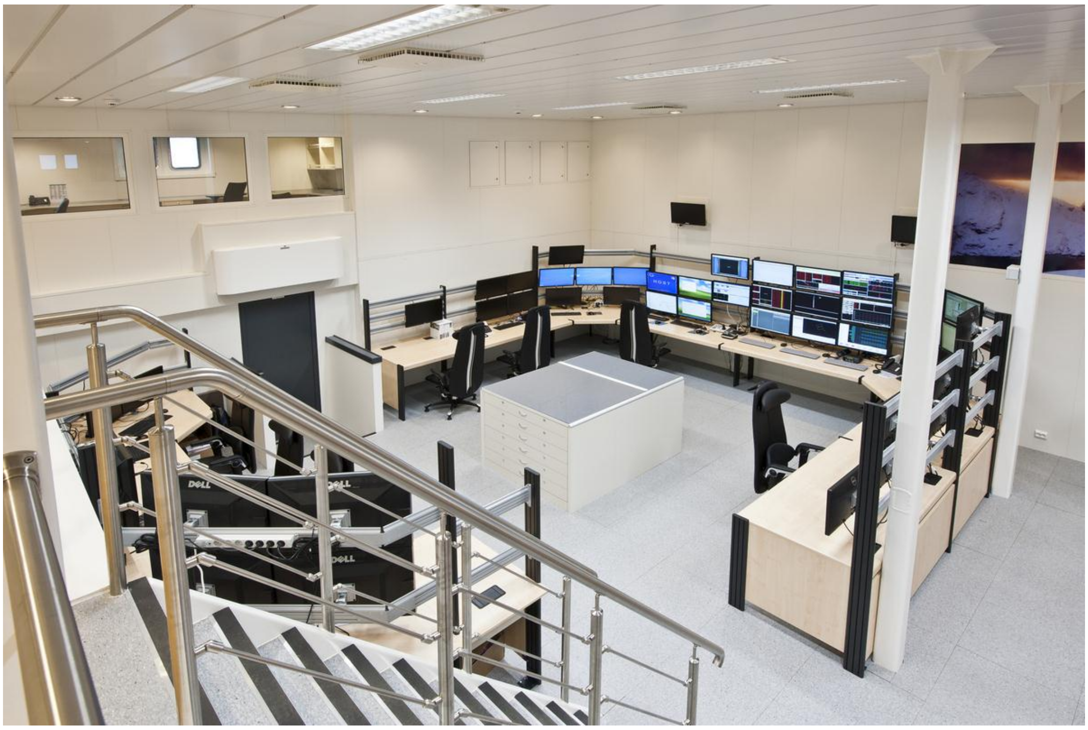


Figure 20: Control Room for the seismic operation aboard a Polarcus vessel.

2.4.2 Integrated Navigation System

The navigation system is implemented as a fully Integrated Navigation System (INS). It is used to plan, carry out and monitor the seismic surveys progression. The INS presents as an umbrella system where each of the software 'nodes' are integrated. Figure 21 shows a schematically illustration of the computer system aboard a seismic vessel. The main functions of the navigation system can be summed up to:

- Navigational data handling and storing
- Prediction of seismic source discharge
- Positioning of in sea hardware and timing of the operation.
- Processing of acquired data with integrated filtering processes.
- Automated integration to the Autopilot
- Inbuilt processes for quality control and quality control analysis.

It is common to utilize Linux operating system do to its superior and stable performance. Vessel positioning is done with Differential Global Positioning System (DGPS). During the seismic survey all navigational issues is decided upon by the crew in the control room. This gives the seismic navigators the full overview of the ships navigational issues (ION, 2011b). The INS specifications and all software nodes are too extensive to describe in this section. However, the acoustic system is relevant for sections later in the thesis. A principal description is described under then next headline. Figure 21 shows a illustrative image of the INS.

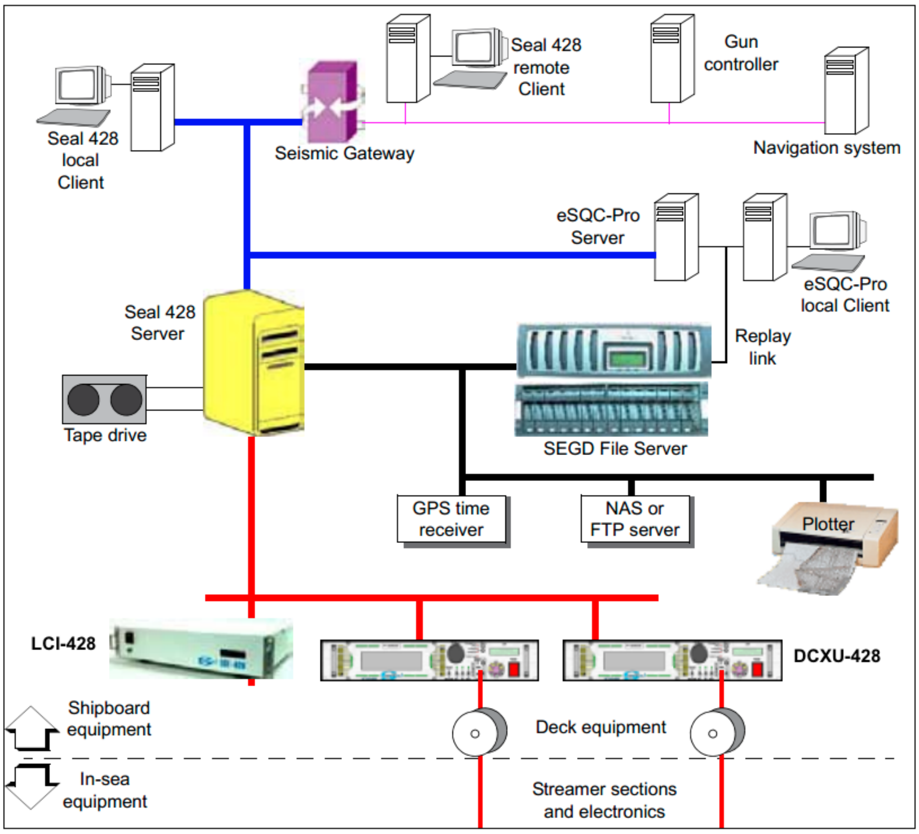


Figure 21: Schematics of an acquisition system aboard a seismic vessel.

2.4.3 Streamer Positioning System

Acoustic positioning systems are based on units who transmit and resave signals. This action provides the coherent computer system a range from the transmitters to the receivers. With algorithms and high rate of transmissions the streamers can be positioned efficiently. This implies that the geometry, distance and numbers of intersections between the acoustic units affect the precision of the position. GPS input is used to transfer the relative position of the acoustic units to GPS coordinates.

Further from the surface-hardware with GNSS positioning equipment, the lager the uncertainty of the position of the acoustic units becomes. Figure 22 shows the pathway of the signals traveling from transmitter to the receiver-units. This process has to be completed in between the seismic source discharge interval (ION, 2011a).

Figure 22 contains a fully acoustic network and it must be specified that other solutions involves segregation of the acoustic system. Sections typically are divided into front- mid- and tail -networks. Figure 23 shows the position of the streamers in regards to the vessel and each other.

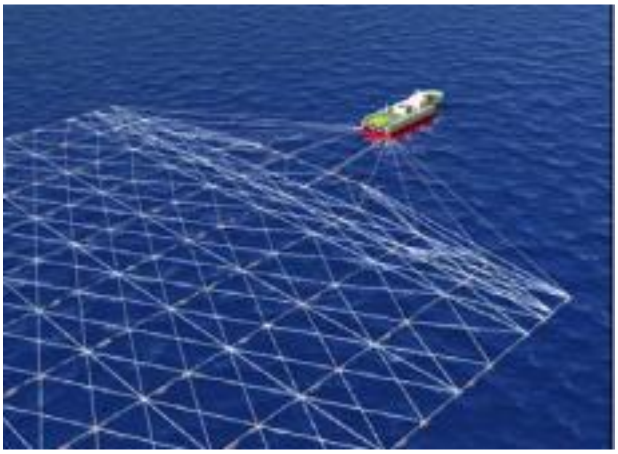


Figure 22: Illustration of the acoustic positioning system located on the towed hardware.

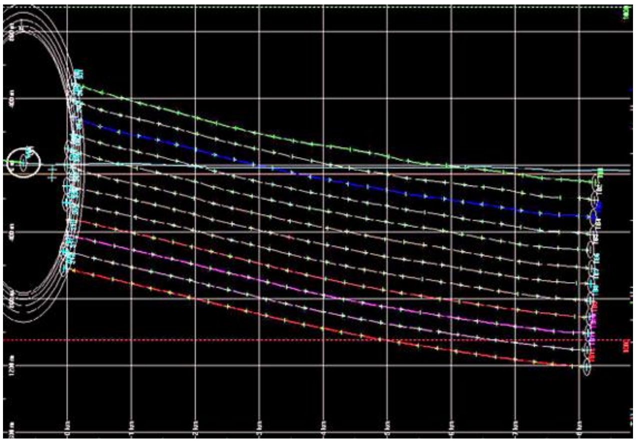


Figure 23: Nautilus positioning system screenshot, during an operation.

3 Seismic Operation and Challenges in the Arctic

3.1 The Arctic Region

Kjerstad (2010 p. 1-2) describes the Arctic as where the conditions are favourable of the midnight sun. The area is limited by the Polar Circles, which is located at 66.5° (90° - 23.5°) north or south. On the northern hemisphere in summer season, the sun will be above the horizon around the clock - it is cirkum polar. At the North Pole a special case where the sun is over the horizon from vernal equinox to autumnal equinox occurs.

According to Weeks (2010 p.2) the Arctic basin sea-surface area is approximately 12.2×10^6 km^2, see Figure 24. Several nations have interests in the area. Canada, Iceland, Greenland, Denmark, Norway, Sweden, Finland, Russia and USA have geographical affiliation with the Arctic and Polar region.

The Artic oceans are divided into several different seas and basins. The Greenland-, Barents-, Kara-, Laptev- and East Siberian -Sea are located along the eastern longitudes. Alongside the western hemisphere the location of Baffin Bay, North West Passage, Beaufort Sea, Canadian Basin and Chukchi Sea are located on the latitude of the Polar Circle. Near the North Pole the location of the Markarov-, Amundsen- and Nansen –Basin are located. The area between Greenland and Svalbard are known as the Fram Straight.

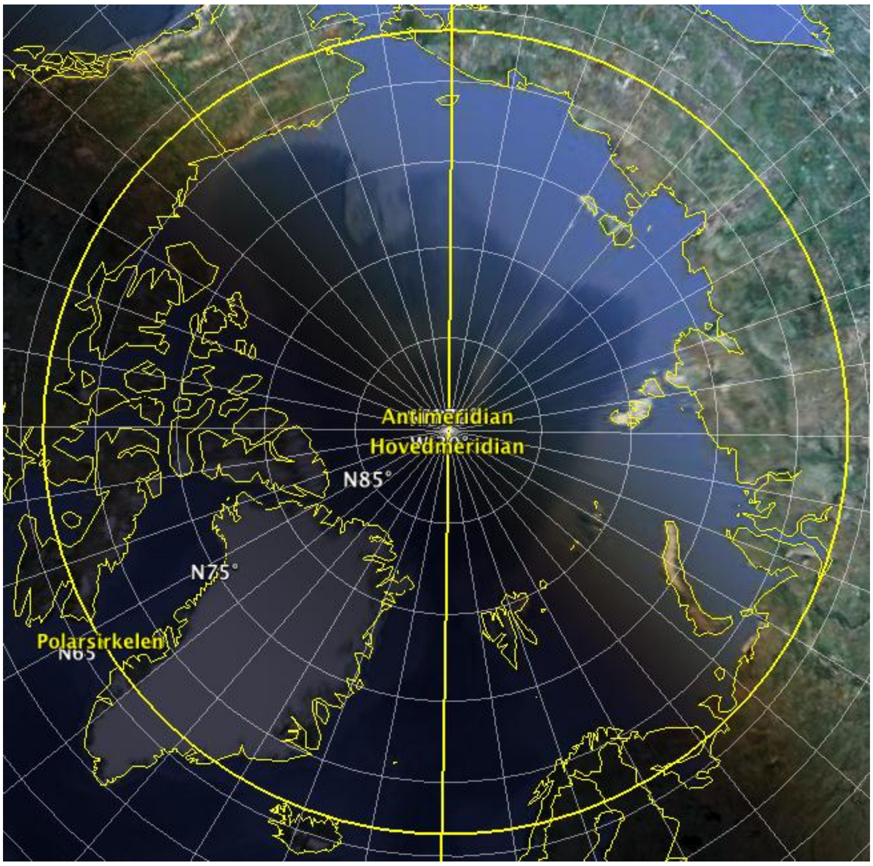
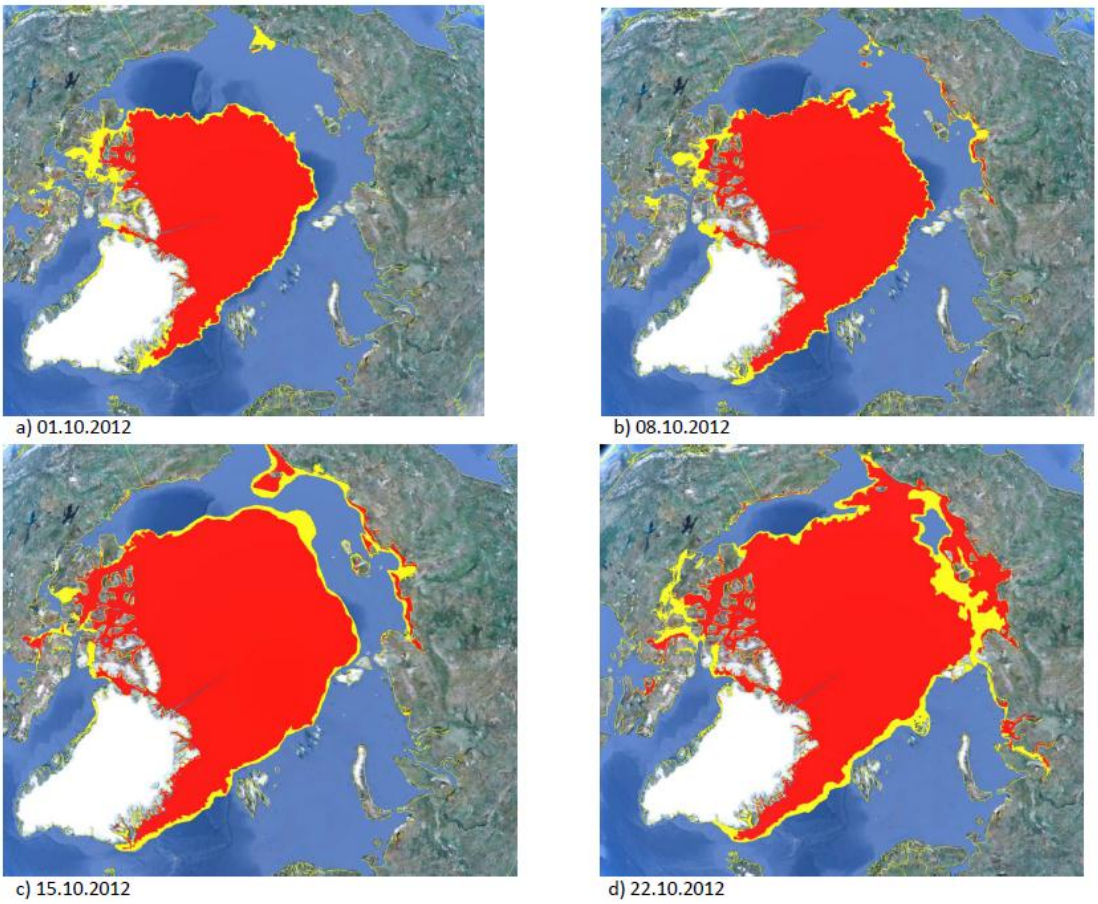


Figure 24: Google Earth illustration of the Arctic and the Polar Circle.

Illustrated in Figure 24 the area of interest contains mostly sea surrounded by landmass. The Polar Ocean is covered by sea ice throughout the year. Fluctuations of sea ice extent occur periodically. Differences between maximum and minimum extension is considerable. Figure 25 shows the Arctic region with ice coverage in October 2012. The read areas represents where the surface consists of more than 90% (90/100[9]) ice coverage. The yellow areas represent the Marginal Ice Zone (MIZ). This collar represents areas where the surface coverage is of less than 80/100. Figure 25 shows the distribution of ice, it is not possible to extrapolate ice thickness from this figure. Weeks (2010) defined the MIZ as:

> "The marginal ice Zone or MIZ, is any portion of the polar sea ice cover sufficiently near to the ice-free “open” ocean such that interactions with the open sea result in the modification of the properties of the ice so that they are different from properties deeper within the pack (Weeks, 2010b p404)."

From this quote one can understand the MIZ as a zone with non-coherent ice, although the presence of ice is considerable. Illustrated by Figure 25; the extensions of the MIZ are vast.



a) 01.10.2012

b) 08.10.2012

c) 15.10.2012

d) 22.10.2012

Figure 25: Google Earth illustration of the ice coverage in the Arctic, on four occasions during November 2012.

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[9] The coverage of ice in an area is described with a fraction where the denominator implies the ice disruption on the surface, and the nominator represents the combined ice and water area.

3.1.1 Arctic Factors

The Arctic environment is harsh. Polar lows with sudden weather changes and strong winds present challenges to MSOs. There are several oceanic currents at play, which have a significant effect on the local climate.

The dominating sea movement of the Polar Sea progress form the Chukchi Sea towards the Fram Strait. Along the Norwegian coast and into the Barents Sea the Gulf Stream is the governing current. The northerly movement of warm water along the coast of Norway and into the southern part of the Barents Sea gives ice-free conditions, during an average ice season. It is clear that regional currents, topography and atmospheric air movement will characterize the local climate.

Climate in the Arctic is highly affected by the different seasons. It is important to understand that the local climate can differ from location to location. This is primarily linked to the different oceanic factors currently governing the Arctic region (BarentsWatch, 2012).

Polar Low pressures appear suddenly and can create dangerous wind and lower the temperature over shorter time intervals. Challenges considering Polar Lows are the short developing time and the difficulty's to predict where they occur (Lippestad, 2012).

3.1.2 Ice

Ice in the Arctic region is as varied as the weather, and local factors must also here be accounted for. There are two main categories of ice in the region; sea- and fresh –ice. Sea ice form when climatically factors are disposed to freeze. When the top 150 meters of the water column is below – 1.8° C. The climatically factors are positive for growth of sea ice. Circumstance coherent with this process is connected to the sinking of colder water from the surface. Atmospheric pressure, wind and current have influence of the accumulation and growth-rate of sea ice.

First stage sea ice developments are the accumulation of ice frazil crystals on the super-cooled surface. The particles will over time develop into pancake ice, see Figure 26. Pancake ice develops in calm conditions as described by Weeks (2010 p. 82).

Early stages of ice is severally affected by wind, do to it is shallow draft compared to area exposed to wind forces. Over time pancake ice will form ice sheets. During the influence of wind and currents ice sheets will form ridges and hummocks due to the effect of wind and currents.

Ice which does not melt during two low ice seasons becomes multiyear ice. Weeks (2010 p.126) refers to ice that has survived one or more ice melting seasons as 'old ice'. Multiyear ice is defined as ice which has survived more than two ice melting seasons. If sea ice survives the first melting season, its physical properties are drastically changed. Salinity content of sea ice is affected by the temperature of the ice. The first melting season young ice experiences causes the salinity fraction (in the ice) to be severely reduced. This level of reduction in salinity is only experienced in the first melting season.

Gravity will affect the characteristics change of young ice. The gravity forces salt and brine down through the ice, into the sea below, leaving the ice with a lower density. The following cold season will contribute to the growth of ice with snow accumulation on top. From this point on the sea ice will increase its density properties (Weeks 2010).

Figure 26: Pancake Ice, one of the early stages of first year ice.

Ice created in a glacier might take several decades to transit down to the wastage zone. Snow accumulated on top of a glacier is the first step for fresh ice creation. As more and more snow falls on the glacial top the weight compress the snow into ice. Over time the weight of the ice and snow causes the glacial to move downwards. Dependent on the characteristics of the glacier and the properties of the local topography underneath the glacier, effects time form snowfall to calving of an iceberg. The rate of calving and the production of icebergs are also a factor of local variables. This process is illustrated in Figure 27.

The movement of an iceberg can be predicted to some extent. There are numerous factors influencing the movement of ice located in the sea. The tide currents inflict the movement of the icebergs and the characteristic cardioidick pattern described by Dmitriev and Nestov (2007) can be observed as a result.

The Cariolis effect, shape, weight, age and wind have influence on the movement of a floating piece of ice.

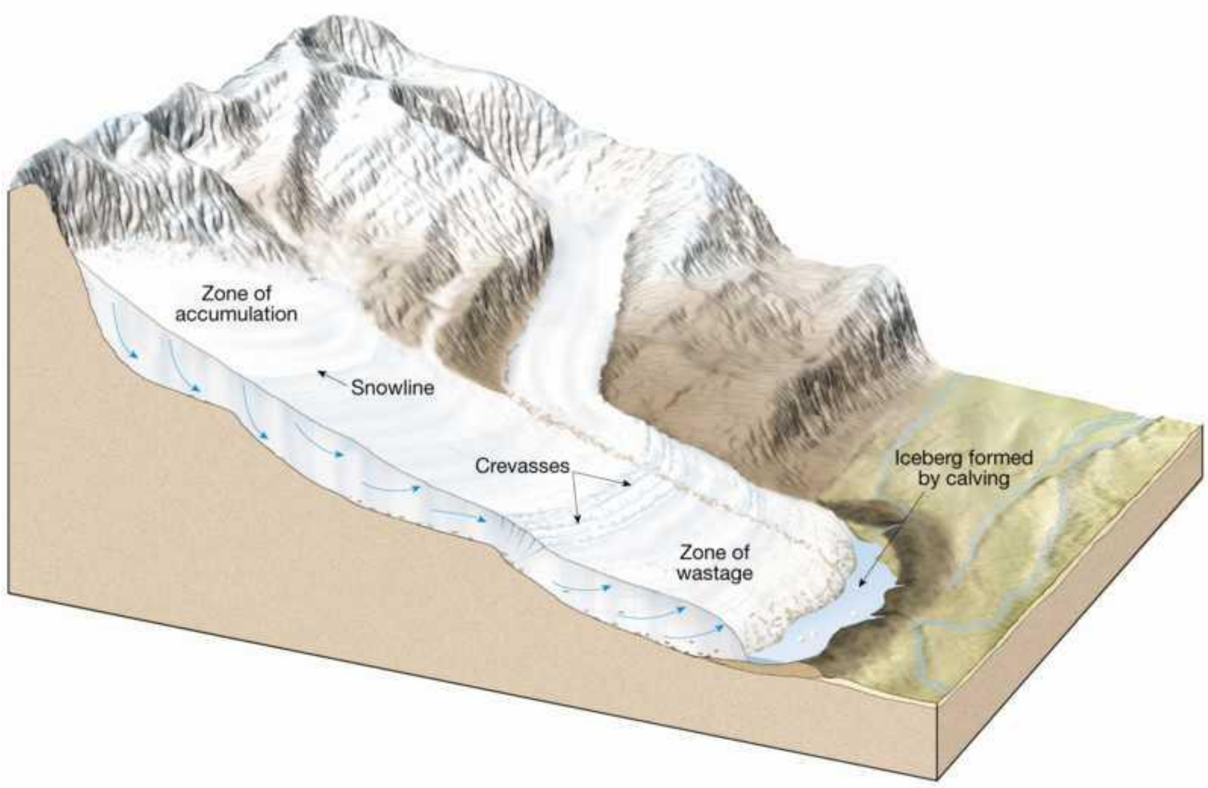

Figure 27: Creation of Ice Bergs in a glacier.

