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Navigation in the Arctic

How can simulator training be used for assessment and reduction of risk?

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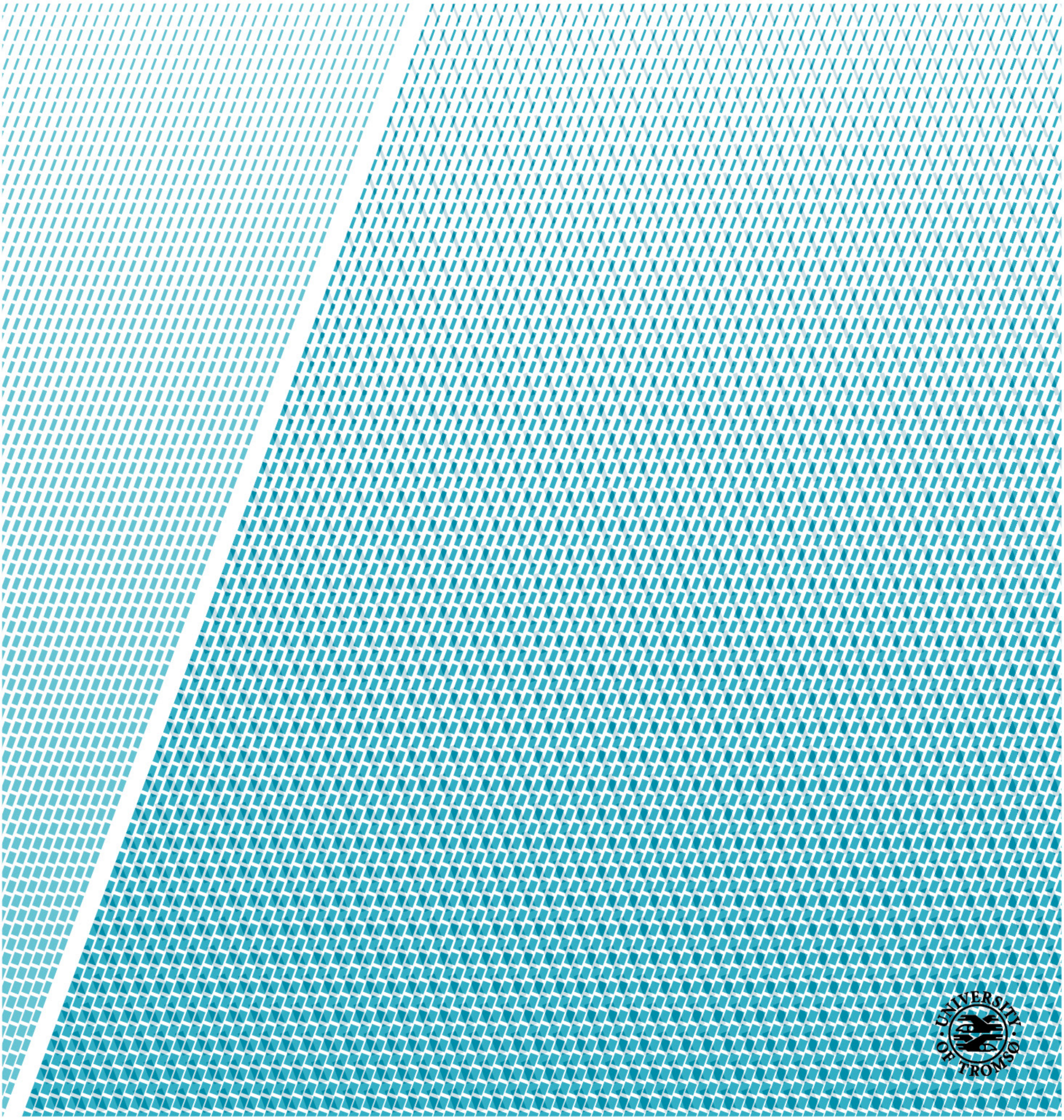
Master's thesis in Technology and Safety in the High North - June 2018



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Working with this thesis has been challenging, and some unforeseen obstacles has emerged along the way. In the end, I am satisfied with the result after some intense last couple of months.

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Abstract

Over the recent years, the ship traffic in the polar areas has increased. There is reason to believe that this traffic, and especially the cruise traffic, will increase further as the ice retracts towards the poles. There is also reason to believe that with the continued focus and exposure of the Polar Region, the cruise tourism to the region will grow.

The increased presence in the polar areas will create positive repercussions for several actors, both on sea and land. There will however also be negative consequences associated with the growing presence in the polar areas. Vessels will be operating with long distance to other vessels and land infrastructures. These vessels will also be operating in climate and conditions that will put extra pressure on both vessel and crew. These challenges need to be solved in order for the ship industry to operate safely in the Polar Region.

To ensure that companies operating in these areas identifies and manages these challenges, the International Maritime Organization (IMO) developed the Polar Code with the intent of increasing the safety for vessels operating in polar waters, and to reduce the impact on humans and environment in the remote, vulnerable and potential harsh area. This code defines a number of requirements that the vessels should operate in accordance with.

The aim for this thesis is to reveal what challenges the vessel and its crew need to deal with when navigating in polar waters. The challenges will be analysed and assessed through the use of a preliminary risk analysis. The goal with this part of the thesis is to determine the potential hazards the vessel is exposed to under operations in polar waters, and to find out what level of risk the different hazards represents for the vessel and its crew. The main goal for the thesis is to find out how the risk levels can be reduced, with particular focus on the use of simulator training as a risk reducing measure. The final goal is to measure the risk towards acceptance criteria, which have been determined prior to conducting the analysis.

Abbreviations

ALARP	As Low As Reasonably Practicable
ARPA	Automatic Radar Plotting Aid
DP	Dynamic Positioning
ECDIS	Electronic Chart Display and Information System
ENC	Electronic Navigational Charts
GMDSS	Global Maritime Distress and Safety System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAZID	HAZard IDentification
IMO	International Maritime Organization
MF	Medium Frequency
NAVTEX	Navigational Telex
RADAR	RAdio Detection And Ranging
SOLAS	Safety Of Life At Sea
VHF	Very High Frequency
WAAS	Wide Area Augmentation System

Contents

Introduction

Chapter 2 in the Polar Code states that a vessel is to prepare an operation manual for polar waters. In this manual, risk should be detected and assessed for every situation the vessel is intended to operate in. When assessing the risk, there are mainly two factors involved, probability and consequence. Due to little statistical data available, it is of high interest to collect estimated data for probability and consequences for different situations through simulator exercises. The main goal with this thesis is to identify what kind of situations that can be assessed through the use of simulator exercises, and establish which situations have to be assessed using other measures. The thesis will also investigate if simulator exercises in general is useful for this kind of risk assessment, or if other techniques should be used. The first step in this process is to detect which hazards the vessel will be exposed to under the different operations it is intended to execute. These hazards can be a challenge itself to reveal, and will vary from vessel to vessel and operation to operation. Simulator exercises can be a useful aid also for detecting situations which can pose a threat to the vessel and/or its crew. In this thesis, the focus will be on assessing general hazards that can expose the vessel to enhanced risk. Which hazards to assess will be chosen by investigating statistical data, literature and by conversation with experts on the field and navigators with experience from operations in polar conditions.

1 Methodology

The work related to this thesis can be composed into three different parts, where different methods have been used. In this chapter, the different methods will be briefly discussed.

1.1 Background information and theory

The first part of the work related to this thesis consist of gathering background information for the risk analysis. In order to perform a HAZID (Hazard Identification) for navigation in polar waters, it is necessary to have knowledge regarding all aspects of the navigational process. Including knowledge not just regarding operation and navigation under polar conditions, but also thorough knowledge regarding systems and equipment vital for the navigational process. Much of this knowledge has been accumulated through a bachelor-degree in Nautical science, but it will still be necessary to do a comprehensive literature study in order to collect the needed background information. The literature study will be supplemented by information gathered through conversation with navigators with experience from operations in polar waters.

It is also necessary to gather information regarding the possibilities within simulation of polar operating conditions. There are not much literature available on this field. The relevant knowledge and theory for this matter has to be accumulated through the solid research community on this field that exist at the Arctic University of Norway here in Tromsø.

1.2 Preliminary Hazard Analysis

After the background information and theory is at a sufficient level, the next step is to perform a preliminary hazard analysis for navigation in polar waters. Preliminary hazard analysis is a technique to identify possible hazards for a system or a process. The principle for the analysis is to identify hazards that could lead to accidents. The aim is to find eventual weaknesses for the system or process before they occur, and then implement corrective measures as a proactive risk management.

The aim with this part is to find out if simulator training can reduce the risk when navigating in polar waters, and for which kind of hazardous situations simulator training could have a risk-reducing effect. It is necessary to perform a full preliminary hazard analysis in order to find out how useful simulator training is compared to other risk-reducing measures. For some situations, regular risk-reducing measures such as duplication of equipment etc. could have larger impact on the risk-reduction.

1.3 Testing of simulator environment

After the literature study, it should be possible to determine the conditions that increases the risk when operating in polar areas. The next step is to investigate how these conditions can be simulated in the most realistic way. This will be done by manual testing of each condition, to see how the different available environmental factors works and interacts with one another. The primary focus for this part will be on failure and inaccuracy for equipment, weather conditions and ice conditions. Other factors will be considered if found to be significant through the preliminary hazard analysis.

2 Challenges related to navigation in the Arctic

Navigation in the Arctic is challenging. The vessel and crew are exposed to a harsh climate that affects the performance both for humans and equipment. In this chapter, the different challenges that impacts navigation in the Arctic are discussed.

2.1 Positioning, navigation and vital equipment

The main goals for the navigational officers is to position the vessel, and to navigate the vessel safely from destination to destination. This can be a challenging task under normal conditions, and even more challenging under polar conditions. In this section, general challenges regarding positioning and navigation on high latitudes is discussed. The theory in this chapter is mainly collected from a textbook for navigational instruments written by Norvald Kjerstad (Kjerstad, Elektroniske og akustiske navigasjonssystemer for maritime studier, 2015). Some of the theory is also based on lecture notes from different subjects regarding navigational instruments at UiT.

2.1.1 Positioning by satellite systems

Several satellite positioning systems are available for positioning of the vessel, such as GPS, GLONASS, GALILEO, BEIDOU etc. All these systems have different strengths and weaknesses, but the thing they have in common is reduced accuracy at high latitudes. The reduction in accuracy is not significant for regular positioning of the vessel. Even at the North-Pole, the satellite-geometry will be sufficient for determining the vessels position by the use of GPS. If two or more different positioning systems is combined, the vessel is well suited for positioning with good accuracy. A sketch showing the orbit for a GPS-satellite is presented in figure 1.

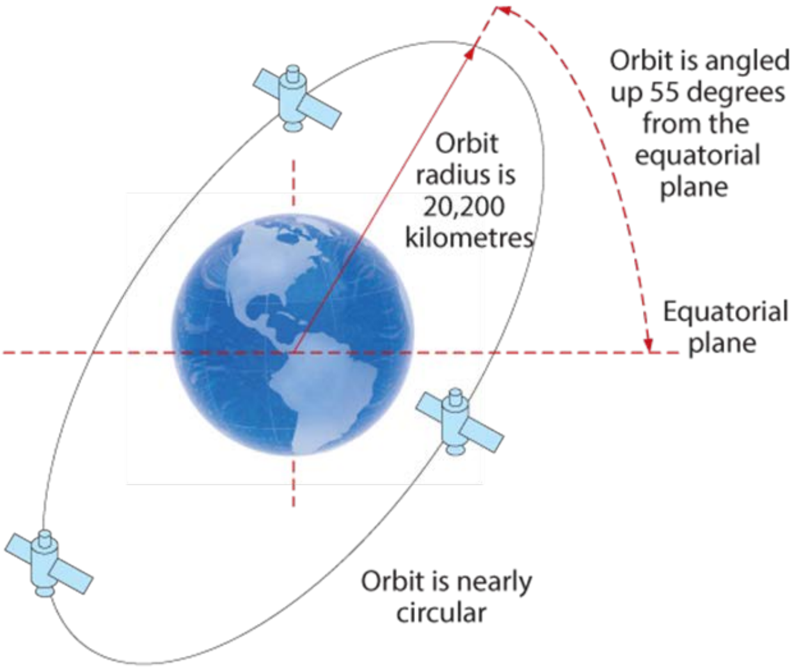


Figure 28 GPS Satellite Orbit

Figure 1 Orbit for GPS-satellite. From Novatel. (2018, May 26). An introduction to GNSS. GPS, GLONASS, BeiDou, Galileo and other global navigation satellite systems, (https://www.novatel.com/an-introduction-to-gnss/chapter-3-satellite-systems/gps/)

The reduced accuracy can be a challenge when performing operations with high demands to precision such as DP-operations. Today the number of high-precision operations executed on high latitudes is limited, but with future exploitation and extraction of oil and gas on high latitudes, DP-operations will be a significant part of both the search, drill, and extraction phase. When a high level of accuracy is required, it is normal to improve the position from the satellite system with the help of differential techniques, so called differential corrections. This correction is based on distance measurement to ground-stations with known position. In polar areas the amount of ground-stations is limited, so the nearest ground-station can be far away, leading to inaccuracy for the correction. In extreme situations, the inaccuracy of the correction from the differential system can lead to a greater inaccuracy of the position. It is therefore necessary to use differential corrections on high latitudes with a high level of caution. Another challenge is that the corrected signal from the ground-station is transferred through communication-satellites, with a limited coverage over the polar areas.

2.1.2 Gyro Compass

The gyro compass is the main method for determination of the vessels true course. The gyro compass uses a gyroscope, a wheel that is spinning at high speed and installed in such a way that that it can rotate in every direction. The wheel will then have three degrees of freedom around the angular-axis, the horizontal axis and the vertical axis. When a gyroscope is rotating at high speed a large angular momentum will be induced. This will lead to the angular-axis pointing towards a fixed point in space if the movement is undisturbed by no external moment of force. The axis will move related to the earth as the planet is rotating. If the gyroscope initially is placed in direction east-west, the elevation ratio of the angular-axis is 15 degrees per hour. If the gyroscope is placed on equator, a special situation occurs where the axis would remain stable and point towards north. If the gyroscope is moved towards north, the angular-axis will be exposed to tilt and drift towards east as a consequence of the earth rotating. Tilt and drift is depending on the latitude (l) and the horizontal angel between the angular-axis and the meridian (a). From this, the expressions for tilt and drift is derived:

$$Tilt = 15°\cos(l)\sin(a) \text{ (Measured in degrees per hour)}$$

$$Drift = 15°\sin(l) \text{ (Measured in degrees per hour)}$$

This shows that the drift is increasing with latitude, which is a key factor when discussing the use of gyro compass on high latitudes.

The gyroscope is made north-seeking by a precession-force induced by gravity. By making the gyroscope top-heavy or bottom-heavy, the gravity-force will press the side of the gyroscope with added weight towards the centre of the earth. The induced precession-force leads to the angular-axis pointing towards north. The problem is that this movement will be un-dampened, leading to the angular-axis oscillating around the meridian. This movement needs to be dampened in order to make a useful compass. This dampening is executed different for top-heavy and for bottom-heavy gyroscopes. On top-heavy gyroscopes, the movement is dampened by the use of an unsymmetrical weight on the vertical axis. This will lead to a precession-force which will dampen the oscillations. The problem with this method is that it induces a constant error for the system, which is dependent on latitude and the dampening-factor for the system. Bottom-heavy gyroscopes use oil-dampening which dampens the horizontal oscillations. This type of compasses will have a dampening-error such as the top-heavy compasses, but the error will not be dependent of latitude. This difference should be considered when deciding which type of gyro-compass to install on vessels intended to operate on high latitudes.

In addition to the dampening-error described, all gyro-compasses will have a speed-/latitude-error as a consequence of the vessels speed in relation to the rotation of the earth. The error is depending on vessel speed, vessel course and latitude. This error can be derived mathematically, and after some simplifications and assumptions the error can be described mathematically as:

Speed-/latitude-error ≈ $(0.0635v\cos(k)/\cos(l)$, where v = Vessel speed, k = Vessel course and l = latitude.

This expression shows that the error will increase if the latitude or speed increases. The error will also increase when steering courses towards north or south. This error is mostly limited to a few degrees, but can be much larger if a vessel is sailing at high speed at a high latitude. If the vessel also is steering a northerly or southerly course the error can be quite significant, as the following example indicates.

Example: Vessel north of Svalbard steering towards north and proceeding with a speed of 20 knots.

