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MASTER THESIS

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Simulator Studies on the Effectiveness of a Collision Avoidance Display in True Motion	
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Abstract

A major concern for the navigator during a voyage is collision avoidance. The IBS (Integrated Bridge System) has a large quantity of marine traffic data available. Complicated and congested traffic may challenge the navigational safety. It is of vital importance that the navigator is equipped with the necessary tools to be able to do a fast assessment of the situation. Visual observation, ARPA and AIS are the main information sources today. The introduction of a collision avoidance display that focus on real-time presentation of danger areas in true motion enables the navigator to judge collision risk for any acquired target and simultaneously identify suitable evasive manoeuvres. The simulator study focused on evaluating two collision avoidance displays, CDP (Collision Danger Presentation) and RTM (Room To Manoeuvre) versus standard ARPA. In addition CDP versus RTM was evaluated. The subjects consisted of experienced navigators from the Royal Norwegian Navy and final year marine cadets from the Royal Norwegian Naval Academy. The study was conducted on a full mission bridge simulator by three trial scenarios with increasing difficulty level. The evaluation was based on descriptive methods and parametric tests. A reflection on making decisions in collision avoidance is given in the thesis. The excellence of both collision avoidance displays was proven, where the major benefit was reduction in reaction time. Between the populations it was found that the cadets benefitted from the collision avoidance displays in both the simple and the congested scenario, whilst the experienced navigators mainly improved their performance in the congested scenario. The evaluation of CDP versus RTM indicated that the CDP display was preferred. As for the collision avoidance tools existing today, the CDP does not take into account the COLREGs. This aspect is, and will in the nearest future, be the navigator's task to incorporate in his choice of evasive manoeuvres.

Proposals for improvement of the beta version the collision avoidance display are given in the end of the document.

Keyword:	Advisor:
Collision Avoidance	
Simulator trials	Prof. Egil Pedersen and Co-advisor Dr. Kensuke Kirimoto
COLREG	

MSc THESIS IN NAUTICAL SCIENCE

SPRING 2011

FOR

STUD. TECHN. Ruben Grepne-Takle

Simulator Studies on the Effectiveness of a Collision Avoidance Display in True Motion

Ship-ship collisions have the potential to cause serious maritime accidents with human casualties and environmental damage. Collision avoidance is a major operative task for the Officers of the Watch (OOW). Large volumes of marine traffic data are available from the shipboard ARPA and AIS systems. However, complicated and congested traffic conditions may cause workloads and stress that challenge navigational safety. Of paramount importance are therefore the quality and availability of anti-collision information and how the OOW process, understand and use this information.

A collision avoidance display that focuses on presenting exact collision danger regions in true motion, according to a suitable target selection procedure from the viewpoint of own ship, was presented in the candidate's project thesis. The display enables collision risk to be judged to any acquired target in true motion and simultaneously identify feasible evasive manoeuvres.

This thesis shall investigate the effectiveness of the display by extensive simulator studies with expert mariners and non-experienced maritime students as subjects. The work requires that the algorithms of the display method, as developed and programmed by the candidate in the project thesis, are implemented on the POLARIS full-mission ship handling simulator at the Royal Norwegian Navy Academy. The work will require assistance by the manufacturer of the simulator, Kongsberg Maritime AS.

The work shall include, but is not limited to, the following:
- Implementation and validation of the collision avoidance display on the POLARIS simulator platform.
- Development and testing of scenarios that enables identification of the advantages/ disadvantages of the display versus standard ARPA functionality.
- Planning and execution of test programmes on the simulator.
- Evaluation of the test results according to scientific procedures.
- Proposals for any improvements of the collision avoidance display.

It is a main objective with this MSc thesis that it shall result in proposals for improved knowledge and training of maritime students in the field of collision avoidance.

In the thesis the candidate shall present his personal contribution to the resolution of problem within the scope of the thesis work.

Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The plan should include a budget for the use of computer and laboratory resources that will be charged to the department. Overruns shall be reported to the supervisor.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The project shall be submitted in two copies:
- Signed by the candidate.
- The text defining the scope included.
- In bound volumes.
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- As pdf file.

Supervisor   : Professor dr.ing. Egil Pedersen, Department of Marine Technology, NTNU
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Start   : 17th January, 2011
Deadline   : 11th June, 2011

Trondheim, 17th January 2011

Egil Pedersen

MASTER THESIS IN NAUTICAL SCIENCE
SPRING 2011
FOR
Stud.techn. Ruben Grepne-Takle

Simulator Studies on the Effectiveness of a Collision Avoidance Display in true Motion

Preface

This thesis is submitted in fulfillment of TMR 4925 Nautical Science master thesis, which is a compulsory part of the international MSc program in Marine Technology Nautical Science.

The topic chosen comes from my background as a Master Mariner and an interesting lecture in "Nautical Science Basic Course". As a navigator and master I have personally experienced the challenges of collision avoidance in various settings. The work in my project thesis (Grepne-Takle, 2010) forms the basis for the master thesis. In the project two core algorithms were developed. These were incorporated in a full mission simulator to study the effectiveness of a Collision Avoidance Support System (CASS) in collision avoidance scenarios. By this work I hope to contribute to improved knowledge and possible solutions in the field of collision avoidance.

Innhold

NOMENCLATURE LIST

AIS   Automatic Identification System

ANOVA   Analysis Of VAriance

ARPA   Automatic Radar Plotting Aid

CASS   Collision Avoidance Support System

CDP   Collision Ranger Representation

COLREG   International Rules for the Prevention of Collisions at Sea 1972

CPA   Closest point of approach

CPAlim   CPA limit

DCPA   Distance to Closest Point of Approach

EBL   Electronic baring Line

IBS   Integrated Bridge System

IMO   International Maritime Organisation

Lpp   Length between perpendiculars

NASA – TLX   National Air and Space Administration Task Load Index

NM   nautical miles (1nm=1.852 kilometers)

OOW   Officer Of the Watch

OS   Own ship

PPC   Potential Point of Collision

PPI   Plan Position Indicator

RTM   Room to Manoeuvre

SD   Standard Deviation

SOLAS   Safety Of Life At Sea

TCPA   Time to Closest Point of Approach

TGT   Target

TS   Target ship

TTC	Time To Collision
VHF	Very High Frequency radio
Vmax	Own ship maximum speed
VRM	Variable Range Marker
WGS 84	World Geodetic System from 1984
WP	Way Point
XTD	Cross Track Deviation

1 Introduction

1.1 Background

Navigation is a process that depends crucially on the navigator's knowledge, experience and judgement. A collision can potentially cost human lives, cause pollution and loss of money. Collision should theoretically be avoided if every vessel abided by the International Rules for the Prevention of Collisions at Sea 1972 (COLREG), which came into force in 1977. Study of collisions, groundings, contacts and near collisions reported to the Marine Accident Investigation Branch (MAIB) in the timeframe 1994 – 2003, revealed that the COLREGs were contravened to varying degrees on all the vessels involved in collisions (MAIB, 2004). The most common contributory factors in all the collisions were poor lookout and poor use of radar. Technology has advanced with regard to radar and ARPA, and the number of crew on vessels has decreased in parallel with increased automation. The Officer Of the Watch (OOW) place more and more reliance on radar and ARPA to maintain lookout and to assess the risk of collision. Also many newer vessels are not even equipped with a gyro pelorus on the bridge with which to take a visual bearing. It is therefore disturbing that the OOWs on 73% (of 33 collisions (MAIB, 2004)) of the vessels involved in collision potentially contravened COLREG 7(b) or 7(c) (IMO, 1972)which state:

Rule 7(b) – proper use shall be made of radar equipment fitted and operational, including long range scanning to obtain early warning of risk of collision and radar plotting or equivalent observation of detected objects.

Rule 7(c) – Assumptions shall not be made on the basis of scanty information, especially scanty radar information.

This thesis will explore the effectiveness of a collision display in true motion versus standard ARPA functionality on radar.

1.2 Purpose of study

The problem a navigator meets in any potential collision situation is three questions:

1. Do I risk collision with any vessel in my vicinity?
2. Should I manoeuvre, if so when?
3. What are the possible alterations of course and /or speed, with regards to all vessels in the vicinity?

With the introduction of the IBS (Integrated Bridge System) the information load can be quite formidable. Acknowledging also that the OOW may be the sole lookout in daylight when certain measures are taken care of (STCW95, 1995), adding simple and easy to understand tools for the navigator is vital. In my project thesis (Grepne-Takle, 2010) I presented two alternative collision avoidance displays in true motion. ARPA is the standard electronic aid today for anti-collision purposes. This thesis will test the developed displays/methods versus each other and standard ARPA functionalities in a full-mission ship handling simulator. The main objective is mapping the potential of the displays as an aid to the navigator for collision avoidance assessment, and proposals for improved knowledge and training of maritime students in the field of collision avoidance.

1.3 Previous work

Pedersen et al. (2003) conducted "Simulator Studies on a Collision Avoidance Display that Facilitates Efficient and Precise Assessment of Evasive Manoeuvres in Congested Waterways". The study comprised conventional speed scenarios and high speed scenarios. In addition the Environmental Stress Model (ES-model) (Inoue, 1999) was used to quantify perceived stress on the subjects. The studies revealed that the collision avoidance display facilitated time-efficient and homogeneous decision-making and execution of precise and safe evasive manoeuvres. It appeared that the need for long-term experience for correct assessment of the collision risk and evasive manoeuvres could be significantly reduced compared to conventional judgement techniques. It was also revealed a risk of temptation to make frequent and minor course alterations, which contravene the COLREGs. In addition Pedersen et al. (2006) wrote a paper that summarized the development of an advanced visualisation-based system that enables collision risk to be predicted and evaluated to multiple targets on electronic chart systems. In addition Szlapczynsky (2009) writes about a system based on the same mathematical principles. He concludes that "The proposed solution is fast enough to be applied in the real-time decision-support system, where fast processing of the data concerning all targets is a necessity". (Szlapczynsky, 2009)

In my project work (Grepne-Takle, 2010) several collision avoidance systems where discussed and two selected system where thoroughly studied; Collision Danger Presentation (CDP) (Pedersen et al., 2003) and Room to Manoeuvre (RTM) (Degré and Lefèvre, 1981) . The core algorithms for the selected systems were developed and program specifications made. Kongsberg Maritime Simulation AS has implemented the core algorithm and enabled the visualisation on Polaris ships bridge simulator ARPA radar.

1.4 Present work

The contribution in this thesis is a study of the collision avoidance problem and different approaches to obtain a feasible solution. The emphasis of the study is to enlighten the challenges in a congested traffic scenario and describe how different presentation techniques on radar in true motion affect the navigator's ability to assess and decide when conducting evasive manoeuvring.

One of the main problems when constructing collision avoidance systems is to incorporate COLREGs, the environmental conditions, topography and hydrography. This work does not aim to solve this challenge. It is the visual presentation of the mathematical solution to the collision problem that is presented. The navigator is expected to incorporate the external factors in his cognitive reasoning when deciding a proper course of action.

2 Collision avoidance methods

When describing CDP and RTM the term DCPA (Distance to Closest Point of Approach) is introduced. The meaning is equal to the term CPA (Closest Point of Approach). DCPA is only a more precise description; it is the distance to the closest point of approach for an acquired target that is interesting, not the location. In the maritime world the term CPA is most commonly used, thus the term CPA will be used from chapter 3.

2.1 ARPA(Automatic Radar Plotting Aid)

In 1984 IMO (International Maritime Organisation) enforced the requirement that every ship above 10,000 gross ton must have ARPA. I addition the rules states that ships keel laid after 1st july 2002 above 300 gross ton must have a plotting device. Today almost all radar systems are being built with ARPA. Figure 1 is an example of a typical PPI (Plan Position Indicator)
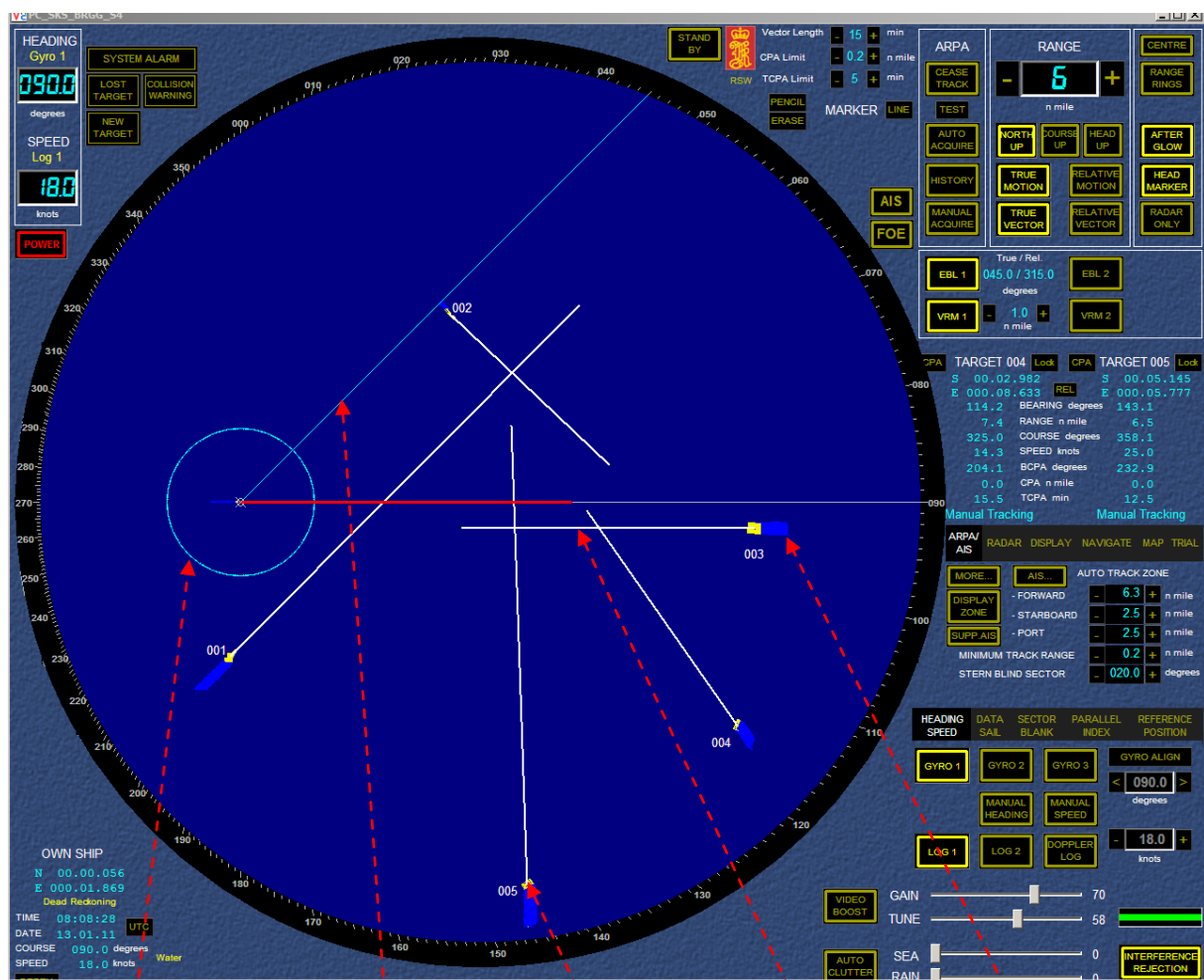
| VRM (variable range marker) | EBL(electronic bearing line) | Target radar echo | True vector | Target trail |

Figure 1, Radar display with 5 plotted targets with true vectors.

IMO have stated the Performance Standard resolutions with a comprehensive description of requirements for an ARPA-system. Some of these are:

- Plotting may be done fully automatic in a preselected sector when echoes come into the sector.
- Alarm for new targets and lost targets (when the system is no longer able to track the target).
- Alarm for when a target comes closer than a pre-designated limit chosen by the operator. (CPA/TCPA).
- Presentation of OS (Own Ship) vector.
- Presentation of TS (Target Ship) vector (both relative and true). Includes TS calculated true course and speed.
- Bearing and range to TS.
- CPA (Closest Point of Approach) and TCPA (Time to CPA) to the chosen TS.
- The system must have a "Trial manoeuvre" option where you can simulate OS speed and course alterations and monitor the development of the situation with regards to the collision danger.

When the possibility of collision arises, the procedure is to enter Trial manoeuvre and perform a manoeuvre test. An alternative method is to use relative vectors and make sure the TS relative vector does not point towards OS. In addition one can use VRM centered on OS to mark the chosen CPA limit and make sure that TS relative vector does not cross the set VRM range.

2.2 Collision Danger Presentation (CDP)

The following section gives a brief description of the method. The derivation of the analytical formulations are given in the project thesis (Grepne-Takle, 2010).

Assumptions:

- OS and TS are considered mass points
- TS maintains constant speed vector
- The origin of the Cartesian coordinate system is located at the center of OS
- Plane sea surface

Definitions:

- (x, y) - relative position of target
- $\mathbf{V}_T(LT^{-1}) = [V_{TX} \quad V_{TY}]$ - true velocity of TS
- $\mathbf{V}_O(LT^{-1}) = [V_{OX} \quad V_{OY}] = [V_O \sin\psi_O \quad V_O \cos\psi_O]$ - velocity of OS
- $\mathbf{V}_R(LT^{-1}) = [V_{RX} \quad V_{RY}] = (\mathbf{V}_T - \mathbf{V}_O)$ - relative velocity
- ψ_O - OS true course
- α - aspect angle (relative bearing)
- $D(L)$ - relative distance
- $t(T)$ - time
- $t_0(T)$ - time reference
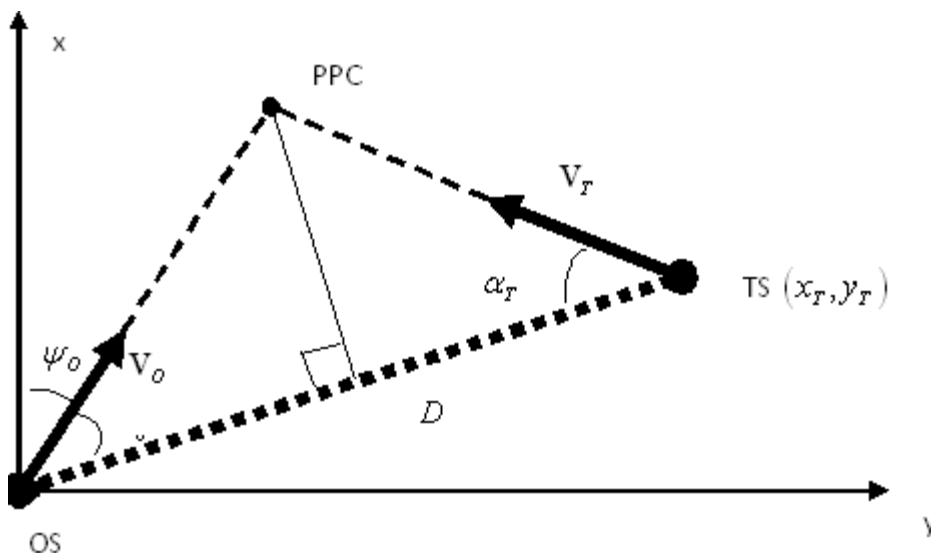- $\Delta t(T)$ - equivalent with vector length in time scale

Figure 2. Definitions, speed – aspect ratio and PPC (Potential Point of Collision)

2.2.1 Geometrical solution

(Pedersen et al., 2003)reported an anti-collision indicator constructed from velocity vectors of both OS and TS. It generates a line (collision danger line, CDL) and an area (collision danger sector, CDS) that represents an operator chosen limit for closest approach to TS. Consider two vessels approaching each other on a collision course.
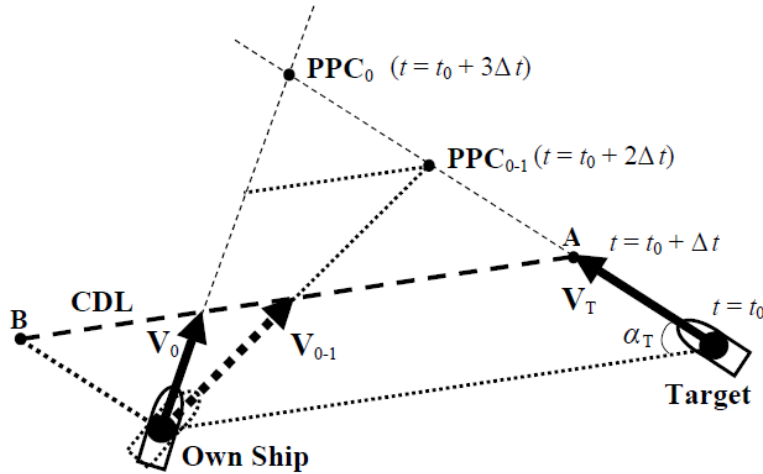

Figure 3. Pedersen et al. (2003). OS (V_0 or V_{0-1}) and TS (V_T)on collision course.

From figure 3 we see that the vessels have a Potential Point of Collision (PPC) at $t(=TCPA) = t_0 + 3\Delta t$ if the motion parameters of OS and TS are unchanged. The mathematical condition for collision can be formulated as follows:

$$|\mathbf{V}_0|\sin\alpha_0 = |\mathbf{V}_T|\sin\alpha_T \qquad (1.1)$$

From eq. (1.1) follows that the PPC can be moved to $t = t_0 + 2\Delta t$ on TS track line if $\mathbf{V}_0$ is altered to $\mathbf{V}_{0-1}$; i.e. $|\mathbf{V}_{0-1}|\sin\alpha_{0-1} = |\mathbf{V}_T|\sin\alpha_T$. Further the PPC can be moved to point (A), which is the tip of TS vector. Thus any manoeuvre that deflects the end of OS velocity vector away from the bold dashed line (line from point A to point B) is a potential collision avoidance manoeuvre. Therefore this line can be regarded as a collision danger line (CDL) in true motion. The CDL can be created by parallel displacement of the bearing line to the TS a distance equal to the length of $\mathbf{V}_T$. The CDL is thus independent of OS movement and can be drawn to any acquired target. The dotted line from the centre of OS, parallel to $\mathbf{V}_T$ represents the course that would result in parallel movement. The interception (B) between this line and the CDL can therefore be regarded as a limit for relevant anti-collision evaluation (Pedersen and Shimizu, 2006).

The general solution of the collision scenario is obtained when a minimum passing distance (CPA limit) is considered. Figure 4 shows a cone-shaped collision region (dashed lines) as it can be imagined on a standard ARPA in relative motion display from the viewpoint of OS. A CPA limit circle is located at the centre of OS, by e.g. using the Variable Range Marker (VRM). The solution to pass at a minimum safe distance astern of TS is shown by the course change $\mathbf{V}_{0-2}$ to starboard. This manoeuvre deflects the relative vector $\mathbf{V}_R$ so its extension becomes a tangent to the *CPA* limit

circle. Figure 4 also illustrates how the imagined cone shaped collision region in the relative display can be transformed to appear in the true motion display (shadowed sector). This region is called Collision Danger Sector (CDS).
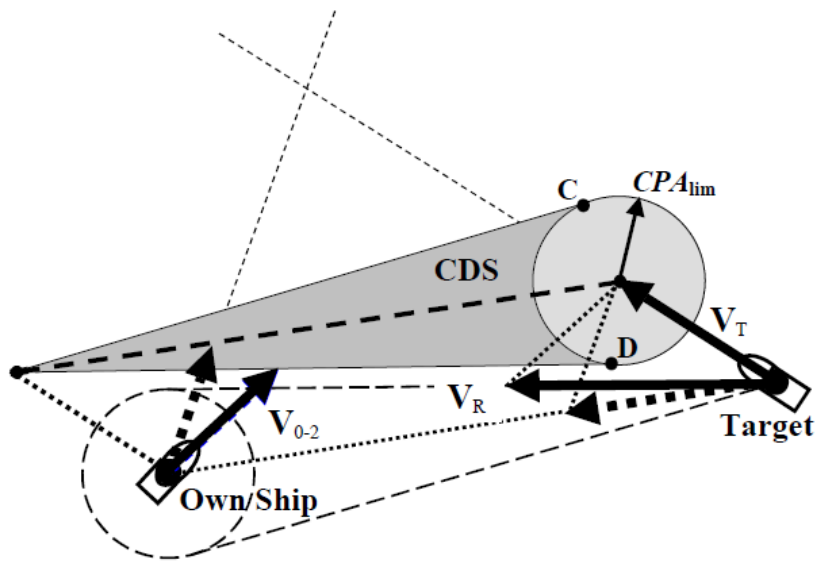
Figure 4. Pedersen et al. (2003). Cone-shaped collision danger regions as they appear in true (shadowed sector) and relative (dashed sector) motion displays.

The position of own ship's vector in relation to the displayed collision danger line and sector shows the severity of the collision threat simultaneously with the possibility of avoidance by changing course and /or speed. There is a direct collision threat if the tip of OS vector reaches the CDL (i.e. CPA=0). If the tip of the vector is at the edge of the CDS, OS will pass a distance equal to the set CPA limit either ahead or astern of the target. Any real or imagined manoeuvre, which deflects the end of OS vector out of the CDS, will be a potential evasive manoeuvre.

2.2.2 Target selection and presentation

In order to avoid overloaded collision avoidance display a target selection procedure is implemented. Pedersen et al. (2006) described a procedure for classification of target risk levels with limits set by operator. The target classification is as follows:

- **'NOT RELEVANT'** if TCPA not in [0, TCPAlim] OR DCPA>DCPAmax
- **'RELEVANT'** if TCPA in [0, TCPAlim] AND DCPA in [DCPAlim, DCPAmax]
- **'DANGEROUS'** if TCPA in [TCPAcrit, TCPAlim] AND DCPA in [0, DCPAlim]
- **'CRITICAL'** if TCPA in [0, TCPAcrit] AND DCPA in [0, DCPAlim]

The user selected parameters are:

- DCPA Limit [NM] – Minimum safety distance at closest point of approach to target. If relative distance to target is equal to, or less than, selected DCPA lim, then only collision danger line is displayed.
- Maximum DCPA [NM] – Maximum time to closest point of approach that is relevant for anti-collision assessment.
- TCPA Limit [min.] – Maximum time to closest point of approach that is relevant for anti-collision assessment.
- TCPA Critical [min.] – Time to closest point of approach when the target is so close that an escape manoeuvre is required.

These four classification levels are to be presented visually and not alphanumerically to the navigator. The following is a proposed visuallisation of the 4 levels with respect to each target using the CDP system:

- Level 1: **'NOT RELEVANT'**, no collision danger lines/sectors are displayed.
- Level2: **'RELEVANT'**, collision danger lines (CDL) and the cone-shaped sector are displayed with dashed lines.
- Level3: **'DANGEROUS'**, the transparent collision danger sector (CDS) is filled with color.
- Level4: **'CRITICAL'**, in addition to the above, the CDL is highlighted by bold solid line.

In addition when the target is within the selected DCPA limit, only the collision danger line (CDL), and the true vectors, should be displayed.