From ISO 19906 (2010) standard categorises different ice pieces as icebergs, bergy bits and growlers. In the Arctic there are several glacial capable of creating large icebergs. Many of the major glaciers are located on Greenland at the west and southeast coast as well as in Russian territory. Rivers might also transport large amounts of freshwater ice that will represent a safety issue towards ships (Kjerstad, 2011).

Kubat and Mohamad at. el. (2007) discusses the environmental influence factors on the floating ice. The main factors discussed are: Surface melting do to solar radiation, melting do to buoyant vertical convection, melting do to forced convection, wave erosion and calving of overhanging slabs.

Not included in this listing are the convection caused by overturning, calving do to differential melting along cracks in the iceberg, and fracture do to internal stress, which also are factors to be considered for a more precise modelling of ice disintegration.

3.2 Maine Seismic Operational Challenges

3.2.1 Technological Challenges

Baradi, Barabady & Markeset (2009) specify three main areas of interest coherent with technological challenges in the *Barents Sea*: Climate conditions, infrastructure and distance to infrastructure/market.

The climate conditions in the Arctic are a challenge, as mention in chapter 3.1.1. There are several issues that must be accounted for, if an operation is to be successfully executed. The environment involves low temperatures, high wind speed, seasonal darkness, high level of precipitation, sea spray, icing etc. Arctic infrastructure is lacking roads, railway, seaports and communication tools adequate for industry purposes. The mentioned elements are not sufficiently developed for the current and future development of the O&G industry in the region.

Reliability issues become a critical factor do to the long downtime, as a result of the long transportation of spear parts from the distributor to the recipient (Baradi, Barabady & Markeset 2009). The distance combined with the insufficient infrastructure push manufacturers to develop technology and solutions in regards to enhanced performance and reliability governed by Arctic conditions.

Considering SMOs in the Arctic region, the most significant factors to evaluate is the ice conditions. Figure 25 shows the growth of the ice during October 2012. The rapid change and the vast expansion of the MIZ are at best unpredictable. Therefore are the windows of opportunity for Arctic SMOs significantly limited. The prediction of the propagation, movement and property of the ice are dependent on several coexisting variables.

Behzad Ghodratis (2005) defined covariates as:

> "All those factors which may have an influence on the reliability characteristics of a system are called covariates. Covariates are also called explanatory variables. Examples of covariates are the operating environment (dust, temperature and humidity, etc.), the skill of the operators."

With regards to the quote above, the request for valid information regarding influence factors on a system are desired. The quantity of historical data with regards to covariates is limited for the area of interest. In a historical view, the Arctic is studied and examined with numerous *expeditions*, not standardised position-fixed operations. Compared to other areas with harsh climatically factors located on lower latitudes.

By comparison the North Sea has also been a region of great interest for the O&G industry. For the past four decades routine operations has been conducted in the North Sea. By studying weather observations and information recorded during this period. Probability models and relatively accurate predictions made on behalf of the gathered information can be produced, for the North Sea. The lack of information regarding covariates in the Arctic can be extrapolated from the application of accelerated failure models to a degree, as described by Barabadi, Barabady & Markeset (2010). Where part of the conclusion states:

> "The lack of suitable data has always been an important challenge for designing reliable system, especially when new challenges are influencing the performance of the equipment. Therefore, in order to use historical data, the effects of environmental conditions need to be considered."

The arguments made in this reference indicate an operation conducted in the Arctic will be executed with a degree of uncertainty. Given that the system is not designed for utilization with regards to Arctic factors. By always applying the best and designed technology based upon the available data, production rates at a satisfying level can be achieved.

3.2.2 Ice Navigation and low Temperature Challenges

As described in section 3.1.2 ice in the Arctic is a considerable challenge. The biggest threats to vessels with the specifications as the Polarcus Alima operating in ice-influenced waters are growlers. Growlers are difficult to detect because of the low freeboard. Furthermore they may be located in-between first year ice. Kjerstad (2011) claims that the detection of multi-year ice within the MIZ can be challenging to observe, because of the interference between first year- and multiyear –ice. As a result of the threat to the ship, a constant lockout is needed to monitor the ice situation during operations during these conditions.

Radar performance is limited in waters covered by ice. Nevertheless, radar-aided ice-navigation can be helpful to some degree. Large ridges and large ice flows can be detected several miles away. In open waters growlers with high freeboard will be detectable. In difficult conditions with high seas the detection rate by radar will be compromised. It is severely difficult to detect bits of ice if the sea clutter[10] function is engaged (Kjerstad, 2011 p. 126).

Icing problems may arise during operations in the Arctic (Kjerstad, 2011p.137). The effect of icing will have an influence on the stability of the ship and might destroy equipment not designed to operate under the influence of Arctic conditions. The stern of the ship will be exposed to this factor, due to a large number of equipment hardware without adequate shielding, low freeboard and an overall large surface due to equipment mounted and operated in exposed areas. The fact that the vessel follows a predetermined track might result in situations where wind and sea approaches the vessel from the stern. Sea spray combined with low temperature can cause massive icing accumulation on the ship.

In the MIZ the effects of wind and current are present. Wind and current does not necessary propagate in the same direction, resulting in compression and dispersion of ice. This produces some areas with difficult and complex ice situations, with coherent navigational challenges.

Classification of ice in the planned path of the vessel must be based upon valid ‘real time’ data-information. At the present there is no standardised equipment capable of providing any contribution to this process.

3.2.3 Navigational Challenges

Arctic areas near the coast line could be challenging to navigate. Examples like MV Hanseatic, which grounded near Svalbard due to difficult ice conditions close to the coastline. The combination of uncertain positioning and an ice situation is an example of the challenges regarding maritime operations in the Arctic.

Map data which form the basis for navigational charts might be based upon or contain inadequate data. This uncertainty can be caused by lack of typography surveys or old surveys conducted manually. The possibility of no chart data is also present. As a result the quality of the map may be unfit for Arctic MSOs.

There are several online services providing ‘close-to-real-time’ satellite images for vessels in high latitude areas. Satellite data provides an overview of the current ice

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[10] Function designed to eliminate radar echoes close to the vessel as a result of waves.

situation. Time factor is critical and movement of ice must be predictable in a definition suitable for MSOs. Time interval from data acquiring to online publication is too long. Several hours will pass before the processing of satellite imaging is published.

Considering MSOs, the information imbedded in satellite pictures do not offer any real navigational value. The definition in the pictures is to low and the processing time from data acquisition to online publications is too extensive to be of service to Arctic MSOs.

Geostationary satellite coverage used for communication purposes are a problem in high latitude areas. The geostationary satellites field of coverage does not include some of the areas where Arctic MSO is likely to be conducted. Geostationary satellites must not be confused with the polar orbit GNSS that provide the GPS-signals.

3.2.4 Human Challenges in the Arctic

To perform tasks and assignments coherent with seismic surveys under conditions described in section 3.1.1, crewmembers requires skill and knowledge. Kumar R., Barabady, Markeset and Kumar, U. (2009) states different factors to be considered when working in harsh climate conditions: Anthropometric-, human sensory-, physiological- and psychological –factors. These are factors which must be considered in non-Arctic areas too. Nevertheless, in the Arctic the effects of the listed factors will be amplified. And measures must be taken to ensure that the crew can perform at a desired reasonable level.

3.2.5 Seismic Operational Issues

Considering the towed hardware described in section 2.3, a large part of the equipment relies on the elements located at the surface. This presents one of the key issues in this thesis: the standard configuration will not be able to perform in waters covered by ice. It must be specified that operations within the Arctic are conducted with success, but limited to open waters. Figure 9 (page 12) provides a visual description of a conventional seismic configuration. The shape of the deflector will work against the purpose under Arctic conditions. As described, by Klavenes (2012), the effect of a collision between a significant mass of ice and the superwide will have a devastating effect on the operation. The ice-loads inflicted on the hardware, located at the surface will be subject to contact forces far outside the structural specification for the hardware.

Discharging of airguns will cause the pressure surrounding the gun to increase. The surrounding water will translate the energy of the air which then propagates to the surface. The result of the volume change of the air discharged from the airgun is the lowering of the temperature surrounding the airgun. This effect might cause accumulation of ice on the airgun if the sea temperature is low enough. If the accumulation of ice is severe, the airgun can fail to discharge, causing delays regarding the operation.

The operational challenges considering the vessels progress through the water is central to the operation. The deflector is dependent of the forward motion relative to the water to ensure the integrity of the configuration. If the forward motion of the vessel is compromised for any reason the outcome might become catastrophic.

3.3 Accomplishment of Arctic Seismic Operations

For the purpose of manipulating hardware and preparing for Arctic MSOs the next sections will provide and describe viable solutions to the issues described in the section above.

Some of the challenges described in the former section: climate factors, infrastructure and distance to infrastructure/market, are factors that need to be addressed when the intended vessels is designed and prepared for Arctic operations.

The pore infrastructure, distance to infrastructure and the transportation of crew, supplies and spare parts remains an issue. This is a logistic planning consideration. Adequate planning will compensate for some of these factors to a degree. When the vessel is operating outside the reach of helicopters, in the Arctic region the vessel and crew has to face all occurring challenges unassisted. This sets special demands for redundancy, recourses and storage aboard the vessel.

3.3.1 Navigational Solutions

Kjerstad (2011 p. 121) argues that the shortest route through an ice field is rarely the quickest route. It is not possible for a seismic vessel to perform the course changes described by Kjerstad, during a MSO. Given the characteristics of the seismic vessel and the necessity of following the pre-planned track the seismic vessel must be able to proceed through the ice field without changing course and without influencing the speed of the vessel. This limits the operational interval in regards to ice thickness. The capability involved in the DNV ice-classification 1A is the option to operate in areas influenced by –first year ice and broken channels with ice thickness up to 0.8 m (DNV, 2013). The limitations towards ice-thickness must be viewed as an operational limit for the Arctic MSOs.

3.3.2 Crew Modification

The crew described in section 2.1.5, and the challenges described in section 3.2.4 must possess or obtain the skills, have the physical and psychological capabilities adequate to Arctic operations.

The navigational skills and the ability to ‘read’ the ice is based much upon the experience and knowledge of the officer of the watch. The experience of the crew determents a significant parts of an Arctic MSOs outcome.

New guidelines and procedures must be developed to assure crew competence for advanced MSOs.

3.3.3 Ice Classification

To ensure the vessels dos not suffer ice damage. The ice thickness must be investigated and classified for the purpose of creating a safe path through areas with ‘high ice to open water’ -ratio. The mapping of sea ice can be done with an Unmanned Aerial Vehicle (UAV) or Autonomous Underwater Vehicle (AUV).

Unmanned Aerial Vehicle

The UAV can be launched and retrieved from the helicopter deck of the vessel. Currently developed UAVs can be relative small. The vehicle must be able to implement a synthetic aperture radar (SAR) -system, which allows the UAV to map the thickness of ice in front of the vessel. By equipping the vehicle with SAR the definition of the acquisition can be much higher than the information obtained from satellite imagery.

With wireless transmission of the data from the UAV to the ship, real time information may assist the officer of the watch with decision making, in regards to safety issues concerning the planned track. More information on a suitable UAV is enclosed in Appendix 3 (page *V*).

Autonomous Underwater Vehicle

An alternative to the UAV is to acquire an autonomous underwater vehicle(s). Today's AUV are suitable platforms for the equipment described below. Kongsberg's 'Remus' would be a preferred tool for underwater ice classification. The Remus can be modified to suit the needs of MSOs in the Arctic. Figure 28 displays the Remus (Kongsberg, 2010).

Figure 28: Autonomous underwater vehicle designed by Kongsberg and a suitable example for utilization during advanced seismic operations.

The Remus 100 specifications relevant for Arctic MSOs are given in Table 3.

Table 3: Ramus specification.

Specifications	**Detail**
Diameter	19 cm
Length	160 cm
Weight in air	37 kg
Trim weight	1 kg
Maximum operating depth	100 m
Power supply	1 kw - hour internally rechargeable
Endurance	>10 hours at 2.3 m/s
Navigation	Long base line, Doppler assisted dead reckoning: inertial navigation system; GPS.

The Ramus AUV system provides a platform with some of the specifications required in advanced MSOs. In addition to the details specified in Table 3, the ice mapping tool must be capable of transferring data in real time to the seismic vessel. With acoustic transponders/revisers mounted both on the ships underside and AUV(s), the possibility for real time data transfer is possible. To ensure the width of the mapped ice is within a satisfactory range, the AUVs can be operated in pairs doubling the width of the scanned ice track. This provides redundancy for the ice classification operation.

Upward Looking Sonar or ULS are a devise using sound signals to map the thickness of ice. Su, Yang, Ji & Du (2010) describe a system where the use of ULSs shows promising results. ULS have been used to estimate the thickness of ice in the Arctic since the 1990s, aboard submarines. The ULS are capable of detecting ice thickness down to 0.5 m.

3.3.4 Seismic Hardware Modification

A new crane unit with the ability to reposition the lead-in behind the ship must be developed and installed. This element is introduced in section 1.4 Present work. The goal with this supplement equipment is to reposition the lead-in, so the cable span behind the vessel is reduced as much as possible. This will force the lead-in down into the sea closer to the stern, within the breadth of the vessel. With this solution the lead-in are better protected from the contact forces.

The wake in ice, created by the ship will generate the necessary open water behind the vessel. To assure the structural integrity of the lead-inns, the cables must be coated with a heavy duty plastic material or steel fairings. Buravtsev & Jokat (1996) describe a suitable solution for the threading of lead-inns and umbilical cords.

Deploying the equipment in open water and then guiding the lead-inns down under the surface with a modification that will inflict a minimal transformation to the ships stern. The deployment of equipment can be done following the same procedures as for a conventional configuration.

When the hardware is positioned, the cranes can seize on to the lead-inns and pull/force them down to the preferred position. With this approach no additional modification to the stern is needed. To eliminate the superwide, the deflector is directly connected to the junction point between lead-in number one and streamer number one via the lever arm. Within the seismic industry this is known as ‘direct-towing’. Vertical control of the deflector is required, to fully eliminate the surface equipment.

Neutral buoyancy is accomplished by modification applied to the flotation device and adding of weight to the lower frame. To achieve depth control a horizontal foil is added to the frame of the deflector. By changing the angle on the foils the depth of the deflector can be controlled relative to the surface. Figure 29 shows a design concept of a depth controlled deflector.

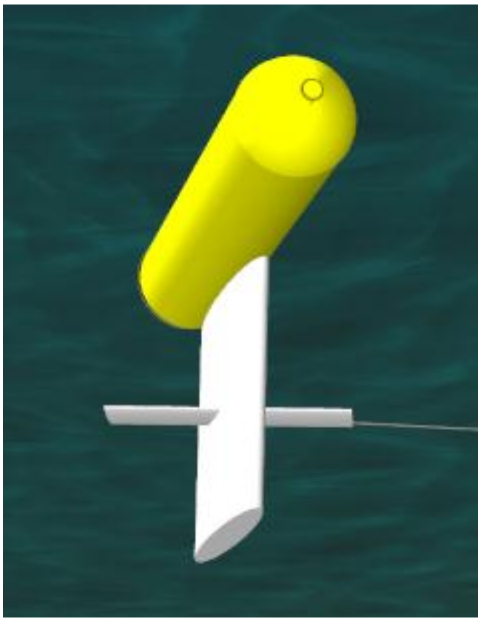

Figure 29: Illustration created in OrcaFlex 3D of a deflector with depth control. Lateral control is induced by a horizontal foil shape.

The number of lead-inns must be reduced to compensate for the breadth limitations considering the wacke behind the vessel. Compared to an ordinary[11] configuration, the Arctic MSOs will cover a smaller area. The surface lines and surface equipment connected to the junction points are replaced with Submergible Depth Controlled Bodies (SDCBs). This is elongated bodies with foils attached on each side, providing the option of depth control to the configuration. SDCBs are attached in the transition between the lead-inns and the streamers. The intended objective of the SDCBs is to ensure that the cables are within the depth interval specified by the client. Additionally the units are capable of inflicting enough force to perform emergency dives to avoid contact with ice flows.

SDCBs are currently a product of the authors' creativity. SDCBs will be subject for the FEM dynamic simulation presented and conducted in chapter four.

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[11] Ordinary- compared to the vessels maximum of 12 streamer configurations.

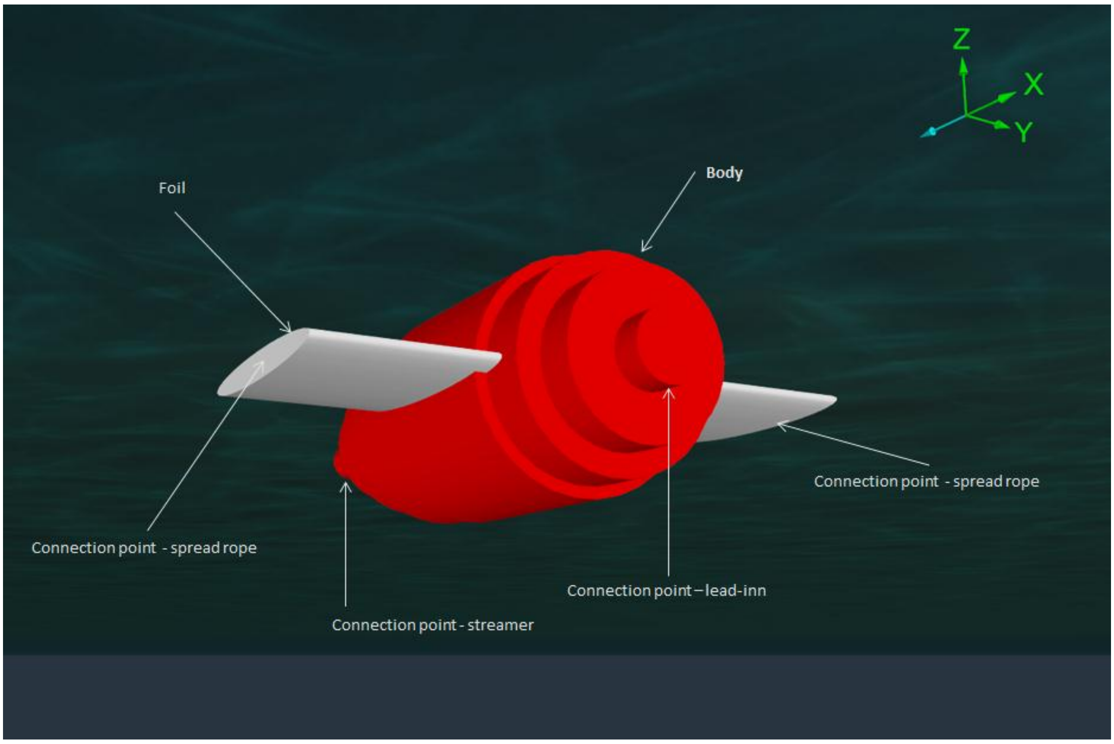

Figure 30: OrcaFlex illustration of a Submergible Depth Controlled Body and details.

To control the depth of the configuration, a SDCBs control unit is required to adjust the angle of attack which will correspond to a given depth. The configuration equipment is buoyancy neutral at a given depth h, and the angle of attack α represents the manipulating variable[12]. Wanted depth is denoted by h_1. The notation Δh is the difference between h_1 and h. To measure the depth each of the SDCUs must be fitted with a depth gauge. The updating time interval of the depth gauge is a contributing variable to the characteristics of the control unit (Haugen, 2003). The updating interval from the depth gauge and the overall processing time of the regulator will have large influence of the response characteristics of the control unit. Theoretical projection of the control process can be viewed in Figure 31.

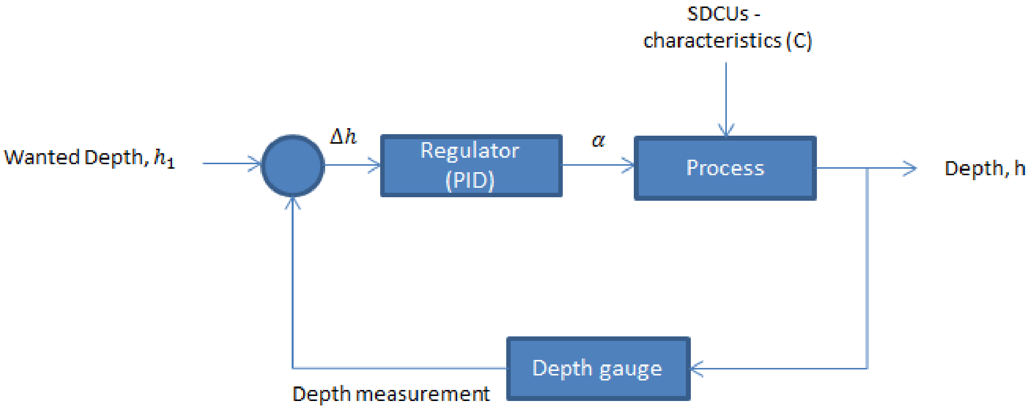

Figure 31: Schematic illustration of a basic PID control unit.

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[12] Manipulating variable - the variable or manipulated variable used to inflict control to the process (Haugen 2003).

This depth control unit is a so-called PID –regulator, for a more information and schematics see Haugen (2003). This section demonstrates the principle for a suitable control unit. Given the high technical specification of the Remus AUV, it is more than likely that an adaptive PID controller will be installed. For more information Haugen (2003, page 99-103) describes the approach.

By elimination of the surface equipment the possibility of positioning the configuration by GPS is compromised. The acoustic system described in section 2.4.3 is dependent on correction input from the GPS data. To counteract the distortion of precision inflicted on the positioning of the deployed hardware, a new towed surface cable is added to the configuration. This cable contains equipment with acoustic positioning systems to interact with the existing acoustic system. To improve the precision of the position, the cable would be equipped with GPS and acoustic transmitter's equipment. The intention of the cable is to float at the surface and provide GPS input to the acoustic system. The aim is to keep the distortion of precision to a minimum.

Design features incorporated in the cable has to accommodate the possibility of severe contact forces between the ice and the cable. To eliminate as much of the cable friction-forces the coating should be as smooth as possible and be able to withstand the forces occurring when the cable is subjected to ice.

4 Theory, Modelling and Simulations

For the purpose of acquiring data regarding the research question stated in chapter one, multiple simulations has been conducted. Simulations have been conducted using OrcaFlex 3D software package. OrcaFlex is 3D time domain finite element software. By utilizing a virtual 3D model and the FEM the program is capable of calculating static and dynamical solutions for flexible cable configurations. This involves that the simulations is designed in a three dimensional virtual space. The virtual space are determined by coordinate system with axes x, y, and z.

