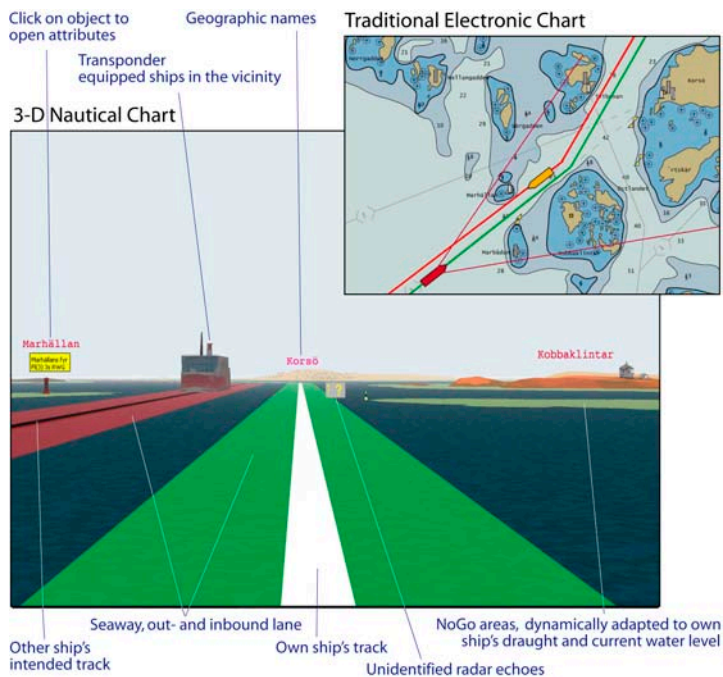


3-D Nautical Charts and Safe Navigation

Thomas Porathe



Mälardalen University Press Dissertations

No. 27

3-D NAUTICAL CHARTS AND SAFE NAVIGATION

Thomas Porathe

2006



MÄLARDALEN UNIVERSITY

Department of Innovation, Design and Product Development
Mälardalen University

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3-D NAUTICAL CHARTS AND SAFE NAVIGATION

Thomas Porathe

Akademisk avhandling

som för avläggande av Technologie doktorsexamen i Innovation och design vid Institutionen för Innovation, Design och Produktutveckling, Mälardalens högskola, kommer att offentligen försvaras måndagen, 22:e maj, 2006, 10.00 i Filen, Verktyget, Smedjegatan 37, Mälardalens högskola.

Fakultetsopponent: Professor Jan-Terje Bjørke, Forsvarets forskningsinstitut, Norge.



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Abstract

In spite of all electronic navigation devices on a modern ship bridge, navigators still lose their orientation. Reasons for this might be excessive cognitive workload caused by too many instruments to read and compile, navigation information that is displayed in a cognitively demanding way, short decision times due to high speed or fatigue due to minimum manning and long work hours.

This work addresses the problem of map information displayed in a less than optimal way. Three new concepts are presented: the bridge perspective, the NoGO area polygons and a dual lane seaway network. Map reading can be difficult due to the problem of mental rotations. By allowing a 3-D nautical chart to be viewed from an egocentric bridge perspective, the need for mental rotations can be removed. The cognitively demanding calculations necessary to find out if there is enough water under the keel can be made by the chart system and the result displayed as of free water and NoGo areas. On land car driving is facilitated by a road-network and a sign system. This notion can be further developed on sea and make navigation easier and safer.

These concepts were then tested in a laboratory experiment, in interviews and in a prototyping project. The results were very promising. The experiment in a laboratory maze showed that map reading from an egocentric perspective was more efficient than using traditional paper and electronic maps. Interviews and expert evaluation of prototypes also showed great interest from practitioners in the field.

for Cristina

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These concepts were then tested in a laboratory experiment, in interviews and in a prototyping project. The results were very promising. The experiment in a laboratory maze showed that map reading from an egocentric perspective was more efficient than using traditional paper and electronic maps. Interviews and expert evaluation of prototypes also showed great interest from practitioners in the field.

Sammanfattning

Trots all elektronisk utrustning på en modern skeppsbygga händer det att navigatörerna förlorar orienteringen. Anledningen kan vara hög kognitiv belastning därför att för många olika instrument måste avläsas och integreras samtidigt, att informationen på instrumenten behöver tolkas på ett kognitivt krävande sätt, att tiden för att fatta beslut blir allt kortare på grund av högre hastigheter till sjöss eller på grund av trötthet.

I detta arbete presenteras tre nya koncept för visualisering av navigationsinformation: *bryggperspektivet*, *djupvarningspolygoner* och *sjövägar*.

Kartläsning kan ibland vara svårt på grund av de mentala rotationer en användare tvingas genomföra för att kunna jämföra kartan med verkligheten. Genom att göra det möjligt för en användare att se sjökortet ur ett egocentriskt bryggperspektiv, så onödiggörs dessa mentala rotationer. De kognitivt krävande beräkningar som navigatören behöver göra för att försäkra sig om att det finns tillräckligt med vatten under kölen, kan utföras av kartsystemet och resultatet visas istället som fria vattenytor och djupvarningsområden (NoGo areas). På land underlättas bilkörning av ett vägnät med körbanor, filer och skyltar. Detta system kan i högre utsträckning införas till sjöss för att underlätta säker navigering.

Dessa koncept har sedan testats genom ett laboratorieexperiment, genom intervjuer och i ett prototyputvecklingsprojekt. Resultaten var mycket lovande. Experimentet i en laboratorielabyrint visade klart att 3D-sjökortet var effektivare än både papperskartan och traditionella elektroniska kartor och intervjuerna och expertutvärderingarna visade på ett stort intresse från yrkesutövare i branschen.

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And thanks to my brave and loving family who stood me by during this time.

April 2006

Thomas Porathe

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List of Abbreviations and Terms

ADVETO: Company making electronic charts.

AIS. Automatic Identification System. A system requiring ships of 300 gross tonnage or more to have a transponder which sends name and position to surrounding ships. Ships will then show up as a symbol with an attached name tag on each other's radar and chart displays.

ARPA. Automatic Radar and Plotting Aid, computerized functions allowing for example tracking of other ships within range and simulations of own and other ships movements a number of minutes into the future, collision warnings etc.

Bare earth elevations: Terrain models not incorporating the height of the vegetation.

Bathymetry. The art or science of measuring depths (in the sea).

Bird's eye perspective. See exocentric perspective.

Break lines. A geometrical feature used when creating polygon meshes for terrain models. By adding a vector line to the model new heights and polygon structures is added to the models.

Bridge perspective. See egocentric perspective.

Buoy. A floating sea-mark.

Cairn. A landmark made by piled stones or concrete. When used for navigation painted in different ways for identification.

Coastal View. A drawing or a photograph of the coast from a point at sea. The coastal views were published in pilot books and used to compare to the optical view when approaching an unknown coast as an aid to positioning. The 3-D chart is a dynamic coastal view.

Conn. To direct the steering of a ship.

Course-up. See Head-up.

Delauney triangulation. A method of triangulating polygon meshes used in creating 3-D terrain models.

DGPS. Differential GPS. A GPS receiver on the ground (knowing its true position and comparing it with the GPS position) calculates the present error due to atmospheric effects and sends the error on to the DGPS receivers. The position error will this way be less than 10 m.

ECDIS. Electronic Cart and Display System. A IMO certified system using ENC.

Egocentric. The everyday view we see through our eyes, sometimes called the forward field of view.

ENC. Electronic Nautical Chart.

ETRS 89. European Terrestrial Reference Frame 1989. A reference system for mapping.

Exocentric. An external view, in this work used for the bird's eye perspective of traditional maps.

Galileo: The European satellite positioning system. The first satellite launched in 2006. Scheduled to be operational by 2008.

GLONASS. The Russian satellite positioning system, similar to the GPS. Currently not fully functional.

GPS. Global Positioning System.

GRS. Geodetic Reference System (1980), reference ellipsoid used by the GPS.

GRT. Grosse Register Tonnage (a register ton is 100 cubic feet), one measure of the size of ships. GRT refers to the volume of the ship interiors except the inside of double hulls and some other compartments.

Head-up. By "head-up" in the maritime context is a display mode for radars or electronic charts. The display technique of the first generation radars where straight ahead was always up on the radar screen, because limited computational capabilities these radars were hard wired to the screens. Modern technology and the merging of information from the gyro compass and GPS allows radars and charts many more display modes, like *north-up*, where north is always up on the display, *course-up*, where a set course is always up. The difference between head-up and course-up is that with course-up the entire screen is not turning if the vessel is swaying some degrees back and forwards on its course. Another mode is often called *true motion*. In this mode the world is frozen on the display and the own ship is traveling over the display instead of always being still in the center – or an off-center point – and the world is moving. When the own ship then has traveled a certain distance over the display the world is updated and "the camera" jumps ahead again.

Head-up is not to be confused with the same term used in aviation context. Modern fighter aircrafts are often equipped with a HUD, a head-up display. Head-up here means that the pilots

can keep their heads up and see important instrument settings through a semitransparent display in the windscreen instead of flying “head-down,” looking at their instrument panel.

Heel. Sideways inclination of a ship (*trim* is the endwise inclination).

HDS. Hardanger Sunnhordlandske Dampskipselskap ASA, the shipping company of *MS Sleipner*.

IALA. International Association of Maritime Aids to Navigation and Lighthouse Authorities. An international technical association concerned with standardizing technical aids to navigation.

IHO. International Hydrographic Organization. An intergovernmental organization concerned with, among other thing, standardizing nautical charts and bathymetry.

IMO. International Maritime Organization. United Nation’s organization for international cooperation in maritime matters.

INS. Inertial Navigation System. A technique using mechanical or optical gyroscopes to measure acceleration in three dimensions.

Isometric. A graphic representation of three-dimensional objects The isometric is one class of orthographic projections.

ITRF 89. International Terrestrial Reference Frame 1989.

Landmark: An object in the landscape, which, by its conspicuousness, serves as a guide in the direction of one's course.

LIDAR. Light Detection And Ranging. A radar technique using laser light instead of microwaves. Used to collect elevation measurements from airplanes or helicopter using laser scanners.

MMSI. Maritime Mobile Service Identity. A unique ship identification number used for VHF radio communication.

nm. Nautical mile (1,852 m)

North-up. See Head-up.

OOW. Officer of the Watch. The conning officer in charge at the bridge.

Orthophoto. An airphoto that has been corrected for distortions due to the single-point perspective of the camera lens so as to become orthographic. An elevation model of the depicted landscape is needed for the rectification process.

Orthographic. (or Orthogonal) “Right-angled.” The object is viewed along parallel lines that are perpendicular to the plane of the drawing. Thus, the lines of sight, called projectors, are parallel rather than convergent (as they are in the central projection of the eye, the camera, and geometric perspective).

Photogrammetry. Measuring from photographs. In this case a method of measuring heights from pairs of stereo air photographes.

- RTK. Real Time Kinematics. A high precision GPS using phase measurements to acquire centimeter accuracy.
- SA. Situation awareness, sometimes also situation assessment.
- SMA. Swedish Maritime Administration (Sjöfartsverket)
- Sounding. The action or process of sounding or ascertaining the depth of water by means of the line and lead (now unusual) or by means of echo sounders.
- Squat. As a ship's speed increases, so does its draught due to the Bernoulli effect.
- Surface perspective. Se egocentric perspective.
- SWEN 01L. Swedish geode model 2001 compensated for land rise ("L")
- SWEREF 99. Swedish Reference System 1999, a Swedish geodetic datum decided in 2001.
- Terracing. A problematic artifact in 3-D terrain models often a result when using height data from elevation contours. The result is a landscape with terraces.
- Tethered. An exocentric viewing perspective from an oblique angle behind the ship, being half way in-between a bird's-eye perspective and an egocentric bridge perspective.
- Texture. Here the picture (painted or photograph) applied on top of the polygon mesh of the terrain model to convey structure.
- TIN. Triangular Irregular Network, a type of structure in polygon meshes.
- Topography. Detailed description of a location or an area.
Topographical maps describe the elevation properties of an area (as well as other properties).
- Transas. A company that produces, among other products, electronic charts and display systems.
- Transponder. A radio transmitter connected to the GPS unit sending the ship's name and position and some other data on the VHF frequency to ships in the vicinity.
- VHF. Very High Frequency. Short for the radio used to communicate at short distances at sea.
- WGS 84. World Geodetic System 1984. A geodetic reference system used by the GPS.

Chapter 1 Introduction

This chapter introduces the project and gives an overview. The three main concept ideas are presented as well as the methods to be used in the study. If you only want to read one chapter this is the one. The findings are then presented in the following chapters and a conclusion in chapter 6.

1.1 Project Overview

This research project suggests a novel way of displaying map information to the navigator on the ship's bridge. The aim is to afford safer navigation. In this research project some different methods were used to try to find out whether this new way of displaying map information is safer or not. This dissertation presents these conceptual ideas and the research done to find out their effectiveness.

The Department of Innovation, Design and Product Development (IDP) in Eskilstuna, consists of three research groups and areas of education: Innovation Management, Information Design, and Product & Process Development. The common research arena is called *Innovation & Design*. This is a research project within Information Design (ID) which is a multidisciplinary field incorporating parts of art and aesthetics, information science, cognition, communication and the language (see Figure 1).

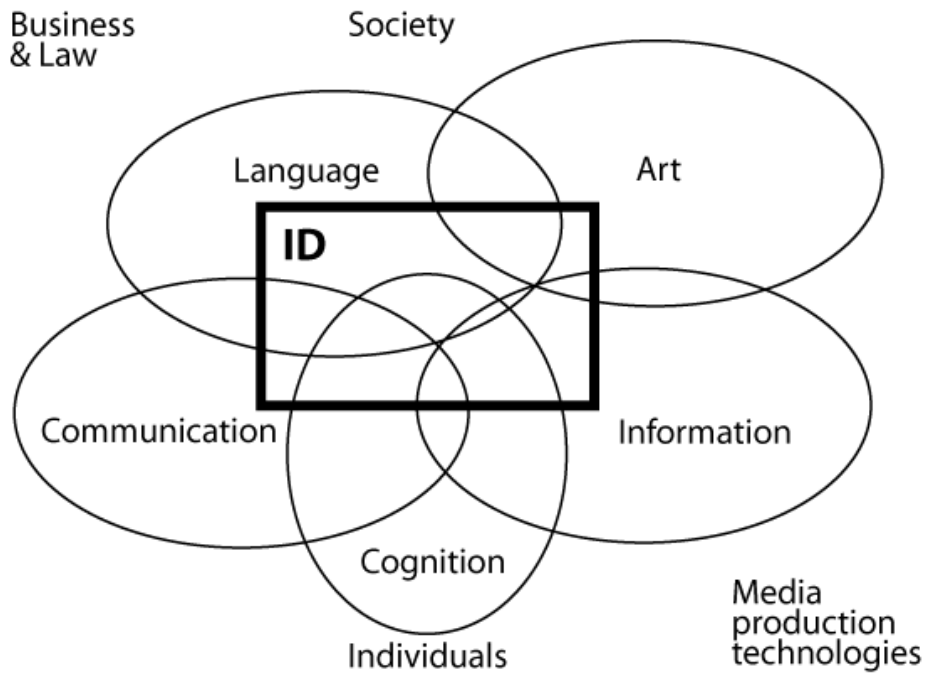


Figure 1. Information Design (ID) is a multidisciplinary field of study (Pettersson, 2002, p. 19).

Information design is about making information understandable. Geographical information is often contained in an ancient construct called *maps*. In this dissertation I will show that maps used to convey spatial understanding can be problematic. The question I have been concerned with is if map design can be further improved to afford better understanding within the navigation context. I will present some new concepts for map design in the maritime domain, where maps are called *nautical charts*, and I will present research on the efficiency of these new representations.

The questions that I put guide my choice of research methods and the choice of methods is important for the answers that I get. All methods are not suitable for all problems and any one method might not be capable of answering all questions. The methods chosen can be compared to flashlights, capable of enlighten only a part of the problem area (see Figure 2).

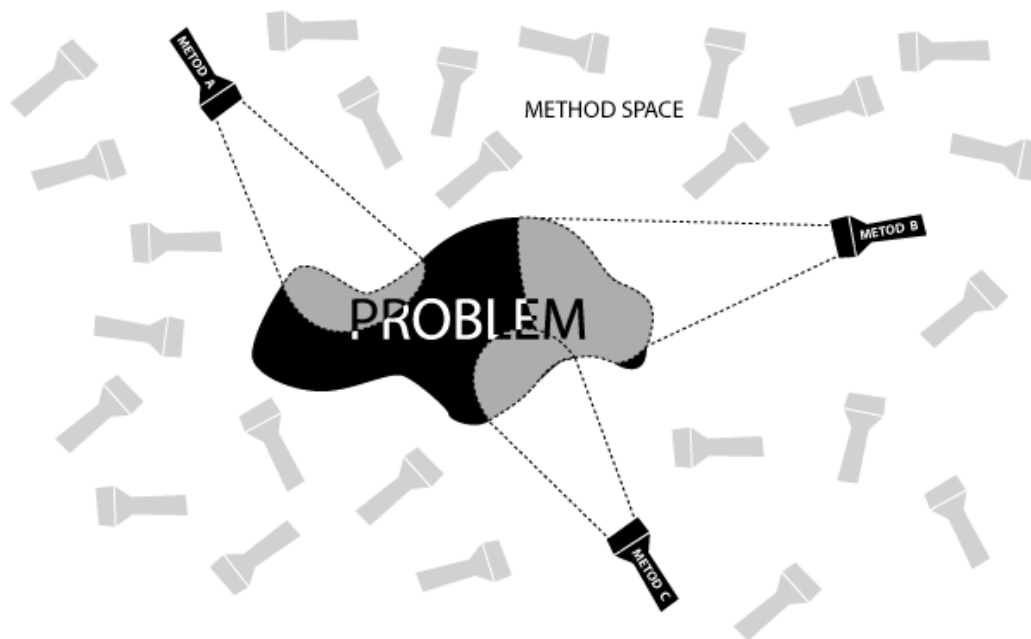


Figure 2. From a selection of possible methods the researcher must choose one or several methods that s/he thinks can enlighten the problem.

So the selection of methods is very important. Based on the research questions (presented later in this chapter) I have chosen a few methods. From the quantitative behaviorist tradition I have chosen a quantitative laboratory experiment; from the cognitive domain I have used a qualitative ethnographic method to make observation in a number of field studies and from the design science area I have used *prototyping* which is an iterative method of Human Centered Design. In Figure 3 an overview of the methods, the knowledge collection process and the content of this dissertation is shown. In the beginning of the methods chapters (2, 3, 4 and 5) each method, the reason for choosing it and its theoretical foundation are presented in more detail.

Much frustration on the ship bridge and elsewhere in society is caused by technological systems created by system designers who do not understand the needs of the user, nor the context the user is working in. Because my role in this project is just that of the system designer I want to start out by giving a personal explanation to convey that my perspective actually is that of a mariner.

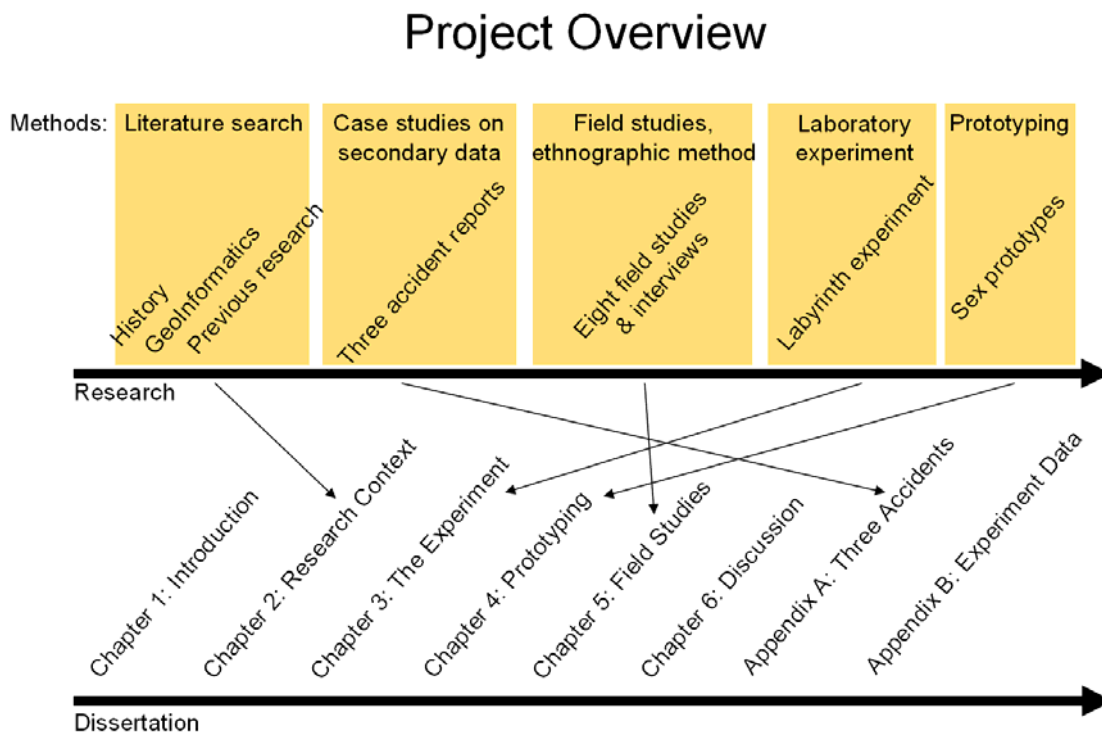


Figure 3. An overview of the methods used and their place in the dissertation. (Three chapters on the historical background, geographic reference systems and map projections, and basic navigation have been omitted in the final text to keep down the size of the book.)

1.2 Defining navigation

The word *navigation* has to do with ships although we today navigate both cars and airplanes and even ourselves in abstract information spaces like the World Wide Web. The encyclopedia tells us that the word originates from the Greek *naus* (which we have in *nautics*) and the Latin word *navis* which both mean “ship”. Adding the Latin *agere*, “to act” or “to put in movement” gives us *navigare*, “to direct a ship”.

So in a narrow context *navigation* is the direction of ships. But the broader context, how man navigates in the world, has been the focus of many studies, particularly in cognitive science. “Navigation is the aggregated task of wayfinding and motion,” says Darken & Petersen (2001) in a much broader definition (this will be presented in more detail in chapter 2).

Chapman's *Piloting and Seamanship* by Elbert Malony (2003) defines navigation as "the art and science of safely and efficiently directing the movements of a vessel from one point to another." (p. 48) Huchins (1995) defines navigation as "a collection of techniques for answering a small number of questions, perhaps the most central of which is 'Where am I?'" (p.12). So, we might conclude that the two major components of ship navigation is:

- Finding the ships position (position fixing)
- Establishing a direction to go

By tradition, marine navigation has been divided in three methods of position fixing:

- Navigation in sight of land, *terrestrial navigation* or *piloting*.
- Navigation without sight of land using the measured angles to astronomical objects, *celestial navigation*.
- *Dead reckoning* (DR). Positions are calculated based on sailed direction and distance from a previously established fix. *Dead* from *deduced* (Bolling & Holm, p. 6).
- The advent of the *satellite based navigations systems*, e.g. GPS, in the 1980's changed all this and outdated many of the old techniques, and now has to be added as a fourth navigation method.

To answer the question "Where am I?" we need some kind of reference system to define a position against. "I am at the tiller, facing forward," could be one answer, although probably not one that would be of much use; nor would an answer like "On the planet Earth, the third planet from the Sun in the galaxy Milky Way." Not that they do not describe a position, but the position has no relevance in the nautical context. "3.5 miles SSE Kinsale head on southern Ireland" is much better; the position defines a specific place in relation to a specific geographic location. The answer "51°36.3' North, 8°31.9' West" is also very good, it defines the same specific location, but relative to a standardized global grid net of longitudes and latitudes. The reference systems used are of outmost importance for navigation. A chapter on this has been omitted as I felt it carried the presentation away from the information design aspect and into too much detail. Texts on reference systems can be acquired elsewhere (e.g. Laurini & Thompson, 1992; Eklund, 2001; Ekman, 2002; Hoffman-Wellenhof, Legat, & Wieser, 2003).

In the olden days navigation was a mysterious task performed by sailors with sextant and chronometer or with an eye to the alidade on the pellagrous. Then seafaring used to be a dangerous business, ship wrecks counted by the dozens after winter storms. Today, with GPS and position plotting electronic charts we may think that navigation has become easy and the maritime business safe. True is that shipping has become much safer, but as I intend to show, much is still left to do.

1.3 Background

The landscape of my childhood was the sea and the archipelago outside the little town of Lysekil on the Swedish west coast. This is where I learned to sail and navigate. My grandfather and I went to sea trolling for mackerel or wreck hunting for fire wood on the barren skerries. In those early days I never saw a chart, my grandfather knowing the archipelago inside and out and his head full of landmarks and ranges that he used for finding his fishing grounds. When the mackerel arrived in the spring it first stood deep feeding on the seaweed on the bottom shelves at sea; later it went further in among the islands. “The church tower over the Harpö sign in the east and the eastern end of Bonden island close to the western tip of Hermanö in the south, that is where she will be,” he would say.

Harpö (Harp island) was one of the outer islands. At the top there was a wooden beacon that looked like a harp. Outside there was an underwater rock called Salthästen (the Salt horse) exposed to the open sea. Around it were good fishing grounds and my grandfather would circle around it while the huge swells rose, became translucent green and broke with a thunder over the rock. It was frightening and wonderful at the same time. On very rare occasions the sea would be dead calm and we would drift over it, watching the naked rock stick its barnacled head through the wood of sea weed under the boat.

When I got my first own sailing dinghy at the age of ten, I never had any problem finding my way. I knew the islands by heart and although I did not know the bottom of the sea, I knew where the dangerous shoals were. Besides, my little dinghy floated almost on top of the water and raising the centerboard I loved investigating the shoals in calm weather. Slowly drifting or paddling over them, leaning over the

side looking down at the fascinating and at the same time frightening sight of rocks and seaweed raising from the deep, now so harmless, but a terrible threat to a bigger boat steaming ahead in bad weather.

In the attic of my grandparents' house lay a mysterious treasure. It was a large number of gray tubes made of soldered sheet metal with herring tins in each end as lids. Inside the tubes were old nautical charts from my great grandfather who had been first mate of the 3-masted braque Hilda. The charts were from the end of the 19th century on to the 1930's and over Scandinavian waters. The very old ones had strange soundings following the shipping routes and almost no figures elsewhere. They all showed lighthouse stations and light ships that were long gone. These charts were fascinating to look at. Once in a while my grandparents took me on longer voyages to Norway and Denmark. Then some of these old charts would be used. When I became older I would protest, saying that the charts were too old and *one always had to sail on fresh charts*. But my grandfather would laugh and say that the islands and the depths were the same, it was only the buoys and lighthouses that might be different, *so you need to pay better attention to the ranges*.

I have always owned a boat. For 15 years I sailed the old wooden gaff rigged ketch, *Myra* (see Figure 4). She was too large to be sailed by me and my family alone so for many years I saw a steady stream of friends trying to solve the mysteries of charts and navigation and it struck me that this was not as easy as I had thought. In hindsight I think that much of what I know of human wayfinding comes from those years trying to help my helmsmen and women to reconcile the map with the physical world around them.

In this work I have tried to keep the perspective of the navigator and mariner, and my ideas are based on my own experiences and problems of people close by.

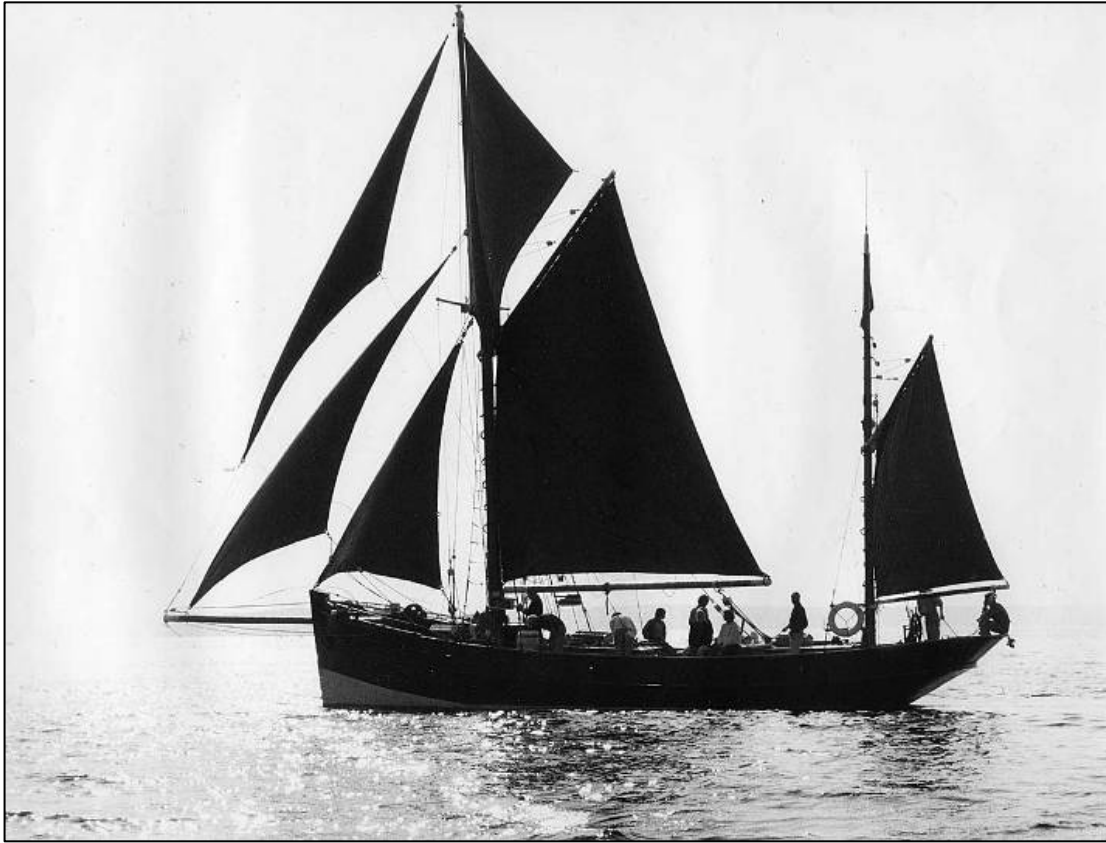


Figure 4. The author's gaff rigged ketch *Myra* in 1996. Photo: Dick Pettersson, UNT Bild.

The *Sleipner* Accident

In November 1999, the high speed ferry *Sleipner* crashed against a rock in the dark of night and in bad weather on the Norwegian Westland. 16 persons drowned as she slid off the rock and sank. (The *Sleipner* accident and two other accidents are presented in detail in appendix A.) I was myself planning a trip to about the same area at that time so I was very interested in what had gone wrong. I asked how it could be that two well trained and experienced officers, traveling on a well-known route, in a highly sophisticated and well equipped vessel could lose their orientation and ground.

I read newspaper clippings as well as the accident report: For a second, after the captain had looked up from his radar screen and found the white light of the beacon he had been heading for was gone, he was lost. During the following seconds, seeing the beacon in red on his

starboard bow, trying desperately to re-fit his mental map to the real world, *Sleipner* ran aground.

I did realize the difficulties in night navigation. No matter how well acquainted you are with an area, how good your own mental map is, you only have a couple of small flashing lights to anchor the map to the real world. I had many times myself been standing over the chart in the red glow of the night vision light and tried to fit the beacons of the chart to the flashing lights around. And then I had had plenty of sea space, and a maximum speed of six knots. *Sleipner* went in 32 knots. But again, she had radar, GPS and an electronic chart that automatically plotted her position. How could she get lost?

Here I had an interesting problem that had something to do with the integration of different sources of information in the head of the navigator. The navigator's aim was to know what was going on, keep his or her *situation awareness* (SA) updated. This could be done by collecting pieces of information from the senses: vision, hearing, balance and so forth. In a navigational task at night a lot of this information would come from instruments, some showing analogue data, like the radar, and some just showing digits, like COG display (Course over Ground). The nautical chart was the center of gravitation and all of this had to be integrated in the head of the navigator, *time* being the crucial factor (see Figure 5).

A couple of years prior to the *Sleipner* accident I had taken up civil engineering studies at Uppsala University and I had become well acquainted with computers and computing. Due to my navigation interest I had in 1995 made some trials with 3-D terrain models but very soon I realized that the computer equipment needed for real-time 3-D in those days were well out of reach for me. But in 1999 the situation had changed and the *Sleipner* accident made me start over again: why not use a navigation simulator as a chart? By connecting a 3-D model of the real world to the GPS signal and displaying fairways and other abstract information together with underwater and land topography a synthetic daylight view of what lay ahead in the dark could be supplied to the navigator.

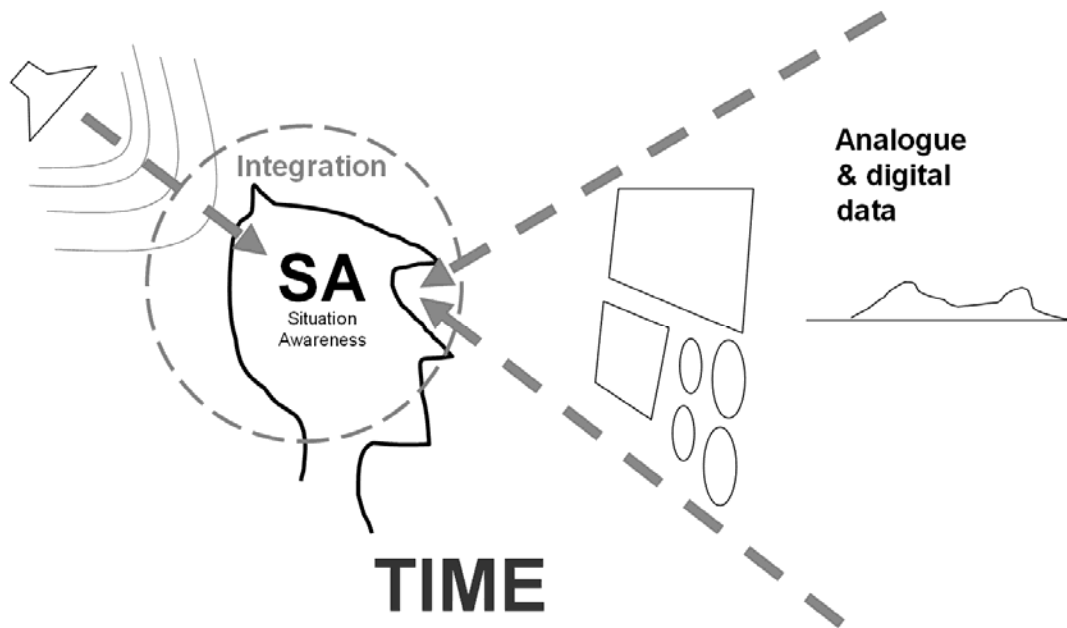


Figure 5. A simple model of the key components of this research.

The picture on this “3-D Nautical Chart” could probably be easily and intuitively understood, as compared to the sometimes difficult comparisons between the chart and the real world.

That was the beginning of this research project and in 2001 I was omitted as a doctoral candidate in information design at Mälardalen University. This dissertation is a report of the process and the findings of this project.

1.4 Problem Statement

To start out broadly, my domain is that of safety at sea. Ships do get lost at sea. In 2004 about 100 ships were lost at sea around the world (ICS, 2005, p. 16). One hundred ships out of a total amount of 29,035 ships in worldwide service 2004 is not much (U.S. Department of Transportation, 2006). But still the risk of an accident at sea is a reality. And every time there is an accident lives and great values, economic as well as environmental, are at stake.

The world seaborne trade continues to grow and is estimated to do so. The recent rise in fuel prices will probably speed up this increase as sea transport is much cheaper than road and rail transport. (Road: 0.5 – 1.2 Mega-joules/ton-km and a standard 1,226 TEU¹ container ship only 0.1 Mega-joules/ton-km. ICS, 2005, p. 16.)

Looking at accidents at sea and not only total losses, the figure will of course be much higher. Of all marine accidents, 80 to 85 percent are generally attributed to *human error* (Perrow, 1999, p.224; Rothblum, 2002; Baker & MacCafferty, 2005). Human error is defined as: “Deviation from planned or appropriate perceptions, information manipulations, decisions, or behaviors” (Baker & MacCafferty, 2004, p. 8). In short: *a misconception or a wrong decision made by a human.*

In one of these studies made by the American Bureau of Shipping on data from 2002 and 2003 in four large databases the figure 80 to 85 percent of all shipping accidents are due to human error, is confirmed. Of these 80 percent, 50 percent were classified as *initiated* by human error, while the other 30 percent were *associated* with human error (Baker & MacCaffery, 2004, p. 1). Of all the accidents attributed to human error a stunning 70 percent were recorded as caused by failure in situation awareness.

Situation awareness means *knowing what is going on around you* and is an important factor on board a ship. When the visual sight is limited, in fog or darkness, information of what is going on is mediated through different electronic instruments on board. The map is often the common ground where this information is synthetized.

Map reading skills are important for the situation awareness. Map reading and navigation is drilled in maritime academies but even so, professionals with sophisticated equipment may lose their orientation. All three examples of the shipping accidents described in appendix A, were caused by loss of situation awareness. The work environment on the ship bridge often includes increasing speeds, more instruments to monitor, a large environmental responsibility, cargo and passengers,

¹ TEU: “20-foot Equivalent Unit”, the volume of a small-size standard container. Simply put: the amount of 20-foot containers the ship can carry.

minimum manning with long work hours. The result is high cognitive work load, short decision times, stress and an increasing risk of fatigue and subsequent slips, lapses and mistakes.

In a field study on high speed ferries in Hong Kong 2001, Eva Olsson (2001) reports on the technical equipment on the bridges. A bridge might have one or two radar displays, one display for the electronic chart, one display for low-light/IR camera, one or several monitors for on board TV-cameras. Besides that, there will be one or several displays informing about propulsion, steering forces, the status of different technical systems on board, navigational warnings etc. Often these systems are not integrated with one another because they are of different brands. Often they are not optimally used because the bridge crew lack sufficient time to learn and train on their different functions (Olsson, 2001, p. 10). A comment was that there were too many instruments to monitor on the bridge and each check on a display caused a certain delay in decision making (p. 8).

Problem statement: High speed, short decision time, un-integrated and complex navigational equipment on the bridge lead to high cognitive workload for the navigator and increases the risk of accidents at sea.

1.5 The Objective

The objective of this study is to investigate if the suggested 3-D nautical chart may lead to safer navigation. The 3-D nautical chart is based on three concept ideas. These are: 1. The Bridge Perspective, 2. The NoGo Area Polygons and 3. The Seaway Network.

The Bridge Perspective

The focus of this research project is *integration* and *cognitive off-loading* in the display of navigational information on the bridge. The important part is human factors, the cooperation between the technical system and the human in performing the navigation task. With *integration* I mean that as much as possible of the information should be integrated beforehand, not to un-necessary burden the cognitive integration work

of the navigator. This can be done by presenting the necessary information at the right moment and in the *right way*. By *right way* I mean that the information is comprehensible with as little cognitive effort as possible, or even is presented in such a way that it takes over some of the cognitive integration work.

In Figure 6 we can see the workplace of the navigator of a Swedish combat boat. In front of him on the table there is a traditional paper map (1), in the maritime domain called a *nautical chart*. This nautical chart is an iconic representation of the world depicted from a bird's eye view. The map reader, the subject, is in his imagination looking at his ship moving over the surface of the map as an object seen from an outside position. I call this map perspective *exocentric*.

Most maps are printed with north as the “up direction.” Texts printed on the map go from west to east (since the days of Ptolemy – Holmes, 1991). If you hold this map so that you can read the text the map is oriented in a *north-up mode*. In front of the navigator, in Figure 6, on the bulkhead are two screens. To the left is an electronic chart display (2). On this display the navigator can see an exocentric view of his own ship (the black symbol in the middle of the screen) plotted on top of an excerpt of the nautical chart. This chart is also presented in a north-up mode and the chart is basically the same as the paper chart but the navigator can choose which scale to work in. He can also to some extent choose what information he wants to display or hide so as not to clutter the display. A problem with these displays is that to offer the same overview as a paper chart the operator has to choose a smaller scale, and then maybe important details will be lost.

In the upper right-hand corner of the chart display the navigator can see that the boat is going 39 knots on course 142°, i.e. in a south-easterly direction (down and to the right on the chart screen). In front of the boat on the chart screen (2) there are two lines, one is the *course line* or the *track*, a line connecting the pre-programmed *waypoints* of the journey; these lines lead through the sound between the two small islands in the lower right-hand corner of the screen. The other line is the *heading line*. (It is actually a course-speed vector showing the momentary heading of the boat with a length that is proportional to the

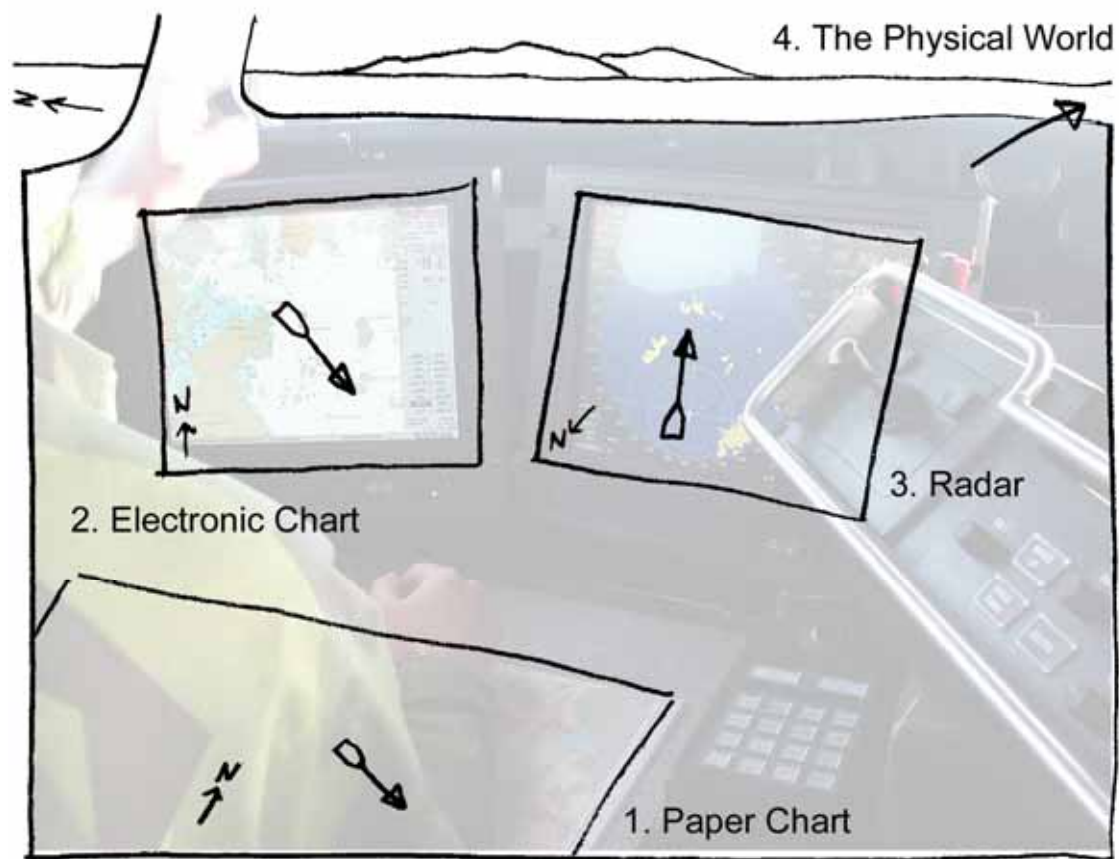


Figure 6. The navigator of a Swedish combat boat is juggling with four different views of the world: the north-up exocentric views of the two charts, the head-up exocentric view of the radar display and the egocentric view outside the window.

speed of the boat. This vector can, for example, be set to show the distance the boat will travel in one minute.) At this moment the navigator can see that the boat is slightly off course, the heading line is pointing at the larger of the two small islands and somewhat to the south-west of the sound the course is set for.

To the right on the bulkhead is the radar screen (3) which also presents an exocentric view of the boat and the surrounding world. The boat is here the small symbol in the center of the distance circles in the lower part of the screen. The line pointing straight up is again the *heading line*, the heading of the boat which at the moment points at the larger of the two islands. Notice the different orientation of the radar screen. The two small islands are here at the top of the screen. The radar is set in *head-up mode*, the boat is traveling in the up direction (or actually, the boat is fixed in the lower part of the screen and the elements of the display are moving downwards.) Radars can normally use different presentation modes; two of them are *head-up* and *north-up*. North-up is the most usual radar presentation mode but smaller crafts – like the combat boat in the picture – do not always have access to the gyro stabilization needed to present the radar picture in north-up mode, (or the electronic chart in an head-up mode).

Outside the navigator's window there is the real world (4). In daylight, when he looks up from his instruments he can see it from a *bridge view perspective*. I call this the *egocentric view*; sometimes it is called the *Forward Field of View*. This is the perspective we have of the world as we go about in our everyday business. The world rushes towards the navigator as the boat is heading for the narrow sound and is perceived by his eyes as an *optical flow*. This optical flow refers to the relative velocity of points across his visual field from a point of expansion. Optical flow is an important cue for the perception of speed and heading (Wickens & Hollands, 2000, p. 163).

At this moment the navigator of this combat boat is working with four different perspectives of the world: 1. the exocentric north-up view of the paper and 2. electronic charts, 3. the exocentric head-up view of the radar and 4. the egocentric view of the real world outside the windscreens. The larger of the islands that in a moment will pass on the *starboard* (right) side of the boat will also be to the right side on the

radar screen. But on the charts the bigger island will be on the left. After having passed the sound, the boat will make a sharp *port* (left) turn. The new direction will at this moment be to the left on the radar screen; but on the charts it is the opposite, towards the right. And this is where the problem is.