2.3 Room to manoeuvre (RTM)

The RTM method (Degré and Lefèvre, 1981) builds upon the same principles as CDP were the operator chooses a predetermined safe distance to encountering vessels. The main difference is that the visual presentation is limited by OS maximum speed, Vmax. A circle centered on the vessel with the radius Vmax will include all the possibilities of manoeuvre in the absence of restrictions.
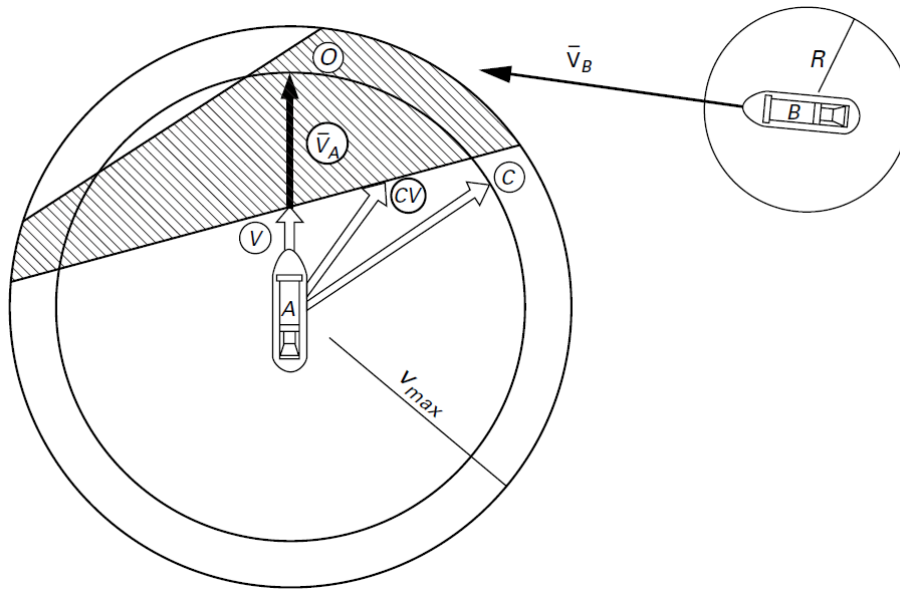
Figure 5. Degré and Lefèvre (1981) room-to-manoeuvre principle for a two ship encounter.

Figure 5 shows vessel A with velocity vector $\overline{V_A}$, TS B with $\overline{V_B}$ and closest safe passing distance R. The unshaded area represents the room to manoeuvre for vessel A in the presence of vessel B. Vmax is the maximum speed of A, the circle O is the extremity of vector $\overline{V_A}$. If $\overline{V_A}$ is located inside the shaded region then A will pass B below the threshold R, therefore in risk of collision. C represent a manoeuvre without change of speed, V is the manoeuvre with speed change but not course alteration, CV is the manoeuvre with both speed course and course alteration. In the presence of a group of vessels the danger zones for speed and course in relation to each ship are shown in figure 6. The shaded area is calculated by the principle of theoretical analysis (Grepne-Takle, 2010).
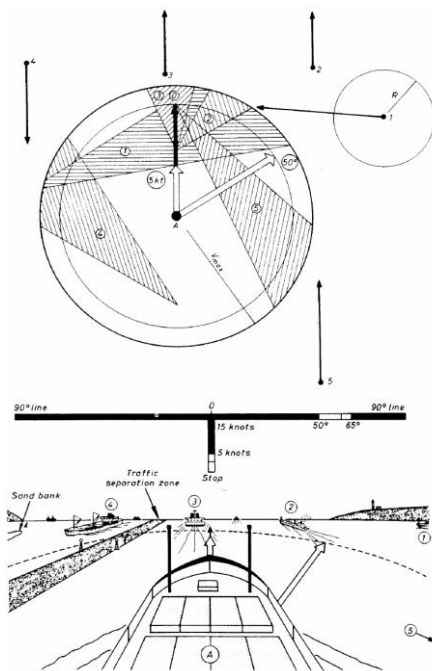
Figure 6. Degré and Lefèvre (1981)

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2.3.1 Target selection and presentation

For the RTM system no collision danger sectors will be displayed outside the circle with the $radius = \mathbf{V}_{max}$. A target will be classified **"NOT RELEVANT"** or **"RELEVANT"**. When a target is classified **"RELEVANT"** the shadowed area will be displayed. In addition when a target enters the perimeter of the RTM circle, or to be more precise, when point A (ref figure 3) is inside the circle, the system should display a full cone-shape. When the target is within the selected DCPA limit, only the collision danger line (CDL), in addition to true vectors, should be displayed.

For RTM the user selected parameters are then:

- Vmax [knots] – Maximum velocity of own ship.
- DCPA Limit [NM] – Minimum safety distance at closest point of approach to target. If relative distance to target is equal to, or less than, selected DCPAlim, then only collision danger line is displayed.
- Maximum DCPA [NM] – Maximum time to closest point of approach that is relevant for anti-collision assessment.
- TCPA Limit [min.] – Maximum time to closest point of approach that is relevant for anti-collision assessment.

2.4 VHF (Very High Frequency radio)

The IMO convention SOLAS (Safety Of Life At Sea) is a set of statutory requirements. Chapter IV deals with radio communications. National regulations based on SOLAS dictates the requirements for radio communication equipment. With regards to Maritime VHF radio, Norwegian regulations state that all professional vessels must be equipped with Maritime VHF. Also leisure boats above 50 gross tonnages have the same requirement.

All vessels with Maritime VHF radio license are obliged to listen channel 16 (SOLAS, 2002). This is the international distress and calling frequency. For non-distress calls, after the initial response the call is to be switched to a working channel. With regards to collision avoidance, mariners often use VHF to arrange safe encounters. The use of Maritime VHF gives the mariner assurance that both parties in the conversation have a common understanding of the developing situation. Still, misunderstandings might occur and the navigator has to constantly check that the situation is progressing as intended. In a congested area the method will not be adequate due to the amount of communication traffic that might be required. In addition the watch-keeping conducted by the navigators is not always adequate. An inspection campaign directed at distress alerting and emergency radio communications revealed that watch-keeping navigators do not pay sufficient attention to distress and safety radio communications (Breivik, 2006).

Even thought Maritime VHF is a good aid, the navigator will have to use other methods to evaluate the need of establishing communication and to monitor that the agreed manoeuvres are conducted as planned.

This thesis will not explore the use of VHF as a collision avoidance aid.

2.5 Automatic Identification System (AIS)

The purpose of AIS is to help identify vessels; assist in target tracking; simplify information exchange (e.g. reduce verbal mandatory ship reporting); and provide additional information to assist situation awareness (IMO, 2001). Resolution A.917 (22) describes AIS as a potential aid in collision avoidance and also highlights the use of AIS as an additional navigation system that supports (but does not replace) the existing navigational system. "All ships of 300 gross tonnage and upwards engaged on international voyage and cargo ships of 500 gross tonnage and upwards not engaged on international voyages and passenger ships irrespective of size shall be fitted with automatic identification system (AIS)" (SOLAS, 2000). Resolution A.917 gives a caution note that some ships, in particular leisure craft, fishing boats and warships might not be fitted with AIS.

All targets were fitted with AIS during the thesis simulator study. The information transmitted was target position, course, speed and name. The participants of the study decided themselves whether to use the information or not. The use of AIS was not be evaluated since it falls out of the scope for the thesis. AIS information was available in order to provide as high degree of realism as possible for the participants of the study.

3 Collision Avoidance Support System (CASS)

Both the CDP and the RTM method was installed on the Kongsberg Maritime Polaris ships bridge simulator ARPA radar. The application was named Collision Avoidance Support System (CASS). A separate button was assigned for the CASS function on the radar. CDP is default CASS setting with RTM as an option by activating the RTM function button in the CASS submenu. Default standard parameters when starting the Polaris radar are the following:

- Vector length : 15 min
- CPA limit   : 0.2 nm
- TCPA limit   :5 min
- Additional CASS default parameters
    - CPA max   : 2.0 nm
    - TCPA critical : 2.5 min

By assigning a dedicated CASS on /off button the navigator is able to fast switch between modes of presentation. The CASS can be used in TRUE MOTION NORTH UP or TRUE MOTION HEAD UP with TRUE vectors. Relative vectors are not to be used while displaying CASS. This combination is possible, but not recommendable since the relative vectors are not coupled to the CASS display.

The target selection in the CASS is done by altering the parameters shown above. For the different levels of classification the following is used:

CDP:

- **NOT RELEVANT**   **:** no presentation
- **RELEVANT**   **:** CDS is presented with dotted lines
- **DANGEROUS**   **:** CDS is presented with full lines
- **CRITICAL**   **:** CDS is presented with bold lines
- In addition when the target is within the selected DCPA limit, CDL and the true vectors is presented

RTM:

- **NOT RELEVANT**   **:** no presentation
- **RELEVANT**   **:** the maximum speed circle and the CDS are presented. Six colors are used for separating different targets. When the tip of targets true vector enters the max-speed circle the display switches to CDP.
- Targets with CDS defined outside the max-speed circle are not presented.

The visual presentation is as described due to the fact that the Polaris radar simulator is an old program. We were not able to find a good solution in order to "fill" the sectors as described in the target selection scheme for CDP and RTM. Thus the described presentation was decided the most adequate. In RTM-mode we were able to use 6 different colors in the RTM mode to separate different targets. The program code cannot handle more than six colors. The described RTM presentation may cause some confusion when there are many targets.
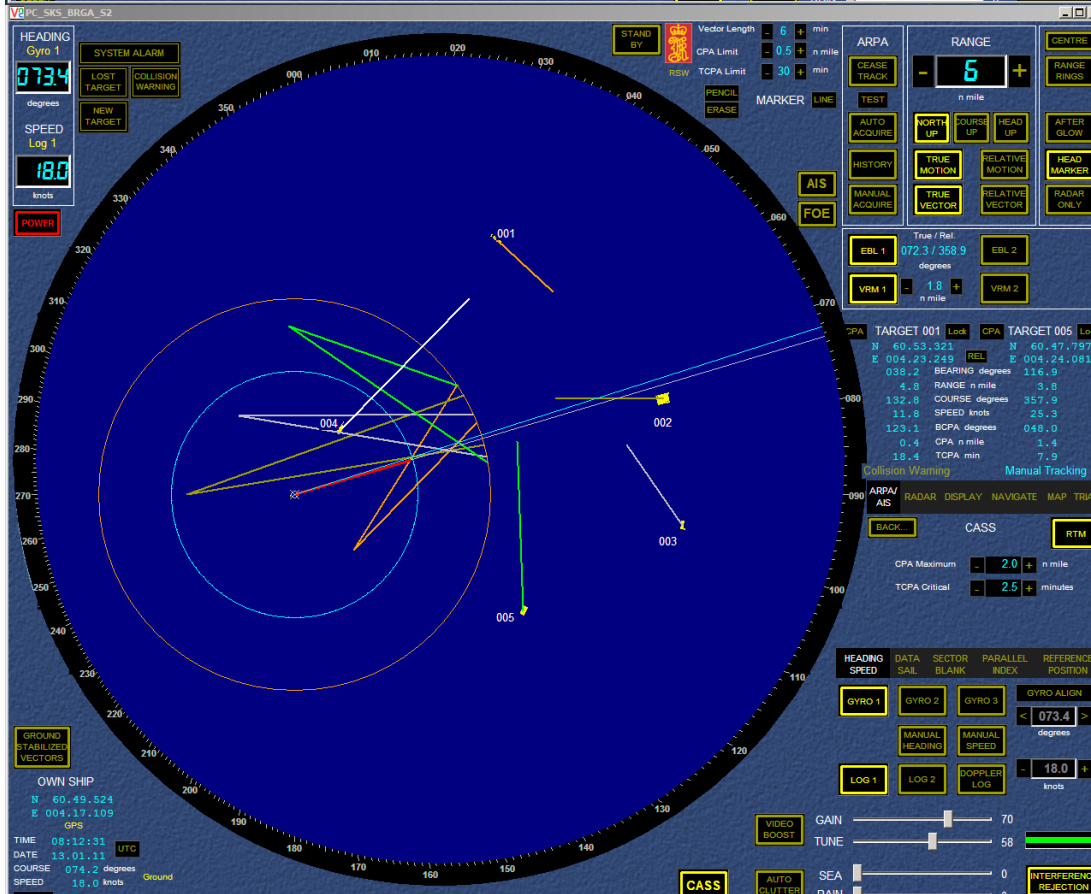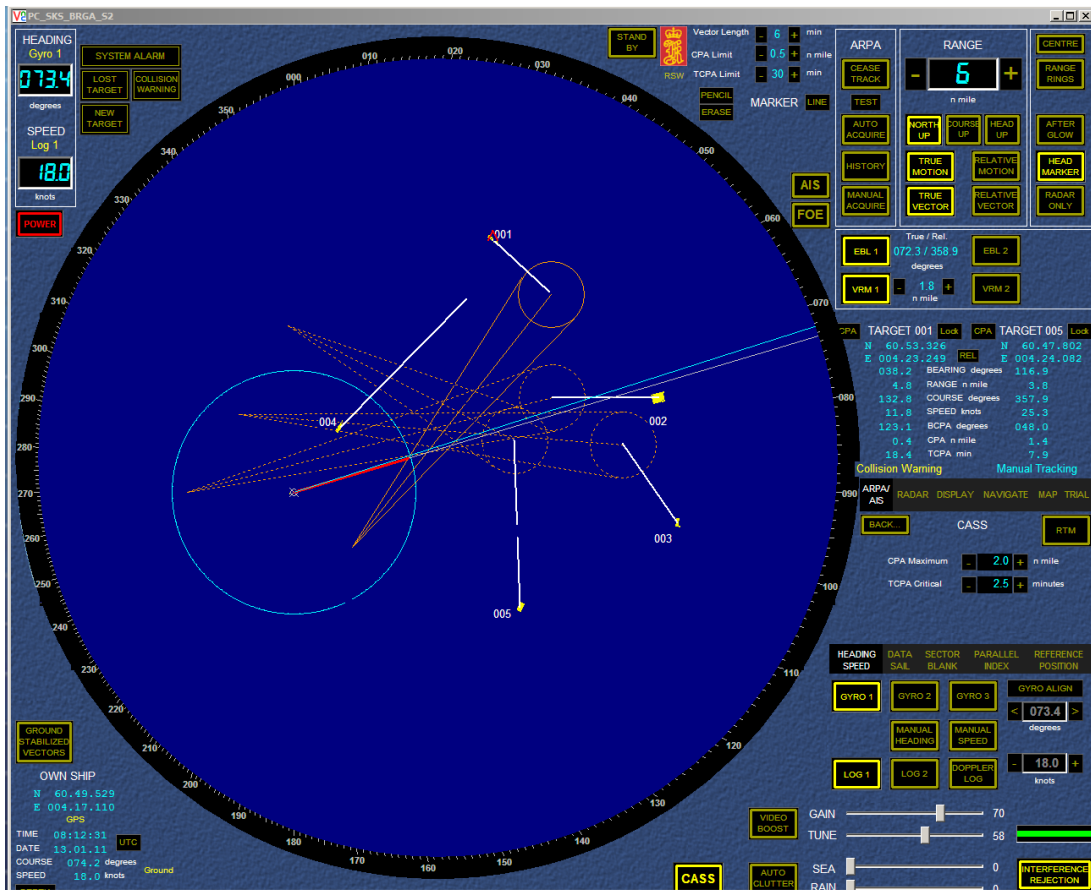
Figure 7. CASS solution. Top display CDP, bottom display RTM.

3.1 Implementation and validation of CASS

The implementation of the core algorithms was done by Tor Arne Johansen, senior engineer at Kongsberg Maritime Simulation AS. The algorithms were sent as Cpp (C ++) files. In addition a program specification was sent, see appendix A1.

Beta test and debugging was done at Kongsberg maritime Simulation AS in Horten by me, supported by the senior software engineer. The software was installed on the simulator at the Royal Norwegian Naval Academy. The aim of the validation test was to verify that the visual presentation was satisfactory, according to specification and running without faults. The test was conducted by entering different target data and user selected parameters. Initially the collision avoidance display was tested with targets in all quadrants were own ship was in the origin with a set speed and course. The target position was in one of the coordinate system's quadrants. The target was given a speed and the course was altered according to the test specifications, see figure 8. All four quadrants were tested. Tests when one of target's position coordinates was on the coordinate system's axis were also done. In addition tests when singularity occurred were conducted. For the RTM system additional tests were conducted to control the performance. See appendix A2, Collision avoidance test specification, for details.
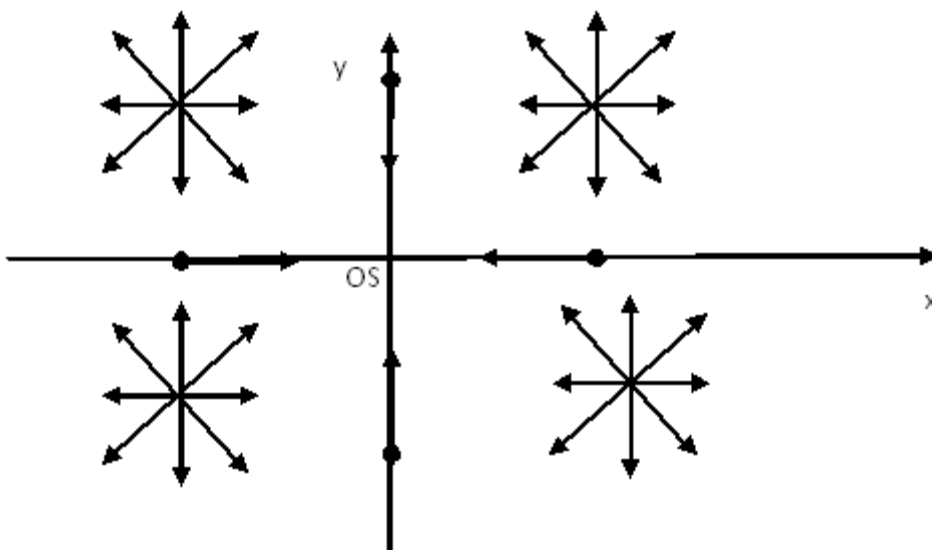
Figure 8. Sketch of scenarios for validation test. OS is located on the origin.

4 Making collision avoidance decisions

4.1 OODA loop

Decisions on the bridge are taken by the OOW. He will utilise all available means to ensure a safe passage with regards to surrounding traffic and topography. These means are visual observation and observation of the navigation systems on the bridge. If we isolate the navigator's many tasks to solely anti-collision with moving targets the means are visual observation, AIS and radar (ARPA).

The process of making a decision can be described by the OODA Loop (Boyd, 1995b) in figure 9
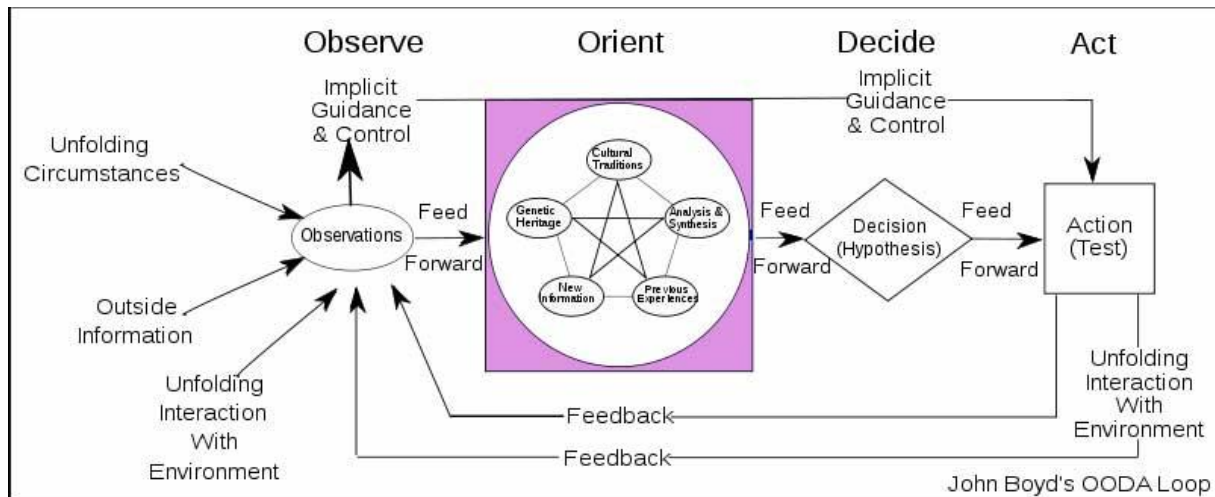
Figure 9. The OODA Loop.

The premise of the model is that making a decision is the result of rational behavior in which problems are viewed as a cycle of Observation, Orientation (situational awareness), Decision and Action.

Making a decision in navigation can be regarded as an outcome of mental cognitive processes, leading to the selection of a course of action among several alternatives. The OODA Loop can be used to describe this process. The OODA Loop's concept is described as follows (Boyd, 1995a):

Observation: Scan the environment and gather information from it.

Orientation: Use the information to form a mental image of the circumstances. The level of details to perceive an event varies from person to person. Often we imply that the reasons people cannot make good decisions is that they are "bad decision makers" – like saying the reason some people cannot drive is that they are bad drivers. However, the real reason most people make bad decisions is that they often fail to place the information that we do have into its proper context. This is where Orientation applies. Orientation emphasizes the context in which events occur, so that we may facilitate our decisions and actions. Orientation helps to turn information into knowledge, and knowledge, not information, is the real predictor of making good decisions.

Decision: Consider options and select a subsequent course of action.

Action: Carry out the conceived decision. Once the result of action is observed one starts over again, hence it is a loop.

The loop does not mean that individuals or organizations have to follow the order as shown in figure 9. The loop should be pictured as an interactive web with orientation at the core, see figure 10. Thus the loop is actually a set of interacting loops that are kept in continuous operation. Orientation is how we interpret a situation, based on culture, experience, new information, analysis, synthesis and heritage.
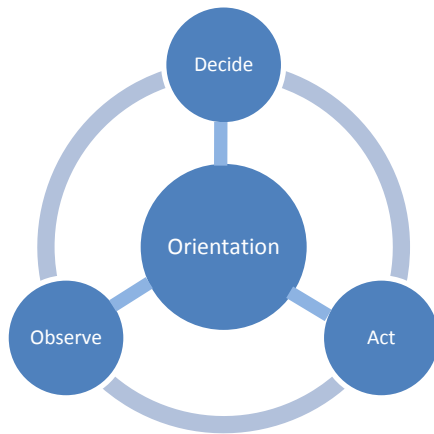
Figure 10. Interactive web

The Orientation part in Boyd's OODA Loop may be translated to situation awareness which is defined as "…the perception of the elements of the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1997). One of the main concerns for a navigator lies in the transition from information to situational awareness. Then one can raise the question if the means for information are adequate and is there room for improvement? The study conducted by MAIB (2004) found that 73% of the collisions were caused by improper or poor use of radar.

In collision avoidance the situational awareness consist of the navigator's perception of own ship relative to the targets. This includes own ship heading, course and speed, the relative own ship position with regards to the respective target's position, target course and speed and DCPA, TCPA. The situational awareness is essential in order to be able to evaluate if a close encounter situation is developing and eventually decide a feasible avoidance manoeuvre. Degradation of one or more of the information givers may contribute to reduction in the situational awareness. If so happens the navigator will need to compensate by other available means to ensure that his situational awareness and decision is not based on sparse information.

As described in the OODA loop, the previous experience plays an important part in Orientation. The naturalistic process of making decisions can be described as recognition primed. " In this process, the experience and knowledge of the decision makers sub-consciously primes an appropriate response to a recognized problem" (Klein, 1999). The practical experience build-up during several years of navigating is partly conscious and partly not. This can be observed when navigators and pilots are asked how a procedure in a navigation task is put into practice. It is much easier for them to describe what they do, than describe what they are thinking while conducting the task. In some literature this human characteristic is named tacit or implied knowledge. The original tacit knowledge held by individuals is unique to them, a product of their total experience, and not a direct source of generalized knowledge (Rust, 2004).

This knowledge is an important element with regards to collision avoidance manoeuvring. It implies an experienced navigator will have better possibilities to find a good solution in a developing close encounter situation. An inexperienced navigator will then in theory need to compensate by seeking more information and advice to enhance his situational awareness and enable good decisions. A collision avoidance display may reduce the need to compensate for lack of experience.

In order to be able to make a decision, or even to set up the necessary goals in navigation, a spatial (3D) awareness needs to be present to navigate and manoeuver. In collision avoidance, as in most navigation operations, the process of making decisions can be seen as an embodied reasoning system. The most important instrument for a navigator is the eye measuring height, width and depth. In combination with the cognitive unconscious, experienced memory, which is only possible through the embodiment of the mind (Lakoff and Johnson, 1999), the navigator experiences the spatial awareness. The experienced way of moving in time and space from a known position A to a destination B demands a spatial prediction or a spatial feeling present in the navigator's control (Hutchins, 1995). During a collision avoidance manoeuvre the navigator has to imagine "in his inner eye" where his own ship and the target ship will be in the future.

In an imminent close encounter situation, gathering all the necessary information in the present (and history) will together with the experience give the navigator an "a priori" solution where both ships will be in the future, with some degree of accuracy. This of course assuming the target ship's speed and course in fixed. A spatial prediction is possible if there is enough information and experience available. A good navigator will calibrate his spatial prediction process like a " human kalman filter" by improvising and adjust the control forces to meet the changing environmental forces (Husjord and Pedersen, 2009).

An important factor that needs to be enlightened is *the time*. The time factor is acting from when an observation starts until a decision is made is important for all navigational aspects. Time is needed to observe, select, compare decide and act. It can be seen as several parallel circular processes acting on, or at, different elements, but also moving beyond or outside the process of making decisions itself. The time-factor is present in every step of the process as shown in figure 11. In the last part of the process of making decisions, or OODA Loop, the decision is more directly connected to the time factor and the navigator's capability to predict the position as a function of time (Husjord and Pedersen, 2009).