4.1 Theory

4.1.1 Finite Element Model

The FEM allows extremely complicated structures to be simplified to the level where dynamic analyses can be performed. FEM simplifies the seismic cable configurations by replacing objects (flexible cables) with nodes and coherent segments. This allows the calculation to be simplified into solvable matrixes. In the 3D view, a given line would be drawn as a smooth curve. The calculations will be done on segments and nodes representing the original line. Numbers of segments can be decided by predetermined standards, or we can specify how many segments we want to utilize on a particular line. This allows the user to reduce the number of segments on secondary and unimportant lines causing the calculation time to be drastically decreased (OrcaFlex, 2013).

4.1.2 Hydrodynamic Loads

In section 2.3.6 under fairings Figure 18 gives a perceptive of how to reduce the drag forces occurring around a cylindrical shape in a moving flow. The effect can be divided into two main categories: *Lift* and *drag*, which are further discussed later in this section.

OrcaFlex 3D calculates the hydrodynamic loads with the use of Morison’s equation, which is commonly used to describe, amongst other applications, the force on a cylindrical object under the influence of waves. Næser (1997) describes the equation as:

$$F = C_m \rho V a + \frac{1}{2} C_d \rho A u|u| \qquad (1)$$

Where a and u are acceleration and velocity, respectively, orthogonal to the axes of the cylinder. The mass coefficient is denoted C_m. V is the volume of the object and A is the area of the object. OrcaFlex 3D will differentiate between the relative direction x, y and z coupled to the local coordinate system. In addition to the elements described in equation (1) above, the software operates with a factor to allow calculations for partly submerged objects. For more information about the OrcaFlex 3D software see appendix 2 (page ii).

Foil Theory

The shape of a foil can be described as symmetrical or asymmetrical in a two dimensional projection. The cross section in Figure 32 shows an asymmetrical foil shape. There are several details on a foil: The leading edge is the foremost edge of the foil. The upper surface is the area from the leading edge to the trailing edge, on top of the foil. Lower surface is the area between leading edge and the trailing edge, at the base of the foil. Chamber line is defined as the line where the profile is half of the thickness relative to the position along the body. The cord line is the shortest distance between the leading edge and the trailing edge.

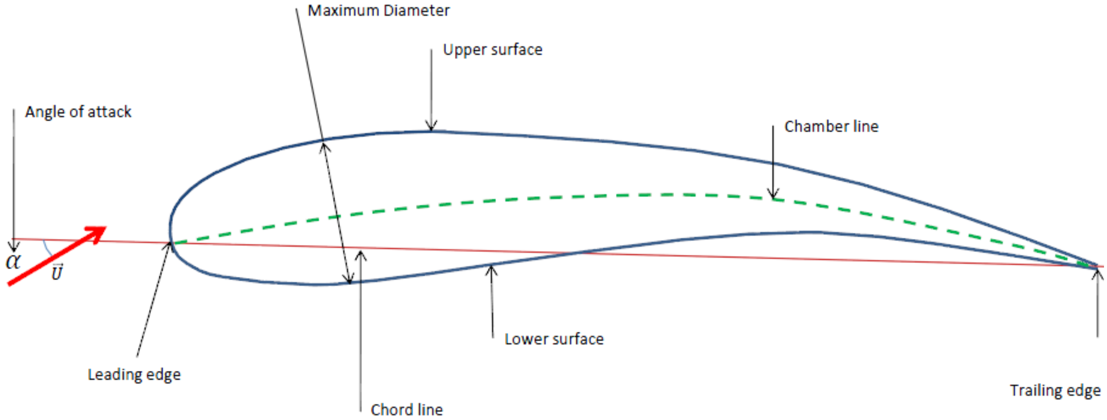

Figure 32: Foil shape in a moving flow with details of the different parts of the foil.

The red arrow in Figure 32Figure 32: indicates the direction of the flow. The angle between the direction of the flow and the chord line is known as ‘angle of attack’, denoted by α.

Laminar Flow

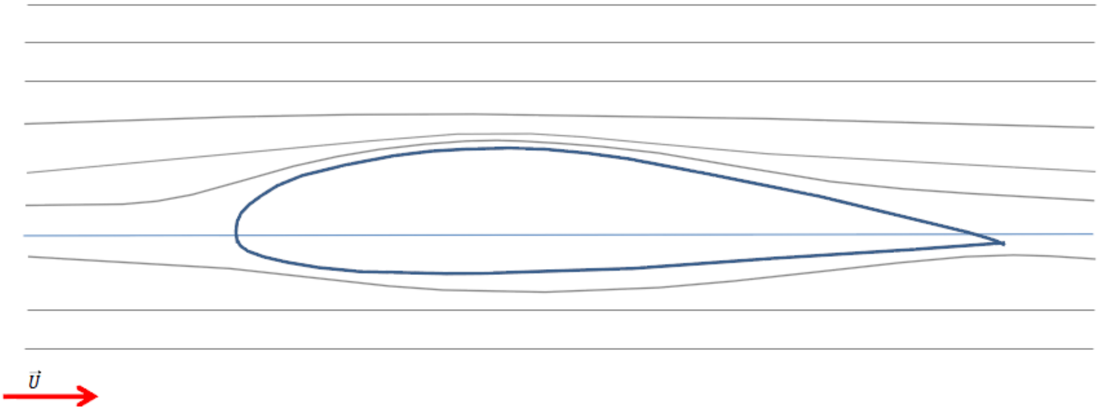

Figure 33: A submerged foil in slow-moving laminar flow.

Figure 33 shows an illustration of a stationary foil in slow-moving laminar flow. At this point in time the velocities of the particles are low, this allows for the particles to follow the foil shape, from the leading edge to the trailing edge. The grey lines illustrate the path of a few particles located in the flow. Notice, that there is no rotation in this flow: the figure illustrates a ‘non-rotational laminar flow’. Particles near the foil are forced to change direction. As a result of the direction change and the characteristics of the ideal fluid the speed near the surface of the foil experience a velocity increase.

Dependent on the medium, density and viscosity of the medium denoted by ρ and $\vec{U}$ respectively, are crucial for the forces occurring on and around the body of the foil. The velocity changes are different on the upper surface compared to the lower surface. As a result the pressure p, is not propagating constantly along the surfaces of the body. Figure 34 shows an illustration of a submerged foil with an illustrative pressure characteristic in a constant laminar flow.

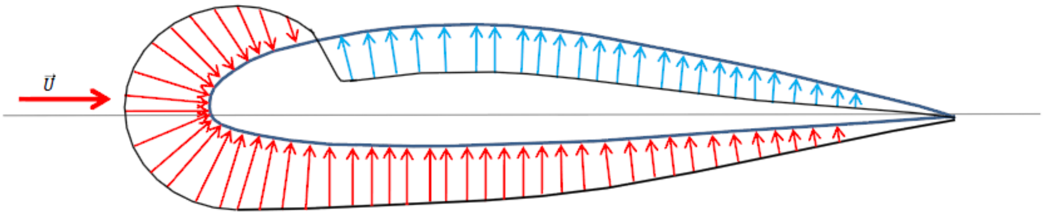

Figure 34: Illustration of foil pressure characteristics of a foil in a moving flow.

As Figure 34 illustrates, the result of the uneven speed distribution over and under the foil, an asymmetrical pressure resultant is formed on the foil, generating *lift*. While examining Figure 34 it is understandable that the resulting lift component must be generated normal to the direction of $\vec{U}$. The blue arrows represent where the pressure is under the surrounding average and the red represent overpressure compared to the surrounding average. Pressure distribution will change correspondingly to velocity, density and viscosity of the medium. Lift performance is also dependent on the angle of attack. If we change the angle between the flow and the cord line, the lift force component will change rapidly in size and direction. The lift can be calculated by the equation (Pedersen, 2013):

$$L = \frac{1}{2}\rho\vec{U}^2 A C_L(\alpha) \tag{2}$$

Where A is the notation for the area of the foil. The figures in this section have been shown as a two dimensional-cross section of a foil. A foil is a three dimensional object and the whole surface must be accounted for in this equation (m^2). The lift coefficient $C_L(\alpha)$ is a variable of the angle of attack. The variable express how 'effective' the body is in regards to the angle of attack.

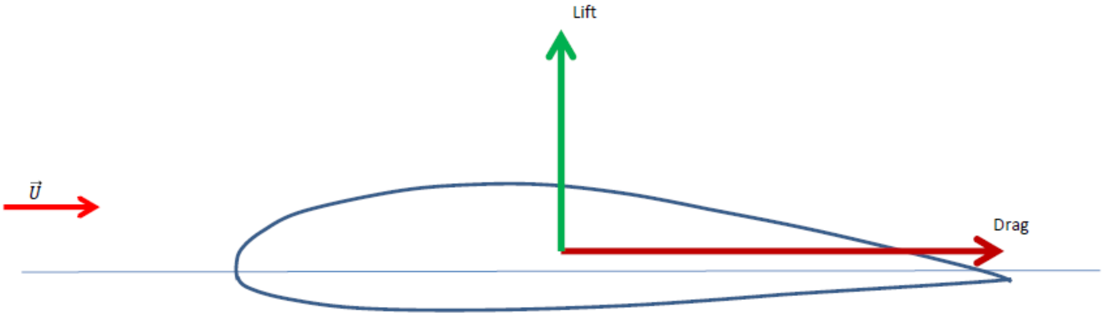

Figure 35: Lift- and drag -components as a result of lift- and drag forces.

The component can be calculated with the expression:

$$D = \frac{1}{2}\rho\vec{U}^2 A C_D(\alpha) \tag{3}$$

If the angle of attack becomes too large the foil will stall and the lift to drag ratio becomes unfavourable. The lift will be significantly reduced and the drag will increase exponentially. The coefficient C_d is known as the drag coefficient.

$$M = \frac{1}{2}\rho\vec{U}^2 A C_m(\alpha) \tag{4}$$

The forces inflicted on the foil gives an origin for a momentum. Considering the change in angle of attack, alter the properties of the foil. If the foil has been constructed to be balanced at a given angle of attack α_1, and the angle is changed to α_2 the un-proportional force resultant gives the origin for a momentum. Abbot and Doenhoff (1959) describe the momentum as the side force perpendicular to the lift and drag acting in the plane of symmetry. The result is the 'pitching momentum', M given in equation (4).

Coefficients

The lift- and drag –coefficients are two important elements included in this thesis. Equation (2) and (3) include the respective coefficients. Abbot and Doenhoff (1959) states:

> A convenient way of describing the aerodynamic characteristics of a wing is to plot the value of the coefficients against the angle of attack, (…). The lift coefficient increases almost linearly with the angle of attack until a maximum value is reached, whereupon the wing is said to "stall." The drag coefficient has a minimum value at a low lift coefficient, and the shape of the curve is approximately parabolic at angles of attack below the stall. (…) (Abbot and Doenhoff, 1959, p4).

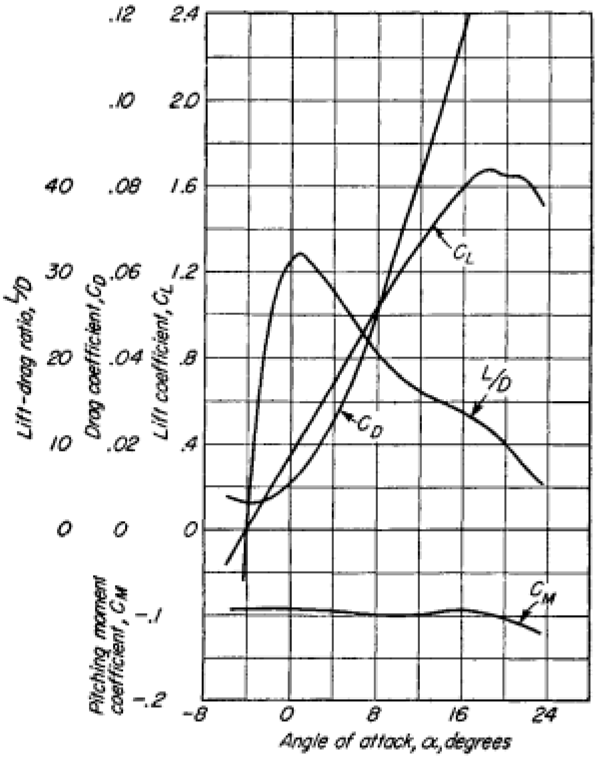

Figure 36: Typical Wing Characteristics as described by Abbot and Doenhoff.

In the citation above Abbot and Doenhoff describe the effects of lift and drag coefficients in respects to each other. Figure 36 is the figure with the coefficients Abbot and Doenhoff describe.

To clarify what Figure 36 implies, visualize a three dimensional wing with a continuous wing profile, submerged in sea-water. This changes equation (2) and (3), the only variable are now the coefficients, because the velocity is constant, the density of the medium is constant and the area of the wing is constant. If $\rho, \vec{U}$ and A (density, velocity of the flow and the area of the wing, respectively) are constant, this part of the expression become trivial, and the result can be plotted as we see in Figure 36.

The coefficient C_m is represented in Figure 36 is close to constant for the interesting interval of angle of attack. This is valid for symmetric foil profiles. High-lift profiles and profiles with flaps have characteristics inflicting larger momentum forces.

4.2 Modelling – creating the simulation

The modelling of the simulation is done with utilization of the software programme OrcaFlex 3D. This section will contain a build-up of the simulation model. OrcaFlex inputs are too extensive to describe in detail, accordingly the most relevant input values are represented in the following paragraphs and tables.

PolarcusX is the representation of the Polarcus Alima in the model. Characteristics implemented in the vessel-model do not influence the outcome of the results within the investigating scope. The vessel-model is located in the centre of the 3D view. Read lines represents the vessel which is illustrated in several of the Figures in the following sections. The vessel has the input data represented in Table 5: Environment and vessel input.

Table 4: General Input

General	Input	Notation
Gravity	9.80665	$\left[{}^{m}/_{s^2}\right]$
Dynamics		
stages	2	$[-]$
Stage 1	0-50	[s]
Stage 2	50-	[s]
Time step	0.01000	[°s]

Table 4 provides information of the dynamic parameters utilized in the simulations. The simulations ‘stages’ are specified in two intervals. The first interval is between 0-50 s. In this interval the configuration will find its ‘steady state’. The time step is set to 0.01000 s. Indicating that software will conduct one set of calculations for each element in the configuration at an interval of 0.01 s. The intention of the initial stage between 0 and 50 s is to achieve the steady state for the simulation. After 50 s the simulated change in angle of attack on the foils attached to the SDCBs will inflict onto the configuration. The simulations were stopped at a stage where the SDCBs reached a steady state and/or the surface for simulation ONE through THREE. For simulation FOUR through SIX the simulations were stopped when the units reached a steady state or the simulation time exceeded the pre-set simulation time.

Table 5: Environment and vessel input

Environment	**Input**	**Notation**
Air temperature	10.000	$[^{\circ}\mathrm{C}]$
Kinematic Viscosity	3.5%	$\left[m^2/_s\right]$
Water density	1.024	$\left[te/_{m^3}\right]$
Water temperature	10.000	$[^{\circ}\mathrm{C}]$
Seabed model	Linear	$[-]$
Seabed Shape	Flat	$[-]$
Seabed origin, Depth	1000	$[m]$
Waves	N.A.	$[-]$
Current Speed	0	$[m/_s]$
Current direction	180	$[^{\circ}]$
Air Speed	0	$[m/_s]$
Vessel	**PolarcusX**	
LOA	88.0	$[m]$
Weight	10.000	$[te]$
Velocity	3.215	$[m/_s]$
Heading	000	$[^{\circ}]$

The configuration is constructed with several different lines and objects. The line-types are represented in Table 6.

Table 6: Line details and characteristics.

Line	**Outer diameter** $[\boldsymbol{m}]$	**Mass per Unit Length** $\left[\boldsymbol{kg}/_{\boldsymbol{m}}\right]$	**Drag Coefficients**	
			$\boldsymbol{C_n}$	$\boldsymbol{C_t}$
Lead-in hairy fairing	0.028	2.0	1.400	0.050
Contact line	0.030	0.88	1.800	0.025
Streamer	0.060	2.9	1.200	0.025
Lead-in Tuffline	0.032	1.0	1.000	0.025
GunUmbilical	0.065	4.2	1.500	0.0080
Spreader	0.016	4.2	2.400	0.0080
GunUmbilical1	0.065	4.2	1.500	0.0080
Spreader1	0.016	0.21	2.400	0.0080
Spacer rope1-2	0.022	1.0	0.400	0.025
SpacerRope2-3	0.018	1.0	0.400	0.025

Table 7: Examples of different line details within the model.

Line	Total Length[m]	Number of sections	Section length[m]	Number of segments	Line type	Connected to: End A	Connected to: End B
Lead-in 1	355	3	20	40	Contact Line	Polarcus X	StreamerConnector1
			155	20	Lead-in hairy fairing		
			180	5	Lead-in hairy fairing		
Lead-in 2	295	3	20	40	Contact Line	Polarcus X	StreamerConnector2
			100	10	Lead-in hairy fairing		
			175	10	Lead-in hairy fairing		
Lead-in 3	253	2	103	40	Lead-in hairy fairing	Polarcus X	StreamerConnector3
			150	20	Lead-in hairy fairing		
Lead-in 4	247	2	102	10	Lead-in hairy fairing	Polarcus X	StreamerConnector4
			145	10	Lead-in hairy fairing		
Lead-in 5	285	2	120	10	Lead-in hairy fairing	Polarcus X	StreamerConnector5
			165	10	Lead-in hairy fairing		
Lead-in 6	345	2	175	10	Lead-in hairy fairing	Polarcus X	StreamerConnector6
			170	10	Lead-in hairy fairing		
Spacer rope 1	100	1	10	10	Spacerrope1-2	StreamerConnector1	StreamerConnector2
Spacer rope 2	102	1	10	10	Spacerrope1-2	StreamerConnector2	StreamerConnector3
Spacer rope 3	102	1	10	10	Spacerrope2-3	StreamerConnector4	StreamerConnector5
Spacer rope 4	100	1	10	10	Spacerrope1-2	StreamerConnector5	StreamerConnector6

Table 7 contains the input values for the lead-inns and the spacer ropes. As an example, investigate Lead-in one: The total length is 355 m, the lead-in is divided into three sections, where the first section is 20 m long, the second is 155 and the third is 180 m. Next column describes the number of segments within each section length. By evaluating the data, it becomes clear that calculations have a higher density surrounding the elements of interest.

The deflector are simulated with multiple elements; Deflector, lift deflector, deflector float, deflector float head, deflector float tail and deflector connector. As stated in section 1.4 the deflector details considering the depth control issues are not implemented in these simulations. Behaviour regarding the deflector is inflicted by a force in vertical direction equal to the force inflicted on the other units of interest.

To simulate the change in angle of attack the SDCBs' mass were manipulated. Mass in form of a buoy with either positive or negative bouncy were attached with a link to the units. To ensure the neutral bouncy of the SDCBs the mass were adjusted. 50 s into the simulation the link between the SDCBs and the additional buoys were severed. Effect of the mass manipulation inflicts a constant force onto the SDCBs.

Construction of the model

The configuration consists of 6 streamer cables 100 m spread ropes and the streamers are 2500 m long. Figure 37 shows the used configuration viewed from behind, slightly to port side.

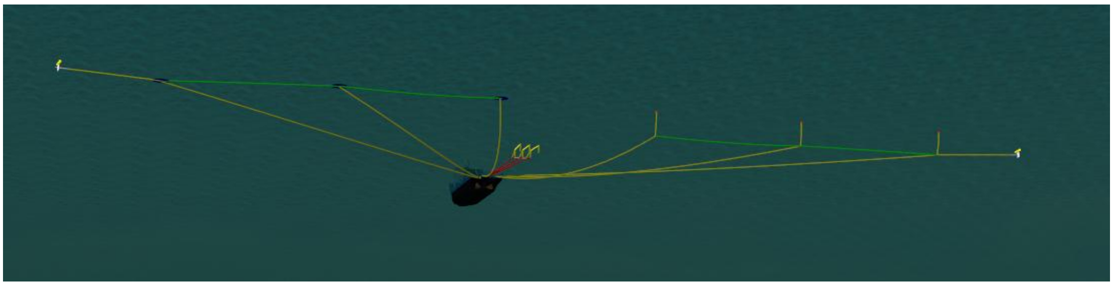

Figure 37: Illustration of the model used in the simulations.

As illustrated the streamers are implanted into the configuration. The simulations are divided into two parts. Starboard configuration is unchanged and the surface equipment is present. Port configuration is the subject of interest.

The following modification have been subject to port configuration: Lead-in one and two has new entry points into the sea level. The new positions are within the projected width of the vessel. This is to reduce the possibility of ice/lead-in interaction. The entry point is also closer to the stern of the vessel, compared to starboard configuration. Figure 37 to 42 illustrate the modifications.

Change in sea-entry position of led-in one and two is enforced by crane unit with a tackle adapted to use on a lead-in with hard fairing. Lead-in three remains unmodified in connection to sea entry coordinates.

The deflector has been put to a depth of -15 m. This is accomplished with manipulating the mass of the deflector. The only additional load on the deflector is a vertical force of -0.250 kN. Replacing the buoys connected to the junction point's width SDCBs allows the connection between lead-inns and streamers to achieve vertical control.

The seismic sources are presented with three gun-arrays and equipped with fins to ensure separation. The fins are simulated by enforcing a marginal force to port and starboard gun-array in positive and negative y-direction, respectively. This allows all the elements in the configuration to achieve a steady state condition.

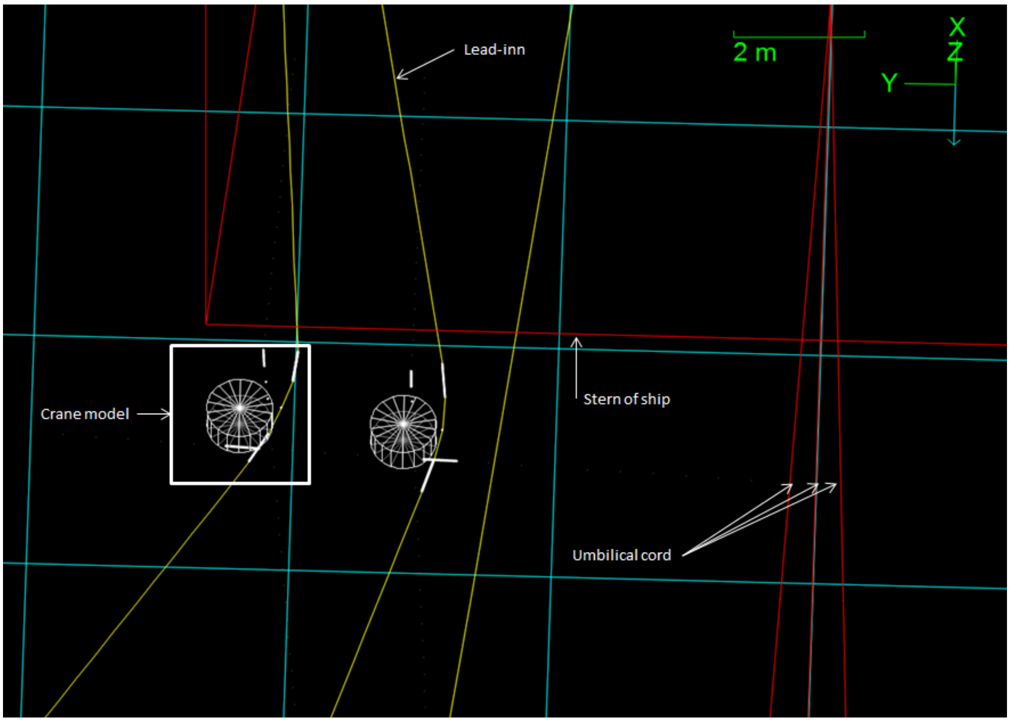

Figure 38: Crane units fitted to reposition the lead-in entry points for lead-in one and two.