Maritime navigation is mostly, by a strong tradition, conducted with map representations in an exocentric north-up view. A navigator moving south trying to match the real world to a map presented in a north-up mode on the wall in front of him will have to switch directions. He will do this as a two step mental rotation. First he has to rotate the map 180° around the vertical z axis and then 90° around the horizontal x axis (see Figure 7).

In some ships the situation is complicated even further when the chart table is placed so that the navigator is standing with his back in the forward direction as he reads the chart (see Figure 8). Recently this has caught some attention from the classification societies and in its latest guidelines to bridge design the American Bureau of Shipping has stated that “the consoles, including a chart table if provided, should be positioned so that the instruments they contain are mounted facing a person who is looking forward” (ABS, 2003, p. 26).

Would it be possible to display chart and radar images integrated in a more intuitive way and by that easing the cognitive workload of the bridge crew? By offering the navigator to literally “climb down” into the map, the need of time consuming and erroneous mental rotations will be removed. This can be done by using a 3-D map that can be displayed both from a traditional exocentric and from an egocentric perspective. If the radar picture also could be integrated into this 3-D nautical chart together with all other information normally found in a nautical chart, the situation for the navigator would be greatly simplified. The idea is illustrated in Figure 9.

It is important to point out that I am not suggesting that the exocentric view be abolished; in many situations this view is to prefer. If we look at the navigation task of a navigator, presented in Figure 10, we can see

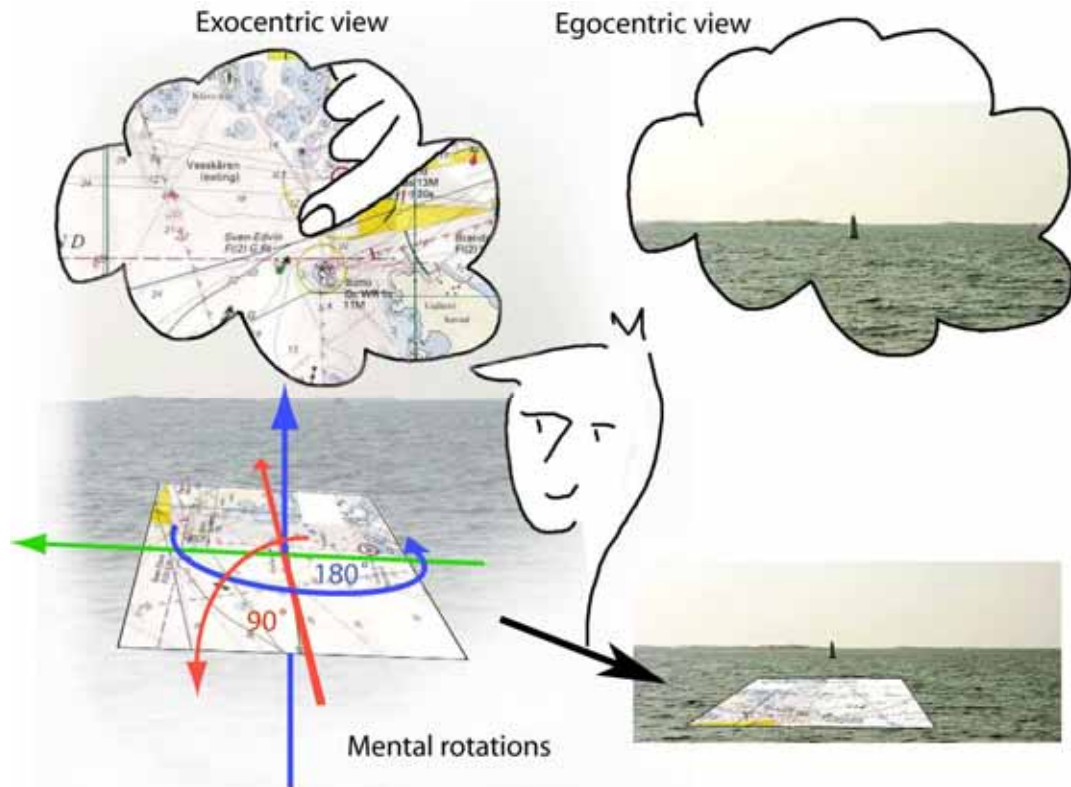


Figure 7. Basic principles used in this dissertation: the navigator experiences the real world through the *egocentric* view he sees with his eyes. Maps present the world in an *exocentric* view, where the navigator has to imagine himself as an object seen from a bird's eye perspective. In order to align the exocentric map with the world the navigator has to perform a series of *mental rotations*.

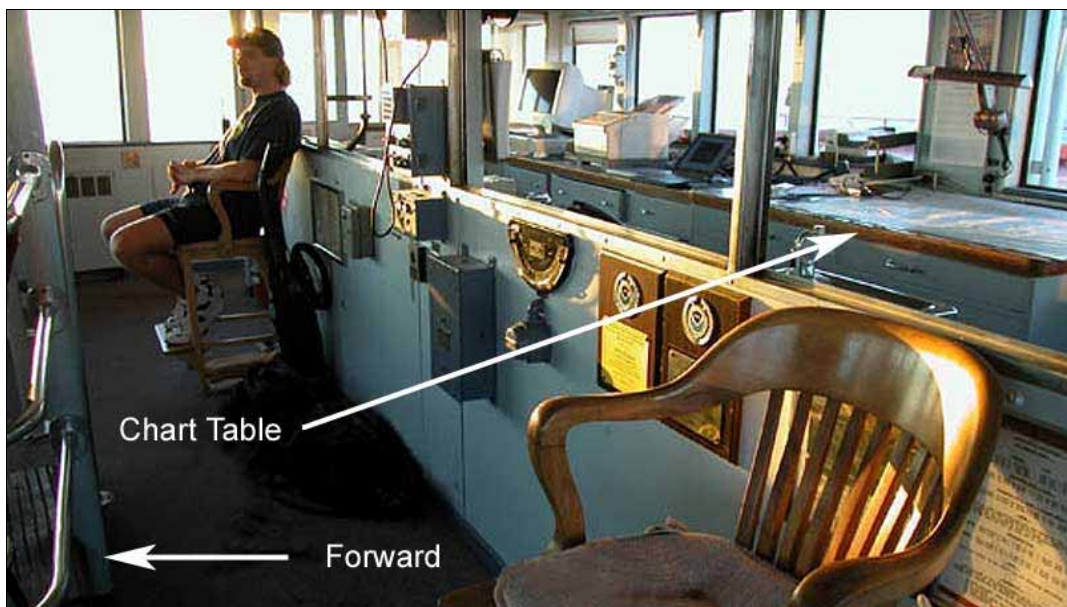


Figure 8. *MS Wilfred Sykes*. The navigator reading the charts is facing aft. Photo: Roger LeLievre, <http://www.boatnerd.com/pictures/fleet/sykesb.htm>, [2006, February].

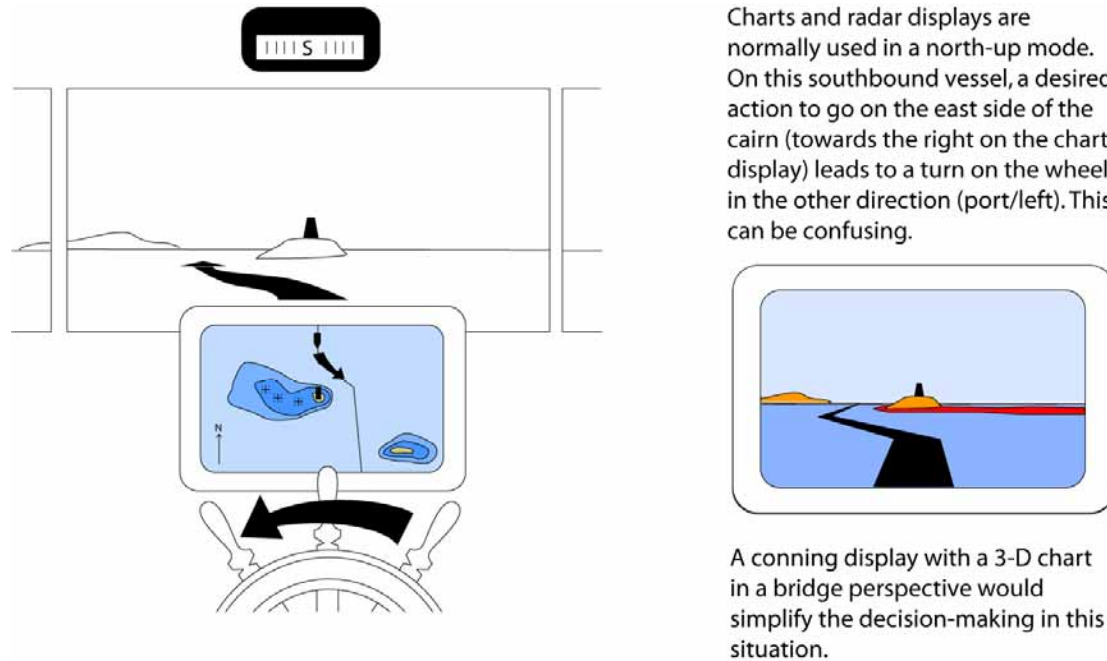


Figure 9. The suggestion of the egocentric bridge view can be summarized in this slide.

that charts are used both before and during the voyage. Prior to the voyage a passage plan is made. Turning points, way points, and course legs are marked with a pencil; distances are measured and compass courses are written into the chart (or programmed into the electronic chart). During the voyage the progress of the ship is “ticked off” by fixes marked into the chart on set time intervals. This is best done in the exocentric north-up perspective. Communication with other ships and pilots on shore with reference to geographical features is also best done from an exocentric north-up perspective which provides a common frame of reference. (“North of the lighthouse” is less ambiguous than “to the right of the lighthouse.”) But I propose that in the conning situation and when communicating with other member onboard the ship the exocentric head-up or egocentric view is better. (“Turn starboard!” – right – is faster executed that “turn east” which requires the helmsman to first look at the compass to infer the relation between the present course and east.)

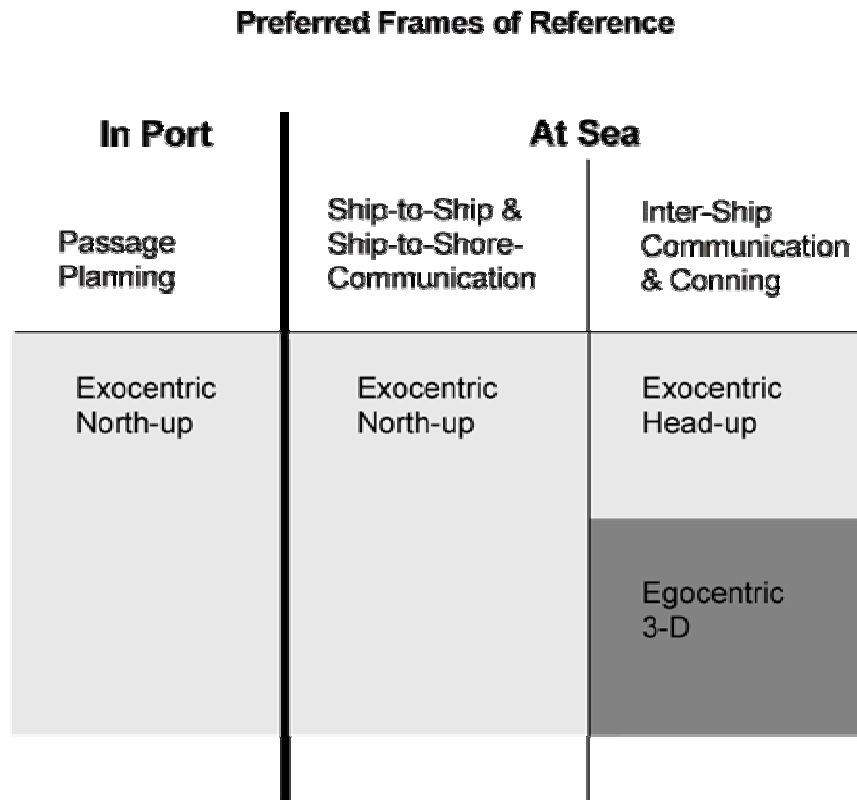


Figure 10. Map use in maritime navigation. Charts are used both before and during the voyage. In many situations the traditional exocentric north-up orientation is to prefer, only in the actual conning situation I suggest it is better to use the chart in an egocentric perspective.

NoGo Area Polygons

One of the most obvious problems for the voyager is the opaque sea that hides underwater rocks where ships may ground. The remedy for this problem has been to make soundings of the water and print the depth as numbers in the nautical chart. But even with the sounding figures, finding out if the water is deep enough is a compelling cognitive task. Figure 11 shows a detail of a chart over southern Norway outside the town of Stavern. The reef Rakkeboene is a boiling inferno in a southwesterly gale, still locals manage to find their way through it. In my childhood, I passed here with my grandparents several times. My grandfather always contemplated taking a shortcut closer to land, trying in vain to make sense of the chart clutter of depth figures, then finally giving up and going around outside the reef.

The problem with the presentation of depth data the way it is done in Figure 11 is that every depth figure has to be read before one can make a decision whether a ship will have enough water under the keel or not.

An improvement of this problem is called chart *generalization*. Soundings are classified into depth intervals connected with isobars called *depth contours* and the areas inside the shallower contours are colored in different shades of blue. Standard curves are, for example, 3, 6 and 10 meters. A generalized chart is much easier to read (see Figure 12).

The chart in Figure 12 depicts a portion of the Swedish east coast outside the nuclear power station Simpsvarp some 300 km south of Stockholm. In the chart the fairway to the power station harbor is marked with an east western line. This track is used by the nuclear waste ship *Sigyn* with a draught of 4.00 m with full load (SKB, 2005). The soundings in the chart show the depth at normal water level. It is part of the duty of the navigation officers to do the passage planning and ascertain that there is enough water under the keel during the entire voyage. According to the Bridge Procedures Guide (ICS, 1998, p. 17, the guideline used by most shipping companies) this should be done prior to the departure. The guide requires that dangers such as shallow water in the vicinity of the track be marked on the chart. (For an example of how this is done, see Figure 146 in the section on the field study onboard a tanker, in chapter 5.) But if something unexpected should happen such as failure of machinery or steering, or an evasive maneuver forces the ship off its planned route, then complex mental calculations have to be made: draught, tidal level and wave amplitude have to be calculated against the soundings in the chart to conclude whether there will be enough water under the keel. Look at the chart in Figure 12, imagine that you are the watch officer of *Sigyn* entering port with a 4 m draught. Now, say that you have 1 m of low water and a significant wave height of 2 m. Where are your dangers?

It will take even a trained eye a while to look through the area and make the necessary calculations. If this is done in peace and quiet beforehand it will just take a while; if it has to be done in a situation and under stress it might lead to a disaster.

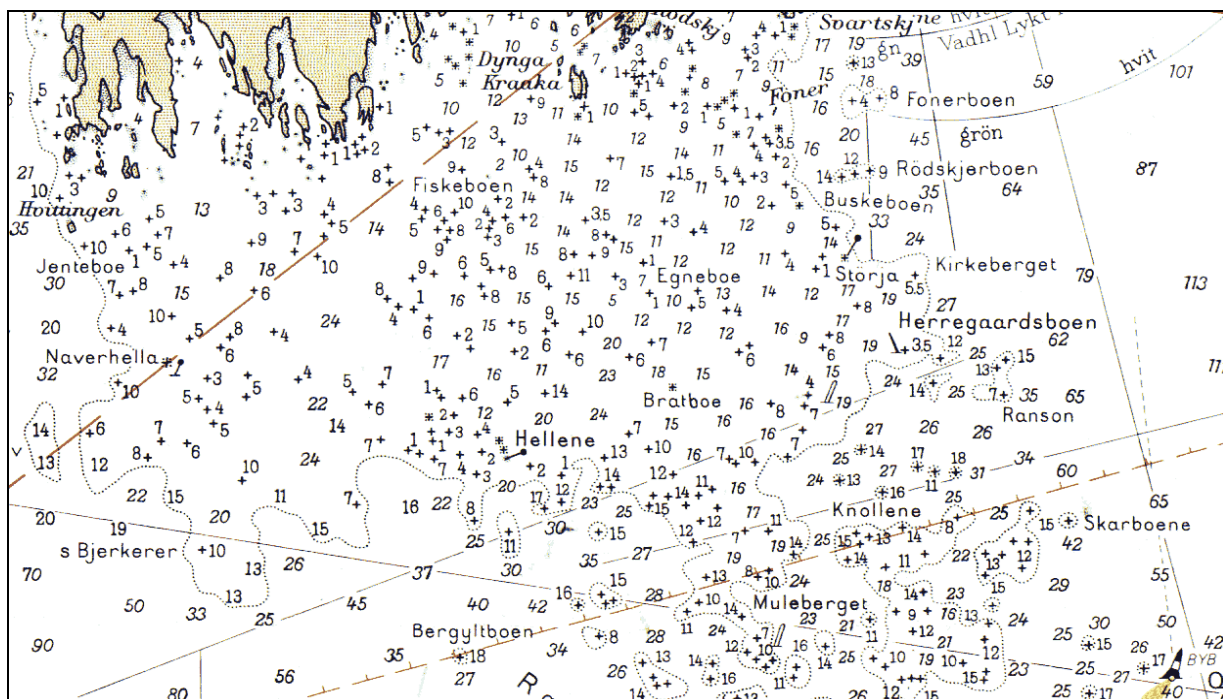


Figure 11. The bank of Rakkeboene outside Stavren on the Norwegian south coast. Norwegian Sjøkartverket chart no. 5, 1986. 1:50.000.

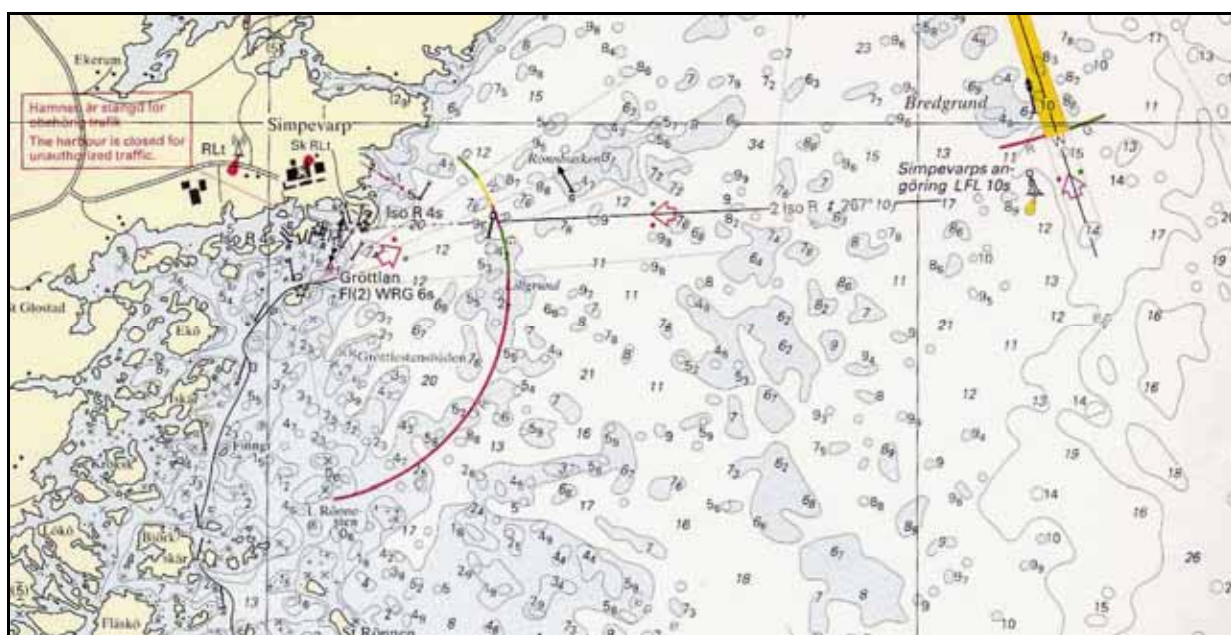


Figure 12. Example of generalized depth soundings on the Swedish east coast. Look along the fairway entering the port of Simpevarp. Imagine you are navigating a ship with a 4 m draught, deduct 1 m low water and heavy seas with 2 m amplitude. Where are your dangers? Swedish Maritime Administration, chart no. 624, 1988. 1:50.000

Not only the mental rotations augment the cognitive workload, this problem does too. Could these calculations needed to find out if the water is deep enough be made by the computer instead and displayed in some way easy to read?

A chart is a map with the depth information displayed as numbers and curves on a flat 2-D space. Of course, a real 3-D chart gives us another possibility. Why not just eliminate the problem; namely the water that hides the bottom topography. Let me illustrate this by a screen shot from a 3-D module from the Canadian company Ican (see Figure 13).

The screen shot in Figure 13 gives us a very good view of the bottom topography. Shading and color texture are cues that communicate shape in 3-D space. The own ship is depicted from a tethered camera view off the starboard quarter. The problem arises as we try to decide exactly over what part of the bottom the ship is at present. Because the 3-D space is represented on a 2-D display there are no depth cues as to the position of the ship unless we orbit the camera and use the parallax effect. A shadow on the bottom could be such a cue; often, as here, a so called *drop-line* is used that anchors the boat to a position on the bottom straight under the ship. If the depth is large, the position might fall

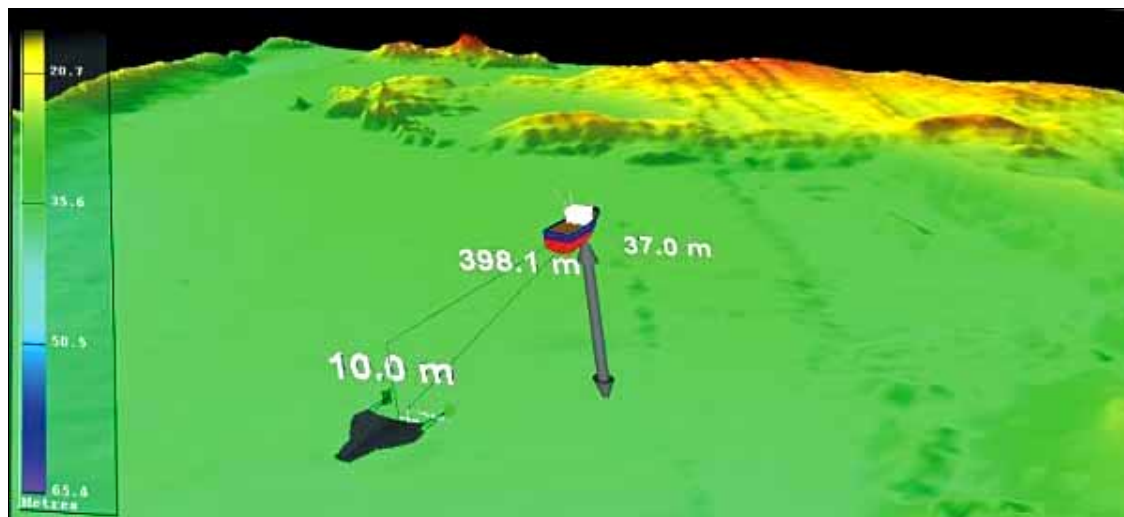


Figure 13. The problem of understanding 3-D space on a 2-D display. Screen from the Canadian company Ican. <http://www.icanmarine.com/3D-Module.htm> [2005, September].

outside the screen space. The drop-line can only be used when the own ship is in view, in a bridge view the drop-line would be out of sight.

Another possible problem with using a 3-D chart without the water surface is that the immediate visual cues between the real world and the 3-D chart will be missing. The 3-D chart landscape without the water might be very different from the landscape outside the windscreen.

Maybe we are not interested in all the different depths of the ocean, if we are not fishermen or submarine hunters. Maybe we only need to know where the water is deep enough for us at any given moment. Maybe we can do this by displaying forbidden *NoGo areas* (too shallow) and update this information dynamically with the change of the tidal water, draught, etc. Look at the suggestion in Figure 14.

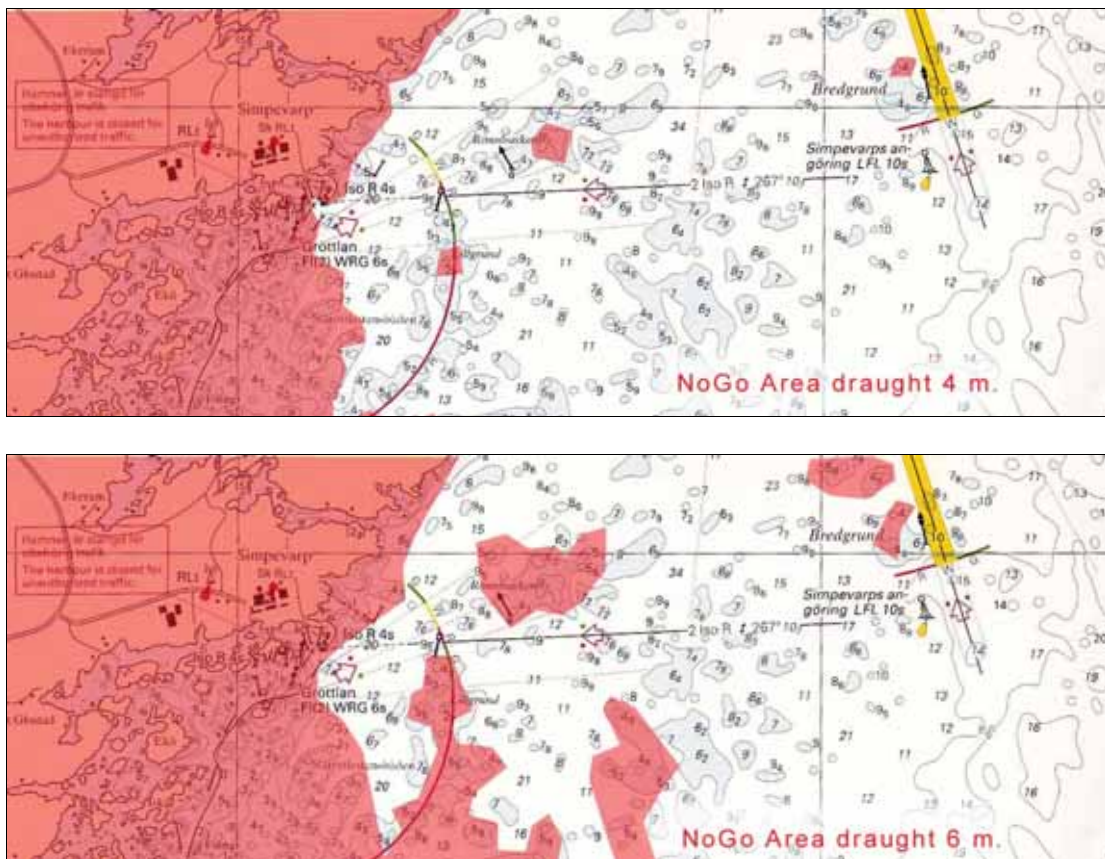


Figure 14. No-Go area warning polygons added to the chart in Figure 12. Top, the polygons show dangers for a vessel with a draught of 4 meters, normal water level and no seas. Bottom, dangers for the same ship with the water level being 1 meter below mean and a wave amplitude of 2 meters. Modification of Swedish Maritime Administration, chart no. 624, 1988. 1:50.000.

The top picture in Figure 14 shows NoGo areas for *Sigyn* for the Simpvarp approach with normal water level, calm seas and no squat. The bottom picture shows the same approach but now in less favorable circumstances with 1 m of low water and 1 m negative heave. The approach suddenly becomes much more complicated. (This example is just to show my point. Maximum low water at Simpvarp is less than 0.7 m.)

ECDIS, the approved electronic chart and display system, allows for the display of *safety contours*. The navigator can enhance a certain depth contour to make shallow areas easier to distinguish. However, only the existing depth contours can be enhanced. See Figure 15 for a detail from an electronic chart.

The existence of a 3-D *bathymetrical* (sea bottom) model opens for interesting possibilities when it comes to displaying safety contours for any depth. This can be done by cutting the sea bottom with a plane located some distance under the sea surface and displaying the intersection area as colored polygons on top of the sea surface. The distance between the sea surface and the cutting plane is dependant of the water level, draught, squat and heave of the ship and also a clearing, a safety margin (see Figure 16).

The equation for finding the depth on which to place the intersection plane (IP) is

$$IP = CD + TL(t) - D(t) - SQ(v) - C - H \quad (\text{Equation 1.})$$

Chart datum (CD) is the reference plane, relative to which all soundings in a chart is expressed. This reference plane is different in different countries. In many countries affected by tidal water the chart datum is placed at *mean lower low water* (MLLW). This means that a lower water stand only rarely falls below MLLW. In Sweden, however, the CD used is *mean sea level* (MSL). The MSL is found by calculating an average sea level through many years of measurements at reference stations along the coasts. This means that the water level frequently falls below the CD. The *tidal level* (TL) is a function of time and place and can in countries affected by tidal water be extracted from empirically

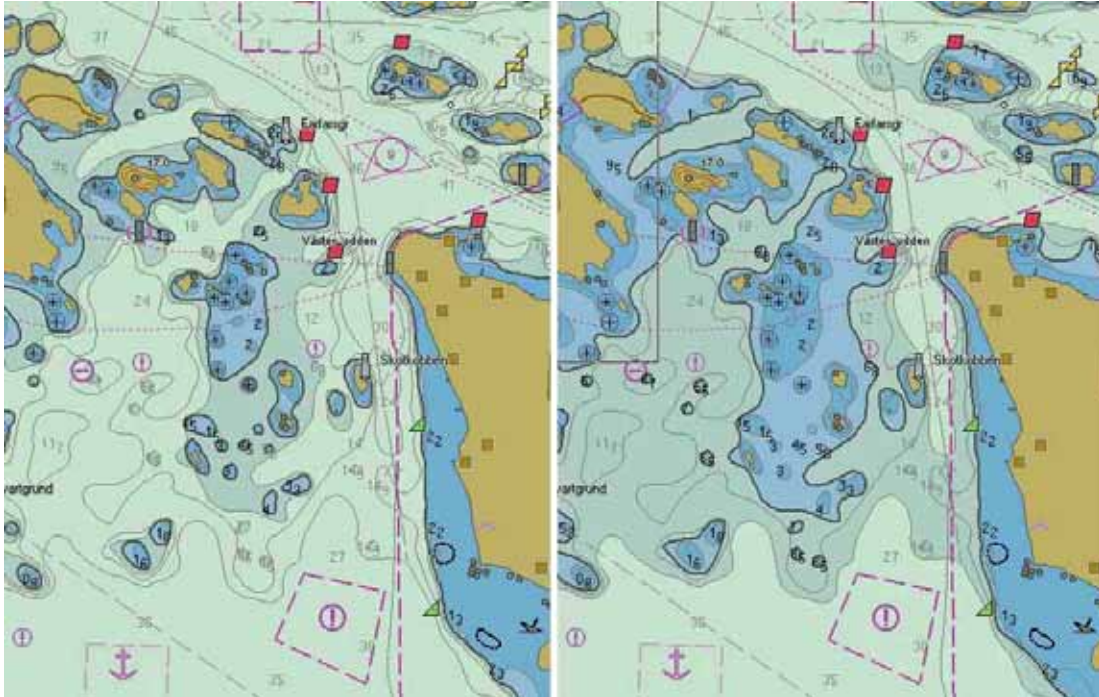
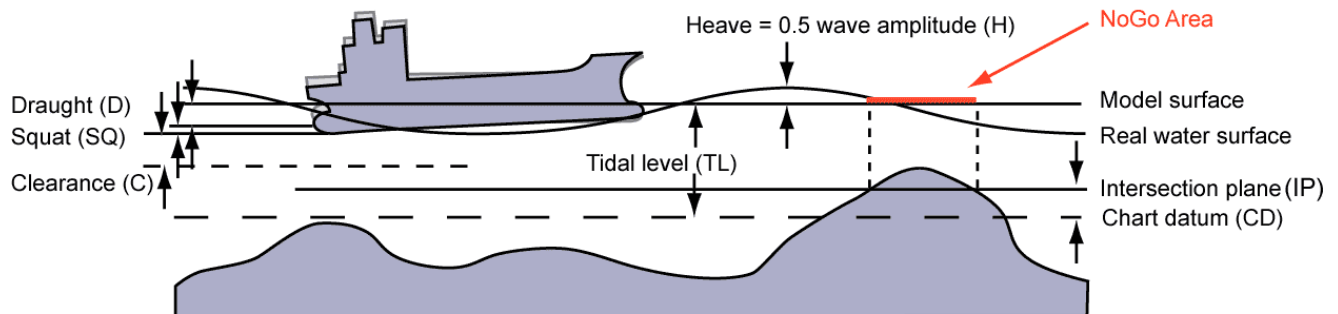


Figure 15. Safety contours in electronic chart with data in the S-57 format. Left , the 6 m contour and right, the 10 m contour are enhanced. Test chart from the Swedish Maritime Administration over the Sandhamn area in the Stockholm archipelago.



$$\text{Depth of the intersection plane (IP)} = \text{TL}(t) - D(t) - \text{SQ}(v) - C - H(t)$$

Figure 16. The dynamic safety contours are produced in real-time by displaying the intersection area between a cutting plane and the terrain skin above of the water surface.

constructed tidal tables, however winds and atmospheric pressure also influence the water level and is not considered in the tidal tables. In countries without significant tidal water, like Sweden, the water level is only a function of wind and air pressure. The on-line water level service

is in Sweden updated every 30 minutes for 19 reference stations along the Swedish coast by the Swedish Meteorological and Hydrological Institute (SMHI, 2005). *Heave* (H) is here defined as the negative half of the ships vertical motion around equilibrium as she is affected by the seas. Heave must be added to the draught and can be measured by onboard INS or RTK sensors. *Squat* (SQ) is the loss of under-keel clearance as the ship moves forward due to the Bernoulli Effect caused by the water flow under the ship. On small ships with low speed the squat will only be a few centimeters. On larger vessels and vessels with high speed the squat can be as high as 2 meters. Squat depends on factors like speed and the depth and width of the channel the ship is traveling through (Barrass, 2004, p. 6). Simply put the squat will increase with higher speed and shallower and narrower waters. In very shallow water the increased water flow under and around the hull might cause what is called *suction* and *bank effects* which can cause sudden dangerous vertical or horizontal movements of the ship.

The Seaway Network

Why is it much easier to navigate a car than a ship? It might have something to do with the roads. The road network is a complicated navigational devise allowing us to safely travel from place to place. Separate lanes keep us (mostly) from colliding. On the road we can drive without a lot of complicated navigation equipment and we might even go on long trips without any map at all, guided by the road signs alone.

When we drive our cars down the highway we might see the road as a practical, convenient and smooth surface which makes it easier for the wheels to roll which gives us a more comfortable ride. Maybe we never see the road as a cognitive tool, simplifying driving by dividing space into lanes for different traffic flows, making it easy to determine the future positions of other cars. Note that we need not constantly check if we are on the right course, we just follow the traffic lane; decision making is clustered to particular places, junctions and cross, where roads signs help us in the wayfinding task. If you ever crossed over an empty department store parking lot, skipping the painted lanes, and suddenly meeting another car in a flat angel coming towards you - "Where is he going? What are his intentions?" - you will know what I mean. This is close to the normal situation at sea.

On land roads are necessary for practical reasons. On the sea they also exist. On the high seas they are called *shipping lanes* and are often the practical shortest route between common destinations. In confined waters they are called *fairways* or *navigational channels*. In the chart they are depicted as a single, or sometimes a double, line. Ships have to keep to starboard when meeting other ships without the help of center line and road side markings both in the chart and in the physical world. Only in very narrow passages and dredged channels there might be ranges or buoys for assistance. However, in some places with dense traffic, *traffic separation schemes* (TTS) are created, like the English Channel. Here the traffic separation scheme works much like a highway on land with two separate lanes with a separation area in-between. In each shipping lane there is one-way traffic (see Figure 17).



Figure 17. Examples of “roads of the sea.” From left to right: single-line fairways in a Swedish chart, dredged, double-lined channels in an Irish chart and the British Coast Guard’s overview of the traffic separation scheme in the English Channel.

In navigational equipment the road metaphor is no novelty either. It has been used in GPS navigators to visualize the cross-track error (see Figure 18).

But the metaphor has not been fully developed here. The center line in the interface shows the optimal track between two waypoints, not the line dividing two lanes with opposite directed traffic. The cross-track error is visualized by how far off from the track you are either to port or to starboard. Careful navigation means being on the track. The track

leads from waypoint to waypoint. Waypoints need to be programmed into the navigator by extracting longitude and latitude from the chart. This can be a cumbersome and time consuming task. Waypoints for popular routes can instead be downloaded from public waypoint libraries or CD discs bundled with boat magazines. The risk of head on collisions with boats traveling in the opposite direction along the same track is increasing with more precise GPS positioning.

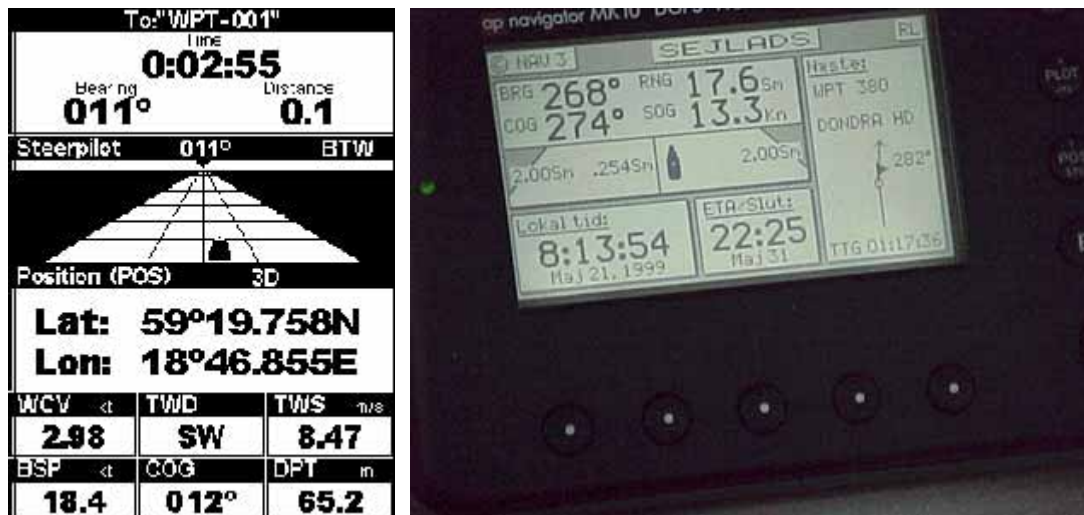


Figure 18. Interface from GPS navigators using the highway metaphor to visualize cross-track error. The thin black line in the middle of the road is your optimal track. Screens from a Silva Multi Centre, 2000, and from an AP Navigator, 1999.

Satellite navigation is getting ever more precise. Refined techniques like *real-time kinematics* (RTK) and new systems like the European *Galileo* will increase performance and add to that of old ones GPS and GLONASS. In the future precision on the centimeter level will be achievable not only for high end systems. With three independent systems the reliability of satellite positioning will become be very high.

This quality of positioning offers the possibility of a new traffic separated infrastructure on the sea much like the road network on land. This *seaway* system could be more extensive than the fairways of today because they will be cheap to develop as no physical artifacts in the real world need to be constructed and maintained. There would be seaways in different classes for different draughts and different sizes of ships. With the road metaphor virtual sign systems could also be added which

would give mariners proper warnings at the right time in contrast to the present system where they have to search for information printed on the chart, in pilot books, Inmarsat-C messages or in Notice to Mariners.

The sea-ways could, for example, be designed as red and green “carpets” with the width correlated to the depth and size of tonnage in the channel and color in conjunction with the IALA²-Region A Buoyage System in countries (e.g. Europe and Asia) using this. Here the green lane is the starboard lane when going in the direction of the seaway (the coloring is then consistent with the colors of the ship’s port and starboard navigation lights). One of the basic rules is that lanes go from the open sea towards harbor. This way the colors of the lateral marks will coincide with the closest carpet’s color. In the IALA-Region B, in North and South America, the colors will be the other way around according to the RRR-rule: “Red on Right Returning (from the sea towards port).

Track-lines

One of the fine things about sailing is the freedom of choosing your own way. Restrictions to this freedom that is not determined by physical or traffic safety reasons will probably be difficult to enforce. It will never be possible to establish seaways for all possible routes, and if the sea is open, ships will want to go their own way.

One might say that the track line between the waypoints of a GPS navigator functions as a road, with the difference that this track line is individual and is not displayed to other ships. See Figure 19 for an example of how track lines can be displayed in the electronic chart plotter.

The track line is very useful for one’s own wayfinding and might be combined with the concept of seaways. One might even argue that waypoints ahead should be broadcast through the AIS transponders, as civil aircraft transponders do, allowing for other ships to optionally view an approaching ship’s *intended* track as an alternative to the course speed vector. Of course, such a track would have to be viewed with

² IALA = International Association of Lighthouse Authorities.

suspicion as there is nothing forcing a ship to take the route that is programmed into the navigation system, it will just signal an intention like the blinking turn light of a car. More on this in the Future Research section of chapter 6.

Navigation is finding your position and from there determining the course to a destination. With satellite positioning we always know where we are. Present-day a journey is carefully planned ahead of time and waypoints are programmed into the navigation computer. Along our voyage the navigation system constantly updates the course to steer to the next waypoint. It is then presented both graphically on the electronic chart and radar screen and numerically on the display of the

navigator. But why can we not be automatically aided with courses all the way to our destination by just entering the name of the harbor?

The suggested seaways visualize the existing navigational channel infrastructure. These seaways are planned by maritime authorities based on existing or preferred patterns of sea transportation and are defined for a maximum draught. Route guidance from a known position to a destination along this system can easily be computed using network analyses. Outside the seaways, the sea is free unless water depth, traffic separation schemes, sanctuaries, military or other limitations hinder. If these hindrances could be added to the chart in the form of No-Go area polygons a two dimensional surface of free and forbidden areas can be created. Then, with a point of departure and a destination, a fairly simple geometrical computation can resolve the same guidance query but outside the existing seaways. This computation will be very much more complicated in tidal areas when allowance for currents and changing depth has to be brought into the equation, particularly in areas exposed to weather. But still it might be feasible.

A decision support system, like the one sketched above, can help the navigator by suggesting different alternative routes to a given goal. The alternatives can be computed based on preferences such as shortest route, most economical route, most weather protected route given wind speed and direction, most sheltered route from a stealth and radar detection point of view based on the height of surrounding islands or underwater topography, etc.

The discussion above calls for another type of seaway, an *own-ship's-track*. This could, for example, be presented as a white carpet in front of the vessel and dynamically attached to the vessel so that if an evasive maneuver is made the track will compensate for the maneuver and continue to show the way from the new position. Whether following the public red and green seaways or an individual route, the white own-ship's-track will be an individual guidance.

Such an individual track could, for example, be broadcast to an approaching ship from port authorities to guide it to a particular berth

in the harbor. The track could be updated in real-time during the approach depending on traffic, weather etc and also contain speed recommendations.

I have now presented the three concept ideas that are to be tested in this research project and I am ready to formulate the research questions.

1.6 Research Questions

The problem was that increasing speeds and more instruments to monitor lead to shorter decision times and also shorter time for the navigator to integrate the information. The suggestion has now been made to lessen the cognitive workload on the bridge by supplying three chart features that supposedly is less cognitively demanding. The main question is now: Can map reading really be made easier using these features? Three specific questions that we want to have answers to can now be formulated:

Research question 1: Does the use of an egocentric display of a 3-D chart lead to better wayfinding (faster decision-making, fewer errors) than a traditional map in the conning situation?

Research question 2: Does the marking of free as well as forbidden water areas with dynamic NoGo area polygons ease the cognitive workload of the navigator?

Research question 3: Do double-lane seaways and sign systems, like road networks on land, simplify wayfinding and enhance safety at sea?

Limitations

This project is limited to the maritime domain. However, much of the discussion and some of the findings could also be of interest in other contexts of vehicle navigation, e.g. aviation and car driving.

1.7 Disposition and Methods Used

I have already in the beginning of this chapter mentioned the different methods used, saving the motivation for, and the more detailed description of these methods to the respective chapter. As each chapter presents a study using a different research method, (apart from this introduction and the concluding chapter) this overview of the disposition of the book also serves as a brief introduction to those methods.

Literature Search (Chapter 2)

That every research project starts with a literature search goes without saying, and should maybe not be called a research method. It is however a technique of data collection. Previous research is presented in Chapter 2, *Research Context*. Domains covered are communication, cartography and geo-informatics, risk management and human factors.

Laboratory Experiment (Chapter 3)

If a map displayed in an egocentric bridge perspective lead to faster decision-making and less errors compared to traditional map types was a research question that suited very well for a laboratory experiment. Psychology and Human Factors have a long tradition based on this type of experiments. Forty-five subjects were navigating through a maze with a traditional paper chart, an electronic chart in north-up mode, an electronic chart in course-up mode, and finally with a 3-D chart. This experiment is presented in chapter three.

Prototyping (Chapter 4)

For the other two research questions I decided to ask potential users for their opinions. To do that I would need a prototype 3-D chart to evaluate. Prototyping is a common method in design research. It is an iterative method of Human-centered design. First a simple physical prototype is constructed and tested on a small sample of the user group or on experts in the field, then faults and malfunctions are corrected and a new prototype is build and tested again. In this way each prototype becomes better and better and necessary changes is hopefully made early in the development chain when changes are cheap. The most important factor is however that the product hopefully is tailored to the

need of the user group. In this research project most of the time spent was put into the development of the prototype which has been a large technical challenge. This work, together with comments from potential users is described in chapter four.

Heuristic Interviews and Field Studies (Chapter 5)

In modern Human Factors it is important to study man-machine interaction in its proper context. Ethnographic methods like field studies and participatory observation are then necessary tools. In a number of field studies during this project I have visited different ship bridges: a 20.000 ton product tanker, a high speed ferry, a navy combat boat and a navy corvette, a police boat, a small passenger ferry and a large passenger ferry as well as three VTS centers. Observations and heuristic interviews were carried out during these field studies and prototypes were shown to the bridge crews to comment on. These studies are presented in chapter 5.