An alternative presentation of the OODA Loop is shown in figure 11. Shaped like a flow diagram the process moves in steps from the top where several input sources are available. The decision-maker chooses what to observe and selects the information needed. This information is compared with other similar experienced situations to try to discover differences and similarities. The results from the comparison are different solutions, which trough the navigator's spatial understanding and prediction gives a final decision (Husjord and Pedersen, 2009). Lack of control of some of the different time factors will by navigators often be referred to as " bad feeling" and can reduce the decision-makers performance, but also function as an in-built alarm that something is not as it should be and corrective measures needs to be taken.
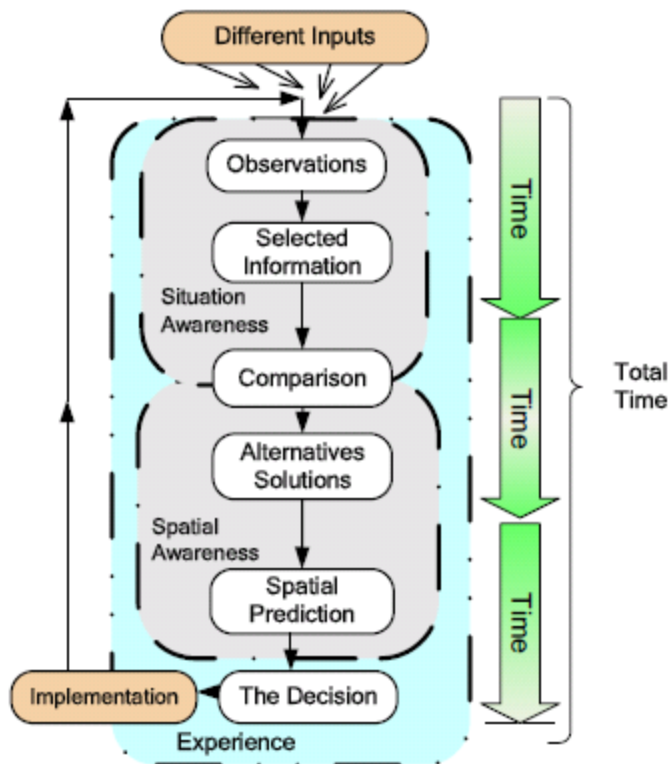
Figure 11. (Husjord and Pedersen, 2009). The complete decision-making cycle: the situational awareness is the first part while spatial awareness is the last part of the process. The experience is acting through the whole process.

4.2 Challenges in the process of making decisions

To analyse the traffic situation and manoeuvre OS feasible in a multi-target scenario demands a high level of mental and problem solving activities. A bad decision is a result of errors in the solving of the collision problem and can cause great damage. "The process can be especially prone if a new element shows up and the task becomes non-routine" (Rasmussen, 1982). This new element can be environmental, number of targets, total work load on the navigator and so on.

As a decision-maker, the human is under influence of several factors such as stress, fatigue, noise, etc. The navigator has a variation in the performance which will vary on the performance scale. Low performance is often called " human error", but some cognitive systems engineers states that this must be seen as a natural variation in the human performance (Hollnagel, 1998). For a navigator it may be difficult to relate to the level of his own performance. Training is necessary to gain and maintain a high level of performance.

4.3 COLREGs and anti-collision

In part B – Steering and Sailing Rules of the COLREGs, we find rule 7 which deal with risk of collision. Firstly it is important to note that the rules in part B applies to any condition of visibility. Rule 7 (IMO, 1972) states the following:

(a) Every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if risk of collision exists. If there is any doubt such risk shall be deemed to exist.

(b) Proper use shall be made of radar equipment if fitted and operational, including long-range scanning to obtain early warning of risk of collision and radar plotting or equivalent systematic observation of detected objects.

(c) Assumptions shall not be made on the basis of scanty information, especially scanty radar information.

(d) In determining if risk of collision exists the following considerations shall be among those taken into account:

(i)   Such risk shall be deemed to exist if the compass bearing of an approaching vessel does not appreciably change;

(ii)   Such risk may sometimes exist even when an appreciable bearing change is evident, particularly when approaching a very large vessel or a tow or when approaching a vessel at close range.

It is clear that the navigator has to ensure his situational awareness is continuously up-to-date, and if in doubt of a potential close quarter, the decisions and following actions should be made assuming a potential collision or close quarter is imminent. Rule 7 enforces the importance of what is described in the models for making a decision as the situational awareness.

COLREG rule 8(c), 19(d) and 19(e) refer to close quarter situation. The distance at which close quarters situation first applies has not been defined in nautical miles. The 1972 Conference considered the possibility of specifying the distance at which it would begin to apply, but after a lengthy discussion it was decided that this distance could not be quantified. For restricted visibility in the open sea, a court interpretation states the following:

In restricted visibility, in the open sea, a close quarter situation is generally considered to begin to apply at a CPA of at least 2 nm in any direction forward of the beam as this is the typical range of the audibility of the whistle of a large vessel in still conditions. However CPA of less than 2 nm may be considered sufficient when proceeding at reduced speed in congested waters, when in an overtaking situation, or, when a vessel is expected to pass astern (Cockcroft and Lameijer, 2004).

Setting the distance defining close quarters demands careful judgment from the captain. During a voyage the captain will most likely brief his navigators of his desired minimum distance to targets (CPAlim) in order to avoid close quarters. This distance vary in accordance to different operating areas; e.g. open waters, channels, port approach; vessel manoeuvring characteristics, vessel size, visibility, speed, etc. To keep the limit the navigator will have to use the available means on the bridge. To accomplish this task the radar is the most natural equipment to use. The task can be solved by traditional ARPA functionalities. The problem arises when the traffic situation is complex/congested and/or there are topographical and hydrographical limitations. The challenge for the navigator is then to extract from the IBS the correct vital information and observation in which to base his situational awareness. Rule 7 is very clear and requires the navigator to apply a considerable amount of his mental focus on the collision problem. Facilitating adequate systems that reduces the amount of work needed from the navigator's side will free mental capacity to conduct proper decisions and actions. In addition good conduct at sea concerning collision avoidance may be somewhat unsuspended from the tacit knowledge. The essence in the COLREGs needs to be repeated regularly by the navigator to ensure good conduct.

5 Simulator trial scenarios

The trials were divided in three. Each participant sailed three trials with one type of collision avoidance display (ARPA, CDP or RTM), i.e. different participants were used for each display type.

5.1 Apparatus

The trials where conducted at the Royal Norwegian Naval Academy Navigation Competence center in the Kongsberg Maritime POLARIS Ship's bridge simulator. The facilities used where 6 full mission ship handling simulators with 210° forward view and 30° stern view (Bridge A, B, C, D, E), 1 simulator bridge with 360° view (Bridge G), two stations in the instructor room and the lecture room. The instrumentation on the bridges was SeaMap 10 ECDIS, Polaris ships bridge simulator ARPA radar, manoeuvring console, GPS, log, VHF and binoculars. The CASS was implemented in the Polaris radar. All bridges and trials were monitored and recorded from the instructor station. The self reported work load was done post-hoc on computers in the navigation laboratory.

The Navigation Competence center provided expert instructors for monitoring and recording the scenario. In addition helmsmen where recruited from the center's own resources.
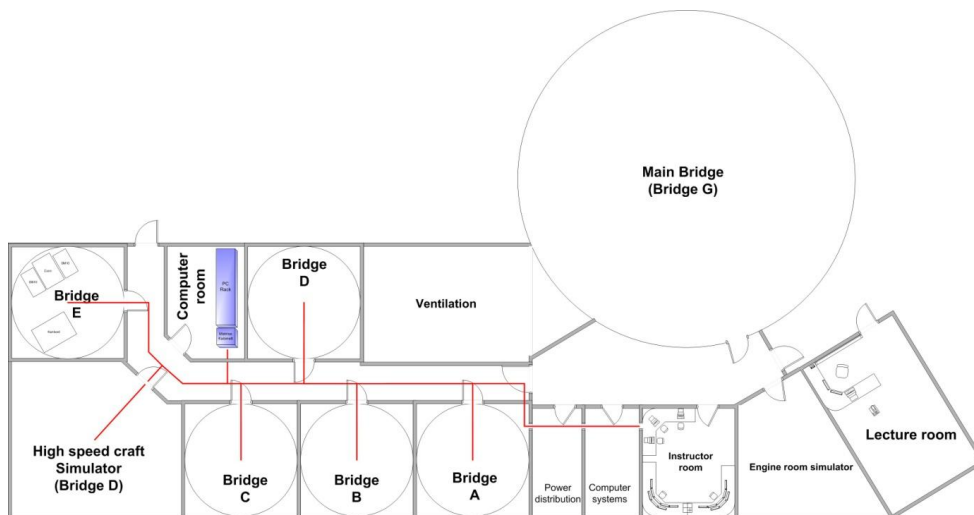
Figure 12. Schematics of the simulator park.

5.2 Participants

15 Naval officers with clearance to stand unsupervised bridge watch and 10 navy cadets participated as subjects. The experienced subjects work in the Norwegian Navy on the following type of vessels: Ula-class submarine (5 subjects), Nansen-class frigate (3 subjects), Patrol boat (1 subject). In addition 6 subjects work at the Norwegian Navy Navigation Competence center. The cadets were all final year students. All participants were familiar with the simulator. See appendix B1 for distribution of participants and collision avoidance display types.

5.3 Scenario

The scenario was divided in three separate trials, open water (uncomplicated traffic), open water advanced (complicated traffic) and inshore (complicated traffic). Own ship was a Norwegian Nansen-class frigate. The scenario was set up such that each trial was connected to the previous by the fact that the participants where sailing towards the gateway of Fensfjorden. The participants were given a preplanned route with the following positions; WP1:60°51.315' North - 003° 54.818' East, WP2:

60°51.315' North - 004° 45.301' East, WP3: 60°50.775' North - 004° 52.142' East. The route describes a voyage starting off coast outside the inlet to Fensjorden. OS speed throughout the voyage was 18 knots.

The participants' aim in the scenario was threefold: keep to preplanned route as good as feasible, avoid any targets closer than preset range (CPAlim) decided by trial manager and arrive destination with a minimum of time delay. The scenarios were constructed to force the participants to manoeuvre in order to avoid close encounters or collisions. The OS speed was fixed and set by trial manager, thus the evasive manoeuvres were restricted to course alterations only.

Testing of the scenario was done by Hans Magne Gloppen (Royal Norwegian Naval Academy, Navigation Competence center) and me. All scenarios were run in real time with the exact conditions as for the trials. The testing focused on detecting flaws in the setup configuration and that the geometry of targets provided the right settings in order to get good data for evaluation.

5.3.1 Frigate model description

5.3.1.1 General description

The propulsion plant consists of:

- Single gas turbine producing a continuous rating of 20855kW
- Two diesel engines each of them producing 4050 kW of power at a rated maximum of 180 rpm shaft revolutions.
- Two main reduction gearboxes.
- Two propeller shafts each with controllable pitch propeller.

The top shaft revolutions are 180 rpm. Top speed of the ship is 26 knots ahead and approximately 11 knots astern. Time from rudder port 35° to starboard 35° is 30 seconds. Being a twin-screw ship it does not tend to turn either to starboard or port when the rudder is midship. The ship has no heading deviation due to pendling effect during starting from stop to full ahead nor during crash stop manoeuvre. Crash stop distance from 26 knots is 291m. Zig-zag tests show the first overshoot angle of 5.1° in the 10-10 degrees test and 12.7° in the 20-20 degrees tests. The manoeuvring ability is very good. The turning ability is fairly good with an advance of 3.3 Lpp and a tactical diameter of 4.2 Lpp. The steering ability is fairly good and the ship is course stable. The simulation model is designed for normal operations loading condition(Zaikov, 2002) .
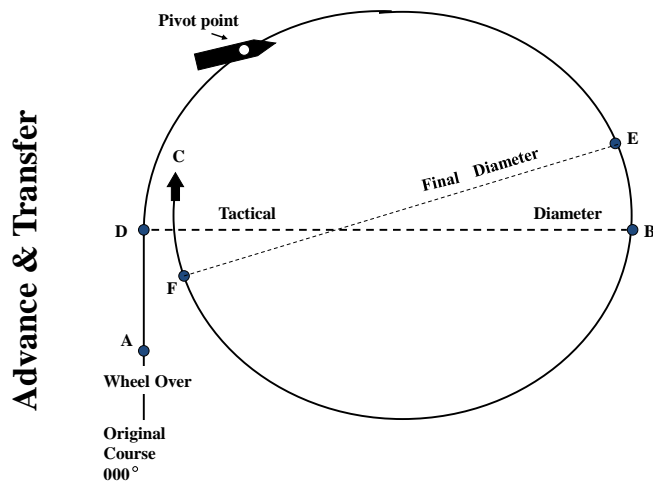
Figure 13. Definitions advance, transfer and tactical diameter

5.3.1.2 Model sources

The Fridtjof Nansen class frigate model is named FRIGT14. The manoeuvring characteristics of the model are largely based on documentation provided by the Royal Norwegian Navy, Norwegian Maritime technology Research Institute MARINTEK, SINTEF Group (Report 601848.00.04, 601848.00.05, date 2001-07-04) and IZAR (Project 6088 New Frigates, Contract 6088 18043, Manoeuvring Test Report, date 2002-01-11).

A number of manoeuvres were specially selected to check model performance against that for the real ship. For speed 22.4 knots and rudder angle starboard/port 35° Advance $A_T = 426$ m and Tactical diameter $D_T = 540$ m are assumed for the model. See appendix B2 for detailed model ship data.

5.3.2 Detailed scenario description

5.3.2.1 Trial artificialities

A daylight scene was chosen. The environmental conditions were clear visibility with no wind or current. The environmental settings were chosen as described to not interfere with the measurement results. All targets kept constant speed and course in open water and open water advanced trial. On the inshore trial the targets kept to a preplanned track and did not respond to participants' OS manoeuvres. Considering the COLREGs the scenario was constructed to not produce any awkward situations that might enforce violation of the regulations. In addition VHF was not used to plan passings and crossings.

The participants' choice of evasive manoeuvre was restricted to only course alterations. No speed changes were allowed. This was done to ensure that the preplanned encounters would happen as schemed and to reduce the parameters that needed to be measured. In real life this restriction is not totally unrealistic since both military and civilian ships have an estimated time of arrival (ETA) on a voyage. In addition speed changes cost money due to fuel consumption. A conventional ship has a "normal operating/transit" speed. This is an optimum speed based on the trade of between fuel consumption and obtained speed on a set rpm. Thus a speed alteration will increase fuel consumption and possibly delay ETA.

5.3.2.2 Trial 1, open water

The participants started in position 60°51.315' North - 004° 00.374' East, initial course 090°, speed 18 knots. The planned route course was 090°. The scenario consisted of three targets with initial CPA= 0 nm, see figure 14. TGT3 is coming from port side. To avoid conflict with COLREG rule 15, Crossing situations, TGT3 was classified a vessel restricted in her ability to maneuver. Thus the participants' vessel became the give-way vessel in accordance with rule 18, Responsibilities between vessels, (IMO, 1972). To make sure all participants were aware of TGT3's condition, the instructors played the captain of the tug and broadcasted her condition on the simulator VHF.

For Trial 1 the preset range was CPAlim= 0.5 nm. The trial was constructed to give the participants a good range of possible course manoeuvres in order comply with trial aims.

Target num. (TGT)	Model name	Dimension (length X width)	Initial Course (degrees)	Initial Speed (knots)	Initial TCPA (minutes)	Initial CPA (nm)	Relative initial position (bearing – range (nm))	Initial position (WGS 84)
Own ship	FRIGT14	132 X 16.8	090	18	-	-	-	60 51.315N – 004 00.374E
1	CARGO02L	205.1 X 32.2	000	19	12	0	136 – 5.22	60 47.5N – 004 07.763E
2	CRUIS05L	260.7 X 31.5	335	18	24	0	122 – 12.1	60 44.798N – 004 21.382E
3	TUGBA02L	179.6 X 25.8	180	12	18	0	056 – 6.47	60 54.92N – 004 11.453E

Table 1. Scenario geometry.
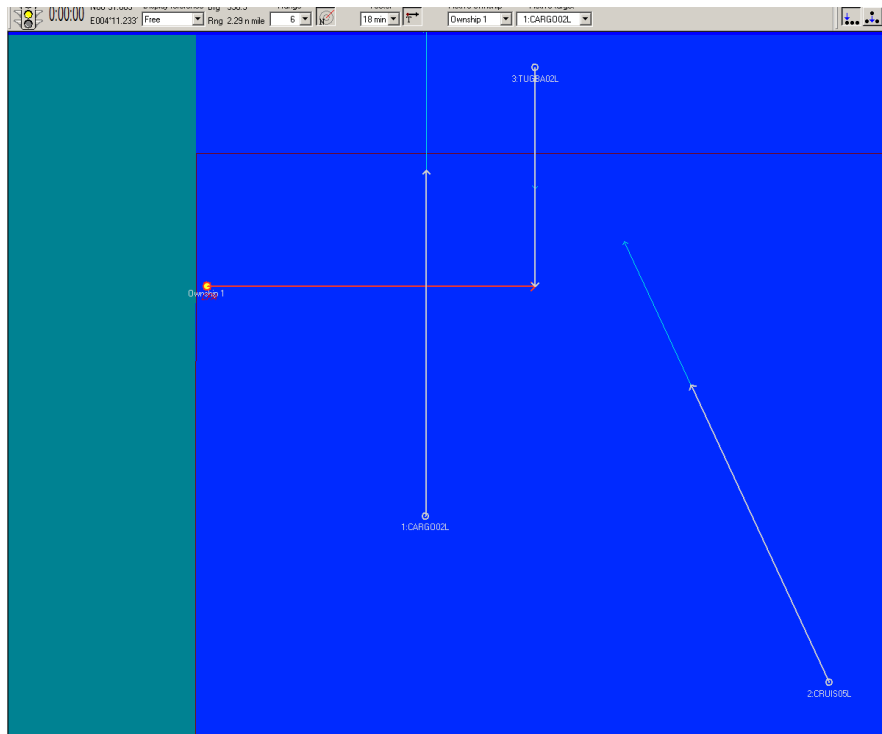
Figure 14. Scenario Trial 1

5.3.2.3 Trial 2, open water advanced

The participants started in position 60°51.315' North - 004° 10.922' East, initial course 090°, speed 18 knots. The planned route course was 090°. The scenario consisted of four targets with initial CPA= 0 nm and one target with initial CPA= 0.36 nm, see figure 15. TGT5 was classified a vessel restricted in her ability to maneuver, thus not conflicting with the COLREGs. As for Trial 1 the target's condition was broadcasted on the VHF.

Target num.	Model name	Dimension (length X width)	Initial Course (degrees)	Initial Speed (knots)	Initial TCPA (minutes)	Initial CPA (nm)	Relative initial position (bearing – range (nm))	Initial position (WGS 84)
Own ship	FRIGT14	132 X 16.8	090	18	-	-	-	60 51.315N – 004 10.922E
1	FRIGT01	131.8 X 16.0	358	25	21	0	143 – 7.83	60 45.061N – 004 20.573E
2	CNTNR07L	294.1 X 32.2	045	27	15	0	183 – 4.8	60 46.525N – 004 10.353E
3	SUPLY10L	82.6 X 19.0	325	14.3	24	0	114 – 11.5	60 46.620N – 004 32.424E
4	VLCC05L	315 X 47.2	270	16.0	21	0.36	092 – 11.8	60 50.951N – 004 35.183E
5	TUGBA02L	179.6 X 25.8	133	12	27	0	048 – 5.59	60 05.043N – 004 19.498E

Table 2. Scenario geometry.
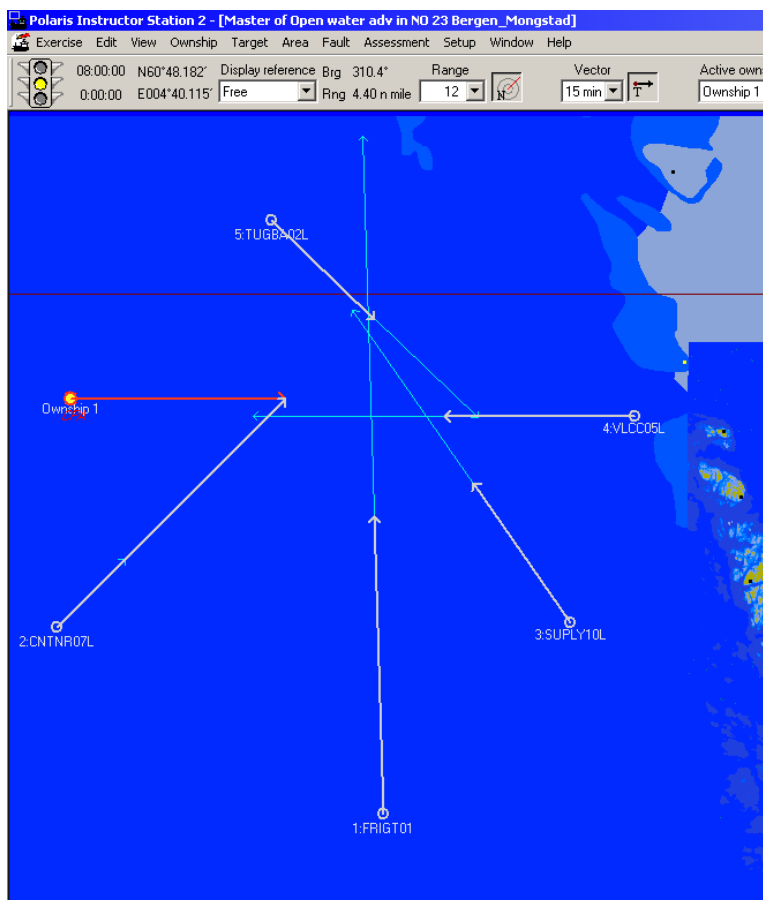
Figure 15. Scenario Trial 2.

For Trial 2 the preset target range limit was CPAlim= 0.5 nm. The trial was constructed to give the participants a more complex traffic situation and increased workload. TGT4 (VLCC05L) was planned as an oncoming vessel to give restrictions in manoeuvring possibilities and to demonstrate a potential weakness of the anti-collision methods. The weakness being that in overtaking and head-on situations with heavy traffic the display may be overloaded (Pedersen and Shimizu, 2006).TGT2 (CNTNR07L) is coming from starboard quarters. This geometry was especially chosen due to reported high environmental stress levels. By using the Environmental Stress Model (ES-model) (Inoue, 1999, Inoue, 2010), Inoue found that the ES values calculated where significantly higher for a target coming from starboard or port quarters with small aspect than when the targets crossed own trajectory with larger aspect coming from a relative bearing larger than 90°. Also considering COLREG rule 13, Overtaking, judging if the target vessel is overtaking or not by definition can be a challenge. Rule 13 (b) defines overtaking as: "A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5° abaft her beam" (IMO, 1972).

5.3.2.4 Trial 3, inshore

The participants started in position 60°51.315' North - 004° 28.110' East, initial course 090°, speed 18 knots. The planned route had two courses 090° and 099° where the course shift was at WP2, abreast of Grimeskjæret light house, see figure 16. The scenario consisted of 8 targets where 5 targets crossed OS route, 1 target was to be overtaken by OS and 2 head-on targets, see figure 17 and table 3 for details.

For Trial 3 the preset target range limit was CPAlim= 0.2 nm. The trial was constructed to give the participants topographical and hydrographical restrictions when conducting evasive manoeuvres. The geometry of the targets was chosen to create the following situations:

- overtaking and head-on situations
- targets crossing from starboard side of OS
- evaluation of collision risk prior to a planned course change in the route
- evasive manoeuvre against a target suddenly appearing out from the islets

Again the overtaking and head-on situations were constructed to enable evaluation of the collision avoidance displays reported ineffectiveness (Grepne-Takle, 2010). Also the geometry was designed so that it might encourage the participants to initially sail north of the planned route, thus the participants end up sailing the port side of the fjord (relative to OS). This is in direct violation of the COLREG rule 9 (a) Narrow Channels, which states: "A vessel proceeding along the course of a narrow channel or fairway shall keep as near to the outer limit of the channel or fairway which lies on her starboard side as is safe and practicable" (IMO, 1972).
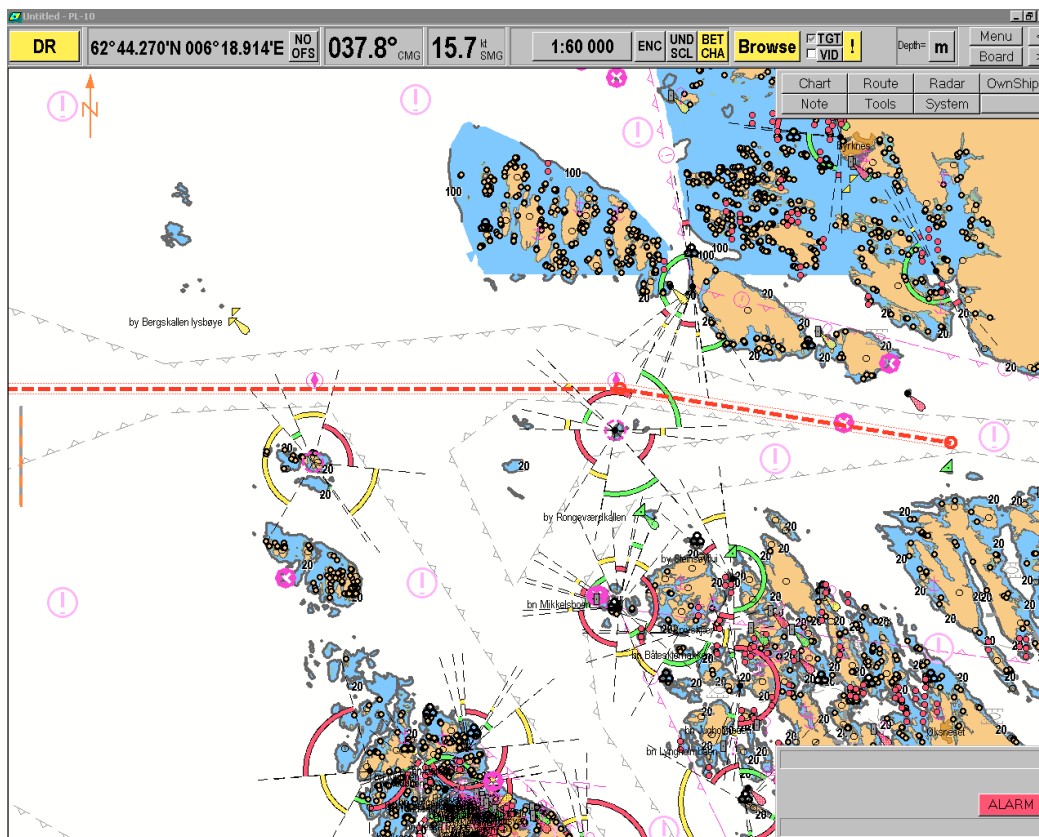
Figure 16. Preplanned route Trial 3. This is the seaward approach to Fensfjorden were Mongstad oil refinery is situated.
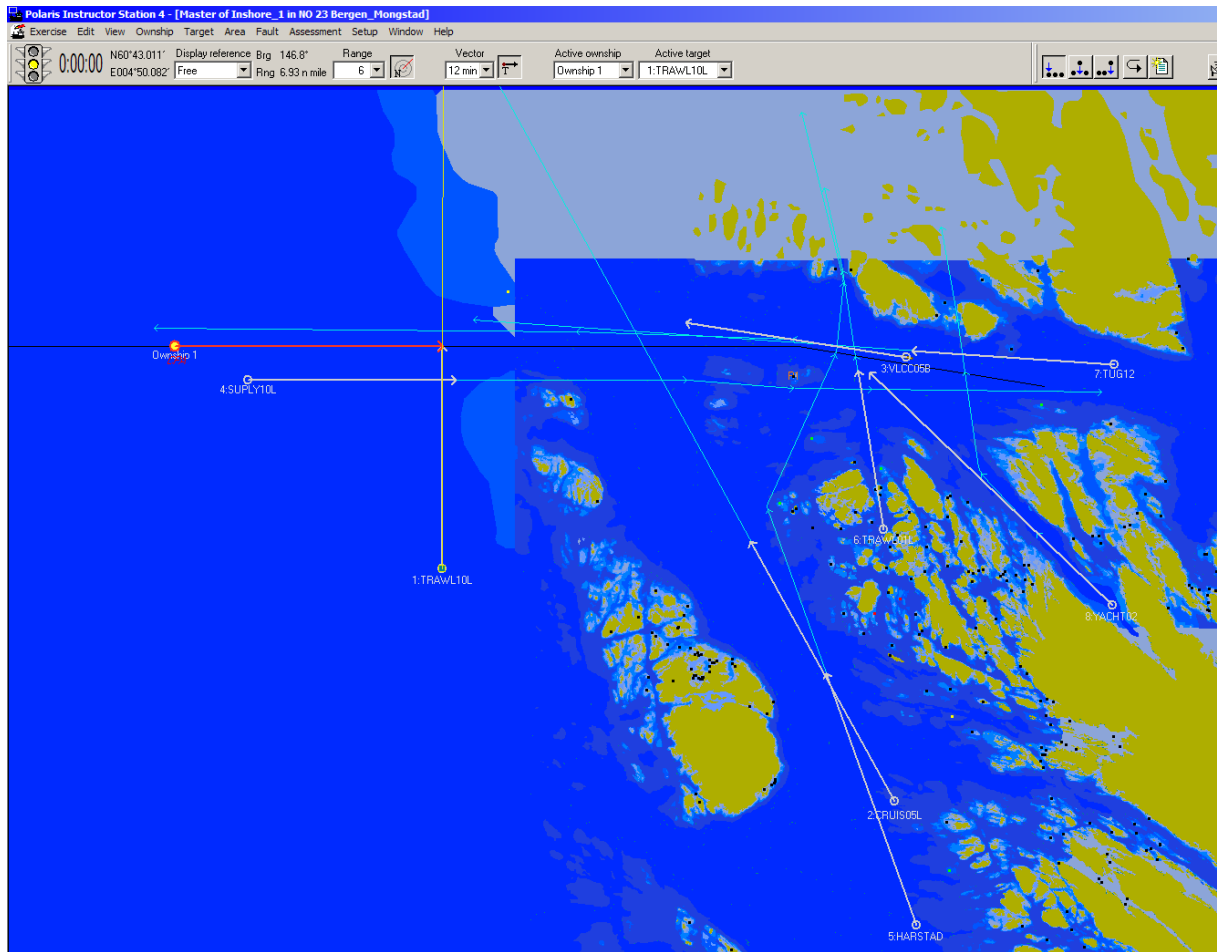
Figure 17. Scenario Trial 3.