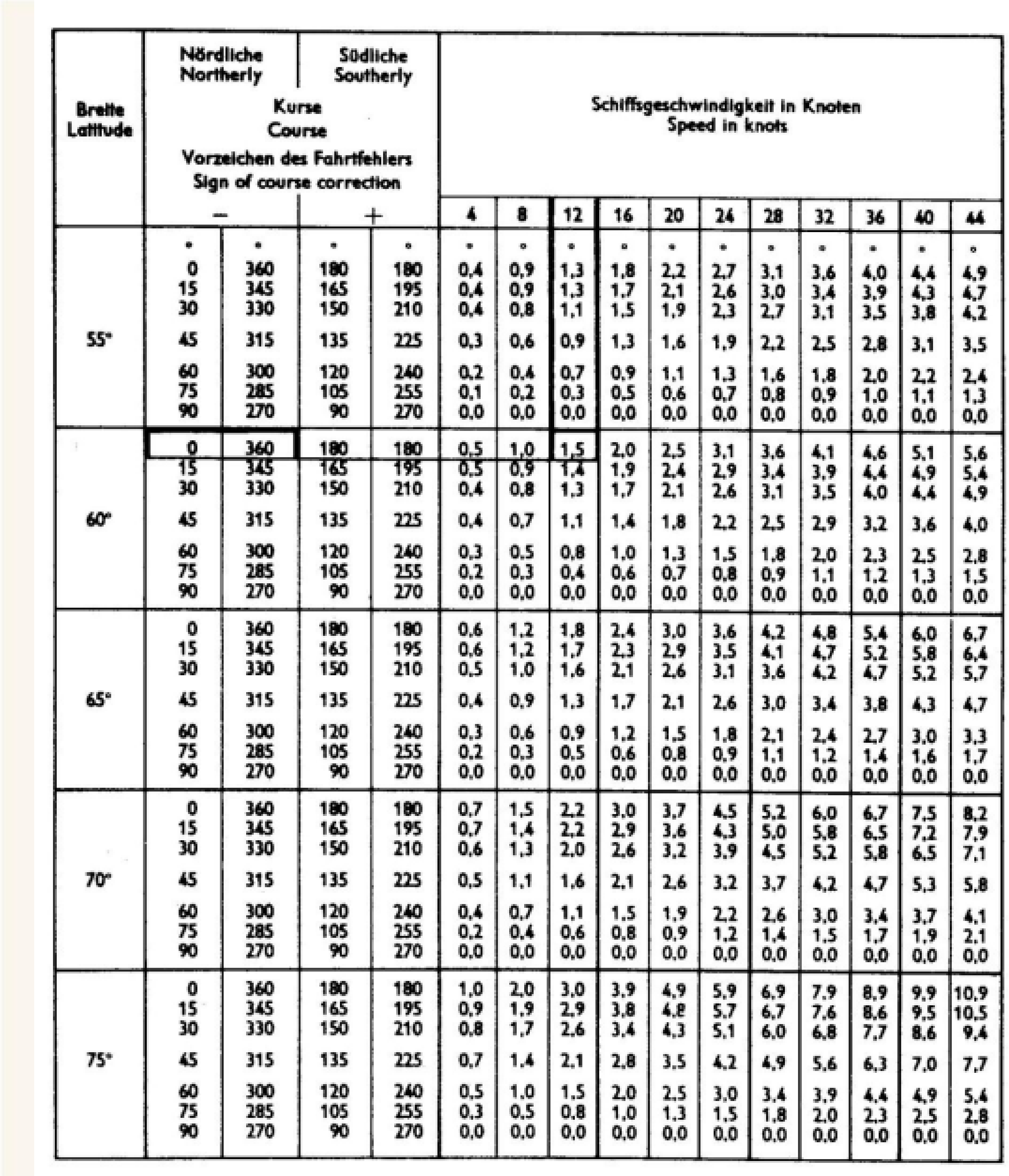
Position: $81^0 00'$N

Course: 000^0

Speed: 20 knots

Error = $(0.0635*20*\cos(0))/\cos(81) = 8.12^0$

This example shows how significant the speed-/latitude-error can be under certain circumstances. This error needs to be compensated for in order to navigate safely. This can be done manually as shown in the example above, or for some compasses by the use of standardized tables where latitude, course and speed is used as input. Such a table from Anschutz, one of the main suppliers of such equipment, is shown in figure 2. The error can for some compasses be automatically compensated for by adjustments on the gyro-compass. If using this application on high latitudes, it is important to remember the fact that error or unavailability in GPS-position can lead to large deviation in gyro-course.



Breite Lattitude	Nördliche Northerly		Südliche Southerly		Schiffsgeschwindigkeit in Knoten Speed in knots										
	Kurse Course Vorzeichen des Fahrtfehlers Sign of course correction														
	−		+		4	8	12	16	20	24	28	32	36	40	44
	°	°	°	°	°	°	°	°	°	°	°	°	°	°	°
55°	0	360	180	180	0,4	0,9	1,3	1,8	2,2	2,7	3,1	3,6	4,0	4,4	4,9
	15	345	165	195	0,4	0,9	1,3	1,7	2,1	2,6	3,0	3,4	3,9	4,3	4,7
	30	330	150	210	0,4	0,8	1,1	1,5	1,9	2,3	2,7	3,1	3,5	3,8	4,2
	45	315	135	225	0,3	0,6	0,9	1,3	1,6	1,9	2,2	2,5	2,8	3,1	3,5
	60	300	120	240	0,2	0,4	0,7	0,9	1,1	1,3	1,6	1,8	2,0	2,2	2,4
	75	285	105	255	0,1	0,2	0,3	0,5	0,6	0,7	0,8	0,9	1,0	1,1	1,3
	90	270	90	270	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
60°	0	360	180	180	0,5	1,0	1,5	2,0	2,5	3,1	3,6	4,1	4,6	5,1	5,6
	15	345	165	195	0,5	0,9	1,4	1,9	2,4	2,9	3,4	3,9	4,4	4,9	5,4
	30	330	150	210	0,4	0,8	1,3	1,7	2,1	2,6	3,1	3,5	4,0	4,4	4,9
	45	315	135	225	0,4	0,7	1,1	1,4	1,8	2,2	2,5	2,9	3,2	3,6	4,0
	60	300	120	240	0,3	0,5	0,8	1,0	1,3	1,5	1,8	2,0	2,3	2,5	2,8
	75	285	105	255	0,2	0,3	0,4	0,6	0,7	0,8	0,9	1,1	1,2	1,3	1,5
	90	270	90	270	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
65°	0	360	180	180	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4	6,0	6,7
	15	345	165	195	0,6	1,2	1,7	2,3	2,9	3,5	4,1	4,7	5,2	5,8	6,4
	30	330	150	210	0,5	1,0	1,6	2,1	2,6	3,1	3,6	4,2	4,7	5,2	5,7
	45	315	135	225	0,4	0,9	1,3	1,7	2,1	2,6	3,0	3,4	3,8	4,3	4,7
	60	300	120	240	0,3	0,6	0,9	1,2	1,5	1,8	2,1	2,4	2,7	3,0	3,3
	75	285	105	255	0,2	0,3	0,5	0,6	0,8	0,9	1,1	1,2	1,4	1,6	1,7
	90	270	90	270	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
70°	0	360	180	180	0,7	1,5	2,2	3,0	3,7	4,5	5,2	6,0	6,7	7,5	8,2
	15	345	165	195	0,7	1,4	2,2	2,9	3,6	4,3	5,0	5,8	6,5	7,2	7,9
	30	330	150	210	0,6	1,3	2,0	2,6	3,2	3,9	4,5	5,2	5,8	6,5	7,1
	45	315	135	225	0,5	1,1	1,6	2,1	2,6	3,2	3,7	4,2	4,7	5,3	5,8
	60	300	120	240	0,4	0,7	1,1	1,5	1,9	2,2	2,6	3,0	3,4	3,7	4,1
	75	285	105	255	0,2	0,4	0,6	0,8	0,9	1,2	1,4	1,5	1,7	1,9	2,1
	90	270	90	270	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
75°	0	360	180	180	1,0	2,0	3,0	3,9	4,9	5,9	6,9	7,9	8,9	9,9	10,9
	15	345	165	195	0,9	1,9	2,9	3,8	4,8	5,7	6,7	7,6	8,6	9,5	10,5
	30	330	150	210	0,8	1,7	2,6	3,4	4,3	5,1	6,0	6,8	7,7	8,6	9,4
	45	315	135	225	0,7	1,4	2,1	2,8	3,5	4,2	4,9	5,6	6,3	7,0	7,7
	60	300	120	240	0,5	1,0	1,5	2,0	2,5	3,0	3,4	3,9	4,4	4,9	5,4
	75	285	105	255	0,3	0,5	0,8	1,0	1,3	1,5	1,8	2,0	2,3	2,5	2,8
	90	270	90	270	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Figure 2 Anschutz Table of corrections for gyro compass. From Kjerstad, N. (2015). Elektroniske og akustiske navigasjonssystemer (Vol. 5), Fagbokforlaget, Bergen

Optical gyro-compasses

In the 1960s the development of optical gyrocompasses started. These special types of gyrocompasses are based on the technique of measurement of angular acceleration through the use of laser-light. Today, it is mainly to types of optical compasses that is used:

- Fibre-optic gyro
- Ring laser gyro

The main advantages for this type of compass is the reduced amount of error sources compared to the classical types of gyro-compasses. The optical compass will not have any errors induced by tilt and/or drift, and no error induced by the vessel speed. The optic compass will have a latitude-dependent error, but it will be significantly reduced compared to the classic gyro-compass. Other advantages are no maintenance and high reliability due to the lack of moving parts, short start-up time and the possibility of acceleration-measurements, meaning that the compass is able to measure vessel-movements such as pitch, heave, roll etc. The main disadvantage, along with the fact that the optical compass is dependent of an external power supply, is the high cost. An optical compass is expensive, and as result of this, the compass is mainly used for military purposes.

2.1.3 Magnetic Compass

The magnetic compass is the first compass-type developed for navigation. The principle is the same as used for finding direction on land. The main advantage for the magnetic compass is that it is not dependent of an external or internal power source, the compass is able to find magnetically north without the use of electricity. Because of this, the magnetic compass is often used as a redundancy for the gyro-compass. Even though most of the navigational operations is executed by the use of gyro-compasses, IMO requires cargo vessels over 150 tonnes and all passenger vessels to be equipped with an authorized magnetic compass. For Norwegian vessels, the Norwegian Maritime Directorate can allow vessels with two authorized and independent gyro-compasses, which is connected to an emergency power supply, to be exempted from the requirements.

The main disadvantage for the magnetic compass is that it is burdened with more sources of error than the gyro-compass, and larger errors. It is mainly to types of errors that affects the accuracy for magnetic compasses. The first one is magnetic variation, which is caused by the magnetic poles not being at the same location as the geographic poles. The magnetic compass will point towards magnetic north, not true north. This magnetic variation will vary from place to place, and it will also vary with time as the position of the magnetic poles is constantly changing. This means that magnetic variation is a difficult error to compensate for, as the compensation factor has to be constantly updated.

The other error present for the magnetic-compass is deviation. Deviation is a measure of the internal magnetism for the vessel. This magnetism will affect the magnetic-compass and lead to the compass-needle not pointing towards the magnetic north. The magnetic deviation is divided into two types of internal magnetism, solid magnetism and fleeting magnetism. The fleeting magnetism will vary as the vessel moves inside the magnetic field of the earth. The solid magnetism is induced during building of the vessel, or if the vessel is sat not moving for a longer period of time. To avoid this type of magnetism becoming too significant, it is normal to turn the vessel 180^0 during the building process. As for the magnetic variation, also the deviation will vary with both position and time. Long lay-ups at the shipyard and smaller or larger rebuilding of the vessel will affect the deviation. This means that the compensation factor also for deviation has to be constantly updated.

If the magnetic compass is to be used as a source for heading information, it is necessary to have updated information regarding both variation and deviation. Information regarding variation is found in special charts that is made for displaying magnetic information. In order to have updated information regarding deviation, the vessel is to perform a deviation-test when newly-built, or if it is reason to believe that the deviation has changed. After the test, it is possible to calibrate the compass by the use of external magnets that work against the deviation.

2.1.4 ECDIS

ECDIS (Electronic Chart Display and Information System) is a system for presentation of chart- and voyage-data. For a system to be classified as an ECDIS, it has to meet the requirements defined by IMO. The main requirements for classification as ECDIS is related to back-up systems and power-supply. IMO has implemented a performance standard (IMO Res. A 232 (82)) where the basic functionality for ECDIS is described:

- ECDIS should contribute to safer navigation.
- With licensed back-up systems, ECDIS should be able to replace the use of paper-charts.
- ECDIS should be able to show all information from the chart-data that is relevant for safe and efficient navigation.
- ECDIS should easily be able to update ENC (Electronic Navigational Chart).
- ECDIS should reduce the work-load for the navigator and give him/her the opportunity to plan and monitor the voyage.
- ECDIS should have the same reliability and availability as regular licensed paper-charts.

- ECDIS should give an alarm if the system has a failure or in given situations as shown in table 1 below:

Table 1 ECDIS Alarm status (IMO Res. A 232 (82))

Information:	**Alarm Status:**
Large scale	Alarm or indication
Off route (Off-track limit)	Alarm
Crossing of safety-contour (Depth etc.)	Alarm
Caution area	Alarm or indication
Deviation from planned route	Alarm
Arrival at “Critical Point”	Alarm
Different datum (Chart and system)	Alarm
System failure	Alarm or indication
Over-scaling of information	Indication
ENC with larger scale available	Indication
Different navigational systems	Indication
Voyage-plan over safety-contour	Indication
Voyage-plan over caution area	Indication
Failure for positioning system	Indication
Failure for system-test	Indication

Regarding the instruments that is to be connected to the ECDIS-system, IMO requires that equipment that provides information regarding position, speed and heading are connected. This is normally done through the connection of a satellite positioning system and a gyro-compass. Radar- and ARPA-information is also often connected to the ECDIS. In addition to the instruments and features that is required as ECDIS-input, a number of other functions is available depending on manufacturer. Some of the functions are listed below, although the list is just a sample as new functions is released at high speed (Kjerstad, Elektroniske og akustiske navigasjonssystemer for maritime studier, 2015)

- Calculation of tidal-water
- Information from echo-sounder
- Harbour information
- Calculation of current
- Implementation of weather-charts
- Track-steering with autopilot
- Trial-manoeuvre
- Logbook
- Magnetic deviation
- Search and Rescue
- Astronomical observation with almanac-function
- Fuel consumption
- Implementation of GIS (Geographic Information System)
- Anemometer (Wind measurement)
- Sonar
- Dynamic Positioning
- Printer-function
- Communication system
- NAVTEX
- Position transponders
- Voyage Data Recorder

2.1.5 RADAR

RADAR (Radio Detection And Ranging/Radio Direction And Ranging) is an aid for detection of targets that is impossible to see visually, and by the use of ARPA (Automatic Radar Plotting Aid) calculate direction and range to targets. The physical principle of a RADAR is quite simple. An electromagnetic pulse is sent out from a transmitter. If the pulse hits an object, it is reflected back in the opposite direction. The reflected signal is then received by the radar-receiver. The time between transmitting and receiving of the signal is measured, and from this the range is calculated. The signal used for detection by radar can have different frequencies. It is mainly two types of frequencies used for maritime radars (Kjerstad, Elektroniske og akustiske navigasjonssystemer for maritime studier, 2015):

- S-band (10 cm) has low frequency (2000-4000 MHz). This leads to high detection range and little disturbance from rain and/or snow. The main disadvantages are increased possibility of missing small targets and increased antenna-size.
- X-band (3 cm) is the most used type of maritime radar. X-band radars has good reach and very good resolution. This leads to increased detection-possibility for small targets compared to the S-band radar. The main disadvantage is large influence by meteorological conditions such as rain and snow.

IMO has defined some requirements for the radar equipment in different resolutions over the years. A brief summary of the operational and technical requirements is given below (IMO, 2004):

Operational requirements:

- If the antenna is placed 15 m above sea-level, the radar should be able to detect a 60 m high shoreline at a range of 20 nm, and a 6 m high shoreline at a range of 8 nm.
- The radar should also be able to detect a vessel of 5000 tonnes at a range of 11 nm, and a 10 m long vessel at a range of 3.4 nm for X-band and 3.0 nm for S-band.
- The radar should be able to detect an object with a radar cross-section area of 10 m^2 at a range of 2.5 nm.

Technical requirements:

- The antenna should be able to operate in a relative wind speed of 100 kts and rotate clockwise with a speed of min 12 rpm.
- The bearing accuracy should be min 2.5^0.
- The minimum detection range should be min 50 m, and the differentiation threshold for range should be min 50 m for scales lower than 2 nm.
- For vessels with a displacement above 500 tonnes, a performance monitor is required. This is an instrument that measures the performance of the radar without any targets present.