Discussion, Conclusion and Future Research (Chapter 6)

Most of the discussion has been done in respective chapter but in the last one some concerns about risks with new technology and general problems with 3-D views are addressed. Looking at the research questions again an outcome of the research is formulated and, finally, a look ahead to further projects in this field.

Case Studies (Appendix A)

This project is about safety at sea. By studying accidents much can be learned about how to avoid them. Although accidents happen, they happen very seldom. By just making field studies and observations on the bridges of different ships it is very unlikely that you will have a chance to witness an accident. One way to learn about the cause of shipping accidents is to study accident reports. I was looking for accidents that had something to do with the loss of situation awareness and orientation. Three simple case studies based on accident reports and newspaper clippings are retold here for the benefit of the interested reader. Two of them, the grounding of the Norwegian high speed ferry *Sleipner* in November 1999 and the Swedish combat boat *881* in April 2003, were caused by a loss of orientation. The third accident, the

grounding of the tanker *Exxon Valdes* in March 1989, depended on a late turn.

1.8 Contributions

Using game technology to put a ship simulator on the bridge and use it as a 3-D nautical chart is simple but has, as far as I know, not been done before.

My contribution to the field of information design lies in:

1. The identification and description of cognitive problems related to interpretation of information sets during navigation at sea and states of stress.
2. The demonstration of possibilities to facilitate interpretations by specific design of information sets used for navigation.

My contribution to the field of innovation and design lies in:

1. The development of a practical system, based on the above findings, to counteract some of these problems.
2. The testing of the above system in some limited ways.

1.9 Published Papers

So far seven conference and workshop papers have been published in this project. The content of these papers have been incorporated into the text and the papers are listed separately after the reference section at the end of this book.

Chapter 2

Research Context

This chapter reflects the background reading of this research. My own field of information design was briefly presented in chapter one, and here I will present theories from the neighboring fields of communication, cartography and cognitive psychology that are relevant to this study. First, a section on safety and accidents in complex systems from the domain of ergonomics to give the context.

2.1 In Control - Safety Issues in Complex Systems

In the dark evening of March 23 1989 the huge tanker *Exxon Valdez* left Alyeska Marine Terminal in the little town of Valdez in southern Alaska, on what was to become a catastrophic voyage. Because of drifting ice in the outbound lane, the tanker took a more southerly course than planned. Seven minutes to midnight the captain left the bridge and the command to the third mate ordering him to change course back to the navigation channel when abeam Busby Islands Light some two minutes ahead. The third mate never ordered this turn. Seven minutes later the lookout reported Blight Reef light buoy broad off starboard bow – the tanker was supposed to have it on her port side when passing. The third mate now orders 10° starboard rudder, two minutes later he orders the helmsman to increase the rudder angle to 20° and another two minutes later to hard starboard rudder, 35°. But the 210, 000-ton *Exxon Valdez* is too slow in turning and another three

minutes later she hits Blight Reef ripping eight of her eleven cargo tanks open pouring a 100,000-ton of crude oil into Prince Williams Sound. The National Transportation Safety Board (NTSB) that investigated the accident determined that the probable causes of the grounding were:

1. The failure of the third mate to properly maneuver the vessel because of fatigue and excessive workload
2. The failure of the master to provide a proper navigation watch because of impairment from alcohol
3. The failure of Exxon Shipping Company to provide a fit master and a rested and sufficient crew for the Exxon Valdez
4. The lack of an effective Vessel Traffic System because of inadequate equipment and manning levels, inadequate personnel training, and deficient management oversight
5. The lack of effective pilotage services (NTSB, 1989, p. 170)

Let us look at a multi-level pyramid where the factors influencing marine transportation system are displayed (see Figure 20). At the bottom of the pyramid are the international rules and regulations from organizations like IMO (International Maritime Organization), above that the rules and regulations from the classification societies like Lloyd's Register and Det Norske Veritas. There are national, company, local port and ship rules and regulations and at the sharp end, we have the individual, the human factor, in the Exxon Valdez case the third mate, Officer of the Watch. There is often a sharp end to be found in any accident, a human error, and "formal accident investigations usually start with the assumption that the operator must have failed, and if this attribution can be made, that is the end of serious inquiry." (Perrow, 1984, p. 146). In the case of the Exxon Valdez the NTSB did not stop at the sharp end but perused on towards the blunt end looking for holes in what has become known as the *Swiss cheese*. This metaphoric concept of the *Swiss Cheese Model* was introduced by the psychologist James Reason in 1990 (see Figure 21).

In the *Exxon Valdez* case there were many holes in the "cheese" barriers. A vigilant third mate might never have failed to order the turn in due time. Now, he had not had any sleep for 18 hours prior to the accident. There was a "hole" in the barrier of maximum working hours. Apart from the third mate there was a look-out and the helmsman at the bridge. None of them warned the third mate. There was a hole in the team work scheme of Bridge Resource Management.

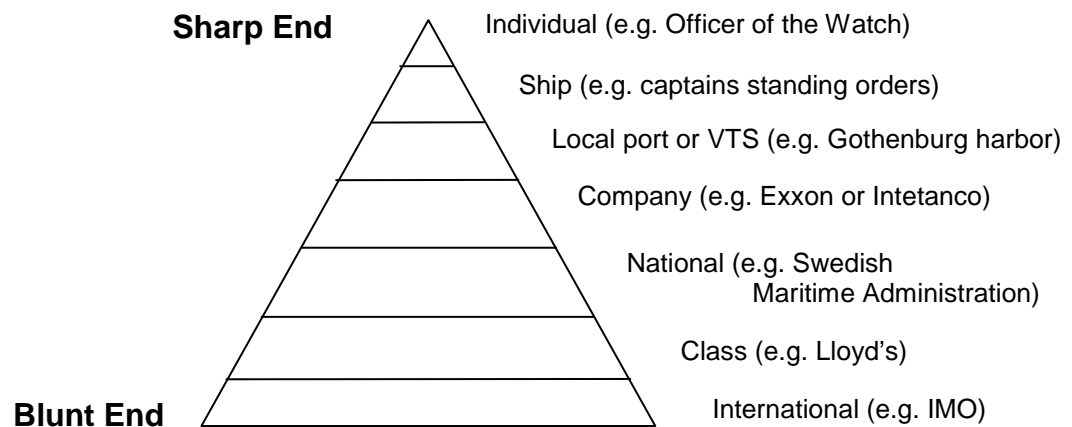


Figure 20. A pyramid view of different levels of factors that influence the maritime transportation system. At *the sharp end* is the individual, at the blunt end are the international organizations influencing the system through rules and regulations.

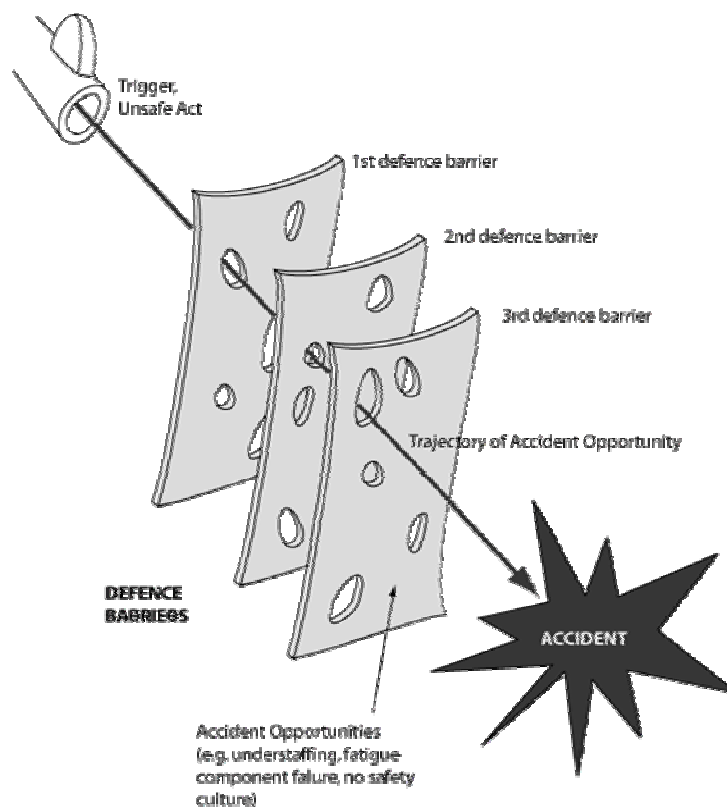


Figure 21. The Swiss Cheese Model of James Reason (1990). Barriers are put up in most systems to prevent an accidental unsafe act from causing an accident. But dynamic accident opportunities move around and allowing the trajectory of accident opportunity to pass trough all safety barriers and cause an accident. Adapted from Reason.

Company regulation stated that there should always be two officers on the bridge going in and out of Valdez and Prince William Sound. The captain left the bridge just minutes before the turn that was never made. There was a hole in the company regulations barrier, maybe because the captain was intoxicated, and this maybe because of slack safety culture onboard and maybe in the whole company. The Valdez Vessel Traffic Service followed the track of *Exxon Valdez* on their radar. Although the VTS have no authority to command the traffic, they are established as a service to the maritime traffic ultimately to prevent failures in navigation like the one that brought *Exxon Valdez* on to Blight Reef. But Valdez VTS never saw that the tanker failed to turn, a long wished-for outer radar station had never been granted. We can go on even further, but this will be sufficient as an illustration. The full story of the *Exxon Valdez* accident can be read in appendix A.

The *Exxon Valdez* accident had no direct casualties, the ship could be repaired and the amount of oil spilled was not of record size; larger oil spills have occurred both before and after. But because of the time and the place, the environmental damage and the time it took before the spill could be cleaned, the accident became a threat to the entire oil transportation system because of pressure from the public opinion. The accident led to a development of systems, rules, procedures and inspections to make sure it would never happen again. (Which it did, as we all know.)

In this project, I am proposing a new type of chart that will allow the bridge officer to see the surrounding world from an egocentric 3-D view. This view will make his task easier and his *situation awareness* better. There was never a question of the third mate of the *Exxon Valdez* not knowing where the ship was because he made a fix when abeam Busby Island Light and marked it in the chart. But he never made the turn. Somehow he never managed to project the course, speed and slow turning of the huge ship into the future.

Navigation is one task in a chain of tasks that makes up the maritime transportation system. By making the navigation task easier it will hopefully also be less error-stricken. The ultimate aim is safety at sea. In this theory chapter I will present some of the theoretical foundations in different domains that are the bases of my work.

I will start off broadly by looking at the domain of accidents and safety systems as an entry to the more detailed studies that are to come. We will look at Perrow and his notion of *normal accidents* in complex systems; continue with the more modern theories of *distributed cognition* and *joint cognitive systems*, narrowing down to theories of ecological display systems, communication, cartography and the cognitive psychology of mental rotations.

Component Failure and System Accidents

Charles Perrow analyzes in his classical *Normal Accidents* the social side of technological risk. He argues that technological systems have become so complex that accidents are norm rather than exception. (Perrow, 1999, orig. 1984; Hollnagel, 2005, p. 6) The *systems* in *Normal Accidents* are first of all nuclear power plants, which to Perrow signify the complex and tightly coupled technology with a multitude of unanticipated interactions just waiting to happen. However, just about all human-technological or human-organizational bodies, from post-offices and universities to mining industries and marine transportation, are *systems* in Perrow's view.

An *accident*, Perrow says, is a failure in a subsystem or a system as a whole that damages more than one *part* or *unit* (mechanical device or human) and in doing so disrupts the ongoing or future output of the system. A failure in a *unit* that does not lead to a failure of the whole system he calls an *incident*. *Accidents* can be of two kinds: *component failures* or *system accidents*. A *component failure accident* is a failure of one or more components that are linked in an anticipated way, i.e. the designers or operators have foreseen that it could happen and have furnished plans or strategies to remedy or repair the failure. *System accidents* involve the unanticipated interaction of multiple failures (Perrow, 1999, pp. 70).

We have just seen examples of such unanticipated interactions in the *Exxon Valdez* case above. Perrow gives an even more striking example in the grounding of the tanker *Dauntless Colocotronis* in 1977. The tanker was berthing to discharge crude oil at a New Orleans pier when she passed over a sunken barge. The wreck was positioned at the wrong location on the chart and the clearance over her was less than stated in

the listings for mariners because the depths had been determined at river high water and not been corrected for low water conditions. The water over the sunken barge was a foot or so too shallow for the tanker and the top parts of the wreck damaged the tanker's bottom plates, ripping a hole and rupturing part of the bulkhead between the center tank and the aft pump room. Oil leaking out from the center tank entered into the pump room and the heat in the pump room made the crude oil less viscous, allowing it to penetrate through a packing into the engine room. The heat in the engine room made the oil evaporate creating an explosive gas. Eventually, a spark ignited the gas, causing an explosion and a fire. The fire spread because a fleeing crew member did not close a fire door behind him. Later the crew tried to fight the fire using water, not realizing that the water only caused the oil to break up into finer and more flammable particles thus spreading the fire. When finally a trained fire crew boarded the ship and started to fight the fire with proper equipment, three empty gas tanks that happened to be stored inside a door that the fire crew just opened exploded. The fire crew, wrongly believing there was more explosive gas in the ship, immediately closed the door again and made no further attempt to put out the fire in that part of the ship thus prolonging the course of the event and increasing the damage made by the accident.

In this example, Perrow explains how an unanticipated connection between two independent, unrelated subsystems that happened to be in close proximity caused an interaction that was not planned nor expected or linear. In fact, many unexpected interactions happened; the oil leaking out into the water, and again leaking into the pump room; then, because of its low viscosity, passing through a watertight packing into the engine room; the fire crew fooled by the empty gas tanks that happened to be stored just inside the door and which exploded as the fire crew entered.

Interaction and Coupling

The concept of unanticipated interactions is important here. Perrow distinguishes between *linear interactions* and *complex interactions*. The *linear interactions* are those in an expected and familiar production or maintenance sequence, and those which are visible even if unplanned. The *complex interactions* are those of unfamiliar, unplanned or unexpected sequences, and neither visible nor immediately

comprehensible. In consequence with this Perrow defines *linear* and *complex systems*. *Linear systems* are systems with spatial segregation, dedicated connections, segregated subsystems, easy substitutions, few feedback loops, single purpose, segregated controls, direct information and extensive understanding. *Complex systems*, on the other hand, are characterized by proximity of units and subsystems, common-mode connections, interconnected subsystems, limited substitutions, feedback loops, multiple and interacting controls, indirect information and limited understanding (Ibid, p. 88).

Furthermore, Perrow introduces the concept of *coupling* in systems. He makes the distinction between *tight* and *loose coupling*. A *tightly coupled* system is a system where delays in processing are not possible, where sequencing is invariant and only one method achieves the goal; where little slack is possible in supplies, equipment and personal, where buffers and redundancies are designed-in and deliberate and substitutions of supplies, equipment and personnel are limited and designed-in. A *loosely coupled* system, on the other hand, is a system where processing delays are possible, where the order of sequences can be changed, where alternative methods are available, slack in resources possible, and buffers, redundancies and substitutions are fortuitously available (Ibid, p. 97).

Perrow's analysis is interesting and relevant although the placement of individual systems can be discussed. In tightly coupled systems there is neither time nor action space available to improvise solutions once something fails. Backup systems and redundancies have to be prepared in advance. If the system is linear this can be simple; it is easy to see what can go wrong and prepare remedies in advance, but if the system is complex, with hidden and unanticipated interactions, we are in trouble.

A ship on the open sea in fine weather conditions with maybe just radio communication and one other ship to handle is a fairly linear and a somewhat loosely coupled system. Linear because events can be taken care of sequentially; there is no tight time constraint. If something happens there is time to fix it, or it can wait until there is. The same ship in high speed in a crowded river in darkness, strong wind, tidal streams, shallow water, bank effects, bridges, crowded radio channels

and city lights in the background, obstructing the navigational lights, is another story altogether.

If the lock of a watertight deck house door breaks in fine weather, it is not a big problem. The door can stand open and be fixed in due time when the boatswain has finished his dinner. But if the wind picks up and the seas start to rise, the swinging door might break its hinges and seas coming on deck might enter the interior, short circuit the electrical fusing box placed inside the door... Now the system is complex.

In 1994 the ro-ro passenger ferry *Estonia* forced her way through a westerly storm in the Baltic Sea. Although other ferries on about the same route at the same time chose to reduce their speed, *Estonia* continued at full service speed, pounding her bow into the waves. An hour after midnight the hinges of the bow visor broke. The accident commission stated in the accident report that they were not constructed to hold for loads to be occasionally expected on the Tallinn – Stockholm track such as the night of the accident. The commission also stated that at the time of construction, facts about hydrodynamic loads on large ship structures were limited, and the design procedures for bow doors were not well-established. (The Joint Accident Investigation Commission of Estonia, Finland and Sweden, 1997, chapter 21) When the hinges broke and the bow visor fell, the fatal unanticipated interaction occurred: The inner water-tight bow ramp was constructed in such a way that when the visor fell off it engaged the top part of the ramp and forced it open, allowing for the dreaded and fatal event of water on to the ro-ro deck.

A marine transportation system in deteriorating environmental conditions is transitioning from the lower left quadrant to the upper right in a two-way interaction/coupling chart used by Perrow (1999, p. 97). See Figure 22.

In fine weather conditions and light traffic a ship can be a system with loose coupling and linear interactions, but as the weather deteriorates and the traffic becomes dense a transition towards tighter coupling and complex interactions takes place.

*Perrow's Interaction/Coupling Chart
adapted for Marine transport*

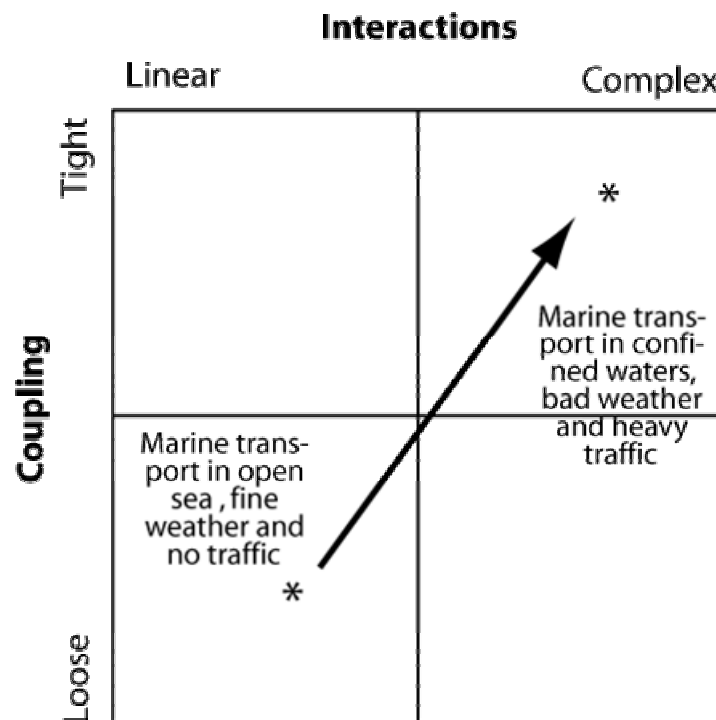


Figure 22. Perrow's interaction/coupling chart adapted for marine transportation in different environmental conditions, causing a transition from loose to tight coupling and from linear to complex interaction.

Parrow (1999, p. 172) calls the marine system an “error-inducing system.” He compares it to the airline system which he calls “error-avoiding.” He sees the reasons for this to be the air traffic control system, the pilots’ union, the flying politicians but also that we are all passengers from time to time and thus dependent on the reliability of the airways system. And also the easy identification of victims and what he calls the “elasticity of demand” (enough people can avoid a certain aircraft type or flying all together, which will have an economic impact). In contrast to this, Parrow says, victims in the marine system are primarily low status, poorly organized sea-men, the third-party victims of pollution and toxic spills are anonymous and random and the effects delayed. Elites, or even people like you and me, do not sail on Liberian tankers, there is no elasticity of demand, shipping companies cannot stop shipping because the last cargo was lost (although in the

case of *Exxon Valdez* the Exxon company was the target for public boycotts). Communication problems are immense in the shipping industry, on the bridge, and between ships. This is the case in the aviation system also, but to a much lesser extent than in the marine system, where the education among seamen is lower and communication is less formalized.

However, Perrow also states that the marine system, although error-inducing, also has built-in robustness. Very few, of a constant stream of failures actually lead to accidents. Because recovery is often possible since the time constraints are not as tight as for example in the airline system; “resources can be redeployed in an ad hoc fashion, damaged ships can continue their voyage” (Ibid, p. 175).

Cognition in the Mind

So systems can be more or less error inducing, according to Perrow. Let us now narrow our scope down to the sharp end: the officer at the bridge and his cooperation with the system, the person who is the *human factor*. How do we study the interplay between the human factor and the system? When psychology became a science in its own right in the 19th century the favored method was introspective *mentalism*. (Hollnagel, 2005, p. 57) At the beginning of the 20th century the calling into question of the objectivity of reported inner experiences led to the development of *Behaviorism*, which preferred methods of objective measuring of stimulus and response. *Cognitive Psychology* developed as an opposition to behaviorism, by introducing mentalist concepts in a more sophisticated way than earlier. Cognition is the study of how we go about to know what we know and make the decisions that we make. Therefore, the new cognitive science naturally came to concentrate on the inner processes of the brain - “cognition in the mind.” Information system processing theories by scientists like Herbert Simon are important here. Information system processing models often try to describe different stages of inner cognitive processing with the help of boxes, just like in Figure 23.

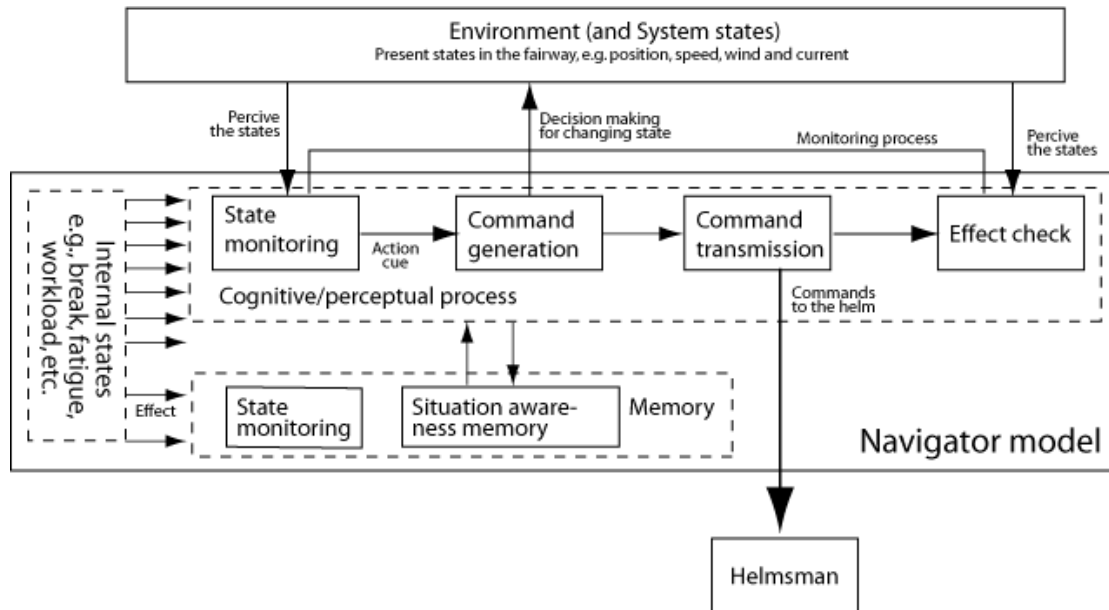


Figure 23. A cognitive model of ship navigation according to Itoh et al. (2001, p. 6).

Figure 23 illustrates an effort to describe the interaction of important factors and stages in the decision-making process of a bridge officer in a navigation task.

Situation Awareness

A particularly interesting part of the information processing system theories, is the one related to the concept of *situation awareness* (SA), as mentioned in chapter one. The concept was coined by Mica Endsley 1988 to describe problems with mastering the ever increasing complexity in aviation systems. Simply put, SA is the concept of knowing what is going on and how this will affect you now and in the future. Endsley defined it as “The perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future” (1988).

Over the years criticism has been brought forward by among others Flach (1995) with the implication that SA is “fuzzy” and difficult to measure, and that it will just be another “box” in the information processing system. But the SA concept seems to have survived together with other “fuzzy” concepts difficult to measure, but yet valuable, like

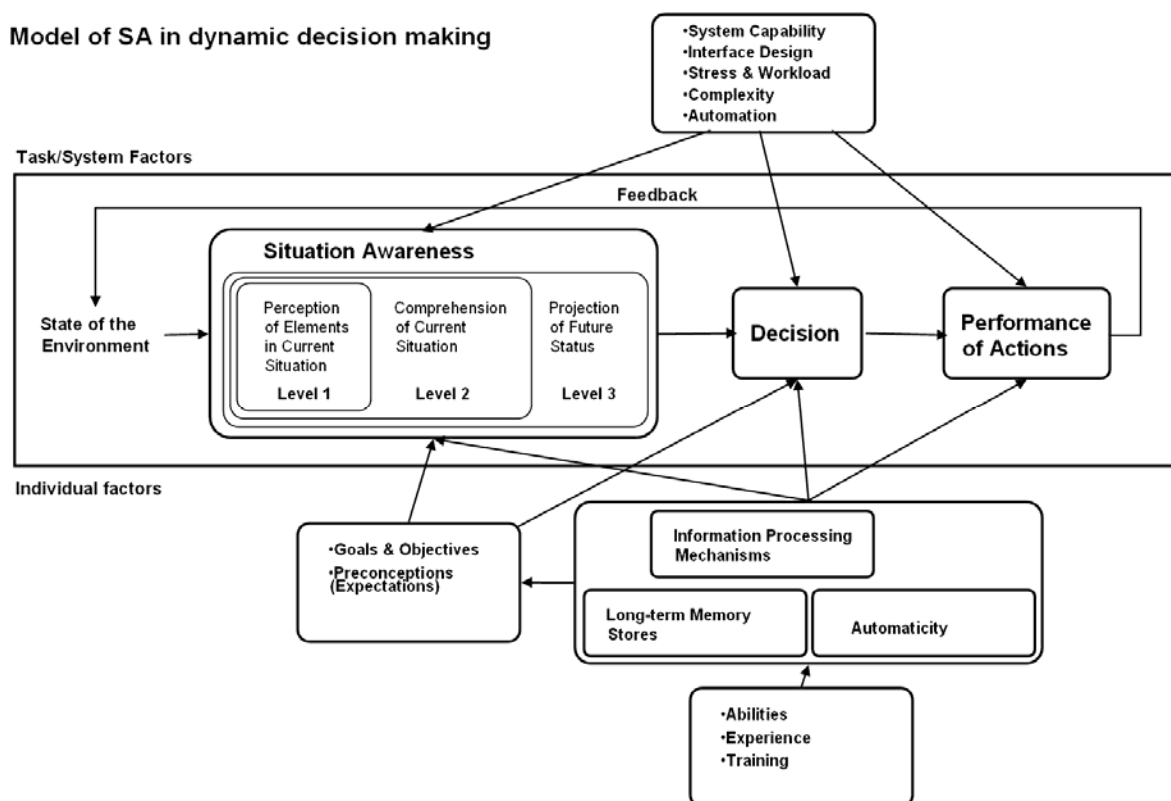


Figure 24. The information processing model of situation awareness in dynamic decision-making put forth by Endsley (1995, p. 3).

intelligence, vigilance, attention, fatigue, stress, compatibility, workload (Pew, 2000).

The information processing model of SA presented by Endsley in Figure 24 gets quite complex, but we can recognize it from the cognitive model put forward by Itoh et al. in Figure 23.

Important are the three levels of SA: Level 1 perception, level 2 comprehension and level 3 projection. Applied on a chart system the three levels would correspond to: 1 The geographical surrounding space, other traffic, weather, terrain, 2 The own ship's position, onboard systems and state of automation and 3 Tasks and future projection of the own and other ships (Wickens, 2000).

How can SA be measured? Several authors have reflected on this (e.g. Endsley, 1995b, Endsley, Bolté & Jones, 2003 and Pritchett & Hansman, 2000). Objective measurements can only be based on performance of the subject, input and output “outside the head”, as it were. In the next chapter a laboratory experiment where navigation using different types of maps will be presented and performance-based measurements are made. But introspective measurements are possible by letting a navigation subject talk out loud during the test (Verbalization) or by stopping a performance test and asking questions (Knowledge-Based Measures). See Figure 25.

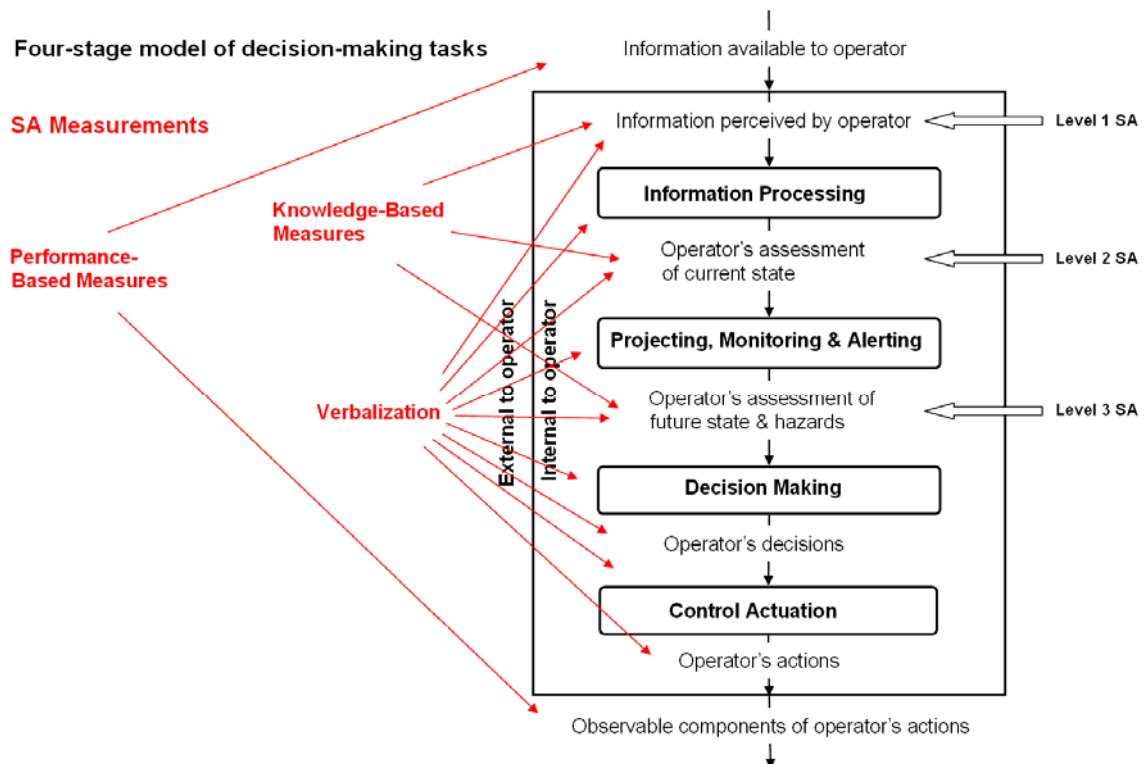


Figure 25. The Four-stage model of decision-making tasks by Pritchett & Hansman (2000, p. 195).

Cognition in the World

However, cognition as an entirely an inner process was called into question in the 1990s. The notion was that cognition does not only take place in the brain, but also in collaboration with other people and the environment. By writing down your thoughts on a piece of paper you put them in the world, you do not have to remember them any longer, and if you need them you can just read the paper. This notion became known as *situated cognition*, *cognition in the world* or as Edwin Hutchins

(1995) called it *cognition in the wild*. His major idea was that cognition was distributed over, for instance, a team, executing the navigation task. They had to their help artifacts which had crystallized the knowledge and practice of generations of mariners into their physical structure, artifacts like the astrolabe, the compass, the chip log and the nautical chart. All was a part of the cognitive process and therefore this process could only be studied *in the world*, on the bridge in its proper context, and not in the confined setting of a laboratory.

Determinants of Control

The bridge is the context of this project. The bridge is also the center of control of the ship operation. Although failures happen in all places onboard, the bridge is often the only place manned at all times. It is from here that everything onboard is monitored and where the decisions are made. (Even machine controls are nowadays often monitored and controlled from the bridge.) In the center of control is the Officer of the Watch. At night he is accompanied by a look-out, but on most ships he is mostly alone at daytime, if the visibility is good. To his help he has a wide variety of artifacts that amplify his abilities. These instruments are often more or less integrated, more or less automatic. I already in chapter one mentioned the Hong Kong high speed ferry study and the bridge officers' complaints that there were too many instruments to monitor. In 2000 the Norwegian high speed ferry *Baronen* ran aground in darkness just after departure. The captain was monitoring the passage of a narrow strait on his radar while briefing the passengers through the PA system. On the radar some shoals in the sound could not be seen. He did not monitor the electronic chart plotter where the shoals and their relative position to the ship were visible. Nor did he turn his head to see if he was in the red sector of a lighthouse just passed. In the court hearing the captain explained that "he could only do one thing at a time." (Bergenavisen, 2000)

Automation is often the chosen way to help the bridge crew in complex tasks. But automation is risky as well. "It has been shown that operators will monitor less effectively when automation is installed, and even more so if the automation has been operating acceptably for a long period" Lützhöft & Dekker (2002) writes in an article in *Journal of Navigation*. Automation creates new human weaknesses and amplifies existing ones. The question is how to turn automates systems into

effective team players. Feedback from the automation is important and Lützhöft & Dekker suggest that representations of automation behavior will have to be:

1. Event-based: Representations need to highlight changes and events in a way that the current generation of state-oriented displays do not;
2. Future-oriented: in addition to historical, human operators in dynamic systems need support for anticipating changes and knowing what to expect and where to look next;
3. Pattern-based: operators must be able to quickly scan displays and pick up possible abnormalities without having to engage in difficult cognitive work (calculations, integrations, extrapolations of disparate pieces of data). By relying on pattern- or form-based representations, automation has an enormous potential to convert arduous mental tasks into straightforward perceptual ones. (Lützhöft & Dekker, 2002, p. 95)

On the bridge the officer of the watch is in control of a powerful dynamic process often of thousands of tons of inertia. If something goes wrong he might not be able to just stop and fix it. If he loses track of his position in confined water he can not stop to regain orientation. So time is a crucial factor in a dynamic system. In Figure 26 some important determinants of control are suggested. (Hollnagel, 2005, p. 76)

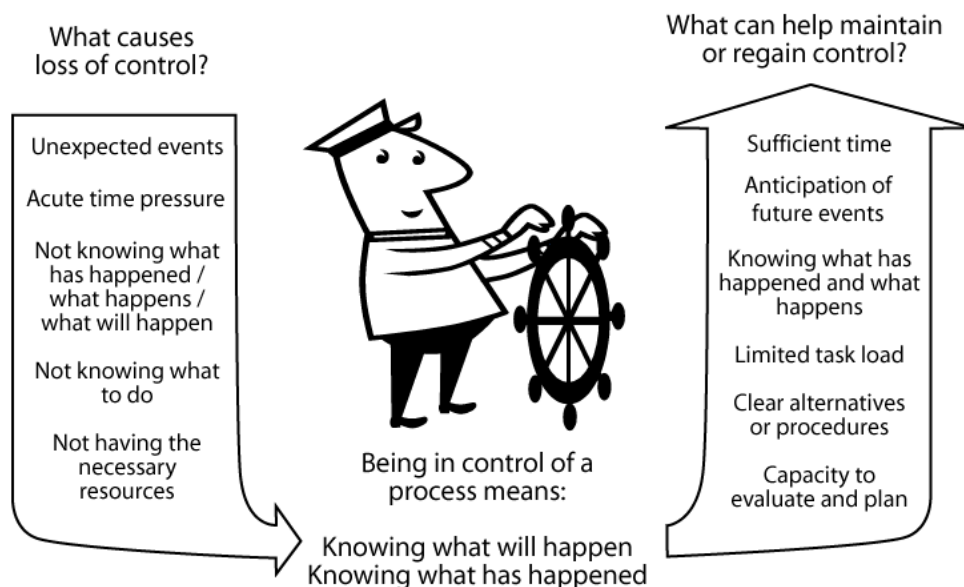


Figure 26. Determinants of control, adapted from Hollnagel (2005, p. 75).

In Hollnagel's model of determinants of control, we see what can help us maintain or regain control. More time is often enough not an option, with higher speeds it is in short supply. The other ones are important for this project and I will return to them later in chapter four, in which we will start constructing a prototype chart.

Before we leave this section on safety issues in complex systems I want to mention a notion that has become known as the *law of requisite variety*. It was formulated in cybernetics in the 1940's and 1950's (Ashby, 1956, Hollnagel, 2005, p. 40) and has become increasingly important as interface design often opt for user-friendliness, meaning simplicity and intuitiveness. The law of requisite variety says that the variety of a controller should match the variety of the system controlled. Effective control is therefore impossible if the controller has less variety than the system and this means that "every good regulator of a system must be a model of that system." (Conant & Ashby, 1970) So, even if a nautical chart system is not a regulator in the strict sense of the word, it is a vital part for the control of a ship because of its function in the navigators' situation assessment.

Now, let us move on, narrowing our scope down even further. We will later in this chapter return to cognition in the mind as we look at mental rotations, but first we will look at maps and the role of maps in mediated communication.

2.2 The Map

According to Encyclopedia Britannica a map is a "graphic representation, drawn to scale and usually on a flat surface, of features – for example geographical, geological or geopolitical – of an area of the Earth or any other celestial body. Globes are maps represented on the surface of a sphere."

The words *map* and *chart* are used somewhat interchangeably. Most often the word *map* is used in the general sense while the word *chart* is used for more specialized maps like *nautical charts* or *aeronautical charts*. The word *map* comes from the Latin *mappa*, meaning *cloth* as in the medieval *mappamundi*, the large symbolic world maps painted on cloth

used by the Church. The word *chart* comes from Egyptian and Greek and means piece of paper (papyrus or parchment).

But a map is so much more. A map is a container of human knowledge, of spatial information. The American cognitive psychologist Edwin Hutchins says in his insightful book *Cognition in the wild* that “a navigation chart represents the accumulation of more observations than any one person could make in a lifetime. It is an artifact that embodies generations of experience and measurements” (1995, p. 111). He also calls it an “analogue computer,” because problems solved on the chart like plotting a position or a course, could as well be represented as equations and solved by symbol-processing techniques (p. 61). With a chart it is possible to compute the relationship between any two positions without this relationship ever being measured. Hutchins sees a trend through Western navigation of crystallizing knowledge and processes into physical structure of artifacts, like for example the nautical chart.

A map is usually a representation of a geographical location on Earth, a planet or the stars. But we have no problems understanding fictional maps like the one of Middle Earth in Tolkien’s *The Fellowship of the Ring* and in fact we often use map-like images to represent theoretical or abstract structures with no actual spatial qualities because the topological qualities of the map might help us understand.

According to Encyclopedia Britannica a map was mostly drawn to scale and on a flat surface. But we usually call the London Underground map, which by no way is drawn to scale, a map, so it seems as if this is not a necessary criterion for a map. How about the flat surface? Many maps include topographical features, mountains and valleys, sometimes represented by height curves and sometimes by a shading of the terrain as if a 3-D model of the terrain was lit by a light source from a certain angle and elevation. I have also seen these kinds of maps printed on sheets of hard plastic where the topography of the terrain has been pressed into the surface so as to become something of a 3-D model. Somewhere here the *map* becomes a *3-D model*. By tradition the map was flat, but modern computer technology makes it very easy to represent the third dimension. This is not done with curves or shading, but by actual elevation of the terrain, and although presented on a flat

screen, a dynamic point of view will allow an understanding of the 3-D qualities. So for the purpose of this project I will frequently refer to 3-D terrain models as just maps.

Having said this, I here define map/chart as a kind of representation, of spatial information of some real or fictional place or information space.

2.3 Communication

“The object of any map is to communicate spatial information from a sender to a receiver,” the Danish cartographer Lars Brodersen writes (1999, p. 16). The classical communication model was introduced by Shannon & Weaver in 1949. It describes communication as a simple, linear process. See Figure 27.

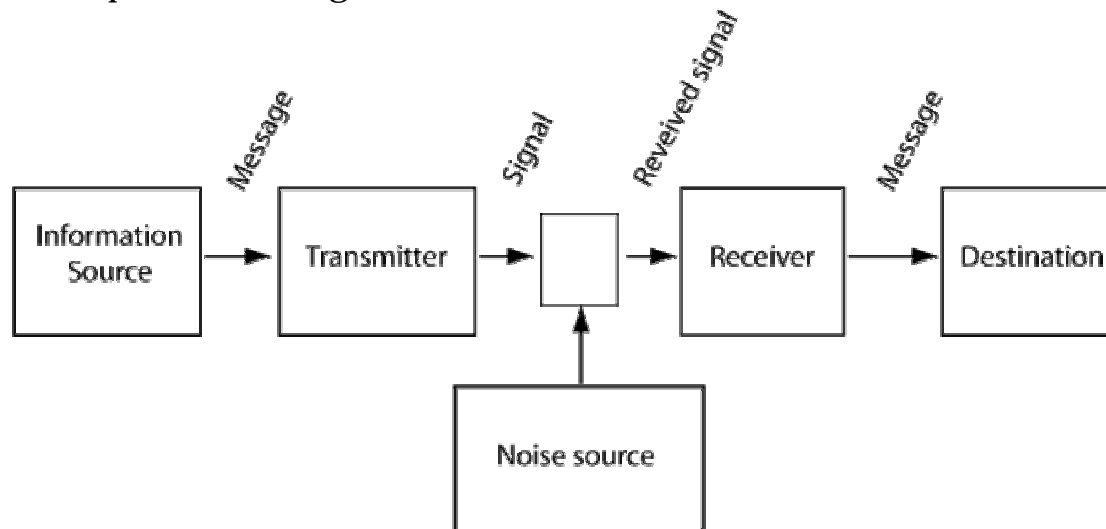


Figure 27. The Shannon & Weaver communication model from 1949. A model adapted for cartographic purposes is presented in Figure 31.

Shannon & Weaver were employed at the Bell Telephone Laboratories and their main concern was to use technical communication channels (the telephone lines) as efficiently as possible. Their communication model has often been used to describe human communication and it might well serve as a starting point to describe mediated communication through a map.

The *information source* is the sender who decides what and when to send. This is the *message*. The message is then re-coded by the *transmitter*; it might be my mouth which translates my thoughts to vibrations in the air or the telephone which translates vibrations in the air to electrical impulses. But it could also be the cartographer who translates geographical features into map symbols. The signal is then transmitted by a *channel* (represented by the empty box in the middle) which is the physical means through which the message is transmitted; it might be the air in which the sound waves from my voice pass through, or the telephone wire. The *receiver* is then my ear, another telephone where the signal is de-coded or a map reader who interprets the map symbols and as s/he understands the message reaches its *destination*.

Shannon & Weaver identified three problem levels in their communication model:

Level A. (Technical) How exactly can communication symbols be transmitted? Problems on this level might be solved by technical solutions, better sound quality or more silent surroundings.

Level B. (Semantic) How exactly do the transmitted symbols describe the intended meaning of the information source? This is more difficult. Here cultural and individual factors play a part. Do we understand the same thing in a certain gesture? What is actually meant by a “green” car, maybe I would call that color “blue” or “turquoise” instead.

Level C. (Efficiency) Does the received message have the intended effect on the receiver? This is the most complex level where many factors are involved. (Fiske, 1990, p. 18)

The nautical chart is a *medium* in such a communication process. The medium can be represented by the empty box in the middle of the Shannon & Weaver model, although this was not their original intention. On the A level communication can be facilitated by clear and distinct symbols and colors in a chart. But an electronic chart display can be placed in an unsuitable position on the bridge, like the one on Sleipner’s bridge which did not allow any of the officers to see a clear picture without bending over. (See the case study of the *Sleipner* accident in appendix B.) On the B level the process of navigation using a chart has to be learned and where there is a need to learn – there is a

risk of error. Bridge officers spend years in school to learn to master the technique of navigation and ship handling. Amateur sailors have to learn the best they can and mistakes are made. Maps can be difficult, I will return to why later in this chapter. Communication problems at the C level are the most difficult ones. Here the whole context around the chart comes in: stress, fatigue, and information overload all of which we have touched on previously.

Redundancy

Redundancy is an important concept in the Shannon-Weaver theory. Redundancy means surplus information. Redundancy in written text makes it possible for us to find misspelled words; it makes it possible for us to understand a message even if some letters or even words disappear. High redundancy is a good thing in communication; it makes the chance of successful communication bigger. The downside is that it is less effective. There are many words and letters that have to be transmitted. Humans do forget, and we might be absent minded and make mistakes. Human communication has to be redundant and so does communication between human and computers. When someone possibly stumbled on the cable to the GPS antenna on the bridge roof of the cruising ship Royal Majesty departing from Bermuda in 1995, leaving the GPS navigator without satellite connection, the navigator automatically switched to a dead reckoning mode. By doing so, a brief sonic alarm similar to that from a wrist watch sounded for one second, furthermore the letters DR (*dead reckoning*) and SOL (*solution*) were displayed on the navigator at the back of the bridge. The autopilot and the chart system displayed at the front of the bridge kept on working without warning with the now invalid positions from the dead reckoning. No one on the bridge noticed the mode shift that caused the 173 meter long passenger ship with 1,500 people onboard to ground off Nantucket Island outside Boston 34 hours later. (Lützhöft & Dekker, 2002) With enough information redundancy, this mode change would not have passed unnoticed. Much navigation information is communicated in non-redundant formats (which Shannon & Weaver calls *entropic*). So are, for instance, waypolint lists programmed into the GPS consists of endless rows of numbers. These lists have to be carefully checked by navigators, number by number, if one number is wrong, the ship might end up on the rock (Lützhöft, 2004, p. 63). Entropic communication is efficient, but it is not for humans, it is for computers. Redundancy is for humans.