Target num.	Model name	Dimension (length X width)	Initial Course (degrees)	Initial Speed (knots)	Initial TCPA (minutes)	Initial CPA (nm)	Relative initial position (bearing – range (nm))	Initial position (WGS 84)
Own ship	FRIGT14	132 X 16.8	090	18	-	-	-	60 51.315N – 004 28.110E
1	TRAWL10L	63.3 X 12.8	000	15.0	12	0	130 – 4.68	60 48.320N – 004 35.490E
2	CRUIS05L	260.7 X 31.5	331	20.0	21	0	122 – 11.5	60 45.190N – 004 47.969E
3	VLCC05B	315.0 X 47.2	279	15.0	18	See rmks	091 – 9.84	60 51.173N – 004 48.310E
4	SUPLY10L	86.2 X 19.0	090	14.0	14.5	0.45	115 – 1.06	60 50.864N – 004 30.109E
5	HARSTAD	83.0 X 15.5	340	18	27	See rmks	128 – 12.7	60 43.521N – 004 48.571
6	TRAWL01L	41.1 X 10.0	351	10.8	30.5	0	104 – 9.85	60 48.856N – 004 47.680E
7	TUG12	41.8 X 11.4	274	13.6	24	0.14	091 – 12.6	60 51.071N – 004 54.046E
8	YACHT02	92.1 X 12.8	314	22.6	35	See rmks	105 – 13.1	60 47.833N – 004 53.982E

Table 3. Scenario geometry.

Remarks:

- TGT3 altered course to 272° in minute 6:05. CPA after course alteration relative to planned route was 0.2 nm.
- TGT5 altered course three times. CPA relative to planned route was 0.25 nm in minute 28:40
- TGT8 altered the course to 350° in minute 31:37. CPA after course alteration relative to planned route was 0 nm.

5.3.3 Execution of trials

The execution of the trials was segmented in 2 separate periods, each with the duration of 1 workday. The reason was availability of simulator time, availability of participants and delivering time from Kongsberg Maritime Simulation AS. In the first conduct only standard ARPA was used during the trials. The second trial period was conducted with ARPA, CDP and RTM on the different bridges. The participants were numbered alphabetically according to their schedule on the simulator.

The trial days were divided in two parts. First day (4 hours) all participants were given a brief of the study's purpose and training in the use of the Polaris radar simulator and the equipment needed in the simulator. Some time had to be spent training on the Polaris radar because not all participants were familiar with the equipment. This is because the military participants are normally trained on DB10 radar simulator or they have other equipment onboard. Still this did not hampered the study since the Polaris radar is a standard radar and easy to learn and understand. Also the respective participants were educated and trained in the use of CDP or RTM. A repetition of ARPA functions was also given. Each participant had at least 1 hour to train on the actual equipment on the bridges in a training scenario. On the second day 5 to 6 bridges were run simultaneously. After each trial section the participants went immediately to the navigation laboratory and conducted the NASA-TLX test. On the second trial day it took about 4 hours per participant to conduct the three. Prior to trial start the participants were given oral and written instructions were recommended Polaris radar settings and ordered CPA limit was described. The participants sailing with CDP or RTM were in addition given CPAmax, TCPAlim, and TCPAcrit default values, selected by trial manage, see table 4. This was done to uniform the collision displays' performance in the test. TCPAlim and vector length was the only parameter the participants adjusted during the trials. The participants were informed that the targets would keep to preplanned track and not respond to OS manoeuvres.

Limit	Trial 1	Trial 2	Trial 3
CPA limit	0,5 nm	0,5 nm	0,2 nm
CPA max	2,0 nm	2,0 nm	2,0 nm
TCPA limit	30 min	30 min	15 min
TCPA critical	2,5 min	2,5 min	2,5 min

Table 4. Limits used during trials. TCPA limit was adjusted during trials.

6 Data collection and analysis

In order to evaluate the performance in the simulator studies, the assessment was divided in objective performance measures and subjective methods.

The objective performance data was recorded from the simulator navigation data. Necessary calculations were done post-hoc. The subjective methods were a self reported workload conducted immediately after completion of each trial using NASA – TLX (Task Load Index) and a quality of manoeuvre assessment with emphasis on COLREGs and good seamanship.

The simulators used were advanced and had high quality; still simulators are always an imitation of reality. The ability to recreate actual operational conditions will therefore never be complete. Thus the experience, viewed from the navigators' side, can never be compared to real life when thinking about possibility of loss of lives and material, etc.

6.1 Data Collection

6.1.1 Objective Performance data

The performance data was collected from the simulator navigation data and recordings from the helmsman. OS simulated GPS track was sampled at a rate of 0.1 Hz and minimum distance to all targets was recorded. Helmsman recorded time of manoeuvre. The obtained CPA was compared with the CPA limit given by the trial manager. The actual sailed tracks were plotted and cross track deviation (XTD) was calculated for each participant.

When managing the logged data some extreme values were observed. The arithmetic mean is sensitive to extreme scores when the population samples are small. Thus the median was chosen as the parameter for statistical analysis. "Medians are less sensitive to extreme scores and are probably a better indicator generally of where the middle of the class is achieving, especially for smaller sample sizes" (NWEA, 2011).

Cross track deviation

The OS ship actual track was compared to the planned route by calculating the XTD. The XTD was calculated as the deviation of the vessel relative to the planned course. The XTD was defined as the perpendicular distance between the participants' planned route and the actual track from the simulator GPS.

$$XTD = \frac{\left| C_X C_Y [(Y_E - Y_S)(X_P - X_S) - (X_E - X_S)(Y_P - Y_S)] \right|}{\sqrt{[C_X (X_E - X_S)]^2 + [C_Y (Y_E - Y_S)]^2}} \tag{2.1}$$

Where (X_P, Y_P) = longitude (X) and latitude (Y) of the point P along the actual track,

(X_S, Y_S) = longitude and latitude of the starting point of the planned route segment,

(X_E, Y_E) = longitude and latitude of the ending point of the planned route segment.

With the latitude and longitude parameters given in decimal degrees the constants become as follows:

C_Y = constant to convert latitude into meters (which is independent of longitude).

$$C_Y = 60*1852 = 111120 \tag{2.2}$$

C_X = constant to convert longitude into meters (for the average latitude of the course),

$$C_X = 60*1852*\cos(\Phi_m) \tag{2.3}$$

Where Φ_m is the average latitude.

The XTD results were used to explore conformity or trends between the different collision avoidance displays and the participants.

6.1.2 Subjective methods

The quality of manoeuvre assessment was done post-hoc with special emphasis on COLREG rule 15 which states: "When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel" (IMO, 1972).

6.1.2.1 Self reported workload (NASA-TLX)

NASA – TLX (Task Load Index) (Hart and Staveland, 1988) has since its origin spread far beyond its original application (aviation) and focus (crew complement). A study concerning evaluation of subjective workload recommended NASA-TLX when the goal is to predict the performance of a particular individual in a task (Rubio et al., 2004). Thus NASA - TLX was chosen to measure the mental workload. The self reported workload recording was done post – hoc on a computer with a PC version of the index (NCARAI) downloaded at http://www.nrl.navy.mil/aic/ide/NASATLX.php .

NASA – TLX is a subjective workload assessment tool which allows users to perform subjective workload assessments on operator working with various man-machines systems. NASA-TLX is a multi-dimensional rating procedure that derives an overall workload score based on a weighted average of ratings on six subscales. These subscales include: mental demands, physical demands, temporal demands, own performance, effort and frustration (Connors) . Table 5 defines the NASA-TLX subscales. Twenty-step bipolar scales are used to obtain ratings for the subscales with a score from 0 to 100 (assigned to the nearest 5). A weighting procedure is used to combine the six individual scale ratings into a global score. The procedure requires a paired comparison to be performed. The paired comparison requires the subject to choose which subscale is more relevant to workload across all pairs of the six subscales. The number of times a subscale is chosen as more relevant is the weighting of the respective subscale for a given task for that subject. A workload score from 0 to 100 is obtained for each rated task by multiplying the weight by the individual subscale score, summing across scales, and dividing by 15 (the total number of paired comparisons).

The NASA-TLX was utilised to map the subjects' perception of the workload for each trial.

EVALUATION OF SUBJECTIVE MENTAL WORKLOAD		
TITLE	**ENDPOINTS**	**DESCRIPTIONS**
MENTAL DEMAND	*Low/High*	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	*Low/High*	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	*Low/High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
EFFORT	*Low/High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
PERFORMANCE	*Good/Poor*	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
FRUSTRATION LEVEL	*Low/High*	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Table 5. Rating scale definitions and endpoints from the NASA Task Load Index

6.2 Data analysis

The data collected from the simulator was analysed by descriptive methods and parametric tests. The parameters evaluated were time of manoeuvre, XTD, distance to targets, self reported workload and quality of tracks. The actual sailed track was also plotted. There were two populations (experienced and cadets) and three groups, ARPA, CDP and RTM (display 1, 2, 3, respectively), with different participants for each condition. The analysis was divided in three parts; (a) experienced mariners, (b) cadets and (c) comparing results from analysis (a) and (b).

ANOVA (analysis of variance) was used to test for significant differences between medians. One factor ANOVA test was conducted to examine the following hypotheses:

H_0 : The three populations are identical with added CDP or RTM; $H_0 : \mu_1 = \mu_2 = \mu_3$

H_1 : The three populations are not identical with added CDP or RTM; $H_1 : \mu_1 \neq \mu_n$

where μ is the mean of each population.

The level of significance α was set as $\alpha = 0.05$. Significances (P<0.05) would be defined by rejecting the null hypothesis (H_0), shoving that there is a significant difference arising from the independent variable (CDP or RTM availability).

If a significant difference was detected, a new ANOVA test was conducted to investigate difference between the means of the CDP and RTM population. Thus testing the following hypotheses:

H_{0_1}: The two populations are identical with added RTM information

H_{1_1}: The two populations are not identical with added RTM information

The level of significance α was set as $\alpha = 0.05$. Significances (P<0.05) would be defined by rejecting the null hypothesis (H_{0_1}), shoving that there is a significant difference arising from the independent variable (RTM availability).

In addition for testing significant differences between the experienced navigators and the cadets the following hypotheses was tested:

H_{0_2}: The two populations are identical.

H_{1_2}: The two populations are not identical.

The level of significance α was set as $\alpha = 0.05$. Significances (P<0.05) would be defined by rejecting the null hypothesis (H_{0_2}).

XTD

The participants' overall mean XTD in each trial was calculated for each display type. In addition graphs were plotted showing the median of the participants mean XTD and the standard deviation.

NASA TLX – self reported workload

The participants' overall median total workload in each trial with regards to display type was calculated for each display type and the ANOVA test conducted. In addition graphs were plotted showing the median and the standard deviation.

Analysis distance to targets

Distance to targets was measured at CPA. Number of CPA violations was counted and plotted. A descriptive analysis of the graphs was done with comparing for each trial the different displays. The emphasis was counting the number of violations from the set CPA limit. A CPA limit violation was defined as shown in eq.

$$CPA_n < [CPA_{\lim} - 0.05] \ (nm) \tag{3.1}$$

Where n is target number.

Time of manoeuvre

All manoeuvres were logged. The median times for first manoeuvre were calculated. ANOVA was used to test for significant differences between the display types.

Track analysis

Evaluation of the tracks with regards to COLREGs was done, with special attention to rule 15, Crossing situations. When considering rule 15 one must divide between open water and inshore waters. Inshore you might encounter situations where it is safer to pass ahead than astern of a crossing target. The evaluation was based on my extensive experience as a navigator and knowledge of the COLREGs. In some cases I have conferred with members of the Royal Norwegian Navy Competence center.

7 Results, evaluation and assessment

The results are divided in experienced navigators (from now OOW, Officer OF the Watch) and cadets. The results of the five evaluated parameters are presented by graphs. In the track graphs a proposed optimum track (colored black) is drawn where no CPA limit is violated and COLREGs are adhered. One must remember the optimum track is a proposed track since there are different possible solutions to the scenario as shown by the participants' choice of tracks.

When the sailed tracks were inspected a few solutions where puzzling. The participants come from an apparently homogenous group; still there are some track solutions that stand out from the rest. An important remark is that the "odd" manoeuvres cannot be connected to a particular participant. They vary between the participants throughout the trials. This can be attributed to the variation in the human performance (Hollnagel, 1998) and the manoeuvring restriction in speed (trial artificiality).

When evaluating the time of initial evasive manoeuvre the calculation to quantify the difference between the displays performance was done as described in eq. (4.1)

$$\left|\frac{A-B}{B}\right| = x \quad \%$$

(4.1)

Here A and B equals display type, e.g. ARPA versus CDP where ARPA equals A and CDP equals B. x is the difference between displays in percent. The reader must remember that the presented value is an absolute value and only reflect the difference. In order to indentify the higher/lower value the respective table must be inspected.

ANOVA was used to test for significant results by first calculating for all display types and then, if a significant value was found, the test was conducted between two and two displays.

7.1 Participant conduct during trials

The conduct of the trials was observed from the simulator instructor room. The radar screen from all bridges was monitored. The participants with ARPA display used the trial manoeuvre function and relative vectors to solve potential close encounters. In the CDP group the participants used VRM to mark OS vector and the EBL to find a suitable course for evasive manoeuvre. The RTM group applied the same functions as the CDP group by using the VRM and EBL to explore possibilities for evasive manoeuvres. In addition it was observed that the RTM group tended to increase the vector length scale in order to make the RTM solution present the full cone shape. As previously described, once the tip of the target vector crosses the Vmax circle in the RTM display, the presentation will be equal to the CDP display. This was mainly done to identify corresponding targets to the RTM presentation.

Prior to the trials it was stressed that it was important to reduce the vector length with decreasing relative distance to be able to supervise the collision risk until the closest target(s) has passed when using CDP or RTM display. During the trials it was observed that some participants struggled with this. Especially since the POLARIS radar solution has a lower vector length limit of 3 minutes. This meant that once TCPA was smaller than 3 minutes, the participants could not use the CDP/RTM display to supervise collision risk. If such monitoring was required the participants used the VRM.

7.2 Manoeuvring time, XTD and NASA TLX

7.2.1 Initial manoeuvring time

Table 6 describes the time of first evasive manoeuvre conducted by theOOWs. The standard deviation (SD) is given in seconds.

Descriptive and statistical results	Manoeuvring time (hours:minnutes:seconds)			
Median results	Display type	TRIAL 1 (SD [s])	TRIAL 2 (SD [s])	TRIAL 3 (SD [s])
	ARPA	00:02:30 (39)	00:03:51 (50)	00:02:47 (68)
	CDP	00:02:07(34)	00:02:10 (47)	00:01:58 (55)
	RTM	00:01:57 (21)	00:01:42 (28)	00:02:03 (22)
	ARPA vs CDP [%]	18	78	42
	ARPA vs RTM [%]	28	128	36
	RTM vs CDP [%]	8	22	4
Statistical results p-value(5%)	Overall	0,1242	***0,0008***	0,139
	RTM – CDP	Nil	0,338	Nil

Table 6. OOW results for initial manoeuvring time.

The CDP and RTM group reacted significantly faster than the ARPA group in Trial 2, p-value=0.0008. A decreased median reaction time of 78% and 128 % shows that the CDP and RTM display enhanced the navigator's ability to assess and take proper action in the complicated traffic scenario. In Trial 1 and Trial 3 the median reaction time was also faster but not statistically significant. No significant difference in reaction time was found when the CDP and RTM display was compared.

Table 7 describes time of first evasive manoeuvre conducted by the cadets.

Descriptive and statistical results	Manoeuvring time cadets (hours:minnutes:seconds)			
Median results	Display type	TRIAL 1 (SD [s])	TRIAL 2 (SD [s])	TRIAL 3 (SD [s])
	ARPA	00:04:15 (119)	00:04:29 (100)	00:02:53 (114)
	CDP	00:01:24 (39)	00:01:42 (29)	00:02:07 (44)
	RTM	00:01:22 (31)	00:01:48 (57)	00:01:08 (35)
	ARPA vs CDP [%]	202	164	37
	ARPA vs RTM [%]	211	149	154
	RTM vs CDP [%]	3	6	46
Statistical results p-value(5%)	Overall	***0,018***	***0,005***	0,0727
	RTM – CDP	0,344	0,669	Nil

Table 7. Cadet results for initial manoeuvring time.

As for the OOWs table 7 shows that the CDP and RTM have an initial evasive manoeuvre statistically significantly faster than the ARPA group. It is clear that the CDP/RTM display enhanced the cadets' situational awareness. An interesting result is that in Trial 1 the cadet CDP/RTM group react about 200% faster than the ARPA group, while for the OOWs there were no significant differences. This is related to the fact that Trial 1 was relatively simple and the CDP or RTM display did not contribute significantly to enhance the situational awareness of the OOWs compared to the ARPA group. The cadets and OOWs in Trial 1 using ARPA display were compared and the OOWs made the initial evasive manoeuvre 70.6% faster than the cadets. This result was significantly different with p-value=0.048. The result can be related to the OOW's experience and tacit knowledge.

In Trial 3 there were no significant differences found in the two populations. Still it is clear that the CDP or RTM display clearly contributed to the navigators' ability to effectively assess the situation and enforce an action in the form of an evasive manoeuvre.

7.2.2 XTD
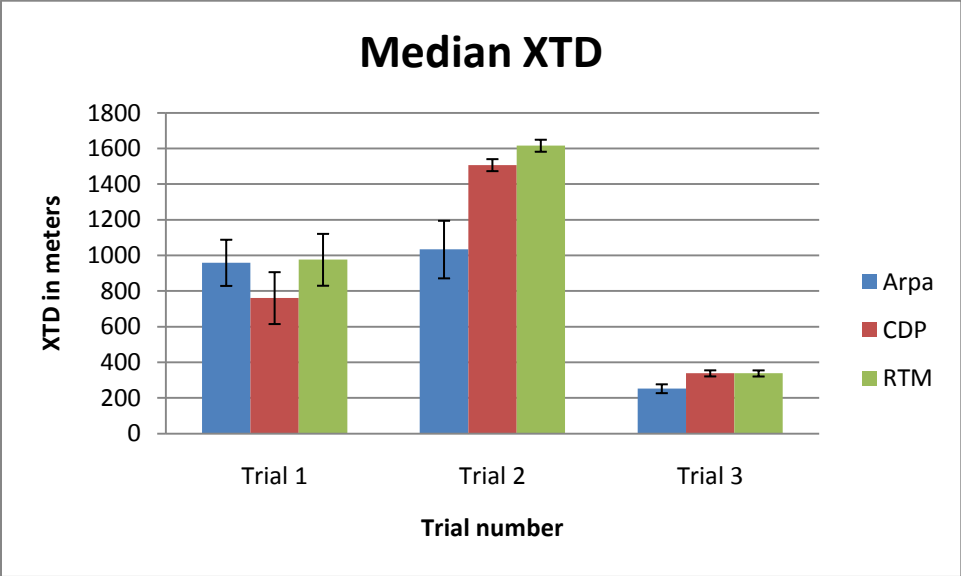
Figure 18. OOW median XTD with bars illustrating the standard deviation (SD).

Figure 18 was constructed by first taking the mean of each participant's XTD for each trial. The standard deviation was calculated for each type of display and trial, and the median for each group was found. The median XTD is of course directly related to the participants' choice of track. As can be seen Trial 2 is the only trial where there is a significant difference between the ARPA group and CDP/RTM group, p-value=0.019. This can be directly linked to the fact that the CDP and RTM group made the initial evasive manoeuvre significantly faster than the ARPA group in Trial 2, thus deviating from the route earlier than the ARPA group. The results from participant R has been omitted due to very unrealistic performance in the CDP group Trial 3. He entered the fjord passing south of the intended gateway; see figure 17 and figure 30.
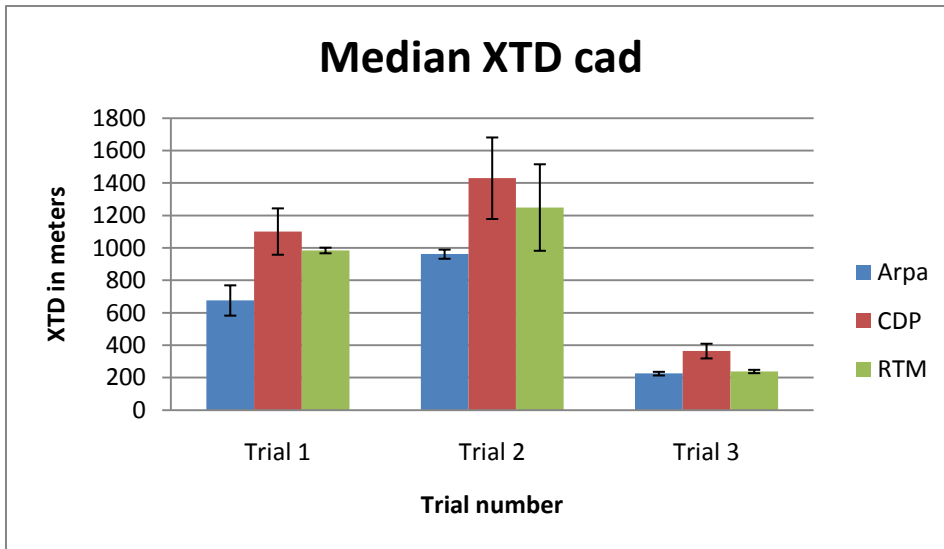
Figure 19. Cadet median XTD with bars illustrating the standard deviation (SD).

From figure 19 it is found that the median XTD values are higher for the CDP and RTM group in both Trial 1 and Trial 2. This is a direct consequence of the fact that the participants made a faster initial evasive manoeuvre than the ARPA group. In Trial 3 there were no significant differences in the values. In the RTM group Trial 3, participant UUs' results have been omitted due to a 360° turn prior to entering the fjord, see figure 31. The consequence of the manoeuvre was that the participant did not encounter any further close quarter situations and with that he did not have to deviate from the route.