Figure 38 shows an illustration of the crane unit's simulated shape. Read lines illustrate the stern and sides of the vessel. Umbilical cords are also in read. Lead-inns are illustrated in yellow and the tackles representing the simulated crane units are white. To simulate the tackle cylindrical object were fitted in a locked position relative to the ship stern. By placing lines in relation to the cylinders the lead-inns were locked in place.

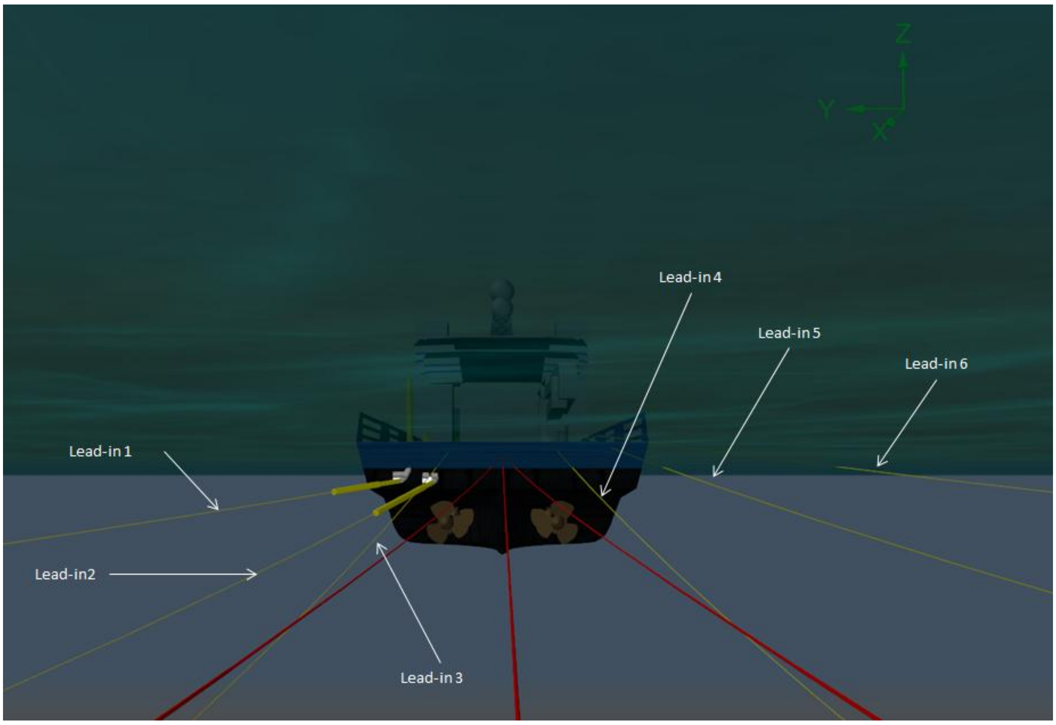

Figure 39: Illustration of the differences between port and starboard configurations.

Effects of the modifications close to the ships stern can be viewed in Figure 39. Lead-in one and two have been repositioned, while Lead-in three remains unmodified. In relations to the contact forces occurring between the lead-inns and the crane modules, the diameter of the first section of the lead-inns were modified, see Table 7. Effects of lead-in characteristic change appear close to the crane units illustrated in Figure 39.

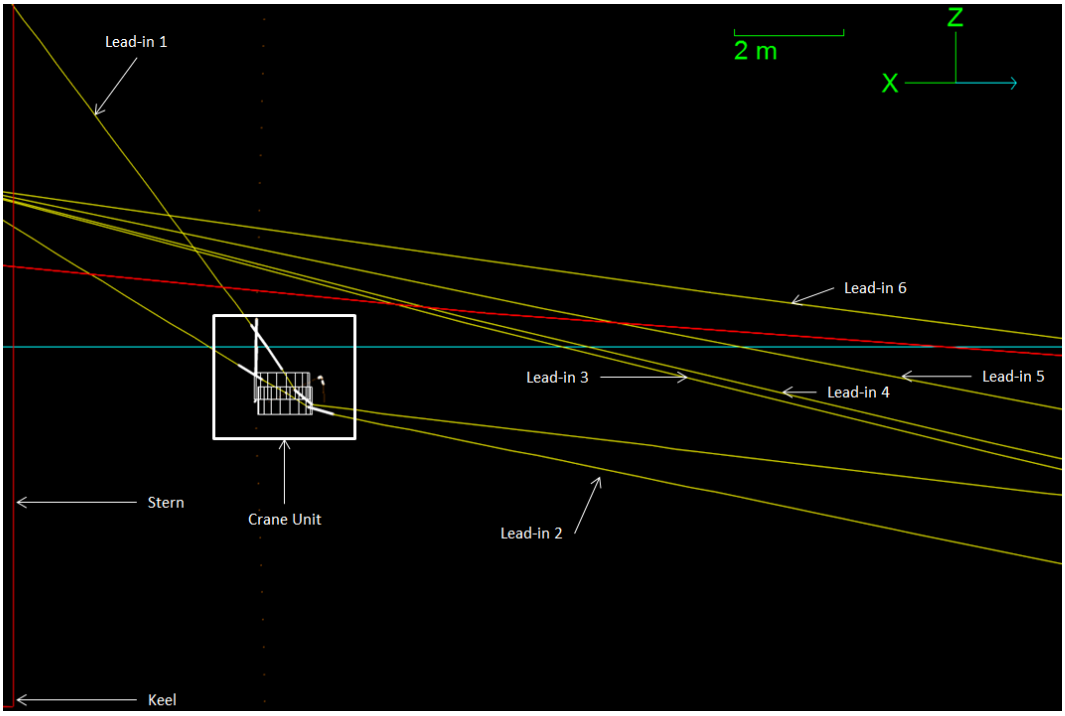

Figure 40: Side view of applied crane units and details in the configuration, viewed for port.

Figure 40 shows the configuration close to the stern of the ship. The desired effect of the crane units and repositioning of the lead-inns one and two are clearly visible.

Figure 41 shows an overview of the configurations. A result of the modification applied to the lead-inns, the length of the lead-inns had to be adjusted to maintain the spread.

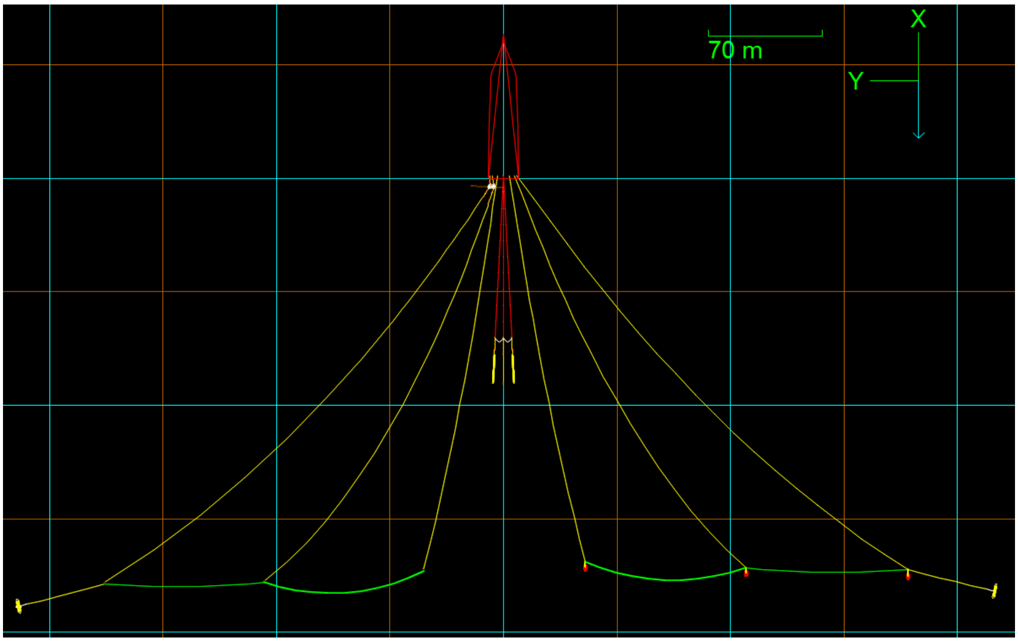

Figure 41: Overview of the configuration, viewed from above.

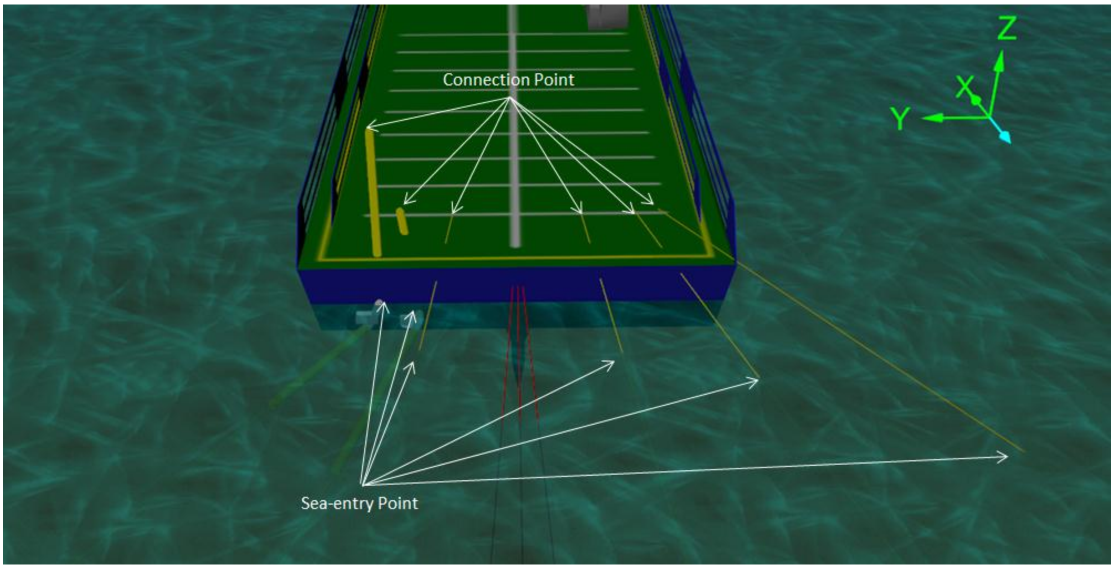

Figure 42: Illustration of the sea entry points of the different lead-inns.

To visualise the effect of the new equipment, Figure 42 shows the entry positions and the differences between the two configurations. The visual differences regarding the shaded graphics mode and the 3D view is slightly offset. This has no infliction on the results.

4.3 Simulations and Results

4.3.1 Simulation input

The objective of the simulations is to investigate the changes and the performance of the configuration with modified hardware and different input values. Table 8 provide an overview of the simulation conducted. Investigations will determine the best effect of the different forces inflicted on the SDCBs.

Table 8: Overview of simulations conducted for the purpose of mapping response time.

Simulation	Description	Objective	Simulation time$[s]$
1	Lift force applied @ t = 50 s 1000 N, towards surface	Investigate the response time until hardware are at the surface	550 s
2	Lift force applied @ t = 50 s 1500 N, towards surface	Investigate the response time until hardware are at the surface	550 s
3	Lift force applied @ t = 50 s 2000 N, towards surface	Investigate the response time until hardware are at the surface	150 s
4	Lift force applied @ t = 50 s, 1000 N in negative z-direction	Investigate the response time until hardware are at the maximum depth	606 s
5	Lift force applied @ t = 50 s, 1500 N in negative z-direction	Investigate the response time until hardware are at the maximum depth	550 s
6	Lift force applied @ t = 50 s, 2000 N in negative z-direction	Investigate the response time until hardware are at the maximum depth	750 s

Table 9: Deflector and SDCBs simulation siput

Simulation	Deflector weight $[te]$	SDCB1 Weight $[te]$	SDCB2 Weight $[te]$	SDCB3 Weight $[te]$	Vertical Force SDCB1 $[N]$	Vertical Force SDCB2 $[N]$	Vertical Force SDCB3 $[N]$	Vertical Force Deflector $[N]$
Initial value	5	0.250	0.250	0.250	0	0	0	-250
1	4.90	0.150	0.150	0.150	1000	1000	1000	1000
2	4.85	0.100	0.100	0.100	1500	1500	1500	1500
3	4.80	0.050	0.050	0.050	2000	2000	2000	2000
4	5.25	0.300	0.200	0.144	-1000	-1000	-1000	-1000
5	5.25	0.250	0.150	0.094	-1500	-1500	-1500	-1500
6	5.25	0.200	0.100	0.044	-2000	-2000	-2000	-2000

4.3.2 Results

The effect of the applied changes done to the vessels stern is represented in Table 10. The X, Y and Z coordinates are referenced to origo of the global coordinate system within OrcaFlex 3D. Origo is in located in the stern of the vessel at the centre line. By comparing the lead-inns coordinates of port- with starboard -configuration the effect is obvious. The results are refferd to simulation ONE @ 49 s for port configuration and 500 s for starboard configuration.

Table 10: Effect of Crane Units on Coordinates, sea entry and spread

Coordinate	**Lead-in 1**	**Lead-in 2**	**Lead-in 3**	**Lead-in 4**	**Lead-in 5**	**Lead-in 6**
X $[m]$	-4.73	-3.64	-10.69	-10.39	-13.17	-20
Y $[m]$	8.05	5.87	5.58	-5.57	-12.59	-24.3
Z $[m]$	0	0	0	0	0	0
Coordinate	**SDCB 1**	**SDCB 2**	**SDCB 3**	**SDCB 4**	**SDCB 5**	**SDCB 6**
X $[m]$	-250	-250.2	-245.2	-238.	-240.5	-241.2
Y $[m]$	246.3	147.49	49.8	-50.43	-149.7	-249.6
Z $[m]$	-7.95	-7.8	-9.2	-15	-15.1	-14.67

The port configuration lead-inn coordinates for entering the sea are well within the width of the vessel. The tension force inflicted on lead-in one after the fitting of crane units are almost unchanged. The force on lead-in one is 48 kN @ 100 s. Compered to tension forces in Lead- in six which is 47 kN @ 100 s, this difference is incremental. Appendix 4 (page *vii*) contains a time plot of both lead-in one and lead-in six.

Tables 11 – 13 contain results of the simulations in regards to the response time. Row one indicates the amount of force applied to the units @ 50 s. Next row indicate if the units reach the surface within reasonable time. Third rows specify the level of depth unit(s) will stabilize.

Table 11: Results Simulation ONE

Simulation ONE	**Deflector**	**SDCB 1**	**SDCB 2**	**SDCB 3**
Force$[N]$ applied @ 50 $[s]$	1000	1000	1000	1000
Surfacing	N.A.	N.A.	N.A.	76,3$[s]$
Stable depth $[m]$ @ time $[s]$	-5.7$[m]$ @ 550 [s]	-5 [m] @ 550 [s]	-0.5 [m] @422 [s]	N.A.

Table 12: Results Simulation TWO

Simulation TWO	**Deflector**	**SDCB 1**	**SDCB 2**	**SDCB 3**
Force$[N]$ applied @ 50 $[s]$	1500	1500	1500	1500
Surfacing	261 $[s]$	N.A	85.0	64$[s]$
Stable depth $[m]$ @ time $[s]$	N.A.	-2.23 $[m]$ @ 264$[s]$	N.A.	N.A.

Table 13: Results Simulation THREE

Simulation THREE	**Deflector**	**SDCB 1**	**SDCB 2**	**SDCB 3**
Force$[N]$ applied @ 50 $[s]$	2000	2000	2000	2000
Surfacing	133 $[s]$	N.A	68 $[s]$	60$[s]$
Stable depth $[m]$ @ time $[s]$	N.A	-1.89$[m]$ @141 $[s]$	N.A.	N.A.

Table 14- 16 contains the result of the simulations conducted with downwards force. The first row in each table displays the force applied to the units in a downward vertical direction. The next row displays the depth the unit have archived within the simulation time.

Table 14: Result of simulation FOUR

Simulation FOURE	**Deflector**	**SDCB 1**	**SDCB 2**	**SDCB 3**
Force $[N]$ applied @ 50 $[s]$	-1000$[m]$	-1000$[m]$	-1000$[m]$	-1000$[m]$
Stable depth $[m]$ @ time $[s]$	-7.8$[m]$@ 600$[s]$	-8.36$[m]$@117$[s]$	-15.7$[m]$@114.9$[s]$	-25.4$[m]$@141.9 $[s]$
Change in depth	0.2$[m]$	0.76$[m]$	4.1$[m]$	15.5$[m]$

Table 15: Result of simulation FIVE

Simulation FIVE	**Deflector**	**SDCB 1**	**SDCB 2**	**SDCB 3**
Force $[N]$ applied @ 50 $[s]$	-1500	-1500	-1500	-1500
Stable depth $[m]$ @ time $[s]$	-12.8$[m]$@550 $[s]$	-13,3$[m]$@500$[s]$	-20.9$[m]$@350$[s]$	$-23[m]$@186$[s]$
Change in depth Δh	5.4$[m]$	5.8$[m]$	9.7$[m]$	23.5$[m]$

Table 16: Result of simulation SIX

Simulation SIX	**Deflector**	**SDCB 1**	**SDCB 2**	**SDCB 3**
Force $[N]$ applied @ 50 $[s]$	-2000	-2000	-2000	-2000
Stable depth $[m]$ @ time $[s]$	-19.9$[m]$@682$[s]$	-19.7$[m]$@535	-27.6$[m]$@489$[s]$	-41.8$[m]$@195$[s]$
Change in depth	12.3$[m]$	12$[m]$	15.9$[m]$	32$[m]$

5 Discussion and Analysis of the Presented Issues

The arguments presented in regards to the climatically characteristics of the Arctic, are factors that must be incorporated in operational standards for Arctic MSOs. The climate-, infrastructure- and distance to market -issues described by Barabadi, Barabady & Markeset (2009) are factors representing challenges. The on-going commitment to Arctic area has and will influence these issues. In a historic perspective there has never been more maritime activity within the Arctic region, regarding O&G-, fishing- and transportation -industry. Pavlenko and Glukhareva (2010) concluding remarks considering the future of Arctic development states:

> “-The scale and rates of Arctic hydrocarbon resources development in these shelf and coastal areas in many respects will define the directions of arctic marine shipping activity.”

Given the reference above the understandable influence O&G companies have regarding infrastructure development in the Arctic are considerable. Increased activity is stimulating for the onshore support functions. Focus on safety and environmental issues in the Arctic increases the readiness and search and rescue response time. David B., at el. (2011) States:

> “The effect of general reduction in sea ice extent, and especially of reduced levels of old sea ice, on commercial shipping and offshore oil and gas activities, will result in generally longer operating seasons, especially in deeper waters.”

In relation to the seismic industry this prediction is positive, if the trend of ice dispersion continues its progress in the future. To increase the season of operation and reduce presents of multiyear ice will allow the Arctic MSOs to be conducted through a longer season. Areas not reachable with today’s ice situation will become accessible in the future.

The future of Seismic industry in the Arctic areas is positive, but challenging. The Norwegian territories within the Arctic represent a considerable amount of undiscovered hydrocarbon resources. The Norwegian Department of Oil states that the search for undiscovered hydrocarbon resources in the period up to 2025 is imperative, if the production rates are to remain at the present level. The period after 2025 search for new oilfields becomes even more important (Lindberg, 2013).

This support the statement mentioned in the introduction, research and technology development within the field of seismic remote sensing are in demand. If the future of the seismic industry is to operate within ice-covered waters the time for research and development of feasible alternatives to conventional seismic surveys must initiate presently.

5.1 Arctic Navigational and Operational Challenges

One of the biggest challenges concerning Arctic MSOs is unpredictable ice- and weather situations. Rapid change and unpredictable movement of the MIZ make operational ice-conditions difficult to predict. Ye & Nesterov (2007) have developed a numeric model for predicting the movement of different sized icebergs. The model becomes inadequate do to the definition of the model-results, regarding utilization in MSOs. The statement is not critique of Ye & Nesterov’s model but an acknowledgement to the reoccurring fact that developed models and information available will not benefit Arctic MSOs due to lack of precision, and coarse definition.

The vessels pre-planned track and the actual route the vessel is able to sail dos not necessary correspond. As a result the specification of the seismic survey must consent to some degree of aberration. In addition to the ice situation, weather and visibility adds complicating factors to operation. Polarcus Alima ice classification class, 1A, does not guarantee the prevention of ice damages. It must be specified Polarcus Alima has no abilities to preform ice-breaking operations. Ice damages can occur within the operational limits of the 1A ice class, even if the limitation has not been exceeded. The ice class does not *guarantee* safe passage through ice.

The ice situation must be of such a character that the vessel can proceed through the obstruction without compromising velocity specified for the operation. As a result of the limitations strict guidelines and operational instructions must be developed for Arctic MSOs.

The speed during a seismic operation is critical, as mentioned earlier in this thesis. To deliberate the argument considers the following examples:

- Given a conventional seismic configuration where the transverse force suddenly disappears, caused by an unforeseen event. The configuration begins to collapse as soon as the transverse force generated by the deflectors disappears. As a result of the diminishing distances between the streamer cables. At this point it is imperative that the seismic crew adjust the depth of every other streamer to high- or low -depth.

  Using a six streamer configuration, streamer one, three and five would be steered towards the surface. Streamer two, four and six would be dropped to a lower depth. The reason for splitting the configuration is to reduce chance of cable-entanglement. Keep in mind, the vessel is still moving forward allowing the control units to change the depth and to some degree horizontal position of the streamer.

  When the unwanted event occurs workboats will deploy to retrieve and/or repair damaged equipment. The problem can be maintained and the operation resumed at the completion of the repair procedure.

- In ice influenced waters loss of forward motion do to navigational miscalculation is a possibility. If the ice situation is severe, there are no possibilities to deploy work boats. Given that the option of proceeding through the ice is exhausted, the only option is to proceed astern. The possibilities of entangling equipment are now pendent. Do to the loss of forward motion the birds are ineffective rendering the streamer cables subject to the current, which will result in entanglement.

  Streamers and equipment that detach from the configuration must be considered lost. Due to lack of tail buoys and surface positioning equipment. By fitting flotation devices that would inflate if a streamer were severed from the configuration is a possibility. There are no guarantees that the inflatable

> flotation devices would have sufficient buoyancy to progress through the ice on the surface.
>
> The result of an incident as the example described above, shows how the outcomes of unwanted incident are amplified under the duress of Arctic factors.