Medium

Channel was the term used by Shannon & Weaver for the physical means needed to transmit the signal. If the signal was my voice the channel was the air needed to propagate the sound waves, or it could be the metal wire needed to propagate the electromagnetic waves of the telephone. For practical reasons a term not used by Shannon & Weaver has been introduced: *medium*. In communication science a medium is a technical or physical means to transform a message to a signal that can be forwarded through a channel. Thus my voice is a medium, and so are radio, web pages on the Internet, and books. Media can be split up in three groups:

Presentational media, for example my voice, my face or my body. At least the sender needs to be present in time and space. We call this *direct communication*.

Representational media, for example books, paintings, architecture, web pages and maps. These media exist independently and are not conditioned by the sender's presence in time or space.

Mechanical media, for example telephone, television and the Internet; these media function as transmitters of the first two categories. (Fiske, 1990, p. 32)

The chart is a representational media whether it is in printed or electronic form. But if the display of an electronic chart is controlled by the vessel's position and the position of other vessels in the vicinity are displayed in the chart based on real-time transponder signal, we are getting closer to some sort of direct communication.

Code

A *code* is a system of meanings that is common for members of a culture or a subculture. A code consists of signs (physical signals that stand for something other than itself) as well as rules and conventions governing how these signals can be used and combined. (Fiske, 1990, p. 34) There is a direct connection between code and channel. The physical properties of the channel decide the nature of the code to be used. For instance, if the channel is *print*, the code is limited to *images* and *text*; if the channel is *telephone* the code is *verbal language* and *paralanguage* (intonation, volume etc.)

A nautical chart is a coded message legible for those versed in that domain. But to look closer at that code we need to orient ourselves in the field of *semiotics*.

Semiotics

Semiotics is the study of signs. When Shannon and Weaver were interested in the linear process of communicating a message from a sender to a receiver, the semiotic school was interested in the structure and the relationship between what they called the *signifier* and the *signified*. The foreground persons are the Swiss linguist Ferdinand de Saussure and the American philosopher Charles S. Peirce. Although there are differences in details, one way of illustrating the semiotic model of the sign is shown in Figure 28.

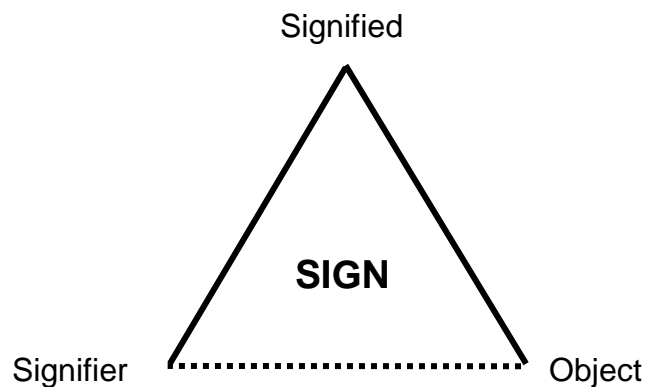


Figure 28. The semiotic triangle. (There are many different ways of illustrating the model among the Semioticians and the terms vary but the essence is the same.) The Signifier (sign vehicle, symbol, representamen) is the form of the sign; the Signified (sense, interpretant) is the sense made of the sign and the Object (referent) is what the sign stands for. The broken line at the base of the triangle indicates that there is not necessarily any observable or direct relationship between the sign vehicle and the referent. (Chandler, 2001)

The basic idea behind the semiotic thought is that a sign is a code that stands for something, an object, or it could also be an abstract idea. The sign is expressed as a symbol, a form that can be either physical or mental; the symbol triggers some kind of meaning, a sense, when we perceive the sign as a sign, otherwise it will not signify anything.

Semiology generally agrees on three types of relationships between signifier and signified:

Symbols, a mode where the signifier does not resemble the signified; the sign is arbitrary and its meaning has to be learned. Examples of this are alphabetical letters, words, numbers, Morse code, most national flags and traffic lights.

Icons, a mode in which the signifier resembles or imitates the signified. Examples are portraits, caricatures, scale-models, onomatopoeic words, metaphors, realistic sounds and many maps.

Index, a mode in which the signifier is not arbitrary but in a direct way connected to the signified. Examples of these are natural signs, like smoke (for fire), footprints (for humans), medical symptoms, measures on measuring instrument, signals (like a door knock), recordings (like photographs, videos, films), personal trademarks like handwriting, etc. (Chandler, 2001)

The map as a whole is iconic in that it tries to depict the land, seas, rivers and islands as seen from an orthographic position. But the map also contains a lot of symbols, icons and indices (see Figure 29).

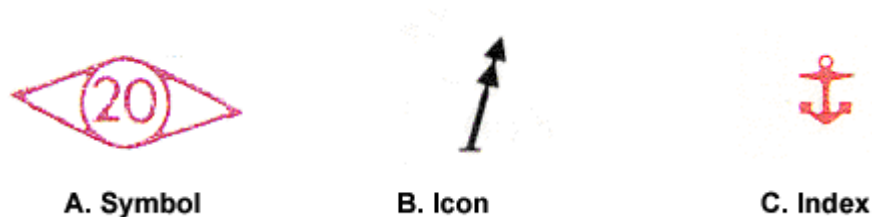


Figure 29. Examples of different modes of signs in a nautical chart. A is an example of a symbol, here a two-way radio reporting point with designation, B is an example of an icon, a north mark spar buoy, and C is an example of an index, an iconic anchor being an index for a ship's anchor berth. (International Hydrographic Organization, 1998)

Some of the icons and indices, like the anchor indicating anchor berth, have a long history and appeared very early (Carta Marina by Olaus Magnus 1439). Icons and indices also have a potential for intuitive understanding. But a nautical chart also contains many symbols whose meanings are not directly understood. It is then necessary to have access to a code key. The code for understanding abbreviations, symbols and terms used in nautical charts is collected in *INT 1, Symbols, abbreviations, terms used on charts*, a standard by the International

Grund			Rocks	
Referensnivåer för höjder Plane of Reference for Heights → H				
10		Alltid synlig sten eller skär Rock (islet) which does not cover, height above height datum		421.1
11		Sten eller skär synligt mellan kartdatum och högvattnet Rock which covers and uncovers, height above chart datum		421.2
12		Bränning/-ar, grund i eller nära kartdatum (i svenska sjökort medelvattenytan) Rock awash at the level of chart datum (MSL in Swedish charts)		421.3
13		Undervattenssten, farligt för ytnavigering, (i svenska sjökort grundare än 2 m) Dangerous underwater rock of uncertain depth		421.4

Figure 30. Detail of page 41 in the Swedish edition of *INT 1, Symbols, abbreviations, terms used on charts*. Note that the edition is bilingual. (IHO,1998)

Hydrographic Organization and published by the maritime administrations of countries publishing charts. In Figure 30 there is an example page.

2.4 Cartography

I started the section on communication theory by quoting the Danish cartographer Lars Brodersen: “The object of any map is to communicate spatial information from a sender to a receiver” (1999, p. 16). He continues by saying: “The map is not a reproduction of the real world, and it is not objective, nor true.” The map has a sender with a purpose and has invested in making and spreading it. The receiver has a need. The negotiated volume of information will be a guide for the design of the map. Brodersen rewrites the communication model, emphasizing comprehended communication and the role of coding and decoding the message (see Figure 31).

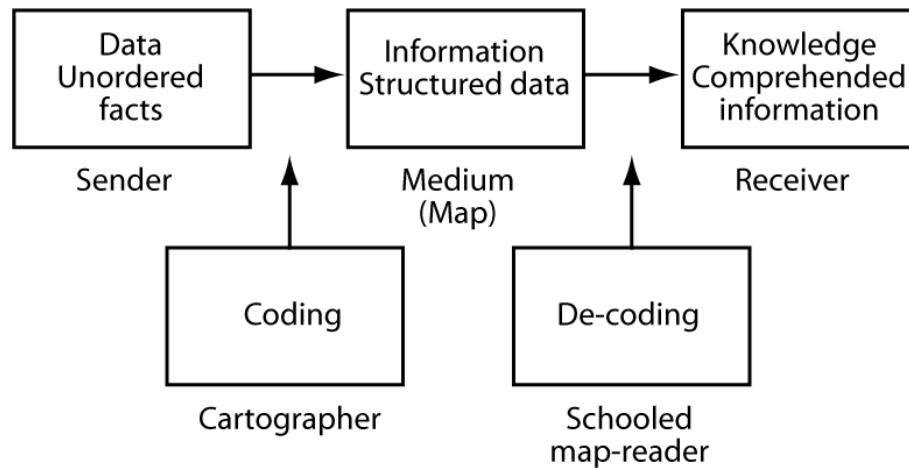


Figure 31. Brodersen's sender-receiver model for map communication. (1999, p. 29)

According to Brodersen's model the sender decides on publishing a map. Maybe he sees a need, a market opportunity: mariners that need nautical charts to voyage the seas and reach a safe haven. He contacts a cartographer to do the work. This cartographer has to know his target group very well; what is the most important information for mariners? Of all the available information he then has to make a choice. Why does he have to make a choice? Why not give the bridge officer all information and let him decide himself what is important and what is not? I will illustrate why by showing a map of the 30,000 communities in France published in the *Semiology of Graphics* by Jaques Bertin. (See Figure 32.)

The map of the communities of France intuitively points out the need for what in cartography is called *generalization*. By showing all the 30,000 communities in a small scale map of France, the result is a *cluttering* that makes communication impossible (unless your intention is to communicate the impression "oh, they are that many!"). You cannot show every grain of sand on the beach, instead you have to make a code saying "sandy beach;" you cannot show every tree in the forest, instead you generalize the trees into an area polygon, color coded as "forest". The difficult decision is to decide what information to leave out and what to keep. Generalization and coding are important tasks of the cartographer. Of course, information density will be different in different scale maps. Modern electronic maps, which give us the option of zooming, also provide us with the possibility to show

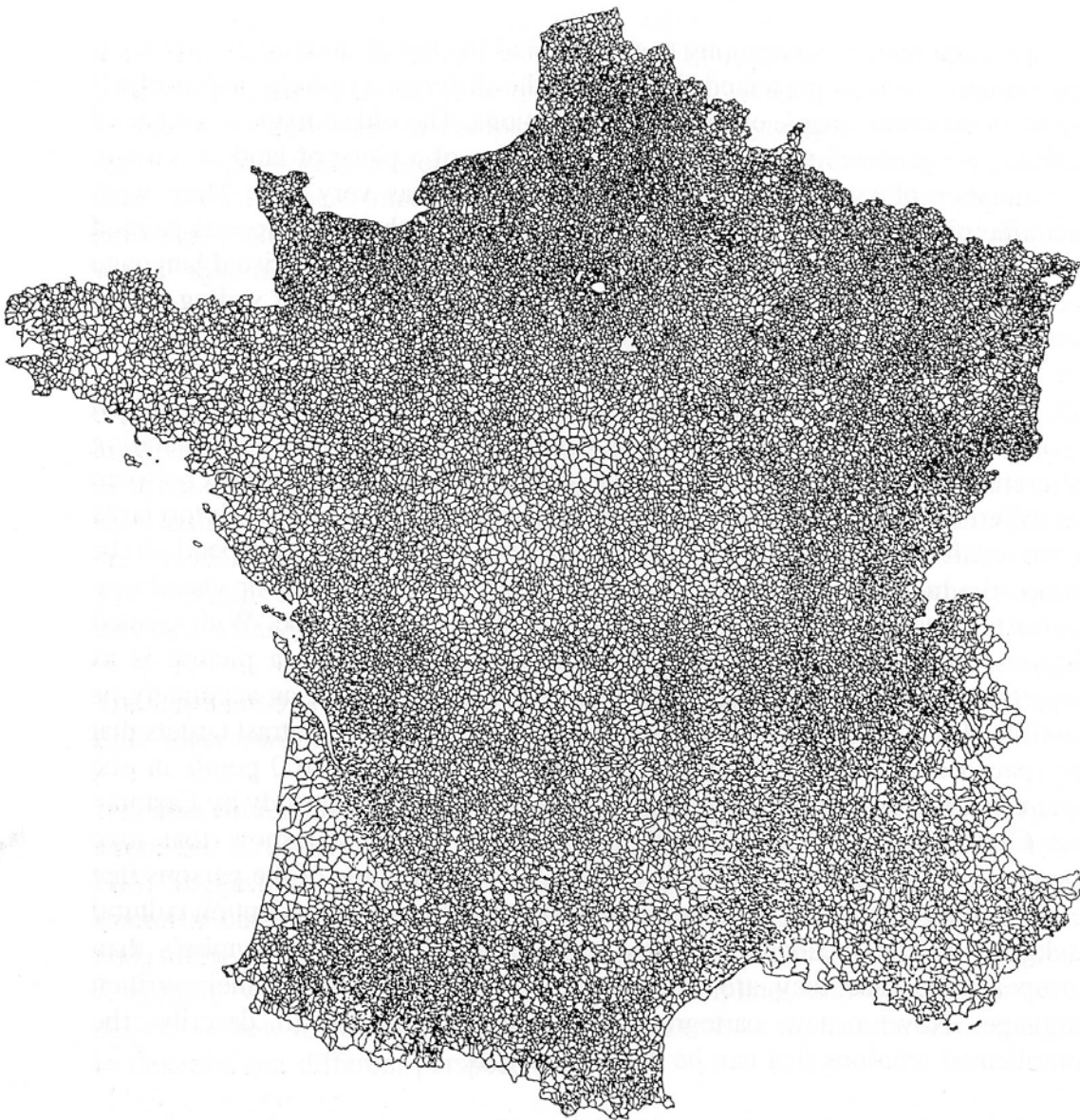


Figure 32. Jaques Bertin's map of the 30,000 communities of France. It says something about the necessity of chart generalization and the connection between generalization and scale. (Bertin, 1983, p. 152)

and hide information depending on which scale we are using. Theoretically, in this way we would be able to really see every tree in the forest in a large enough scale. The job of the cartographer is then to decide what information to show in the different scales. See Figure 33.

When the decision of what information to keep and what to discard has been made, the cartographer has to code the information. To his help he

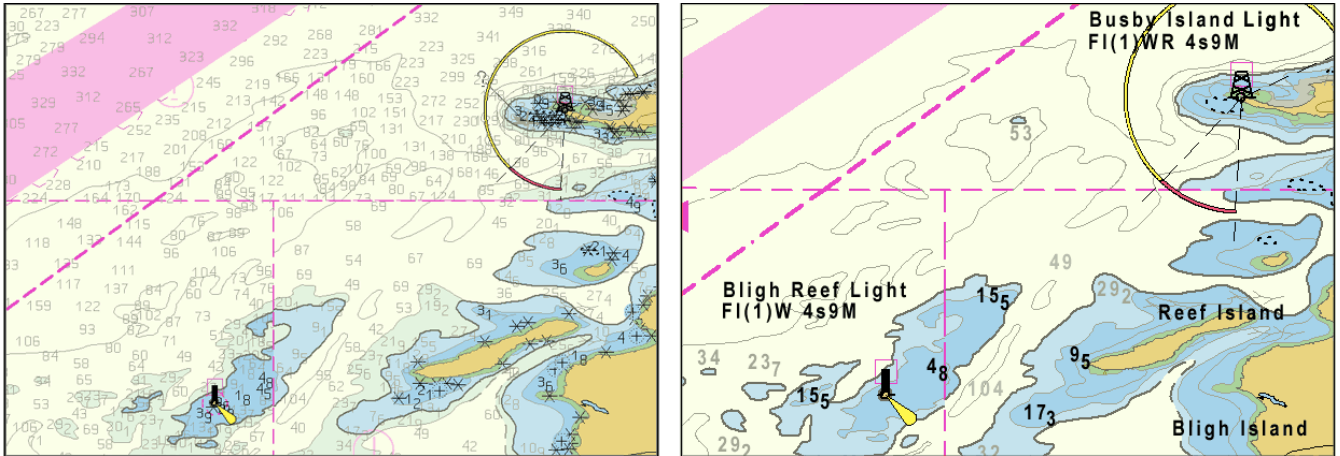


Figure 33. When too much information is shown on a particular scale the effect is a *cluttered* display (left). Modern electronic chart displays have the option of turning off and on information layers and adapt the amount of information to the current resolution (right). Bligh Reef, where Exxon Valdez grounded in 1989. National Oceanic and Atmospheric Administration Electronic Navigational Chart US5AK11, 24 and 25M over Prince William Sound, Alaska.

has a *legend*, a code key where symbols, icons, line shapes, area colors etc. are listed. We previously saw an example of a legend in Figure 30. The cartographer may use the explicit meaning of the sign he chooses to use, what the French semiologist Roland Barthes calls their *denotations*, but he also has to be aware of the hidden associations arising from cultural differences, what Barthes calls *connotations*. “The purpose of cartographic generalization is to create communication with the least possible uncertainty in the shortest possible time”, Brodersen writes (p. 23). He does this by making selections from the total amount of data, simplifying and compiling it into groups, exaggerating the essential and taking away the unessential (p. 52). An important aspects of relevance for generalization is the *time* the map user can spend on finding the information, compare for example the forest hiker and the air fighter pilot; what sort of information the map reader is interested in (compare the motorist and the sailor); also the knowledge and the homogeneity of the user group (compare pupils on a forest hike and the elite orienteer). Here are some examples of what map generalization does:

Simplification, e.g. a curved shore line is straightened

Enlargement, e.g. a bridge is drawn wider than in scale to be more prominent

Displacement, e.g. buildings are moved away from the shore line to be more prominent

Merging, e.g. a group of rock is merged into one rock symbol

Selection, e.g. only a few houses are left to represent a whole village

Symbolization, e.g. a whole town is symbolized by a dot.
(Kraak, 1996, p. 95)

In Figure 34 the result of generalization and coding towards different user groups can be seen. To the left “the real world” in the form of an air photo over Ägnö in the Stockholm archipelago. In the middle, the same area from the nautical chart aimed at sailors; on land only a few houses seen from the sea are left, all other information is concentrated to show the underwater topography. To the right, a hiking map intended for the general public and outdoor life. Some nautical information is kept but the main focus is on land, showing topography, vegetation, buildings and routes.

Before leaving this very short overview on cartography a few words about *map semantics* or the language of the map, are in place. The French



Figure 34. Ägnö in the Stockholm archipelago. To the left an air photo, in the middle the same part from the nautical chart in scale 1:25,000 from the Swedish Maritime Administration and to the right the “Green map”, in scale 1:50,000 from Lantmäteriet.

cartographer Jaques Bertin published in 1967 the standard work in this field, *Sémiologie graphique* (The Semiology of Graphics – we met him in the 30,000 communities of France above). While de Saussure and Peirce laid the philosophical foundation for the science of semiology covering all aspects of human signs, Bertin concentrated on the language of graphics. He starts by defining the *plane*, the background of the sign and its prerequisite. He limits his investigation to the immobile and visible sign. In this framework Bertin defines *the eight graphical variables*:

- Vertical position
- Horizontal position
- Shape
- Color
- Size
- Value
- Orientation
- Texture

These eight variables can then be used by the three types (Bertin calls them *implants*) of signs: the *point*, the *line* and the *area*. (Bertin, 1983, p. 7) Colin Ware summarizes the graphical code available to the cartographer in Figure 35.

2.5 Cognition

Spatial Knowledge and Wayfinding

In a narrow sense of the word *navigation* means *to direct a ship*, but in a broader sense navigation mean *to find ones way*. The ability to navigate to hunting grounds in search for food and back to the cave must have been essential for human survival. What is this ability to navigate?

Darken & Petersen defined navigation as “the aggregated task of wayfinding and motion” (2001). Golledge sees two types of human guiding processes: *navigation*, formally guiding ships or aircraft, but colloquially “to deliberately walk or make ones way through space,”











Graphical code	Visual Instantiation	Semantics
1. Closed contour.		Geographic region.
2. Colored region.		Geographic region.
3. Textured region.		Geographic region.
4. Line.		Linear map features such as rivers, roads, etc. Depends on scale.
5. Dot.		Point features such as town, building. Depends on scale.
6. Dot on line.		Point feature such as town on line feature such as road.
7. Dot in closed contour.		Point feature such as town located within a geographic region.
8. Line crosses closed-conture region.		Linear feature such as a river crossing geographic region.
9. Line exits closed-conture region.		Linear feature such as a river terminates in a geographic region.
10. Overlapping contour, colored regions, textured regions.		Overlapping geographically defined areas.

Figure 35. The graphical code available to the cartographer. After Ware (Ware, 2004, p. 216)

and *wayfinding*, a process which involves selecting paths from a network (1999, pp. 6-7).

To be able to navigate or find our way we first have to understand the world around us. Researchers seem to agree that spatial knowledge is gradually being built up in a process involving three phases. A first important prerequisite for all navigation and wayfinding seems to be some sort of spatial knowledge of the world through which we are to move. Siegel & White (1975) proposed that spatial knowledge involves three different kinds of knowledge. Researchers today generally seem to agree on that, although the terminology differs.

To begin with, *Landmark Knowledge* is the declarative knowledge of particular, well recognizable places, like the Eiffel tower, the railway station, “the blue house with the funny windows” or “the island with the lonely tree on the top”. Kevin Lynch, in his classical *Image of the City* pointed on the importance of landmarks to make the city space understandable and facilitate wayfinding (1960). But in maritime navigation the term *landmark* is used in the current meaning from at least the 10th century, being the anchor point for ranges and bearings. Landmark knowledge does not, according to Siegel & White (1975), mean that there is any understanding of the spatial relationship between the landmarks, only knowledge that makes it possible to identify them on sight.

A more complex kind of knowledge was by Siegel & White (1975) called *Procedural Knowledge*, often called *Route Knowledge*. It involves learning the routes from one landmark to another such as “Go straight until you come to the ICA store, then turn left, go one block...” It allows us to navigate through space although we do not fully understand it. Route knowledge is often used to communicate wayfinding information. Route knowledge has an egocentric perspective and uses egocentric terms like *left* and *right*, *in front of* or *behind*.

The most complex kind of spatial knowledge is called *Survey Knowledge* or *Configuration Knowledge* (Thorndyke & Hayes-Roth, 1982). This is the kind of knowledge where we understand spatial relationship. It makes it possible for us to take short cuts where we have never gone before,

point from one place to another and draw inferences from this about the distance between objects. Survey knowledge often has an exocentric perspective where exocentric terms like *north*, *south*, *east* or *west* are used. It does not take the perspective of a subject present in the wayfinding task.

It has been debated whether survey knowledge builds up stepwise through landmark and route knowledge, but research has shown that survey knowledge can be acquired directly by studying an area from an elevated position where it can be overlooked all at one time or through a map. Thorndyke & Hayes-Roth (1982) showed that subjects after just 20 minutes of map study could judge distances and locations in a large office building equally well as a group of secretaries that had worked there for two years.

Cognitive Maps

The term *cognitive map* is often used for internal spatial representations, mental memories or images of space. It was first used by Edward C. Tolman (1948), reporting on an experiment with rats learning short cuts through a maze. He used the term metaphorically; *as if* the places the rats remembered were recorded in a maplike manner. “We believe that in the course of learning, something like a field map of the environment gets established in the rat’s brain” (Ibid, p. 192).

The concept of cognitive maps is both widely accepted and widely discussed. We are all aware that we do have some kind of mental representation to help us navigate and find our way in familiar environments, just as we are aware of the absence of such a mental map when we try to find our way in unknown environments. But we do not know exactly what a cognitive map is.

Stanford cognitive psychologist Barbara Tversky (1993) questions the *map* expression which she means implies metric and coherent structure. She points out the many systematic and other errors in people’s memory for environments. Instead, she says, people acquire disparate pieces of knowledge about environments; pieces like recollections of journeys, memories of maps, bits of verbal directions and facts, and more. Instead of *maps* she wants to call these internal representations

cognitive collages. “[Cognitive] collages are thematic overlays of multimedia from different points of view. They lack the coherence of maps, but do contain figures, partial information, and differing perspectives” (Ibid, p. 15). But she also states:

In other situations, especially where environments are simple or well-learned, people seem to have quite accurate mental representations of spatial layouts. On close examination, these representations capture the categorical spatial relations among elements coherently, allowing perspective-taking, reorientation, and spatial inferences. (Ibid, p.15)

Tversky terms these mental representations *spatial mental models*, and remarks that although they do not preserve metric information, they do preserve coarse spatial relations coherently. As to the structure, Tversky finds that:

These spatial mental models are akin to an architect’s model or a structural description of an object. They have no prescribed perspective, but permit many perspectives to be taken on them. Thus, spatial mental models are more abstract than images, which are restricted to a specific point of view. (Ibid, p. 20)

In a series of studies Tversky finds that subjects making descriptions of their spatial mental models take two different, but very specific, perspectives. Tversky calls them *route* and *survey perspective*. The essence of the route perspective is the coherent moving viewpoint changing location and orientation in relation to the frame of reference, while the essence of the survey perspective is the fixed perspective allowing for the description of the location of a landmark relative to the location of another landmark. She notes that: “descriptions used either route or survey perspectives or a combination of both. No other style of description emerged.” (Ibid, p. 20)

Mental Rotations

You can navigate without a map. For example you can drive a car from one unknown place to another by just following the road and road signs. Reginald Golledge calls this *route following* (1999, p. 20). It implies

that a route already exists and has been planned in advance. In navigation which is not just a question of route following, but also a question of wayfinding, a map normally is used, a spatial mental model (cognitive map) or an ordinary map. Sholl (1996) suggests that traveling requires people to activate two processes that facilitate spatial knowledge acquisition: individual *person-to-object* relationship that changes dynamically as the voyage takes place (egocentric referencing), and more stable *object-to-object* relationships that anchor an object on the map or in the spatial mental model with the same object in the real world. When this anchor process fails we get lost even if we have access to a correct map or mental model. The officers on the bridge of the Norwegian high speed ferry *Sleipner* that speeded towards her grounding in the dark of the night, had a very good mental model of the coast, having passed there numerous times in daylight. In the dark their mental model was pinned to and kept aligned to the real world by the flashing lighthouses along the coast and the radar images on their screens. When the radars failed to detect the position of the rock and the navigators momentarily lost visual contact with the flash of the beacon their spatial mental models lost alignment with the real world; they had lost their orientation. (See appendix A for details of the *Sleipner* grounding.)

Maps are traditionally oriented with north direction pointing up. This orientation was introduced by Ptolemy around 100 A.D., at the same time as he introduced the longitude and latitude grid system. Maps introduced by the church, however, used east-up. They were called T-in-O maps and the crucified Christ (the T) was inscribed in the Mediterranean Sea and Jerusalem and the Orient was at the top; hence the word “orientation” (Holmes, 1991, p. 35). But the Christian maps were never used for actual navigation, and when Mercator introduced the map projection that was to become world maritime standard, north-up was used as the standard orientation.

“A real sailor never turns the chart upside down!” During interviews and studies made for this project I have heard that, and similar phrases many times. There seem to be an unwritten tradition among mariners to always keep the chart north up. There could be practical reasons for this, nautical charts are fairly large, typically 1.1 m by 0.8 m. and not so easily handled on the chart tables of the bridge. It certainly facilitates

reading of the text and in a context where many ships need to communicate, the north-up chart is a common reference frame. But it also forces the navigator to mentally rotate the map on courses other than north.

On a south bound course a buoy that is on the left side of the course line of a north-up chart will appear on the right (starboard) side of the ship. The navigator who wants to compare the map with the real world outside the windscreen must mentally rotate the map 180° around the vertical z axes (azimuth rotation) and then 90° around the new y axes (altitude rotation) to get the tilt right. Mental rotations take time. This was shown by Shepard & Metzler (1971). They showed pairs of 3-D forms to their subjects. The forms were either the same form, one just being rotated a number of degrees, or they were different forms – one being a mirrored variant of the first form which then had been rotated. The subjects were to judge whether the two forms were actually the same or not (see Figure 36).

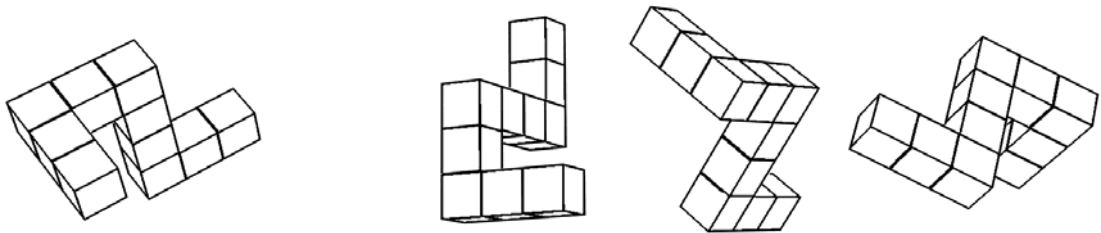


Figure 36. Typical visual forms used by Shepard & Metzler. Is any of the three objects to the right the same as the reference object to the left, only rotated? Adapted after Shepard & Metzler (1971).

The amount of rotation of the second form and the time it took to decide was logged. Of the times collected this way, only the ones concerning the pairs of “same” forms was used. The times and rotations were then analyzed with rotation as the independent variable and the decision time as the dependent. Much to everyone’s surprise, it turned out that the decision time was a nice linear function of the amount of rotation, where about every 50° took one second. (Solso, 2001, p. 298) See Figure 37.

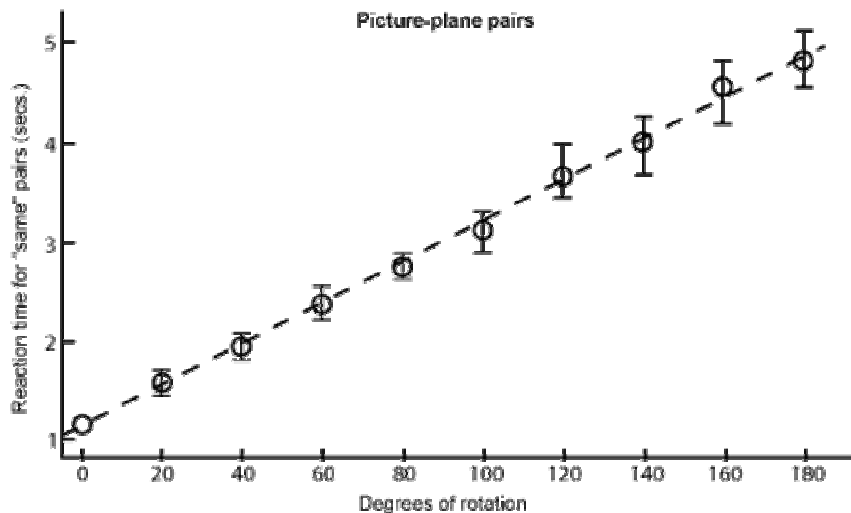


Figure 37. Reaction time is a nice linear function of degree of rotation of a form. About every 50° of rotation takes one second. Adapted from Shepard & Metzler (1971).

The interesting point with Shepard & Metzler's experiment is not the number of seconds it took, for this might well differ depending on individual abilities, training and the complexity of the forms rotated, but the fact that this rotation takes time and is a linear function of the angle of rotation.

In a somewhat similar experiment with more direct implications to this project, Malcolm Eley tested map-to-landform matching on practiced map users (undergraduates in geography, geology and surveying, and successful orienteering sports men and women). He first let the subjects study a simple contour map. See top left in Figure 38 for an example. In this first phase the subjects were told to study the contour map for as long as needed to determine the shape of the landform. In the next phase the subjects were shown a direction pointer. See top right in Figure 38. They were then told to take the time needed to determine the shape as viewed from the indicated direction. This time was logged. In the third phase the subjects were shown a surface drawing similar to any of the bottom six bottom pictures in Figure 38. This drawing was a 3-D surface of the contour map rotated at intervals of 60° counter clockwise from the 0° angle. The subjects were then to judge the surface drawing as a true or false description of the mapped landform as seen

from the direction indicated in phase two. The third phase decision time was again logged (Eley, 1988, p. 359).

Just like in the Shepard & Metzler experiment, Eley found that the phase two preparation times and the phase three decision times of his subjects were a linear function of the amount of viewing angle offset from the north-up angle, so that when the surface was rotated 180°, the preparation and decision times were longer than when the rotation was smaller or none at all.

Eley interpreted this to mean that if the map and the viewed surface is not in the same orientation they cannot be compared without some mental adjustments, and that the extent of such adjustments was related to the magnitude of the orientation misalignment. Eley suggests that when the map user attempts to match a map to a landform surface s/he first seeks to generate a mental image of what the mapped surface should look like. This image is then compared to the viewed criterion (Eley, 1989, p. 106).

This and some other experiments led Eley to the suggestion that an experienced map user first studies the map in order to specifically detect a set of distinctive features, such as hills, valleys, ridges and other forms and that these are then spatially arranged to form a mental representation that can be judged against the real world (Eley, 1989, p. 107).

The conclusion that Eley does not draw in his article but which is obvious from his results, is that by orienting the map in a head- or course-up manner, the mental azimuth or z axes rotation becomes superfluous and decision time is minimized. Orienteering sports men and women always orient their maps head-up. This is not done by “real sailors”.

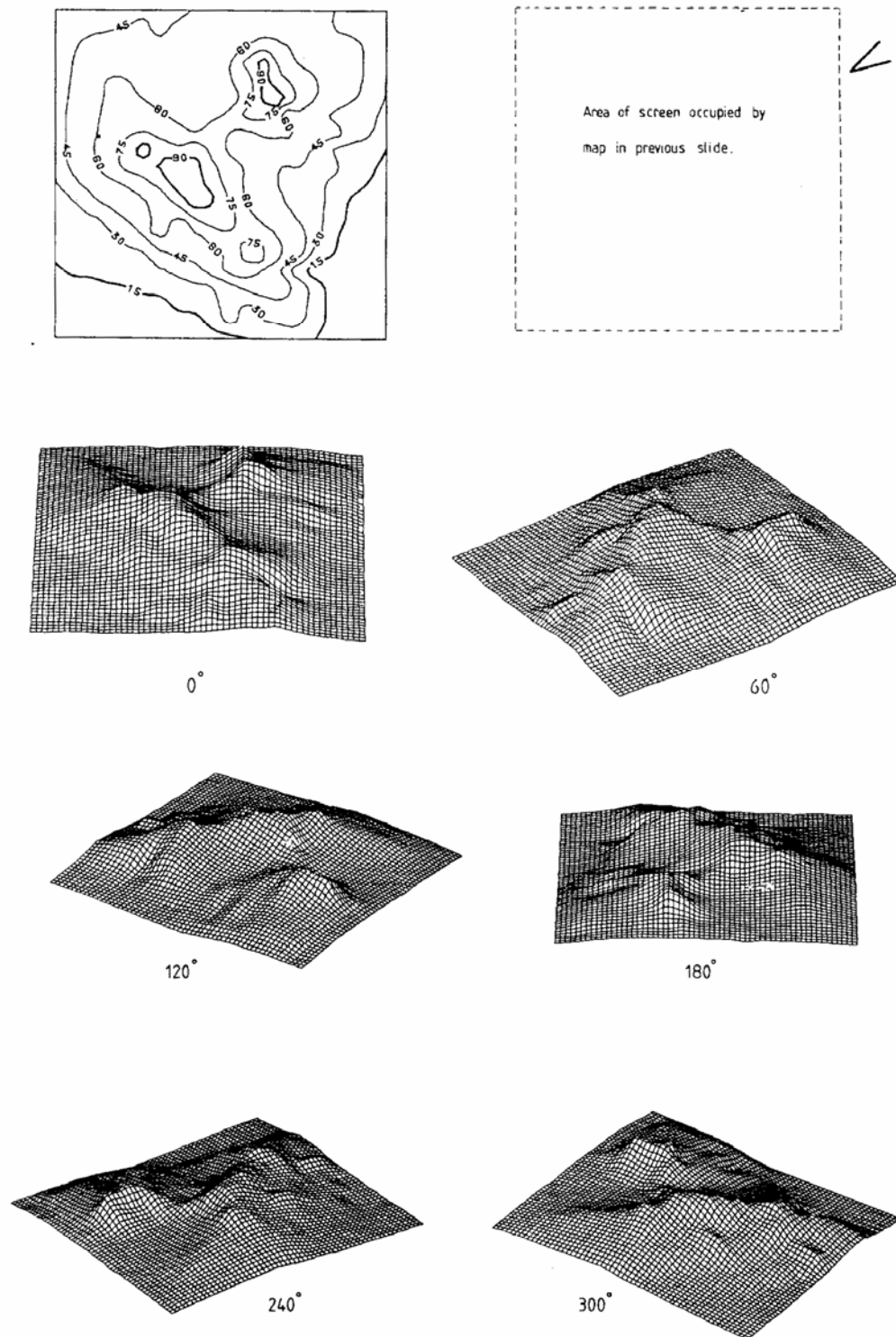


Figure 38. The experiment setting of Eley's experiment 1 (1988). Subject were to judge if one of the bottom six 3-D landform surfaces corresponded to the landform in the top left contour map seen from the top right viewing angle. (The right answer here is the 120° surface.) Illustration by Eley (1988, p. 358)

Canonical Orientation

A downside to turning the map upside down is that you may lose some familiarity with the map itself. Route planning and map study are normally made on a map in a north-up orientation. Features on the map, like shapes of islands, coasts and even directions of route lines, are then memorized in this orientation. Franklin & Tversky (1990) call this the *canonical* or preferred orientation. At school we usually learn geography from north-up maps. In Figure 39 a European country is shown in a non-canonical orientation, upside down. It will take you slightly longer to recognize this country in this perspective than if it had been shown in its canonical orientation (turn the book around and see). Wickens & Hollands (2000, p. 164) observes that viewing an image of an environment from the same direction as the canonical orientation will improve spatial judgments made about that image.

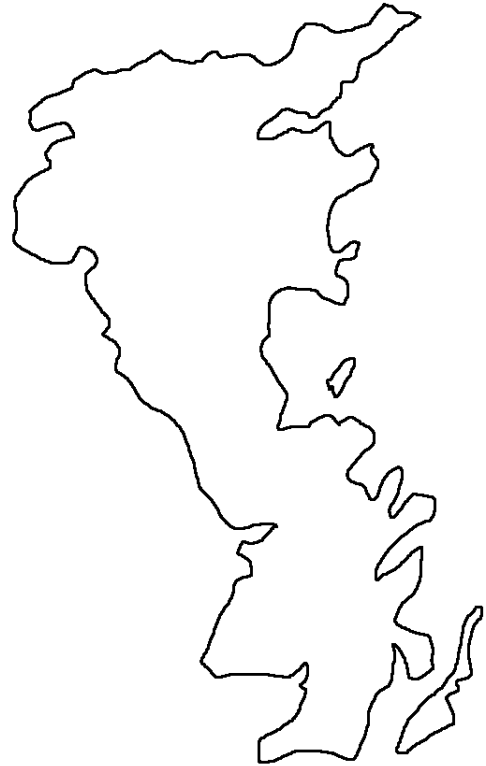


Figure 39. It will take you slightly longer time to recognize this European country in this non-canonical orientation than if it would have been shown rotated 180°.

Spatial mental models can sometimes, too, according to Franklin & Tversky (1990), have a canonical orientation. If you usually enter an area from a certain direction, let us say through a certain underground station, your mental model of that area might have this canonical orientation. Arriving through another underground station will then be confusing and you may need some time for necessary mental rotations to be made, to get it all right.

“You-are-here” maps are often seen on tourist locations or as orientation and evacuation maps in large buildings or hotel facilities. They address people who are unfamiliar with the environment. Such

maps include a “you-are-here” mark which pinpoints the person-to-map relationship. But it is also important that the map is oriented head-up, so that a person facing the map has the up direction in his field of view. (Levine, 1982) I have many times seen evacuation maps on the inside of hotel room doors printed in north-up or some other rectilinear orientation where maps are the same for rooms on both sides of the corridor, only the you-are-here dot differs. For the guests on the “wrong” side of the corridor this means that a suggested evacuation route towards the right on the map will actually be towards the left in the corridor. This might be dangerous in emergency situations for guests who have not taken time to study the evacuation route in advance.

Task Dependencies

A lot of research on navigation has been done in the aviation industry. Some of this research has been done on navigation, mental rotations and wayfinding in different frames of references. As speeds on the sea increase in a much more complex maritime environment, much of this aviation research becomes interesting for maritime human factors.

The answer to the question of which frame of reference is the best – exocentric or egocentric – depends on the task. “Navigation, or actual travel through the environment, is best supported by greater features of egocentricity,” Wickens & Hollands suggest (2000, p. 169). The reasons for this are the following:

1. The egocentric view point is the view point of our eyes as we go about our daily lives. It is the most natural frame of reference. (MacCormick et al., 1998; Olmos et al., 1999; Wickens & Prevett, 1995.)
2. This viewpoint provides the traveler with a better view of what lies ahead in the path and obstacles to be avoided.
3. The map user need not mentally rotate the map to make a comparison with the real world, which is time consuming and a source of errors and mental workload. (Aretz, 1991; Shepard & Hurwitz, 1984; Warren et al., 1990; Wickens et al., 1996.)
4. The image provided by an immersed egocentric viewpoint more closely corresponds to the view we see through the windscreen

and hence allows a more fluent judgment of location. (Schreiber et al., 1998; Hickox & Wickens, 1999.)

But tasks that involve spatial understanding, like passage planning, are best supported by an exocentric point of view. (Wickens et al, 1996; MacCormick et al., 1998; Williams et al., 1996, Wickens, 1999.) The reasons for this are:

1. The egocentric view point provides the user with a “keyhole view”. To find out what lies outside his field of view he has to look around and mentally piece the space together. Also distant features might be occluded by close islands. (Woods, 1984; Wickens, Thomas & Merlo, 1999.)
2. An exocentric fixed view point provides more consistency and allows for better spatial learning. (Aretz, 1991; Barfield & Rosenberg, 1995.)
3. The foreshortening along the line of sight in an immersed egocentric view tends to degrade distance and depth judgments. (Mervin et al., 1997; Olmos et al., 1999; Wickens et al. 1996; Smallman & St. John, 2005.)

Verbal Route Lists

Research on car guidance systems has shown the benefit of using verbal commands, so called route lists. (Dingus et al., 1997; Srinivasan & Jovanis, 1997.) The most beneficial is that drivers keep their eyes on the road while listening to instructions from the system.

These instructions come in the form of a *route list*, for example “turn left at the church, go two blocks and turn right at the hardware store”. On sea route lists are used by very fast navy ships navigating in complex archipelago environments. The language then needs to be highly specialized to be efficient and lot of training is needed to navigate full speed this way. (For more on this, see the section on the combat boat accident in appendix B and the interview section.) However, using route lists might become problematic if they are very complex and the course legs are short so the reading of the list takes longer than actually passing the leg. A particular problem with verbal route lists on sea, is

that distinct landmarks are usually scarce in an archipelago where skerries and islands all look the same.

Verbal instructions are also given in a frame of reference. Terms like “left”, “right”, “in front of”, and “behind” all implies an egocentric frame of reference. We have already said that traveling is a typically egocentric task and is best performed in an egocentric frame of reference. Instructions like “turn right” can immediately be implemented while an exocentric instruction like “turn north” requires time to find out the current course and its relation to north before the command can be carried out. (Wickens & Hollands, 2000, p. 166)

In other situations with multiple participants an exocentric frame of reference might be preferable. Here exocentric terms like “north” or “180 degrees” provide a neutral unambiguous frame of reference.

2.6 Previous Research

In this section I will present a brief overview of existing research and commercial 3D nautical chart projects that I have come across during this research period. I have made an extensive search and asked to help similar project in presentations at several international scientific conferences where I have participated. Much to my surprise there have been few projects trying to use the well-known maritime academy ship simulator technology on the bridges for navigational purposes.

FFI, 1994

In 2004 it came to my knowledge that the Norwegian Defense Research Establishment (Forsvarets forskningsinstitutt – FFI) already in 1994 had made a study and published a report *Integrated Bridge for High Speed Marine Craft*. (Bråthen, 1994). The aim of this project was to develop concepts for the next generation of integrated bridge systems for high speed marine craft.

The report states that the workload of a high speed craft navigator in confined waters is equal to that of an airplane pilot under landing. The aim of the project was to propose new and improved bridge design for

high speed craft and suggestions were made both on the over all physical design of the bridge and the detailed instrument and interface design. Key words were integration of systems and easy man machine communication.

From my point of view the most interesting suggestion was the perspective view shown in Figure 40.

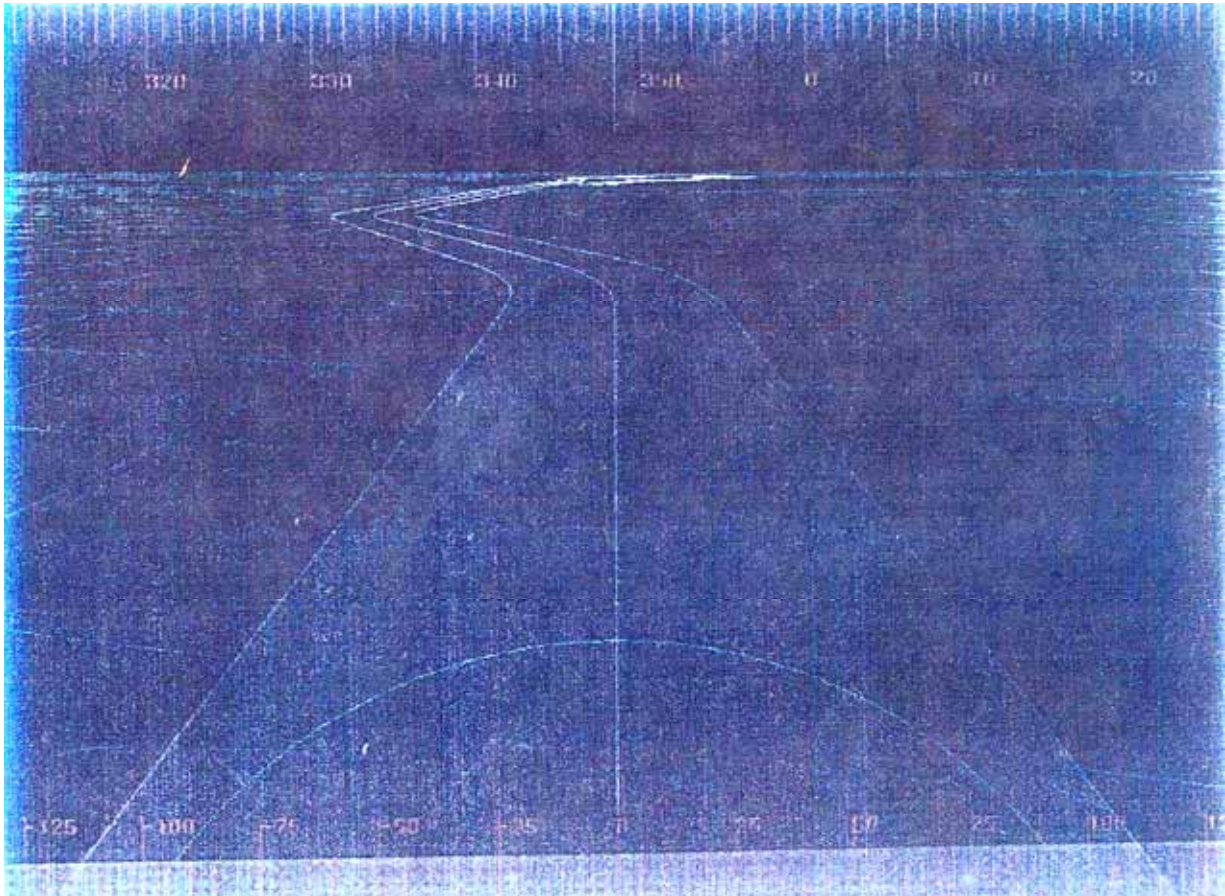


Figure 40. A "perspective view" from the Norwegian Defense Research Establishment's High Speed Craft Bridge project.