7.2.3 NASA TLX
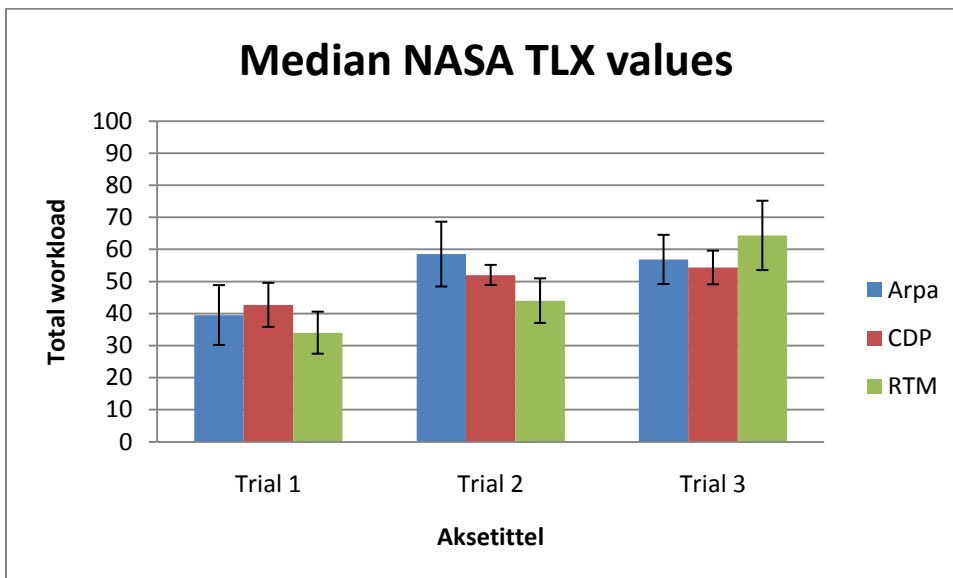
Figure 20. OOW median NASA TLX results with SD bars.

Figure 20 was constructed by finding the median total workload in each group and calculating the standard deviation. The figure illustrates that the experienced total workload for each display type is generally increasing as the complexity of the scenarios increases. This was as expected. There are

some differences between the values of the different display types, but none can be classified as statistically significant. The CDP or RTM display did not give the navigator a reduced experienced mental workload. A reason for this might be that the navigator may need more time to familiarize with the new type of display to be able to use it optimally. An equally important result is that the alternative displays did not contribute to an increased workload even though the participants had only one hour of practice in addition to the given introduction. In technological applications there is a constant need to ensure that the design of the human-machine interface does not add to operator workload.
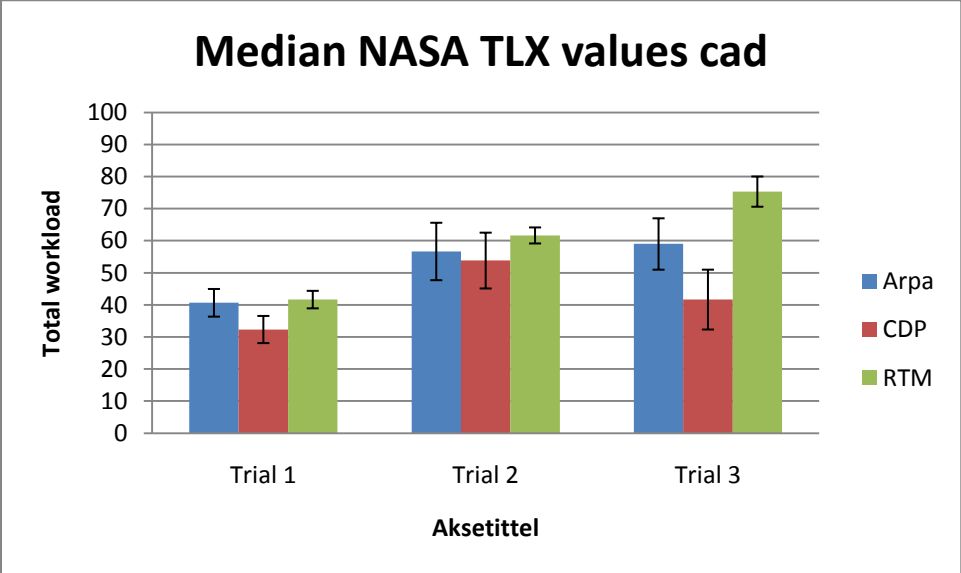
Figure 21. Cadet median NASA TLX results with SD bars.

Figure 21 shows, as for the OOWs, a generally increasing value of the total workload for each trial. No statistically significant difference was found between the different displays. When inspecting the figure the experienced median total work load of the RTM group seems to be higher than the other groups in Trial 3. This may indicate that the RTM display was not optimal when operating inshore. In general, as for the OOW population, the RTM and CDP display did neither contribute to a decreased nor an increased experienced total workload.

7.2.4 CPA

After completion of the trials, the numbers of CPA violations were recorded following the criteria previously described in subchapter 6.2. The results are presented in figure 22 and figure 23. The results from participant R has been omitted due to very unrealistic performance in the CDP group Trial 3.
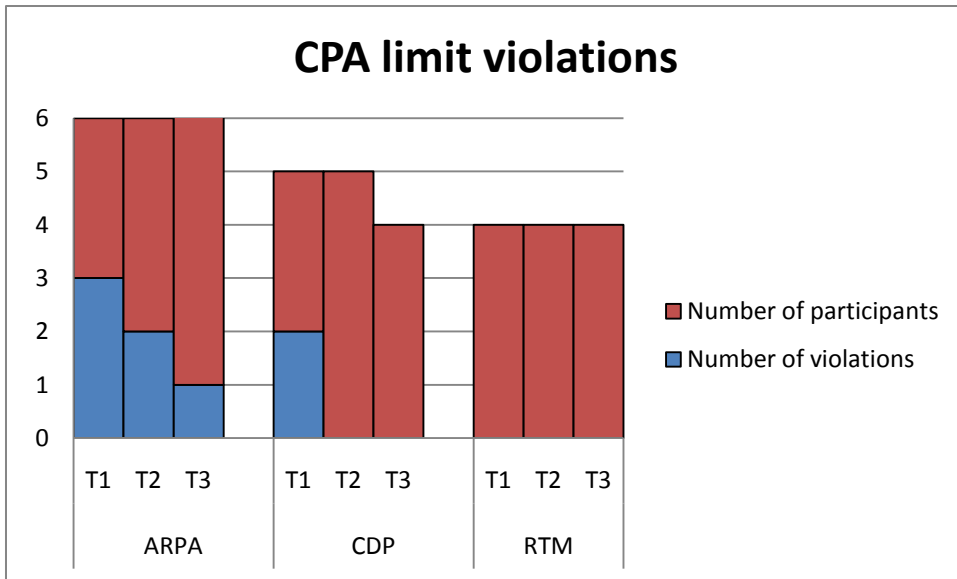
Figure 22. OOW number of CPA limit violations and number of participants.
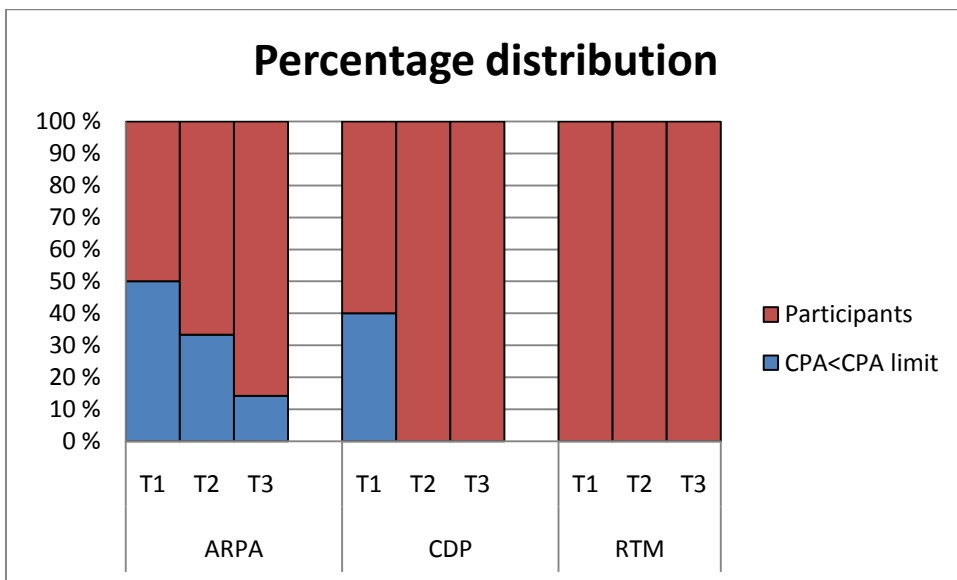
Figure 23. OOW distribution of participants and CPA violations in percentage.

Figure 22 illustrates the absolute number of CPA limit violations with the blue column. The red column gives the number of participants, e.g. in the ARPA group Trial 1 there are three CPA violations and the total number of participants is six. As can be seen in figure 23 the ARPA group has a percentage share of 50%, 30% and 10% in Trial 1, Trial 2 and Trial 3 respectively and the CDP group 40% in Trial 1. From the figures it is clear that the participants in the CDP and RTM group have fewer absolute violations of the CPA limit and the percentage share is smaller.
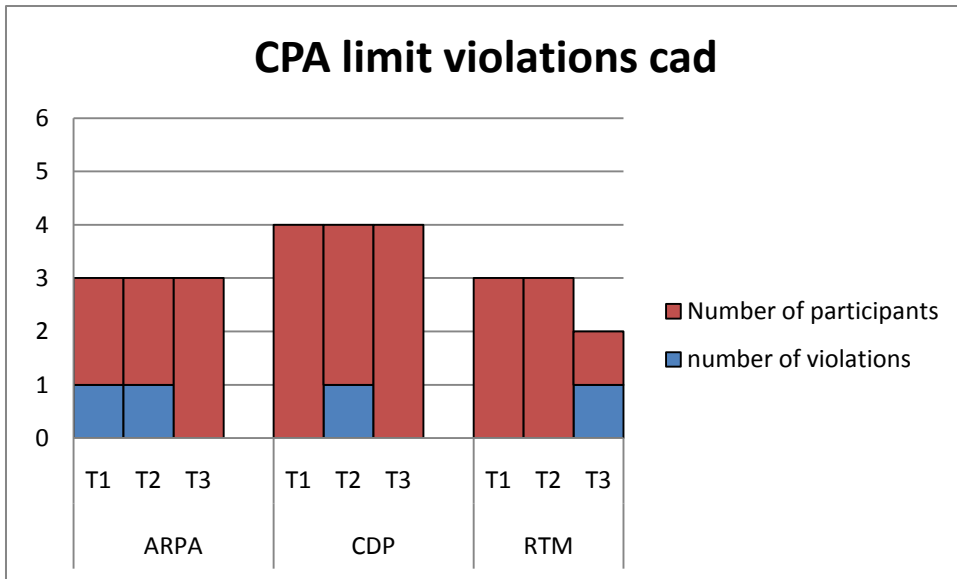
Figure 24. Cadet number of CPA limit violations and number of participants.
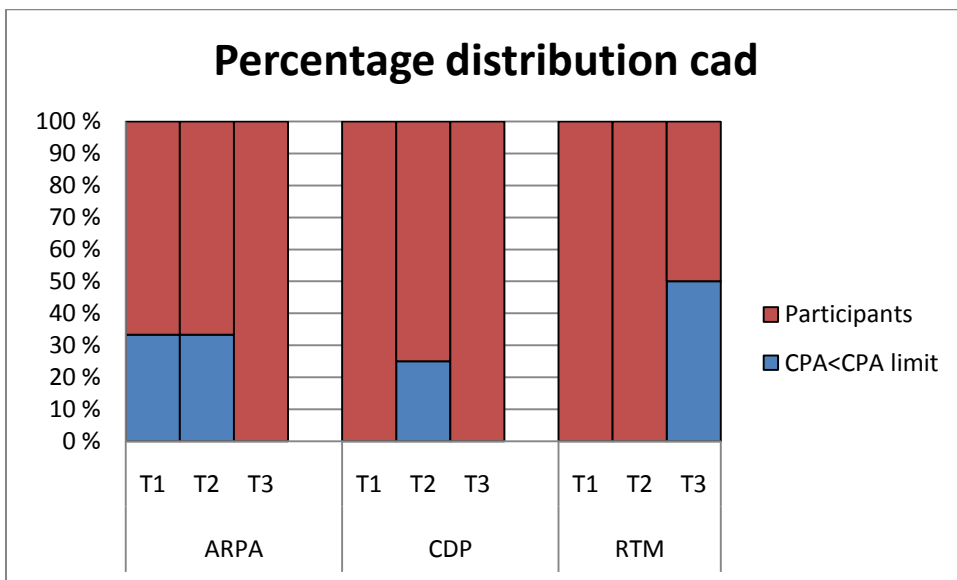
Figure 25. Cadet distribution of participants and CPA violations in percentage.

In the RTM group Trial 3, participant UUs' results have been omitted due to a 360° turn prior to entering the fjord. The absolute number of cadet CPA limit violations and number of participants in each group is shown in figure 24. Figure 25 shows a percentage share of 33 % in the ARPA group in Trial 1 and Trial 2. The CDP has a percentage share of 25% in Trial 2 and the RTM group 50% in Trial 3. The results show that the participants that used CDP display had the fewest CPA limit violations.

When taking in to account the results found from the experienced navigator population it is clear that the CDP and RTM display contributed to a decreased number of CPA limit violations in all trials. No significant difference was found between the DCP and RTM, except an indication that the RTM display is not optimal in inshore waters. This assumption is also supported by the reported total workload for the cadet RTM group found in figure 21.

7.3 Track analysis

7.3.1 Trial 1

7.3.1.1Experienced navigators (OOW)
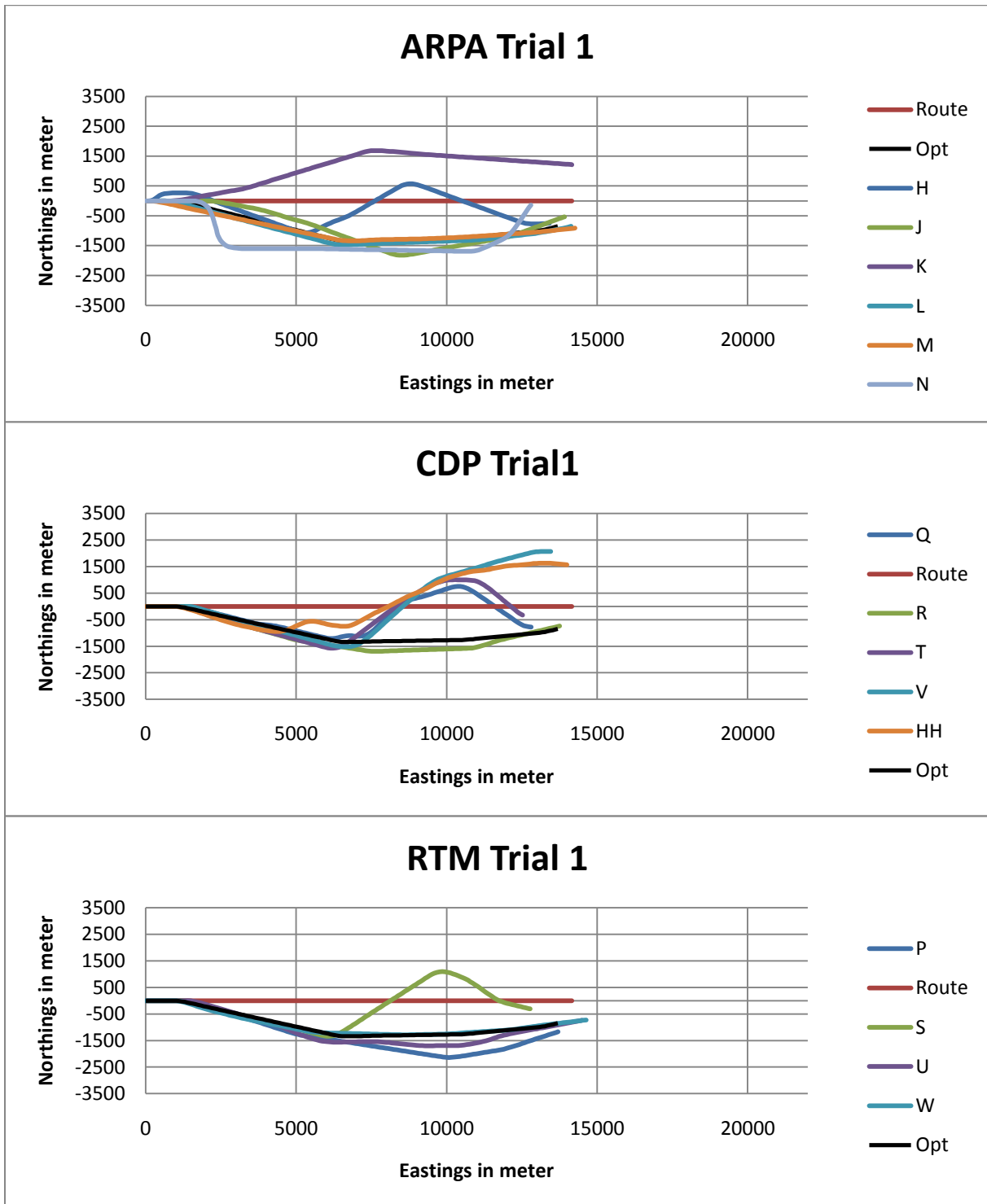
Figure 26. OOW track during Trial 1. Black track shows proposed optimum solution

Figure 26 shows the participants actual sailed tracks and we can identify two preferred solutions; one similar to the proposed optimum track and one where the participants turn port after clearing TGT 1. In the optimum track one will pass astern of TGT 1 and TGT 2, and ahead of TGT3, see figure 14. In Trial 1 passing ahead of TGT 3 with minimum CPA of 0,5nm (926 meters) is not a problem with regards to COLREGs due to the target's speed, 12 knots, provided OS intention and manoeuvre is executed in ample time.

ARPA group

The tracks of participant M, J and L were similar to the optimum solution. M and J kept the CPA limit. J broke the CPA limit when passing TGT1 (CPA=780m). Participant K is the only one that made an initial port manoeuvre thus passing ahead of TGT 1 and TGT2 and astern of TGT3 keeping the CPA limit. With regards to COLREGs this was not an optimum solution. Participant H passed astern of all targets, which was a good plan, but he failed twice to keep the CPA limit (TGT1 CPA=776m, TGT3 CPA=700m). Participant N chose to make three almost 90° turns, which was not a very supple way of sailing. He passed astern TGT1 and TGT2 and ahead of TGT3 keeping the CPA limit.

CDP group

All five participants made an initially starboard manoeuvre. R kept to the south and had a track similar to the optimum keeping CPA limit. Participant T and Q turned port after clearing TGT1 and passed astern the two remaining targets which was a good solution, but Q broke CPA limit when passing astern of TGT3 (CPA=815). Participant V and HH chose to pass ahead of TGT2, thus ending far north of the route and not acting in accordance with COLREG rule 15. In addition HH broke the CPA limit when he passed astern TGT1 (CPA=691 m).

RTM Group

All participants exempt S kept to the optimum track. Participant S chose to go astern of all targets which also was a very good solution.

Summing up the evaluations of the three groups:

- ARPA: 5 of 6 participants made a sensible initial evasive manoeuvre of which 3 had a sensible total track.
- CDP: All (5) participants made a sensible initial evasive manoeuvre of which 3 had a sensible total track.
- RTM: All (4) participants sailed a sensible total track

The track study show that 3 participants did not act in accordance with the COLREGs in some part of the trial. In the CDP group 2 participants chose to pass ahead of the last target. This is a puzzling decision which may be attributed to improper use of the CDP display in the final stage of the trial. The navigators based their decision solely on the geometrical solution, not taking into account the COLREGs. The remaining participants acted in accordance with the COLREGs. Taking into account the parameters discussed in subchapter 7.2, the preliminary ranking of the display types is as follows: 1. RTM, 2.CDP, 3. ARPA.
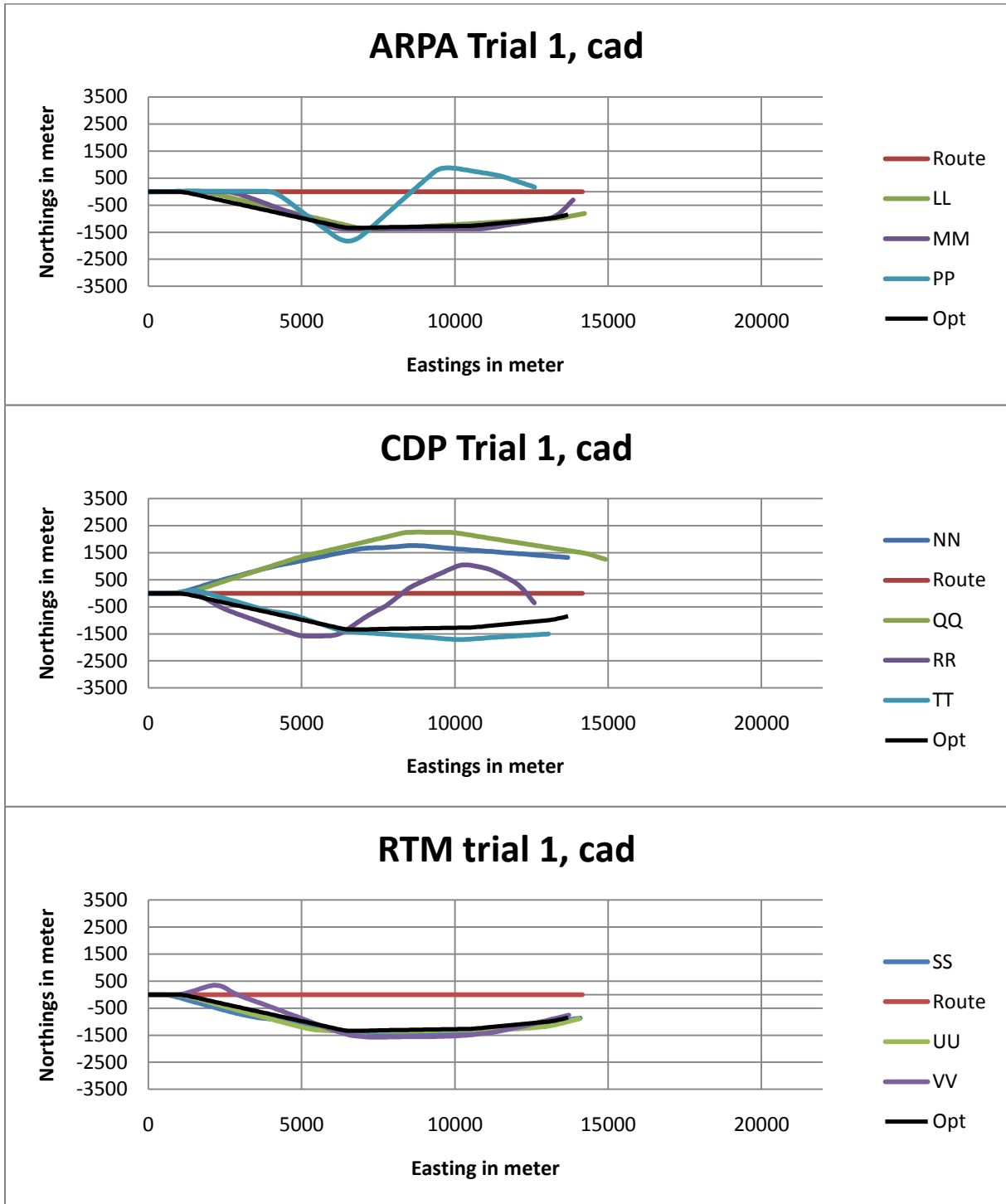
Figure 27. Cadet track during Trial 1. Black track shows proposed optimum solution

Figure 27 shows the tracks of the cadet population. The proposed optimum solution is the same as for the experienced navigator population.

ARPA group

The track of participant MM and LL are similar to the optimum track. Both participants kept the CPA limit. Participant PP passed astern of all targets, which was a good plan, but he broke the CPA limit of TGT2 (CPA=785m) and the initial evasive manoeuvre was executed very late.

CDP group

Participant TT had a track resembling the optimum solution and he kept the CPA limit. Participant RR passed astern of all targets keeping the CPA limit, which is considered a sensible track. Participant NN and QQ chose to take a northern path passing ahead of TGT1 and TGT2 and astern of TGT3. This track was not in accordance with COLREG rule 15. Both participants kept the CPA limit.

RTM group

All participants sailed a track resembling the optimum solution keeping the CPA limit. Participant VV made an initial manoeuvre to port, but changed his plan in ample time and chose a southern path.

Summing up the evaluations of the three groups:

- ARPA: 2 of 3 participants made a sensible initial evasive manoeuvre. 2 participants had a sensible total track. 1 participant executed the initial manoeuvre very late.
- CDP: 2 of 4 participants made a sensible initial evasive manoeuvre. 2 participants had a sensible total track.
- RTM: All (3) participants sailed a sensible total track

The track study indicates that 3 participants failed to act in accordance with the COLREGs. One participant made a very late initial evasive manoeuvre in the ARPA group. 2 participants in the CDP failed to take in to account the COLREGS and focused on the geometrical solution presented by the CDP display. Taking into account parameters from subchapter 7.2 the preliminary ranking is as follows: 1.RTM, 2 CDP, 3 ARPA.

7.3.2 Trial 2

7.3.2.1 Experienced navigators (OOW)
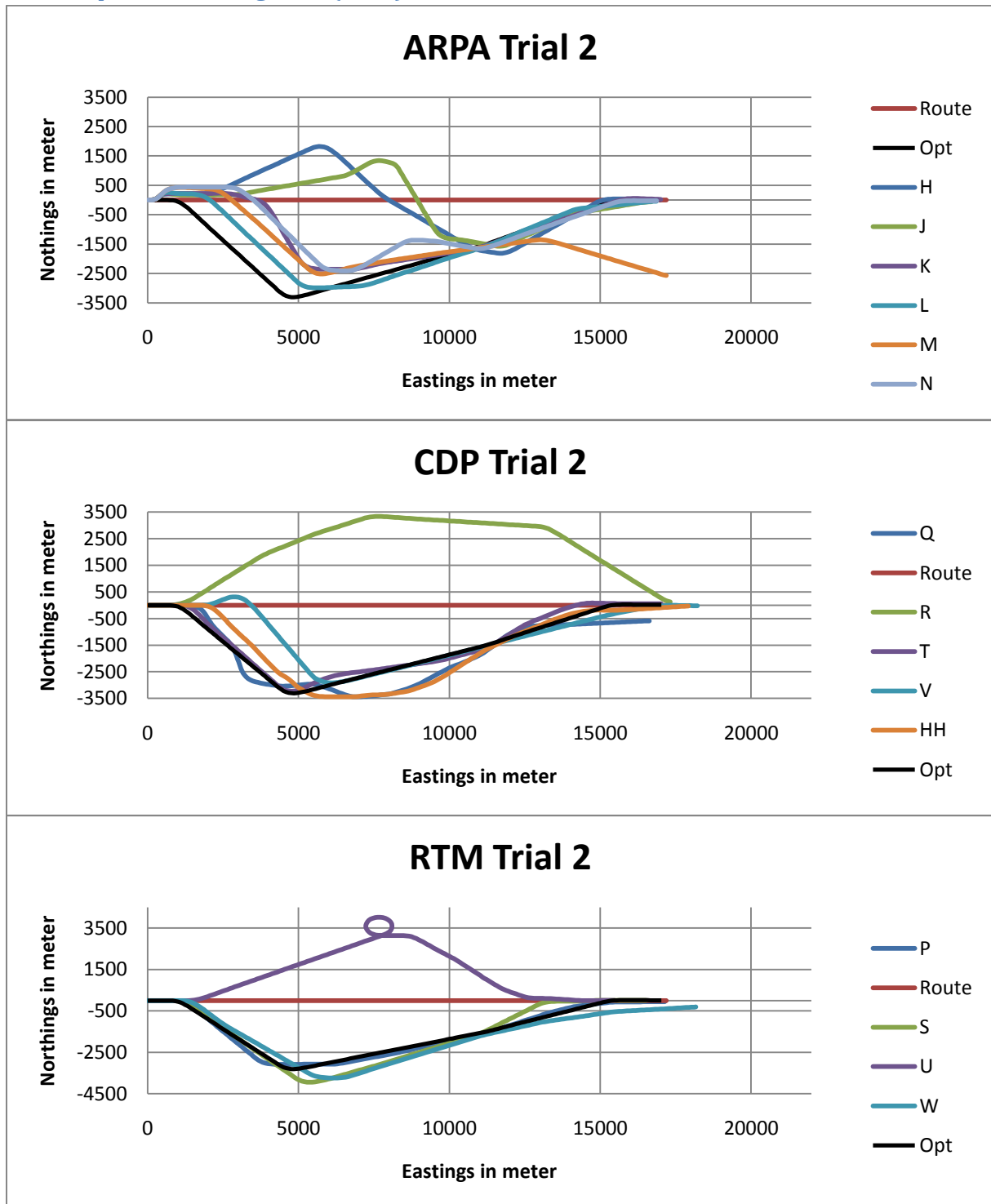
Figure 28. OOW track during Trial 2. Black track shows proposed optimum solution

Figure 28 clearly indicates that most participants chose a southern track. The proposed optimum track is in accordance with the COLREGs and good seamanship. Sailing the optimum track one will pass astern of all crossing targets and TGT 4 will be passed on OS port side. Careful inspection of the ARPA group's tracks show an initial course alteration to port for all participants. This was due to a

simulator fault in the steering console. The fault was rectified for the remaining of the trials. Thus the port manoeuvre is omitted from the analysis. The course alteration did not have a significant impact on the trial in total.