The two examples presented enlighten several important elements that are imperative to Arctic MSOs:

- Under no circumstance can the ice situation be undermined. The effect of a configuration collapse would involve potential dangerous operations during attempts for equipment retrieval. Potential for loss and damages inflicted on the equipment in situations involving configuration collapse are likely.

- The velocity of the vessel cannot be compromised at any time for any reason. A ‘man over board’ situation during a standard seismic survey will not cause the ship to reduce speed. Other procedures utilizing mob-boats are implemented for search and rescue purposes. In ice-covered water this procedures will be counter effective.

As the effects of unwanted events caused by the factors in the Arctic are potentially extreme, special measures within the operational standards for advanced MSOs are needed.

In chapter two, section 2.1.4 describes the opportunity to utilize multiple vessels in a seismic operation. In regards to Arctic MSOs the use of ice-breakers might be a possibility. This will inflict redundancy in regards to safety issues. The redundancy aspects of the multiple ship operation are interesting and open possibilities for operations under harsher ice conditions than limited by ice class 1A. As a standard operation icebreaker assisting the Arctic MSOs full time is not viable in regards to economic boundaries. This logic will not comply with the research scope of this thesis.

5.2 Crew Training and Modifications

Given the harsh climatically factors and the amplified risk and safety factors involved in Arctic MSOs, crew competence is critical. As the seismic industry recruits crew members world-wide, procedures from how to dress, to being able to avoid dehydration must be implemented. Crew members must be able to adapt to the Arctic operation factors. Xueli, Barabady and Markeset (2010) describe the challenges for crews in harsh environment:

“In a harsh environment, maintenance activities may be more difficult to perform (e.g. cold climate will seriously affect work force’s productivity) and frequency of maintenance intervals may be different as well. Low temperatures, in combination with wind, snowfall and darkness, may reduce operational effectiveness drastically.”

As the citation implies, knowledge and experience in all aspects of Arctic operation is important. The Seismic industry is a global industry, with multinational crews the importance to develop and educate crews to a satisfying level is critical for the safety of the crew, vessel and operation.

Crew welfare must also be acknowledged. Given the distance to infrastructure and the long distance to civilisation longer deployment periods must be expected. Supplying a good leisure activity programme to motivate and entertain the crew will have a positive effect on the crew.

5.3 Ice Classification Hardware Solutions

Solutions' regarding utilization of UAVs or AUVs provides several advantages. The systems described in section 3.3.3 are suitable systems for the purpose of mapping ice thickness and typography.

A UAV is an option to consider. The relative small size leaves the option of a rocket assisted take-off and net[13] assisted landings on the helicopter deck. Appendix 3 (page *v*) contain an example UAV. Controlling the UAV is a challenge, and the reliability of this option is questionable, due to the rapidly changeable weather parameters.

For the purpose of mapping ice, the AUV will be the best alternative given that it is not subjected to the atmospheric climate factors as the UAV is. Implementation of acoustic positioning transmitters on the ships keel and receiving nodes mounted within the AUVs. This option renders the positioning of the AUVs achievable. The control AUVs can be programmed to mimic the vessels movement with a control unit.

The technical level involved in an operation with AUVs or UAVs is a factor that must be considered. Systems involved are highly sophisticated, crewmembers and operators need special competence regardless of which alternative are chosen.

With the complexity of the AUVs and UAVs operating software and the level of integration possible considering existing systems aboard, much of the operational assignment can be computerized. The positioning relative to the seismic vessel can be fully automated. Processing gathered data and interpretation of dangerous ice fields can be handled with implementation of new software. The processed information can then be presented to the navigators on the ECDIS using an overlay function[14].

Johansen (2008) describe a lacking legal description regarding the use of UAVs, in Norwegian airspace. If the UAV option is chosen for implementation in Arctic MSOs the competence level of the technicians, pilot etc. should be documented for the purpose of operation integrity. This is not required by legal applications, based on the fact that the laws defining UAVs are unspecific and inadequate.

5.4 Seismic Hardware Adjustments

The modifications described both in section 3.3.4 and in chapter four are meant to be the least comprehensive options. The objective is to increase the window of opportunity for Arctic MSOs, without extensive rebuilding of the ship. Regardless, some modifications must be expected.

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[13] A net is deployed on the helicopter deck to catch the UAV, thereby eliminate the need of a runway.

[14] Overlay function apply radar information on to the ECDIS.

The modification to the vessels stern is within boundaries of what is realistic. Modifications and crane units must be fitted in such a way that ordinary operations in ice free waters does not suffer from the instalment of new cranes. The crane unit's stand by position cannot inflict on the standard operations. A convenient solution would be to use cranes, fitted with hydraulic cylinders to inflict the necessary force. It is absolutely imperative that the crane unit does not fail during operations in ice. Use of hydraulic systems under the influence of Arctic conditions might be a source of failure. Design features regarding the crane units must be met. For the purpose of limiting the occurrence of icing and the possibility of hydraulic oil spill. An alternative to hydraulic systems can be utilization of wires and winches located internally in the ship. This option demands a more comprehensive modification of the vessels stern and the alternative is more extensive.

The lead-in cables and umbilical cords must be fitted with protective coating, as described in by Buravtsev & Jokat (1996), in their experiment the lead-in were fitted with steal fairings. The air hoses (umbilical cords) were fitted with protective rubber hoses 0.01 m thick. The modified configuration described in chapter three and four assume that the configuration is deployed in open waters.

Considering the fact that only parts of the cable configuration needs to be coated with protective modifications. As Buravtsev & Jokat proved, rubber hosing were effective in ice between 80/100 to 100/100 coverage in broken ice up to 0.4m thick. With comparison to the modified configuration utilized in chapter four. Steel reinforced rubber coating would be adequate, considering operational limitations. The coating could perform as a bend restrictor at the interaction between the crane unit and the lead-in, allowing for the elimination of the tackle on the crane.

Design modification applied to the deflector result in a challenge regarding deployment. Originally the deflectors would be launched directly into the sea from the ships side. Redesigning and adding of wing section permitting vertical control to be achieved. This implies the need for new deployment procedures and methods.

The direct towing of the deflector increases the tension forces on the lead inn cable. In any case, the reduction of streamers used in this configuration reduces the need for transverse force. The deflector angle of attack is therefore reduced to 13 degrees, assumed that the Baro 48 is still used. Direct towing allows for the elimination of the superwide as described in chapter 3.3.4. This eliminates the unfortunate scenarios described in by Klavenes (2012). By adding the option of vertical control some form of communication and power supply- link must be established, between the vessel and the deflector. Supplementing a channel of communication to lead-in one and six, and thereafter implement a cable in the leaver arm to the deflector. With this modification power and the control signals can be transferred continuously to and from the deflector.

The modified streamer configurations used in ice-covered waters are reduced regarding number of streamers. Compared to the vessels maximum production-rate utilizing 12 streamer configurations the production-rate is significantly reduced. Spread of a 12x100x8000 m streamer configuration is equivalent to cover 9.600.000 m^2. By comparison the modified configuration 6x100x2500 covers 1.500.000 m^2.

The reduction is massive considering the crew members and operational costs have increased compared to an operation conducted outside ice influenced waters.

Implementations of the SDCBs are based upon the fact that surface equipment must be eliminated as a countermeasure regarding the ice. To keep the first sections of streamers at predetermined depth, SDCBs must be capable of inducing a force equivalent to the weight of the cable sections. As the streamers are bouncy neutral at a predetermined depth, the weight of lead-inns will contribute to the downward force.

To increase the agility of the modified configuration the SDCBs are fitted with foils on each side. Changing of the angle of attack will inflict force in the vertical direction. This gives the configuration the opportunity to increase or decrease the depth at a relatively short time interval. By eliminating the surface buoys the movement of the waves has been reduced. This implies that a source of disturbance has been eliminated.

Loss of surface equipment eliminates the option of GPS assisted positioning. Positioning of the acoustic system relative to the GPS data from the vessel itself is unsatisfactory. Therefor a surface cable with integrated GPS antennas in the exterior wall of the cable is added to the configuration. The cable must also contain acoustic transmitters for communication with the existing acoustic network already imbedded on the streamers cables. A potential problem occurs if the transmitters in the cable are lifted out of the water because of the ice.

The cable would be subject to severe contact forces between ice and cable. To reduce the friction forces the surface should be smooth. Because of the overhanging possibility of contact with ice, lateral control cannot be achieved. If fins were to be connected to the underside, ice forces would rip them off during first contact.

5.5 Discussion and Analysis of the Simulations

Utilization of dynamic models for analysis is an efficient process to extrapolate information regarding the research subjects as the one presented in this thesis. With high ratio of calculation, complex dynamic solutions can be produced in a relative short period of time. Given the high complexion of the simulations, knowledge and critical thinking must be applied for the evaluation of the results.

Environmental inputs regarding the simulation described in chapter 4.2 are secondary. The focus of the simulation is on the performance and forces regarding the configuration. Input regarding ice dispersion and ice modelling is non-existent. Despite the arguments stated in the former sections, regarding ice, the simulation focused on the technical solution of depth controlled configurations. Implementation of ice could be simulated with the infliction of oscillating forces with alternating magnitude. Presently there is no ice models incorporated in the software. This means that the ice model must be developed, if desired.

Crane Units

Comparing the x, y and z coordinates displayed in table 10 to each other, yields that the desired effect has been achieved. Entry points for lead-in one and two are now located directly behind the vessel and within the width of the ship.

Consequence of limiting the position for sea entry of the lead-in cables has not restricted the spread. Differences between port- and starboard -configuration can be neglected, when assessing the result in Table 10-in regards to the spread. Additional forces added to the lead-in connection points after the fitting of the crane units are incremental. Compared to the overall force inflicting on the vessel, additional forces regarding the manipulation of the sea entry position can be ignored.

Angles regarding lead-in one and two, from the connection point of the vessel to the crane units' are unlike by design. As stated in the paragraph above the changes in tension forces are incremental, regarding the crane units. The force direction must be accounted for when the design of the crane units are evaluated.

By examining Figure 39 the effect of the propeller wash must be discussed. The model does not incorporate the effect of accelerated turbulent flow from the propellers. Unwanted effect of the flow generated by the propeller could accumulate nuisance effect, vortex induce vibrations and higher levels of oscillations.

Response Time –Upwards Force
Results from each of the simulations are varied, as expected when inflicting different amounts of forces onto the units. Comparing the results to each other illustrates the effect of the different lift forces, see Figure 43.

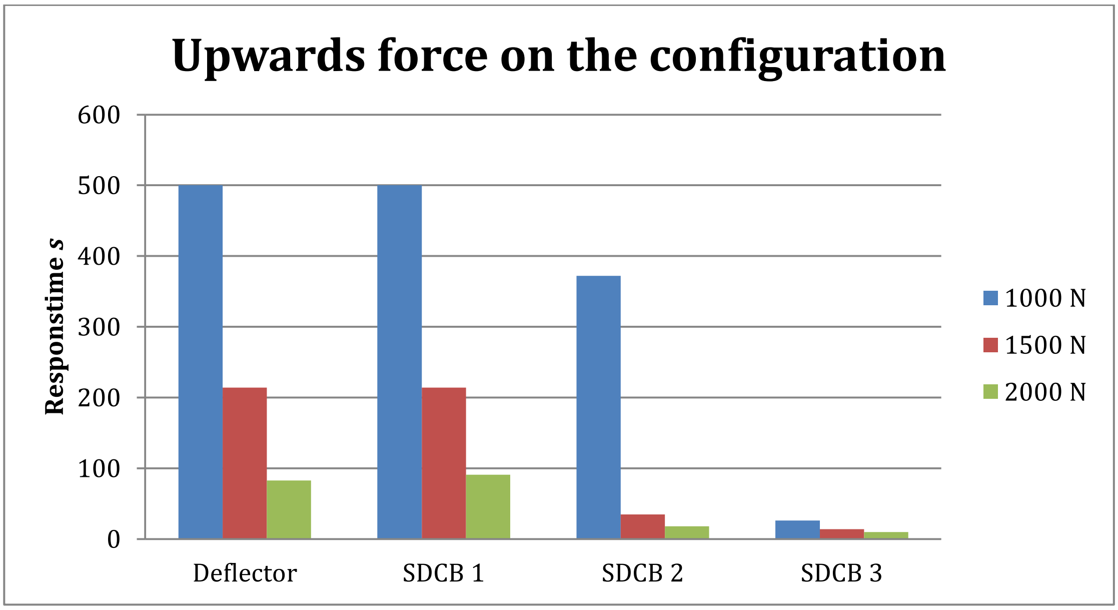

Figure 43: Response time results simulation ONE, TWO and THREE.

Figure 43 indicate the different lifting forces applied by the SDCBs and the deflector. A trend in the data suggests that the deflector will have a significant influence on the response time of the configuration. This is explained by the deflectors' greater mass compared to the SDCBs. Considering that the same amount of force is inflicted on all units of interest. SDCB1 are prohibited by the deflector in simulation ONE and TWO to reach the surface within reasonable time.

Response Time –Downward Force

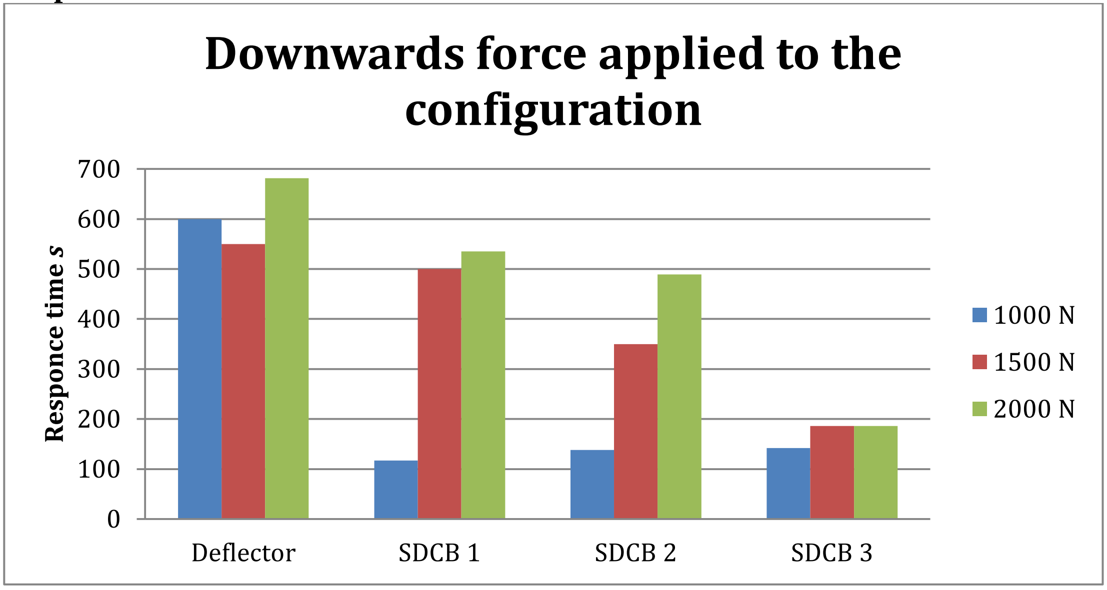

Figure 44: Response time results simulations FOUR, FIVE and SIX.

Data from table 14, 15 and 16, are presented in figure 44. The deflector does not reach steady state in any of the simulated scenarios. The results from simulation ONE, TWO and THREE displays the same tendencies, but not so clearly do to the fact that the deflector are breaching the surface.

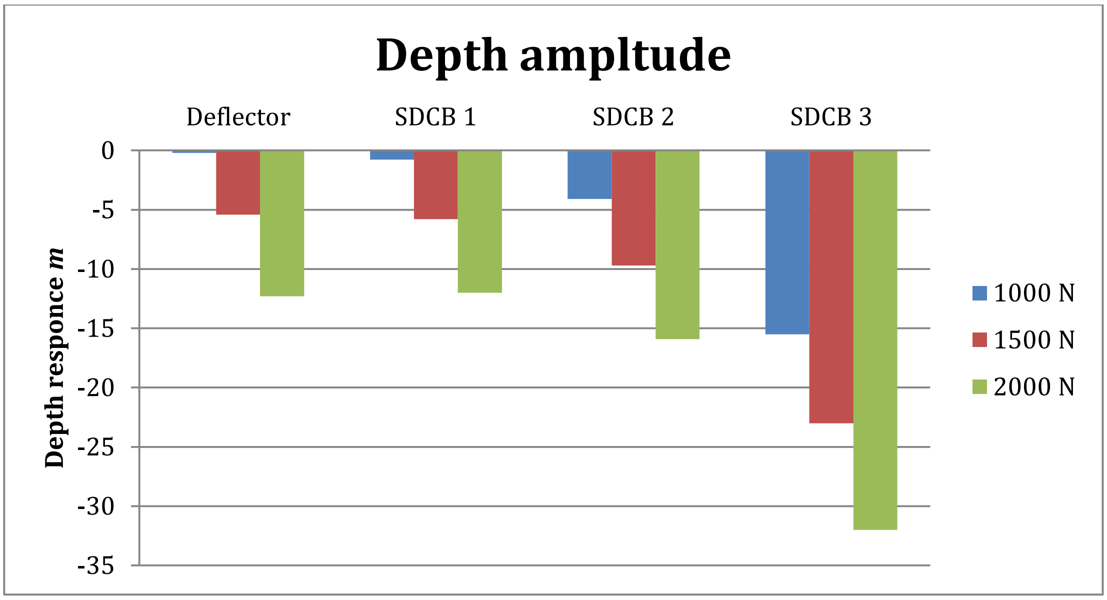

Figure 45: Depth response in regards to force aplitude.

Figure 45 displays the change of depth of each of the units. The change in depth are determined by the depth difference from simulation time interval 50 s to the time of steady state described in table 11 – 16. With the consideration of the result it becomes clear that the deflector has a great effect on the response time and amplification of the depth.

SDCBs

The SDCBs were originally simulated with 6D buoys with six degrees of freedom. Rotational movement of the buoys resulted in a too complicated simulation model with additional trivial results. To rectify the problem 6D buoys were replaced with 3D buoys, resulting in far less simulation time. The results of the response time are a good indicator for the required amount of force supplied by the foils attached to the SDCBs. This will affect the section profile chosen for the foils.

The SDCBs are designed to have predetermined buoyancy resulting in a natural level of depth. If unwanted events were to occur involving the foils attached the SDCBs an option of ejecting the wings should be implemented. The option of ejecting the wings allows the configuration to return to its steady state at a given depth. Implementations of the SDCBs present a challenge in regards to power supply to the units. Today's lead-inns are not equipped for transfer of power and communication to equipment like the SDCBs.

If one of the spreader ropes or the deflectors is detached from the configuration the option of lateral control inflicted by the SDCBs might be a possibility. The idea is to use the SDCBs to assure the separation of the configuration until the vessel are in open water and the hardware can be retrieved and/or maintained. This option implies that the foil sections fixed to the SDCBs can be controlled individually.

Application of the Results

The results presented above shows that the effect of 2000 N applied to the unit will give the best effect. Equation (2) can be converted to express:

$$A = \frac{L}{\frac{1}{2}\rho \vec{U}^2 C_L(\alpha)} \qquad (2.1)$$

Where;

Variable	Value	Description	Unit
L	2000	Lift force	$[N]$
ρ	1.024	Density of medium	$\left[{}^{te}\!/_{m^3}\right]$
$\vec{U}$	2.315	Velocity of flow	$[{}^{m}\!/_{s}]$
$C_l(14°)$	1.3	Lift coefficient	$[-]$
A	0.560	Area of the wing	m^2

Gives;

$$\frac{2000}{\frac{1}{2}1024(2.315)^2 1.3} = \underline{0.56\, m^2}$$

By using 2 kN of force to induce lift both upwards and downwards direction the wing section described by Abbott and Doenhoff (1959) page 632 following the instructions for NACA 65 series on page 120. It seems that the wing section NACA 65_3-018 is a suitable wing section. Each of the foils attached to the SDCBs will have an area of 0.280 m^2. This is a reasonable size for handling by the crew and in regards to storage capacity.

5.6 Uncertainty Evaluation and Results

Data acquired from the simulations has corresponded to the expectancy of the input data. There has not been presented any reason for reservation in regards to the information integrity connected to the simulation. Nevertheless, a discussion of the uncertainty regarding the result should be presented.

The results of the simulations are greatly affected by the simulation time. The force implied at simulation time 50 s does not always provide enough time for the unit to achieve steady state. The variance of unit- depth internal in the configuration is also a situation which is outside of the preferred interval.

Dampening coefficients of viscosity in vertical direction are not included in the simulations. Based upon experience and advice from the teaching advisor viscosity coefficients were excluded from the model. To support this decision Figure 58 in the Appendix 7 (page xii) can be investigated. The speed of SDCB 3 from simulation SIX is displayed. The object experiences an instantaneously change in velocity after the simulation time of 50 s. This effect is a result of the inflicted force on the object. The experienced velocity change is not natural and must be disregarded. The maximum value is $3.2 {}^{m}/_{s}$. SDCB 3 is an example, all units of interest in the simulation are subject to the same change. Considering the low velocity, the effect of the dampening is marginal and can be ignored.

The extractions of information from the time plots located in the Appendixes were double checked to eliminate miss readings of information. The depth information was extracted directly from the software with a precision of +/- 0.5 m. Definition of steady state is set estimated to within this interval. Several of the simulations were cancelled because the model input failed to produce static equilibrium the initiating phase of for the model. The simulation time varied from 3-4 hours to over 8-houres dependent on the input and duration time of the simulation.

6 Concluding Remarks

6.1 Conclusion

Areas influenced by ice are currently unviable for vessels using towed seismic hardware. For the understanding of the challenges regarding MSOs in ice-covered waters the hardware and Arctic has been introduced. Theoretical knowledge upon the subject of hydrodynamic lift and drag forces has been investigated. Elements considering the technical solutions have been subject to the simulations conducted with the FEM based software.

The limitations regarding climate factors must be accounted for. Level of planning and preparations must be expected to be higher compared to ordinary marine seismic operations. This will allow the operations to be accomplished- at least in regards to these factors. Based upon the discussion and result of the simulations presented in this thesis conclusive recommendations for advanced seismic operations in the Arctic, are positive.

Implementation of AUV is critical for the accomplishment of seismic surveys in ice-covered waters. The subscribed solution is a viable alternative. Classification of ice is absolutely critical. This is supported by the fact that vessel velocity cannot be compromised at any given time throughout an operation. Modification of the vessel will be extensive, however, not unrealistic. The crane arrangement fitted to the stern of the ship is a manageable solution. Interaction between lead-in cable and ice are solved with fitting of protective fairings constructed from high strength materials. Reduction in production regarding smaller configurations must be accepted. The compromising effect of reduction in production rate is an effect of the direct towing and the implementation of the crane solution. Replacement of the surface buoys in the lead-in/streamer junction with SDCBs is proven to be a viable solution, supported by the evaluation of the simulation-results.

The result of the simulations shows that the most promising characteristics are found in simulation THREE and SIX, where the applied force is 2 kN. The application of result shows that NACA 65_3-018 is a suitable wing profile for the SDCBs. The connection between the applied force and the response time is positive. Response time in the lower regions of 90 seconds is a suitable response. When considering the level of depth reach within this time interval.