ARPA

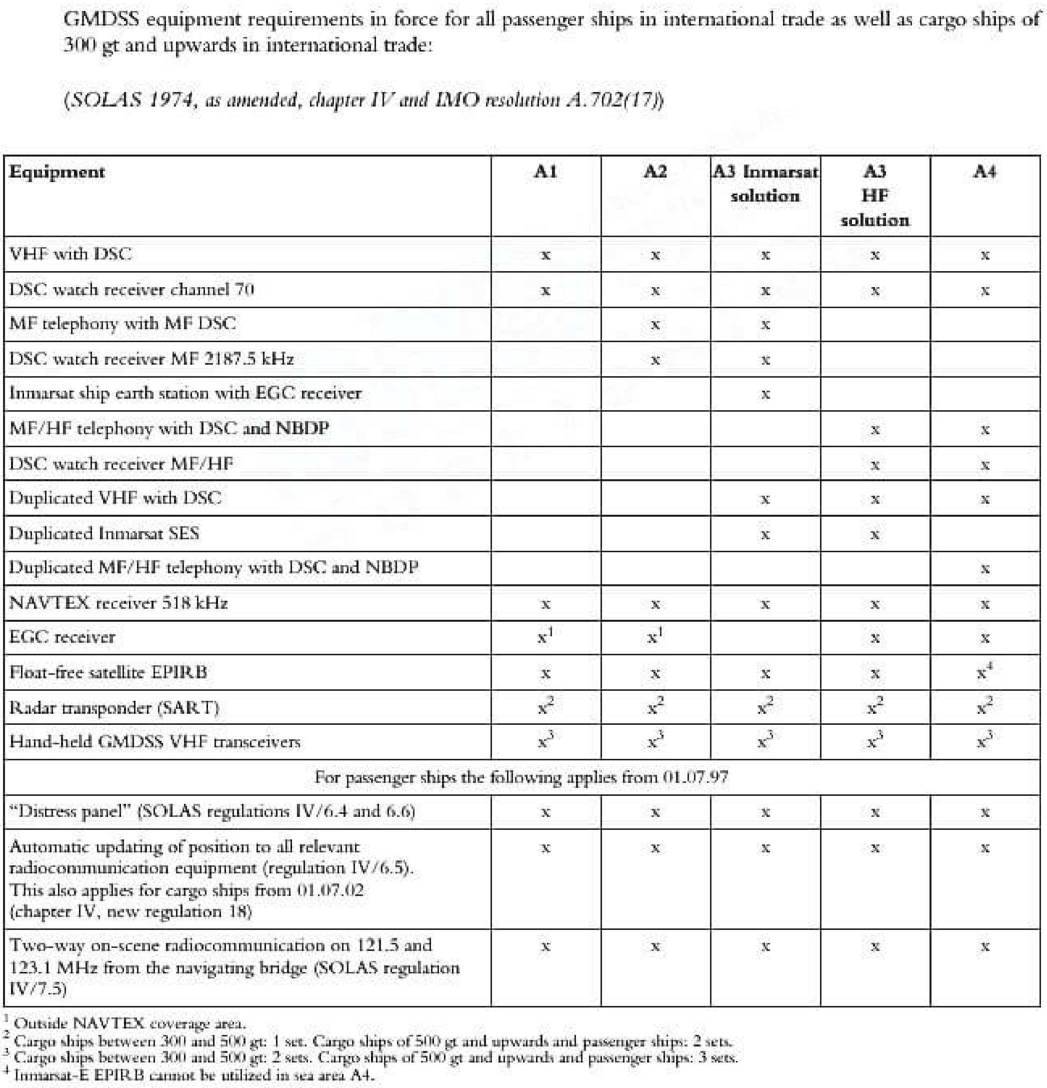
ARPA (Automatic Radar Plotting Aid) is a tool that calculates the movement for the own-ship and targets. Based on these calculations, a vector is presented for each vessel that indicates the movement for the vessel in the near future (0-30 min). The movement is calculated from the change in position between two subsequent radar-sweeps. Based on the information from the ARPA-system, the navigator can anticipate how to clear traffic in accordance with the nautical rules of the road.

2.1.6 Communications

In 1992, IMO introduced the GMDSS (Global Maritime Distress and Safety System). The main goal with the GMDSS is that every vessel in all waters should be able to communicate with coastal services and other vessels. Vessels in distress should be able to automatically alarm land stations. In order to achieve this goal, IMO has divided the sea-areas into four zones with different requirements for the vessels operating in the zones:

- A1 - Sea-areas that are within radiotelephone-coverage of at least one VHF coastal radio-station.
- A2 - Sea-areas that are within radiotelephone-coverage of at least one MF coastal radio-station.
- A3 – Sea-areas outside A1 and A2 that are within the coverage of Inmarsat geostationary satellite-system.
- A4 – All sea-areas outside A1, A2, A3.

This thesis will focus on the polar areas, which will be an A4-area in the GMDSS. Below, the equipment required for vessels operating in the A4-area is shown in figure 3.



GMDSS equipment requirements in force for all passenger ships in international trade as well as cargo ships of 300 gt and upwards in international trade:

(SOLAS 1974, as amended, chapter IV and IMO resolution A.702(17))

Equipment	**A1**	**A2**	**A3 Inmarsat solution**	**A3 HF solution**	**A4**
VHF with DSC	x	x	x	x	x
DSC watch receiver channel 70	x	x	x	x	x
MF telephony with MF DSC		x	x		
DSC watch receiver MF 2187.5 kHz		x	x		
Inmarsat ship earth station with EGC receiver			x		
MF/HF telephony with DSC and NBDP				x	x
DSC watch receiver MF/HF				x	x
Duplicated VHF with DSC			x	x	x
Duplicated Inmarsat SES			x	x	
Duplicated MF/HF telephony with DSC and NBDP					x
NAVTEX receiver 518 kHz	x	x	x	x	x
EGC receiver	x[1]	x[1]		x	x
Float-free satellite EPIRB	x	x	x	x	x[4]
Radar transponder (SART)	x[2]	x[2]	x[2]	x[2]	x[2]
Hand-held GMDSS VHF transceivers	x[3]	x[3]	x[3]	x[3]	x[3]
For passenger ships the following applies from 01.07.97					
"Distress panel" (SOLAS regulations IV/6.4 and 6.6)	x	x	x	x	x
Automatic updating of position to all relevant radiocommunication equipment (regulation IV/6.5). This also applies for cargo ships from 01.07.02 (chapter IV, new regulation 18)	x	x	x	x	x
Two-way on-scene radiocommunication on 121.5 and 123.1 MHz from the navigating bridge (SOLAS regulation IV/7.5)	x	x	x	x	x

[1] Outside NAVTEX coverage area.

[2] Cargo ships between 300 and 500 gt: 1 set. Cargo ships of 500 gt and upwards and passenger ships: 2 sets.

[3] Cargo ships between 300 and 500 gt: 2 sets. Cargo ships of 500 gt and upwards and passenger ships: 3 sets.

[4] Inmarsat-E EPIRB cannot be utilized in sea area A4.

Figure 3 GMDSS Equipment Requirements. From Cult of sea. (2018, May 26). GMDSS Radio Equipment Requirements on Ship as per SOLAS, (https://www.cultofsea.com/gmdss/gmdss-radio-equipment-requirements-on-ship-as-per-solas/)

2.2 Environmental conditions

Vessels operating in the Polar Region is exposed to harsh climate conditions which can significantly affect the operation of the vessel. These conditions can affect not only the vessel itself, but also affect subsystems that are vital for operating the vessel. In this chapter the most influent environmental parameters for operation of the vessel will be discussed.

2.2.1 Icing

Icing is the main environmental concern when operating in cold temperatures. An example of severe icing is shown in figure 4. Marine icing on hull and superstructure is the type of icing that is most often discussed, but in this thesis the focus will be on marine and atmospheric icing on vital equipment and subsystems. The reason for this is that marine icing on hull and superstructure is a wide-ranging and complex field that requires a lot of data and resources to discuss in detail. Marine icing is also mainly a problem for smaller vessels such as fishing vessels, and most vessels certified in accordance with the Polar Code is of relative large size. The Polar Code also requires heating arrangements for vessels operating in cold temperature, reducing the marine icing to a minimum.

Figure 4 Severe icing. From Groupocean. (2018, May 26). De-icing a cargo-boat. (https://www.groupocean.com/en/achievements/view/21)

Icing on antennas could reduce the reach for the radio signals dramatically. This can be solved through electric heating of the antenna, although this can lead to other difficulties as the antennas are sensitive electronic equipment that can be disturbed when exposed for electromagnetic radiation. Another aspect when discussing problems related to antennas is the quality of the insulation on the antenna-cables, and especially the connection between the antenna and the cable. If the ice accumulated on the antennas melts, the risk of water entering the cable increases if the insulation is damaged. Water entering the cables could significantly reduce the signal-strength, and could in a worst case scenario lead to the equipment connected the antenna being useless.

2.2.2 Power Source Capacity

IMO has through the SOLAS-convention stated some requirements for the vessels redundancy power source. An example from SOLAS-requirements regarding capacity for redundancy power source is shown below:

The redundancy power source should be able to operate the radio installation for:

- One hour for vessels equipped with an authorized emergency power supply for operating the radio installation for at least 18 hours for cargo vessels and 18 hours for passenger vessels.
- Six hours for vessels which are not equipped with an authorized emergency power supply.

It is worth mentioning that the capacity for lead-acid accumulators normally is calculated from a discharge time of 20 hours and an operational temperature of 20^{O}C. This means that it can be necessary to enhance the capacity for the redundancy power source in order to meet the SOLAS-requirements if operating in low temperatures.

2.3 Human error

It is impossible to discuss risk regarding maritime operations without mentioning human factors. The technology has improved drastically as the years has gone by, but the occurrence of accidents are still high. The reason for this is the human factor that is a vital part of nearly all maritime operations. In fact, about 75-96% of maritime casualties are caused, at least in by some form of human error (Rothblaum, et al., 2002). An illustration of top causes for liability loss in insurance cases is shown in figure 5. This shows that human error is an important factor when the aim is to reduce the risk of accidents. The question is if human error is as significant when it comes to operations in polar conditions. It is obvious that polar conditions has an impact on materialistic factors and equipment reliability, but does it also have an effect on the risk of human error? The answer is yes. The human being is affected by climatic and environmental factors just like the vessel itself and equipment. In addition to the physical influence, humans has a psychological influence that the vessel and equipment does not have. This means that the human is more affected by polar operating conditions than the other parameters involved in maritime operations.

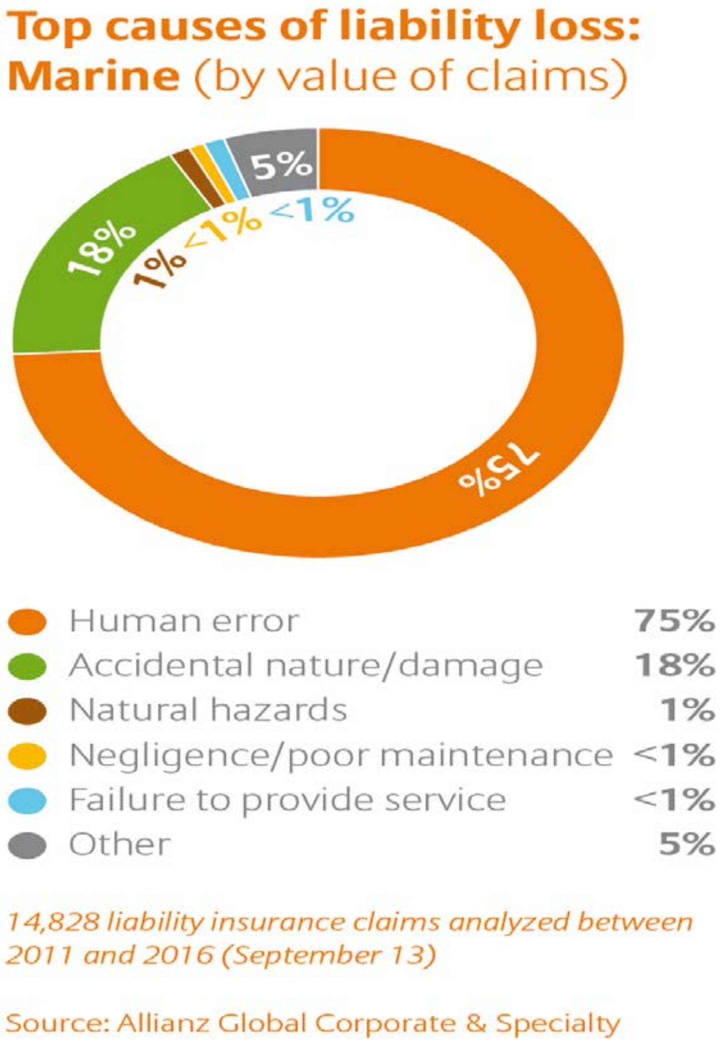


Figure 5 Top causes of liability loss. From Ship Management International. (2018, May 26). Human error blamed for 75% of marine liability losses. (http://shipmanagementinternational.com/human-error-blamed-for-75-of-marine-liability-losses/)

The statement that the risk of human error is affected by polar operation conditions is further strengthened by the findings in the report "Causal analysis of groundings and collision in Norwegian waters" from Kystverket (DNV GL, 2014). The reports states that the region where the largest part of the accidents is found to be caused by human error is Troms and Finnmark. Even though Troms and Finnmark not is included in the Arctic by the definition from the Polar Code, it is safe to say that vessels operating in this area is experiencing polar operating conditions during winter time. In other definitions of the Arctic, Troms and Finnmark is included, e.g. by the use of the Arctic Circle as the definition of the Arctic.

To find the risk of human error is a very challenging task. Human error is a complex field with many factors contributing to the risk of error. The risk is strongly dependent on factors such as experience, physical and psychological medical condition, attitude of crew etc. There are also different background factors that could lead to human error. For this thesis, only the factors that are influenced by polar operating conditions is discussed and analysed in the preliminary hazard analysis. How the factors are influenced by polar operating conditions is discussed in chapter 4.2.

2.3.1 Fatigue

Fatigue is defined as “extreme tiredness resulting from mental or physical exertion or illness.” In the maritime industry, fatigue is mainly used for tiredness caused by long working hours combined with lack of sleep. Fatigue is a very common condition to experience, at least at some level. Fatigue is found to be the “number one” concern of mariners in two different studies (Marine Transportation Research Board; 1976; National Research Council, 1990), (Rothblaum, et al., 2002).

2.3.2 Complacency

Complacency is defined as “a feeling of smug or uncritical satisfaction with oneself or one's achievements.” Complacency is most often developed when the navigator has gained some experience and is comfortable when performing the work tasks. The risk of complacency increases if the working-days are alike and contains little action. The risk of complacency is reduced by the use of attitude forming of the personnel and implementation of a well-working reporting culture.

2.3.3 Inadequate general technical knowledge

Over the years, the available amount of equipment for the navigator has increased dramatically. Earlier the navigator relied on a paper-chart, a compass and maybe a radar. Today, the navigator has a number of sources to gather information from. Many of these sources is connected to complex systems such as ECDIS. Many navigators does not understand how these systems are working, and which sources of information is being used at which time. This can lead to incorrect use of equipment, or that the navigators choose not to use a source of information due to lack of knowledge. In one study, (Wagenaar & Groeneweg, 1987), inadequate technical knowledge was responsible for 35% of the casualties (Rothblaum, et al., 2002).

2.3.4 Poor equipment design

A vessel fully equipped for operations in polar areas has a lot of equipment which is not present at a vessel operating under normal conditions. On the bridge, extra equipment such as ice-radars, infra-red cameras, controls for extra search-lights etc. is often installed. This equipment has to be placed in accordance with the other standard-equipment on the bridge. This often represents problems whether the extra equipment is installed after the vessel is built, or when building the vessel, as the issue of bridge ergonomics and where to install different equipments is well known. For operations in polar areas it can be necessary to adjust standard-equipment to make sure to avoid light-pollution etc. The already mentioned study by Wagenaar & Groenweg (Wagenar & Groeneweg, 1987) found that poor equipment design was cited as a causal factor in one-third of major marine casualties (Rothblaum, et al., 2002).

2.3.5 Decisions based on inadequate information

This type of human error is strongly connected to complacency and inadequate general technical knowledge. A complacent navigator will probably rely on the sources that he/she normally relies on without making sure that the information is correct or if other sources have other or better relevant information that affects the voyage. A navigator with inadequate general technical knowledge is probable to rely on information from the sources he/she is familiar with. Information from other sources is in danger to be ignored, either because the navigator does not understand the information or that he/she does not rely on the information because they are unfamiliar with the source of the information.

2.3.6 Poor judgement

Poor judgement will happen from time to time, and occasionally the navigators will be punished. The risk of poor judgement is strongly connected to all the above-mentioned human errors, and an increase in the probability for one or more of them will lead to an increase in the risk of poor judgement. Examples of poor judgement can be passing to closely to a danger, too high speed under the given conditions, ignoring potential risks etc.