ARPA group

Four participants chose an initial starboard manoeuvre and sailed a track profile similar to the optimum solution. In addition all four participants kept the CPA limit. From the figure it is clear that the participants' manoeuvre was executed significantly later than the proposed optimum track. This was also confirmed in table 6. Participant N made more course alterations than necessary with the possible consequence of not demonstrating clearly his intentions. Participant H and J chose an initial starboard manoeuvre. When asked the reason for this manoeuvre, the participants replied that the decision was based on the initial relative distance to TGT2, which was considered to be large, and the failure to inspect the targets speed (27 knots). As can be seen from the tracks both participants chose to alter the initial plan of passing ahead of TGT2 by eventually turning starboard and then passing astern of all crossing targets and passing TGT 4 on OS port side. Participant J did not make the starboard course change in ample time as can be seen by the large course alteration needed. He also failed to keep the CPA limit to TGT2 (CPA=507m) and TGT4 (CPA=740m).The tracks of participant H and J are not in accordance with the COLREGs and participant J's track violates the COLREGs more severe than participant H. A puzzling manoeuvre was done by participant M in the final stage of the trial. He chose to pass ahead of TGT5. This was not in accordance with the COLREGs and the aims of the trial (keep to preplanned route as good as feasible).

CDP group

4 of 5 participants chose a track profile similar to the optimum solution and kept the CPA limit. Participant V had an initial port manoeuvre but quickly changed the plan and sailed a southern track. Participant R chose a northern track and passed ahead of TGT1 and TGT3, astern of TGT2 and TGT5 and TGT4 was cleared on OS starboard side. Participant R's track was not in accordance with the COLREGs. The participant reported that the decision to evade to port was based on the large initial relative distance to TGT2. He failed to observe the TCPA and the targets speed. If the TCPA and target speed had been evaluated he would had most likely altered the course to starboard. As can be seen from the track plot, the CDP group executed the initial evasive much earlier than the ARPA group. This is also confirmed by the results given in table 6.

RTM group

As for the CDP group all participants in the RTM group kept the CPA limit. 3 participants had a track profile similar to the optimum track and all initial evasive manoeuvres were executed faster than the ARPA group. Participant U chose a northern part based on the same reasons as discussed in the previous section. The 360° turn was done when the participant realised he was not able to pass ahead of TGT2 without getting a very large track deviation. The decision to pass astern TGT2 was made very late. In order to not violate the CPA limit and make a course alteration towards TGT2 he chose to turn away from the target, which was a good decision at the given time. The participant passed astern of all crossing targets and cleared TGT4 on OS starboard side. Summing up participants U's track, he made an initial decision based solely on the geometrical solution, forgetting to check

TCPA and target speed. The decision to pass astern TGT2 was made to late and forced the participant to make a 360° turn.

Summing up the evaluations of the three groups:

- ARPA: 4 of 6 participants made a sensible initial evasive manoeuvre of which 3 participants had a sensible total track.
- CDP: 3 of 5 participants made a sensible initial evasive manoeuvre. 4 participants had a sensible total track.
- RTM: 3 of 4 participants made a sensible initial evasive manoeuvre. 3 participants sailed a sensible total track

As identified in the track evaluation TGT2 constituted a challenge for many participants as anticipated. The failures of not taking into account all available information lead to some inappropriate decisions. COLREG rule 7 part (c) reads: "Assumptions shall not be made on the basis of scanty information, especially scanty radar information"(IMO, 1972). The participants who indentified and executed a sound solution for clearing TGT2 obtained a more or less similar track profile. When observing figure 28 it is obvious that the CDP and RTM group executed the initial manoeuvre significantly earlier than the ARPA group, which is also confirmed by table 6 (p-value=0.008). Taking into account parameters from subchapter 7.2 the preliminary ranking is as follows: 1.CDP, 2 RTM, 3 ARPA.

7.3.2.2 Cadets
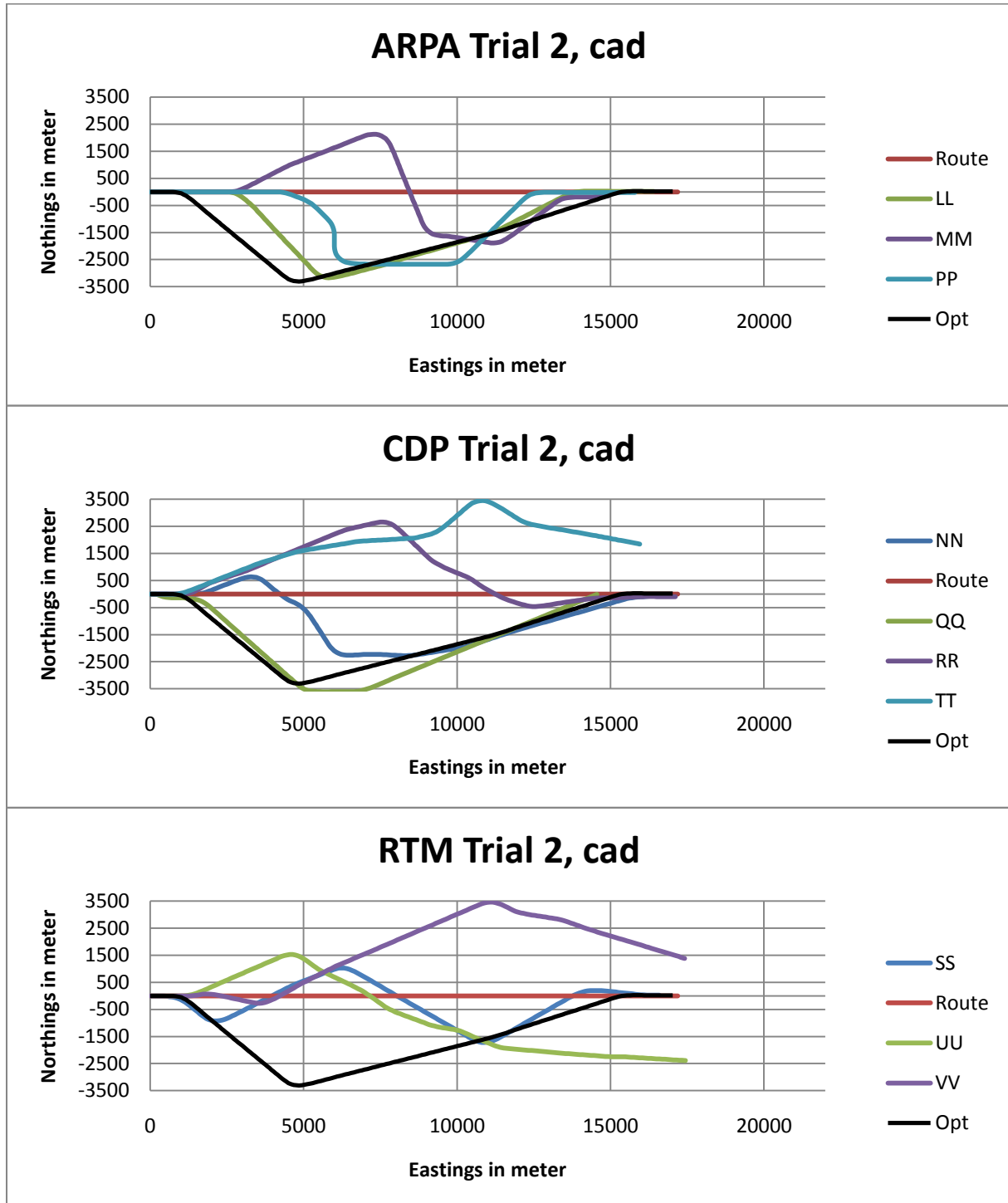
Figure 29. Cadet track during Trial 2. Black track shows proposed optimum solution

The optimum solution is the same as for the experienced navigator population.

ARPA group

All participants passed astern of crossing targets and the head-on target (TGT 4) was passed on OS port side. From figure 29 it is observed that the participants made the initial evasive manoeuvre significantly later than the proposed optimum track. Participant LL and PP made an initial manoeuvre

to starboard, which is a good decision. Participant LL kept the CPA limit for all targets. Participant PP made the initial manoeuvre very late and was forced to do a very large course change to be able to clear TGT2, still he was not able to keep the CPA limit (CPA=610m). In addition it can be observed that the participant was late compared to the optimum track when manoeuvring back towards the route. Participant MM chose an initial evasive manoeuvre to port, later he altered course to starboard and managed to keep the CPA limit for all targets. The starboard turn was not conducted in ample time thus forcing a very large course change.

CDP group

Only one participant (QQ) made an initial evasive manoeuvre to starboard. Participant NN turned initially to port but quickly reconsidered the plan and turned to starboard. Further during his track one can identify several small course adjustments. This is unfortunate since many small course changes do not demonstrate clearly OS intentions and may confuse surrounding traffic. Both participant QQ and NN kept the CPA limit. Participant RR and TT chose an initially evasive manoeuvre to port. As previously discussed this is not a good solution. RR eventually turned starboard and passed astern of TGT2. He passed astern the rest of the crossing targets and cleared TGT4 on OS starboard side, which is reasonable since he avoided crossing the path of the target. The CPA limits were kept. Participant TT proceeded a northern track and passed ahead of TGT 1 and TGT3 and astern of TGT 2. TGT4 was cleared on OS starboard side. He broke the CPA limit of TGT1 (CPA=610m). All in all this track was not in accordance with the COLREGs nor did it keep the CPA limit.

RTM group

No participants had a track profile similar to the proposed optimum solution. All participants kept the CPA limit. Participant SS was the only with an initial evasive manoeuvre to starboard but he then altered course to port before TGT2 was cleared. This was a puzzling manoeuvre. The participant then altered the course again to starboard and passed astern of all crossing targets and cleared TGT4 on OS port side. Considering COLREGs the manoeuvres conducted before passing TGT2 do not clearly indicate the participants' intentions.

Participant UU made an initial evasive manoeuvre to port and later reconsidered and altered course to starboard and passed astern TGT1, TGT2 and TGT3 and ahead of TGT5. TGT4 was cleared on OS port side. Again the initial manoeuvre can be attributed to failure of not taking into account all target data available when making the decision. The decision of passing ahead of TGT5 is very inappropriate and violates the COLREGs and the trial aim. Participant VV made an initial starboard manoeuvre and then a port manoeuvre. Once on a northern path the participant did not alter his plan. He passed ahead of TGT1 and TGT3, astern of TGT2 and TG5. TGT4 was cleared on OS starboard side. Also in this track the initial intentions are not clear in addition the participant do not follow the COLREGs.

Summing up the evaluations of the three groups:

- ARPA: 2 of 3 participants made a sensible initial evasive manoeuvre of which 1 participant had a sensible total track.
- CDP: 1 of 4 participants made a sensible initial evasive manoeuvre. 2 participants had a sensible total track.

- RTM: 2 of 3 participants made a sensible initial evasive manoeuvre. No participants sailed a sensible total track.

As for the experienced navigators, TGT2 was very challenging. When observing figure 29 it is obvious the cadets have suffered on lack of experience when evaluating the initial manoeuvre. Decisions were based on scanty information, crossing targets were passed ahead and small course alterations were made, thus violating COLREG rule 7, rule 8 and rule 15. When considering time of initial manoeuvre the CDP and RTM group reacted significantly faster than the ARPA group, p-value=0.005 ref. table 7. Evaluating the display types against each other was very hard since Trial 2 clearly was very challenging for the cadet population. Taking into account parameters from subchapter 7.2 the preliminary ranking is as follows: 1CDP, 2 RTM, 3 ARPA.

7.3.3 Trial 3

7.3.3.1 Experienced navigators (OOW)
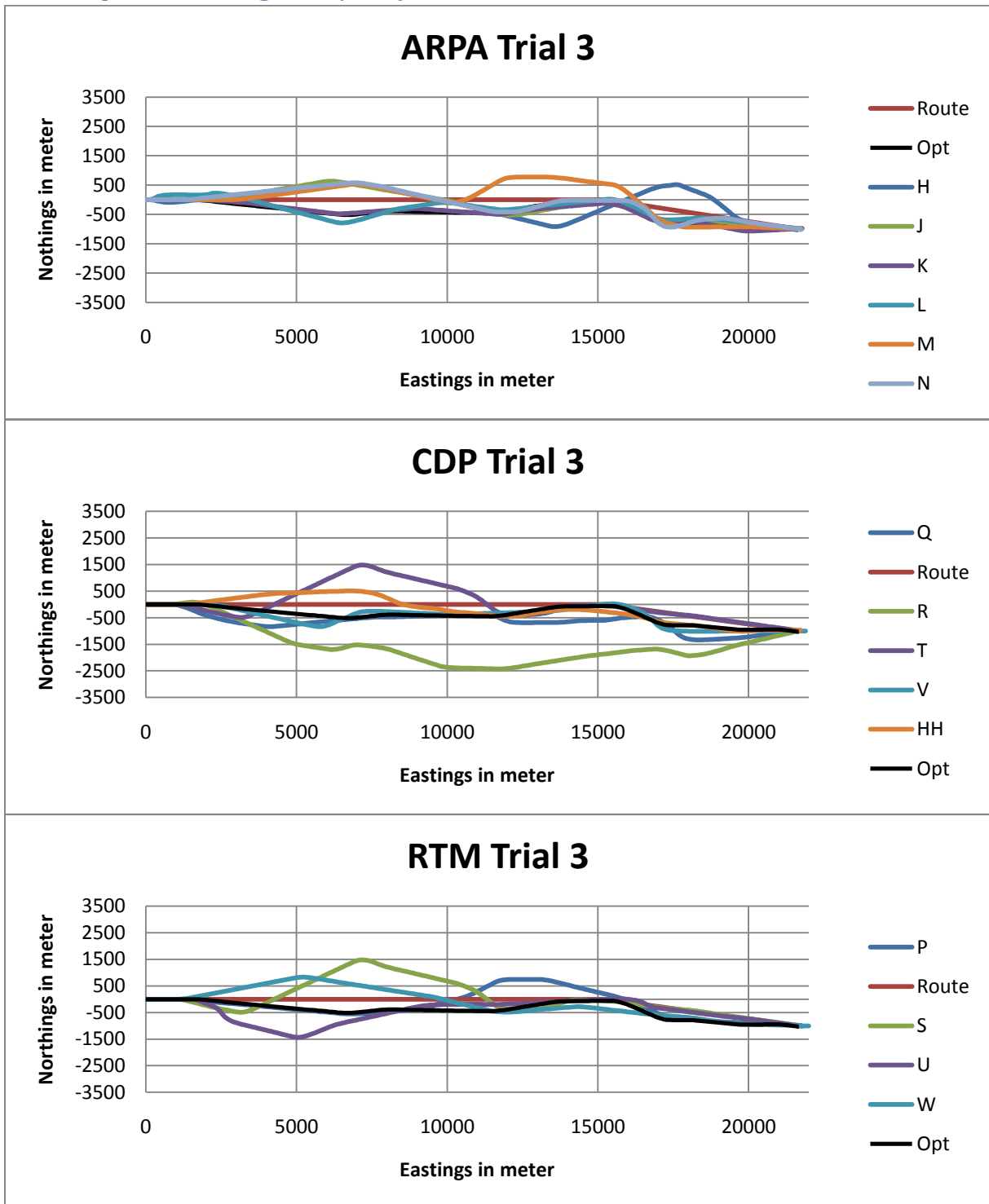
Figure 30. OOW track during Trial 3. Black track shows proposed optimum solution

By sailing the proposed optimum track in figure 30 the CPA limit is kept and all crossing targets are passed astern, meeting targets are cleared on OS port side and overtaken targets cleared on OS starboard side. Considering COLREGs this is the best solution. Before entering the fjord the participants had to pass TGT1 and TGT4. There are two possibilities; alter course to starboard and

pass astern of TGT1 whilst keeping adequate distance to TGT 4, or alter course to port and pass ahead of TGT1, which is not in accordance with the COLREGs. The design of the scenario was made in such a way that it was difficult to find the "correct" way of entering the fjord.

ARPA group

Participant L and K made an initial evasive manoeuvre to starboard. Participants K's track was more or less identical to the proposed optimum solution and participant L's track had some small deviations from the proposed optimum track. The remaining four participants made an initial manoeuvre to port with the consequence that all four passed ahead of TGT1 and they crossed ahead of TGT 3 before clearing the target on OS port side. Participant J and N then kept to the south of the route. Participant N broke the CPA limit on TGT6 (CPA=274m). This was a direct consequence of late evasive manoeuvre. From the track profile it can be observed that the participant made a large course alteration. Participant M passed ahead of TGT2 and cleared TGT7 on OS starboard side. The chosen manoeuvre also forced the participant very close to the northern side of the fjord. This is considered a poor decision not in accordance with the COLREGs. The correct and smooth way would have been to pass astern of TGT2 and then clearing TGT7 on OS port side. Participant H sails unnecessary far south before passing Grimeskjæret light house on OS starboard side. He then proceeded to pass ahead of TGT6 before passing astern of TGT8. The reason for participant H's actions was related to TGT5's track and the fact that he was on a northeasterly course when he passed the light house. Thus he chose to pass ahead of TGT6. Considering COLREGs the track profile is not very good.

CDP group

Participant R's track is omitted from the evaluation based on the arguments discussed in subchapter 7.2. All participants kept the CPA limit. Three participants chose to do an initial evasive manoeuvre to starboard. Participant V and Q have a track profile similar to the proposed optimum track with the exception that participant Q passed very close (CPA=148m) to Grimeskjæret light house. Participant T made an initial manoeuvre to starboard but then reconsidered and turned port which resulted in passing ahead of TGT2. Further he crossed ahead of TGT3 and cleared the target on OS port side. The phase prior to entering the fjord until TGT3 is cleared is considered to not be in accordance the COLREGs. For the rest of the trial the participant had a sensible track. Participant HH made an initial evasive manoeuvre to port with the result that he passed ahead of TGT2 and crossed ahead of TGT3. This phase is considered to be a violation of the COLREGs. The rest of the track was sensible.

RTM group

All participants kept the CPA limit. The participants' tracks where quite scattered until they passed Grimeskjæret light house from where the remaining tracks were similar to the proposed optimum solution. Three participants made an initial evasive manoeuvre to starboard of where one turned port before passing any targets. Participant U passed all targets in accordance with the COLREGs but one element needs to be addressed. The participant actually crossed the wake of TGT4 before he proceeded to a more northeasterly course. This manoeuvre might have been perceived as strange and confusing by the navigator on TGT4, even though COLREG rule 13 clearly states that the overtaking vessel is the give way vessel. Participant P's track profile had one phase where the participant did not act in accordance with the COLREGs, which was that he chose to pass ahead of

TGT2. Participant S had two manoeuvres before he passed ahead of TGT1. This was not in accordance with COLREGs. One positive element is that he chose to not cross TGT4 trajectory and cleared the target on OS starboard side. Participant W made an initial evasive manoeuvre to port, thus he passed ahead of TGT1 and proceeded to cross ahead of TGT4 before clearing the target on OS port side, which was a solution that was not in accordance with the COLREGs.

Summing up the evaluations of the three groups:

- ARPA: 2 of 6 participants made a sensible initial evasive manoeuvre. 2 participants had a sensible total track.
- CDP: 3 of 4 participants made a sensible initial evasive manoeuvre of which 2 participants had a sensible total track.
- RTM: 3 of 4 participants made a sensible initial evasive manoeuvre of which 2 participants had a sensible total track.

Observing figure 30 it is clear that the first phase of Trial 3 was very challenging. In both the CDP and the RTM group one participant reconsidered his decision after making an initial starboard evasive manoeuvre. This may be related to the fact that one had to observe carefully the geometric solution to see that there was a possibility to pass astern of TGT1. The failure of recognising this possibility may be related to inappropriate settings of the vector lengths and the TCPA limit. Once the participants had entered the fjord the CDP and RTM group sailed more sensible tracks than the ARPA group, except for participant P in the RTM group who chose to pass ahead of TGT2. Taking into account parameters from subchapter 7.2 the preliminary ranking is as follows: 1CDP, 2 RTM, 3 ARPA.
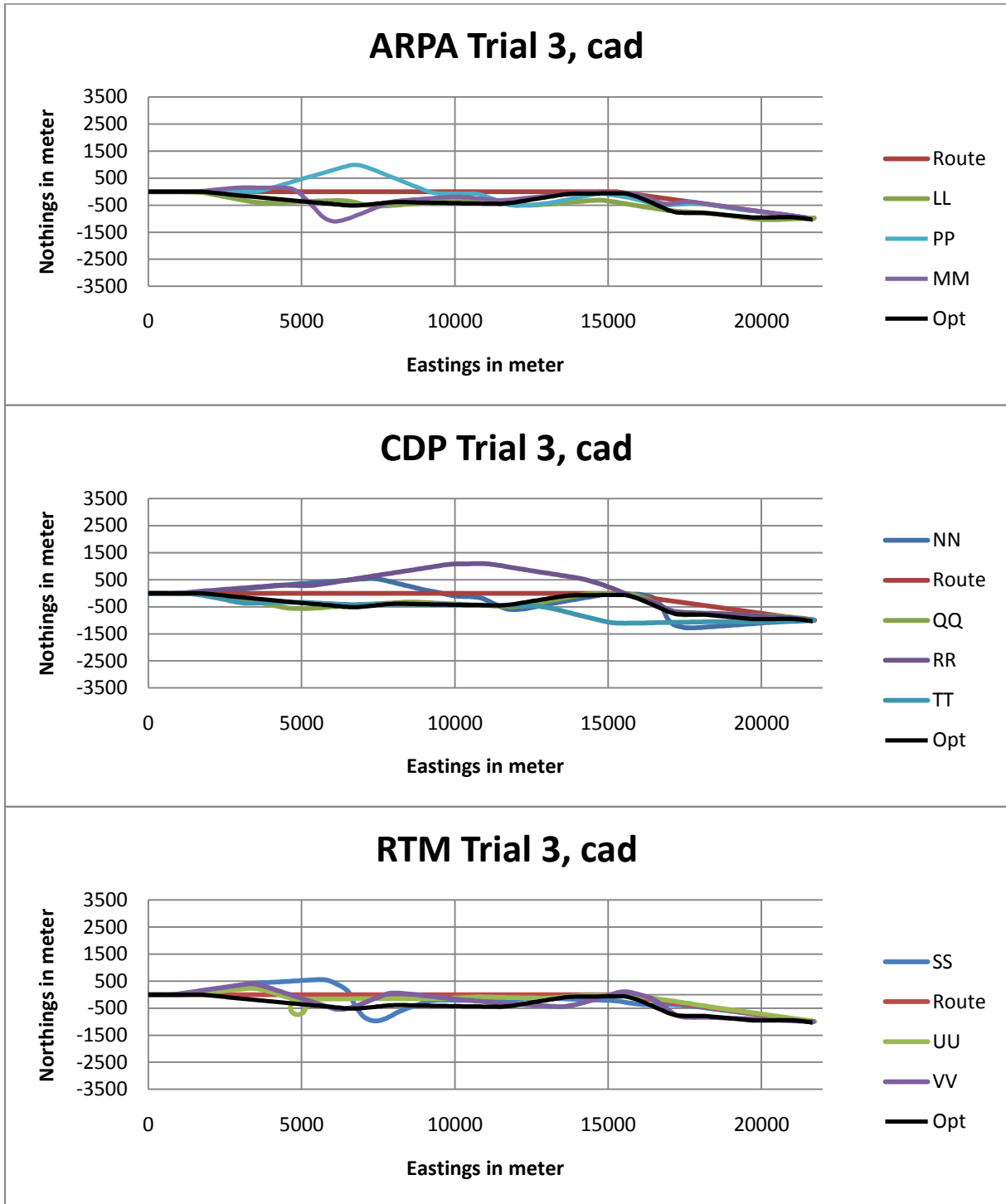
Figure 31. Cadet track during Trial 3. Black track shows proposed optimum solution

Proposed optimum track is the same as for the experienced navigators.

ARPA group

All participants kept the CPA limit. The track profile of LL participant was very similar to the proposed optimum solution. Participant MM made an appropriate initial evasive manoeuvre except for that it was conducted very late as can be seen from the figure. In addition he came very close to the wake

of TGT4 which could have lead to confusion of his intentions onboard TGT4. Participant PP made a late initial evasive manoeuvre to port and passed ahead of TGT1 and crossed ahead of TGT3 before clearing the target on OS port side. The manoeuvres before passing TGT3 are in violation of the COLREGs. All participants had a similar track profile to the proposed optimum solution after passing TGT3.

CDP group

The track profile of participant QQ is similar to the proposed optimum solution. Participant TT also had a similar profile except for that he sailed south of Grimeskjæret light house. Participant RR and NN made an initial evasive manoeuvre to port and passed ahead of TGT1. Participant NN crossed ahead of TGT3 before clearing the target on OS port side. For the rest of the trial the track profile was similar to the proposed optimum solution. The passing ahead of TGT1 and the crossing ahead of TGT3 is considered to violate the COLREGs. After TGT1 is passed participant RR chose to clear TGT3 and TGT7 on OS starboard side, which is sensible. Still the initial manoeuvre was in violation of the COLREGs.

RTM group

All participants made an initial evasive manoeuvre to port, but participant VV and UU reconsidered and subsequently turned starboard. After the starboard turn, participant VV had a sensible track. Participant UU chose do a 360° manoeuvre to clear the targets prior to entering the fjord gateway. The result was that he did not encounter any more close quarter situations. This choice of manoeuvre is directly linked with the given restriction in speed change. Participant SS also reconsidered his plan to pass ahead of TGT1, but the decision came very late and he broke the CPA limit of TGT1 (CPA=104m). In the remaining part of the trial the track was sensible.