The research scope in this thesis has been to describe a solution for the enabling of a conventional seismic configuration to perform in ice-covered waters. The solution is described with focus on containment of the modification done to the vessel and seismic hardware. All systems implemented in the described solution are based on existing technology.

Concluding remarks regarding the accomplishment of the solution, renders overall high probability of success for the project.

6.2 Recommendations for Future Work

With regards to the solutions described, investigated and discussed in this thesis some issues are in need of further exposition.

Elimination of the surface equipment has prohibited the option of GPS assisted positioning to the acoustic system. The described solution will not compensate for the terminated equipment during operations within ice-covered waters. This situation must be further investigated if the seismic surveys in ice-covered waters are to become a reality.

Depth control of the deflector must be elucidated. Results of the simulations conclude; larger forces must be applied to the deflector to achieve the same response times as the SDCBs. The simulations indicate that the deflector has a considerable effect on the response time and depth increment. Method for deployment of the deflectors must be redesigned. With horizontal wings attached to the frame of the deflector a commercial launch is unsuited. Crane units fitted to the stern of the ship must be further investigated. The mechanical solution and force calculation must be completed before the solution can be applied to the vessel.

An alternative to the foils attached to deflector might be a buoyancy controlled option. This solution needs further investergation.

The SDCBs need further development. The scenarios described in the simulations shows that the SDCBs will have the desired effect on the configuration. However, mechanical solution to the adjustment of the wings, physical form and flow characteristics of the bodies must be examined. The power supply needed for the SDCBs must be transported through the lead inns, this imply a solution where the SDCBs are mounted in an ‘in-line’ position. This solution will need implementation into the existing system and is a subject for further work.

The implementation of AUV assisted seismic operations will acquire further investigation. Subjects of interests are the underwater positioning, communications and overall performance of the AUV. Interface between existing and ice information from the AUVs must be explored.

The airgun problematic regarding ice accumulation must be redesigned. The solution must incorporate measures to counteract the icing problems, without compromising the pulse characteristics.

Ocean Bottom –Systems

The Ocean Bottom Cable (OBC) concept is based on the deployment of cables directly onto the sea bed. When the cables are deployed, a ship can sail over the area with the OBCs and discharge the seismic sources. In this way RAZ surveys data can be obtained. It is normal for several ships to be involved in this operation.

Because the sensors in OBCs are placed directly onto the sea bed, more information can be extrapolated from the operation. The shear impedance which towed seismic hardware is unable to record can be recorded with OBCs.

Ocean Bottom Nodes (OBN) is a similar concept compared to OBCs, but the nodes utilized in this concept are not attached to a cable. OBNs are deployed using a Remotely Operated Vehicle (ROV), nodes are placed on the sea bed one by one. OBN operations can be accomplished with a single vessel operation. This method of seismic operation will also produce data models with more detail than conventional towed seismic operations.

The advantages of utilizing OBS are the elimination of streamers regarding conventional seismic operations. Comparing OBC and OBN operations the elimination of the cable with the OBC alternative gives the OBN an advantage in rugged sea floor conditions.

By utilizing OBC or OBN operations in ice-covered waters can be accomplished. Compared to towed seismic surveys the OB-systems are slow and resource demanding. Rate of production and cost associated with OB-seismic operations are currently too low and too high, respectively.

With further work invested in sensor technology for the purpose of cutting cost and finding new method for deployment and retrieval of the OBSs. If these factors are improved, OBN- systems could become an alternative to the solution described in this thesis.

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Appendix 1: Streamer Elements

Streamer element	**Detail(s)**
Lead-in	Armoured Electro – optical cable Traction resistance: up to 570 KN Length: Up to 1300m
SHS	Short Head Section Flexible section Pulling attachment as an option Length: 6m
HESA	Head Elastic Section Adaptor Elastic adaptor ø70mm – ø 50mm Length: 10m
HAU – 428	Head Auxiliary Unit Streamer tensile stress measurement Head buoy power supply as an option Length: 0,277m
RVIM	Radial Vibration Isolation Module Isolation of vessel vibrations Length 17,5m
TES	Tail Elastic Section Isolation of tail buoy vibrations Length 50m
LAUM – 428	Line Acquisition Unit Module Data routing and power supply of active channels (limited to 60 channels). Internal temperature monitoring Length: 0,256m
TAPU – 428	Tail Acquisition and Power Unit Data routing and power supply of the last active channels Tail buoy power supply Length: 0,335m
SSAS	Sentinel Active Sections Data acquisition sections Field repairable Customizable hydrophone group spacing Length: 150m
SNS	Short Nautilus Section Short flexible section Ø70mm/ø50mm and Male/female option for use in Head or Tail. Length: 0,717m

(Sercel, 2011)

Appendix 2: Software Theory

OrcaFlex 3D software package
The software package is a versatile three-dimensional dynamic model based interface, and the calculations can be done static and/or dynamic. The 3D model is created in the virtual space of the program using lines and prefabricated objects. As the model is created it is possible to give each line or object different characteristics by manipulating the coherent coefficients in the model browser.

The time step between calculations can be selected. OrcaFlex will suggest a suitable time step. Before the simulation begins the programme will run a static simulation to ease the transfer between static and dynamic calculations. To further ease the transition OrcaFlex will use a ramp up interval where the coefficients in the calculations will gradually be multiplied with a factor from 0 to 1 over the ramp up interval (OrcaFlex, 2013).

Calculations of a single time step are done in five steps. Figure 46 shows the elements OrcaFlex uses during these calculations. The figure shows a 3D diagram of the nodes and segments whit the spring and damper coefficients to every axis. Regardless the torsion calculations are optional.

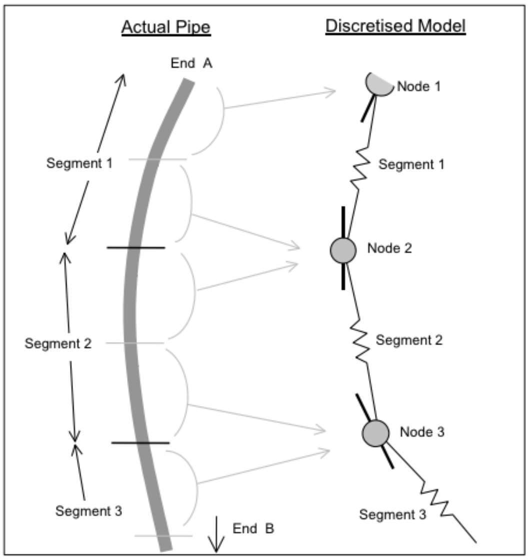


Figure 46: Simplification of Lines in regards to the simulation.

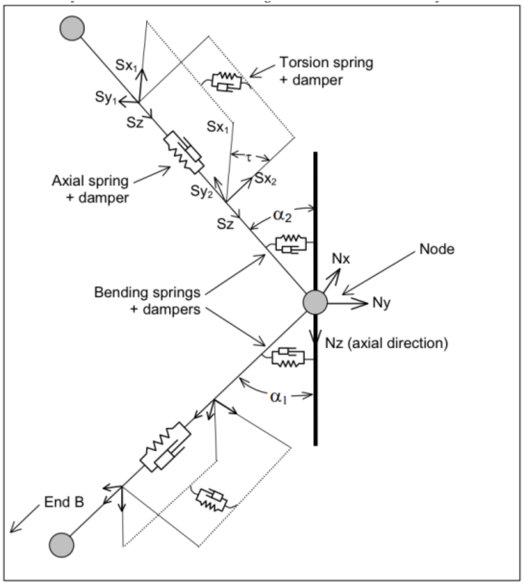


Figure 47: Structural model details.

The first stage is to calculate the tension forces on the lines. This is conducted by calculating the distance and rate of change between the nodes at the end of the coherent segment. At the same time the axial unit vector between the two nodes are calculated. In the centre of each segment the axial tension is calculated from the stiffness spring and dampening coefficients. The vector S_z size is then calculated. The model uses axial stiffness, external/internal pressure and axial dampening to complete the calculations. This is valid for linear axial stiffness. The calculated vector is applied to the nodes at each end of the segment. This means that a given node is affected by two different vectors form each connected segment.

For non-linear axial stiffness the effective tension is calculate with regards to the variation of the wall tension, external and internal pressure and the axial dampening given the nominal axial stiffness (defined as the axial stiffness at zero strain). The result is also here that the vector is linked to the node. Every node (except the ones on the ends) has two vectors, one from each connected segment (OrcaFlex, 2013).

Step two is to calculate the bend moments. Figure 47 illustrate each node which has a spring- and dampening -coefficient on each side (of the node). The spring- and dampening -effect acts between the N_z and the S_z axis, see Figure 30. The two coefficients depend on the angle α, which is the angle between the segment direction and the node direction. The segment and node direction are associated with the frames for the objects. From the figure we can see the different coordinate (N and S) system and the angle between them, α_2. These frames are the same as the frames utilized in step one. And the effective curvature vector can now be calculated. When this is done the programme will make account for the following calculations:

- Linear, isotopic bending stiffness
- Linear, non – isotropic bending stiffness
- Non -linear, isotropic bending stiffness (Elastic or Hysteretic)
- Elastic or Hysteretic Bending Model

(OrcaFlex, 2013)

Having completed stage 2 for each of the segment in the time step, the shear forces can be calculated. The result of stage 2 is that each segment (straight line) has two bending moments acting on both sides. This gives the opportunity to find the shear force vector by the following logic:

$$\frac{M_2 - M_1}{l} = Shear\ Force\ Vector \qquad \text{(A)}$$

Where M_2 and M_1 are vectors representing the momentum applied to each node. The length of the segment is denoted *l*. When the shear force vector is found it is applied to the nodes at each end (OrcaFlex, 2013).

The option of calculating torsion moments must be selected for the programme to calculate these moments. First task within this option is to find the unknown vectors: S_{x1}, S_{y1}, S_{x2} and S_{y2}. By rotating the nodes coordinate system until the N_z axis is orthogonal to S_z, and with the information found in step 1-3 the vectors can be found. The S_{x1} and S_{y1} are derived in the same way, but the rotation of the coordinate system will be in the opposite direction. Then the programme will calculate the torque with regards to linear or none linear torsional stiffness (OrcaFlex, 2013).

The final step of the calculation cycle is the total lode calculation on each node. By combining all forces experienced by the node described in the former steps. The result is then combined with the other non-structural loads like drag, contact forces, weight, added mass and so on. From this point OrcaFlex calculate translational and rotational acceleration of the node, thereafter the programme integrates to get the nodes velocity and position by the next time step (OrcaFlex, 2013).

Clashing Model

There are two different ways to model contact between lines; the Line Contact model and the Line Clashing model. The option to calculate clash forces is by default set to "no", this is because the process is complex and time consuming. The model assumes constant spring stiffness and ignores friction. The algorithm used in the model will push the lines apart from another if they try passing through another. After the contact the model allows the lines to be separated again.

Fore a line to be allowed to clash with another the stiffness must be set to any other (positive) value than zero. The model determines if there is contact between two lines, if the combined diameter of the two lines are greater than the radius of the first line plus the radius of the second line. If this is true then there is no contact. If this is false then there is contact. If there is contact, the contact forces are calculated with the term:

$$F_{contact} = (Stiffness\ Term) + (Dampening\ Term) \qquad \text{(B)}$$

The stiffness is a constant given by the combined contact-stiffness of the segments, the minimum distance between the segments and the combined radius of the lines. The dampening term is defined by the combined contact dampening value of the two segments and the rate of penetration which gives the values of the lines moving apart or if the penetration is increasing (OrcaFlex, 2013).

Appendix 3: UAV- Penguin B

Figure 48: Penguin B

This Appendix contains the description and performance characteristics of the Penguin B UAV as described by: Unmanned Ground, Aerial, Sea and Space Systems (2012):

Penguin B by UAV Factory LLC, USA

Designed as a high performance unmanned airframe, Penguin B is one of the most capable airframes available today. With a small footprint of 3.3 meter wingspan, Penguin B can handle up to 11.5 kg of combined fuel and payload weight. Modular composite structure, fast assembly, large access hatches, removable payload bay, are the key features of the Penguin B innovative design. Available as an airframe ready for the autopilot and payload integration.

PERFORMANCE

Sleek and efficient design gives the best in class performance. Optimized for endurance, Penguin has enough internal volume to lift 7.5 litres of fuel which will provide 20+ hours endurance using efficient Honda 4 stroke engine. The optimized high lift flap system provides stall speeds of <13 m/s while giving excellent flight handling qualities due to a well-designed V-tail geometry.

Specification	**Details**
Weight included fuel and cargo	21.5
Empty Weight	10kg
Wing Span	3.3m
Length	2.27m
Wing Area	0.79m^2
Powerplant	1.3-2.5hp
Max Payload	10kg
Take-off method	Runway or car top launch
Environmental Protection	Sealed against rain
Endurance	20+ hours
Cruise Speed	22m/s
Take-off Run	30m

Stall Speed (with high lift system)	13m/s
Max level speed	36 m/s
C_l max (45° flap deflection)	1.7
C_l max (clean wing)	1.3
Ceiling	5000m

(Unmanned, 2012)

Appendix 4: Extended Simulations Results

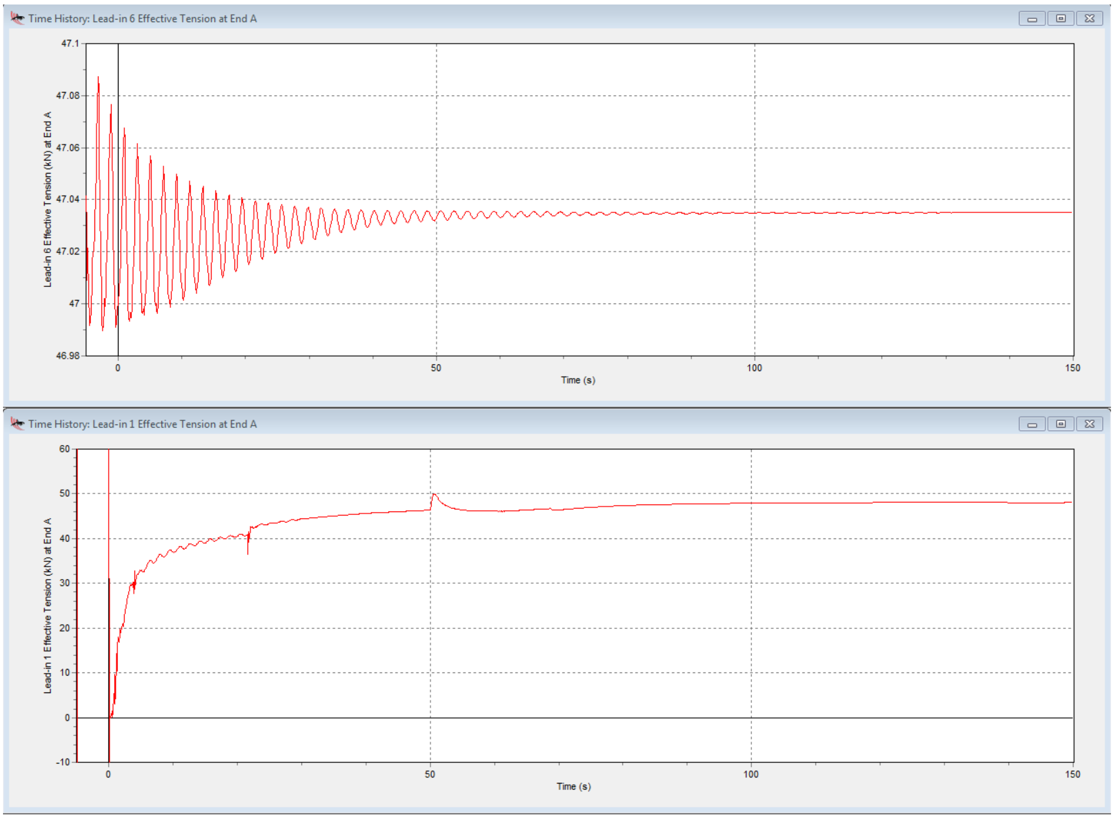


Figure 49: Tension forces in lead-in one vs. lead- in six from simulation ONE.

Simulation ONE

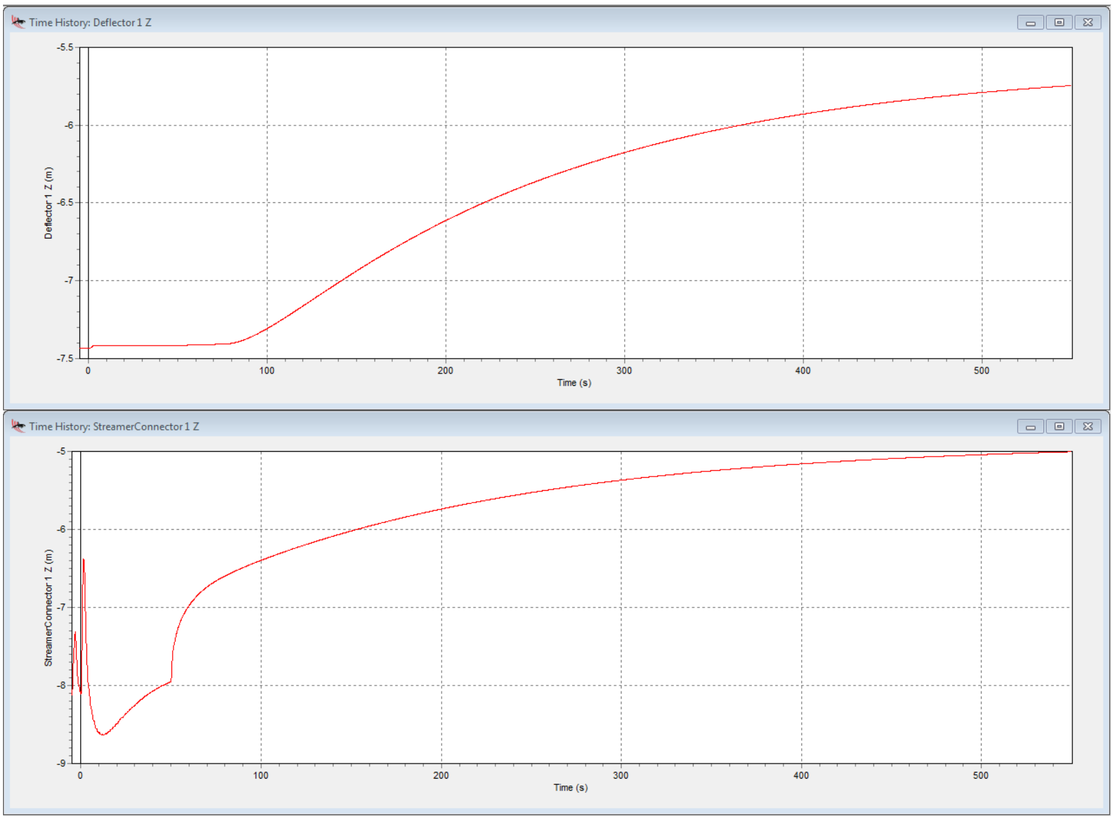


Figure 50: Simulation ONE, deflector and SDCB 1, time plot of the variable depth.

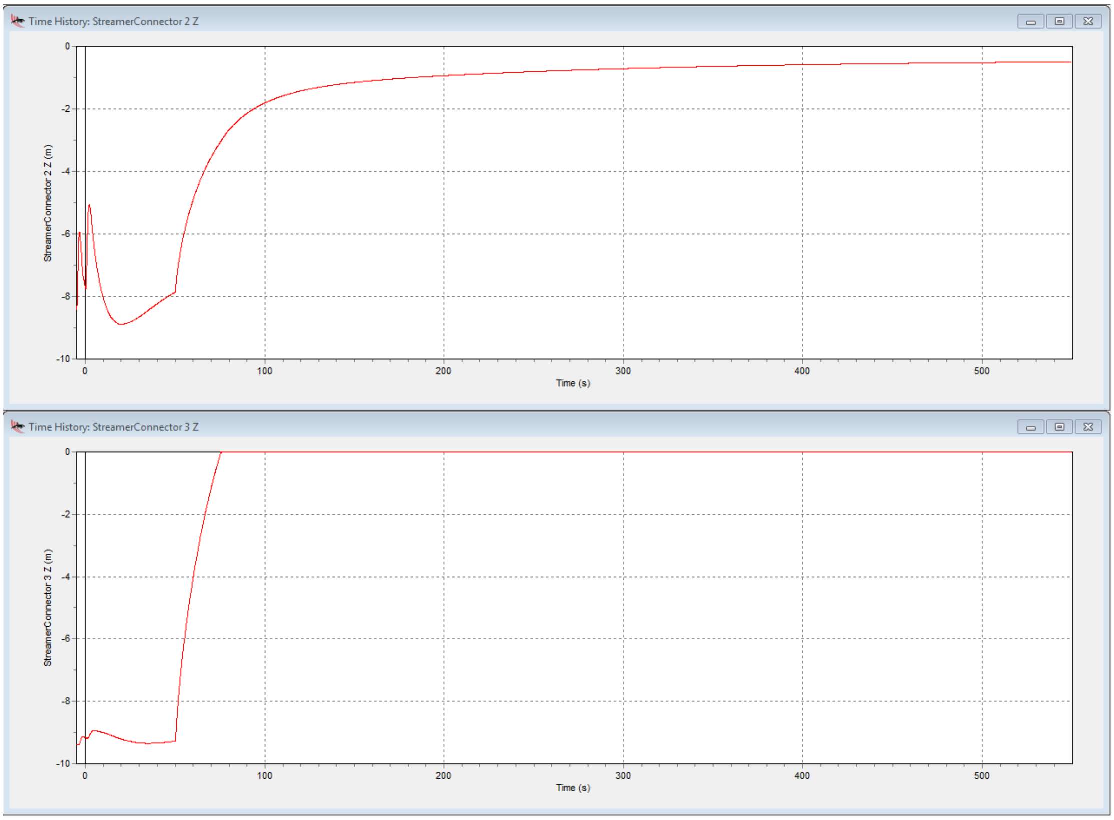


Figure 51: Simulation ONE, SDCB 2 and SDCB 3, time plot of the variable depth.