2.3.7 Faulty standards, policies and practices

This category of human error is often the underlying cause of many of the above-mentioned factors. The safest way is not always the most lucrative way when it comes to making money in a short term perspective. In a market where many companies are surviving from day to day because of low income and high costs, it is easy to choose solutions that encourages higher risk-taking, but also a higher earning. It is also a fact that it can be a problem for companies to have written, precise operational procedures on-board all vessels. To develop such procedures requires competence in risk-assessment and HSE-procedures, along with knowledge regarding the vessel, its equipment and the procedures to be performed on-board the vessel. The crew on the vessel is often lacking competence regarding risk-assessment and development of procedures. This leads to the shore-offices often dealing with the risk-assessment and developing the procedures, with lack of knowledge regarding the vessel and the operations being performed. The result is imprecise procedures that are difficult to use for the crew when performing operations. Healthy standards, policies and practices must start from the top of the company and then be spread down to each vessel. The key to implement this in a successful way is attitude forming and upgrading of skills.

2.4 Navigation in ice

The theory in this chapter is mainly collected from a textbook in navigation written by Norvald Kjerstad (Kjerstad, Fremføring av skip med navigasjonskontroll for maritime studier, 2013). Some of the theory is also based on lecture notes in different subjects regarding navigation at UiT.

If possible, operations in ice should be avoided, although it can be necessary to pass through areas with drift ice or similar. The most important factor to consider when passing through such an area is to navigate the vessel as careful as possible to avoid damages to hull and machinery. This means that the speed should be adjusted in accordance with the current situation, and that icebergs and large ice floes should be avoided. Norvald Kjerstad, one of the leading experts in Norway regarding navigation in ice, has written in one of his textbooks regarding navigation that “The fastest way through the ice is seldom the shortest one.” (Kjerstad, Fremføring av skip med navigasjonskontroll for maritime studier, 2013).

Most vessels have regular hulls without ice-strengthening. For those vessels the most relevant situation will be navigation in drift ice. If a vessel needs to cross through an area with drift ice, there are often some indications that can be used for planning the crossing. An example of a very helpful indication is the phenomenon “ice blink”. This is a meteorological phenomenon where the ice is reflected onto the sky. For this phenomenon to be present is it necessary to have clear weather with a thin cloud cover. In the direction the ice blink is observed it will be much ice, and it will be preferable to avoid steering in this direction if possible. It is also possible to detect channels or wakes in the ice as dark stripes in the ice blink. Such channels or wakes could be helpful to navigate by if they are leading in the headed direction.

Other indications to be aware of is for instance swells in the ice. If swells are observed, it is probable that the ice conditions are lighter in the direction that the swells are coming from. Fog with yellow-white colour often indicates waters with ice. Small lumps of ice in the water is a certain indication of waters with ice ahead. Another sign indicating the same could be a sudden drop in air- and water-temperature.

It is also possible to detect ice by the use of hearing. Breakers can be heard from a long distance. This can be very useful if the visibility is limited, although the noise level from the vessel can drown out the sounds from the ice.

2.4.1 Entering the ice

When all information regarding the ice and the surrounding environment is collected, the next step should be to plan the entering of the area with ice. First, it is necessary to find the best possible position for entering the ice. This position is determined based on ice-conditions and the intended route further into the ice. It is often necessary to observe the ice-edge for some time, both visually and by radar, before deciding where to enter.

2.4.2 Radar in ice

The use of a standard maritime radar can be very helpful in the process of detecting ice in water, although it is important to keep in mind the limitations for such equipment. It is important not to take it for granted that the water is free of ice even though the radar-image indicates no sign of ice. The possibility of detection of ice by radar is strongly dependent on the ice-conditions. Drift-ice can be difficult to detect, especially if the size of the ice-units is small. The same goes if the ice is glassy, meaning that the ice is not granulated. The possibility of detection of icebergs is dependent on the angle of gradient for the side of the iceberg that is exposed to the radar. This angle can often affect the possibility of detection more than parameters like size and range. If the aim is to detect ice at a short range, the best possible radar-configuration is a 3-cm radar with long antenna. The pulse-length should be set to medium or long. The possibility of detection of drift-ice, growlers etc. is strongly dependent on the sea-state and the antenna-height.

In calm sea, the detection range for different ice-conditions are estimated as shown in table 2:

Table 2 Detection range for different ice conditions (Kjerstad, Fremføring av skip med navigasjonskontroll for maritime studier, 2013)

Type of ice:	Detection range:
Large icebergs	15-20 nm
Large growlers	2 nm
Belts of scattered drift-ice	Difficult to detect even at short range
Dense belt of drift-ice	5-6 nm

In heavy sea, the possibility of detection of dangerous ice like growlers and belts of dense drift-ice would be very low due to echoes from the sea that will induce noise on the radar-screen. Under these conditions, the navigator would have to rely on other sources of information in order to navigate safely. The “Echo trails”-function on the radar can be very helpful if the radar-screen is disturbed by noise from the sea. By the use of this function, it can be easier to divide echoes from ice and echoes from the sea. The clutter-functions, which is a mathematically filter that removes noise, can also be helpful. However, these functions should be used with extreme care, as they can easily remove targets that in fact are ice, or even worse, another vessel.

Ice Radar

Over the years, several special radars for detection and/or classification of ice have been introduced. These systems are not found on all vessels operating in ice, mainly as a result of high purchase price. The technique behind the ice-radars is the use of Scan Correlation. This technique correlates multiple scans that then are put together to a radar image provided for the user. This means that the processing can take some time, but the resulting radar image can be very informative for detection and classification of ice. An example of a radar-image for an ice-radar is shown in figure 6.

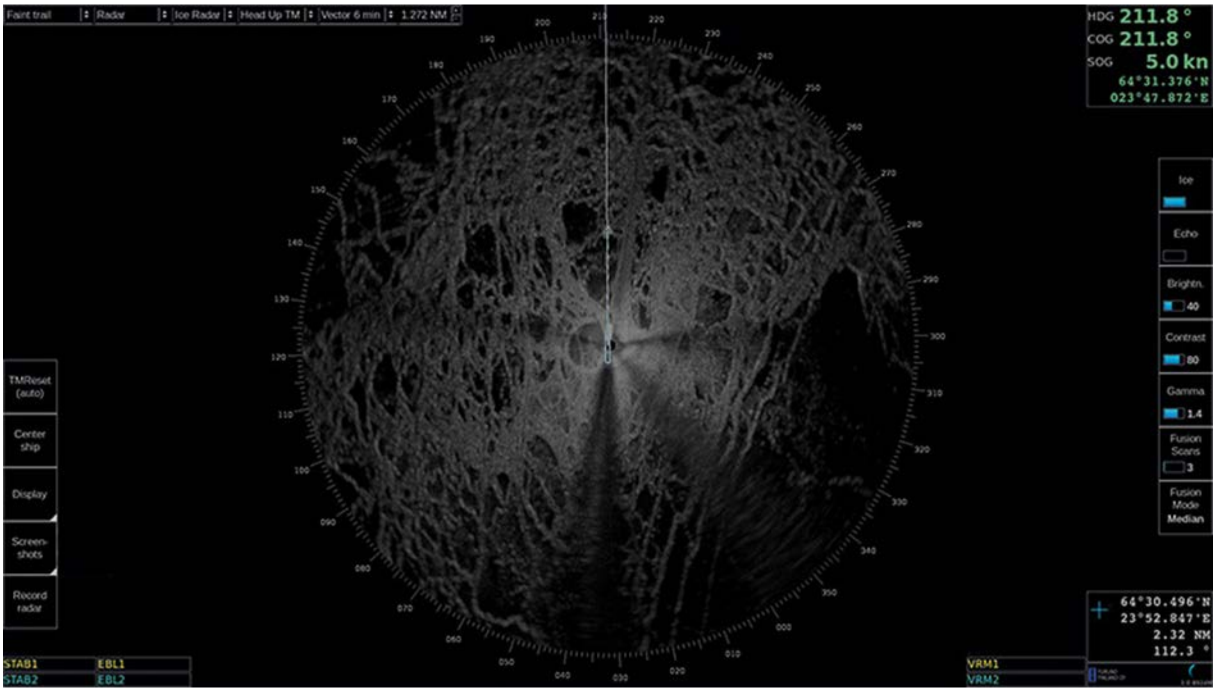


Figure 6 Radar image for ice-radar. From Furuno. (2018, May 26). Ice-Radar. (http://www.furuno.com/en/merchant/iceradar/)

2.4.3 Routines for navigation in ice

When navigating in waters with ice, it can be useful to have routines that lowers the risk of collision with dangerous ice. In this chapter, some vital general routines are presented. However, each vessel has to implement their own routines for the operations they are intended to execute. Some vital routines, derived from a textbook in ice-navigation (Kjerstad, Fremføring av skip med navigasjonskontroll for maritime studier, 2013) is presented below:

- Manoeuvring-system ready for action
  When navigating in waters with ice, it is of high importance that the manoeuvring-system is ready for immediate action, especially for being able to stop the vessel fast if ice is detected in front of the vessel. It is also important to be vigilant when it comes to stopping distance when sailing in convoy behind an icebreaker. One of the situations that leads to most damage on vessels when navigating in ice is collision under convoy-operations. It is important to monitor the distance between the vessels both visually and by the use of radar.

- Manual steering

  Autopilot should not be used when navigating in ice. It will be necessary to change course often due to the ice-conditions. It can also be necessary to use the rudder to avoid the vessel getting stuck in the ice. In these situations, the rudder will have to be used actively with large rudder deflections. When using autopilot, the rudder deflection is limited. It is also recommended to have both pumps on the steering engine running for being able to alternate course rapidly.

- Positioning and work in chart

  Normally, it would be necessary to deviate strongly from the intended course in the chart due to the ice-conditions. This will lead to difficulties regarding always being in control over the vessels position in the chart. When considering the earlier mentioned challenges regarding GNSS-signals and the quality of available chart-information, control of the vessels position should be a high priority. It can be very useful to control the vessels position by the use of parallel-indexes if there are available land-areas or maritime infrastructure for such methods.

- Communication

  If several vessels are operating together, e.g. in convoy-operations, communication should be a high priority. In the International Code of Signals, standardised signals for use in convoy-operations is defined. In addition to this code, local regulations and procedures regarding communication can exist, usually found in local pilot-descriptions.

- Lookout

  Lookout by radar and searchlight will reduce the risk of collision with ice. The visual lookout should be combined with lookout by radar. If the light-conditions makes it possible, night goggles could be used.

- Tactical preparation

  The most important routine is to place the intended route where the ice-conditions is least problematic. This means that all earlier mentioned factors such as meteorological warnings, statistics and local meteorological phenomenon should be considered.

3 The Polar Code

The International Code of Safety for Ships Operating in Polar Waters (Polar Code) is a mandatory code developed by IMO. The aim for the code is to improve the safety of shipping and to mitigate harmful effects of shipping on the environment in the remote, vulnerable and potentially harsh polar waters (IMO, 2017).

3.1 Content and structure

In this paragraph the structure (chapters) of the code is presented and a brief summary of the content for the chapters that involve the navigation process is given. The information in this paragraph is derived directly from the code (IMO, 2017), although some parts that does not have relevance for the navigational process is left out.

3.1.1 Chapter 1 General

In the first chapter information regarding the code and the buildup of the code is explained. Definitions that are used later in the code is listed. It is stated which ships the code applies for, and that these ships needs a certificate to document that they are constructed, equipped and operated in accordance with the code. In the end of the chapter, the code defines what they call quality standards, which ensures that the ship and its equipment will be functional under the conditions they intend to operate. The ships are also required to execute an operational assessment, meaning that the operational circumstances the ship is meant to operate under needs to be assessed. Factors to be considered here are among others, but not limited to, temperature conditions, ice conditions, operations on high latitudes, and potential for having to leave the ship in the ice or at shore.

Chapter 1 also requires the ship to assess possible dangers to the ship. In the introduction for the code, the IMO have given some dangers that is always to be assessed:

- Ice that can lead to damage to the hull, loss of stability, damage to machinery, influence on the navigation, influence on the work environment outdoors, affect maintenance and other tasks, and could lead to failure for safety equipment and systems.
- Icing on the superstructure and hull above waterline with subsequent reduction in stability and functionality of equipment.

- Low temperatures, that effects work environment and human performance, maintenance and emergency preparedness, properties of materials and efficiency of equipment, survival ability and the performance of safety equipment and systems.
- Long periods of darkness or daylight, as this can affect both navigation and human performance.
- High latitude, as this affects navigational systems, communication systems and the quality of satellite images for information regarding ice conditions.
- Remote locations, and possible lack of accurate and complete hydrographic data and information, reduced availability of navigational aids and seamarks with following increased risk of grounding, limited availability of search and rescue services with following delay in emergency response, and limited communication ability.
- Possible lack of experience among the crew regarding operations in polar waters, with following potential for human error.
- Possible lack of suitable emergency equipment, with following potential reduced efficiency in mitigation measures.
- Varying and difficult weather conditions.
- The environment regarding vulnerability towards harmful substances and other damages to the environment, and the need for longer restitution time.

If the ship identifies further sources that can be a danger to the ship, the code requires the ship to assess them in the same manner as the above mentioned.

3.1.2 Chapter 2 Operation manual for polar waters

Chapter 2 states that the ship is to prepare an operation manual for polar waters. The aim for this manual is to give the company, operator, captain and crew information regarding the operational capacities and limitations for the ship. The code defines some aspects the manual should consider, such as:

- Information regarding capacities and limitations for the ship in connection with the operational assessments from chapter 1.

- The manual should include or refer to specific procedures that should be followed in normal operations. These procedures should make sure that the ship operates within its limitations.

- The manual should include or refer to specific procedures that should be followed if unwanted events occurs in polar waters.

- The manual should include or refer to specific procedures that should be followed if the ship find itself in a situation which exceeds its capacities or limitations.

- The manual should include or refer to procedures that should be followed if assistance from icebreaker is required.

To make sure that the ship complies with these requirements, the code has established some rules to be followed when operating in polar waters:

- The manual should be kept onboard the ship.

- The manual should include the methodology used for determining characteristics and limitations in ice.

- The manual should include risk-based procedures for the following aspects:

    1. Route planning in order to avoid ice and/or temperatures that exceeds the construction capabilities or limitations for the ship.

    2. Arrangements to receive warnings regarding the environmental conditions.

    3. Means to handle possible limitations due to the available hydrographic, meteorological and navigational information.

    4. Operation of equipment required in other chapters in the code.

    5. Implementation of specific measures for ensuring the functionality of equipment and systems under low temperatures, icing on the hull above the waterline and occurrence of sea ice, if relevant.

    6. Contact with rescue services related to salvage, search and rescue, oil spill etc., if relevant.

    7. For ships with ice strengthening in accordance with chapter 3, procedures for maintaining survival equipment and the ships integrity if the ship is stuck in the ice for a long period of time.

- The manual should include procedures to be followed for measures that need to be taken if the ship experiences ice and/or temperatures that exceeds it construction capabilities or limitations.

The manual should include risk-based procedures for monitoring and maintaining the safety under operations in ice, including possible requirements for escort operations or icebreaker assistance. Different operational limitations can be relevant depending on if the ship operates independent or with icebreaker escort. If relevant, the manual should include both alternatives.

3.1.3 Chapter 9 Safe Navigation

The main goal with chapter 9 in the Polar Code is to ensure safe navigation. To achieve this goal, the code establishes some functional requirements for the ship:

- The ship should be capable of receiving up to date information, including information regarding ice, for safe navigation.
- Navigational equipment and systems should be shaped, constructed and installed for remaining functional during the expected environmental conditions in the operation area.
- Systems for position reference and position determination should be suitable for the planned operation areas.
- The ship should be able to visually detect ice when operating in darkness.
- Ships involved in operations involving icebreaker escort should have suitable means for informing when the ship is stopped.

For ensuring that these functional requirements are fulfilled, the code establishes some rules to be followed:

Regarding nautical information:

- The ship should have means for receiving and displaying up to date information regarding the ice conditions for the operation area.

Regarding functionality for navigational equipment:

- Ships built on the 1. January 2017 or later, which is ice strengthened in accordance with chapter 3 in the Polar Code, should be equipped with either two independent echo sounders, or one echo sounder with two separate independent transducers.

- The ship should operate in accordance with SOLAS rule V/22.1.9.4 (“A clear view through at least two of the navigation bridge front windows and, depending on the bridge design, an additional number of clear-view windows, shall be provided at all times, regardless of weather conditions”), independent of building date, size and, depending on the bridge design, clear visibility astern.
- For ships operating in areas, and in periods, where icing can occur, there should be means made available to avoid accumulation of ice on antennas vital for navigation and communication.
- In addition, for ships with ice-strengthened hull in accordance with chapter 3, the following applies:
    1. Where equipment required after SOLAS chapter V or this chapter have hull-mounted sensors, such sensors should be protected against ice.
    2. For ships of category A and B build on the 1. January 2017 or later, the “bridge-wings” should be covered or shaped to protect navigational equipment and personell.
- Ships should have two non-magnetic means for determining and presenting the vessels course. Both means should be independent and should be connected to the ships main- and emergency power supplies.
- Ships intended to operate above the 80 degree of latitude should be equipped with at least one GNSS-compass or equivalent, which should be connected to the ships main- and emergency power supplies.