 Summing up the evaluations of the three groups:

- ARPA: 2 of 3 participants made a sensible initial evasive manoeuvre of which 1 participant had a sensible total track.
- CDP: 2 of 4 participants made a sensible initial evasive manoeuvre. 3 participants had a sensible total track.
- RTM: 0 of 3 participants made a sensible initial evasive manoeuvre. 2 participants sailed a sensible total track

When considering time of manoeuvre it is clear that 2 of the participants in the ARPA group made the initial manoeuvre very late. The ANOVA test gave no statistically significant difference between the groups due to the fact that one ARPA participant made an early manoeuvre. In the CDP and RTM group all participants executed the first manoeuvre early. The port manoeuvres were not in accordance with the COLREGs and can be attributed to failure of emphasising the COLREGs when evaluating the situation. If NASA TLX values and CPA limit are added to the track analysis it is obvious that the RTM group experienced a higher mental workload than the rest of the population and they broke the CPA limit. Taking into account parameters from subchapter 7.2 the preliminary ranking is as follows: 1CDP, 2 RTM, 3 ARPA.

8 Conclusions

## 8.1 Conclusion

The CDP and RTM displays are independent of OS movements. By inspecting the tip of OS vector in relation to the displayed collision danger sectors the navigator can assess the risk of collision in multiple encounter scenarios and simultaneously identify adequate evasive manoeuvres which satisfy a minimum safety distance threshold. The whole process is conducted in true motion and real time.

The collected data and the analysis clearly leads to that the proposed collision avoidance displays (CDP/RTM) improved the navigator's situational awareness and contributed to accelerate the decision and execution of evasive manoeuvres. This corresponds to the results found in the simulator studies conducted by Pedersen et al. (2003). For experienced navigators the CDP/RTM accelerated the execution time of the initial evasive manoeuvre by about 100% in the complex traffic scenario. In the cadet population the CDP/RTM display had effect in both the simple and the complex scenario, about 200% and 150% respectively.

Weiner (1989) introduced the term *clumsy automation* to describe automation that places additional and unevenly distributed workload, communication and coordination demands on pilots without adequate support (Weiner, 1989). In short clumsy automation is automation that makes easy tasks easier and hard tasks harder when there are problems. The use of the new collision avoidance display did not lead to a total increase in the participants' mental workload, except in the inshore scenario where the RTM group reported higher values of workload. When comparing CDP and RTM the analysis leads to the conclusion that CDP is the preferred display type. This is based on the following factors:

- CDP gives unambiguous identification to which target the collision danger zone belongs to.
- The CDP display has a clear geometry from target acquisition until the target is passed, in contrast to the RTM display were the collision danger sector is replaced by the full cone shape once the target's vector tip is inside the Vmax circle.
- The RTM display requires more instruction since the navigator must understand the concept of the Vmax circle and the sectors in addition to the cone-shaped collision danger regions from the CDP display.
- The RTM display performed poorly in the inshore scenario

With regards to workload, the levels will most likely decrease as the navigator gets more familiar with the CDP display.

In the track analysis several violations of the COLREGs were identified. None of the displays tested in this thesis gives the navigator a solution that takes into account the COLREGs. The geometrical solution in all three displays is designed to support the navigator in arriving at a correct decision and not as an infallible anti-collision device. The point being that the navigator's knowledge of the COLREGs is paramount to conduct sensible evasive manoeuvres. The study of Pedersen et. al (2003) concluded there was a: "risk of temptation to make frequent and minor course alterations". This conduct was also observed in some cases during the thesis trials, but it was registered in all display groups and both populations. Thus it seems like the use of frequent small manoeuvres is not connected to which display type the participant is using. Anyway this is an issue that needs to be

addressed in a training program. Further unfortunate settings with regards to target selection might cause the display to be very busy, especially when sailing in traffic lanes where the targets have a course more or less parallel to OS. To avoid a busy display the navigator has to adjust the target selection thresholds adequately. The CDP treats both OS and TS as mass points, thus the ship domain is not accounted for. This flaw has to be included in the settings for accepted CPA limit. The major excellence of the CDP is that the graphical presentation provides easy target recognition and good real time overview in true motion that supports the navigator's situational awareness.

Addressing the navigator's experience, the results in the cadet population showed that the CDP display seemed to reduce the need for tacit knowledge to enable a fast decision and execution of an evasive manoeuvre. One complaint in this context is that the conducted manoeuvres are not always in accordance with the COLREGs, but this is also the case for the experienced navigators. This confirms the assumption that good conduct at sea concerning collision avoidance may be somewhat unsuspended from the tacit knowledge. It is also evident that the CDP display gives the experienced navigator an improved situational awareness which better the ability to make fast decisions in congested and complicated traffic scenarios.

When augmenting the bridge with electronic tools the aim is to aid the navigator to do his job more effective, faster and safer when the system is employed correctly. To achieve a proper use of the new instrumentation the navigator needs to know the system limits and he must be able to combine the system output with his visual comprehension of the situation together with the principles of good seamanship and the COLREGs.

8.2 Proposal for improvements

Factors for improvement were discovered during the preliminary testing and the trials. As identified from the analysis of the trials, the CDP display is preferred. The improvement factors are the following:

- Circle with origin at OS with radius equal to OS true vector length.
- An improved EBL that visualises OS possible scaled speed by the navigator's choice.
- The scaling factor for vector lengths should have a minimum value of 30 seconds or less. A warning when scaling factor is larger than the smallest TCPA should be given.

The listed factors will simplify the navigator's task to evaluate and identify possible suitable collision avoidance manoeuvres. All functions must be designed such that they are available at the navigator's choice.

In the project thesis the time to manoeuvre was discussed (Grepne-Takle, 2010). To incorporate the time to manoeuvre a time lag Δt must be added to the calculations. Thus the target's relative position will have the following form

$$\begin{aligned} x_{\Delta t}(t) &= x(t_0) + V_{RX}(t + \Delta t) \\ y_{\Delta t}(t) &= y(t_0) + V_{RY}(t + \Delta t) \end{aligned}$$

(5.1)

One can then in addition design an EBL which visualises OS chosen turn rate and radius. This will enable the navigator to see how the manoeuvre will take effect in the future. This function is very similar to today's existing ARPA trial manoeuvre. To use such a function the navigator will have to set

the display in a trial mode to visualise future target movement. The concept of CDP is that you do the evaluation in real time, thus this function is rejected.

8.2.1 OS true vector circle

In order to simplify the task of evaluating possible manoeuvres without a speed change, a circle with the radius equal to OS true vector length will give a visual presentation of the manoeuvring range. Thus the navigator can simply use EBL to find a suitable new course. The radius must of course be scaled according to the vector length scale. The radius is given by eq.(5.2), origin is center of OS.

$$R = \left[\sqrt{V_{OX}^2 + V_{OY}^2} \right] \tau \tag{5.2}$$

Figure 32   illustrates the concept.
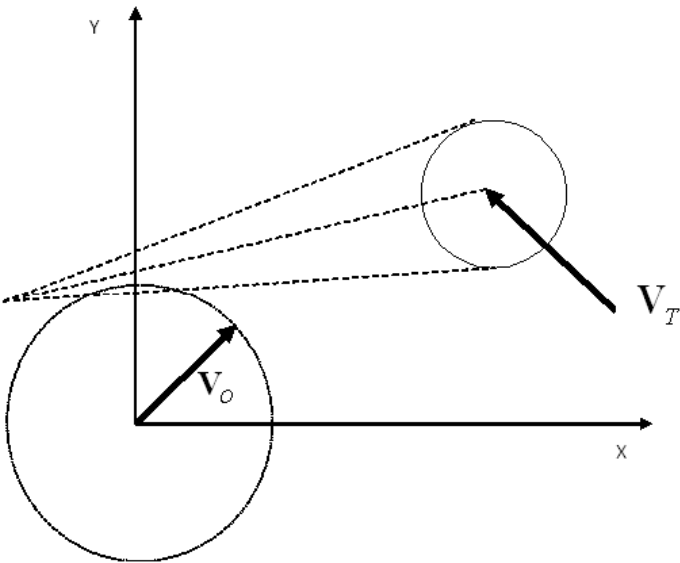
Figure 32. CDP with circle where the radius equals OS vector length

8.2.2 Improved EBL for CDP

To facilitate fast evaluation of combined course and speed changes an improved EBL is proposed. The EBL should have the following capacity:

- As today, show the navigator which direction the EBL is pointing.
- Visualise by a movable point (small sphere) speed according to chosen vector scale. The scale should go from 0 knots to OS maximum speed. Default value when activating the improved EBL should be OS actual speed.

When the navigator wants to explore a collision avoidance manoeuvre with combined course and speed change or just speed change, he can simply move the EBL in azimuth and or the speed pointer to an adequate speed. The speed should be presented alphanumerically unscaled.

Figure 33 illustrates the concept.
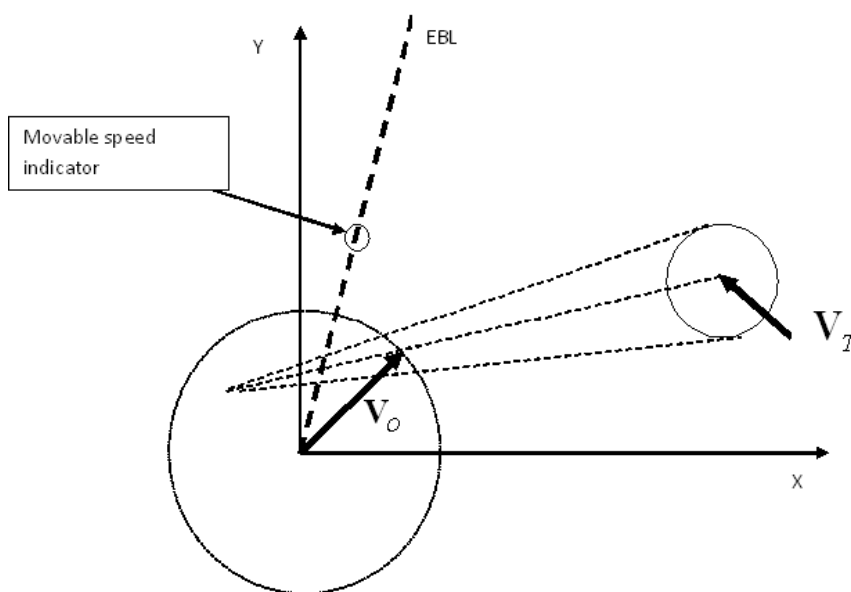
Figure 33. Improved EBL combined with OS vector circle.

8.2.3 Scaling factor larger than TCPA

During trials the participants had to keep in mind the scaling of the vectors. With decreasing relative distances to the targets, the vector length must be reduced to be able to supervise the collision risk. If the situation described in eq. (5.3) exists, the navigator is not able to monitor the collision risk.

$$\tau > TCPA_n \tag{5.3}$$

τ is defined as the scaling factor and n is target number.

When operating with the CDP display in a multiple target situation one might be unfortunate to base an avoidance manoeuvre on false data if the situation in eq. (5.3) is valid. To avoid this, the navigator must be warned when the condition arises by clearly marking the relevant target(s). Thus the navigator will be able to see that he cannot evaluate the target(s) with the present scaling. The marking can be done by drawing the cone shape with bold red lines.

The scaling factor τ should have a minimum value of 30 seconds or less. From $\tau = 0.05\ hours$ (3 minutes) the scaling should be step less.

8.3 Proposal for maritime student training

Alternative presentation of the collision danger is mentioned briefly in today's existing textbooks. Examples are PPC (Possible Point of Collision), PAD (Predicted Area of Danger) and SOD (Sector Of Danger) (Kjerstad, 2008). The challenge a lecturer often faces when introducing new theories and knowledge is to make sure the student actually understand how the theory is physically realised. When lecturing radar plotting, ARPA and collision theory many students struggle with understanding the concept of relative course and speed, which is used to establish the danger of collision. The textbook "Elektroniske og akustiske navigasjonssystemer" by Kjerstad (2008) is widely used for maritime studies in Norway. When treating radar plotting and ARPA, the textbook explain the relative vector by manual plotting on a plotting diagram. No mathematical derivation of how to construct the relative vector is given. To support the plotting theory the mathematical definitions of OS, target and relative vectors should be introduced (see subchapter 2.2). In addition the criteria for collision should be presented, see eq. (5.4) and figure 2.

$$\frac{d\alpha_0}{dt} = \frac{d\alpha_T}{dt} = 0$$
$$\Updownarrow$$
$$|\mathbf{V}_0|\sin\alpha_0 = |\mathbf{V}_T|\sin\alpha_T \tag{5.4}$$
$$\Updownarrow$$
$$CPA_i = 0$$

The equations in (5.4) states CPA for target i is equal to 0 if and only if OS and TS relative bearing is constant and if and only if OS and TS true velocity times sinus to the aspect angle is equal.

If collision avoidance also is introduced using true vectors in true motion, the challenge of understanding what is actually happening should be easier. By introducing the concept of PPC and CDL (see figure 3) the collision problem is graphically presented in a plain manner. When lecturing about CPA, the cone shaped collision danger regions (see figure 4) may be used to present a graphically result of what a CPA limit represents for the navigator. The figure will help to understand

the restrictions in manoeuvring possibilities a navigator faces when encountering a vessel. The described proposals must be considered as an amendment to enhance the students understanding of relative plotting and ARPA theory.

The thesis study revealed that the essence in the COLREGs was manifested by varying degree. There is a great need for study and careful consideration by maritime students of the regulations before being presented with a situation of danger in reality. The lecturing of the regulations needs to be backed up by examples from incidents and practical experience. Here the use of simulator is of vital importance to provide a good understanding. In the thesis simulator study the trials were constructed with increasing difficulty level. If scenarios with increasing complexity level explicitly designed to train the regulations and collision avoidance is introduced, the students will experience control and the understanding of the collision theory will increase. To support or verify the effectiveness of the simulator training, a tool to evaluate the subjective mental workload of the students may be applied, e.g. NASA TLX, SWAT (Subjective Workload Assessment Technique (Reid and Nygren, 1988)) or WP (Workload Profile (Tsang and Velazquez, 1996)).

8.4 Future work

The study revealed that the introduction of the CDP/RTM display generally did not increase the experienced mental workload. To verify the CDP display's excellence versus ARPA, a study of how the mental work load evolves over time should be done. This can be done in a simulator where the population is divided in an ARPA group and a CDP group. The two groups must sail multiple scenarios over a prolonged period of time. Say 5 hours per week in 4 weeks. Thus the development of the experienced work load can be monitored as the participants get more and more familiar with the display.

Another result of the trials was that the cadets had a significantly improved performance in both Trial 1 and 2 when using CDP/RTM display. The experienced navigators had only significantly improvement in trial 2. In this context one question could be interesting to explore. If the experienced navigators are classified experts, will a cadet using CDP display become expert faster than a cadet using traditional ARPA? Such a study will be quite demanding. This can be realised following a group of cadets from when commencing education until e.g. two years after completion of the final exams. The main challenge will be to get the CDP solution installed onboard a vessel.

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10 APPENDIX A

A1 Program specification for collision avoidance methods

A1.1 Preface

The collision avoidance method has two modes of visual presentation, Collision Danger Presentation (DCP) and Room to Manoeuvre (RTM). The following program description is divided in two parts, CDP and RTM with the respective source codes. The difference between the two is mainly that the visual presentation of RTM is limited by own ship speed vector and it's scaling. Otherwise the two methods are founded on the same mathematical principles. The source code files are in separate files.

Kongsberg Maritime Simulation AS is to develop the visualisation of the results produced by the core algorithms.

Kongsberg is also requested to have the new anti collision method ready for use by the end of February 2011 due to time limitations with regards to trial work after installation on simulator. The beta release is to be installed on the Simulator at Sjøkrigsskolen bridge A, B, C, E and F.

A1.2 Abbreviations

CDL	Collision Danger Line
CDP	Collision Danger Presentation
DCPA	Distance to Closest Point of Approach
ECDIS	Electronic Chart Display Information System
Nm	Nautical miles
OS	Own Ship
RTM	Room To Manoeuvre
TCPA	Time to Closest Point of Approach
TS	Target Ship

A1.3 Input descriptions

Own ship (OS) data fed from OS systems:

- Position (x_0, y_0)
- Course ψ_0
- True velocity vector: $\mathbf{V}_0 = [V_{0x} \quad V_{0y}] = [V_0 \sin\psi_0 \quad V_0 \cos\psi_0]$

Target ship (TS) data fed from Radar or AIS:

- Position (x_T, y_T)
- True velocity vector: $\mathbf{V}_T = [V_{Tx} \quad V_{Ty}]$

Relative position and velocity:

- Relative position: $(x_R, y_R) = (x_T - x_0, y_T - y_0)$
- Relative distance: $D = \sqrt{(x_T - x_0)^2 + (y_T - y_0)^2}$
- Relative velocity: $\mathbf{V}_R = [V_{Rx} \quad V_{Ry}] = \mathbf{V}_T - \mathbf{V}_0$

Global coordinate system
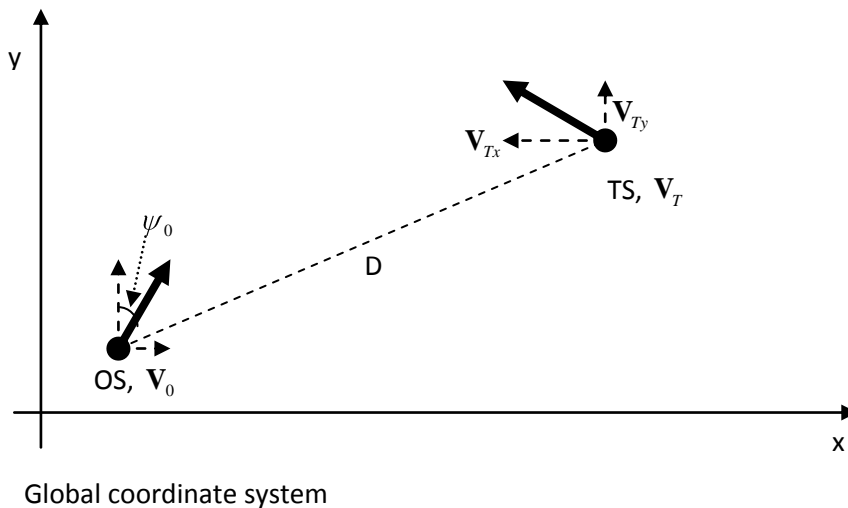
A1.4 Program specification Collision Danger Presentation (CDP)

User selected parameters for target selection:

- DCPA Limit [NM] – Minimum safety distance at closest point of approach to target. Exemplified value: the interval [0.0, 5.0] nautical miles (nm). If relative distance to target is equal to, or less than, selected DCPAlim, then only collision danger line is displayed (see figure 1 for definition of CDL).
- Maximum DCPA [NM] – Maximum time to closest point of approach that is relevant for anti-collision assessment. Exemplified value: the interval [DCPAlim, 20.0] nm.
- TCPA Limit [hours.] – Maximum time to closest point of approach that is relevant for anti-collision assessment. Exemplified value: the interval [0.0, 1.0] hours.

- TCPA Critical [hours.] – Time to closest point of approach when the target is so close that an escape manoeuvre is required. Exemplified value: the interval [0.0, TCPAlim].

Also we have the scaling factor τ for vector lengths (user selected) given in tenths of an hour. E.g. $\tau = 0.1$ is equivalent to 6 minutes.

A1.4.1 Output Descriptions

The program code will calculate the four points A, B, C and D to enable construction of the cone shaped collision danger representation. See figure 1.
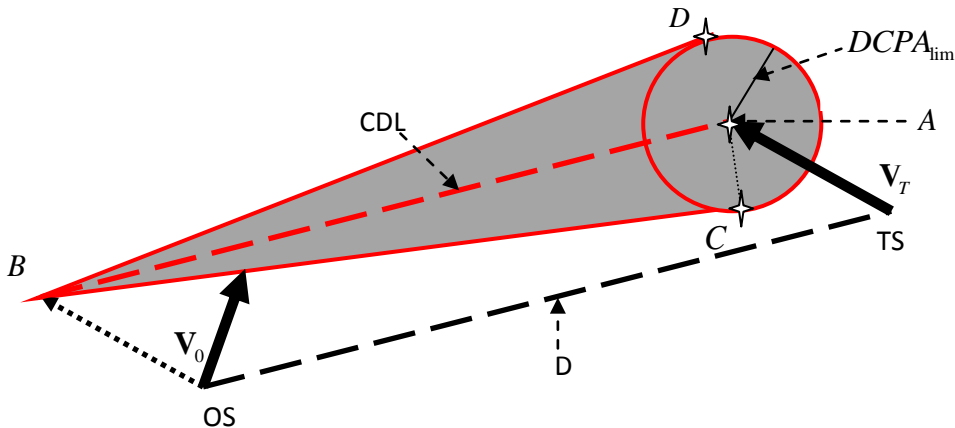
Figure 1. Cone shape definition by point A, B, C, D and $DCPA_{lim}$.

The graphical output should be presented on a suitable display, e.g. radar, ECDIS or simulator.
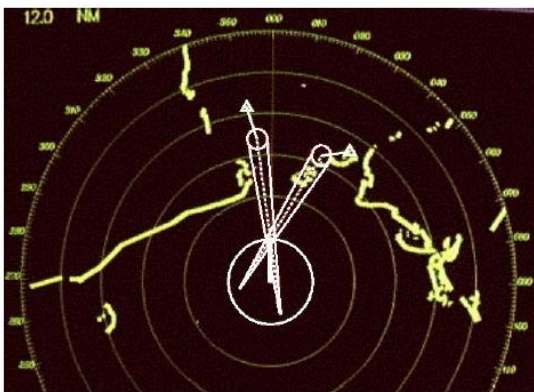
Figure 2. Example of CDP display on radar. Radar range=12nm, vector lengths 12 minutes, CPA limit 0.5 nm.

The program operates with 4 different threat levels for target presentation to avoid an overloaded presentation:

- **'NOT RELEVANT'** if TCPA not in [0, TCPAlim] OR DCPA>DCPAmax
- **'RELEVANT'** if TCPA in [0, TCPAlim] AND DCPA in [DCPAlim, DCPAmax]
- **'DANGEROUS'** if TCPA in [TCPAcrit, TCPAlim] AND DCPA in [0, DCPAlim]
- **'CRITICAL'** if TCPA in [0, TCPAcrit] AND DCPA in [0, DCPAlim]

These four classification levels are to be presented visually and not alphanumerically to the navigator. The following is a proposed visuallisation of the 4 levels with respect to each target using the CDP system:

- Level 1: **'NOT RELEVANT'**, no collision danger lines/sectors are displayed.
- Level2: **'RELEVANT'**, collision danger lines (CDL) and the cone-shaped sector are displayed with dashed lines.
- Level3: **'DANGEROUS'**, the transparent collision danger sector (CDS) is filled with color.
- Level4: **'CRITICAL'**, in addition to the above, the CDL is highlighted by bold solid line.

In addition when the target is within the selected DCPA limit $(D < CPA_{\text{lim}})$, only the collision danger line (CDL) and true vectors should be displayed.

A1.4.2 Program description
The program should be described as an "added functionality" in the base platform. The platform must run in true motion (show true vectors).

The program will run in accordance with the flowchart. The program has two ways of calculating point C and D. This is due to a singularity problem that arises when the x-coordinate of the relative distance is equal to the selected DCPA limit, i.e. $x_R - DCPA_{\text{lim}} = 0$. When the singularity problem arises the program follows the alternative calculation for point C and D.

When point A, B, C and D is acquired the cone shape figure must be sketched. Draw lines between the points as illustrated by red lines in fig. 1 and the scheme for threat level. The circle with the centre in point A has the radius equal to the selected DCPA limit.

Flowchart collision danger representation

Read own ship and target data → User selected parameters → Calculate point A and B → $D < DCPA_{lim}$

$D < DCPA_{lim}$ — NO →

$D < DCPA_{lim}$ — YES → Show point A and B

TCPA>TCPAlim or DCPA>DCPAmax — YES → NOT RELEVANT → Show nothing

TCPA>TCPAlim or DCPA>DCPAmax — NO ↓

TCPA in[0,TCPAlim] and DCPA in [DCPAlim,DCPAmax] — NO → TCPA in [TCPAcrit,TCPAlim] andDCPA in [0,DCPAlim] — NO → TCPA in [0,TCPAcrit] and DCPA in [0,DCPAlim]

TCPA in[0,TCPAlim] and DCPA in [DCPAlim,DCPAmax] — YES → RELEVANT

TCPA in [TCPAcrit,TCPAlim] andDCPA in [0,DCPAlim] — YES → DANGEROUS

TCPA in [0,TCPAcrit] and DCPA in [0,DCPAlim] — YES → CRITICAL

$$x^2(t_0) = DCPA^2$$

$x^2(t_0) = DCPA^2$ — NO → Calculate point C and D by $\dfrac{V_{Ry}}{V_{Rx}}$

$x^2(t_0) = DCPA^2$ — YES → Calculate point C and D via point M

Show point A,B,C,D

A1.5 Program specification Room to Manoeuvre (RTM)

User selected parameters for target selection:

- Vmax – Maximum velocity of own ship.
- DCPA Limit [NM] – Minimum safety distance at closest point of approach to target. Exemplified value: the interval [0.0, 5.0]nm. If relative distance to target is equal to, or less than, selected DCPAlim, then only collision danger line is displayed.
- Maximum DCPA [NM] – Maximum time to closest point of approach that is relevant for anti-collision assessment. Exemplified value: the interval [DCPAlim, 20.0] nm.
- TCPA Limit [hours.] – Maximum time to closest point of approach that is relevant for anti-collision assessment. Exemplified value: the interval [0.0, 1.0] hours.

Also we have the scaling factor τ for vector lengths (user selected) given in tenths of an hour. E.g. $\tau = 0.1$ is equivalent to 6 minutes.

A1.5.1 Output Descriptions

The program code will calculate the four points A, B, C ,D and then find the intersections between the lines BC and BD with the room to manoeuvre (RTM) circle with the radius = Vmax. See figure 3.
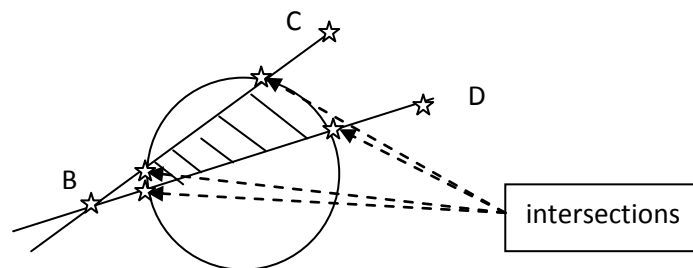
Figure 3.The lines cross the circle, four intersections.