Simulation TWO

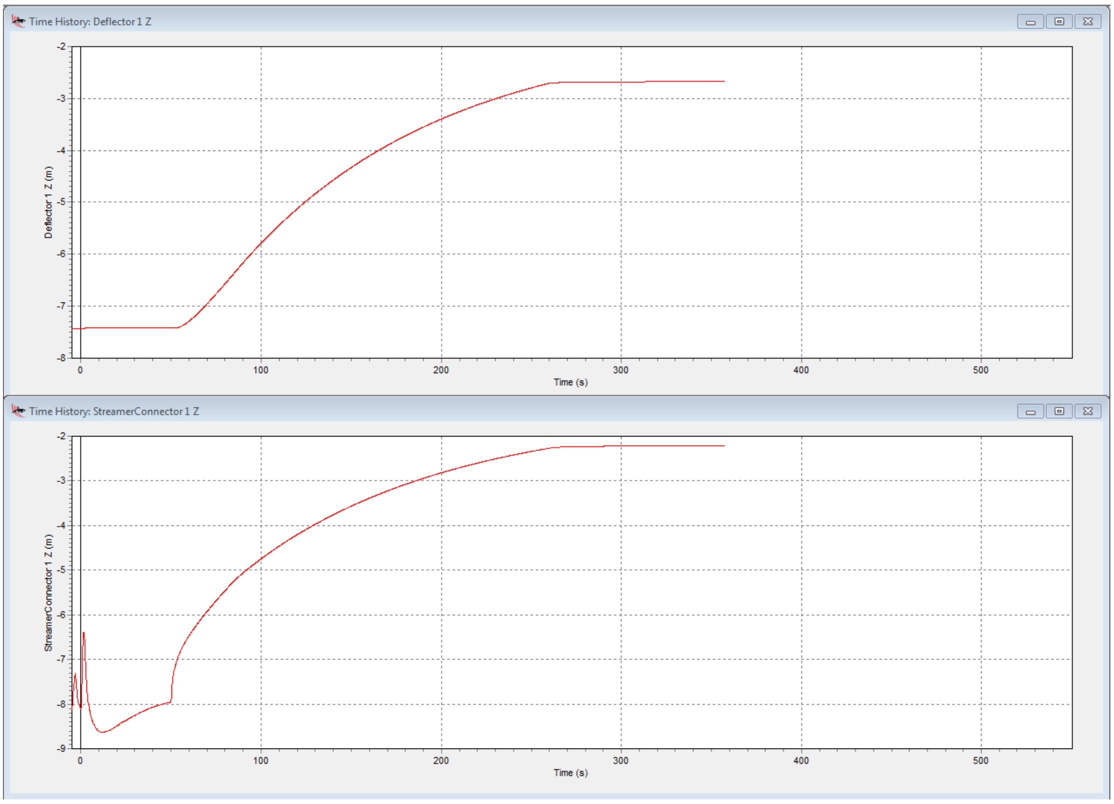


Figure 52: Simulation TWO deflector and SDCB 1, time plot of the variable depth.

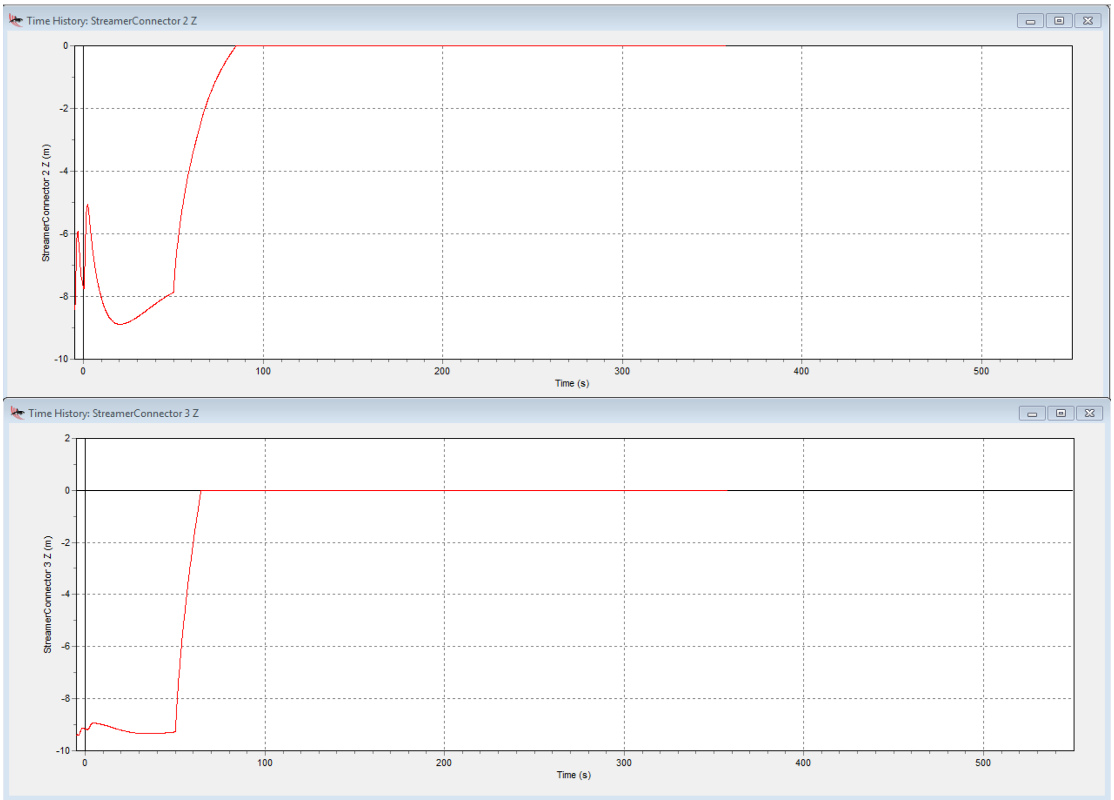


Figure 53: Simulation TWO SDCB 2 and SDCB 3, time plot of the variable depth.

Simulation THREE

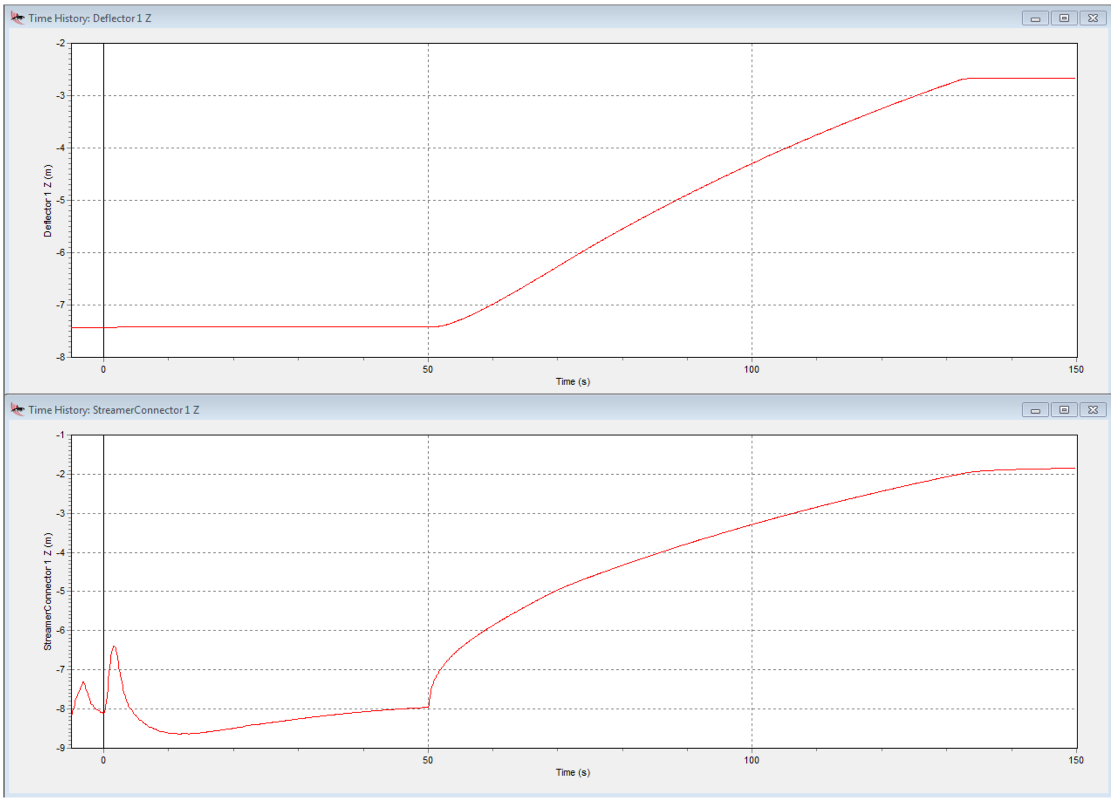


Figure 54: Simulation THREE deflector and SDCB 1, time plot of the variable depth.

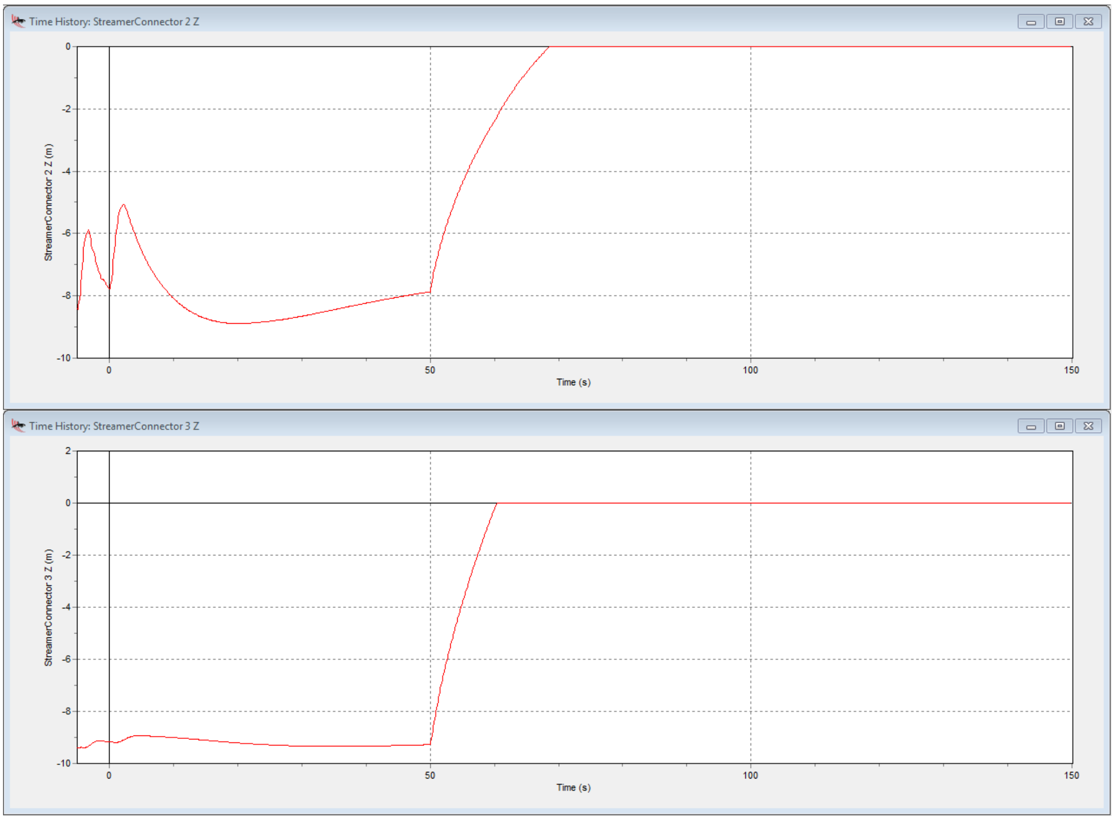


Figure 55: Simulation THREE SDCB2 and SDCB3, time plot of the variable depth.

Simulation FOUR

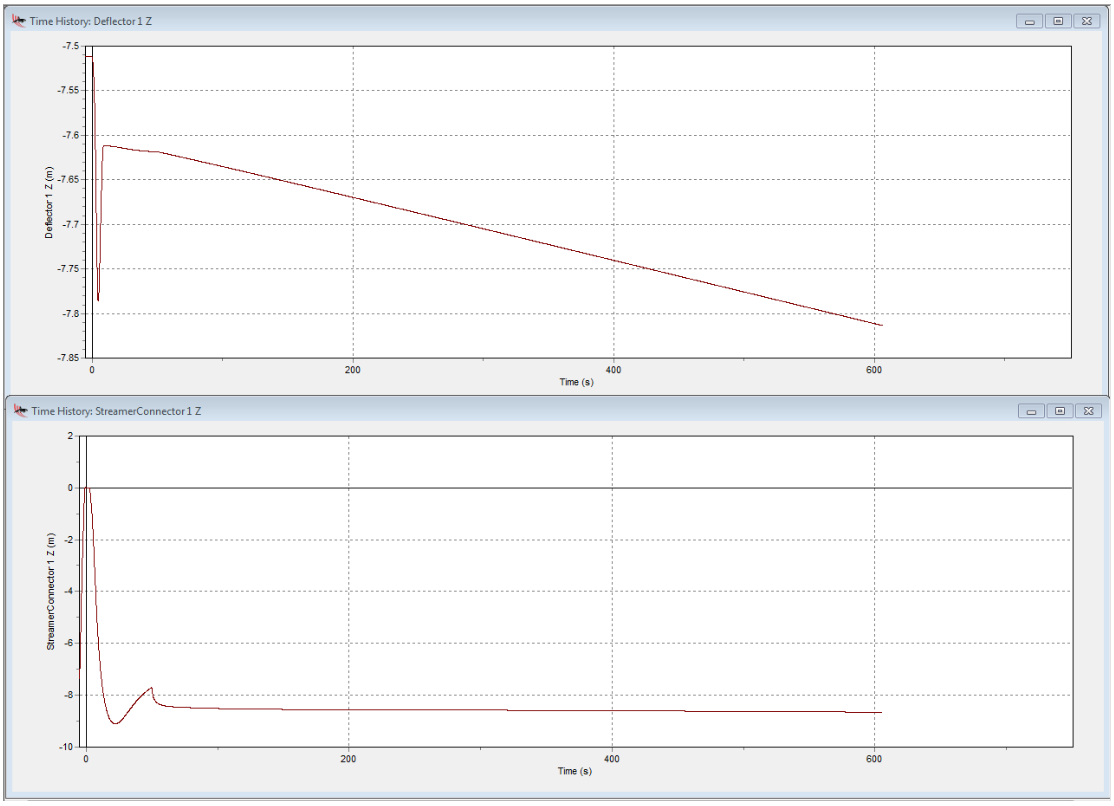


Figure 56: Simulation FOURE Deflector and SDCB 1, time plot of the variable depth.

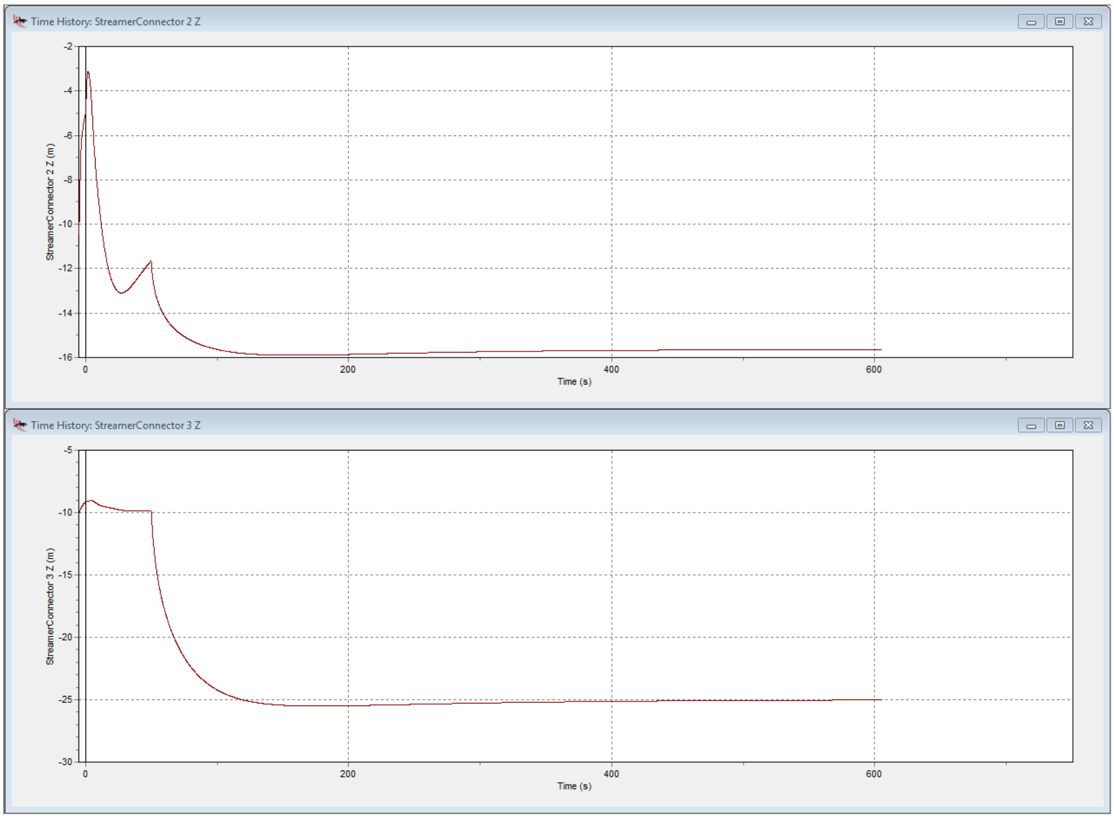


Figure 57: Simulation FOURE SDCB 1 and SDCB 2, time plot of the variable depth

Simulation FIVE

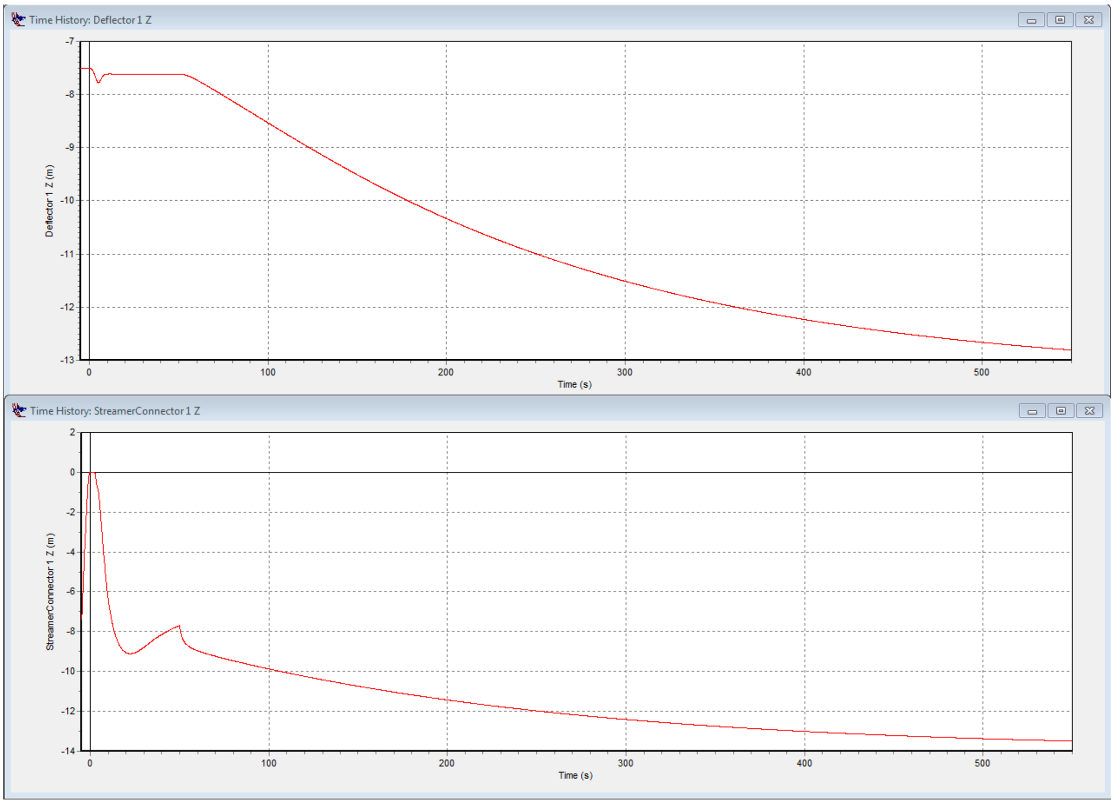


Figure 58: Simulation FIVE Deflector and SDCB 1, time plot of the variable depth.

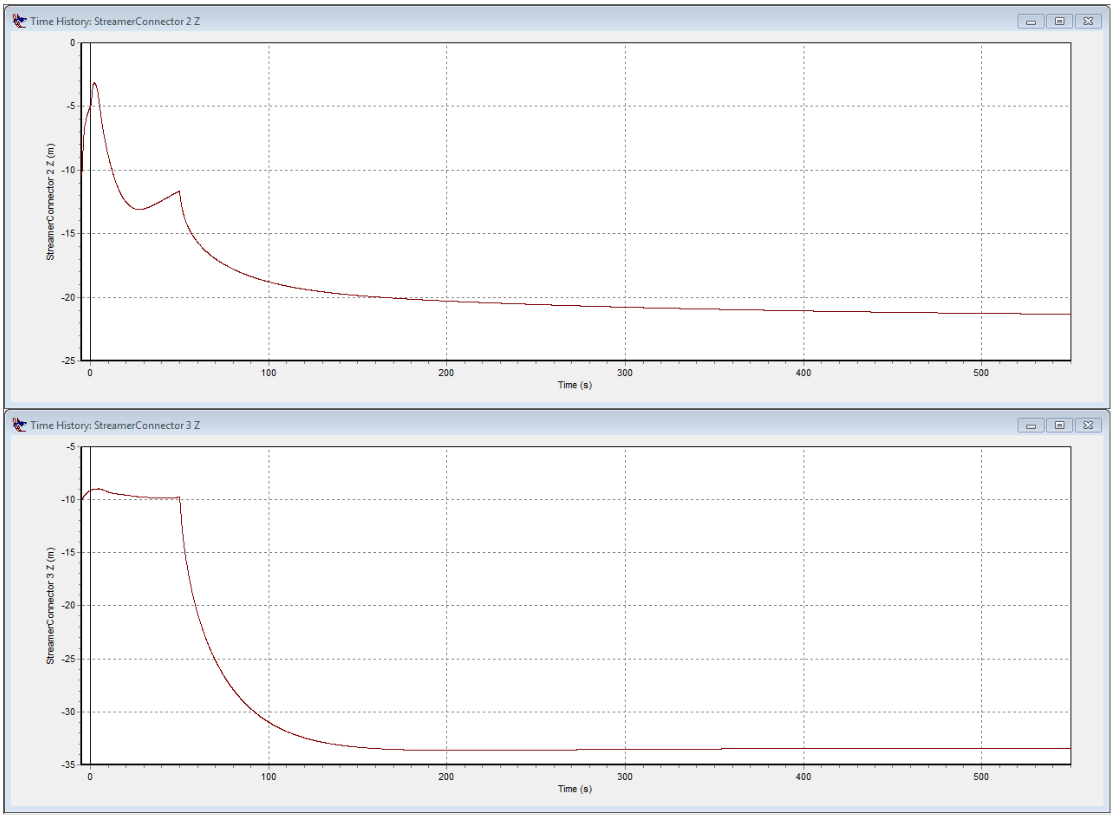


Figure 59: Simulation Five SDCB 2 and SDCB 3, time plot of the variable depth.