Regarding extra navigational equipment:

- Ships, with exception for ships only operating in areas with 24 hour daylight, should be equipped with two remote-rotatable searchlights with narrow beam which can be controlled from the bridge for illuminating the horizon around the ship, or other means for visually detection of ice.
- Ships involved in operations involving icebreaker-escort should be equipped with a blinking red light which is started up manually and is visible from astern for informing when the ship is stopped. This light should be visible within a distance of at least two nautical miles, and the horizontal and vertical visibility-sectors should be in accordance with the specifications for aft-lanterns in COLREGS (Regulations for prevention of collision at sea).

4 Simulator training

Operation of vessels under polar conditions can be described as a high-risk operation. The vessel is exposed to several challenges that makes the process of safe navigation more complex. A vessel operating in polar areas is most often of a considerable size and equipped for operations in such areas. This means that the vessel represents a valuable asset for the owner. Another aspect is that the vessel is carrying human beings on-board, represented by crew and potential passengers. If the vessel finds itself in some sort of crisis, it is certain that the risk of loss of lives is significant, due to harsh climatic conditions and lack of available infrastructure for assistance in emergency situations.

4.1 Why use simulator training?

Operation of vessels under polar conditions can be considered a high-risk operation, as described earlier. The high level of risk is strongly connected to the high consequences for a potential accident. Nearly 80% of all accidents in the maritime sector is related to human error. If the risk of human error is reduced, the total risk will be significantly reduced.

Research shows that training of the crew can be a successful risk-reducing measure.

Operation of vessels under polar conditions induces increased risk compared to operation of vessels under normal conditions. The accessible data available for the crew (weather forecasts, chart data, statistical wave data) is limited, the risk of failure and/or inaccuracy for mechanical and electrical equipment is increased and the risk of human error is increased. All factors due to the challenging operating conditions and complex situations where different kind of equipment have to be used at the same time in order to execute the operation safely.

It is possible to use real life training as a method for improving the competence of the crew, as less experienced crewmembers can work alongside more experienced personnel. It is however preferable that the crewmembers have some experience before having to deal with the situations, considering the high consequences of a possible human error. It is also worth mentioning that some of the situations the crewmembers need to have knowledge about occurs very rarely. It is possible to operate a vessel for a long time without experiencing loss of position from the satellite-positioning systems, for example by the use of a triple-receiver that allows the user to take in signals from multiple satellite systems at the same time.

Considering the abovementioned aspects, being consequences of a possible failure and difficulty in inducing relevant failure modes, it is useful to apply simulator training to increase crew competence in execution of polar operations. The crew can train in a safe environment where wrong decisions does not have large consequences. The crew can also train their reactions to failure modes and emergency situations which they rarely will experience in real life, but where fast and correct response is key to a successful solution of the problem.

The maritime industry has not done much research about the results simulator training has on the performance for the navigators, but in this chapter some of the literature regarding the subject will be analysed.

4.1.1 The Sleipner A towing operation

When preparing for towing the Sleipner A(2) platform from the construction site in Gandsfjorden, Norway, to the installation site in the North-Sea, a decision was made by the project management to train the towing team by the use of simulator training. The project management made the assumption that the simulator training would reduce the likelihood of a navigating error, and increase the reliability of responding to either a navigation error or a tow line error. When deciding how to estimate the magnitude of the performance improvement, human error databases and psychological literature were reviewed (Williams, 1988, Swain and Guttman, 1983). From this, the project management concluded that the risk could be reduced by a factor of 10. This led to a reduction for the probability for total loss of platform from $6.3*10^{-5}$ for untrained personnel to $3.3*10^{-7}$ for trained personnel (Gudmestad, et al., 1995).

From the paper “Use of simulator training to reduce to reduce risk in offshore marine operations”, the following statements regarding simulator training can be found:

- “As experienced for previous tows, the simulator training proved to be of great value to those who were in charge of manoeuvring the platform. Lots of knowledge and confidence were gained during the simulator training.” (Gudmestad, et al., 1995)
- “Another aspect of simulator training is the fact that the team members are brought together. They are working together, discussing various approaches and digging deep into and solving problems long before they potentially could become serious.” (Gudmestad, et al., 1995)

- “Simulator training is considered to represent an excellent tool in reducing risk in complex offshore marine operations.” (Gudmestad, et al., 1995)
- “The tow out of Sleipner A was very successful as all personnel involved had gained confidence in the tow operations and emergency procedures through involvement in the simulator training programme.” (Gudmestad, et al., 1995)

The process of navigating a vessel safely under polar conditions can be described as a complex marine operation, and the findings from the Sleipner tow project management is thereby transferable to the situation this thesis is focusing on.

4.1.2 Other studies

There are not many other studies available that deals with simulator training and its effect on the navigators, but one recent article about the subject is “Reducing Risk of Arctic Operations with Ice Simulator” written by J. Koponen from Aker Artic Technology Inc., Helsinki, Finland. Some of his findings is shown in this subchapter:

- “During the process of development of the Full Mission Bridge Simulator, I have come in to a conclusion that an important part of a successful learning process is the ability to train with a high fidelity bridge simulator.” (Koponen, 2015)
- “The most cost-effective way to improve special skills needed in the Polar waters is to include bridge simulator training to the Deck Officers requirements.” (Koponen, 2015)
- “The simulator is needed for different reasons: cost, safety, easiness of teaching, efficiency in teaching, testing of design and in finding out operational limits.” (Koponen, 2015)
- “In many cases it is not possible to organize training in a real environment, and arctic especially should not be the place where real life practicing takes place. Simulator enables training of risky and hazardous operations safely and operators insufficient skills can’t harm real nature, lives or material.” (Koponen, 2015)

Although there is a limited amount of literature available regarding use of simulator for maritime navigation purposes, it is possible to use literature and research material from the aviation industry to discuss the use of simulator training in general. The aviation industry has done more research on the use of simulator as a tool for training and education of personnel. It is possible to use findings from this research also for the maritime industry as the general findings regarding simulator training are transferable between the different industries. If looking into the aviation-industry, some key factors regarding the use of simulator can be found in the paper "FLIGHT SIMULATOR AS AN ESSENTIAL DEVICE SUPPORTING THE PROCESS OF SHAPING PILOT'S SITUATIONAL AWARENESS" written by J. Kozuba and A. Bondaruk from the Polish Air Force Academy (Kozuba & Bondaruk, 2014). In this work, it is revealed that some of the main benefits of using simulator, that also are relevant for maritime navigational training, are:

- High training effectiveness.
- Maintaining high standards of training and safety
- Availability
- Repeatability
- Predictability
- "Learning from mistakes"

High training effectiveness is one of the primary benefits also for maritime navigational training. An hour of simulator training can include several different scenarios in different geographical locations. This is impossible in real-life training. It is also a fact that the instructors will have more capacity for instructing and guiding during simulator exercises than in real life situations. If the training takes place on an actual vessel, the instructors will often be in charge of the navigation and safety of the vessel as well as the instructor tasks. This will lead to the instructors having less capacity available for guiding the participants in the training.

The safety factor is a key factor. It is always a risk connected to training of inexperienced personnel. This risk can be completely eliminated if the training is done through simulator exercises.

Availability is connected to the fact that simulator training is independent of external factors such as weather-conditions, other vessels etc. In simulator exercises, the desired conditions are applied and adjusted in accordance with the wanted learning-outcome of the exercises. In real life situations, it can be necessary to wait a long period of time for the right conditions to appear. It can also be necessary to travel long distances to find the right conditions.

Repeatability is found to be significant when it comes to learning of procedures etc. In a simulator exercise, it is possible to repeat situations multiple times until both instructor and participants in the training is satisfied.

Predictability is connected to the fact that it is possible to conduct the training without interruption from unwanted external factors. In real life, the training could be impeded by other vessels or a change in environmental conditions etc. In simulator training, all the focus can be pointed towards the factors that are connected to the learning-outcomes for the training.

Learning from mistakes is a very useful way of learning, but not something that is wanted in a real-life situation. In simulator training, the participants can make mistakes which in real life could lead to massive consequences like grounding or collision.

4.2 Simulator exercises

To utilize the simulator training in the best possible way, it is necessary to make sure that the quality of the simulator exercises is high. In order to ensure that the quality of the exercises is of an adequate standard, it can be useful to determine some requirements to be followed when preparing the exercises. When preparing exercises for use in the maritime education at UiT, the responsible simulator-instructor has to develop the exercises in accordance with standards from the STCW-convention (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers). It is possible to use some of these requirements as a basis also when developing other types of simulator exercises not primarily meant for education of nautical students. Some of the key factors that can be considered when developing exercises are (UiT, 2014):

- Often, it is necessary to use several exercises with increasing level of complexity to successfully simulate a given situation. If this is the case, a plan should be developed that ensures that the exercises are progressing in accordance with the predefined goals for the simulation of the situation.

- Learning objectives should be developed for each exercise. The participants in the simulator exercises should be informed of the learning objectives prior to the exercise.

- In the program at UiT, a predefined layout is used for description of the exercises. This can be used also for the polar exercises. This template should include title, area, description of scenario and learning outcome.

- There should be a briefing prior to the simulator exercise. On the briefing, the scenario for the exercise should be discussed in detail, alongside with the learning outcomes. When the exercise is finished there should be a debriefing where the participants in the exercise is given feedback on their performance. If the exercise consists of teamwork between the participants, it is often useful if the participants evaluate their own performance as well as the team performance in whole.

5 Preliminary Hazard Analysis

Preliminary hazard analysis is a technique to identify possible hazards for a system or a process. The principle for the analysis is to identify hazards that could lead to accidents. The aim is to find eventual weaknesses for the system or process before they occur, and then implement corrective measures as a proactive risk management.

5.1 Preliminary Hazard Analysis for navigation in polar areas

The polar code requires that the vessel identifies all hazards that can be a threat for the vessel, crew and cargo. This can be done through the use of a preliminary hazard analysis. The first step in the preliminary hazard analysis is to reveal all relevant hazards that can be a threat to the vessel. In this thesis this is done through the use of literature, statistical data, and through information gathered through conversation with navigators with experience from operations under polar operating conditions.

The next step in the analysis would be to identify the underlying causes for the hazards, and what possible consequences the hazards represents. From the information gathered through this process, a probability and a consequence for each hazard is derived. One of the main challenges when performing a preliminary hazard analysis is to quantify the probability and consequence based on the available information. In this analysis, the probability is given a value from 1 to 5, where 1 means very low probability and 5 means very high probability. The possible consequence is given a value from A to E, where A is minimal consequence and E is very high consequence. The correlation between probability and consequence is shown in table 3 below.

For determination of risk acceptance criteria, the ALARP (As Low As Reasonably Possible)-principle is used. For this particular analysis, this means that risk in the red area is unacceptable, risk in the yellow area can be accepted under certain conditions, and risk in the green area is accepted.

Table 3 Risk Matrix

Consequence→ Probability ↓	A Minimal	B Low	C Medium	D High	E Very high
5-Very high	🟨	🟨	🟥	🟥	🟥
4-High	🟩	🟨	🟨	🟥	🟥
3-Medium	🟩	🟩	🟨	🟨	🟥
2-Low	🟩	🟩	🟩	🟨	🟨
1-Very low	🟩	🟩	🟩	🟩	🟨

The preliminary hazard analysis is presented in table 4. Comments to the different parts of the analysis is presented in chapter 5.2.

Table 4 Preliminary Hazard Analysis

Hazard number	Problem	Cause	Possible consequences	Pre risk-reducing measures risk	Risk reducing measures	Post risk-reducing measures risk
Natural and environmental hazards						
1.1	Icing on hull	-Icing due to sea spray and metrological factors	Reduced stability, reduced maneuverability, danger of equipment failure	🟨 P: 3 C: D	Heating of hull and equipment, manual removing of ice	🟩 P: 2 C: B

1.2	Difficulty to keep the vessel on course	Wave-, wind- or current-forces affecting the movement of the vessel through the water	Trouble following the intended route, possible grounding.	P: 4 C: D	Planning based on weather-information, adequate monitioring of the voyage, well trained personnel	P: 2 C: B
1.3	Reduced visibility	Icing on windows, reduced visibility due to fog, snow or rain.	Difficult to navigate by the use of optical techniques, difficult to detect other vessels or obstacles (ice), possible grounding or collision	P: 4 C: D	Deicing of windows, planning based on weather information, use of other equipment for navigational purposes, training of personnel	P: 2 C: B
Failure and inaccuracy for equipment						
2.1	Loss of GNSS-position	GNSS blackout	No position available, ECDIS failure, possible grounding	P: 2 C: C	Redundancy, training of personnel	P: 1 C: B

2.2	Inaccuracy for GNSS-position	Satellite-geometry, manipulation of satellite signal	Wrong position displayed to user, wrong position as ECDIS-input, possible grounding	P: 3 C: C	Use of more than one satellite system, training of personnel	P: 2 C: B
2.3	Freezing of GNSS-position	Icing on antenna, failure of receiver	Wrong position displayed to user, wrong position as ECDIS-input, possible grounding	P: 3 C: C	Deicing of antenna, redundancy, training of personnel	P: 1 C: B
2.4	Gyro Failure	Blackout, mechanical failure	No heading-information provided to user, ECDIS-failure	P: 1 C: D	Redundancy, heading from magnetic compass, training of personnel	P: 1 C: B
2.5	Gyro Inaccuracy	High latitude, high speed, steering N-/S-course	Wrong heading-information provided to user, wrong heading as ECDIS and radar input	P: 5 C: C	Manual or automatic compensation for error, use of more advanced compasses, monitoring of voyage, training of personnel	P: 4 C: A

2.6	Magnetic compass failure	Frozen fluid, mechanical failure	No heading from magnetic compass provided for user	P: 1 C: A	No risk reducing measures needed	P: 1 C: A
2.7	Magnetic compass inaccuracy	Magnetic deviation, magnetic variation, un-calibrated compass	Wrong heading-information from magnetic compass provided for user	P: 5 C: A	Manual compensation for error, monitioring of voyage, training of personnel	P: 3 C: A
Human error						
3.1	Fatigue	Lack of sleep, darkness, daylight	Reduced attention, increased response time, possible grounding/collision	P: 4 C: D	Reduced time on watch, extra lookout, training of personnel	P: 3 C: C
3.2	Complacency	Long watches with little action	Reduced attention, increased response time, possible grounding/collision	P: 3 C: D	Reduced time on watch, extra crew, attitude forming, training of personnel	P: 2 C: C
3.3	Inadequate technical knowledge	Special equipment only used under certain circumstances	Increased response time, wrong use of equipment, possible grounding/collision	P: 3 C: D	Checklists, follow-up on crew-competence, extra crew,	P: 1 C: C

		(Ice-radar, ice-charts)			training of personnel	
3.4	Poor equipment design	Loss of night-vision due to light pollution, equipment being inefficient placed	Navigational error, possible grounding/collision	P: 2 C: D	Testing of equipment, user feedback, personnel training	P: 1 C: D
3.5	Decisions based on inadequate information	Only use one method or aid, relay on limited information, complacency	Navigational error, possible grounding/collision	P: 3 C: D	Checklists, attitude forming, training of personnel	P: 2 C: D
3.6	Poor judgement	Lack of information, lack of experience, fatigue, complacency	Navigational error, possible grounding/collision	P: 4 C: D	Checklists, attitude forming, training of personnel	P: 3 C: D
3.7	Faulty standards, policies or practices	Lack of procedures, pressure to meet schedules, profit first thinking	Navigational error, possible grounding/collision	P: 3 C: D	Regulations and control by authorities, inspections, attitude forming	P: 2 C: D

5.2 Comments to the Preliminary Hazard Analysis

To do a preliminary hazard analysis is a challenging task when the background data for determination of consequence and probability is limited. In this chapter, the different parts of the analysis will be briefly discussed, and the background for the determination of risk levels for each hazard will be explained. The risk for hazard 3.1, 3.5, 3.6 and 3.7 is set to yellow after risk reducing measures, but can still be accepted. This is due to the fact that further reduction is difficult to achieve, and the effectiveness of further risk-reducing measures is uncertain. All these hazards are connected to human errors, which is the most complex type of errors to prevent. Companies put a lot of effort and money into reducing the amount of human errors, but still it is the main reason for accidents. Based on the possible consequences of an accident, it is necessary for each vessel to determine if risk in the yellow area can be accepted.