Figure 4 gives an example of the RTM display with one target.
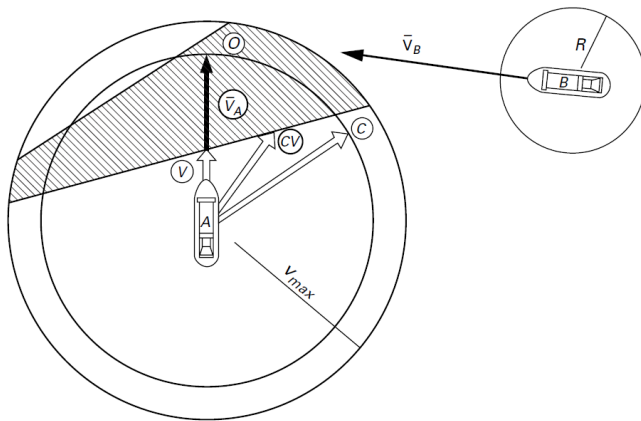
Figure 4 shows vessel A with velocity vector $\overline{V_A}$, TS B with $\overline{V_B}$ and closest safe passing distance R. The unshaded area represents the room to manoeuvre for vessel A in the presence of vessel B. $V_{\max}$ is the maximum speed of A, the circle O is the extremity of vector $\overline{V_A}$. If $\overline{V_A}$ is located inside the shaded region then A will pass B below the threshold R, therefore in risk of collision. C represents a manoeuvre without change of speed, V is the manoeuvre with speed change but not course alteration, CV is the manoeuvre with both speed course and course alteration. In the presence of a group of vessels the danger zones for speed and course in relation to each ship are shown in fig. 3. The shaded area is calculated by the principle of theoretical analysis of the relative motion.

The four points A, B, C and D also enables construction of the cone shaped collision danger representation when the target enters the perimeter of the RTM circle. See figure 3
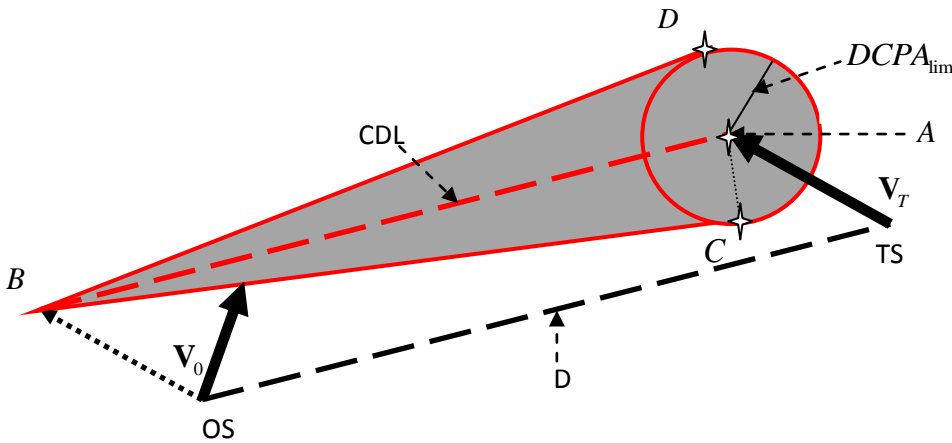
Figure 5. Cone shape definition by point A, B, C, D and $CPA_{\lim}$.

The graphical output should be presented on a suitable display, e.g. radar, ECDIS or simulator.
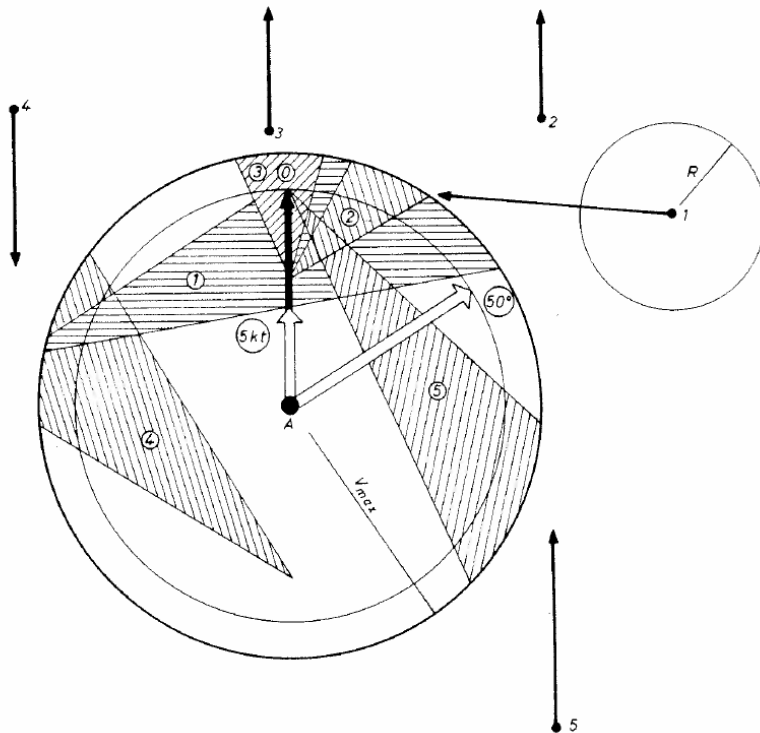
Figure 6. Group of vessels with the danger zones for speed and course in relation to each ship are shown.

The program operates with two different threat levels for target presentation to avoid an overloaded presentation:

- **'NOT RELEVANT'** if TCPA not in [0, TCPAlim] OR DCPA>DCPAmax
- **'RELEVANT'** if TCPA in [0, TCPAlim] AND DCPA in [DCPAlim, DCPAmax]

These two classification levels are to be presented visually and not alphanumerically to the navigator. The following is a proposed visuallisation of the 2 levels with respect to each target using the RTM system:

- Level 1: **'NOT RELEVANT'**, no shaded area, cone shape or CDL is displayed.
- Level2: **'RELEVANT'**, display shaded area, cone shape, or CDL.

In addition when a target enters the perimeter of the RTM circle, or to be more precise, when point A (see fig. 5) is inside the circle, the system should display a full cone-shape. When the target is within the selected DCPA limit $(D < DCPA_{\text{lim}})$, only the collision danger line (CDL) and to true vectors should be displayed.
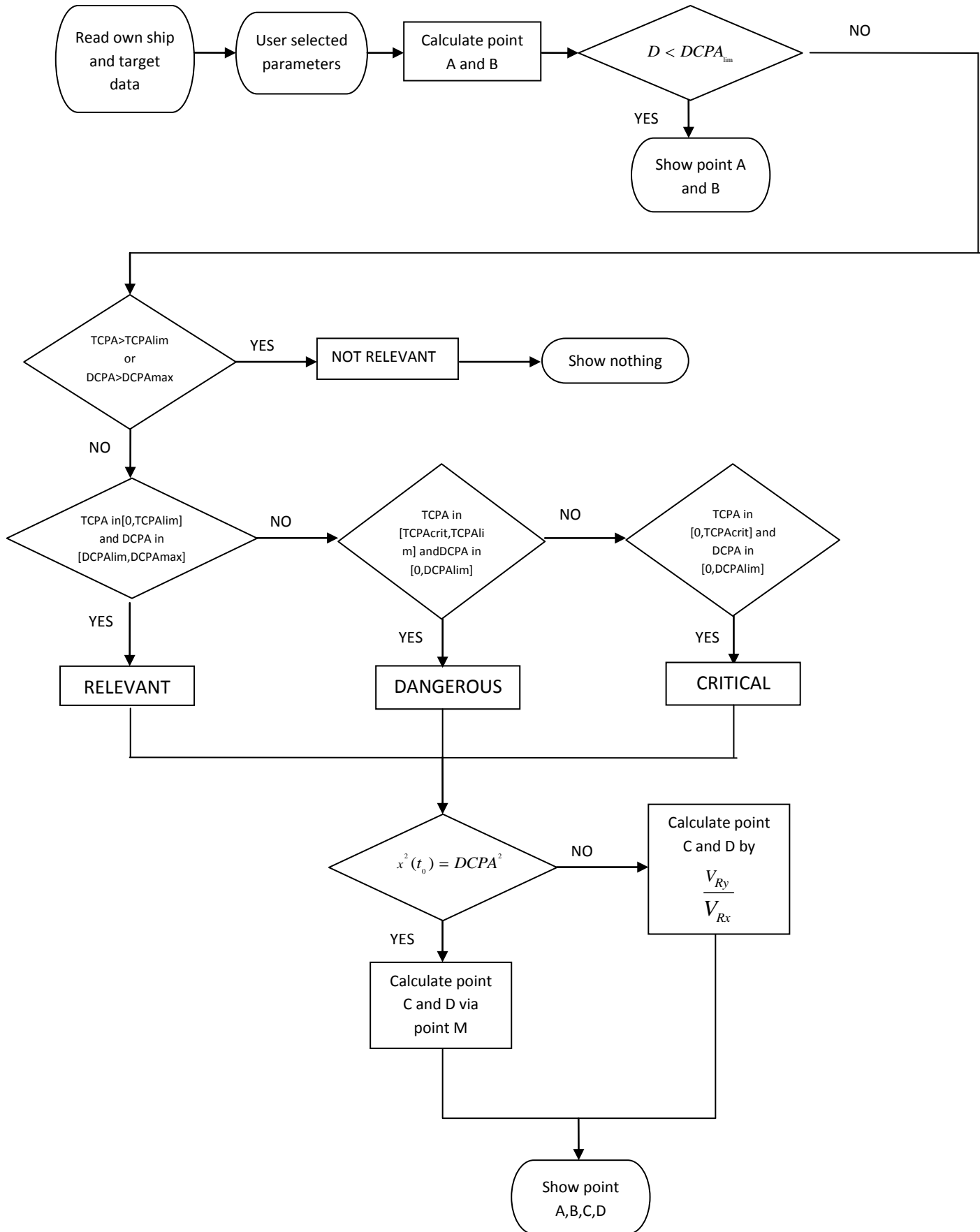
A1.5.2 Program description
The program should be described as an "added functionality" in the base platform. The platform must run in true motion (show true vectors).

The program will run in accordance with the flowchart. The program has two ways of calculating point C and D. This is due to a singularity problem that arises when the x-coordinate of the relative distance is equal to the selected DCPA limit, i.e. $x_R - DCPA_{\text{lim}} = 0$. When singularity problem arises the program follows the alternative calculation for point C and D.

As mentioned the program will calculate the intersections between the RTM circle and the lines BC and BD. When a target is classified **"RELEVANT"** the program differs, in addition to the singularity case, the following cases:

1. The lines do not cross the circle, no intersections.
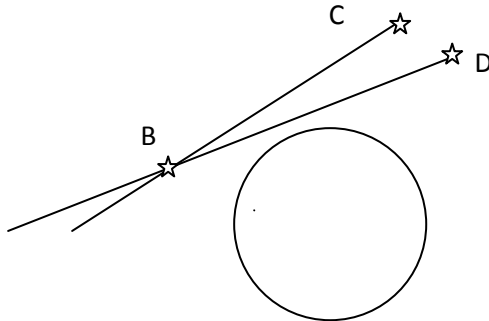
Figure 7.1

2. One line does not cross the line and one is tangent to the circle or crosses the circle, two intersections

Figure 7.2

or
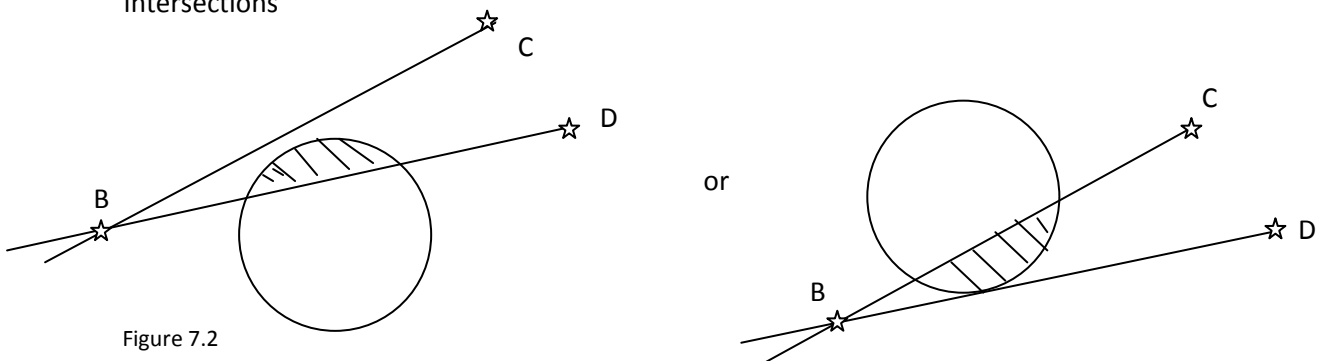
3. The lines cross the circle, four intersections.
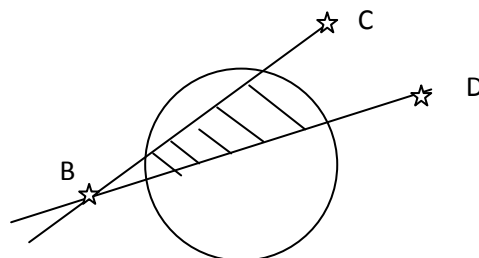
Figure 7.3

Also the following considerations are taken care of:

- Point A within the DCPA limit. Point A is then inside the circle. No intersections are needed; we draw the collision danger line (CDL).
- Point A within the RTM circle. Draw the cone shape

- Point B within the RTM circle. Two intersections. Draw shaded area.
- Point B on the RTM circle, i.e. the coordinates of point B coincidence with the radius = Vmax. Draw shaded area if the lines BC and/or BD intersect with the radius of the RTM circle

As described, point A, B, C and D will also be used to sketch the cone shape figure when point A is inside the RTM circle. Draw lines between the points as illustrated by red lines in fig. 2. The circle with the centre in point A has the radius equal to the selected DCPA limit.

As seen from the flow chart there are several situations described. The program will present the needed points and intersect data to enable the position of the shaded area, the cone shape or the CDL, that should be sketched within the RTM circle.

Room to manoeuvre flowchart

Read own ship and target data.

User selected parameters

Target relevant? — NO → NOT RELEVANT → Show nothing

YES → Calculate point A and B →

$x^2(t_0) + y^2(t_0) < DCPA^2_{lim}$ — NO

YES → Show point A and B

$x(t_0) = DCPA$ — NO → Calculate point C and D by $\dfrac{V_{Ry}}{V_{Rx}}$ → Point A in the circle? — YES → No intersections. → Show point A, B, C, D.

YES → Calculate point C and D via point M

NO

Equivalent separate process

Point B is in the circle

Point B is on the circle

Point B is outside the circle

Show results

Show nothing

Show results

See next page

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```

Show results   Show nothing   Show nothing   Show results   Show nothing

Point of contact

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A2 Collision avoidance test specification

The following test specification is to be run in Horten prior to installing the beta version in the simulator at the Naval Academy. The aim of the test is to verify that the visual presentation is satisfactory, according to specification and running without faults.

A2.1 Test scenario description

Initially the anti collision method must be tested with targets in all quadrants. The sketch in figure 1 illustrates the test scenario. Own ship is in the origin with a set speed and course, e.g. course 000 speed 18 knots. The target position is in one of the coordinate system's quadrants. There the target is to be given a speed and the course is to be altered according to figure 1. All the four quadrants are to be tested. Also the target must be tested when one of the position coordinates is on the coordinate system's axis. The target course should be according to figure 1.
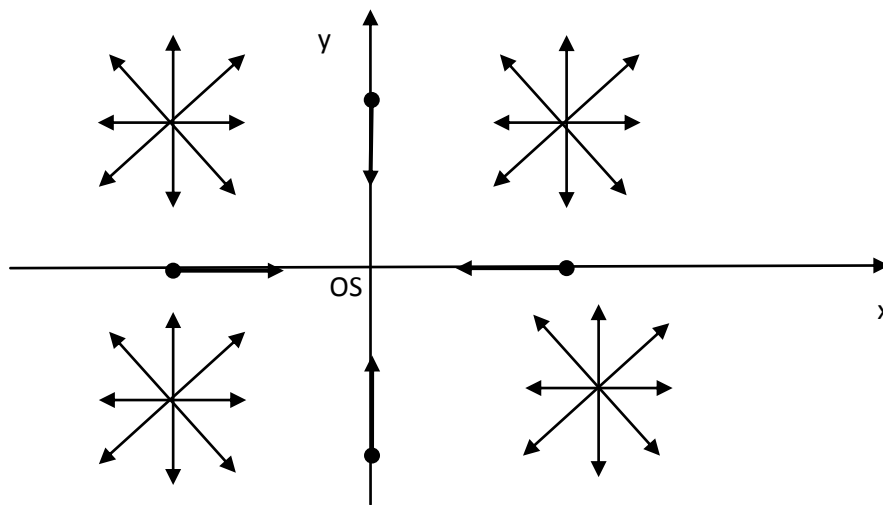
Figure 1. Sketch of scenarios for validation test. OS is located in the origin.

In addition tests when singularity occurs must be conducted by setting target ship's x-coordinate equal Distance to CPA (DCPA) limit, i.e. $x(t_0) = DCPA_{\lim}$. Also the special case were the line $\overline{BC}$ becomes parallel with the x-axis must be tested. Figure 2 shows definition of line $\overline{BC}$.
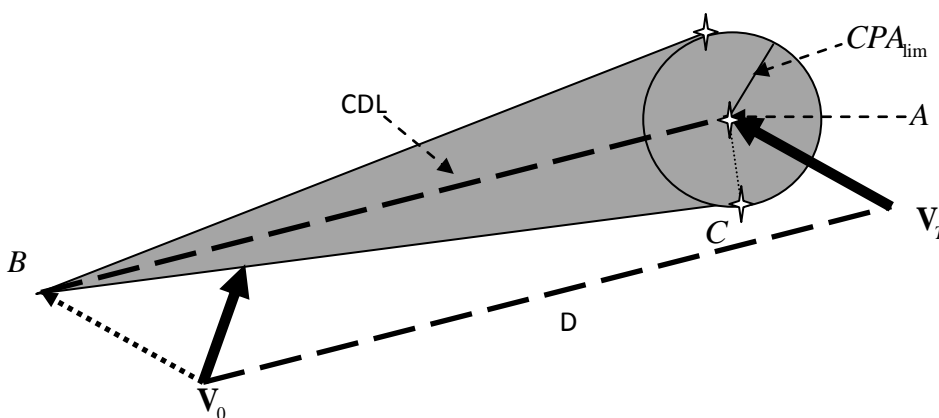
Figure 2. Cone shape definition by point A, B, C, D and $CPA_{\lim}$.

For the RTM (Room to Manoeuvre) system additional tests must be conducted to control the performance in the following situations:

- Point B in the Vmax (maximum own ship speed) circle.
- Point B on the Vmax circle with and without intersections.
- Point B outside the Vmax circle with 4 and two intersections.
- Point B outside the Vmax circle with no intersections and the situation were the extension of the lines $\overline{BC}$ and $\overline{BD}$ intersect (no shaded area should be drawn).

Finally the parameters set by the operator concerning target selection must be tested

A2.1.1 Suggested own ship and target data settings for validation test.

Own ship parameters through the test:

Course: 000

Speed: 18 knots

Vector scaling factor should be set to 6 or 12 minutes.

A2.1.1.1 Target in the four quadrants

POSITION (relative to own ship)			COURSE	SPEED
[X Y] (nm)	β (bearing)	Range		
[4 4]	045	5.657	000, 045, 135, 090, 135, 180, 225, 270, 315	16
[-4 4]	315	5.657	000, 045, 135, 090, 135, 180, 225, 270, 315	16
[-4 -4]	225	5.657	000, 045, 135, 090, 135, 180, 225, 270, 315	16
[4 -4]	135	5.657	000, 045, 135, 090, 135, 180, 225, 270, 315	16
[4 0]	090	4	270	16
[0 4]	000	4	180	16
[-4 0]	270	4	090	16
[0 -4]	180	4	000	16

Target selection settings:

- DCPA lim = 0.5 nm
- DCPA max = 10 nm
- TCPA lim = 90 minutes
- TCPA crit = 60 minutes

A2.1.1.2 Singularity test

POSITION (relative to own ship)			COURSE	SPEED
[X Y] (nm)	β (bearing)	Range		
[1 1]	045	1,414	045	16

Target selection settings:

- DCPA lim = 1 nm
- DCPA max = 10 nm
- TCPA lim = 90 minutes
- TCPA crit = 60 minutes

A2.1.1.3 Line BC parallel with the x-axis

POSITION (relative to own ship)			COURSE	SPEED
[X Y] (nm)	β (bearing)	Range		
[2 1]	063.435	2.236	135	14.142

Target selection settings:

- DCPA lim = 1 nm
- DCPA max = 10 nm
- TCPA lim = 90 minutes
- TCPA crit = 60 minutes

A2.1.1.4 RTM only
Operator selected parameters:

- Vmax=20 knots
- DCPA lim = 0.5 nm
- DCPA max = 10 nm
- TCPA lim = 60 minutes

Point B in the Vmax circle

POSITION (relative to own ship)			COURSE	SPEED
[X Y] (nm)	β (bearing)	Range		
[4 4]	045	5.657	315	16

Point B on the Vmax circle with and without intersections

POSITION (relative to own ship)			COURSE	SPEED	
[X Y] (nm)	β (bearing)	Range			
[4 -4]	135	5.657	315	20	intersections
[4 -4]	135	5.657	135	20	No intersec.

Point B outside the Vmax circle with 4 and two intersections

POSITION (relative to own ship)			COURSE	SPEED	
[X Y] (nm)	β (bearing)	Range			
[4 4]	045	5.657	225	25	4 intersections
[4 4]	045	5.657	270	28	2 intersec.

Point B outside the Vmax circle with no intersections

POSITION (relative to own ship)			COURSE	SPEED
[X Y] (nm)	β (bearing)	Range		
[4 4]	045	5.657	315	25

Point B outside the Vmax circle and were the extension of lines BC and BD intersect.

POSITION (relative to own ship)			COURSE	SPEED
[X Y] (nm)	β (bearing)	Range		
[4 4]	045	5.657	045	25

A2.1.1.5 Operator target selection parameters

TARGET POSITION (relative to own ship)			COURSE	SPEED
[X Y] (nm)	β (bearing)	Range		
[5 5]	045	7.071	270	16

This target will generate TCPA =17.5862 minutes (0.2931 hours) and DCPA =0.41523 nm with present own ship course and speed settings

For CDP

Target selection parameters		Status
DCPA lim	0.2	**NOT RELEVANT** Because DCPA>DCPAmax
DCPA max	0.3	
TCPA lim	20	
TCPA crit	3	
DCPA lim	0.2	**NOT RELEVANT** Because TCPA>TCPAlim
DCPA max	2	
TCPA lim	10	
TCPA crit	1	
DCPA lim	0.2	**RELEVANT** Because TCPA in [0,TCPAlim] and DCPA in [DCPAlim, DCPAmax]
DCPA max	2	
TCPA lim	10	
TCPA crit	1	
DCPA lim	0.5	**DANGEROUS** Because TCPA in [TCPAcrit, TCPAlim] and DCPA in [0, DCPAlim]
DCPA max	2	
TCPA lim	20	
TCPA crit	1	
DCPA lim	0.5	**DANGEROUS** Because TCPA in [0, TCPAcrit] and DCPA in [0, DCPAlim]
DCPA max	2	
TCPA lim	20	
TCPA crit	15.9	

For RTM

Vmax is set to 20 knots

Target selection parameters		Status
DCPA lim	0.2	**NOT RELEVANT** Because DCPA>DCPAmax
DCPA max	0.4	
TCPA lim	5	
DCPA lim	0.2	**NOT RELEVANT** Because TCPA>TCPAlim
DCPA max	2	
TCPA lim	12	
DCPA lim	0.2	**RELEVANT** Because TCPA in [0,TCPAlim] and DCPA in [DCPAlim, DCPAmax]
DCPA max	2	
TCPA lim	30	

A2.1.1.6 Dynamic tests

- Target crossing from east to west and vice versa with CPA=0.1, 0.5 and 1 ahead and astern of OS. Test both CDP and RTM to check graphical visualisation is correct throughout.
- Target in head on and overtaking situation

APPENDIX B

B1 Participants

Participant	Belonging	Display type
H	Navigation competence center	ARPA
J	Navigation competence center	ARPA
K	Navigation competence center	ARPA
L	Navigation competence center	ARPA
M	Navigation competence center	ARPA
N	Patrol boat	ARPA
P	Submarine	RTM
Q	Submarine	CDP
R	Submarine	CDP
S	Submarine	RTM
T	Submarine	CDP
U	Frigate	RTM
V	Frigate	CDP
W	Frigate	RTM
HH	Patrol boat	CDP
JJ		RTM
LL	Cadet	ARPA
MM	Cadet	ARPA
NN	Cadet	CDP
PP	Cadet	ARPA
QQ	Cadet	CDP
RR	Cadet	CDP
SS	Cadet	RTM
TT	Cadet	CDP
UU	Cadet	RTM
VV	Cadet	RTM

B2 Model ship data

Identification

Model name FRIGT14

Ship database file name FRIGT14.sdb

Type of ship .... Fridtjof Nansen Class Frigate

Loading condition.. Normal, 5175,9t

Ship's name .... KNM Fridtjof Nansen

General Data

Deadweight, DWT.. 0

Displacement, tonne 5,025

Length between perpendiculars, m............................... 121.4

Length overall, m.. 132

Beam moulded, m... 16.8

Draught fore, m... 5.07

Draught aft, m... 5.07

Block coefficient.. 0.474

Radius of inertia, multiples of L_{pp} 20.96

Speed ahead, knot 26.01

Speed astern, knot.. 11

Engines

Number of engines... 2

Type of engine .... turbine

Total shaft power, kW 28,312

Revolutions, rpm.. 180

Propellers

Number of propellers 2

Type of propeller .... normal

Revolutions, rpm.. 180

Direction of rotation ....inwards

Diameter, m 4.2

Pitch, $P D$ @ $0.7R$ 1.45

Rudders

Number of rudders 2

Rudder type.. normal

Max rudder angle, deg.. 35

Max rudder rate, deg/sec... 2.3

Rudder area, m² 6.5

Total rudder area, % of $L T_{pp \otimes}$ 2.1

FRIGT14, Fridtjof Nansen Class Frigate
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Bow Thrusters

Number of bow thrusters 0

Power, kW ....

Propeller revolutions, rpm ....

Propeller diameter, m...

Propeller pitch, $P D$ @ $0.7R$ ....

Stern Thrusters

Number of stern thrusters 0

Power, kW ....

Propeller revolutions, rpm ....

Propeller diameter, m..

Propeller pitch, *P D* @ 0.7*R* ....

Azimuth Thrusters

Number of azimuth thrusters 1

Power, kW 1,000

Propeller revolutions, rpm 241

Propeller diameter, m.. 2.1

Propeller pitch, *P D* @ 0.7*R* 0.937

Bow Anchors

Number of bow anchors... 1

Mass, tonne 0.91

Chain break load, tonne 23.1

Stern Anchors

Number of stern anchors.. 0

Mass, tonne ....

Chain break load, tonne ....

Radar Position

Longitudinal radar position, m 14.39

Lateral radar position, m..-0.13

Vertical radar position, m 20.6

Viewpoint Position

Longitudinal viewpoint position, m................................. 28.5

Lateral viewpoint position, m.. 0

Vertical viewpoint position, m 11.3