According to the report a conning display mixing a close proximity view from a Low Light Television (LLT) system, with a distance real-time 3-D view. "We want to see a development away from the use of symbolic pictures to a more direct representation of the world around the high speed craft based on mans natural abilities of perception."

(Bråthen, 1994, p. 25.) The perspective view is also suggested being displayed on a Head Up Display (HUD) in the window of the driver.

The Norwegian high speed craft bridge report is of course directly relevant to my project and if the research behind it had been finished there would probably not have been any need for the research I have been doing in the last years. However, the project was discontinued shortly after the publication of the report.

Ford, 2002

In an article published in the geographical information systems company ESRI from 2002, Captain Stephen F. Ford, Master Mariner with 15 years of seagoing experience, presents “the first three-dimensional nautical chart” over the Cape Cod Canal in eastern United States. (Ford, 2002, p. 117) Ford describes in the article the construction of a 3-D elevation model of the Cap Cod Canal. The model is based on digitalized nautical paper charts and available 3-D federal GIS data. Ford writes that “there are many benefits for the mariner to be derived from peeling back the water layer which per force obstructs the view of the underwater bathymetry” (p. 122). Ford’s intention is to “lift off” the water and let the navigator fly over the bottom topography to facilitate navigation an thus “maneuver the vessel in a fashion similar to the way an automobile is driven” (p. 122). In a picture from the article Ford illustrates his intentions (see Figure 41).

Ford writes that “the use of 3-D objects as an aid to navigation will reduce the amount of text required on a raster chart image, and will reduce the amount of time and effort needed by mariners to identify and interpret navigational aids. This in turn reduces the risks of an incident due to faulty navigation and increases the amount of time a mariner can spend ‘looking out’ (the best collision reducer)” (Ford, 2002, p. 129).

Highway on the Sea (HOTS), 2003

At the Aalesund University College in Norway, Ove Bjørneseth conducted a study on what he called *highway on the sea* (HOTS) that was published in 2003. (Bjorneseth, 2003) The study was based on the

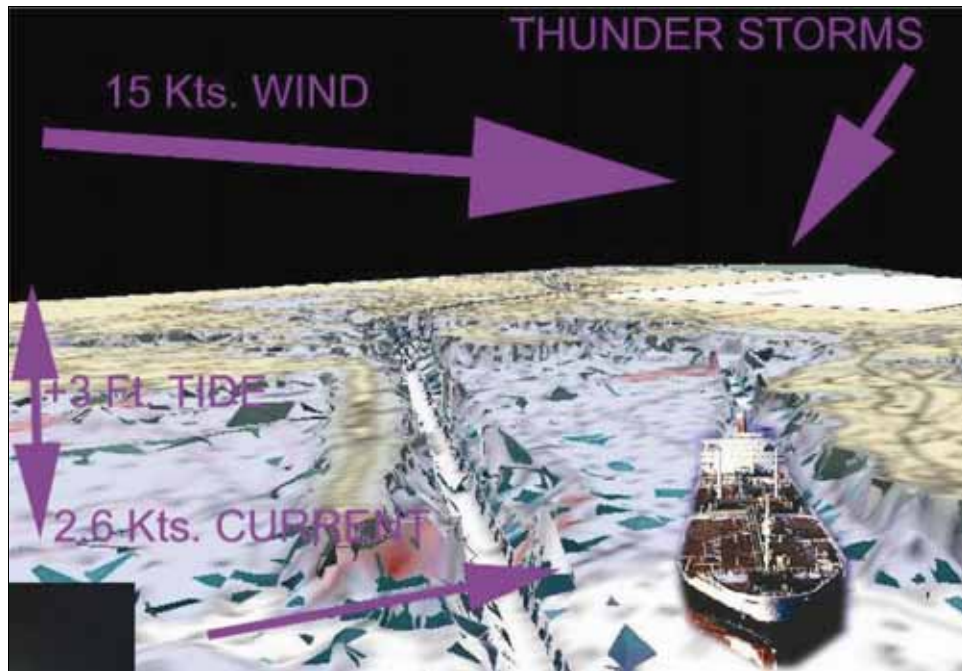


Figure 41. A portion of a 3-D nautical chart of the Buzzards Bay exit of the Cape Cod Canal overlain with planned parameters for an extension of the 3-D chart. (© Ford, <http://gis.esri.com/library/userconf/proc00/professional/papers/PAP199/p199.htm>)

aviation concept of *tunnel-in-the-sky* and aimed at improving the situation awareness of bridge crews of high speed craft (HSC) in poor visibility conditions.

Bjørneseth compares low-visibility navigation of a HSC in the confined waters of the Norwegian archipelago with a continuous poor visibility landing phase of an airplane (p. 1). As a result of several high speed craft accidents in Norway that have taken place during low-visibility conditions, Bjørneseth concludes that “the instrumentation in common use today are not adequate or too time-consuming to operate taking into account the speed the HSC’s operate under” (p. 2).

Bjørneseth uses the analogy of conventional automobile highways and suggests that information about the ships own track is projected on an HUD display in front of the driver. In Figure 42 the suggested synthetic information to be projected is shown and in Figure 43 a simulation of the combined effect of the synthetic information and the real world can be seen.

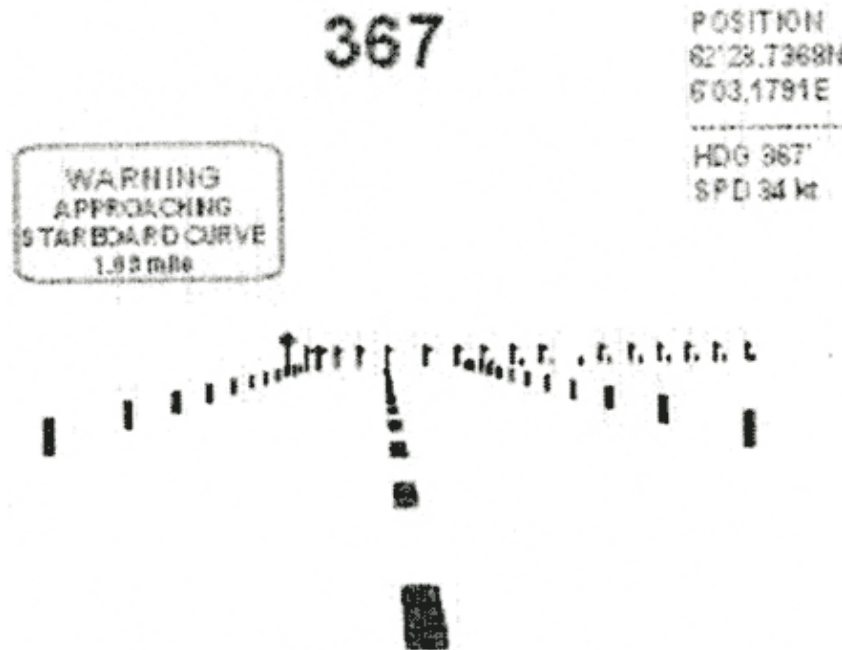


Figure 42. Highway of the Sea (HOTS). Synthetic information about ships track, optimal center line, edge markings and virtual billboards, projected on the windscreen in front of the driver. The combined effect with the exterior terrain can be seen in the next figure. (Bjørneseth, 2003, p. 4)



Figure 43. Highway of the Sea (HOTS). The synthetic information from the previous figure projected on the windscreen in front of the driver in combination with the exterior terrain. (Bjørneseth, 2003, p. 5)

The center line of the virtual road shows the optimal track of the ship and the edge markings the maximum off track limit. This notion is not equivalent to the highway centerline which divides the road into two lanes for traffic in opposite directions. On straight legs the edge markings are simple and in curves they carry a small “flag” pointing in the direction of the curve. Billboard warning of an approaching curve can be seen in the figures above.

Bjørneseth also suggests the display of scene-enhancements, such as 3D-terrain, virtual navigational lights and the graphical outline of ships that may be invisible in the real world due to low-visibility (p. 3). Sound and voice warnings are also suggested.

NOAA and USGS Work on a Common Datum Standard

Since 2001 the U.S. National Oceanic & Atmospheric Administration’s (NOAA) National Ocean Service and the U.S. Geological Survey (USGS) have in a joint research project merged bathymetric and topographic data into a digital elevation model (DEM) over the Tampa Bay area in

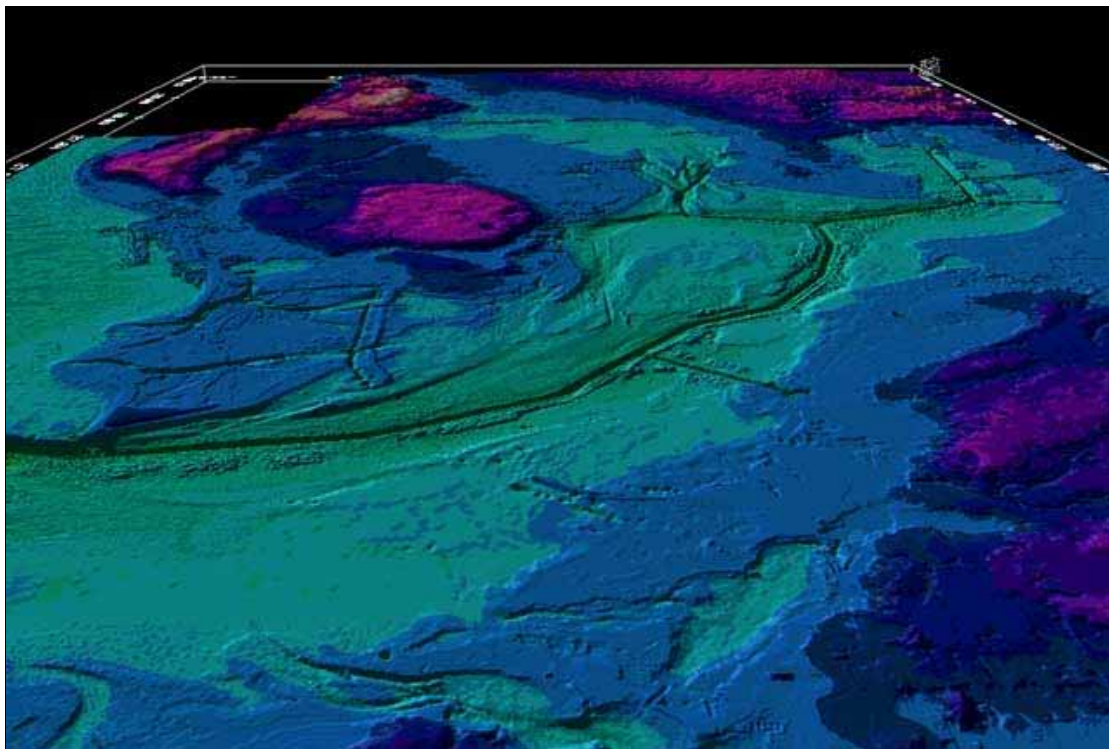


Figure 44. Isometric view of the DEM made from merged bathymetrical and topographical data of the Tampa Bay area in western Florida, looking north. Picture from the joint NOAA/USGS project. (NOAA/USGA, 2005)

Florida. (NOAA/USGS, 2005) The problem is dense since there by tradition different vertical map data have been used by land and bathymetrical survey. Important is also the work on a common shore line definition, particularly in areas affected by tidal water (more on this subject can be found in appendix D, Reference Systems). The Tampa Bay project can be studied on <http://nauticalcharts.noaa.gov/bathytopo> (See Figure 44.)

Commercial Applications

On the commercial scene several examples of 3-D charts have appeared during the last years. Some only show the underwater topography, but the most recent ones also show the topography of the land areas. They all seem to be based on the technique of “peeling off” the water and show the bottom topography. Some show the position of the own ship in the map and some do not. The problem of showing the position of the ship in an unambiguous way is in some cases solved with *drop-lines*, a vertical vector between the boat symbol and the bottom.

Beneath are some uncommented examples of recent commercial applications.

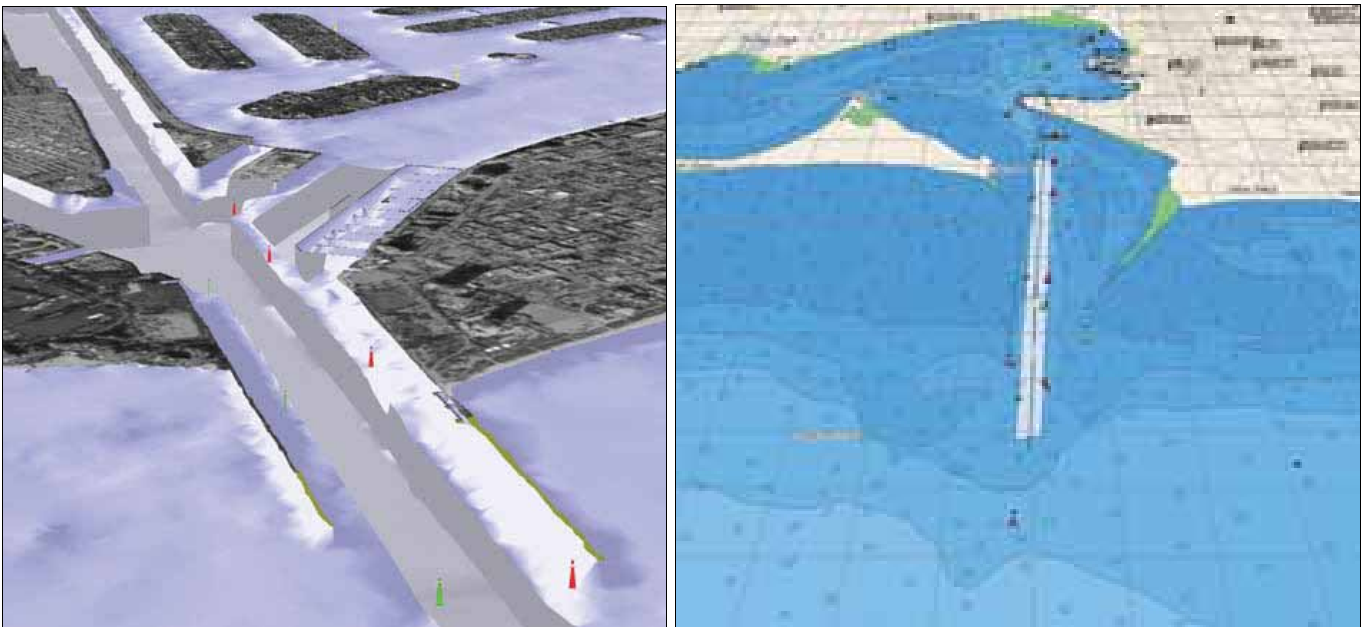


Figure 45. In 2005 C-Map introduced the new Max chart format which includes 3-D and perspective views. (Company screen shots from <http://www.maxnavigator.com/index.html>, [2006, January].)



Figure 46. In 2005 Navtronics Platinum 3-D mode on a Raymarine chart plotter. (Company screen shot from <http://www.raymarine.com>, [2006, January].)

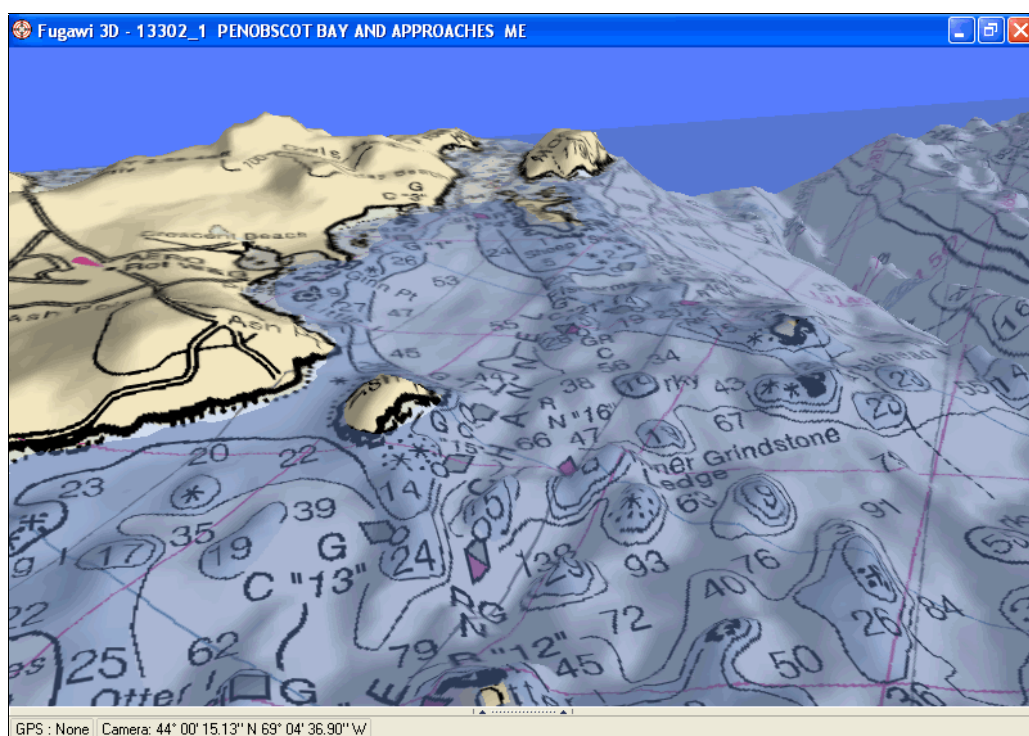


Figure 47. Fugawi marine ENC with 3-D data for the U.S. (Company screen shot from <http://www.fugawi.com/docs/marineenc.html>, [2006, January].)

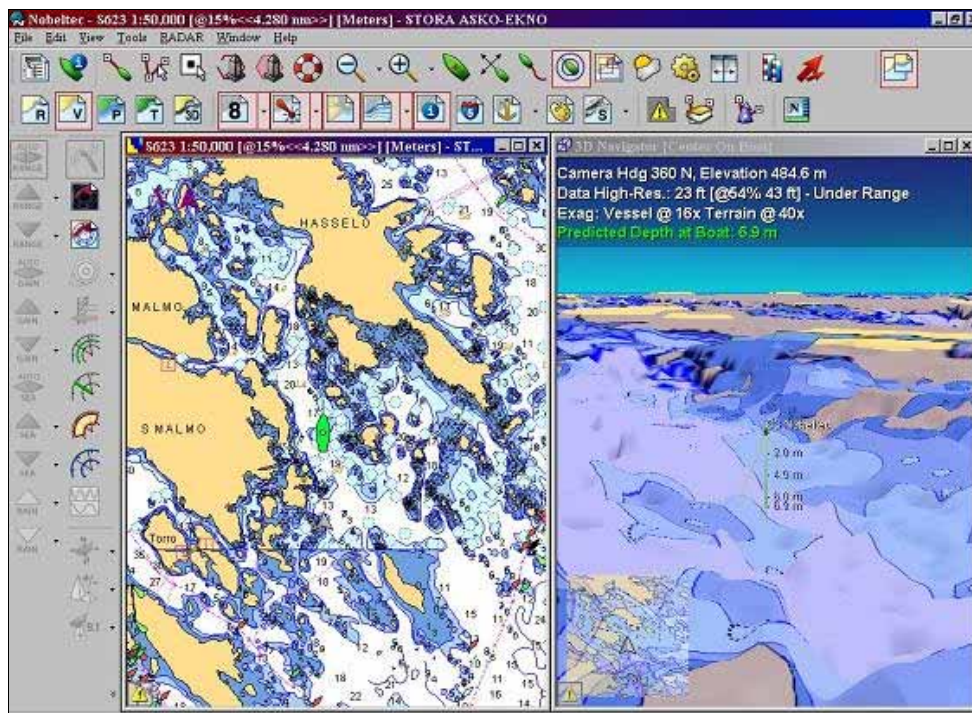


Figure 48. Nobeltec Admiral 8.1 with a traditional and a 3-D view. (Company screen shot from <http://www.nobeltec.se/>, [2006, January].)

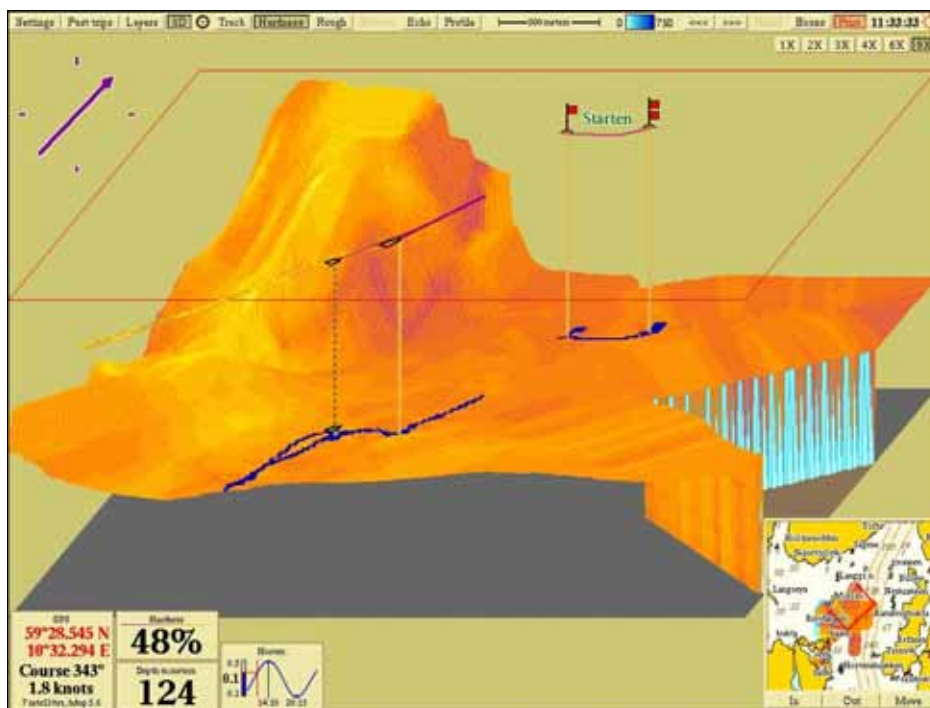


Figure 49. The Norwegian Olex system for navigation, plotting and sea floor charting. (Company screen shot from <http://www.olex.no>, [2006, January].)

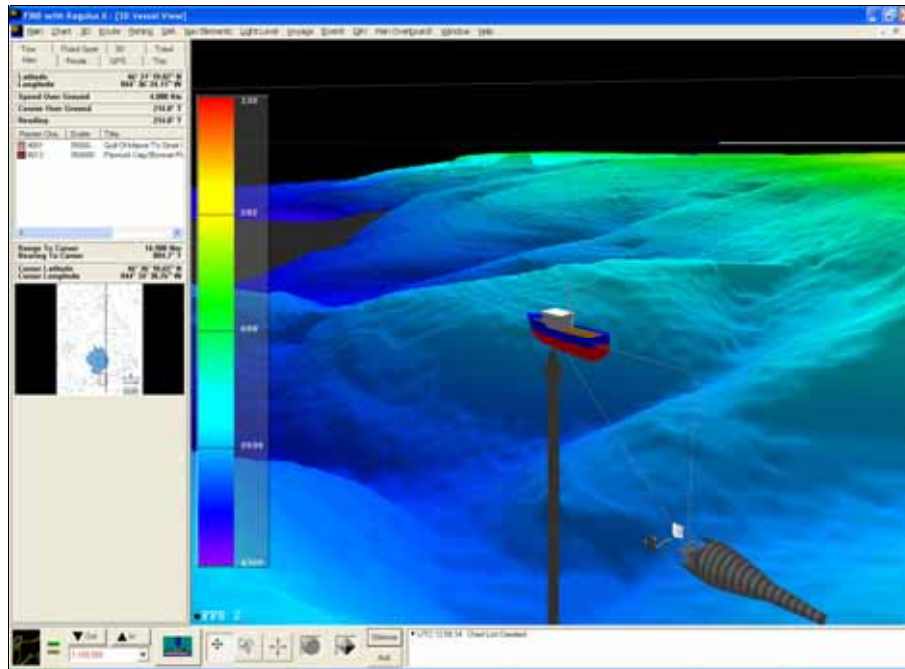


Figure 50. The Fishing Information & Navigation System (FINS) from Canadian ICAN shows the own ship and fishing equipment. A drop-line is used to show position in the 3-D view. (Company screen shot from <http://www.icanmarine.com/FINS.htm>, [2006, January].)

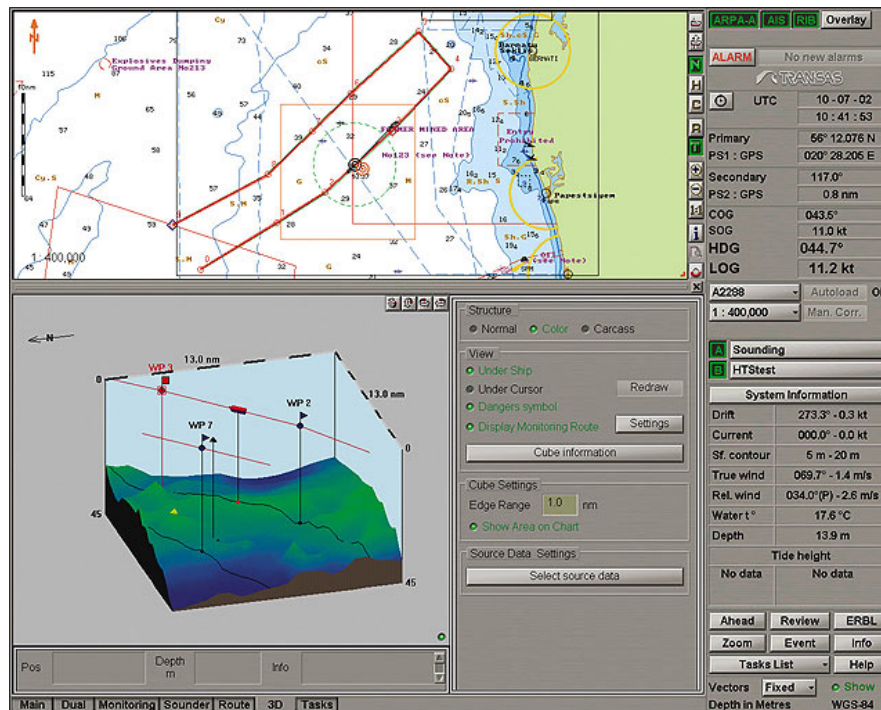


Figure 51. Chart and 3-D view from the Transas Navi-Fisher 300. (Company screen shot from <http://www.transas.com>, [2006, January].)

Chapter 3

A Laboratory Experiment

This chapter presents the laboratory experiment conducted to test the hypothesis that the 3-D chart was better (faster decision-making and less errors) than traditional map types. Forty-five subjects tested four different types of maps and the results were very promising.

3.1 Purpose

The purpose in this experiment was to test my first research question, which now becomes the hypothesis that navigating in an egocentric frame of reference is more efficient (faster, due to quicker decision making, and less errors) than traditional methods such as electronic maps in head-up or north-up modes or traditional paper maps. A small laboratory maze mimicking the confined waters of an archipelago was used to test the hypothesis.

The alternative would have been a field experiment in a real world archipelago. It would enable me to test other important features of a 3-D chart, such as the ability to see the topography of the islands and thus compare map and real world during day-time, and to keep an updated and correct cognitive model during night and low visibility. A field study would provide the full context of the navigation task as required by Hutchins, as mentioned in the previous chapter. A downside would be that not all environmental factors, such as weather and traffic, could be fully controlled.

The obvious benefit of a laboratory setting would of course be that the environment could be totally controlled and kept the same for all test subjects and hopefully the central hypothesis could be tested equally well. The tracking system used as an indoor GPS system would also allow higher frequency and accuracy in the positioning than the real GPS, thus freeing me from the need of an inertial navigation system (INS).

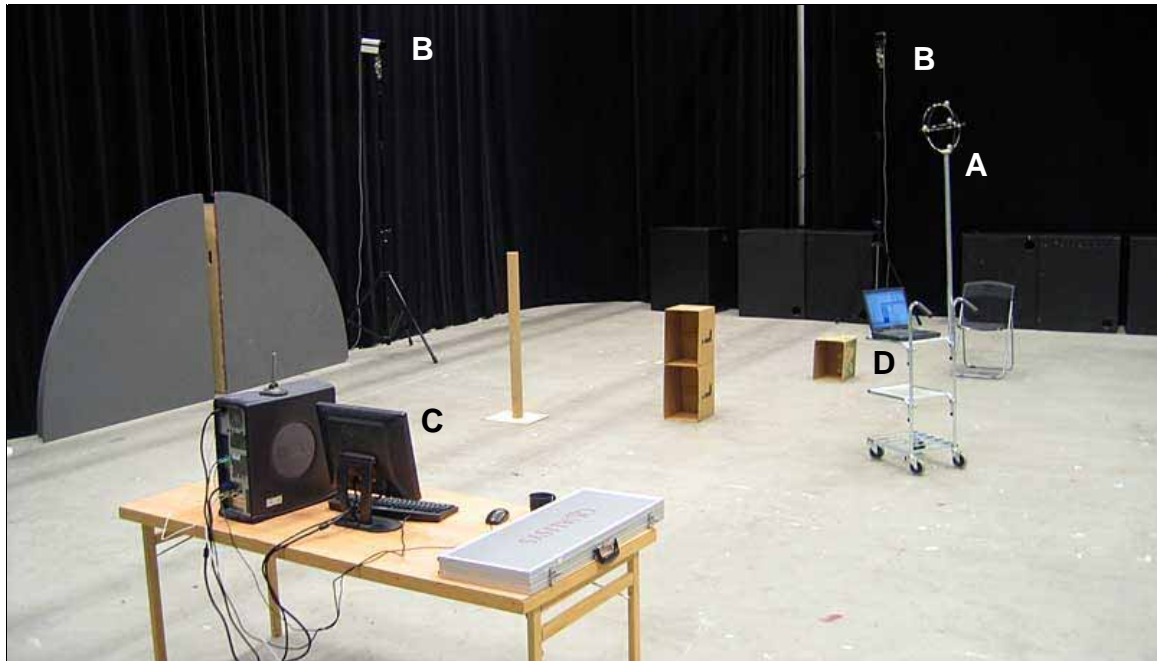


Figure 52. The studio setting. Four reflective balls mounted on the mast of a cart (A) were measured by two infrared cameras (B). The picture from these two cameras was then sent to a computer calculating the position of the cart (C). From the calculation computer coordinates were sent in real-time with a frequency of 50 Hz by wireless LAN to the laptop computer on the cart (D).

3.2 Experimental Setting

The laboratory archipelago was constructed in a studio setting as can be seen in Figure 52. The studio used was a naked room with concrete floor measuring 13 by 15 meters and normally used by the information scenographers at our department.

The Boat

As a boat a small four-wheeled cart covering a ground plane of 0.45 by 0.38 meter was used. All four wheels could rotate, making the cart easy to maneuver – but it would also easily slide while turning if the test subject was not careful. The cart had a shelf where a portable computer was fitted. The computer ran on batteries so no cords had to be attached to the cart during the experiment. The computer was fitted with a custom made real-time 3-D software application (EON Studio Professional 5.2) that was used to show both the 3-D egocentric chart and the 2-D exocentric north-up and head-up charts. The application was also used to monitor and log time on track and the number of “groundings” made by the subject. Coordinates (x, y, z, heading, roll and pitch) were sent from the tracking system to the lap top by wireless LAN.

The Archipelago

As an archipelago a 6 by 6 meters square was marked with tape on the floor in a corner of the studio. The square was divided into an invisible grid, 10 by 10 grid squares. Four landmarks in the form of one double and one single cardboard box, one paper cylinder and one chair were placed in the area to serve as reference points. Four different archipelagos were designed and one conventional 2-D map and one 3-D model for each archipelago were constructed. Figure 53 shows one of the archipelagos with its respective maps.

The four archipelagos were constructed in the same grid. Each archipelago consisted of deep-water areas where passage was possible and shallow-water areas where a “grounding” was recorded. The deep-water areas had a light (yellow or brownish) color on the maps and the shallow areas had a darker red or brown color. It was possible to navigate through each archipelago along a track of deep water from a “start” position to an “exit”. There was only one track through the maze so no choices had to be made which way to go. Each track through the archipelagos was of about the same length and with about the same amount of turns in different directions. The four archipelagos were named track 1 to 4. In Figure 54 the four tracks can be seen.

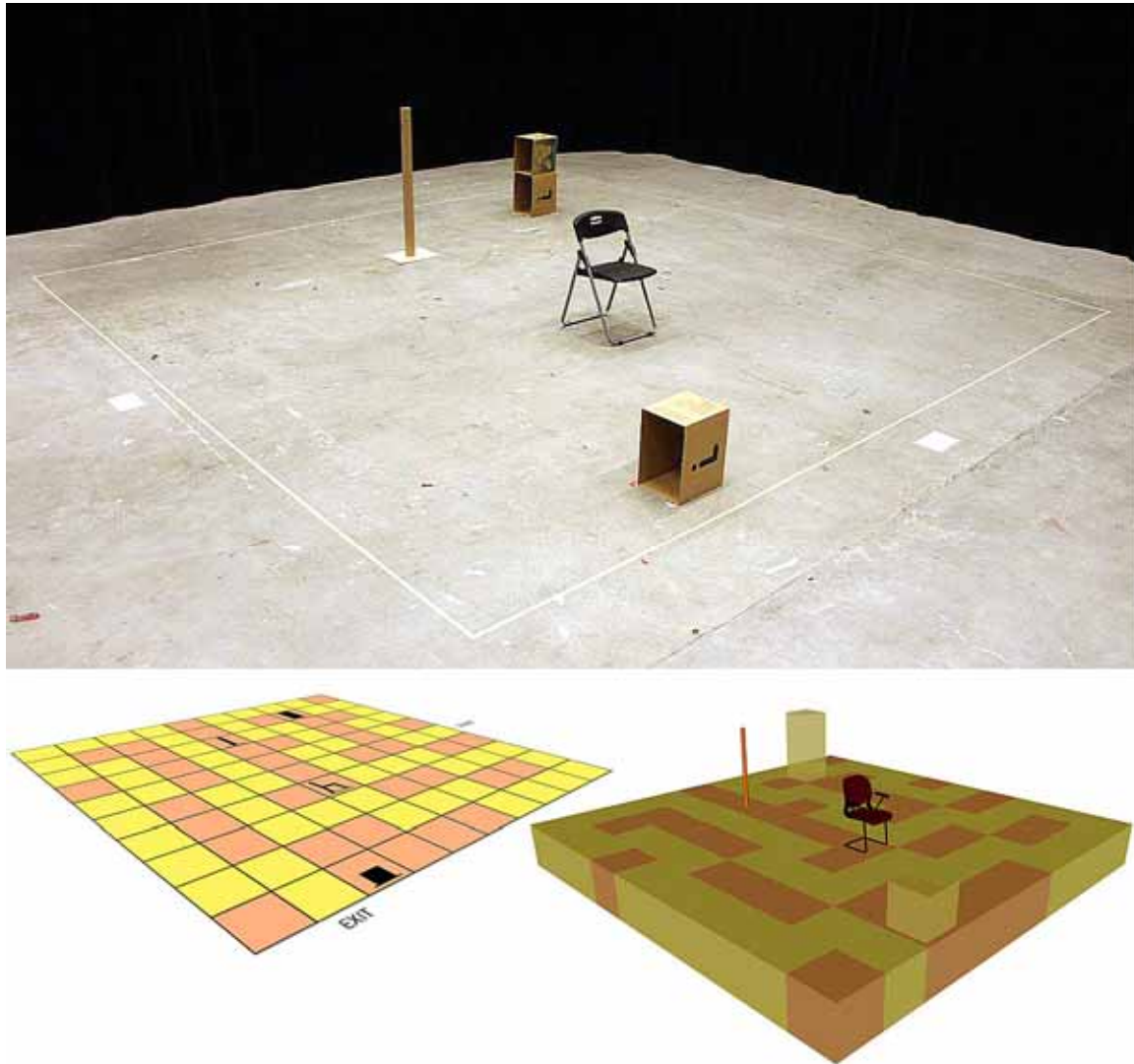


Figure 53. Top, the laboratory archipelago (here “Track 2”), a 6 by 6 meters area with four landmarks. Bottom left, the 2-D map of the same area and bottom right, the 3-D map. The darker areas on the maps depict “shallow water” where a “grounding” is recorded.

The “north” (map up) direction vis-à-vis the studio was also rotated and different in the four tracks.

Randomization of What Map Type on Which Track

The subjects always used the four different tracks from 1 to 4 in that order, but the map type used for each track was randomized. A person beforehand picked one of four Lego pieces out of a bowl without seeing

which piece she picked. The pieces were marked with “3-D”, “Head-up”, “North-up” or “Paper map”. The person continued to pick the pieces until the bowl was empty to complete the round. The procedure was repeated for every subject. Randomization worked which is showed by calculating the mean values of track numbers for each map type which is, for the paper map 2.60, the north-up map 2.38, the head-up map 2.53 and the 3-D map 2.44. The ideal value would be 2.50. The exact outcome can be studied in the complete experiment record in appendix B.

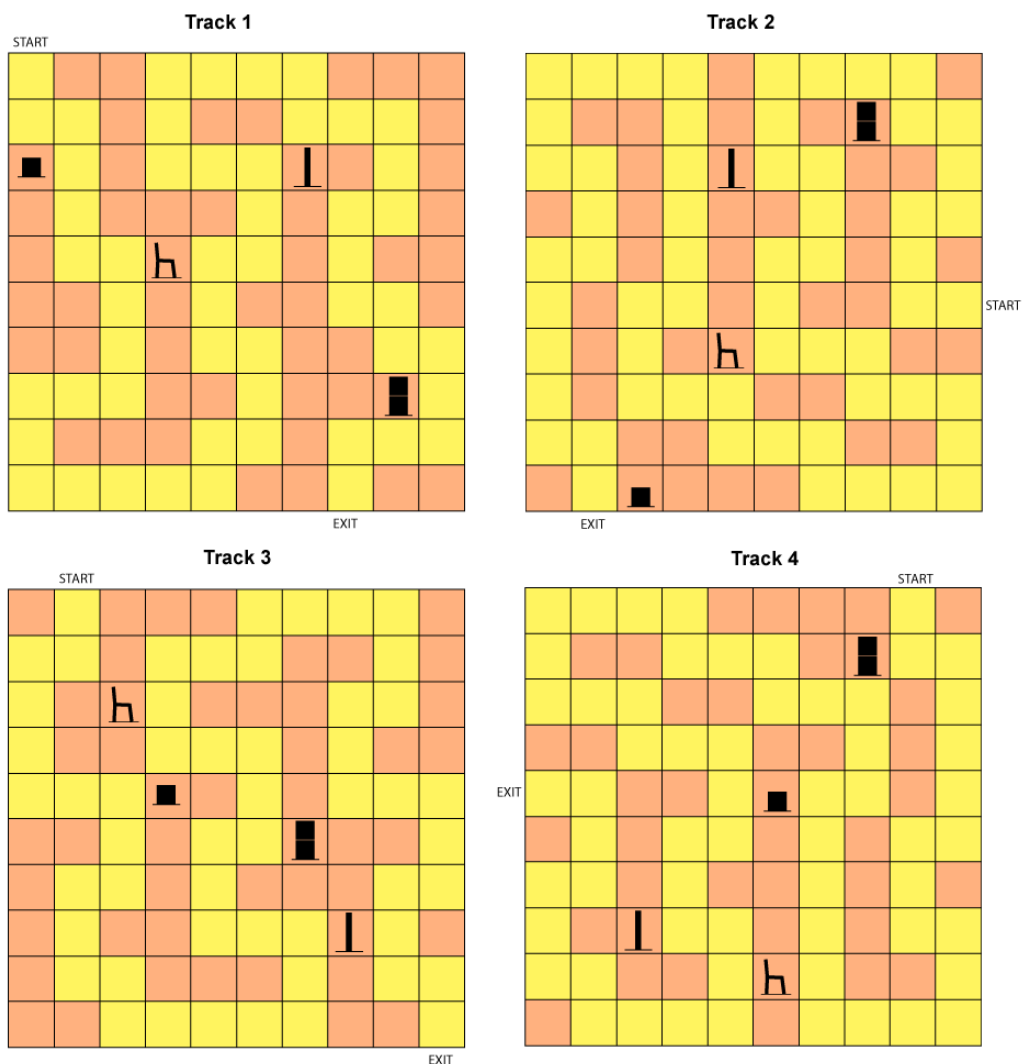


Figure 54. The design of the four different tracks used. Each of them has about the same length and about the same amount of turns in different directions. The order in which each test person used the different reference frames on the four tracks was randomized.

The Tracking System

Because the GPS navigator cannot pick up the satellite signal indoors an alternative positioning system had to be used. I had some difficulty finding a tracking system that would allow me to track the movements of the cart over such a wide area as I required. The most common tracking systems are used to track the movements of a head mounted display (HMD) and are restricted to a smaller area, typically 2 by 2 meters.

Different techniques are used by different systems. Some use electro-magnetic field to track movement. Such systems can not be used with any metal gear like the cart I used. Some use infrared light and some even ultrasound.

Finally, I managed to find a Swedish system from Qualisys Medical in Gothenburg. They manufacture a system that can track wide areas with the help of several infrared emitting and receiving cameras. The system was designed to track the movements of ship models in large wave tanks, used in hydrodynamic research, and the system can also be used for motion capture used to transfer movements of humans to animated 3-D models, or to study the movement of, for example, the human body. In the first case the movement of one body was recorded with all six degrees of freedom (x, y, z, heading, roll and pitch), in the latter cases the movements of several reflectors attached to the human body were recorded with three degrees of freedom (x, y and z).



Figure 55. The cart with the “antenna” of four reflective pebbles and the centre of the local coordinate system visualized by the pen at the bottom of the cart. Photo by Emilie Porathe.

Originally, I intended the tracked area to be 10 by 10 meters, but it turned out the cameras did not have the wide-angle lenses necessary to cover the whole area so the archipelago had to be scaled down to 6 by 6 meters.

The “antenna” on the cart was a metal globe fitted with four light pebbles with a diameter of 0.03 meter. The pebbles were covered with a reflective material and thus reflecting the infrared light from the cameras.

Two cameras were used which was the minimum configuration. Each camera detected a 2-D picture of the reflector device and sent that on to a computer running the Qualisys Track Manager (QTM) 1.7 software.

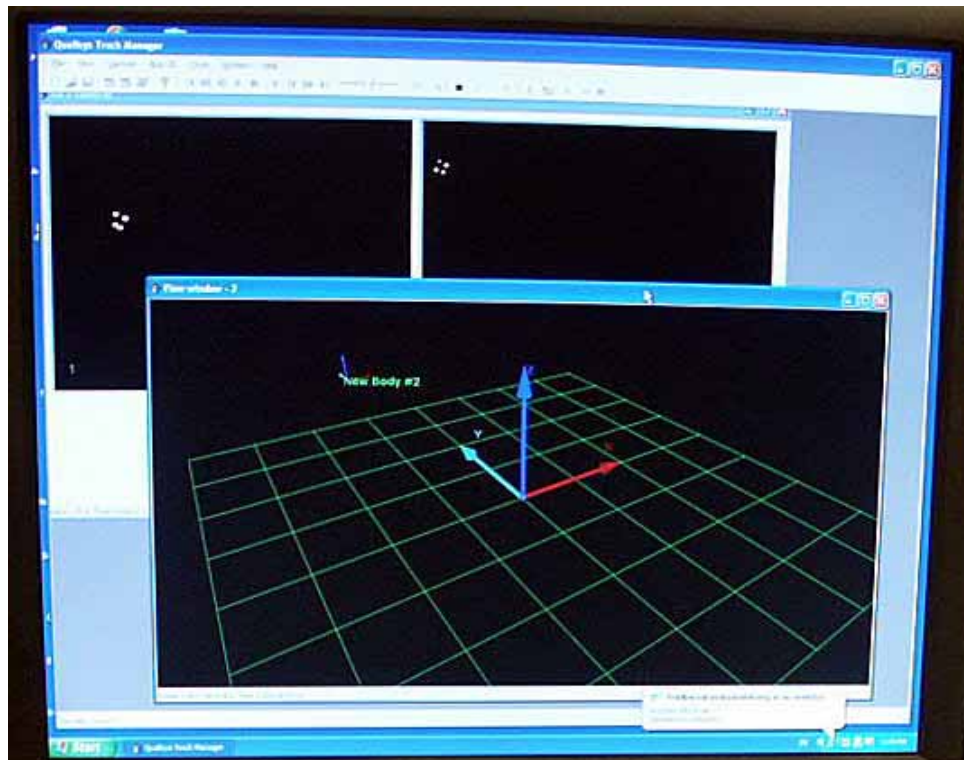


Figure 56. A screen dump from the Qualisys Track Manager software. The 2-D views from the two cameras can be seen in the windows in the background. In the 3-D window the centre of the reference system can be seen in the middle and the local coordinate system of the cart in the back.