5.2.1 Icing on HULL (1.1)

Icing on hull is a situation that all vessels operating in arctic climatic conditions will experience from time to time. In most cases, the icing is not severe and represents mostly a practical obstacle for the crew working on deck. It will also have a negative economic effect as the vessel will have increased displacement and therefore use more fuel to sail the same distance during a specified period of time. Alternatively, the vessel will have to reduce speed, and thereby use longer time, which means a loss of income for the company. This is important factors to consider for the company, but it is not the reason why the risk is set to medium for this hazard. The risk is connected to the few cases where the vessel will experience severe icing which will strongly affect the stability, freeboard and manoeuvrability for the vessel. This is a very serious situation that can be an immediate threat to the vessel and its crew. The history shows examples of several vessels that is lost due to icing, but it is worth mentioning that the vessels lost due to icing mainly is of a relatively small size. Nevertheless, icing can be a problem also for larger vessels, e.g. the Norwegian Coast Guard Vessel KV Nordkapp in the Barents Sea in 1987, described in an article written at UiT (Samuelsen, Løset, & Edvardsen, 2015).

The risk-reducing measures can consist of installing heating arrangements that can either be proactive with heating up the hull and thereby prevent icing, or passive systems that are turned on if icing should occur. Routines and equipment for manual removing ice is also a measure that reduces the risk significantly.

5.2.2 Difficulty to keep the vessel on course (1.2)

If the external forces affecting the vessel gets larger than the forces created by the vessels machinery and steering equipment, the vessel will have trouble steering the intended course. These external forces are typically generated by wind, waves or current. This can be a critical situation, where the vessel can be put in danger as the navigators will lose control of the movement of the vessel. The key to avoiding this situation is proper planning of the voyage and knowledge regarding the operational limitations for the vessel, in addition to knowledge regarding how the vessel reacts when affected by external forces. This knowledge can be gathered through training of the personnel, either in real life or in simulator. Simulator training is a helpful aid in gaining this knowledge, as each of the external forces can be applied individually, and thereafter as a complex situation with multiple forces applied at the same time. This type of training is difficult to achieve in real life, as the vessel can operate for long periods of time without these situations occurring.

5.2.3 Reduced visibility (1.3)

Reduced visibility is a problem that very often occurs in polar waters. One factor that can lead to this problem is marine or meteorological icing on windows. This can be avoided by installing windows with built-in hot-wires which prevents icing. Reduced visibility as a result of rain, snow or fog is a more complex factor to avoid, but the vessel and its crew has several methods for safe navigation by the use of other means than the optical when the visibility is reduced. If these means are used correctly, and the right means are used in the right situations, the risk is dramatically reduced. Operation in reduced visibility is well suited for simulator training, as the level of visibility can be adjusted to the intended learning-outcome of the simulator exercises. It is also possible to make different equipment available in different situations so that the navigators can learn to use different equipment and means under changing circumstances. If the aim is to the train the navigators in planning according to available weather information, it is possible to provide them with updated maritime safety information by the use of both VHF and NAVTEX.

5.2.4 Loss of GNSS-position (2.1)

Loss of GNSS-position is a situation all vessels should be prepared for although it happens very rarely. Total loss of GNSS-position is most often related to total blackout for GNSS-receiver, either by failure for the receiver itself or by total blackout for the whole vessel. In the latter situation the emergency power supply for the vessel should be activated, and the position will be available after a short period of time. The GNSS-position is the main source for positioning of the vessel, although the vessel can be manually positioned by using different types of manual positioning methods. This is more problematically in polar areas due to the lack of maritime infrastructure such as lights and other navigational marks. This means that loss of GNSS-position will have a bigger consequence in polar areas than in other areas with more infrastructure. The risk can be reduced by the use of redundancy, meaning instalment of more than one receiver, and by using different GNSS-systems. It is worth mentioning that for example GPS originally is an American military system that can be completely switched off if a politically crisis or war situation occurs. The probability of this happening is very low, and can be completely neglected by the use of more than one GNSS-system. At the end, the main source for reducing the risk if a GNSS-blackout occurs is a well-trained crew that knows how to react if the situation occurs. This can be practiced in simulator exercises where the GNSS-receiver can be turned off in different situations to assess how the crew reacts.

5.2.5 Inaccuracy for GNSS-position (2.2)

It is a fact that the inaccuracy for the position received from the GNSS-system will increase at higher latitudes. This is mainly due to the lack of satellites over the polar areas, which will lead to a poor satellite-geometry that will result in inaccuracy for the position. This problem has been reduced, and today it is possible to position the vessel with adequate accuracy even on the north pole. Today, the highest risk is connected to jamming and spoofing of the GNSS-signals. In the northern part of Norway, jamming of the GPS-signal from the Russian military has led to difficulties for aircrafts over Finnmark. This can be the case in the northern areas also, as both the American, Russian and the Norwegian military is putting a lot of resources into techniques for manipulation of GNSS-signals. The risk of large inaccuracies for GNSS-position can be significantly reduced by using more than one GNSS-system. This can easily be done by the use of a triple-receiver which lets the user take in signals from satellites that belongs to different GNSS-systems. The position will then be less vulnerable to manipulation of the signal from one of the GNSS-systems. The other factor that is significant for risk-reduction is to have a well-trained crew that knows how to handle the situation if the GNSS-position gets inaccurate. A well-trained crew will also detect changes and discrepancies for the position at an early stage, which is key to avoiding the situation from developing into a hazardous situation where the vessel and its crew are put in danger.

5.2.6 Freezing of GNSS-position (2.3)

Freeze of GNSS-position is a situation that can occur if the receiver does not get signal from the satellites. This can mainly be induced by to types of failures, being internal failure for the GNSS-receiver or problems with the antenna. The main antenna-related problem in polar areas is icing. If the receiver is incapable of getting a signal from the antenna, then the position will freeze. This means that the GNSS-position will not change even though the vessel is moving. This will not give an alert in the ECDIS-system, since the system still will have GNSS-input. The key to detect this problem at an early stage is vigilant navigators that pays attention to the GNSS-receiver and the ECDIS-system. The problem can easily be detected on the ECDIS-screen, as the ownship-vector is depending on information from the GNSS-receiver. This means that no vector will be displayed if the GNSS-position is frozen even though the vessel has a speed in a given direction.

5.2.7 Gyro failure (2.4)

Failure for the gyro compass is a situation that very rarely occurs. The gyro-compass is maintenance-free, and is controlled during surveys of the vessel. IMO also has requirements regarding redundancy for gyro-compasses. The consequence of a gyro-failure can be significant, as the gyro-compass is the main source for heading information both directly to the navigators and to navigational systems such as the ECDIS. This consequence can be reduced by the use of redundancy from both multiple gyro-compasses and magnetic-compass. It is also important that the crew is familiar with the process of changing input sources to different navigational systems such as ECDIS and Radar/ARPA. This can be done through simulator exercises, where different sensors can be taken out, leading to the navigators having to choose which input to rely on, and then make sure this input is used for all relevant systems. If redundancy is implemented and the crew is well trained, the risk connected to gyro-failure can be set to an absolute minimum.

5.2.8 Gyro inaccuracy (2.5)

Gyro inaccuracy on high latitude is a well-known problem that will occur if the circumstances is right. This means that the probability of experiencing inaccuracy in gyro-course is very high when operating on high latitudes. If not compensated for, this will lead to wrong input to essential navigational systems such as ECDIS and autopilot. It will also provide the navigators with the wrong course, as the gyro-compass is the main source for heading-information. The good news regarding gyro inaccuracy is that the error easily can be compensated for, either manually by the use of formulas or tables, or the gyro-compass could have a built-in function that automatically compensates for the error. The inaccuracy can also be significantly reduced if more advanced gyro-compasses is used, e.g. fibre-optic gyro-compass or ring-laser gyro. Another alternative is to use a GPS-compass, but then the risks connected to the GNSS-systems have to be considered. Independent of which technique that is used, it is important to have a competent crew that have knowledge in how to detect and quantify the inaccuracy, and then knows how to compensate for it. Then the possible consequence will be reduced to very low, and the risk can be set to low.

5.2.9 Magnetic compass failure (2.6)

Failure of the magnetic compass is something that very rarely occurs. The magnetic compass is a stand-alone system independent of external power-supply. The magnetic compass has no movable parts except from the compass-needle. This means that it very little chance of any mechanical failure for the magnetic compass. The only known source to failure except from mechanical failure to the compass-needle is freezing of the fluid in the compass-bowl. This will only occur if the fluid in the compass-bowl is replaced by water. The consequence of a magnetic compass failure is also very low, as the magnetic compass mainly is used as redundancy and therefore only has a standby-function at normal operation. Since both probability and consequence is set to very low, no risk reducing measures is necessary.

5.2.10 Magnetic compass inaccuracy (2.7)

The magnetic compass is an inaccurate instrument. It is mainly due to the large amount of inaccuracies for the magnetic compass that the gyrocompass is used as the prime source for heading information. The main factors affecting the magnetic compass is magnetic deviation and magnetic variation. These two factors will always be present, and they will not be constant, meaning that the compass will have to be calibrated with regular intervals. Between the calibrations the compass will become more and more inaccurate. Another factor that makes these errors challenging is that they vary both geographically/for different courses and over time. This means that even though the errors can be compensated for, both manually and automatically, the compensation factor will have to be adjusted after some time. The consequence of this inaccuracy is set to very low, as the magnetic compass mainly is used as redundancy and therefore only has a standby-function at normal operation. The total risk can also be set to very low if the crew is competent and knows how to compensate for the errors if necessary.

5.2.11 Fatigue (3.1)

Fatigue is a very common human-factor related problem in all industries, but it is extra common in the maritime industry due to the watch-rotation that can interrupt the circadian rhythm of the workers. In the Polar Region, the risk of experiencing fatigue increases as the vessel may operate in nearly total darkness 24-hours a day when operating in wintertime. In the summer, the opposite situation occurs with total daylight 24 hours a day, which can worsen sleep-problems. Most navigators have experienced fatigue, and it is a situation which can be serious, especially if the navigator is alone on watch and is unaware of the fact that he/she is experiencing fatigue. The risk of fatigue is difficult to reduce to a wanted level, but it is important to take action so the risk is as low as possible. Such actions could be working hours adjusted, or extra crew on watch. The best way to reduce the risk is to have a well-trained crew, both physically and mentally. Through simulator exercises, the crew can develop techniques for detecting, and even better avoiding fatigue.

5.2.12 Complacency (3.2)

Navigating in the polar areas can be very challenging and exciting, but it can also be long and uneventful periods. Under such periods, it is quite easy for navigators to develop complacency. This can be very dangerous, as one of the key characteristics regarding polar conditions is how quickly they change. It is therefore of high interest to have vigilant and focused navigators that are able to detect hazards at an early stage. The most efficient way to reduce this risk is attitude forming of the personnel, in addition to making the working-day as productive as possible even though the level of action is low.

5.2.13 Inadequate technical knowledge (3.3)

When performing maritime operations under polar conditions, the crew often have to make use of special equipment which is rarely used in other operations, e.g. ice-radar. This means that the navigators may be unfamiliar with the use of the equipment which can lead to increased response time and, in a worst-case scenario, wrong use of the equipment that results in a grounding/collision. As always, training of personnel is a key factor to reduce the risk. By the use of simulator training, navigators can familiarize themselves with advanced equipment and systems, and be instantly ready to use them when required in real-life. In addition to training, the use of checklists and standard procedures will help the navigators to remember what to do in stressful situations. If these risk-reducing measures is implemented, the risk of accidents connected to inadequate technical knowledge of equipment and systems can be set to very low.

5.2.14 Poor equipment design (3.4)

Poor equipment design has been a contributing factor in many accidents in maritime operations. When considering maritime operations in the arctic, it is mainly two types of errors that is connected to poor equipment design. The most common is light-pollution, either from equipment installed by the shipyard under the building-process or from equipment installed by the crew afterwards, e.g. coffee-makers etc. The other common type of poor equipment design is that vital equipment is placed in unsuitable places. Some equipment, such as the ice-radar, are for some vessels very rarely in use. It is therefore possible that this equipment is given a lower priority when it is installed. The problem is that when the equipment is needed, it is often used together with other navigational equipment, which was given a higher priority under the installation. This can lead to misunderstandings and miscommunication which can lead to grounding/collision. This risk can be eliminated if the users are included in the building process at an early stage, as they have the best knowledge when it comes to how the bridge-environment should be. If the equipment already is installed, the best way to reduce the risk is to train the personnel so that they can compensate for the eventual limitations induced by placement and installation of equipment. If these actions are taken it is possible to reduce the risk to very low.

5.2.15 Decisions based on inadequate information (3.5)

It is a common source of error that personnel make decisions based on information from sources they are familiar with, without making sure that the information actually is correct. These types of error is connected to complacency, if something looks correct it is no need to make sure that the information is correct, if something worked last time it will probably work this time and so on. It is difficult to reduce this risk, but with the use of attitude forming and checklists to make sure that all relevant information is considered, it can be reduced to an acceptable level.

5.2.16 Poor judgement (3.6)

Just like decisions based on inadequate information, poor judgement is a human error that is very difficult to prevent. It will happen from time to time regardless of how competent and skilled the crew is. Poor judgement is strongly connected to other kinds of human errors such as fatigue and complacency. If risk-reducing measures is implemented in connection to these kind of human errors, it will have an effect also on the risk of accidents caused by poor judgement. Other factors that can result in poor judgement is lack of information and lack of experience. The latter is possible to prevent by implementing simulator training before taking part in real life operations.

5.2.17 Faulty standards, policies and/or practices (3.7)

Operation in polar areas demands extra equipment, extra training and extra competency. This leads to extra expenses. This is a problem in a market where the economic situation is challenging and the “profit first-thinking” is normal. Regulations from the authorities has made it difficult for the companies to operate in an unsafe manner, but it is nevertheless a fact that some companies are willing to take risks to gain a higher profit. This risk can only be reduced by attitude forming which have to start on the top and be implemented through the companies down to each crewmember on each vessel. If this task is taken seriously, and combined by audits from the authorities, it is possible to reduce the risk to an acceptable level.

6 Simulation of polar operating conditions

The main aim for this thesis is to identify how simulator exercises can be used for assessing and analysing situations and factors that can be a hazard to the vessel. It is preferable to assess situations in a simulated environment as a first step in a total risk assessment. It is possible to simulate situations that would be impossible to construct in real life due to safety and economic factors. In order to use simulator exercises in an efficient way it is necessary to make sure that the simulated situations are comparable to the real-life situation that the exercise is trying to analyse. In this chapter the simulation of different situations that could lead to hazards for the vessel is discussed, and in the end different means for improving the simulation of polar operational conditions is suggested.

6.1 K-sim Navigation

When discussing simulation of polar conditions in this thesis, it is related to simulation by using the K-sim platform from Kongsberg Maritime. This is mainly due to that it this is the available tool for simulation at UiT. Everyone involved with the simulation chapter of this thesis have experience with the K-sim platform, and is thereby able to make use of the different features available for the platform. Simulation of polar operating conditions can be achieved through other suppliers than Kongsberg, but it is safe to say that Kongsberg is one of the leading actors in the market for simulation of maritime operations. K-sim Navigation is also a new platform that has replaced the earlier K-sim Polaris. K-sim Navigation uses a new advanced physical engine along with state-of-the-art hydrodynamic modelling that allows vessels, objects and equipment to behave and interact as in real life (Kongsberg Maritime, 2018). This is important for simulation of vessel movement in ice. In addition, Kongsberg states that "Vessels and objects including various geographical training areas and all possible weather conditions are brought to life with a sophisticated new visual system." (Kongsberg Maritime, 2018). This is key to simulating operational conditions which is as realistic as possible.

6.2 Failures and inaccuracy for equipment

Failures and inaccuracy for vital navigational equipment is a vital challenge for navigation under polar operating conditions. Equipment that are normally seen as nearly maintenance-free and almost always reliable, such as Gyro-compasses and GPS can be strongly influenced by polar conditions. In this chapter, some of the main operational limitations for vital navigational equipment will be discussed, and how it can be simulated for preparation and development of risk-reducing measures for operation in polar areas.

6.2.1 GPS

Today, GPS and other satellite-based positioning system is the main source for determination of the vessels position. The focus will be pointed towards GPS, as this is the only possible satellite-based positioning system available for simulation on the K-Sim-platform. Other systems, such as GLONASS, GALILEO and BEIDOU will have the same challenges and limitations under polar conditions although having differences in the structure of the systems. For GPS, it is mainly two different kind of challenges related to operation under polar conditions. The first and most common is reduced accuracy due to bad satellite-geometry. This can be simulated as an offset for the available GPS-position. It is also possible to simulate offset in position for the differential positioning system. These kind of errors can be difficult to detect for the users, as the availability of other measures for positioning is limited. It can therefore be of interest to assess if navigators detect this kind of errors, and how they respond in order to compensate for the inaccuracy.