Simulation SIX

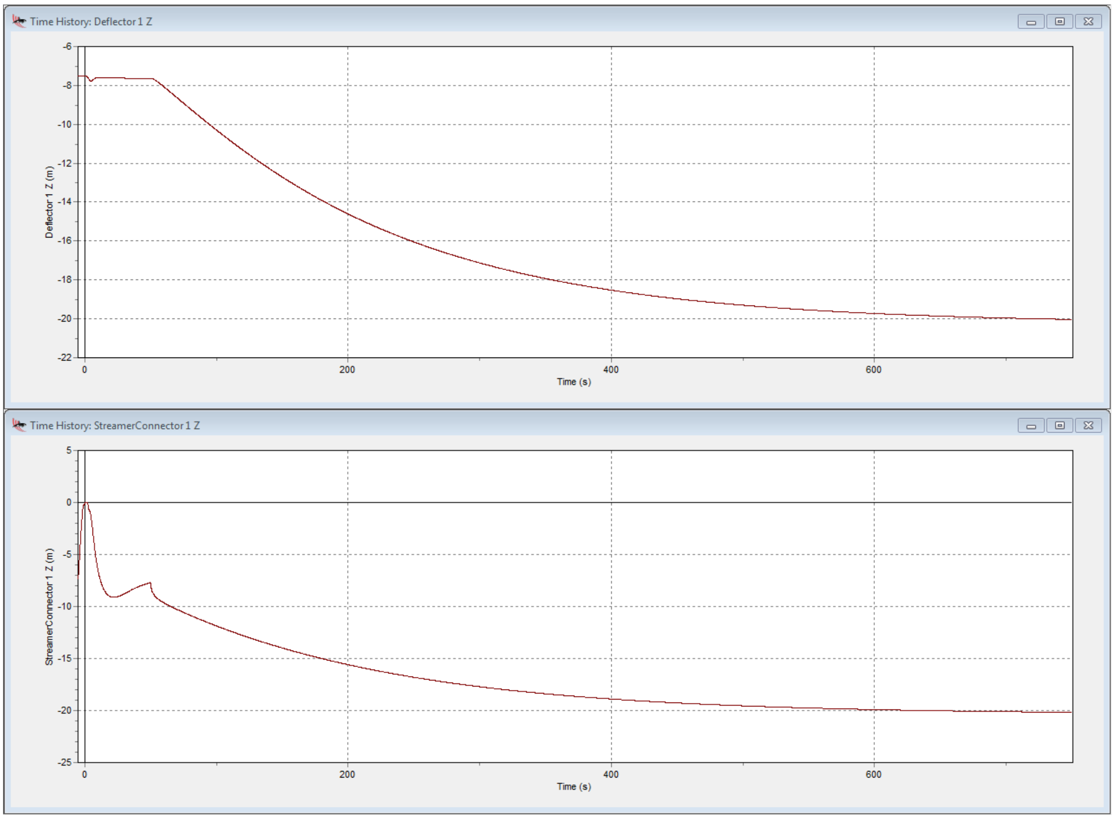


Figure 60: Simulation SIX Deflector and SDCB 1, time plot of the variable depth.

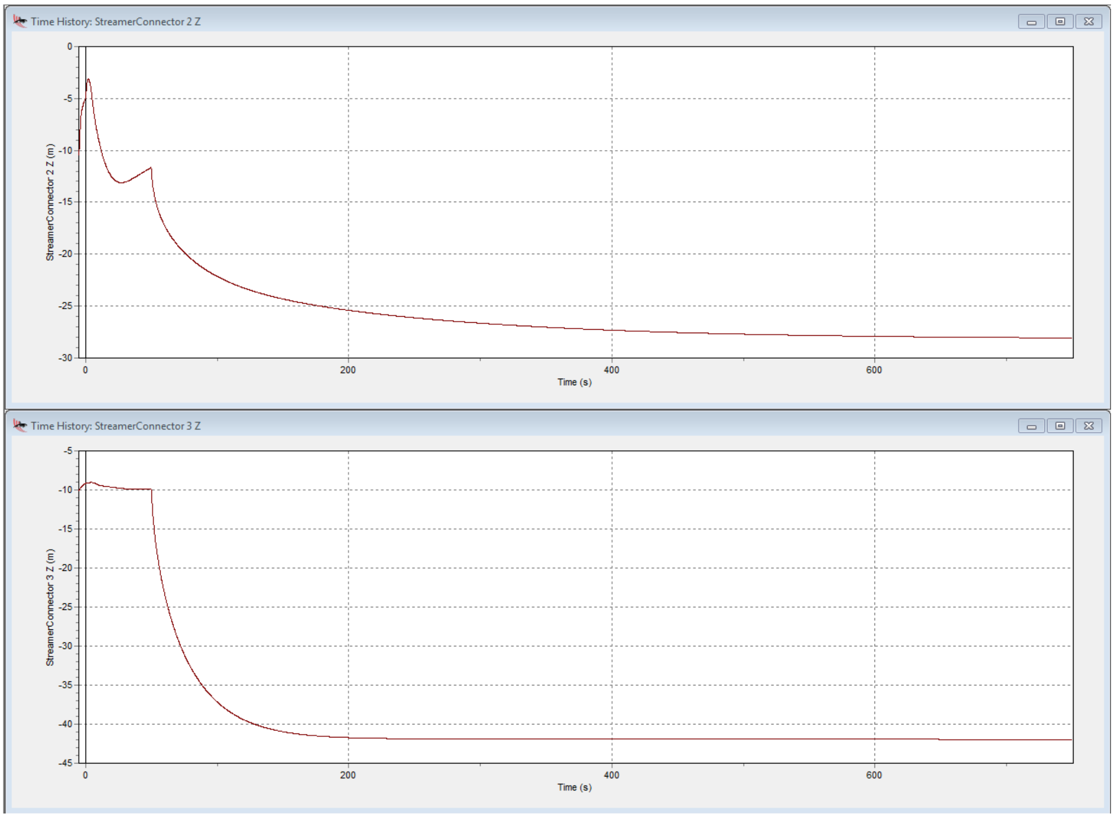


Figure 61: Simulation SIX SDCB 2 and SDCB 3, time plot of the variable depth.

Appendix 5: Velocity-time plot of SDCB 1

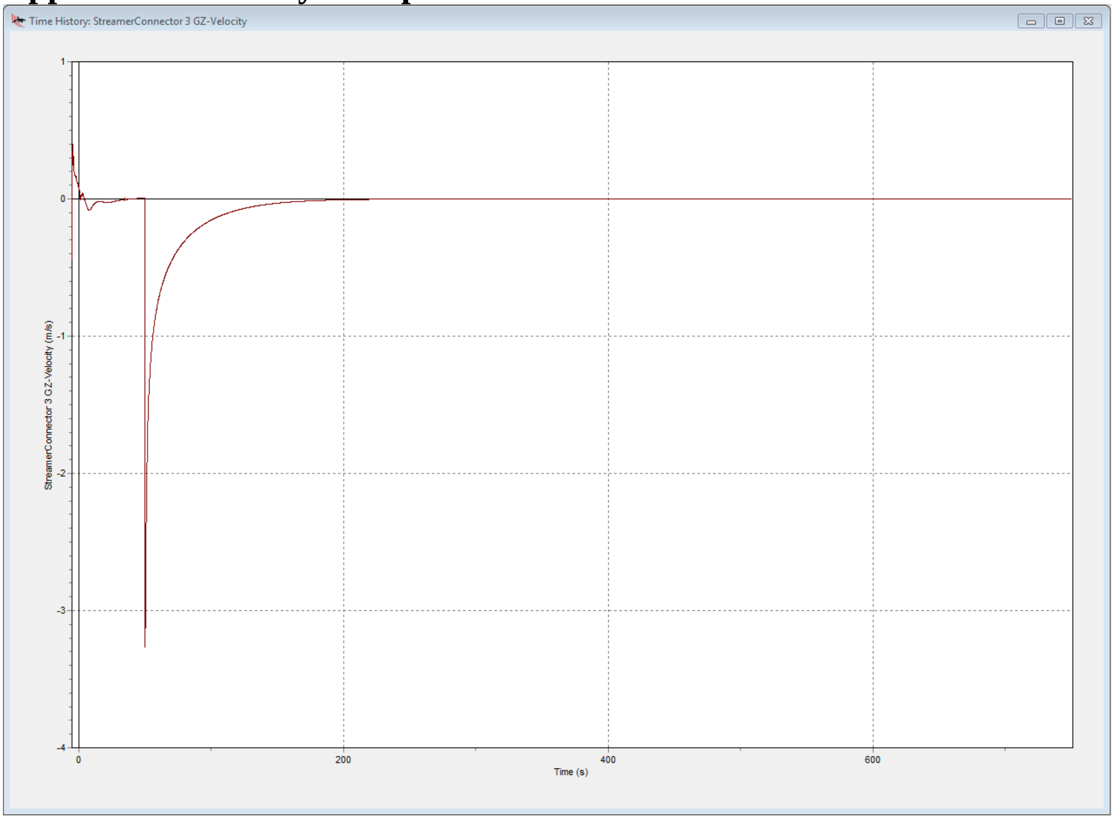
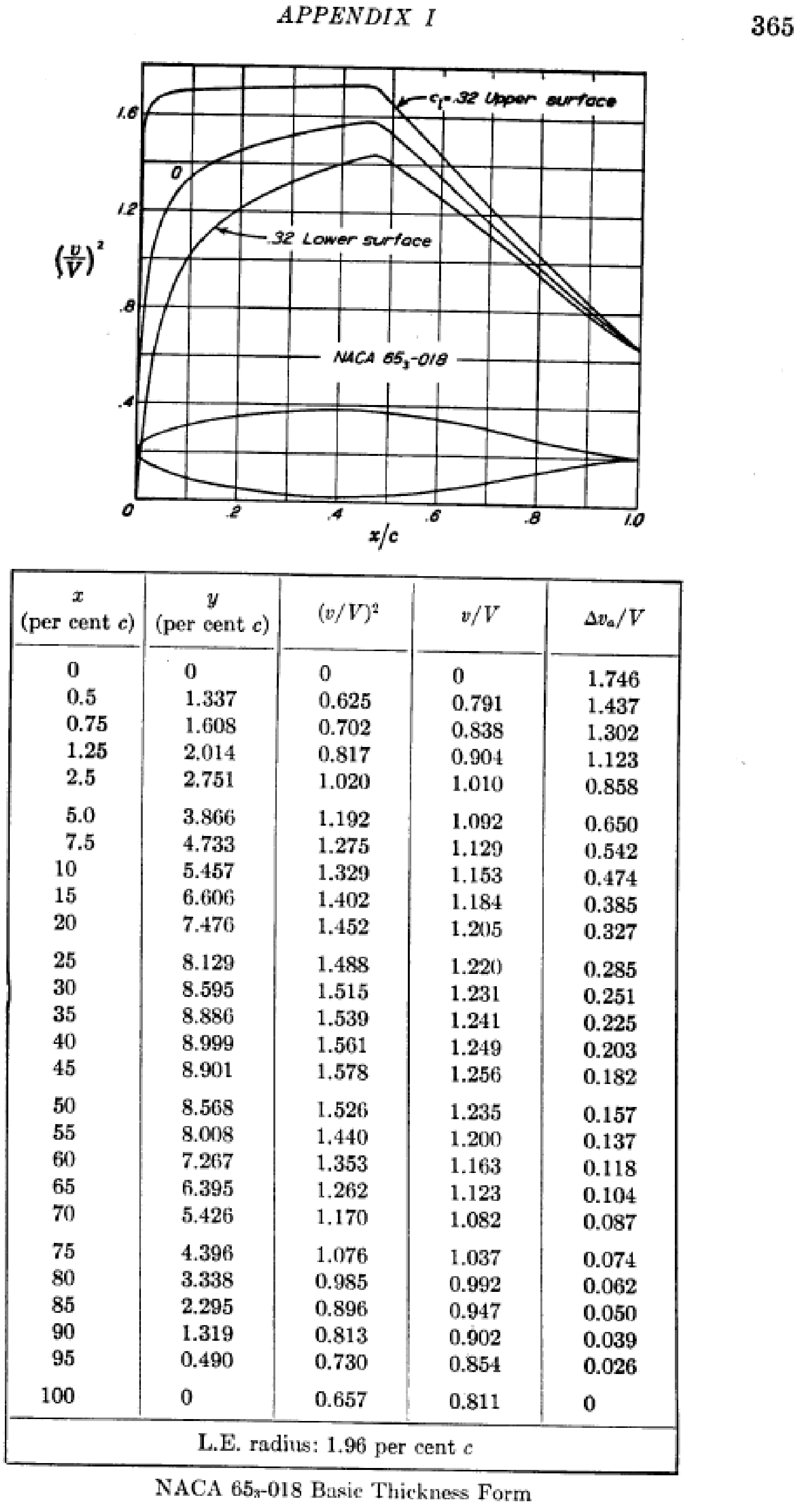


Figure 62: Velocity-time plot of SDCB 3 during simulation SIX

Appendix 6: Abbott and Doenhoff (1959) page 365, 632 and 633



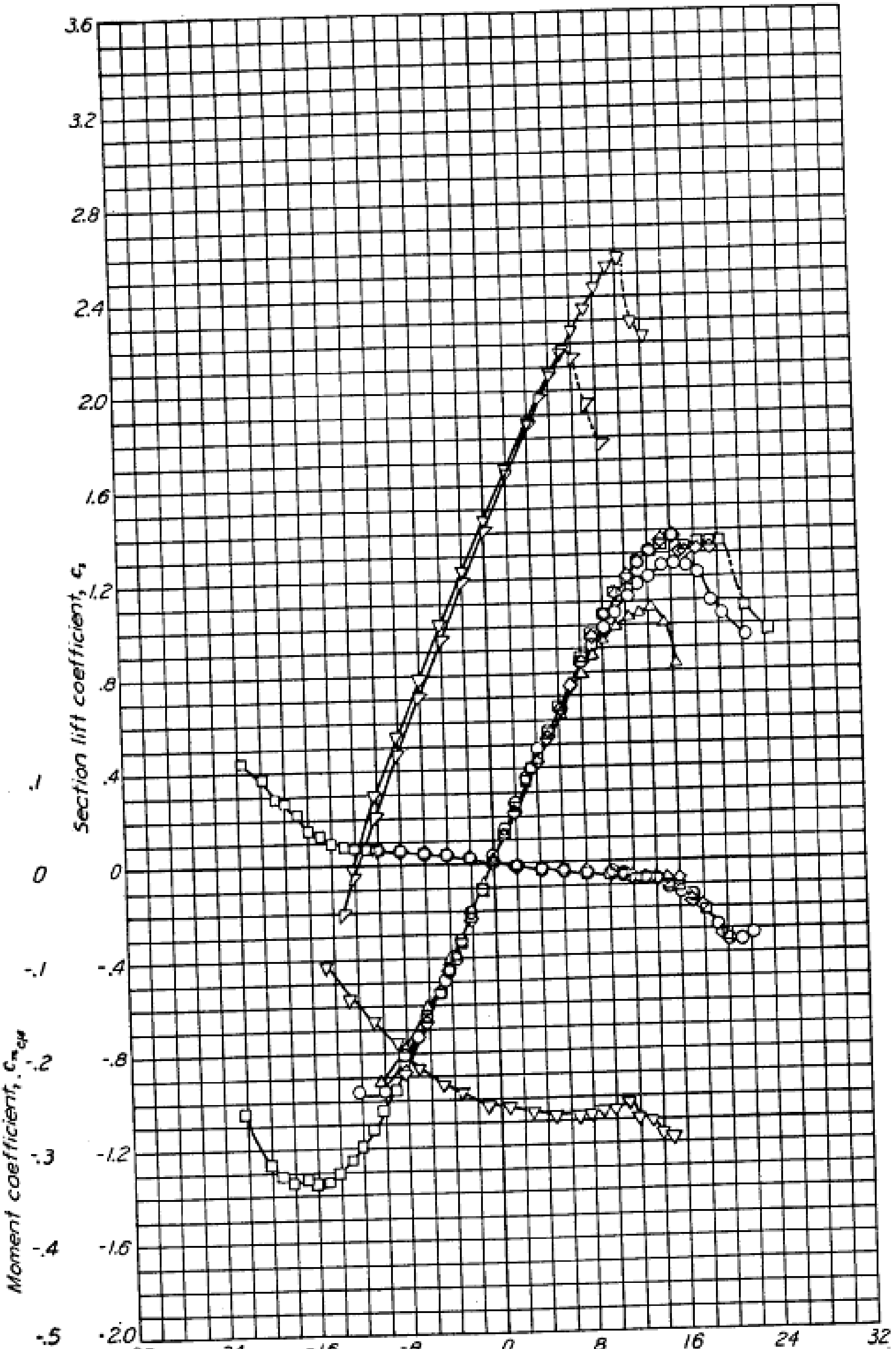
APPENDIX I 365

x (per cent c)	y (per cent c)	$(v/V)^2$	v/V	$\Delta v_a/V$
0	0	0	0	1.746
0.5	1.337	0.625	0.791	1.437
0.75	1.608	0.702	0.838	1.302
1.25	2.014	0.817	0.904	1.123
2.5	2.751	1.020	1.010	0.858
5.0	3.866	1.192	1.092	0.650
7.5	4.733	1.275	1.129	0.542
10	5.457	1.329	1.153	0.474
15	6.606	1.402	1.184	0.385
20	7.476	1.452	1.205	0.327
25	8.129	1.488	1.220	0.285
30	8.595	1.515	1.231	0.251
35	8.886	1.539	1.241	0.225
40	8.999	1.561	1.249	0.203
45	8.901	1.578	1.256	0.182
50	8.568	1.526	1.235	0.157
55	8.008	1.440	1.200	0.137
60	7.267	1.353	1.163	0.118
65	6.395	1.262	1.123	0.104
70	5.426	1.170	1.082	0.087
75	4.396	1.076	1.037	0.074
80	3.338	0.985	0.992	0.062
85	2.295	0.896	0.947	0.050
90	1.319	0.813	0.902	0.039
95	0.490	0.730	0.854	0.026
100	0	0.657	0.811	0

L.E. radius: 1.96 per cent c

NACA 65_3-018 Basic Thickness Form

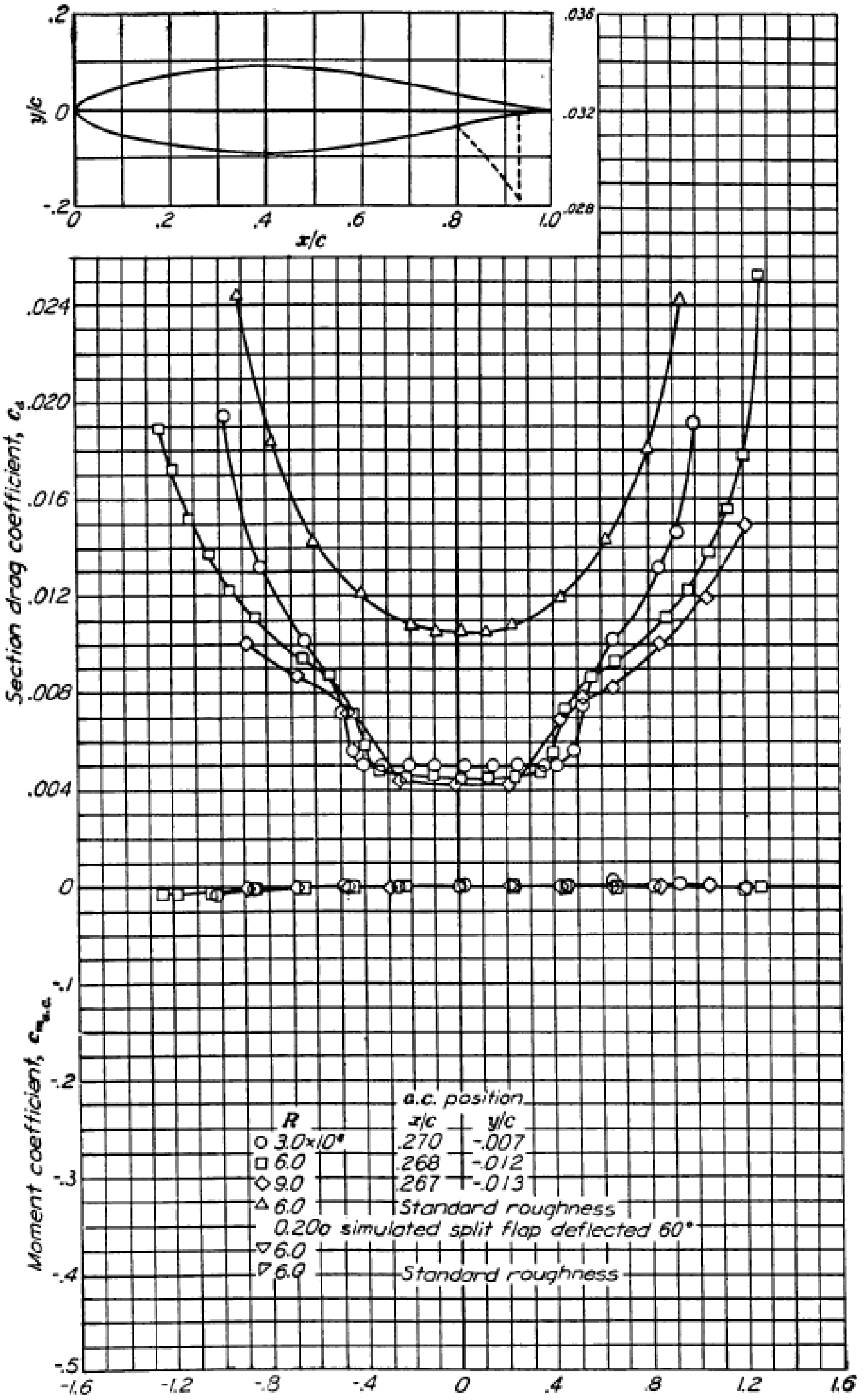
Figure 63: Page 365 Abbot and Doenhoff (1959)



NACA 65_3-018 Wing Section

Figure 64: Page 632 Abbott and Doenhoff (1959). Lift coefficient for NACA 65_3-018.

APPENDIX IV 633



NACA 65_3-018 Wing Section (*Continued*)

Figure 65: Page 633 Abbott and Doenhoff (1959). Dracg coefficient in regards to lift coefficient.

Appendix 7: Creation of Figures

Figure 26 has been constructed with the computer program Google Earth. Ice data from the U.S. National ice centre (NIC) which is a multi-agency operational centre operated by: United States Navy, National Oceanic and Atmospheric Administration and the United States Coastguard.

The products available online at: <http://www.natice.noaa.gov/Main_Products.htm>. There are options to download ice data in .kmz files, which may be opened in Google Earth. The Ice data are update once every 24 hours.

Figure 29: Arctic and Polar Circle is a snapshot from Google Earth.

Other figure has been made in Microsoft's Power point. This is also valid for the illustration on the front page picture. The pictures included in the front page can be located with the following references:
<http://subseaworldnews.com/2013/04/16/uae-polarcus-names-new-chief-operating-officer/>
<http://www.seadiscovery.com/mtStories.aspx?ShowStory=106655>
<http://beauty-places.com/beauty-of-ice/>
<http://www.listofimages.com/formula-mathematics-math-other.html>
<http://sevendesktop.com/deep-iceberg-wallpaper.html>
The pictures have been subjected to manipulation. In addition figure 30: Submergible Depth Controlled Unit and a screenshot of OrcaFlex 3D is incorporated in the picture.

All figures in the Appendix originating from OrcaFlex 3D is presented without modification to the information of the time plots.

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