Calibration

At the beginning of every session the system first had to be calibrated. The cameras were mounted and four small reflectors were placed in the corners of the measurement area to ascertain that both cameras could see the whole area.

Then a calibration device with four reflectors was placed in one corner of the square so as to act as the center of the reference system to be defined. During the 30 seconds calibration period a wand, also with reflectors, was moved around in the area. With the help of the pictures from the two cameras the QTM software defined the 3-D reference space in which the movement of the cart was to be measured.

Once the calibration was done the calibration device and the wand were removed.

The antenna with the four reflective pebbles also had to be calibrated to establish the local coordinate system of the cart. The center of the local cart system was placed on the floor with $x = 0$ and $y = 0$ at the tip of a pen taped on to the bottom of the cart. See Figure 55.

The accuracy of the system was high. By driving the cart along the tape marking the outer border of the measuring area the accuracy was estimated to better than 3 cm.

Because the minimum configuration with only two cameras was used and the system needed both cameras to see all four reflectors the whole time to calculate a 3-D position, there were some difficulties at the beginning getting the system to work properly. A third camera might have been useful. Now I had to try several camera placements before the system would work without dropouts. At rare occasions the system failed in detecting a position because one reflector became shaded by one of the other reflectors, causing a temporary freeze of the vehicle or causing it to vibrate approximately 10 cm back and forth and on some very rare occasion this vibration might have affected the results by causing an extra “grounding.”

The update frequency of the tracking system was set to 50 Hz.

The Experiment Application

A custom software application was designed to display the 3-D egocentric map and the 2-D exocentric maps run in head-up and north-up modes. The application was also logging the experiment starting a clock on entering the track and stopping the clock on leaving the track at the exit position. The groundings were also recorded during the test.

The application was built using EON Studio 5.2, a real-time 3-D software. The 3-D model of the archipelago was constructed from 100 cubes representing the grid. Dark brown cubes represented the shallow water and light brown cubes represented the deep. All cubes were fitted with collision detection acting on a tall green rod representing the center of the cart and guided by positions from the tracking system. When the rod entered into a deep water cube this changed color from

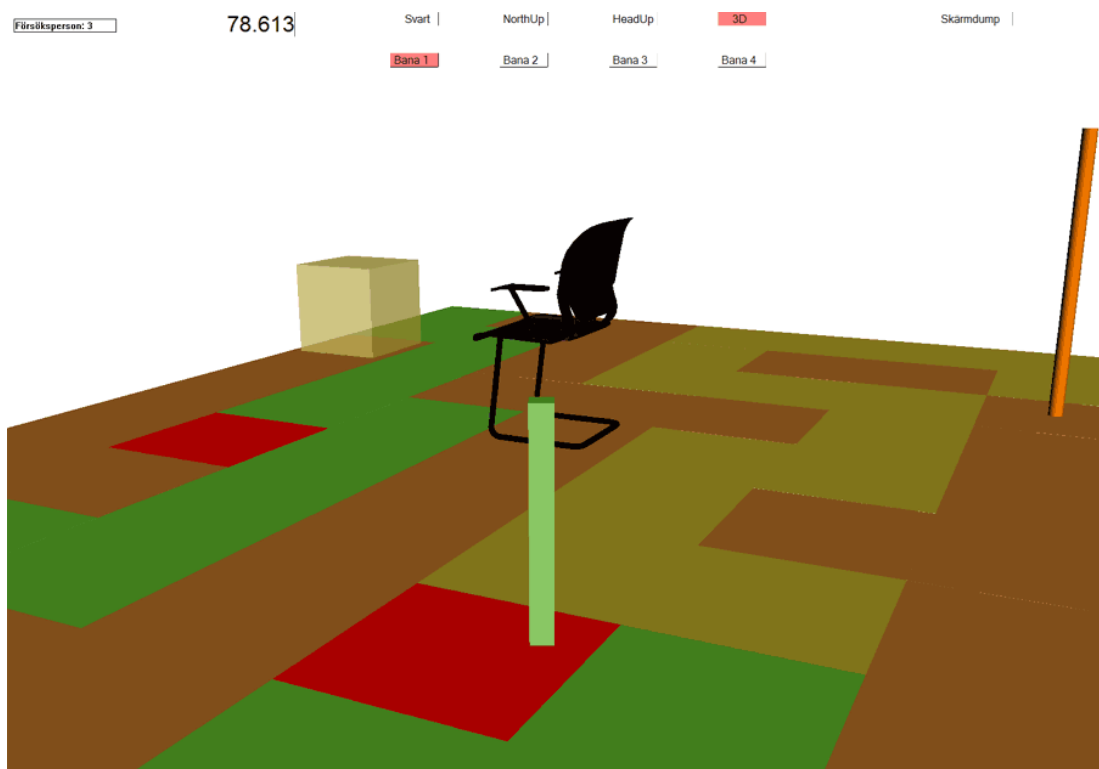


Figure 57. A screen dump from the test application. At the top of the screen from left: Subject number, timer, and then buttons to choose map types in the upper line and track numbers in the line below. To the far right the screen dump button. Tracking and error logging were made by colouring the cubes of the grid. The cart was represented by the moving green rod connected to the tracking system. A “grounding” resulted in a red cube and an alarm sounding. The test subject was then stopped and had to back off from the ground.

light brown to green, thus marking a track behind the cart. When the rod entered into a shallow water cube the cube changed color from dark brown to red and a sound alarm went off notifying the test subject that they had ran aground.

The egocentric camera in the 3-D view was actually a tethered camera looking from some where “over the shoulder” of the test person. The subject was instructed to regard the green rod as the center of the cart. The ground plane size of the rod was about 0.05 by 0.05 meter. Each grid square was 0.6 by 0.6 meter leaving the cart some 0.27 meter on either side of the centerline of the track as a clearing before running aground (see Figure 57).

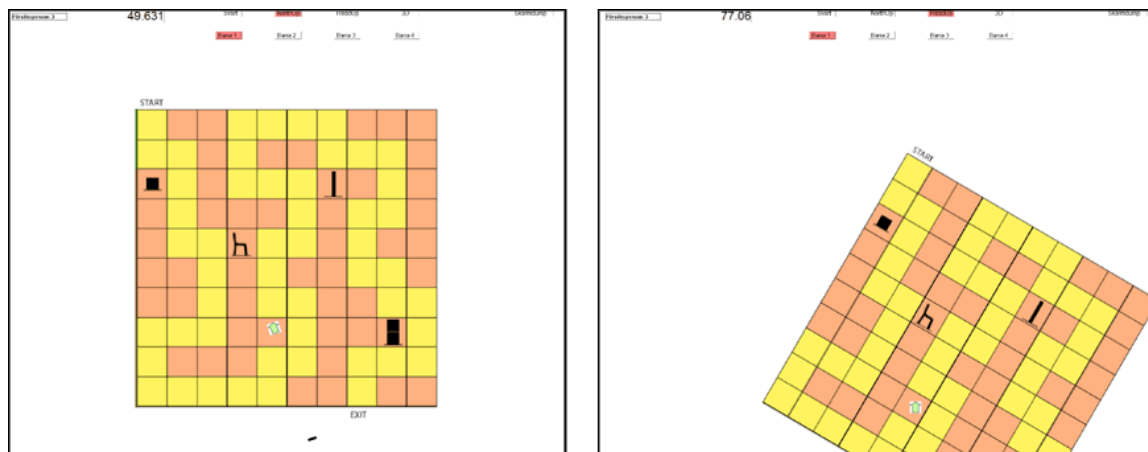


Figure 58. The 2-D map in the experiment application. Left the fixed north-up map, with the small green arrow depicting the current position, and right the head-up map where the arrow is fixed in the lower central part of the frame while the map is moved and rotated.

The application could also display the 2-D map from both an exocentric north-up and head-up frame of reference (see Figure 58).

The north-up map was fixed in the middle of the screen and the position of the cart was depicted by a moving green arrow. In the head-up map the green arrow was fixed in the central lower part of the screen while the map was moving and rotating.

During the test with the traditional paper map the application showed a black screen while actually recording the session in the same way as all the others and sounding the alarm when the cart went aground.

Logging

Logging of each test was done by saving a screen dump of the 3-D map. See Figure 59 for an example of such a screen dump. On the screen dump the settings of the test (track number, frame of reference, test person number, time and the amount of groundings) could be seen. Completed track could be identified by the yellow grid cubes having turned to a green color. The number of groundings was defined by the number of dark grid cubes colored red. Because the track sometimes passed a ground on the other side there was a possibility that a grounding could occur on that same cube more than once. In this case only one grounding was recorded. This was very rare. Having observed all the experiment sessions it is my impression that this was not a source of significant error.



Figure 59. Example of a screen dump used to record the experiment. Top left the line the number of the test person, next is the time on track in seconds. Next section top line registers the map type (*Svart* - black - is the traditional paper map) and below the number of the track: *Bana 1* (Track 2). To the far right is the button setting the display in the screen dump position depicted here.

Before the testing started each subject did a practice to make sure s/he know what to do, then the four tests were made with the four different map types. During the practice and the experiment comments made by the subjects about the navigation were recorded by the research assistant.

Spatial Test

Finally the subjects were asked to take a psychological spatial test. The test was “Figure rotations” and was a part of the *DS-Batteriet*, a standardized test published by Psykologiförlaget AB. The test consisted of 20 questions. Each question consisted of a reference figure placed to the far left on the line. To the right were 6 other figures. These were

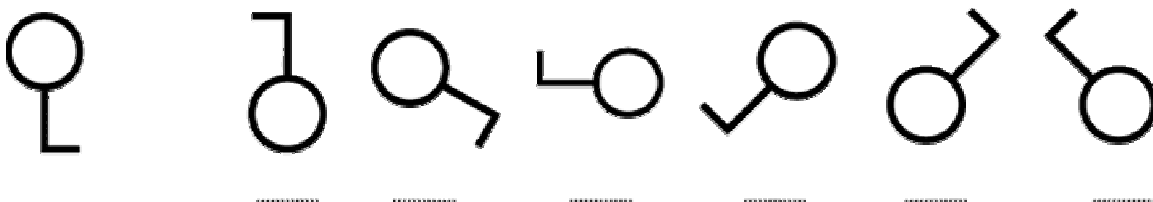


Figure 60. Example of the figure rotation test used to test the subject for spatial ability. The figure to the far left is the reference figure. The subjects are then to judge which of the six rightmost figures are the same as the reference figure, only rotated. Some of these figures are not only rotated, they are also mirrored and therefore not the same.

either the same figure as the one to the left but rotated, or a mirrored and rotated figure. The test subject was to put an “x” under the figures that were the same as the one to the left, only rotated (see Figure 60).

These 20 questions were to be answered within 7 minutes. The purpose of asking the subjects to do a spatial test was to find out whether there was a correlation between the ability to do mental rotations of figures and the results of the driving tests with different map types. See the section on reliability and validity at the end of this chapter.

Another benefit was that the spatial test was standardized. The standardization was made in 1954 on a random sample in the ages from 15 – 64 from a rural population. The sample structure was by then judged to be representative for a population from the middle of

Sweden. The raw score in the test has then been transformed into a *stanine* scale, that is a standard scale with 9 grades, mean value is 5, containing 20 % of the standardization group, 4 and 6 contains 14 % each, 3 and 7 12 % each, 2 and 8, 7 % each and finally 1 and 9, 4 % of the standardization group each. The table used to transform raw points into the stanine value showed that allowance was made for gender and age so that a raw point of 39 gave a male subject between 15 – 19 a stanine value of 5, while a female subject of the same age got the value 6; in the age group between 55 – 64 the same raw point gave both male and female subjects a stanine value of 6.

It was obvious that in the standardization group spatial ability had declined with age and also that female subjects had scored less than male. These discrepancies were then normalized through the standardization procedure. The ability to make mental rotations of imagery is slowing down in old age which was shown by Dror and Kosslyn (1994). Sex differences in spatial ability are much discussed but a number of studies show male advantage at spatial tests. The reasons can be many and are discussed by Diane F. Halpern in *Sex Differences in Cognitive Abilities* (2000).

In the years 1956-66 the scale was compared to a group of academic students and the mean value for the academic group was 6 on the scale standardized with the rural group. (Psykologiförlaget, 1971)

Interviews

The subjects were also asked whether they considered themselves as having a good or a poor sense of direction. Their answer was classified and parameterized to 1 for “poor” and “2” for “good”. Their experience with maps was documented on the questionnaire (see appendix B) and was later classified and parameterized to 1 for “little”, 2 for “average” and 3 for “large.” Large meant that they had been active in orienteering sports or had a large experience with navigating boats of their own. One of the subjects was a trained navy corvette navigator. The subjects’ gender and age were also recorded.

Then they had to fill in a form to rank the four different frames of references in the experiment in order of user-friendliness, where 1

would be the easiest one to use and 4 the most difficult one. They had to make one choice, no two equally difficult rankings were allowed.

In summary, we have a number of independent variables: map type, experience, gender, age, self taxed sense of direction and scores on the figure rotation test. We also have a number of dependent variables, time-on-track, number-of-groundings and user-friendliness. For a summary see Table 1.

Test Subjects

45 subjects were randomly picked from a population of available students, teachers and staff at my department at the university and also some “outsiders” (a wife, a daughter, a husband and a boyfriend). By “random” I here mean that there was no system in how they were chosen. My research assistant and I asked in different classes and went down the corridor asking employees. We tried to get subjects of varying ages and also as many female as male ones, but we found it difficult to

Table 1. Summary over recorded variables

Independent variable	Dependent variables
Map types (Paper, North-up, Head-up, 3-D)	Time-on-track
Gender	Number-of-groundings
Age	Subjective ranking of user-friendliness
Navigational experience	
Self taxed sense of direction	
Score on figure rotation test	

get female students to volunteer while having to reject male students who wanted to do the experiment. The result was a group of 45 subjects, 24 male and 21 female. Ages varied from 16 to 63, with the

majority in ages 20-30. The variables can be studied in the complete test records in appendix B.

Instructions to the Test Subjects

When entering the studio the test subjects were briefed about the purpose of the experiment. The archipelago with the hidden shoals was explained to them with the help of a map. The function of the cart was explained and that it would stand in as a boat. They were told that their task was to proceed “as quickly as possible with as little grounding as possible” through the track from start to finish. They were also told that several strategies were possible from “quick and sloppy” to “slow and careful”. They were asked to pick a strategy that they felt comfortable with and to keep to the same strategy through out the four tests.

The test subject was then guided through a practice session on a special trial track (actually it was track 4 backwards). During this practice session the display started in a 3-D mode, then automatically switched to head-up, north-up and finally black screen for the paper map test. During this practice I walked along the test person to assist him or her and answering questions. For the paper map trial the subject was told that he or she could handle the map as they preferred, rotating it or keeping it static. When the subject agreed on having understood the process, the session started (see Figure 61).



Figure 61. A subject navigating the laboratory archipelago under supervision of the author. Photo Lisa Gustafsson.

Track 1 was prepared by the research assistant and the laptop computer set to the correct track number and the beforehand randomized map type. The subject could then start when she wanted as the timer started automatically as the cart entered the track. The subjects were allowed but not asked to comment as they went along. Their comments were noted down by me and the assistant. All four driving tests followed in a row with only a minor pause to change the settings of the tracks, save a screen dump and reset the computer.

After the four driving tests a short interview took place. The subjects were asked if they considered themselves as having a good sense of direction or not, and what they understood by the expression “sense of direction”. They were then asked to fill in a ranking form (see Appendix B), to rank the four map types after user-friendliness and also state their experience with maps.

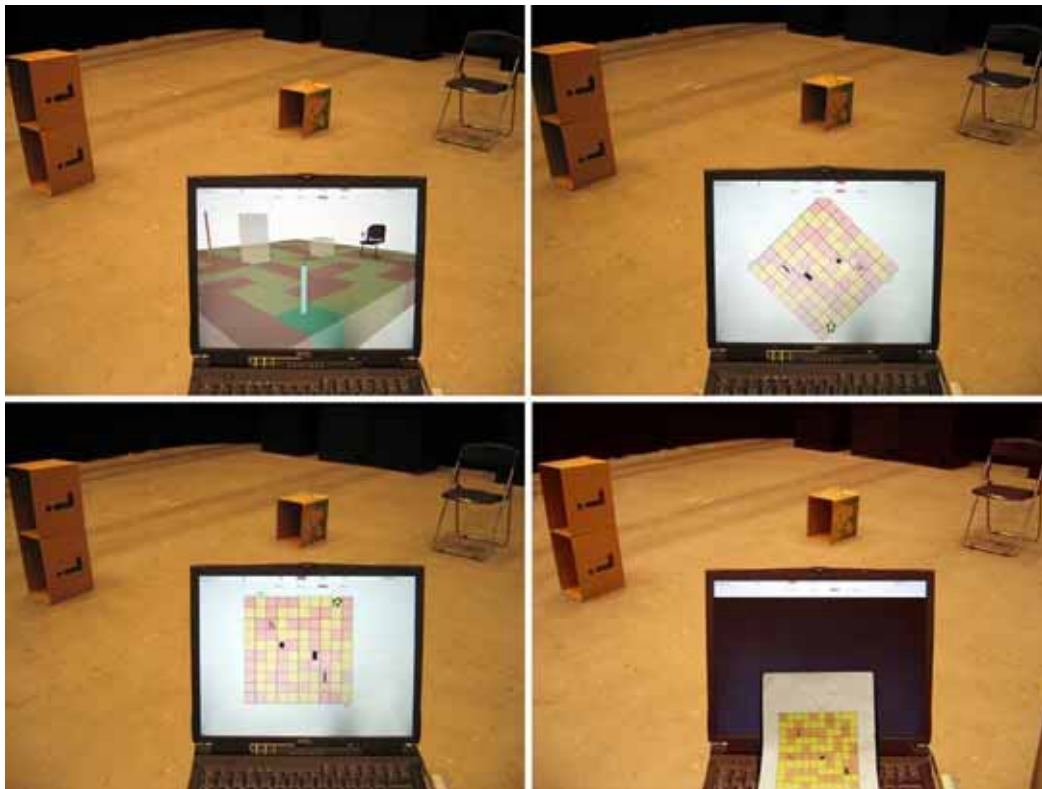


Figure 62. The four different map types. Top left is the 3-D map with the egocentric frame of reference, top right is the 2-D map with the exocentric head-up frame of reference, bottom left is the 2-D map with the exocentric, static north-up frame of reference and bottom right is the black screen used with the traditional paper map. The pictures also show the relationship between the physical landmarks in the archipelago and the different map types.

Finally the subjects were asked to do the spatial test. The test was on one sheet of paper with instructions on one side of the paper and the test on the other side. The subjects were instructed to read the instructions page and ask if anything was unclear. When they agreed to having understood the instructions they were asked to turn the page. They would now have 7 minutes to complete the test with 20 different figure rotation problems. They were alerted at half-time had passed and when there was 30 seconds left. They were also told that they were not allowed to rotate the paper to solve the problems.

3.3 Results

The Main Result

After a series of pre-tests the final experiment was conducted during a five week period in January and February 2005. The 45 subjects were scheduled for an hour each to perform the training and the four experiment tests in the four different archipelagos. Afterwards they answered the questions and did the psychological test.

One of the 45 subjects refused to state age and that subject's results were therefore removed from statistical analyses where age was a factor. The results of another subject were damaged when a screen dump by mistake was saved with only two colors, making it impossible to see the number of groundings. Time on track was fully visible. This person's results were used in the analyses not involving number of groundings. This is the reason why some analyses contain 45 results and some only 44.

The means of all the subject time on track and number of groundings split up per map type are shown in Table 2 and Table 3 and in Figure 63 and Figure 64. The complete test results can be found in Appendix B.

The results show that the use of the 3-D map in an egocentric frame of reference allowed the fastest decision-making with a mean time-on-track for all 45 participants of 111.4 seconds (standard deviation $SD = 42.1$ seconds), the head-up map came second with a mean of 142.1 seconds ($SD = 60.9$), then the north-up map with 167.4 ($SD = 60.0$) and the paper chart with 230.4 seconds ($SD = 105.2$). In this test, decision

making using the north-up map with the position plotted was 1.4 times faster than using a traditional paper map, the head-up map 1.6 times faster and the 3-D map 2.1 times faster than using the paper chart and 1.2 times faster than using the head-up map. Also note that the variability for the 3-D map is smaller.

Table 2. Results of time-on-track

Variable	Mean	SD	Variance	Min.	Max.	N
3-Dmap	111.4	42.1	1768.4	55	230	45
Head-up	142.1	60.9	3706.5	53	406	45
North-up	167.4	60.0	3603.9	71	377	45
Paper map	230.4	105.2	11068.8	77	555	45

Looking at means for the number of groundings gave the same results: use of the 3-D map resulted in the least number of groundings with a mean of 1.7 groundings ($SD = 2.1$) for the whole group of 44, the mean number of errors using the head-up map was 3.6 ($SD = 3.9$), north-up 4.2 ($SD = 4.1$) and the paper map 8.2 ($SD = 5.1$). Navigation using a head-up map resulted in more than twice as many groundings as navigation using the 3-D map, and using a north-up map resulted in two and a half times as many groundings. Using the paper map resulted in almost five times as many groundings as using the 3-D map. It is interesting in this case too, to note that the standard deviation (SD) was smaller using the 3-D map, than using any of the other types.

Table 3. Results of number-of-groundings

Variable	Mean	SD	Variance	Min.	Max.	N
3-Dmap	1.7	2.1	4.5	0	9	44
Head-up	3.6	3.9	15.6	0	19	44
North-up	4.2	4.1	16.8	0	16	44
Paper map	8.2	5.1	25.9	1	20	44

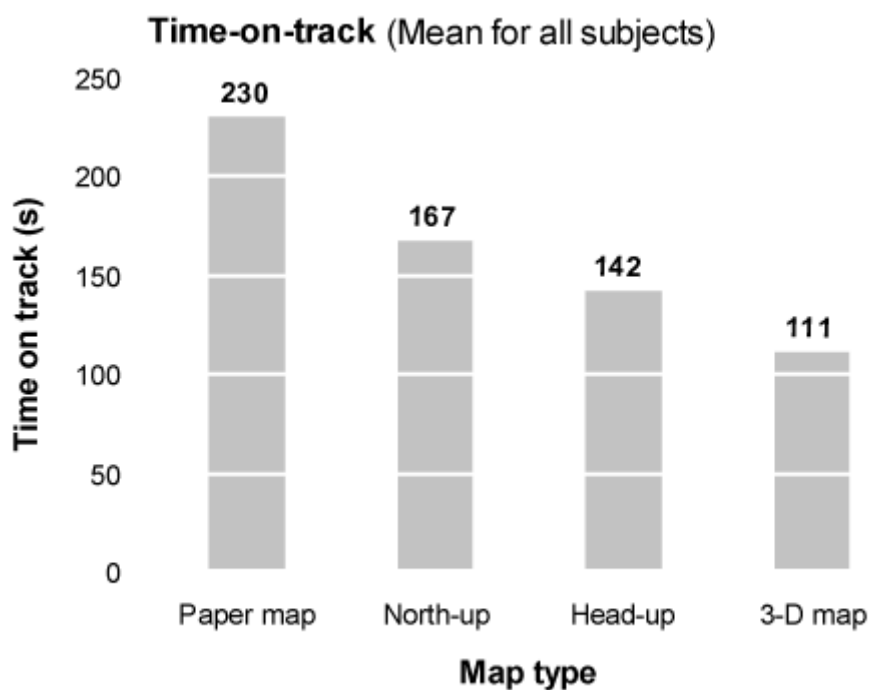


Figure 63. Diagram showing the mean time for all 45 subjects on the four different map types.

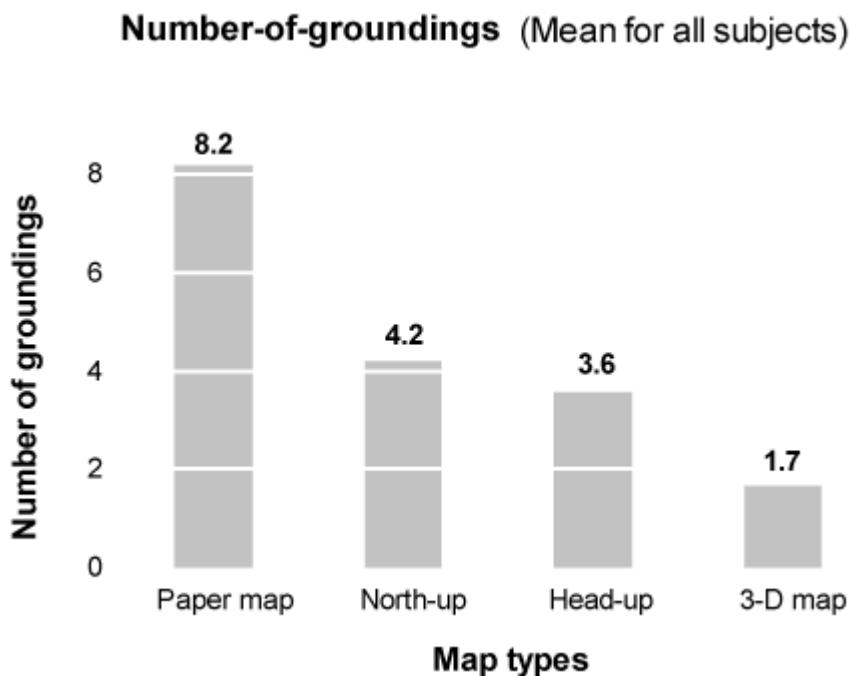


Figure 64. Diagram showing the mean number of “groundings” done by all (in this case 44) subjects for the four different map types.

This looks easy and clear, but the question was now if those figures reflected a real difference or a difference which was the result of chance alone. To answer that I made a two-way analysis of variance (see Table 4).

Table 4. The results of the two-way analyses of the variables map type and test subjects.

ANOVA						
<i>Source of variation</i>	<i>Sum of squares</i>	<i>Degree of freedom</i>	<i>Mean squares</i>	<i>F ratio</i>	<i>P value</i>	<i>F criteria</i>
Subjects	559653.7	44	12719.4	5.136913	1.4820E-13	1.468722
Map type	344764	3	114921.3	46.41262	1.512461E-20	2.673218
Error	326842.5	132	2476.079			
Total	1231260	179				

From the table we can see that the null hypothesis of equal mean population performance for the four types of map types is clearly rejected at the 1 % significance level. ($F_{(3,132,0.01)} = 46.4$, $p < 0.01$). In plain words, the differences in time on track between the map types are statistically significant. The same was true for the number of “groundings”. The influence of the map type on the number of groundings was statistically significant at the 1 % level ($F_{(3,129,0.01)} = 3.94$, $p < 0.01$).

It seems as we could come to the conclusion that in our laboratory archipelago the 3-D map displayed in an egocentric frame of reference is more efficient than 2-D maps in head-up or north-up mode, or a traditional paper map.

Looking on Data in More Detail

Removing Extreme Values

A check was made to find out if extreme values could have anything to do with the results. The two high and two low extreme values based on the time on track for the paper map were removed, i.e. all four results of four subjects. The results shown in Figure 65.

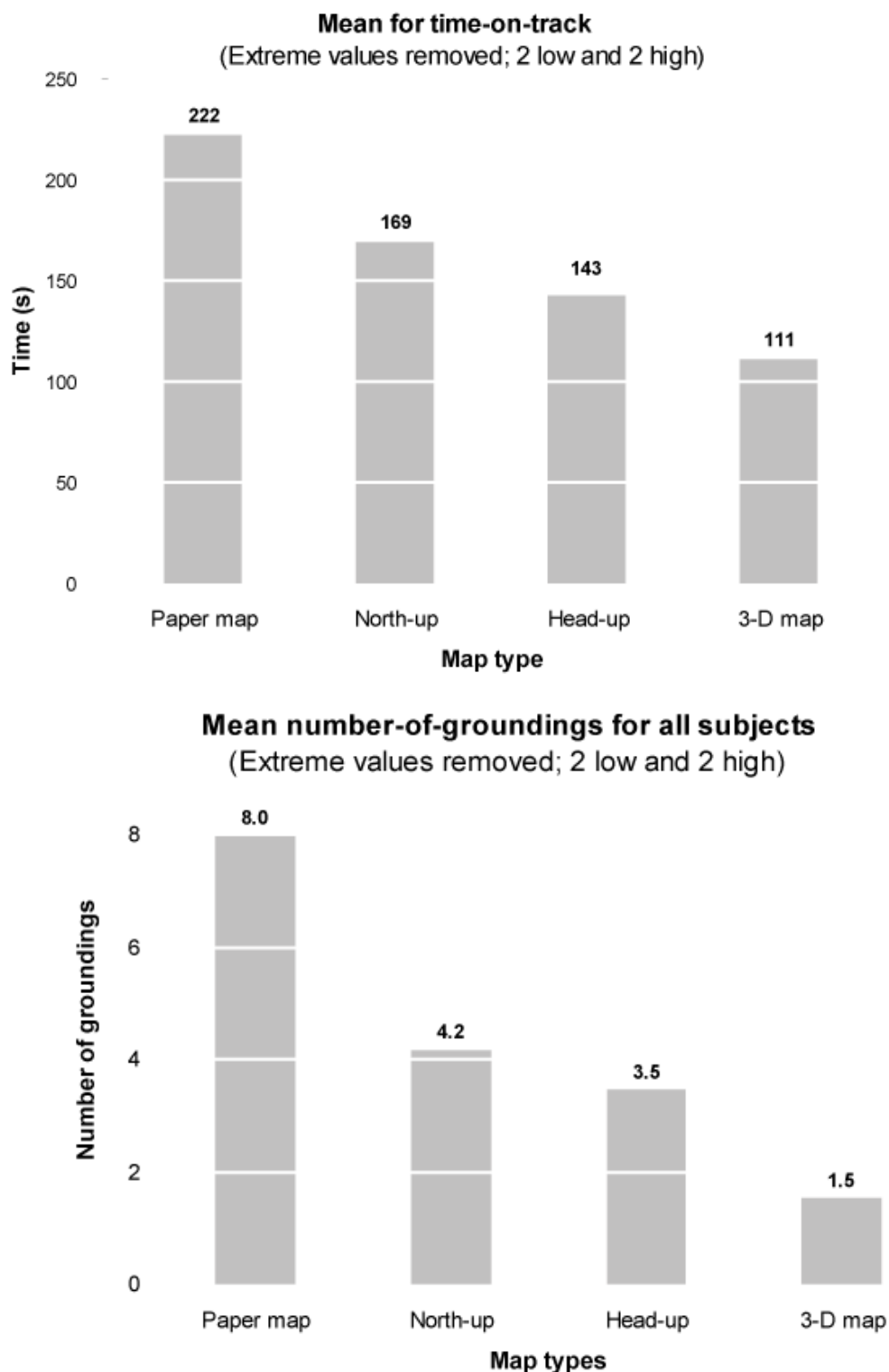


Figure 65. Mean values for time on track and number of groundings for all subjects but with two top and two low extreme values removed. There is no change in the tendency of the results, showing that the influence of extreme values does not corrupt the result of the test.

No major difference can be seen compared to the full test material showing that the influence of extreme values is minor.

I thought it would be interesting to break down the test group in sub groups and look if different parameters like experience, age, etc. make any difference to the results. The size of the test group is too small for any far-reaching conclusions to be drawn but I have made some diagrams below to point at some tendencies in the material.

The Influence of Experience on the Results

The subjects were asked to state their experience in chart, map and plan reading. The answers to this question was then parameterized to a scale from 1 to 3 where 1 meant “no” experience, 2 “average” experience and 3 “large” experience. A “large” experience could for example mean that the subject had been competing in orientation, had long experience of navigating leisure boats etc.

Splitting the test group this way resulted in a small group of 9 classified as having “little” experience, 23 as having an “average” experience and 12 as having a “large” experience. Taking the mean values of *time-on-track* and *number-of-groundings* for each experience group gave the two charts in Figure 66.

The light gray bars in both charts are the “experienced” navigators, the middle gray bars are the “average” navigator and the dark bars are the navigators with “no” experience.

Drawing any conclusions from this small sample is of course very questionable but a tendency that experience does indeed play a role is clearly distinguishable from the graphs above. It seems also clear that the 3-D map is more efficient both for experienced and inexperienced users. The difference in *time-on-track* between the “no” experience group and the “large” experience group is significant on the 5 % level (Paper map: $p = 0.007$ and 3-D Map: $p = 0.006$).

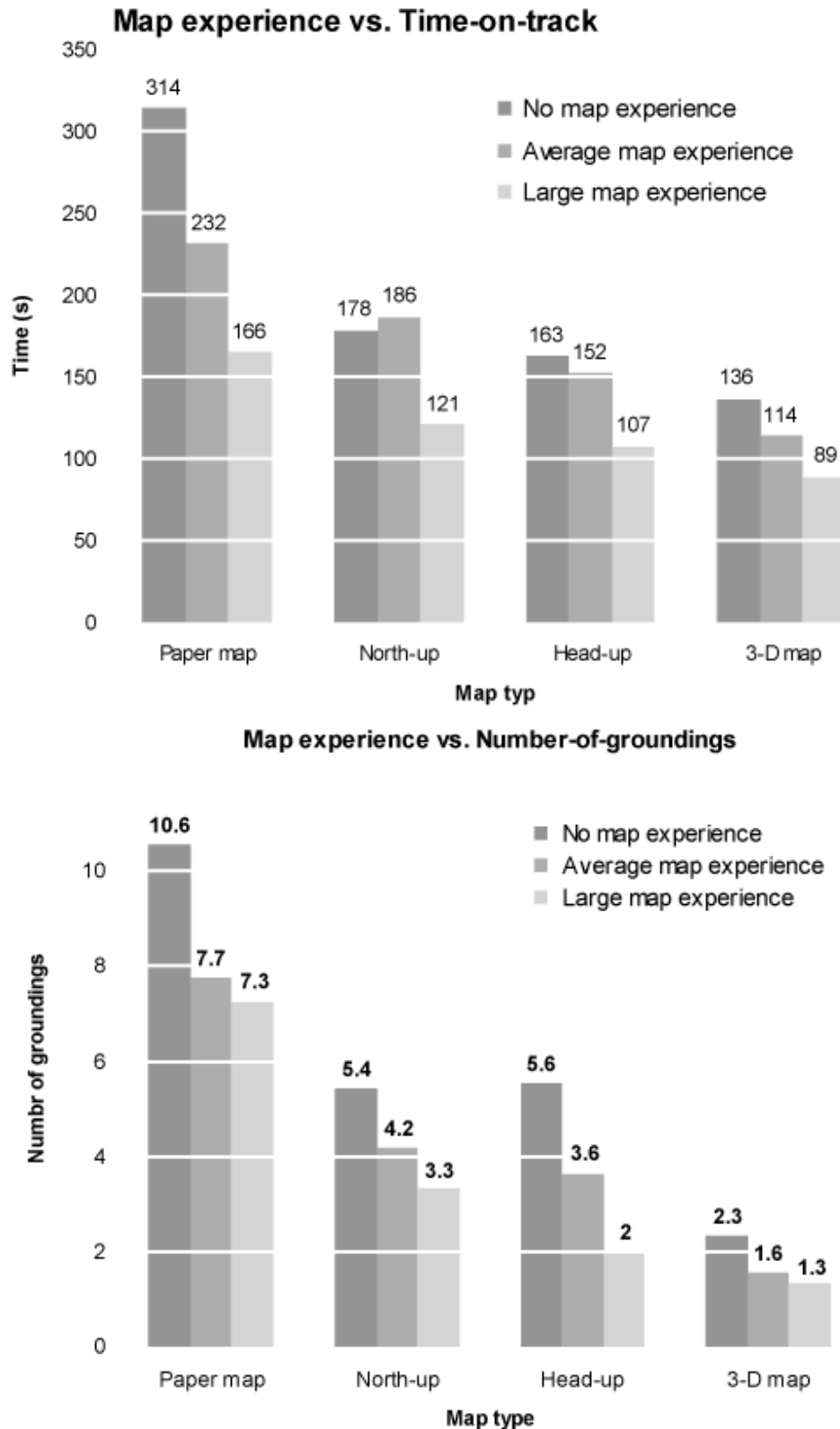


Figure 66. Time on track and number of groundings divided up into three different experience groups. The tendency is that experience does play a role in *time-on-track* and *number-of-groundings*.

Results suggesting that navigation experience influences the results of a navigation experiment should not, of course, come as a surprise. The tendency is also that navigational experience is less important in using the 3-D map than in using the conventional exocentric map types. This tendency is shown in the clustering of the *time-on-track* and *number-of-groundings* score for the 3-D map. This clustering however is evident also for the North-up and Head-up maps and might be a result of representation plotting the position of the vehicle in the map.

The Influence of Self Taxed "Sense of Direction"

The subjects were also asked whether they had a good sense of direction or not. Taking their words for it, a "1" was awarded those who said that they had "no" or "bad" sense of direction and a "2" those who had "normal" or "good" sense of location. Only 6 subjects said they had "no" or "bad" sense of direction, and the other 39 stated "normal" or "good." Plotting the mean values of time on track and number of groundings for each group, resulted in the charts in Figure 67.

The dark bars in both charts represents the small group that stated "no sense of direction", showing that they took longer time on track and made more groundings than those that belonged to the group that stated "normal" or "good sense of direction".

Also here a tendency is distinguishable. The group who considered themselves as having a "normal" or a "good" sense of direction is doing better both at time on track and at the number of groundings. A nice clustering on the same time score for both groups using the 3-D map suggests that the 3-D map lifts bad navigators to the same level as good ones, but with the small sample size and the dubious value of self taxation no conclusions can be drawn from this. It seems clear though, that the difference between the groups is larger when it comes to navigating with the paper map than with the electronic maps which includes plotting of one's own ship's position.

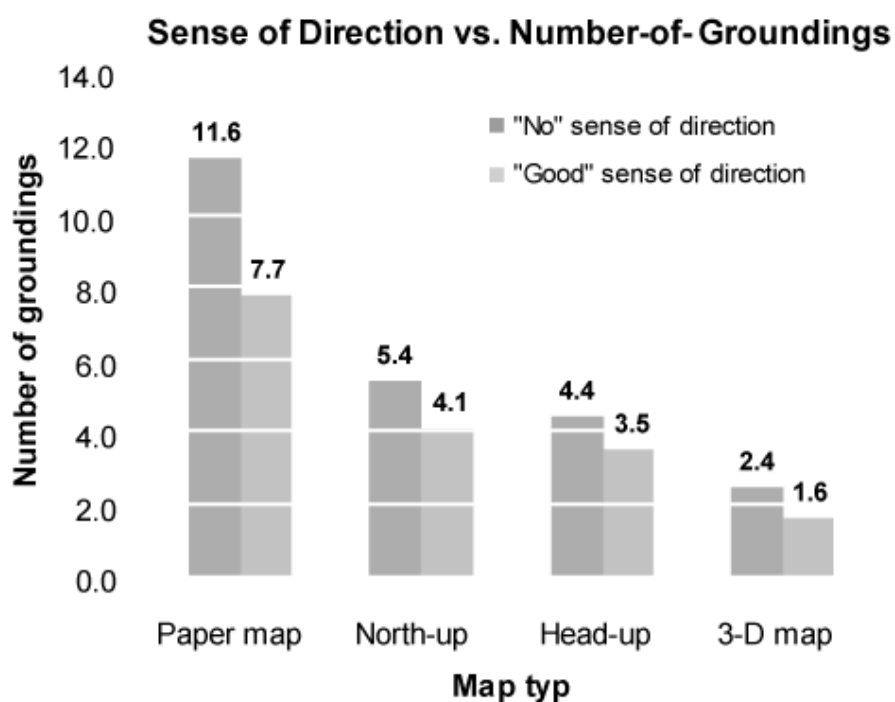
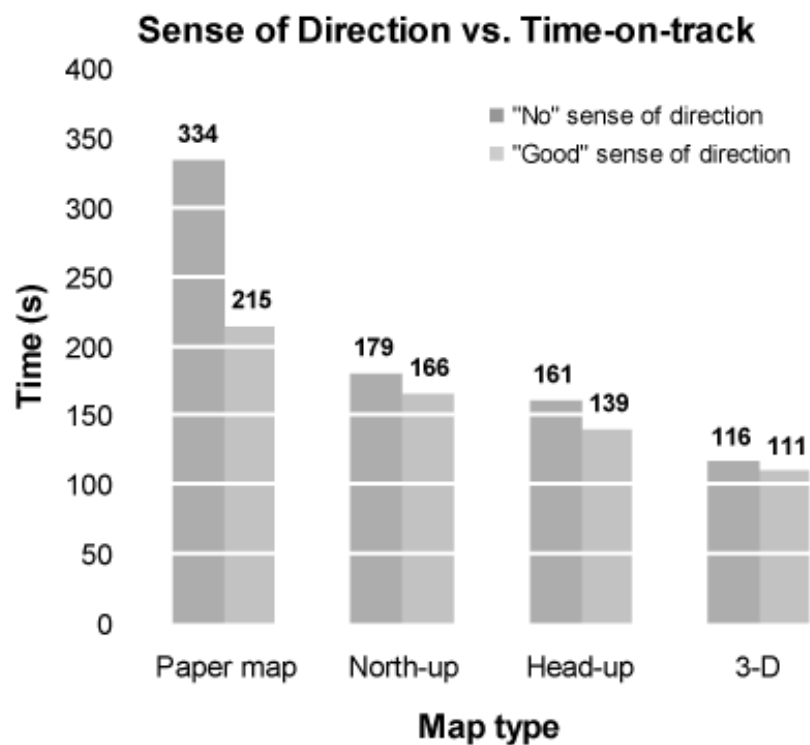


Figure 67. In these two diagrams the group of test subjects is classified into two sub groups of persons with "good" or "bad" sense of direction. A tendency is visible in that those who considered themselves as having a "good" sense of direction were faster on the track and had fewer groundings.

The Influence of Classification Based on the Spatial Test

At the end of the session each subject took the 7-minute-long figure-rotations test that has been described above. The purpose was to find out if there was some correlation between the results of the spatial test and the results of the experiment.

The test consisted of 20 questions containing one reference figure and 6 alternatives each. The score was calculated so that each figure that was rightly identified as “the same” gave one point and each figure that was wrongly identified deducted one point. The maximum score was 54. The raw points from the test were then recalculated into a standardized *stanine* value on a scale from 1 to 9 where 9 meant high spatial ability. The scale was standardized in 1954 for a Mid-Swedish rural population and the mean of the standardization group was 5. The mean for the group tested by me was 6.87, showing that they had a higher ability than the standardization group. The score distribution of the experimental group of 45 can be seen in Figure 68.

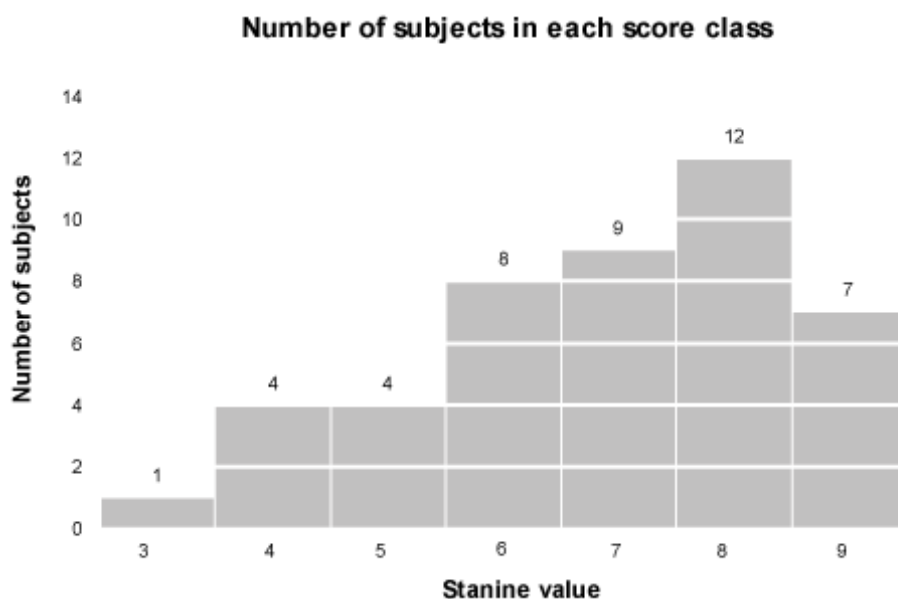


Figure 68. The distribution of stanine score on the spatial test (mean 6.87) shows that the group of test subjects had a spatial ability much above the normal distribution of the standardization group in 1954 (mean 5.0).