The other challenge that can occur is loss of GPS-position due to icing on the GPS-antenna. This can be simulated through failure for the GPS-receiver, and the user will then be alarmed that no position is available. This error is less common, as heating of antennas is a requirement in the Polar Code. In addition, antennas are often being placed under sheltered conditions.

To summarize, the different available failure modes regarding GPS for the K-Sim simulating tool are presented:

- Failure for the differential positioning system, DGPS. This will lead to a decrease in positioning accuracy if the corrections from the differential system is reliable
- Failure of the WAAS-system (Wide Area Augmentation System). WAAS is a satellite based differential positioning system that increases the positioning accuracy for the GPS-system.
- “Freeze-failure”, where the GPS-position freezes.
- “Defect-failure”, where the GPS-receiver is defect and no GPS-position is made available for the user.

All the failures mention above are incidents that occur from time to time, and can be challenging for the navigational officers to detect and manage. However, the failures are not especially related to operation under polar conditions. DGPS, for instance, is rarely available in the polar region, and the risk of the GPS freezing is not higher under polar conditions than under normal operations. Icing on the antenna can lead to lack of available GPS-position, which can be simulated through the use of the "Defect-function" in the K-Sim platform.

The most interesting failure modes from a polar point of view is the possibility of simulating inaccuracy for the GPS-position presented to the user. This is done through manipulation of the latitude and/or longitude values. The different manipulation methods are presented below:

- Fixed failure, meaning that the latitude/longitude is locked to a certain value.
- Oscillating error, inducing an error in position that varies with time. Input values for this error are amplitude and period.
- Offset error, inducing an offset for the latitude/longitude value.
- Drift error, inducing an error in position that increases with time until a certain limit. The limit is set by the instructor.
- Noise error, inducing noise that interferes with the GPS-signal. Can be used to simulate electromagnetic radiation.
- Manipulation of dead band and hysteresis width. Will not be discussed further due to low significance for the situations analysed in this thesis.

6.2.2 Gyro Compass

Gyro-compass is the main source for determination of vessel course. Failure and/or inaccuracy in gyro-course is therefore a significant challenge when navigating the vessel. The available failure modes for the gyro-compass are listed below:

- Oscillating error, inducing an error in heading that varies with time. Input values for this error are amplitude and period.
- Offset error, inducing an offset for the heading displayed to the user.
- Drift error, inducing an error in heading that varies with time until a certain limit.
- Noise error, inducing noise that interferes with the gyro-heading. This leads to a disturbance in the heading displayed for the user and for the systems using the gyro-heading as input, such as ECDIS.

In addition to these failure modes, the K-sim platform includes an option called “Gyro correction”. This option makes it possible to automatically compensate for different kind of errors, e.g. the speed-/latitude-error mentioned in chapter 2.1.2.

6.2.3 . Magnetic compass

Magnetic compass is mainly used as redundancy for heading information. The magnetic compass has two types of errors, magnetic variation and magnetic deviation. The available failure modes for the magnetic-compass is listed below:

- Magnetic variation, measured in degrees.
- Magnetic deviation, measured in degrees. Input values are degrees and heading (N, E, S, W)

6.3 Climatic Conditions

It is possible to simulate various kinds of climatic conditions on the K-sim platform. In this chapter, the available modes for simulation of different climatic conditions, such as weather and ice conditions, are discussed.

6.3.1 Simulation of weather conditions

Simulation of different weather conditions is important for making simulator exercises that are as close to real-life situations as possible. The K-sim platform offers various settings for simulation of weather conditions. A summary is given below:

- A very important factor for simulation of weather conditions is the possibility for simulation of wind. This can be done directly by inserting values for direction, given in degrees, and speed, given in knots. It is also possible to implement an automatic change in wind conditions over a given time. If special wind conditions are wanted for a specific area, it is possible to establish a local wind polygon, where the applied wind conditions only will be present inside the polygon. If a special type of variation in wind conditions is wanted, the K-sim platform also offers the possibility of using wind-spectrums in the exercises. As a special feature regarding wind conditions, it is also possible to simulate gusts. It is then necessary to insert values for direction and speed also for the gusts. When discussing air conditions, it is also possible to adjust the values for temperature, humidity and air pressure (barometer).

- Another factor that needs to be considered when creating simulator exercises is the properties for the sea. The most interesting factor to simulate regarding this matter is current, which can be simulated by inserting values for direction, in degrees, and speed, in knots. As for air, it is possible to adjust the temperature for the seawater. It is also possible to change the colour of the sea. As for the wind conditions, it is possible to simulate current for a specified area by the use of a local current polygon.

- Probably the most important factor for simulation of weather conditions is the possibility to simulate waves. This can be done in three ways. The first choice is by using the “Auto” function, where the program itself simulates a realistic wave-condition that is connected to the simulated wind situation. The other possibility is to use the “Wind waves and swell” function. This gives the user the possibility to adjust the wave-conditions as wanted. The wind generated waves is connected to the chosen wind-conditions, but it is possible to adjust the age of the waves, meaning for how long the waves has had to build up energy. The age is given in percentage between 0-100%. For swells it is possible to adjust height in meters and direction in degrees in addition to age. The last possible choice for simulation of a wave-condition is to use a wave-spectrum. As for wind and current, it is possible to create a local wave polygon for simulation of waves for a specified area.

- The last important factor for simulation of weather conditions is the possibility of simulation of precipitation. This is important since it affects the visibility, which is one of the key challenges for navigators. Precipitation is dependent of clouds, and for the K-sim platform, four different types of clouds is available for simulation. This is nimbostratus, altostratus, cirrus and cirrostratus. It is also possible to adjust the cloud density, which is given in percentage from 0-100%. The possible versions of precipitation are rain, hail, fog and snow, all given in percentage from 0-100%. It is possible to create local polygons for each type of precipitation if it is wanted for a specified area.

6.3.2 Simulation of ice conditions

The K-sim platform has a various amount of available ice conditions for simulation of different operations. The simulation of ice has mainly two features, a visual element and a physical element that affects the movement of the vessel. The different types of ice available for simulation is shown below, with print screens from the K-sim Navigation simulator showing the visual view and the radar image for each ice-condition.

- Sludge ice, which is ice that is not yet frozen to solid ice, but is in an early stage of freezing. Sludge ice is like a viscous fluid, but it is usually not more than 30 cm thick. It does not affect the movement of the vessel much, although it can freeze to solid ice over a short period of time. This can lead to the vessel getting stuck. Voyage through sludge ice can be very useful as a simulator exercise as it is a situation that most vessels operating in polar areas can be exposed to. Heavier ice conditions are most relevant for ice breakers and convoy-operations. Visual scene and radar-image for sludge ice are shown in figure 7 and figure 8.

Figure 7 Sludge ice, concentration 5/10, thickness 0.1m

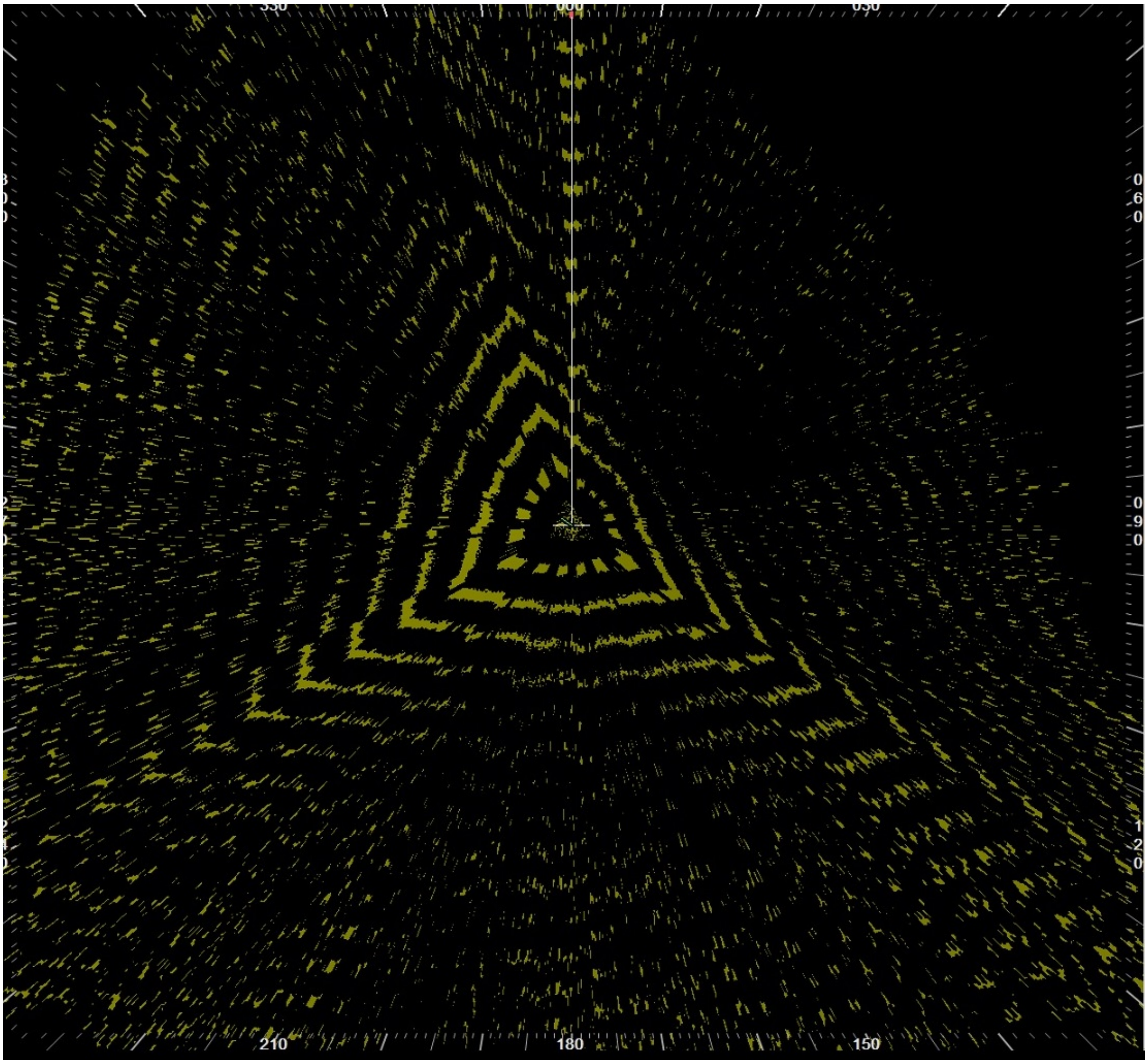


Figure 8 Radar image Sludge ice

- Pancake ice, which is circular pieces of ice with diameter from 30 cm to 3 m. The thickness is up to 10 cm. Visual scene and radar-image for pancake ice are shown in figure 9 and figure 10.

Figure 9 Pancake ice, concentration 5/10, thickness 0.1m

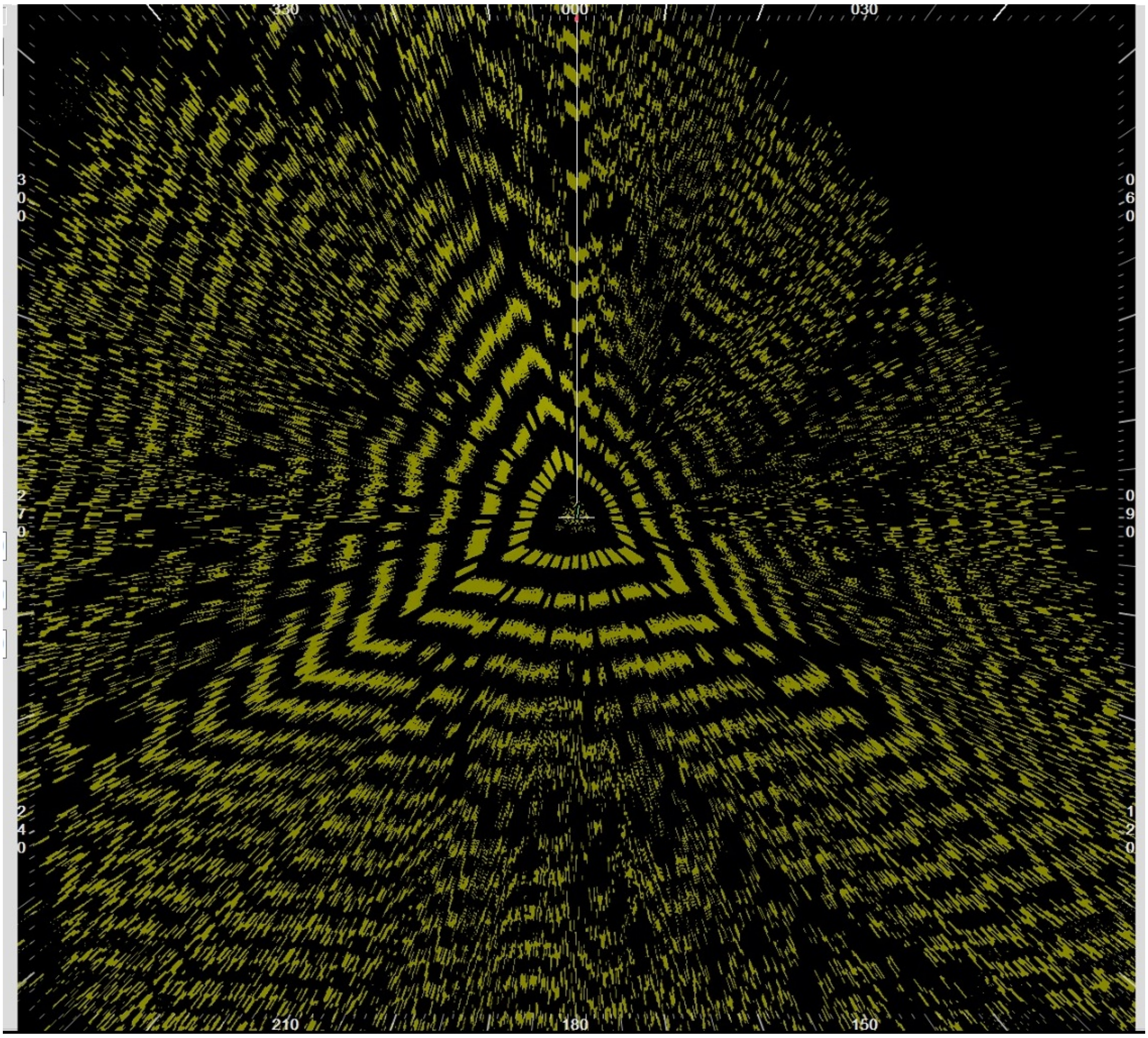


Figure 10 Radar image Pancake ice

- Solid one-year ice, which is solid ice from the current season. The thickness vary from 0.3 m to 2 m. This is the ice-conditions which most vessels want to avoid without icebreaker assistance. Visual scene and radar-image for solid one-year ice are shown in figure 11 and figure 12.