Based on the stanine score of the spatial test, three groups were formed. The first group was those with a stanine value of between 3 and 5 (there was no one with a lower score than 3). This group consisted of 9

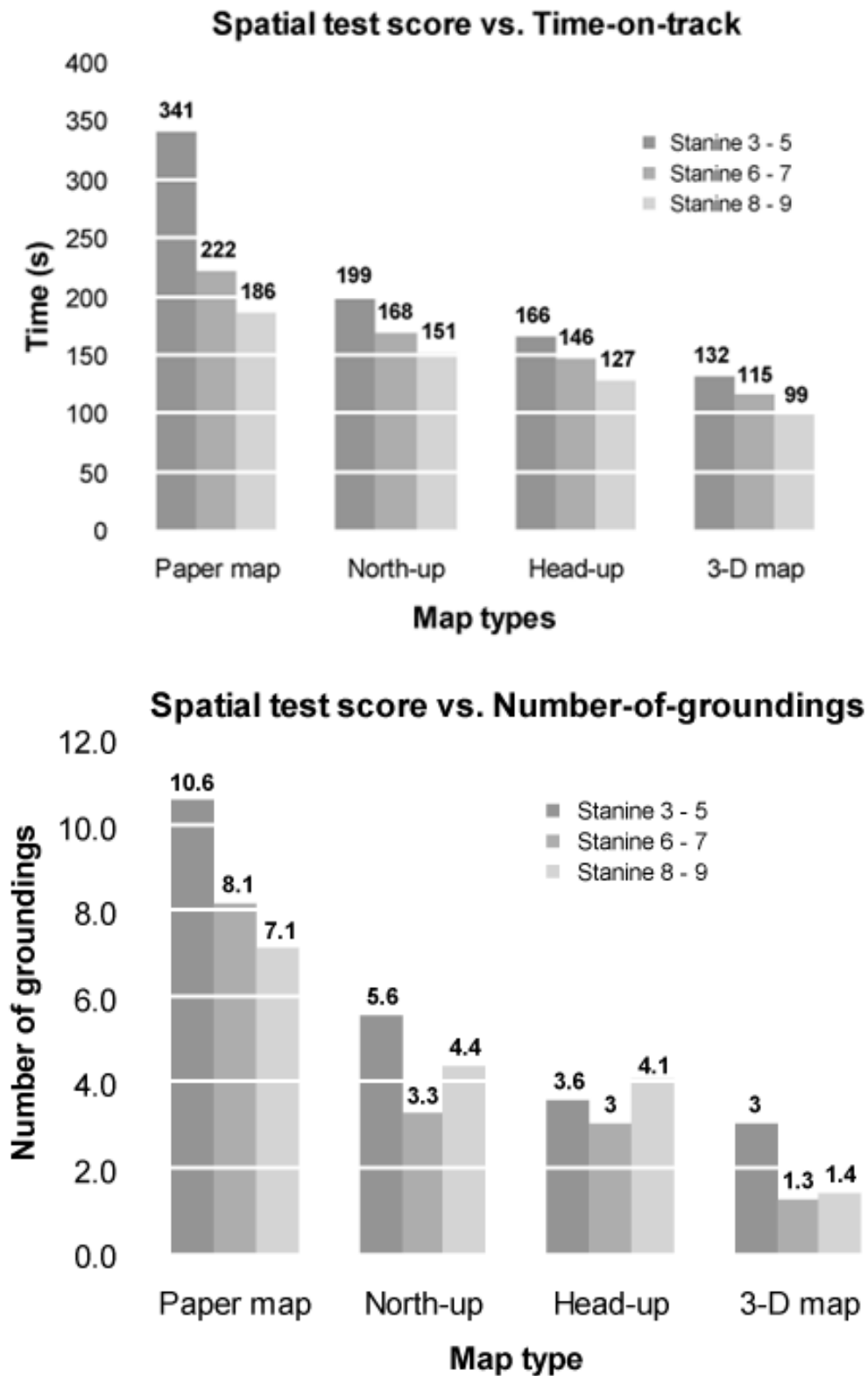


Figure 69. The results of three groups, formed according to the outcome of the spatial test, on time on track and number of groundings. On *time-on-track* a tendency is obvious, on *number-of-groundings* the result is more ambiguous.

individuals. The second group consisted of those with a stanine score between 6 and 7, 17 individuals, and the last group of those with a stanine score between 8 and 9, 19 individuals.

The results of these three groups for *time-on-track* and *number-of-groundings* are depicted in Figure 69.

As far as the results of the *time-on-track* table show there seems to be a distinguishable tendency, but when it comes to the number of groundings the result is more ambiguous. The over-all tendency of doing better with 3-D maps than with head-up and north-up etc. is clear, but it seems like the group with high spatial scores are doing better than the group with low spatial scores. Possibly this can be an indication that there is indeed a correspondence between high spatial ability measured with the figure-rotations test and navigation skill as measured in the laboratory archipelago.

The Influence of Gender

Splitting the test results for the 21 female and the 24 male subjects and looking at the mean value for *time-on-track* and *number-of-groundings* we see a small difference in the results favoring male navigation in the maze. The difference reached almost significance on the 5 % level for the paper map test for *time-on-track* ($p = 0.051$) and *number-of-groundings* ($p = 0.054$). For the 3-D map the sex difference was not significant, $p = 0.119$ for *time-on-track* and $p = 0.162$ for *number-of-groundings* (see Figure 70).

Diane F. Halpen, professor in psychology at California State University in San Bernardino, states that “findings of sex differences in visual-spatial ability are the most robust (found consistently) of the cognitive sex differences, but the size of the effect varies depending on which visual-spatial task is being assessed. It also appears that the largest sex differences are found here.” (2000, p. 111) Sex differences favoring males are among other tasks found in learning routes from a 2-D map (Galena & Kimura, 1993) and studies with computer-simulated mazes have shown a “large and reliable sex difference” favoring males (Astur, Ortiz & Sutherland, 1998, p. 185). My findings are consistent with previous research and strengthen the notion that this experiment work as intended.

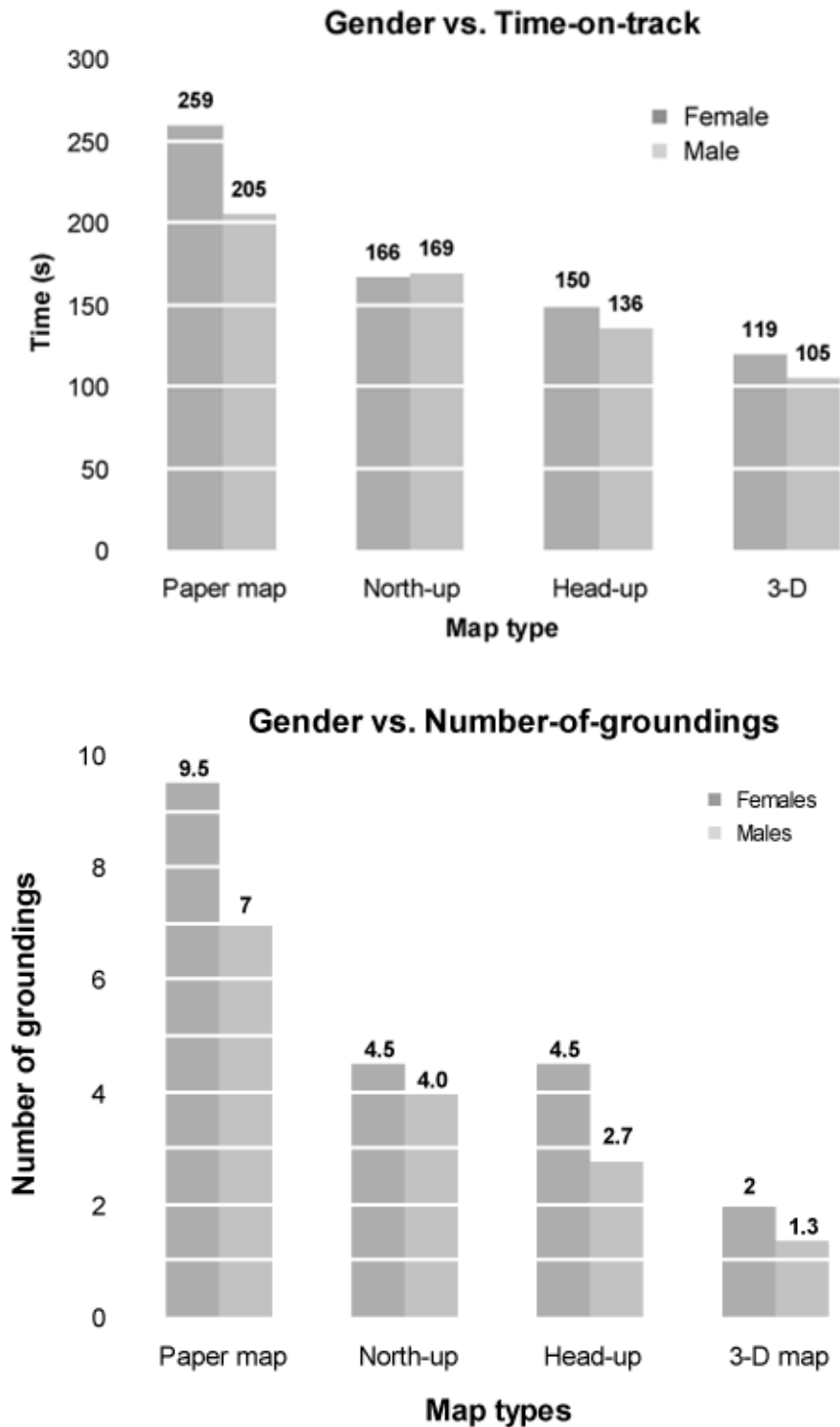


Figure 70. These two diagrams show the *time-on-track* and *number-of-groundings* with the different map types based on gender. A non-significant tendency favours male performance.

The Influence of Age

A division into age groups was made to see if there was any difference in the results of navigation between people of different ages. Three groups were formed: age 16-29 (19 persons), age 30-49 (14 persons) and age 50-63 (11 persons).

As far as navigating with the paper map there is a significant difference on the 5 % level between the age groups 16 – 29 and 50 – 63 for *number-of-groundings* ($p = 0.031$) and very close to significance for *time-on-track* ($p = 0.053$). This is consistent with the notion that spatial ability declines with age (see Chapter 6 Discussion).

It is well established that visual-spatial abilities decline with age. (e.g. Halpen, 2000, p. 107; Winograd & Simon, 1980; Dollinger, 1995). The experiment results are consistent with this notion.

Ranking of User-friendliness

After the navigation sessions the subjects were asked to rank the user-friendliness of the different map types from 1 – 4, where “1” was the easiest and “4” the most difficult map to use. The form and the individual answers can be studied in appendix E. The mean values for this index were calculated and are presented as the filled black circles in Figure 72.

The 3-D map was classified as the easiest one to handle with a mean index of 1.13 followed by the head-up map with a mean index of 2.29. The indices for north-up and paper map was 3.24 and 3.33 respectively. The paper and the north-up maps were considered almost equally difficult to use.

We can compare this to some sort of “objective” ranking by calculating a similar index from the placement of the individual values for each map type, where 1 has the shortest and 4 the longest *time-on-track*. The mean of these 45 objective indices for each map type is presented as the outlined circles in Figure 72. The index for the 3-D map, which as we have already seen had the shortest time on track, is 1.16. The head-up, north-up and paper maps had indices of 2.13, 3.02 and 3.69

respectively.

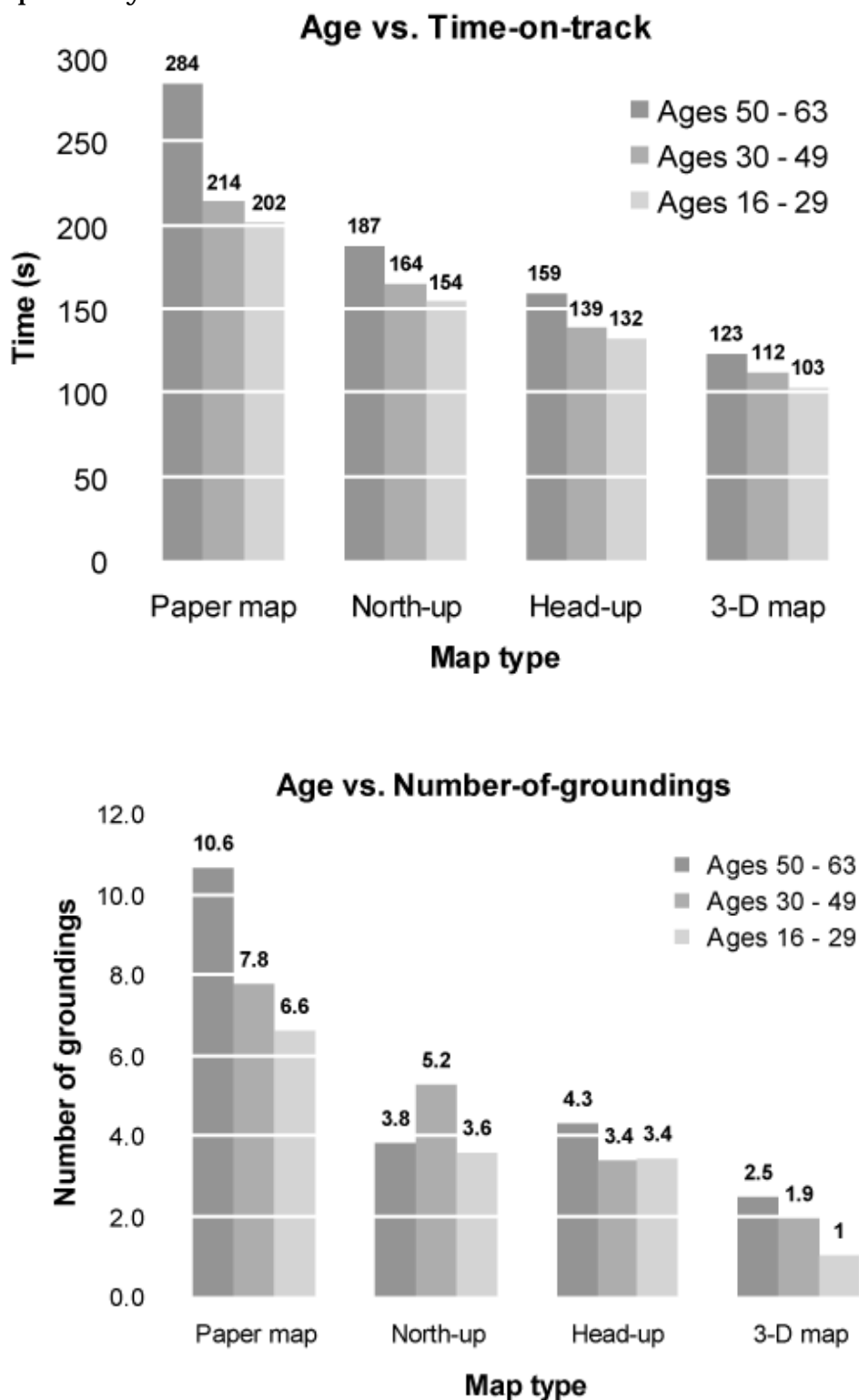


Figure 71. Diagrams comparing the results of the three age groups for *time-on-track* and *number-of-groundings* with the different map types. The tendency is that navigation ability declines with age.

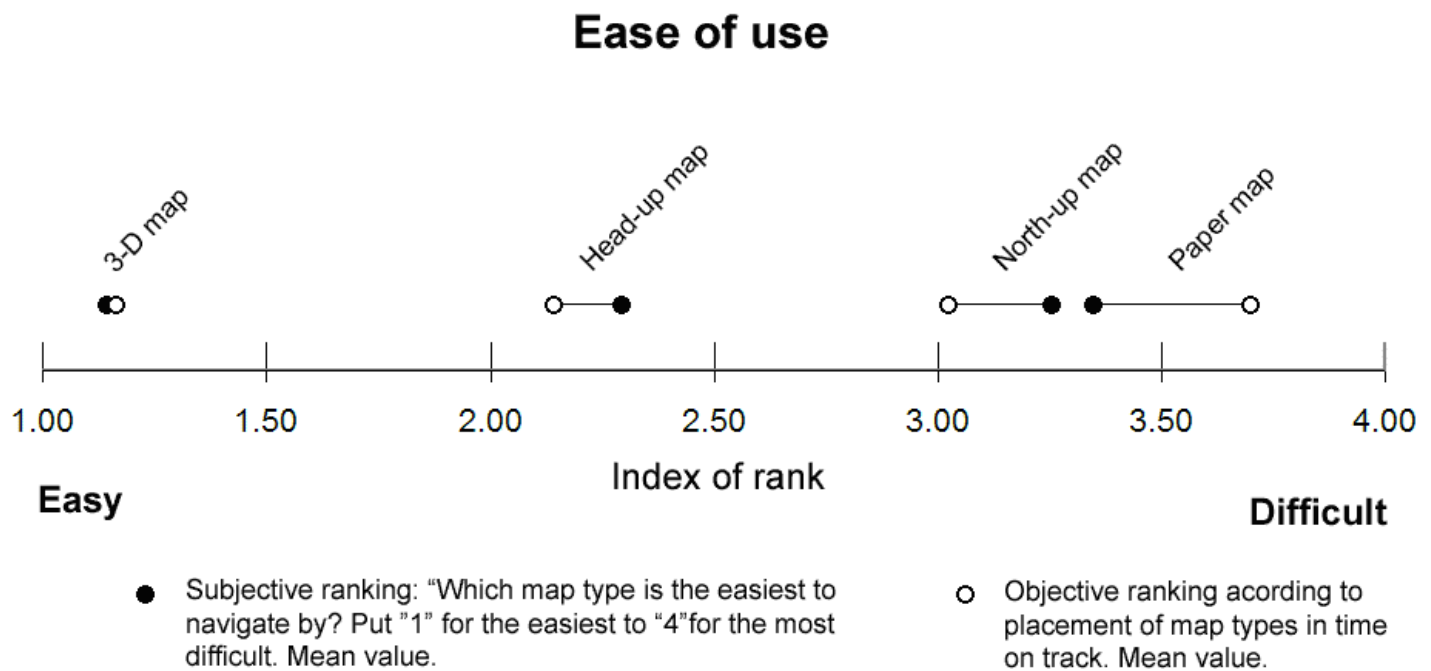


Figure 72. Ranking the user-friendliness for each map type by the subjects. The filled circles are the subjective ranking as filled in on the form in appendix E in answer to the question "Which map type is easiest to navigate by? Put 1 for the easiest to 4 for the most difficult." The outlined circles represent the "objective" ranking interpreted as the placement of the map type in time on track. Mean values.

The result of the subjective and the objective rankings is striking. One might note that the subjects felt that the north-up map was somewhat more difficult than the actual results showed, and that the paper map, on the contrary, was felt to be somewhat less difficult than the actual results showed.

Observations

Besides the quantitative data presented above the experiment also gave interesting qualitative data. It happened quite often that the subjects commented on their doings during the experiment. These comments were recorded by the research assistant Lisa Gustafsson and myself during the experiment and directly after.

A certain learning effect could be noticed as the subjects during the four trials became more familiar with the size of the invisible grid squares that made up the track. Some subjects commented on this also saying that they acquired a feeling for how many steps there were to the next turn. Because the map types were randomly assigned to the different tracks, the effects of this bias will cancel out over the whole group.

The Paper Map

The most prominent observation from the paper map tests was that navigation by this map type required considerable concentration compared to navigation by the other map types. The subjects became silent and commented less on their doings. I interpret this as the cognitive load was heavier. Comments like “Oh, this is difficult” were common.

The paper map encouraged the subjects to use the landmarks for orientation. The other three map types had real-time plotting of the current position on the computer screen which resulted in many subjects staring at the display most of the time instead of looking up on the track. The landmarks could be used to compare a position in relation to the chair, the boxes or the paper tube. All turns were placed “at the longitude or latitude” of a landmark, or just before or after. Some subjects caught on to this technique really fast, while others only slowly realized that the landmarks could be used for orientation. They at first tried to guess the distance to a turn and then used trial and error, listening for the grounding beep from the computer for a confirmation of where the limits of the track were.

The traditional method at sea is to read the paper chart north-up. This tradition is very strong in the maritime community. In orienteering sports the methodology is instead to read the map head up, holding the compass and the map in one hand and constantly turning the map while running so that map north faces north and the forward track is up on the map. As the orienteering sport is a quest for tenths of seconds this method has shown to be the most effective. Interesting enough almost all subjects rotated the paper map the orienteering way as they went along the track, meaning that they read it head-up. This was also true for the subjects with large maritime navigational experience. I

believe that if we had required the subject to keep the map north-up the results of the paper map condition would have been even worse.

One of the subjects (#36) read the map in a north up position and went along in quite a flow for almost half the track, then completely lost her orientation and had to stop and make a major reorientation with the help of the landmarks. It was typical of those few subjects who turned the map in a head-up fashion that they managed for a couple of turns to stay oriented but then had to stop and make a major reorientation.

11 of the subjects had better time on track with the paper map than with the north-up map. From my observations I think this is due to the fact that they rotated the map all the time so that the map actually became a head-up map minus current position plotting.

The North-up Map

Also with this map type the experiment sessions were much quieter with fewer comments than with the head-up and 3-D maps. The subjects were clearly concentrated when working their way along the track. When comments were made they often showed concern particularly from those subjects who had done the head-up and 3-D maps before this map. Comments like "This is difficult", "Oh, it works the other way around", "Here I need to think" and so on were common.

These comments and all difficulties experienced by the subjects are concentrated on south going where the directions of the turns for the subjects are opposite to those on the map. On south going one's own ship's symbol on the north-up map is moving downwards, similarly a turn to the left on the map is a right turn for the subject. Almost all subjects had trouble with this. Even those who went fast and had few errors could be seen hesitating and sometimes make trial turns, checking the movement of the map symbol before making the actual turn. This was a very typical observation.

The ones who did best (shortest times and fewest groundings) stated that they used the landmarks and calculated the upcoming turn in terms of "turn towards the chair", "turn away from the box". This showed that these subjects also kept a mental link between the "real

world” and the map. The majority of them concentrated on the display, turning navigation into a computer game where the goal was to move the green arrow through the maze.

The Head-up Map

The subjects generally had few problems with the head-up map. Because the map was rotating, the directions of turns were always consistent with the directions on the screen. A left turn in the real world would always be shown as a left turn on the map. The ease with which the subjects navigated along the track by this type of map was quite obvious.

However, I noted another interesting problem that suddenly faced many of the tested subjects (maybe as many as half of the sample group). When the cart was moving forward along a straight portion of the track and came too close to one of the sides of the tracks, the subjects often made a sideways correction in the wrong direction. (!) The subjects could not say why they did so. My hypothesis is that because the map was moving and the green arrow representing one's own ship was static, they figured that it was the map that they were controlling with the cart. This effect was not seen when the subjects were making the actual turns.

The 3-D Map

There was quite a noticeable difference between the test sessions with the 3-D map and all the other map types. The subjects were more relaxed and commented freely. It was as if the navigation could be performed without any cognitive work load.

When comments were made about the map type, they were often positive remarks of how easy it was to navigate. There seemed to be little trouble with this type of map. The only problems were on rare occasions when the tracking system on the first three turns of track 1 would lose track and cause the map to freeze for a second or two.

One subject (#24) commented on the benefit of the “wake water” trail (the green coloring of boxes already passed). By being able to see the

track behind, he never came in any doubts about which way to go, something that could happen in confused situations with, for example, the north-up map.

3.4 Reliability and Validity

In experimentation, reliability is the precision and stability of the instrument used to measure the dependent variables. In this case the two main measures are time-on-track and number-of-groundings. Both depend on the reliability of the tracking system. Time-on-track because the positioning system determines when to stop and start the timer (which uses the computer's system clock), and number-of-groundings because it is the tracking system that determines if the vehicle has hit a red square and scores a grounding. If the tracking system is unreliable, groundings will be scored although the vehicle is on the track, or no grounding will be scored although the vehicle enters NoGo areas. Because the actual triggering of the grounding is done by the VR system based on collision detection between the rod (positioned by the tracking system) and the red grid cubes, it is probable that unreliability in the tracking system would manifest itself by sideways or unexpected movements by the rod when the vehicle was stopped or was driving straight and thus would be detected. No such unexpected movements were reported except for 2-3 places where a reflector was shadowed (as mentioned before). In these cases the result was a second long freeze on the display and the subjects were forewarned of this and instructed to continue to drive and the positioning would come back again. This problem affected all map types and in my opinion did not influence the outcome of the test.

The calibration and stability of the system was also monitored under each test because the outer border of the 6 by 6 meter square was marked on the floor by a white tape, and during those few parts of each test where the track went along one of the borders the positioning on the display could be easily compared to that between the vehicle and the tape on the floor. The same goes for the four landmarks, the chair, the cardboard boxes and the paper tube.

Before each day's testing the cart was driven on the tape border around the tracking area and uncertainty was all the way less than 3 cm.

Validity is a more complex notion often divided into other subgroups. Internal and external validity is two such groups. Internal validity, concerns the question of whether I really measure what I think I am measuring, in this case the ability to navigate quickly along the track without grounding and not some other thing, for example experience in computer gaming. To check this I asked the subjects about their navigation experience and sense of direction and I also had tested them for spatial ability through the figure rotation test. The idea was that if I really was measuring the efficiency of the different map types, navigational experience, sense of direction and spatial ability would all show up in the results in a linear way: larger experience, better sense of direction and higher spatial ability should lead to better results. If I was measuring something else, these experiences and abilities would not show up in a consistent way.

As shown, the results indicate that larger experience, better sense of direction and higher spatial ability also leads to better results on the tests (faster and less errors), but that the map types through all groups keep their internal positions. I propose that these three properties have something to do with navigation and that the way they show up in the results is an indicator for good validity.

External validity concerns generalizing; does the measured behavior in the laboratory maze really predict something about the behavior of the different map types in the real world? Here the answerer must be more open. As I have mentioned above, I think that driving in the maze might be more representative for high speed navigation in very confined inner archipelagos, if the 3-D map also is more efficient than the other map types in more open navigation situations remain to be seen.

3.5 Experiment Conclusion

This experiment was designed to give an answer to the question whether a 3-D map shown in an egocentric frame of reference really was “better” to navigate by than conventional map types that exist on ships today. With “better” I then mean leading to faster decision making and fewer errors. With conventional maps I mean the traditional paper chart and the modern GPS supported electronic chart systems used on ships where the position of the ship is plotted in the display. These displays can be used in a north-up and a head-up (or course-up) mode.

I also wanted to see if it was possible to identify some groups that were weaker in navigating, people with less map experience, with poor sense of direction, with less spatial ability etc., and to see if the 3-D chart – if better – could compensate for smaller navigational skills.

In the first case it seems as if the experiment has been successful. The results from the laboratory archipelago clearly show that the egocentric 3-D chart is indeed “better” than all the compared map types. It also shows that electronic map used in a head-up mode is “better” than electronic map used in a north-up mode, which is common practice onboard ships.

As far as the second case goes, there is a tendency in the test results suggesting that a 3-D map could indeed compensate for smaller navigational abilities due to for example, experience, spatial ability etc. When the test group is divided into subgroups this way, they become too small to show but a tendency, so new tests would have to be made to make sure these tendencies actually hold.

When it comes to drawing general conclusions from my results, I would have to be very careful. One may ask whether navigating a cart through a 36 square meter laboratory archipelago really has anything to do with navigating a ship in a real archipelago. The answer will have to wait until the relevant field experiments have been made.

Nevertheless the experiment results are very promising and surprisingly consistent. If the subjects had been forced by some means to keep a maximum speed through the maze, straining their cognitive abilities even more I think that the results would have been even more favorable to the hypothesis to be tested.

Chapter 4

The Prototype

This chapter presents the practical work developing prototypes of the 3-D chart. The chapter looks in detail on how the different new concepts and features suggested earlier were implemented in practice. Six prototypes have been constructed so far and these have been presented for and commented on by members of the user group.

4.1 Prototyping

One of the most common design methods is called *prototyping*. It is an iterative method of *human-centered design* (Norman & Draper, 1986). Prototyping basically means that the designer very early in the design process starts making simple prototypes of his product and tests them on members of the user group (Ehn & Kyng, 1991). These *usability tests* are often made in an informal manner with few participants, the main focus being to catch large design flaws, re-design and test again. This method is different from the traditional *water-fall method*, where an application is developed from the specifications of the customer and only tested at the end when changes are difficult and expensive (Kuniavsky, 2003, p. 30).

In the laboratory experiment described in chapter 3 the number of subjects was aimed at reaching statistical significance. In a product development process often more practical aspects matter more. Finding

problems in the user interface of a software prototype will need another approach. To spend two weeks on testing a product on 30 subjects is often a waste of time when the major problems are obvious already after the first 3-5 subjects, and smaller design problems hidden under the big ones anyway (Klein et al., 2006, p. 8). Jacob Nielsen (2000) claims that tests with 5 users find 85 % of the usability problems. A cost-benefit analysis made by Nielsen & Landauer (1993, p. 212) shows that 3-5 users is the optimal number depending on the style of testing.

The prototyping method is decried by for example Lundequist (1995, p. 106). It is both theoretical and practical. First a cognitive model is created, the abstract concept of the product to be developed. Then a physical prototype is constructed and tested on a user group or on expertise within the field. Faults and malfunctions are corrected and a new prototype is build. In this way prototyping leads to a better and better product.

This heuristic research approach was chosen as a practical way to quickly develop a concrete application to illustrate the hypotheses. *Action research* would have been an alternative method. An action research approach to this problem would mean to work in close collaboration with a shipping company and the bridge crew of, for instance, a high speed ferry or combat boat and together with the practitioners develop and test the application in its proper context. This has for practical reasons not been possible.

Instead I have tried to test the prototypes as often as possible in small and informal manners, to try to catch problems and get new suggestions. As I often carry my laptop computer with me, I have tried to shown the current prototype whenever I had the opportunity and then maybe get valuable reactions. After presentations, people have often come up and talked to me and I have received many comments from both amateur and professional mariners.

In this chapter I will describe the practical work with constructing the six prototypes I have made so far. I will be rather specific as to which approach I have chosen to solve problems, but I will not go down on a technical level as this is a project in information design and not in

computer graphics. I have chosen to describe each prototype by feature in a logic way starting with the under and overwater terrain models and moving on to symbolic features. First at the end of the chapter, will there be a short chronological résumé of extent of the six prototypes. Comments from persons to whom the chart has been demonstrated are inserted whenever relevant.

4.2 The Exocentric and Egocentric Views

A simple approach to the problem of supplying egocentric and exocentric views of a 3-D landscape model is to work with a real-time 3-D, or *virtual reality* (VR), application. Standard gaming techniques can then be used to move around in 3-D space, showing and hiding information and picking different views from virtual cameras. I have used the Swedish developed EON Studio from EON Reality as VR tool. The terrain models have been prepared in ArcView, TerraVista, TerraScan, TerraModeller and 3ds Max, and then imported into the VR tool.

The first major task was to create the two main views: the egocentric bridge view of the world ahead of the ship and the traditional exocentric bird's eye view. A problem of creating a transition between the two views would also need to be addressed.

With the 3-D terrain model imported into a virtual world I could use a virtual camera that could hang over the model and depict the landscape using *orthographic* projection, to supply the exocentric bird's eye view; orthographic (or *isometric*) is a synthetic projection method that will depict all points in the landscape from straight above. The aim for this view would be to get the chart to look as similar to today's charts as possible. For the egocentric bridge view, the camera would need to be placed close to the water surface, at the same height and position as the bridge and oriented in the same direction as the ship, using a *perspective* projection. This is a method of projection that closely resembles that of the human eye; the projection lines focus in one point. Orthographic and perspective projections are inherent methods of cameras in most VR/3-D tools. A third view type called *tethered* would also be interesting to try out. It is a semi-egocentric view were the camera hangs above and behind the ship showing the world from an oblique

position with the ship in view and the perspective halfway between egocentric and exocentric (Wickens & Hollands, 2000, p. 167). By switching between these camera positions the user could choose which view, exocentric or egocentric, s/he prefers (see Figure 73).

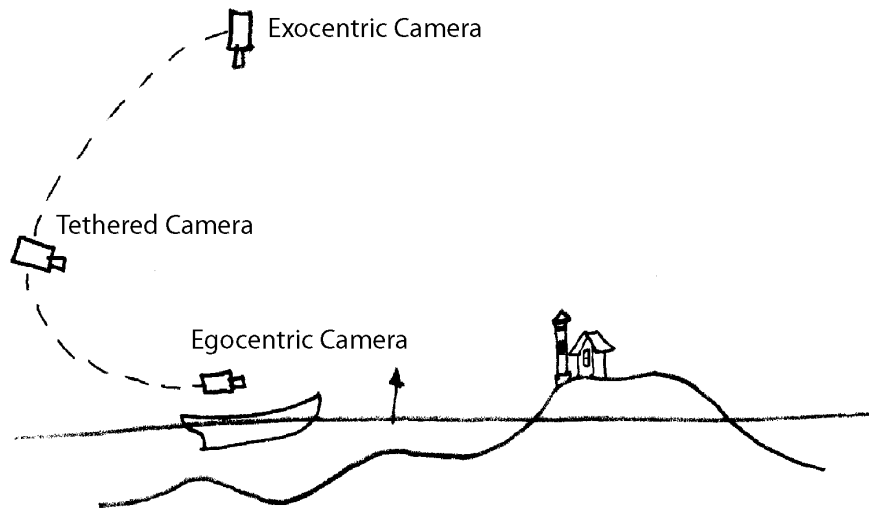


Figure 73. The different camera positions in the VR tool.

The view transition between the exocentric and egocentric views needed some thought. Either the two views could be shown in parallel on two different screens, or parts of the screen, or they could be shown in one window allowing for a transition between the two. In taxis I had seen car navigators abruptly switching between different map scales whereby I lost track of my whereabouts. An abrupt shift between the views in the 3-D chart would probably give the same result. A smooth camera transition, keeping a vital position somewhere in front of the ship in the same location on the screen, would probably help users not to get disorientated during the transition (Wickens & Hollands, 2000, p. 184).

This was the simple technical strategy I started out with and that eventually would need to be tested on the users. But before I could start with that I had to have a terrain model.

4.3 The Terrain Model

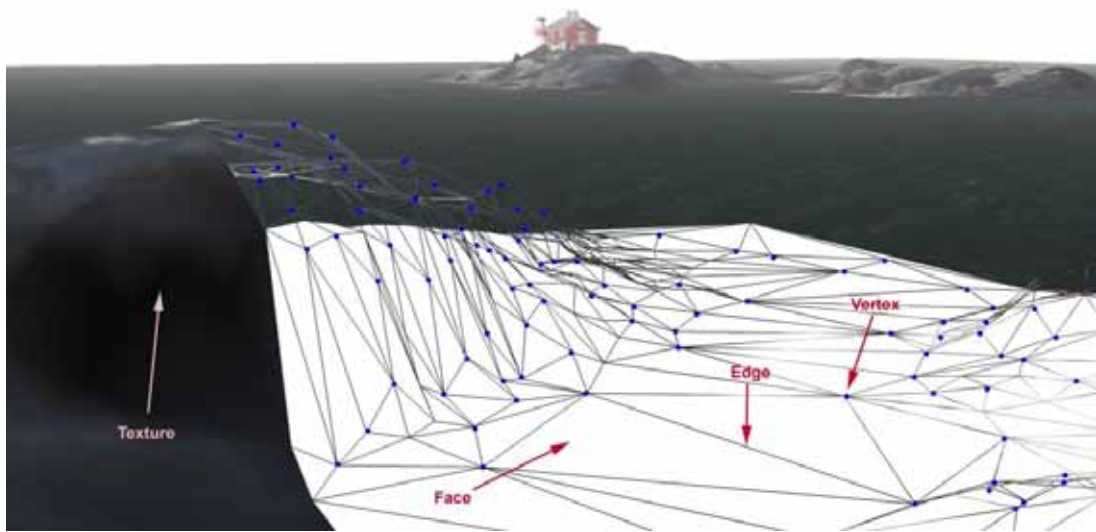


Figure 74. The terrain model produced from laser scanned elevation data and orthophoto is a polygon mesh draped with the photo texture. Gäveskär lighthouse from Prototype 6, of Gothenburg archipelago.

Creating a realistic 3-D model of the land- and seascape has been the biggest challenge in this project. A map is already an iconic model of the physical world. In this project there was a need for an even higher degree of iconicity in the 3-D model. (I will later discuss other non-realistic possibilities.)

The 3-D chart is a *geographical information system* (GIS) containing a geographical database as well as the traditional chart information. The geo-database consists of a *terrain model* of the earth's surface. A terrain is a 2-D surface in 3-D space with the special property that every vertical line intersects it in only one point, if it intersects it at all. As the earth is round this definition is not good on a global scale but on a local scale it will do. Another limitation of defining the terrain in this way, is that it cannot model overhanging cliffs or caves. In most practical cases it will, however, make a fairly good approximation (de Berg et al., 2000, p. 183). *Surface* models such as terrains are sometimes referred to as 2.5-D, as the elevation values are kept as attributes in a 2-D grid structure, this as opposed to *solid* models, with are based on a true 3-D grid, where the cells are three dimensional and called *voxels* instead of *pixels*, allowing

the user to model overhanging cliffs and caves, but also, for example, changing temperature and salinity in a water volume (Ronxing Li, 1999). In the future when computers have become even more powerful this kind of data architecture will allow 3-D charts to make powerful computations of the behaviors of currents and sea states. Until then we will have to stay with 2.5-D surface model.

The terrain model is assembled from land and underwater elevation data. These data can not generally be acquired from one source, but has to be bought separately and merged together. The land part can be produced from official digital elevation data (DEM), photogrammetry from stereo photos or from airborne laser scans. The underwater surface can be produced from bathymetrical sonar data, airborne laser bathymetry or official depth data from nautical charts. I will now go through my methods for acquiring data to the terrain model.

Iconic Features

The Underwater Terrain

The medium for nautical charts has changed over the centuries from hand painted parchment over copper engraved prints to digital computer displayed charts. From the early beginning depths were measured with rods or plumb line. In 1919 the echo sounder was invented which is now in extensive use and with the latest multi-beam technology depths can be measured with high resolution in a broad stripe under the survey vessel. In Figure 75 a 3-D model made from such high resolution bathymetrical data can be seen.

High resolution bathymetrical data is seldom made public; not only does it require huge amount of data storage capacity but it is often classified for military reasons. Instead the data is generalized into chart data showing just a few typical depths and depth contours for standardized intervals like: 3, 6, 10, 15, 20, 50 and 100 meters. In Figure 76 a nautical chart over the same area as the high resolution model can be seen. Only very little of the topographical information remains.

In this research project I have not been able to access high resolution data. This is, of course, a disappointment to me.

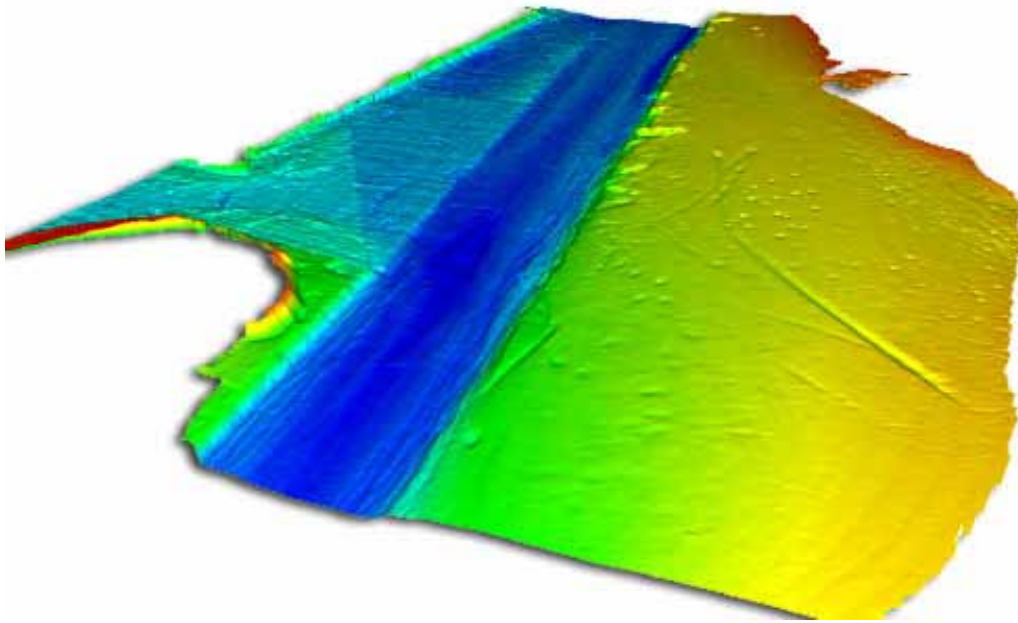


Figure 75. A 3-D model of the sea floor based on high resolution bathymetrical data collected with multi-beam echo sounder. Section of the entrance to Gothenburg harbor, scars from dredging to the left. And from anchors and ship groundings to the right. Pseudo coloring using depth as parameter . Picture from Marin Mätteknik AB (<http://www.mmtab.se/>, [2006, January]).

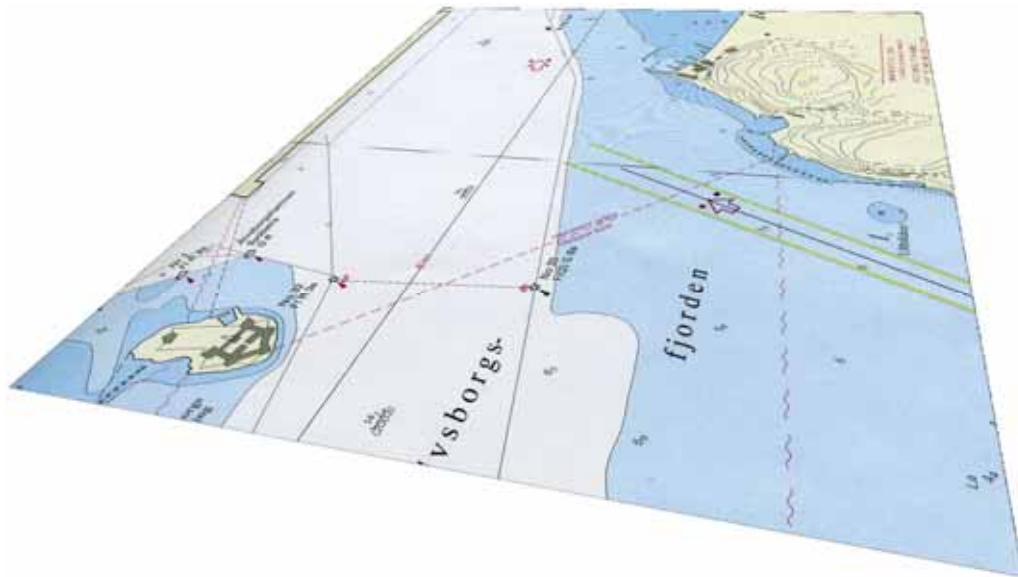


Figure 76. A perspective view of chart data over the same section of Älvsborgsfjorden as the high resolution bathymetrical model in Figure 75. (Note that the 3-D model is clipped along the dark blue 3 m curve.) Swedish Maritime Administration chart no. 9312, 1982, ed. 3, 2004.

In order to make the most out of 3-D chart technique high resolution bathymetrical data is a must. In many countries national security restricts access to such data but hopefully this will change in the future. Data could perhaps be filtered so that holes in the bottom, suitable for submarines to hide in (which is a reason for military classification), can be removed, and the underwater grounds that are of interest to surface navigation are kept. Access to high resolution data will be of increasing importance in the future as back-up methods for satellite positioning will use, among other things, underwater topography to compute probable position (Karlsson, 2005).

The bathymetrical data used in this project is generalized chart data. It is of no importance from an information design perspective, the point I am targeting can be made anyway, but from a navigation perspective it is of importance that data of better quality is made available for chart production. High resolution data can not be displayed in a 2-D chart using numbers – remember the cluttering in the Norwegian chart in chapter 1. But when displayed as a terrain surface, as in Figure 75, we have no problems reading it. Probably will we have a problem understanding it when properly made into NoGo area polygons either.

Sea Bottom as an Interpolation Surface of Low Resolution Data

For my underwater terrain models I have used scanned paper charts. A better alternative would have been to use S-57 vector charts. They contain the same information as the paper charts but the S-57 contains already digitalized data. S-57 is a map standard created by the International Hydrographic Organization (IHO) to be used in the Electronic Chart and Display Information System (ECDIS) which is the electronic chart system approved by the International Maritime Organization (IMO). In the S-57 standard, 145 feature and spatial objects are defined, allowing several attributes and connections between objects to be made. Spatial locations will be unprojected and geographical coordinates must be used. A screen shot of a section from an S-57 chart is shown in Figure 77.

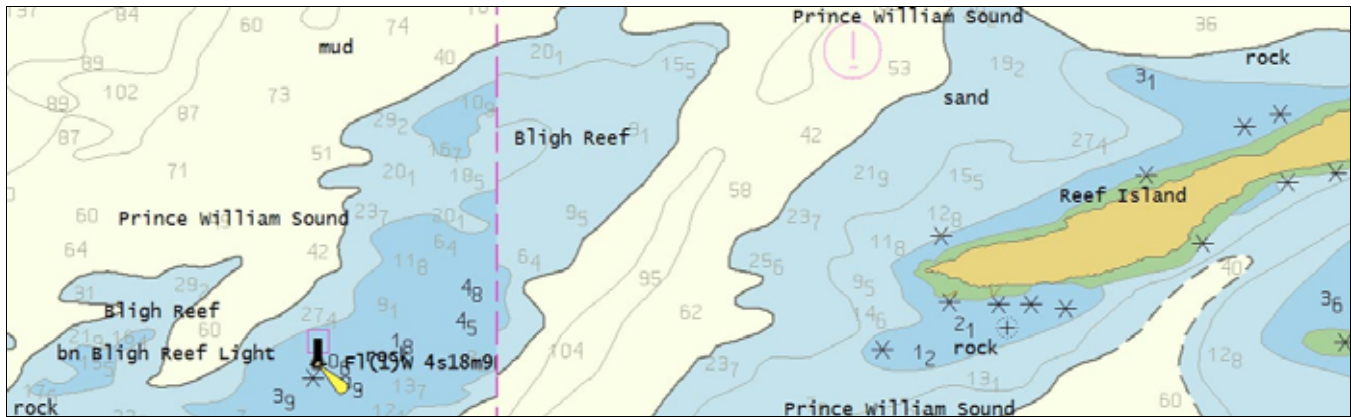


Figure 77. Electronic chart with data in the S-57 format. Bligh Reef in the Prince William Sound, Alaska, famous for the *Exxon Valdez* grounding in 1989. NOAA Chart US5AK11M and US4AK24M. <http://nauticalcharts.noaa.gov/mcd/enc/index.htm>, [2006. February].

In the absence of high resolution data the S-57 data sets seem to be the best source. The bathymetrical information is contained in two different objects, the soundings (the *SOUNDG* point object) and in the depth contours (the *DEPCNT* line object). In the United States S-57 chart data over American waters can be downloaded free of charge from www.noaa.gov. In Europe, however, access to S-57 data is restricted and when distributed in the form of an electronic nautical chart it is encrypted to a format that is not possible to use for the construction of 3-D models. For this reason scanned and vectorized paper charts were used.