Figure 11 Solid one-year ice, thickness 0.3m

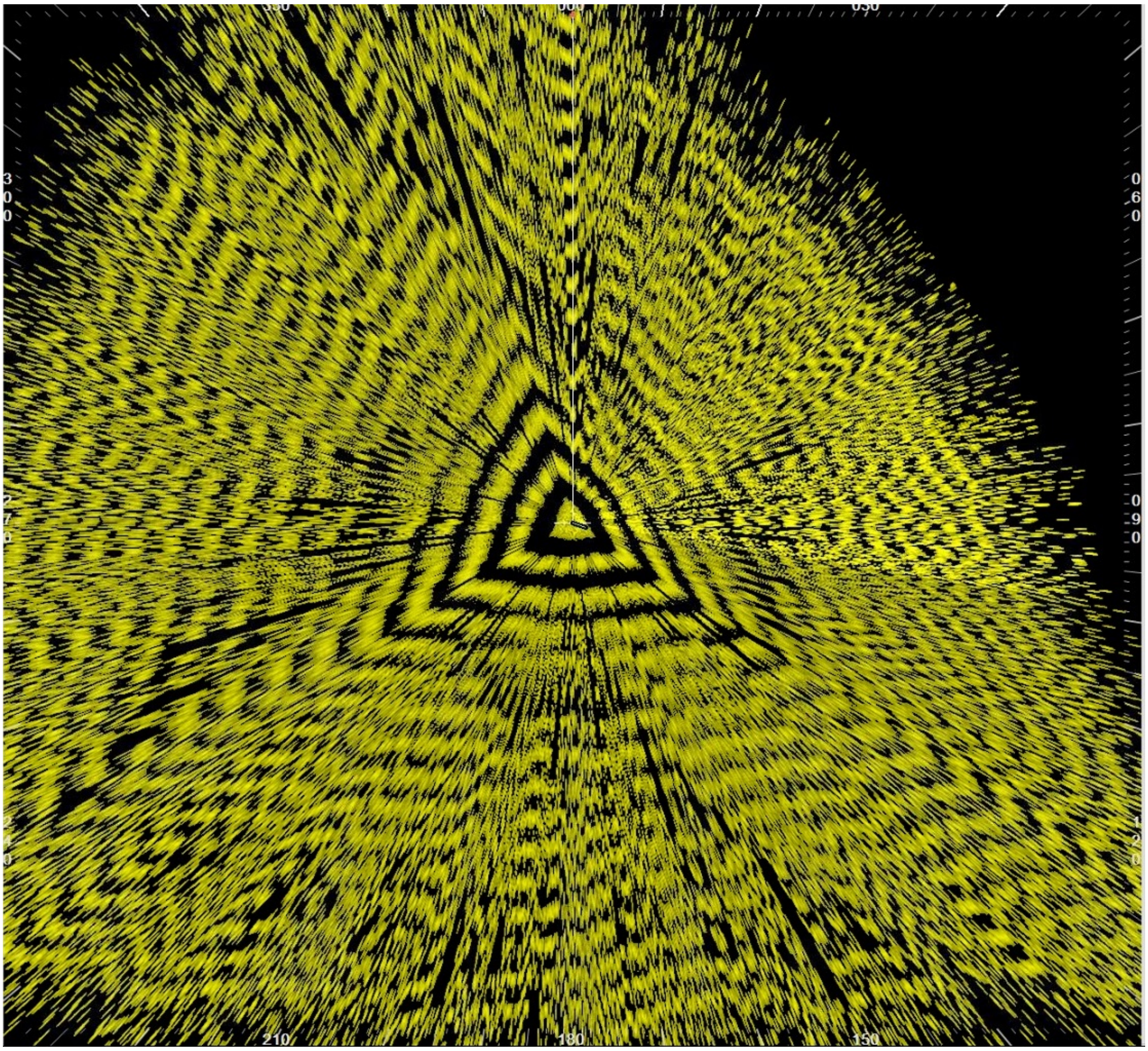


Figure 12 Radar image Solid one-year ice

- Solid multiyear ice, which is solid ice that have survived multiple seasons. It is harder than one-year ice due to the fact that it contains less brine than first-year ice. Voyage in multiyear ice is preferably avoided, even for icebreakers. Visual scene and radar-image for solid multiyear ice are shown in figure 13 and figure 14.

Figure 13 Solid multiyear ice, thickness 1.0m

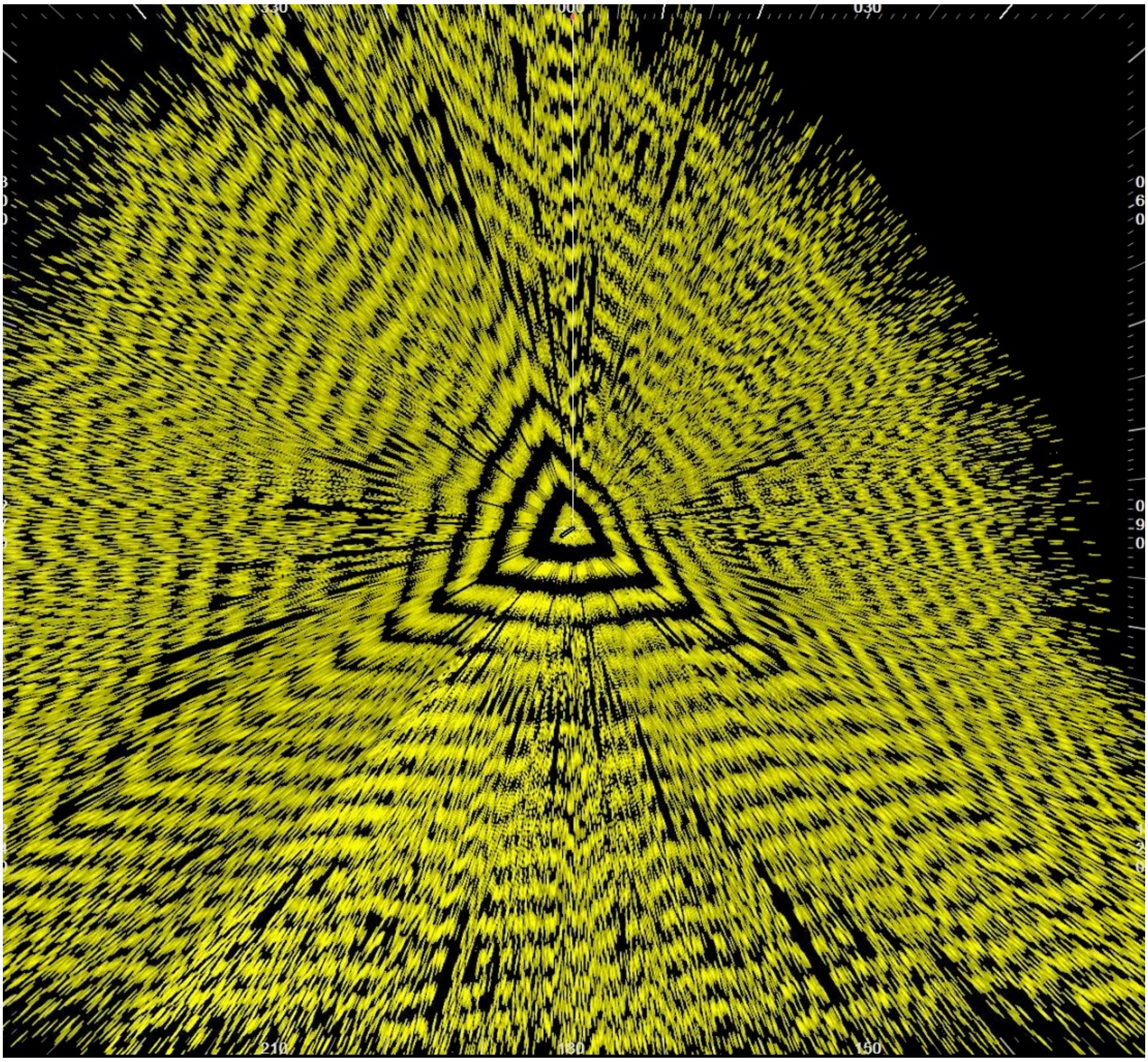


Figure 14 Radar image Solid multiyear ice

- Hummocked ice, which is solid ice that is exposed to pressure and thereby are broken up and placed on top of each other. This forms an uneven surface that looks like hillocks. Visual scene and radar-image for hummocked ice are shown in figure 15 and figure 16.

Figure 15 Hummocked ice, concentration 8/10, medium average floe size, thickness 1.0m

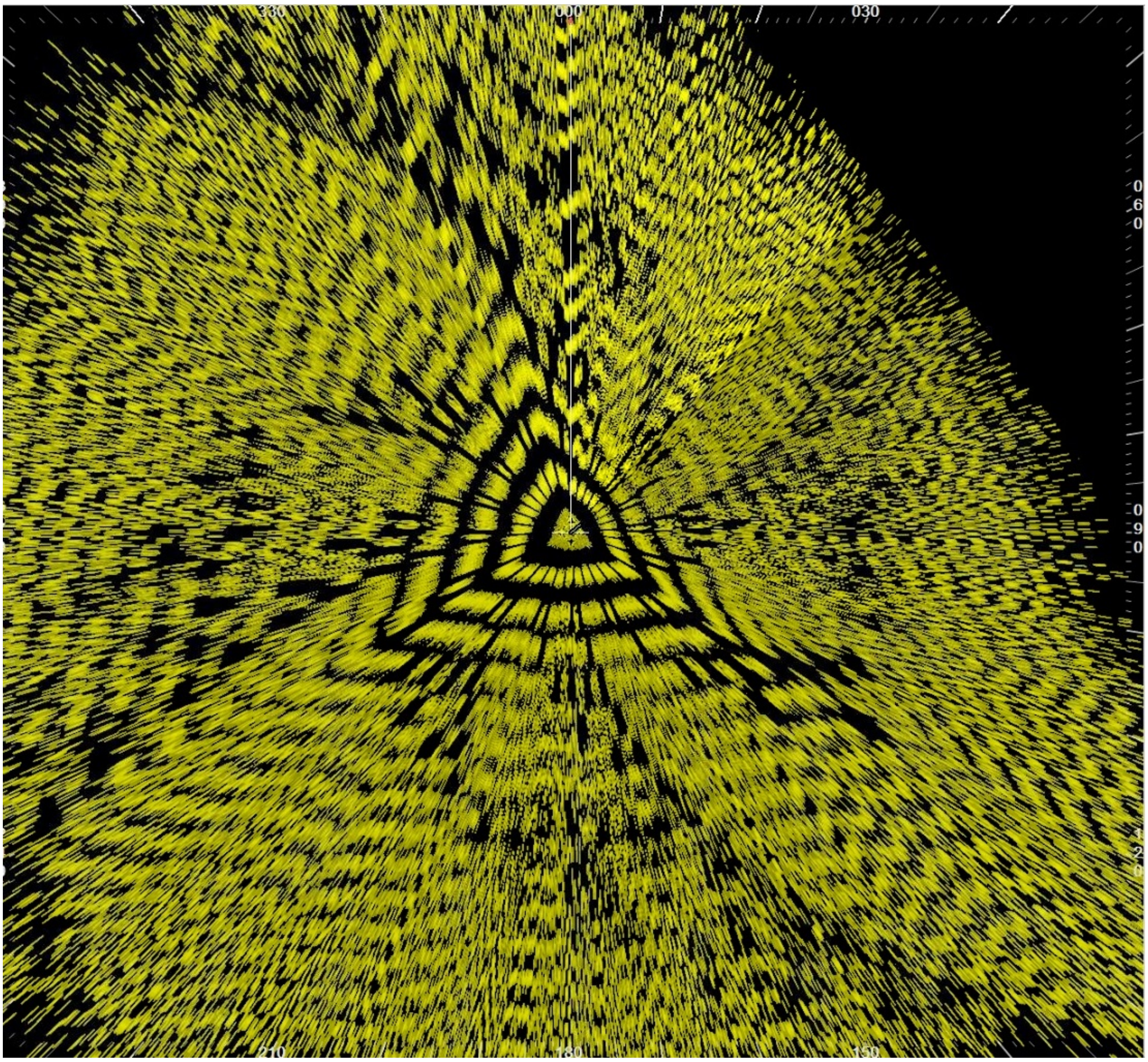


Figure 16 Radar image Hummocked ice

After the type of ice to simulate is chosen, it is possible to adjust the ice-conditions by the use of four parameters:

- Concentration described by a value from 1-10, where 1 is very low concentration of ice and 10 is very high. This parameter is only available for pancake-, sludge- and hummocked-ice. For solid ice, it is not possible to adjust the concentration, as the concentration is a measure of the amount of ice in open water.

- Average floe size described by the use of small/medium/large floe size.

- Thickness, measured in meters.

- Compression speed, measured in meters per hour.

By the use of these available modes for simulation of ice, it is possible to simulate a generic ice condition that varies with time and position. The visual aspect of the simulation is quite good, it is possible to detect different ice-conditions only by the use of visual means. If the simulated environment is modelled in accordance with an ice-chart that is made available for the navigators, it is possible to train both on the preliminary planning before a voyage in ice, and thereafter execute the planned voyage.

The K-sim platform has one main disadvantage related to simulation of ice, and that is the radar-image for detection of and navigation in ice. It is difficult to categorize which type of ice that is present by the use of radar. There is also no available application on the K-sim platform at this time which can simulate the use of ice-radar. This can be solved by the use of video from rea life ice-radars. The exercise can then be created in accordance with the video from the ice-radar. To collect ice-radar video for different situations and ice-conditions is a time-consuming process, not to mention the process of fitting the simulator exercises to the video footage. As a result of this, it is necessary to build-up the simulator exercises in such a way that radar is not the prime source for ice detection and characterization.

In addition to the ice-conditions mentioned above, it is also possible to simulate icebergs. Icebergs is one of the most dangerous obstacles a navigator can run into. Icebergs can be very difficult to detect, as only 10% of the icebergs are visible above the sea-surface. it can also be difficult to determine the extension of the part of the iceberg under the sea-surface, meaning it is a risk of collision with the iceberg even with a long passing distance to the visible part of the iceberg.

For the K-sim platform, three types of icebergs are available. The icebergs are modelled as targets, meaning that it is not possible to adjust the properties for the icebergs, as opposed to the sea ice. The types of icebergs available for selection when creating an exercise:

- Iceberg 12, which is a large sized iceberg with a weight of 400000 tonnes. The length is 110 meters and the width is 61,20 meters.

- Iceberg 13, which is a medium sized iceberg with a weight of 36000 tonnes. The length is 30 meters and the width is 20 meters.

- Iceberg 14, which is a small sized iceberg. Both the length and the width are 3 meters. This type of iceberg can be used to simulate so-called growlers, which can be a very dangerous threat to a vessel as it can be extremely difficult to detect and yet have a large potential of damage.

For ice-breaking operations, the K-sim platform has two extra features for adjustments of the ice-conditions, so called ice breaking factors. These are “crushing factor” and “friction factor”. This adjust the properties for the ice that is to be broken. This is a special feature that will not be discussed in detail.

How the vessel movement is affected by the ice is not discussed further in this thesis, as this is strongly dependent of the vessel characteristics. This thesis is not related to operations for a specified vessel or type of vessel. Assessment on how the ice affects vessel movement has to be done in cooperation with a navigator with thorough knowledge of the vessel being modelled in the simulator exercise.

6.4 Feedback from experts regarding simulation of ice-conditions

To support the findings collected during the testing of the ice-conditions, feedback regarding the simulation of ice-conditions were collected during a Polar Code certification-course at UiT in week 22. The participants on this course were Norwegian pilots who are piloting in the waters around Svalbard. The pilots participated in a standard simulator exercise for certification courses for the Polar Code at UiT. The exercise included several different types of ice including icebergs. After the simulation exercise, two of the pilots shared their thoughts regarding the simulation of ice. Their opinions are:

- In general, the simulated environment is realistic and close to the real life scenario.
- The visual factor is good, but in real life it is easier to assess the thickness of the ice. In the simulator exercise, it was difficult to detect which ice that was too thick to pass through.
- The radar-image is not so indistinct compared to a real life radar. It can nevertheless not be compared to an ice-radar.
- For training of personnel that are intended to operate in the waters around Svalbard, it will be very useful to participate in a simulator exercise with sludge ice with elements of small icebergs and growlers, as these are normal operating conditions around Svalbard.
- The use of simulator exercises can absolutely reduce risk compared to having unexperienced personnel training in real life situations.

The abovementioned factors is important to keep in mind when designing exercises for use as a risk-reducing measure. The eventual weaknesses for the simulated environment can to some degree be compensated for when designing the exercises.

7 Conclusions and suggestions for further work

The preliminary hazard analysis performed in chapter 4 shows that simulator training can contribute in reducing the risk for most of the hazards that is found to be a threat in polar operating conditions. Especially when it comes to human error, which is the main source of error in the maritime industry, simulator training is found to be one of few effective ways in reducing risk. For more technical types of errors, such as equipment failure, simulator training is found to be useful, but then as an addition to conventional risk reducing measures such as duplication of equipment, regular maintenance etc.

It is unquestionable that operation of vessels in the polar area is connected with high risk due to increased possibility for accidents to happen and increased consequences due to lack of infrastructure and harsh environmental conditions. A vessel operating in these areas without preparation and adjustments for such operations is not only breaking the law. It is also operating under a risk level that exposes the vessel and crew for immediate danger that can result in loss of lives and materialistic values. The preliminary risk analysis shows that the risk can be reduced to an acceptable level if mitigation measures is implemented.

Now, the next step would be to develop simulator exercises that can be used as a risk-reducing measure before operation in polar areas. These exercises would have to be assessed by experts on the field that has experience with operations under such conditions to make the simulated environment as close to real life as possible. It may then be necessary to adjust the preliminary hazard analysis, as some of the simulated situations may not have the intended effect on the risk. The preliminary hazard analysis would however be a useful tool for development of the initial simulator exercises.

Regarding the technical part of the simulation, the main finding when trying out the different features regarding simulation of polar operating conditions is that K-sim platform experiences some problems when it comes to simulation of radar-image in ice. It would therefore be interesting to investigate if it is possible to implement real-life radar images as a part of the simulator exercises. This is something that has to be considered when developing the simulator exercises.

Otherwise, the K-sim platform is found to be realistic when it comes to ice, especially the visual part. This is further strengthened by the feedback from the Norwegian pilots, who have experience from operations in polar waters. The level of realism is however something that have to be assessed through the initial simulator exercises before it is possible to determine how close to reality the simulator exercises can be. The level of risk-reduction through simulator exercises is strongly dependent on the realism in the exercises.

The main suggestions for further work:

- Development of general simulator exercises to be used as a risk reducing measure for operation in polar areas.
- Quality assurance of the exercises through feedback from experts on the field with experience from such conditions.

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