In order to construct a 3-D terrain surface from the points and lines of soundings and depth curves, an interpolation has to be made. The linear interpolation based on such an irregular grid of elevation points is can be made using an algorithm known as Delaunay triangulation and the mesh – or polygon structure – derived is called a TIN (Triangular Irregular Network). It will be out of the scope of this dissertation to go deeper into this here, but those interested can get an overview of the area through for instance, de Berg (2000, p. 183) and Klinkenberg & Poiker, (2000).

A TIN model makes more economical use of the computer intensive polygons than a regular grid model and yet allows many small triangles

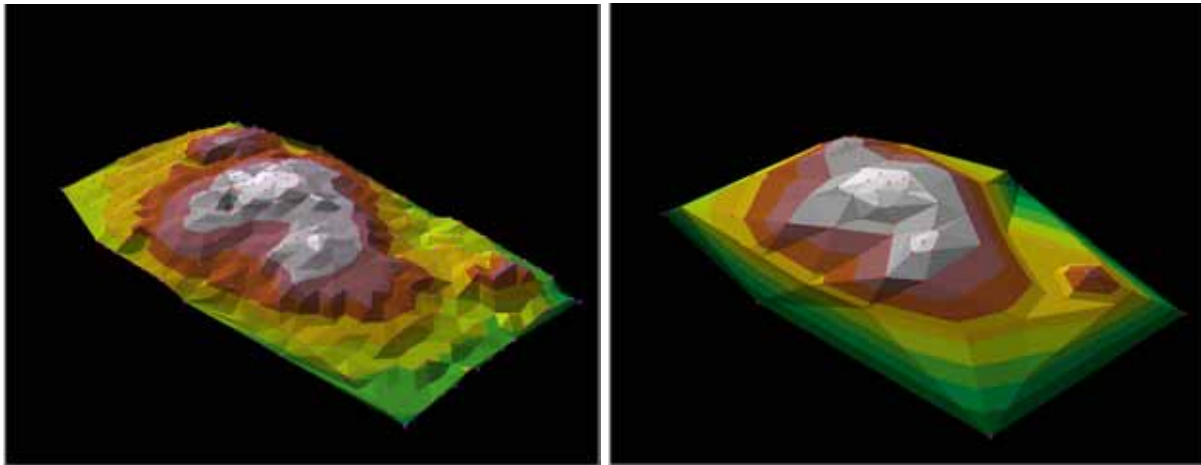


Figure 78. Left a regular grid terrain which can be used to represent a high resolution bathymetrical database (570 soundings) and right a TIN model which represents a terrain based on generalized chart data (7 soundings and 61 vertices on contours, i.e. 68 points).

in areas with dense soundings and few triangles in others. A hypothetical example of a regular grid high resolution terrain model and a low resolution TIN model can be seen in Figure 78.

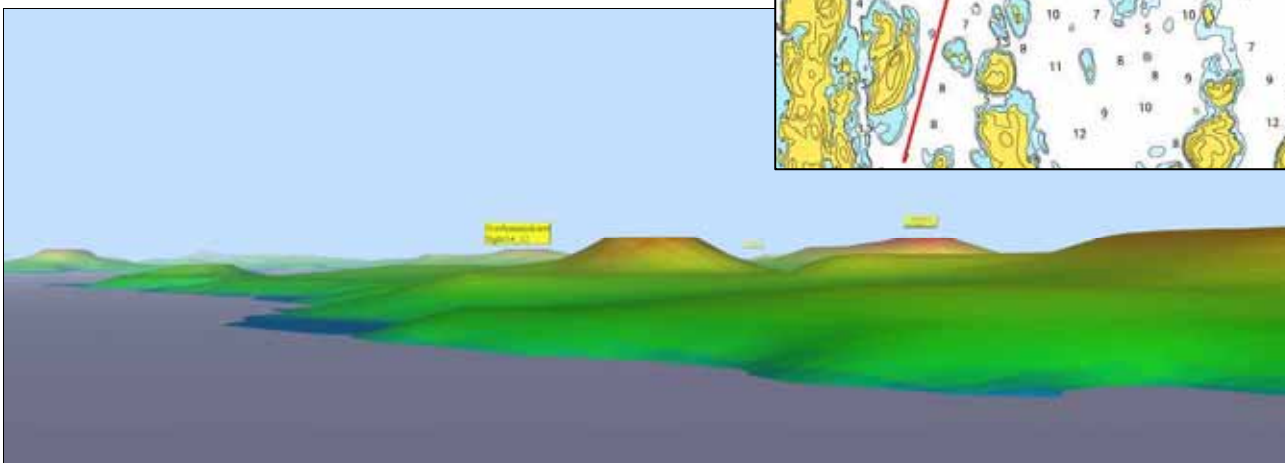
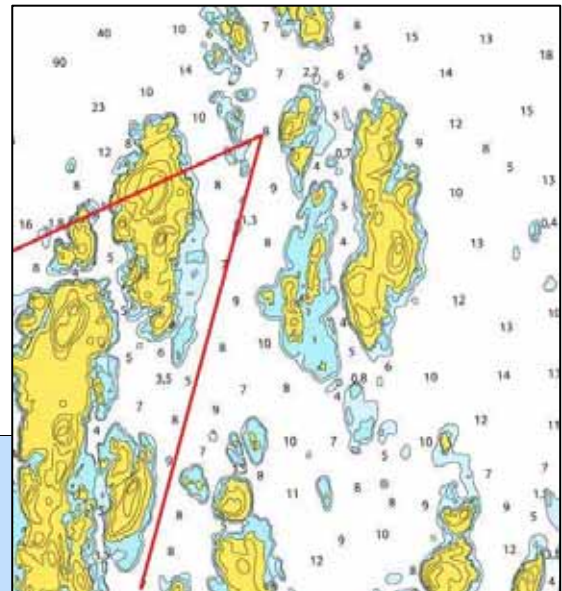


Figure 79. Unwanted terracing in a TIN model where the land surface was made from elevation curves. Northern Stora Nassa archipelago east of Stockholm. Screen shot from Prototype 4 and map data from Hydrographica's chart 613-11.

A TIN model is basically a linear interpolation of the depths between all soundings in the chart database. A problem in using the Delaunay triangulation method when creating TIN models from contour lines is terracing. In the terrain in Figure 78 from Prototype 4, St. Nassa in the Stockholm archipelago, the land surface was made entirely from elevation contours, which can be clearly seen on the flat terraced island tops.

To illustrate some problems in building an underwater surface using low resolution chart data, I will use the bottom around Vinga lighthouse at the entrance to Gothenburg. The underwater data available were the soundings and contours in Figure 80.

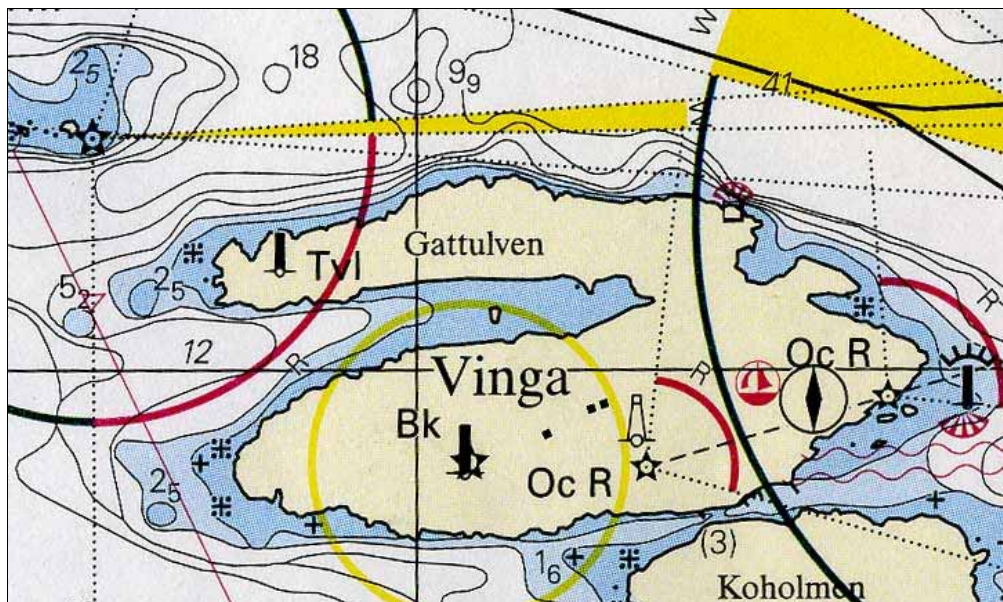


Figure 80. Chart data used to create the underwater model around Vinga lighthouse in the Gothenburg approach. Swedish Maritime Administration chart no. 9313.

The TIN model created from that data (and high resolution overwater data – to which we will return shortly) is presented in Figure 81. Note the terracing that “floods” inlets and sounds. Some of these areas are marked with yellow arrows.

To remedy this problem *break lines* was added to the data. The break lines were given “plausible” depths, for example 3 meters at the most shallow part of the sound between Vinga island and Koholmen,

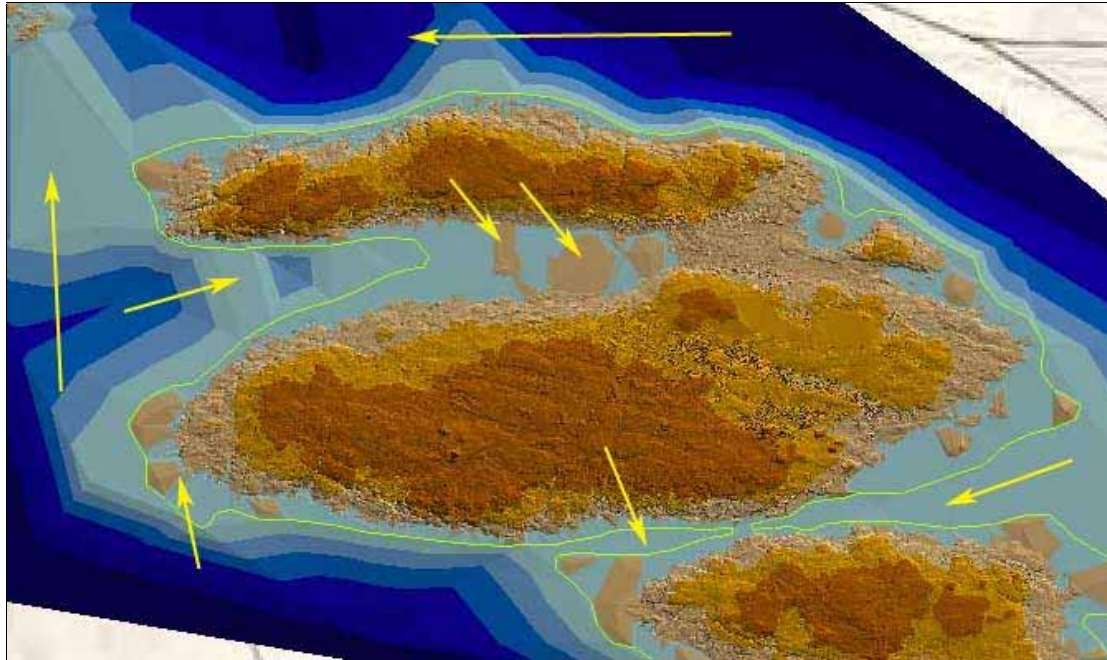


Figure 81. Look at the underwater area. The TIN model is created from the chart data in Figure 80 (plus an older chart not shown here). Note the terraced areas. Some of them, which must be dealt with, are marked with yellow arrows.

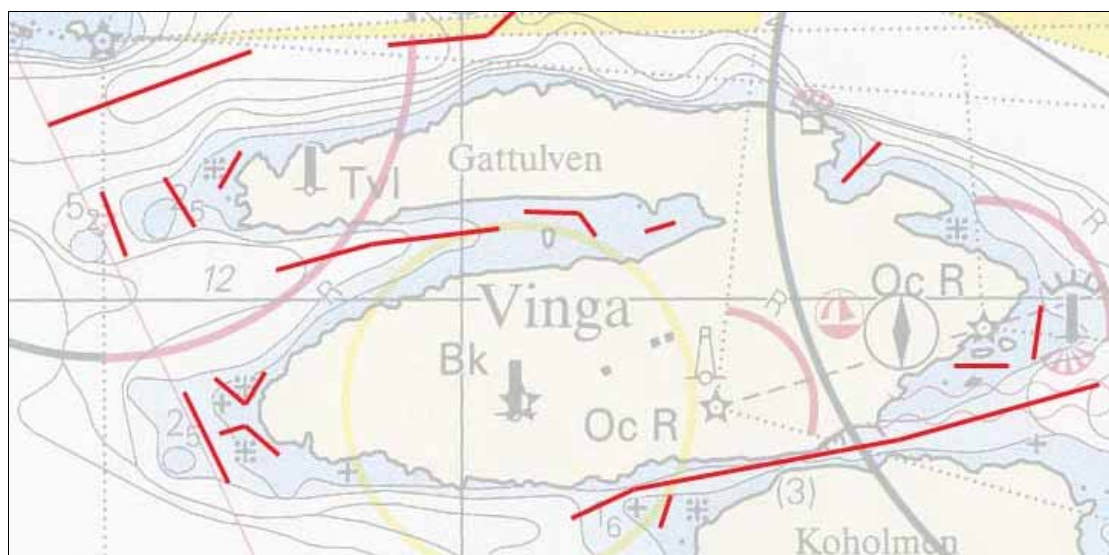


Figure 82. Break lines added in critical places (the red lines) to prevent terracing.

deeper further out in each end. These “fake” additions are shown in red in Figure 82.

The modified terrain model in Figure 83 looks much better and is probably more true to the real world than the first one.

Adding “fake” data like this is of course, unacceptable. It also it means manual fixing of underwater terrain, a work that in larger areas would be very time consuming. So, there is not only a need for data in higher resolution, but also for a more suitable format for production of 3-D models. (For more on this discussion, see the next section on the overwater terrain.)

Interpolation will always be necessary as soundings are point data. Interpolations can be made in many ways, but common for them all is that the surface that is presented in-between soundings is mathematically created and does not represent a real depth. In the

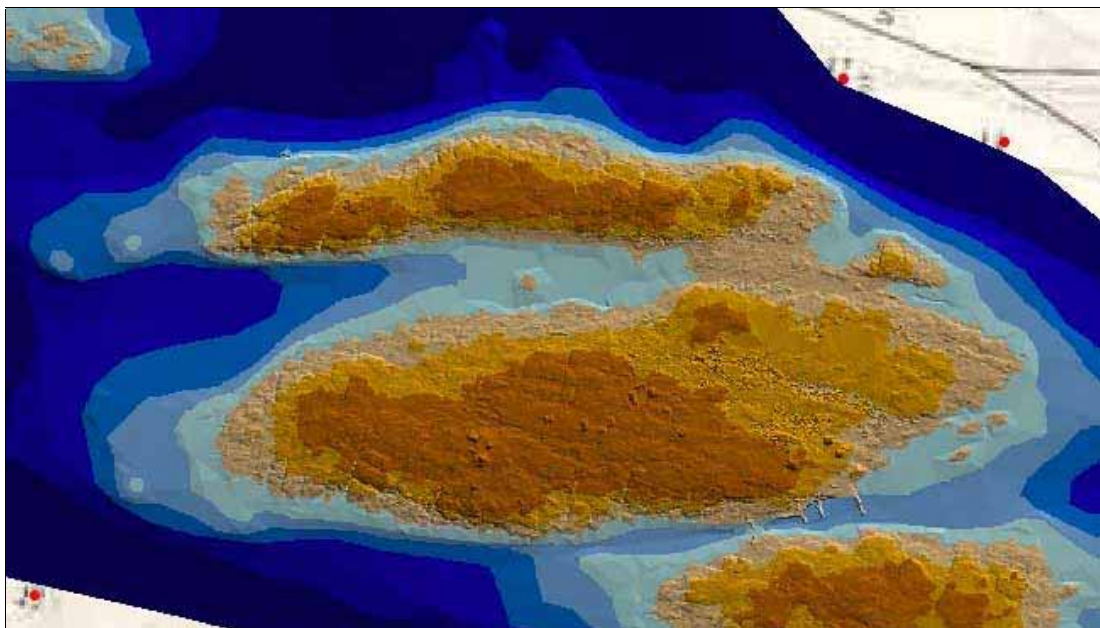


Figure 83. The “better” underwater model based on fake data added to remedy the terracing phenomenon.

physical world we can switch on our echo sounder at any location and get a true value. In a 3-D terrain model you can also switch on your virtual echo sounder at any place and get a reading. The difference is that this reading will only be true if it happens to be on the exact spot of an original sounding. In between soundings the depth will be a mathematical interpolation. With low resolution chart data this will of course be a problem. It is not that this problem does not exist with today's charts, only that in these nothing explicitly is said about the depths in the "white" areas; in a 3-D chart you can always get an explicit reading. One method to display this uncertainty could be to add an uncertainty grading to a depth reading, depending on how far from a true sounding it is.

The Overwater Terrain

Although the coastal silhouette can be an important landmark for navigation, elevation data is often missing in nautical charts. In some nations, elevation curves are printed in the nautical charts (see Figure 84 for an example from a British Admiralty chart).

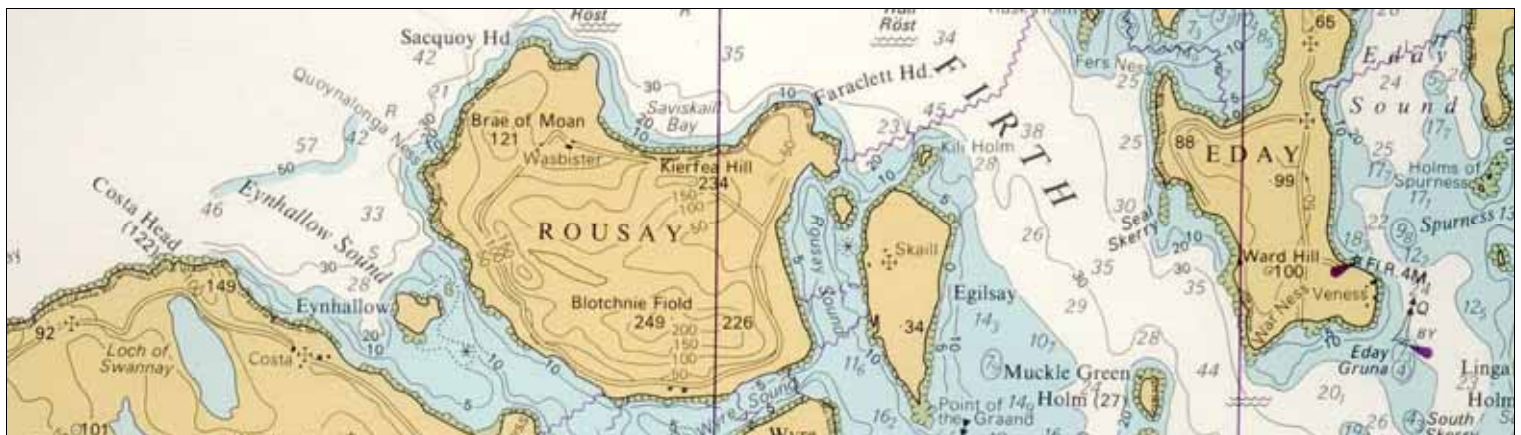


Figure 84. Example of topographical information on land areas. Rousay in the Orkney islands. Detail from Hydrographic Office, 'Scotland - north coast, Cape Wrath to Pentland Firth including the Orkney Islands, chart no. 1954 (int. 1601), International Chart Series, Taunton, 1993.

In Swedish charts, as well as in those of many other nations, this kind of topographical information is not printed although some particularly important hills or mountains might be marked. Instead, the mariner has a *Pilot*, a book of sailing directions, where he might find a *coastal view* of his area of interest. In Figure 85 an example of a coastal view is shown.

Data of interest to navigation often missing in nautical charts are land elevations and land textures, the physical geometry and textures of beacons and buoys and other buildings.

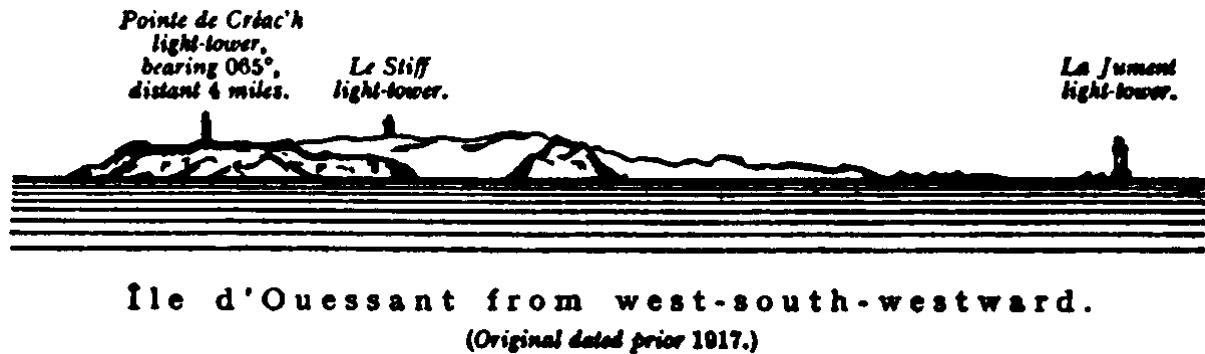


Figure 85. An excerpt from the 1956 edition of Admiralty Pilot with a coastal view of the islands of Ushant, Ile d'Ouessant at the western tip of Bretagne. (Taylor, 1956, p. 169)

The easiest way of acquiring land elevations is to use topographical maps. See the example with the air photo, the chart and the topographical map in chapter 2, Figure 34. From Hydrographica AB I acquired elevation curves with an equidistance of 2.5 m over the Stora Nassa area in the outer Stockholm archipelago. From the underwater and overwater curves I produced the terrain model previously shown in Figure 79. (Prototype 4.) In Figure 86 a detail of the original data, the 2-D map, is shown and in Figure 87, top, the 3-D model. The position and direction of the view is marked in Figure 86.

In Figure 87, top, the terrain model made from this data with its terracing is shown. Below is a photograph from the same location. The “flooding” effect that is mentioned above is clearly illustrated by the fact that the channel between the small rocks in the right-hand part of the picture becomes incorporated with the island. When the terrain was shown to users familiar with the area they commented that it was difficult to recognize islands in the model. I think this is partly because of the terracing, but also because of the smooth structure of these land shapes. Without any reference to size like the fractal structure of the rocks (or a boat for that matter) the smoothness of the surface makes the observer overestimate the size of the landscape. Details such as the clefts and steeps of the rock, as well as texture, are needed to get a sense of scale. Trees are also such details.

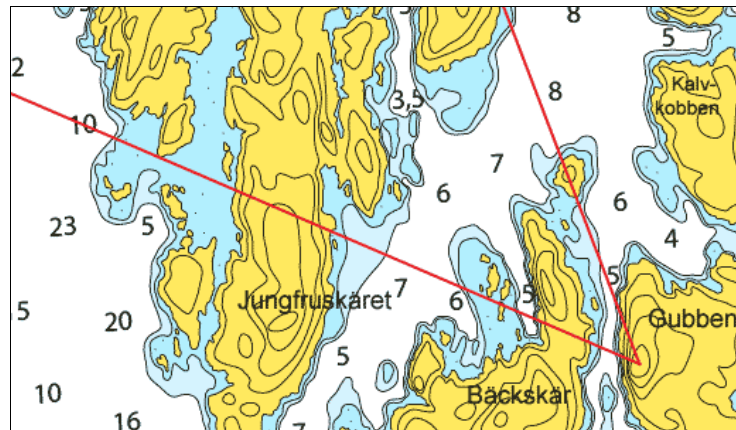


Figure 86. Detail of Stora Nassa. The view cone of the egocentric views in Figure 87 is marked. From Hydrographica's chart 613-11, St. Nassa.

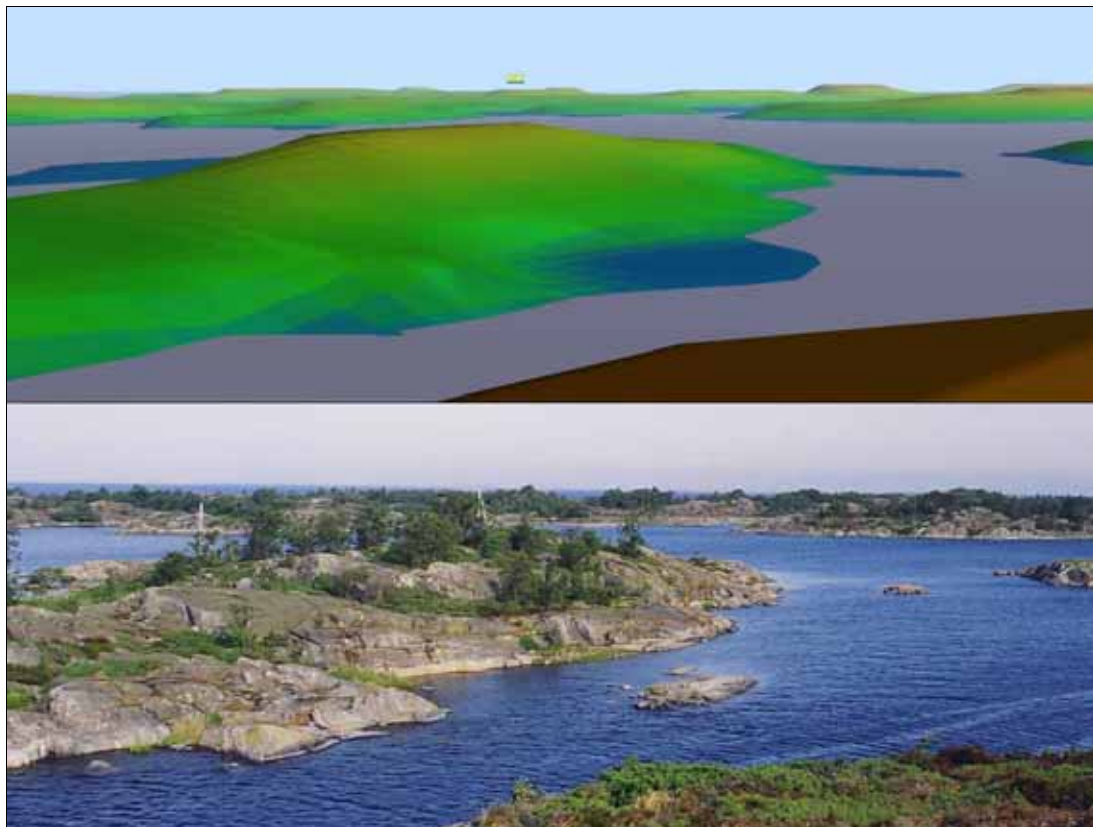


Figure 87. Top, detail from Prototype 4, Stora Nassa. Below, a photograph of the same view. The absence of reference objects like trees or boats, as well as the smoothness of the 3-D terrain, makes it easy to misjudge the scale. The terracing and flooding problem mentioned above, that occurs when making 3-D models from line data is evident. Screen shot from Prototype 4, and photo from <http://www.seascout.net/ship361/Sweden01/bcj2/2/index.html> [2006, February].

Land elevations, *Digital Elevation Models* (DEM), are typically made from satellite or air surveyes. The U.S. Geological Survey (USGS) makes elevation models available free over U.S. territory. Satellite data often comes as elevation points in a regular grid. But also here the resolution is a problem – at least at this moment. Figure 88 shows a part of a 3-D model made of Prince William Sound in Alaska. This model was made very quickly while I studied the grounding of Exxon Valdez, described in appendix A. The model is made from USGS data with 350 meters between grid data points. Compare the photograph of Valdez Narrows and the same view of the 3-D model. Too much information has disappeared between the elevation points, for example the important rock and beacon Middle Rock in the middle of the sound. For a 3-D chart the grid resolution needs to be much better.

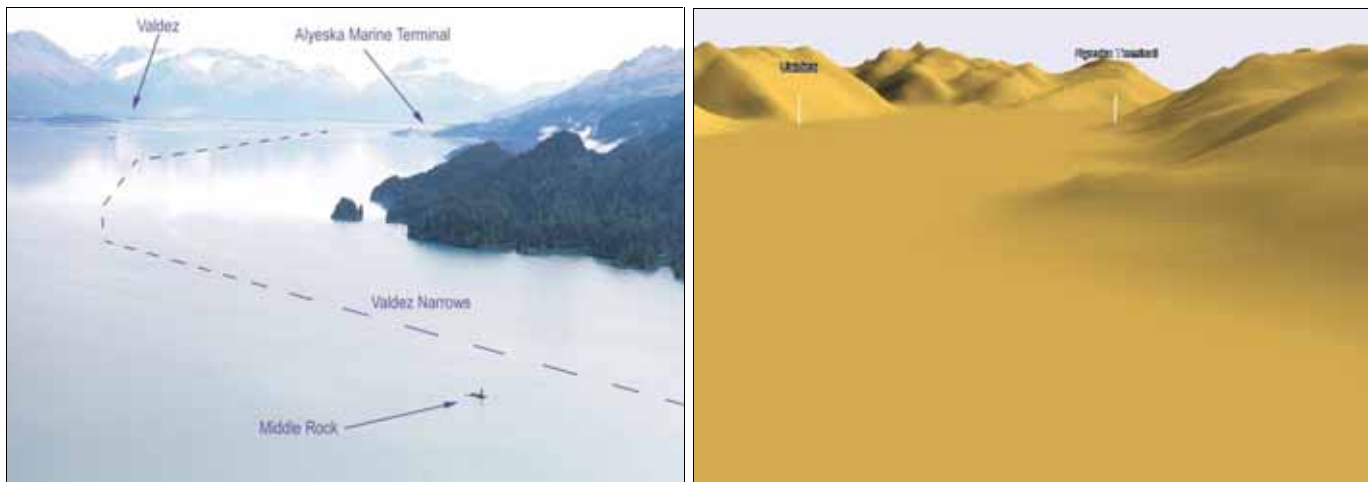


Figure 88. Left a photo of the Valdez Narrows in Alaska. Through this sound the tanker Exxon Valdez passed along the dashed line shortly before she grounded in 1989. Right, an overwater terrain produced from a Digital Elevation Model with 350 meters grid size. Much information vanishes, e.g. Middle Rock lighthouse. Photo: US Coast Pilot 9 (2005, p. 157) and screen shot from an experiment model.

In Sweden, official elevation data can be acquired from the land survey, Lantmäteriet. These data are from orthophotos but a common feature is that the resolution is low. DEMs with regular grid resolution of 50 meters are available. The mean vertical error of this data is 2.5 meters but in many cases this is doubtful and it may be even bigger (Talts,

1999). A 50 meters grid is not good enough for 3-D charts, too many features risk being left out.

The resolution of satellite data is improving with technical development. In the summer of 2006 the German TerraSAR-X satellite is due to be launched promising DEM data with a resolution of 1-2 meters (DLR - Deutsches Zentrum für Luft- und Raumfahrt, 2005). This resolution would do well for overwater terrain if only accuracy is enough.

While waiting for better and cheaper satellite data, photos and LIDAR data from airplane and helicopter is what is available. Because these aircrafts fly lower and slower than satellites, the resolution is better. It is, however, very expensive and because data is often not in store, operations have to be commissioned which raises the price even further.

One method of gathering elevation data is by photogrammetry from stereo air photos. By measuring the same location in two air photos taken from two different airplane locations the three-dimensional position relative a known position on the ground can be determined. In 2002 I managed to acquire 18 square kilometers of elevation and orthophoto data over a part of the Stockholm archipelago from a commercial air photo company. From that data I built Prototype 5, Ägnö archipelago. In Figure 89, top, the grid pattern of elevation points with a 2 meter resolution can be seen overlaid an orthophoto. Below a terrain model made from that same data.

The 2 meter resolution of elevation data allowed a reasonable compromise allowing cliffs and crevices to be visible. Inlets and small rocks are present and the model allows smaller boats to navigate close to land in the archipelago. See Figure 90.

Subjects testing Prototype 5 agreed that the resolution of 2 meters of the terrain model was enough, but there was a problem with the so called *bare earth elevation*. The elevation points were all measured to the ground level and in this way the terrain was stripped of vegetation. Losing the vegetation meant losing the realistic canopy of the islands.

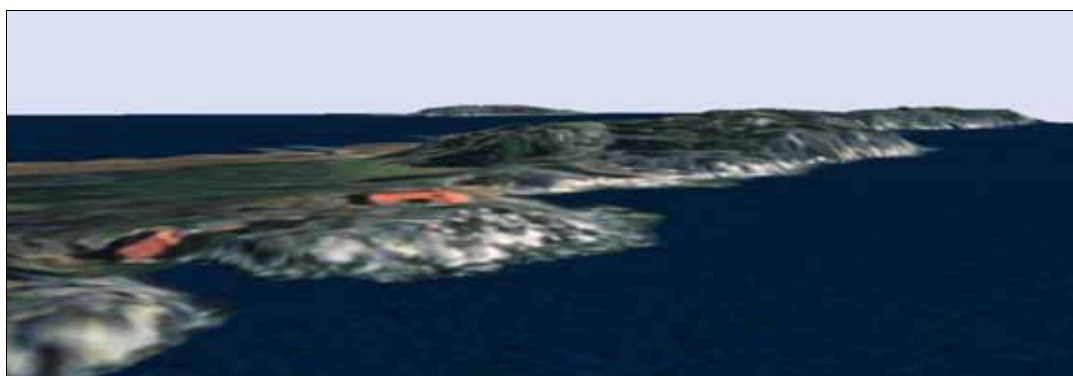


Figure 89. Top, the blue points are elevation points in a regular 2 meter grid pattern on top of a orthophoto. Bottom, a terrain model made from this data.

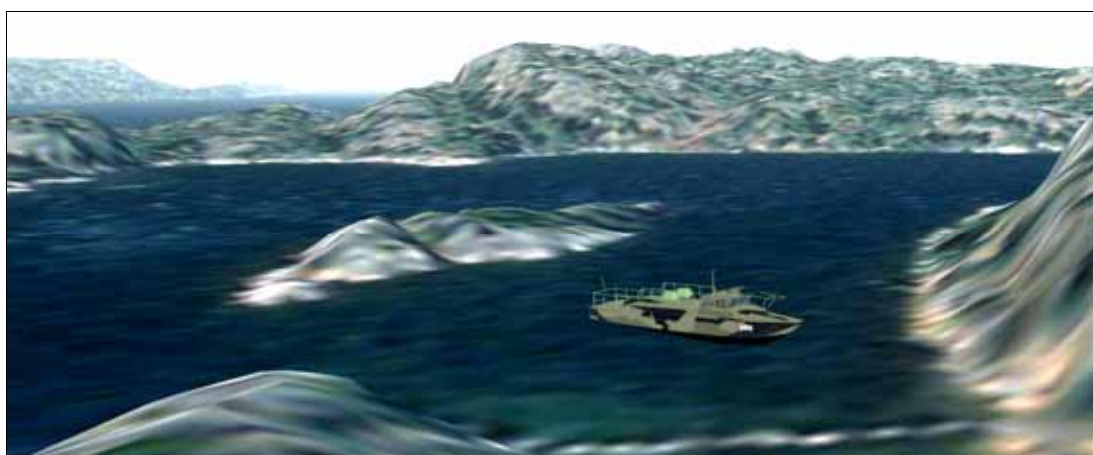


Figure 90. The Ägnö terrain model with elevation data of 2 meters resolution. Here a combat boat 90 in the bay of Lilla Korpomaren in the Ägnö archipelago (Prototype 5). Boat model by Svante Fransson.

Comments indicated that this made orientation in the 3-D chart difficult as the realistic silhouette disappeared.

To remedy this I went on looking at laser radar technique (often called LIDAR – *light detection and ranging*). An airborne laser is used to send light pulses to the ground. The reflected light is then recorded and the travel time gives the distance between the helicopter or airplane and the reflected point. The laser swings back and forth under the aircraft measuring a zigzag track on the ground. The resolution depends on flying altitude, speed and number of passages. Data is not girded but arbitrary and a typical resolution is about 0.5 meter. Accuracy is very high – sub centimeter. (TopEye, 2005)

In 2002 I could commission a remote sensing company to collect LIDAR data of the approach to Gothenburg harbor an area of 100 square kilometers. This was to become Prototype 6. In Figure 91, a top and a front view of a typical point cloud can be seen. In the front view the buildings are outlined by hits on the parts visible from above. In the top view the swells give good reflectance as the helicopter sweeps out over the sea. Otherwise, a calm water surface will reflect off light pulses that do not hit orthogonally. Black tar-paper and black metal roofs also have a tendency to “disappear.” In Figure 92 a terrain model prepared from the point cloud to a surface interpolated to a 2-meter grid and draped with orthophoto. Note the strange and “melted” appearance of the buildings, compared with the real ones in the photo.

A comment made by a subject who was shown this “raw-model” was that the realism of the terrain was very convincing but the buildings looked strange, like some sort of “organic outgrowths of the landscape” because of their “melted” look. One reason for the melted look is the down-sampling of the point cloud needed to keep the model within size for the computer. Another reason is that there will always be some distance between two points in a scan, two points cannot be on top of each other, which would be necessary to truly depict the shape of a vertical wall. A further reason for the strange look of the buildings is that they lack texture on the sides. The orthophotos only provide a horizontal texture and when this is applied to a vertical wall one or two pixels become stretched out along the whole wall. Several users commented that it is important that buildings serving as landmarks are represented in a realistic way and easy to recognize.

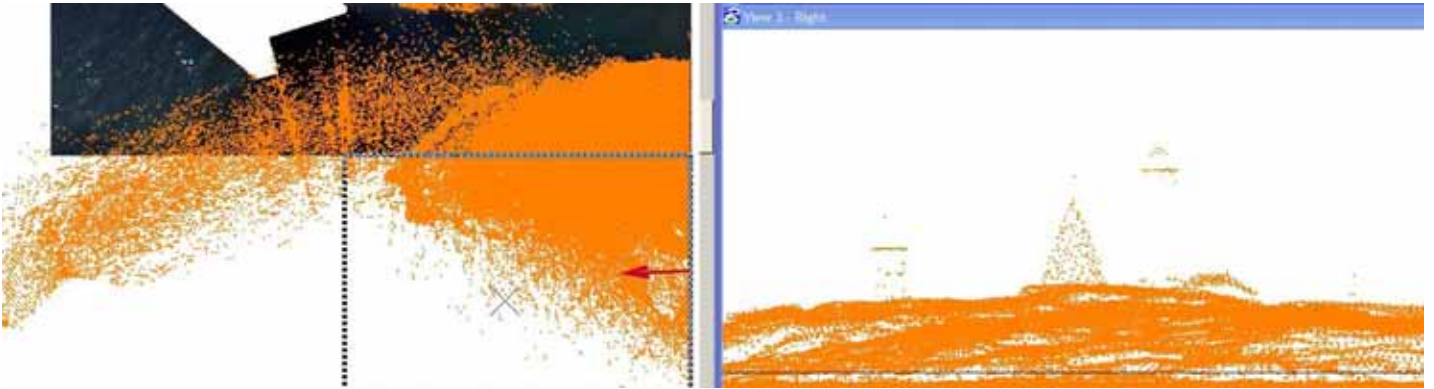


Figure 91. Left, a top view showing the horizontal spread of the point cloud, the darker upper part is a piece of the orthophoto of the water area. Right is a front view of the point cloud showing Vinga lighthouse, beacon and watch tower. A terrain model made from this data is shown below in Figure 92. Screen dump from the LIDAR classification software TerraScan.



Figure 92. A raw digital terrain model made from LIDAR data, down-sampled to 2 meter resolution and draped with orthophoto with a resolution of 25 cm per pixel. Note the somewhat “melted” look of the lighthouse, beacon and watch-tower of Vinga. Here the sea surface is not yet removed and due to heavy swells the sea surface gave good reflection for the laser pulses. The inserted photo shows the real silhouette of the beacons.

In conclusion, laser data for construction of the overwater terrain model showed very good results. The negative side is the very high price of acquisition. Hope stands to the future possibility of using satellite data with the same resolution.

Textures

The texture of the 3-D terrain surface is very important. An un-textured and un-shaded terrain is impossible to read (see Figure 93, top). By lighting the terrain model, shades and reflexes immediately start to convey form to us (see Figure 93, middle). Terrain models can also be draped with a 2-D image; this is what we call a *texture*. This image can be a drawings or photographic pictures of different kinds of surface types, such as grass, forest canopies, bedrock, etc. that is multiplied over areas classified as belonging to one group or another. But a texture can also be a photograph taken by airplane or satellite over precisely the same location described by the elevation data. Such photos have to be ortho-rectified before they can be used. The reason is that even if the camera is taking the picture straight down from underneath the plane, only the central part of the picture will be a true top view due to the small area of the lens. The outer rim of the picture will be depicted from a somewhat oblique angle. This causes distortions in that have to be corrected. The corrected picture is called an orthophoto instead of an airphoto. See the example of the terrain draped with orthophoto, bottom in Figure 93.

The representation of land forms by orthophoto draped terrain models is very realistic. All subjects who were shown the orthophoto draped terrains of Prototypes 5 and 6 preferred that to the untextured models. Small but characteristic features do not have to be represented by polygon mesh but can be represented by texture, thus creating a smaller computer file. One lasting problem is both the collection and presentation of coasts with steep, overhanging cliffs and caves. Look at the steep rock to the left in Figure 93, see how the texture is smeared out in vertical stripes as a few pixels of orthophoto have to cover a larger section of the terrain.

There is of course a cost involved in acquiring orthophotos as well, but as these can be collected at the same time as the LIDAR data, the extra cost is not dramatic. In the case of elevation models from stereo photos the raw material is often satellite or air photos which can be used both to extract elevation models and for texturing.

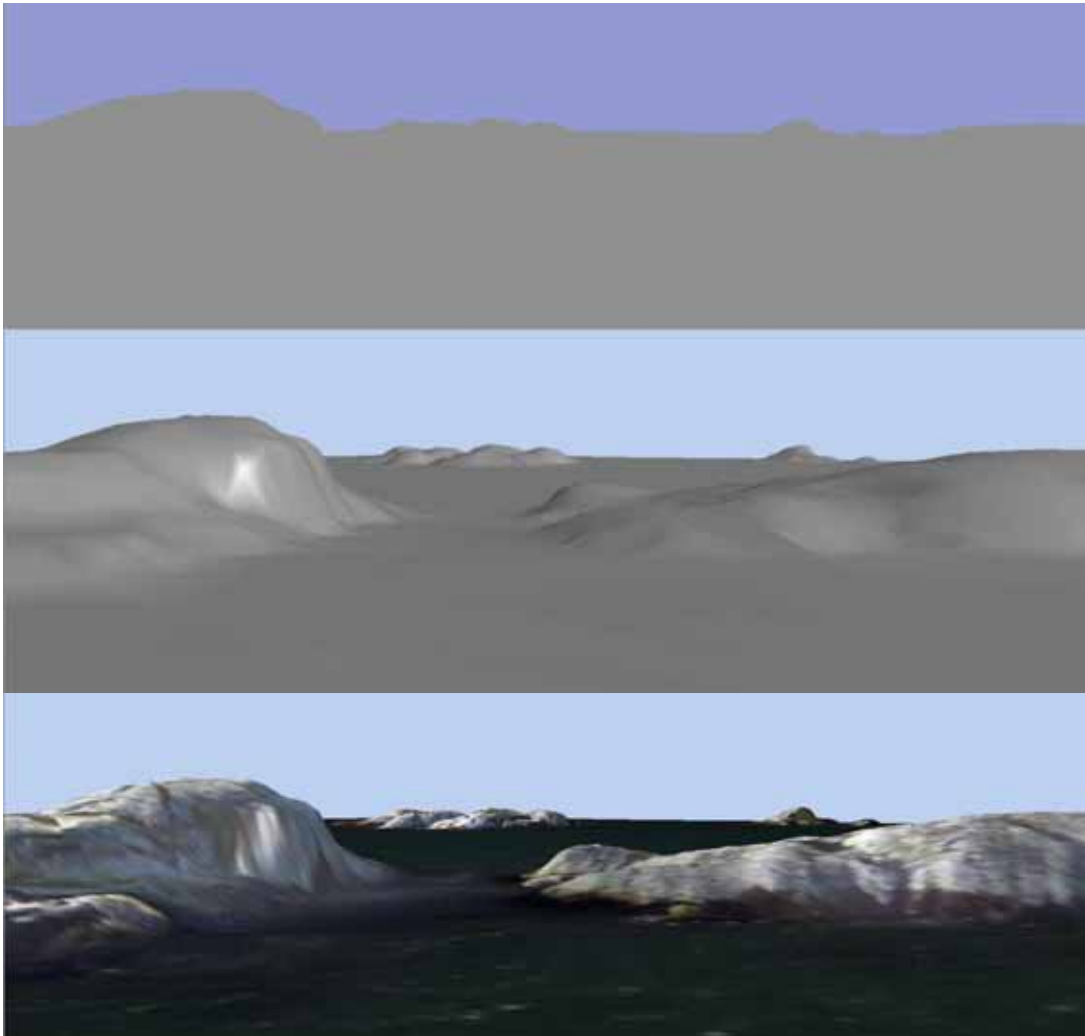


Figure 93. Shading and texture are important keys to our understanding of the world. Top, an untextured and unshaded 3-D terrain. In the middle, the same terrain but shaded, and bottom, the textured terrain. Here the shading is built into the orthophoto by the sun's shadows. From Prototype 6, the Gothenburg archipelago.

Hand-painted textures were also tried, although the amount of manual labor involved here will prevent any larger quantity of terrain from being built this way. See Figure 94 for an example from Prototype 3, Mariehamn entrance, Åland .

Subjects shown un-textured terrain (top in Figure 94) and hand-painted texture (in Figure 94, bottom), preferred the hand-texture which at least conveyed some sense of form.

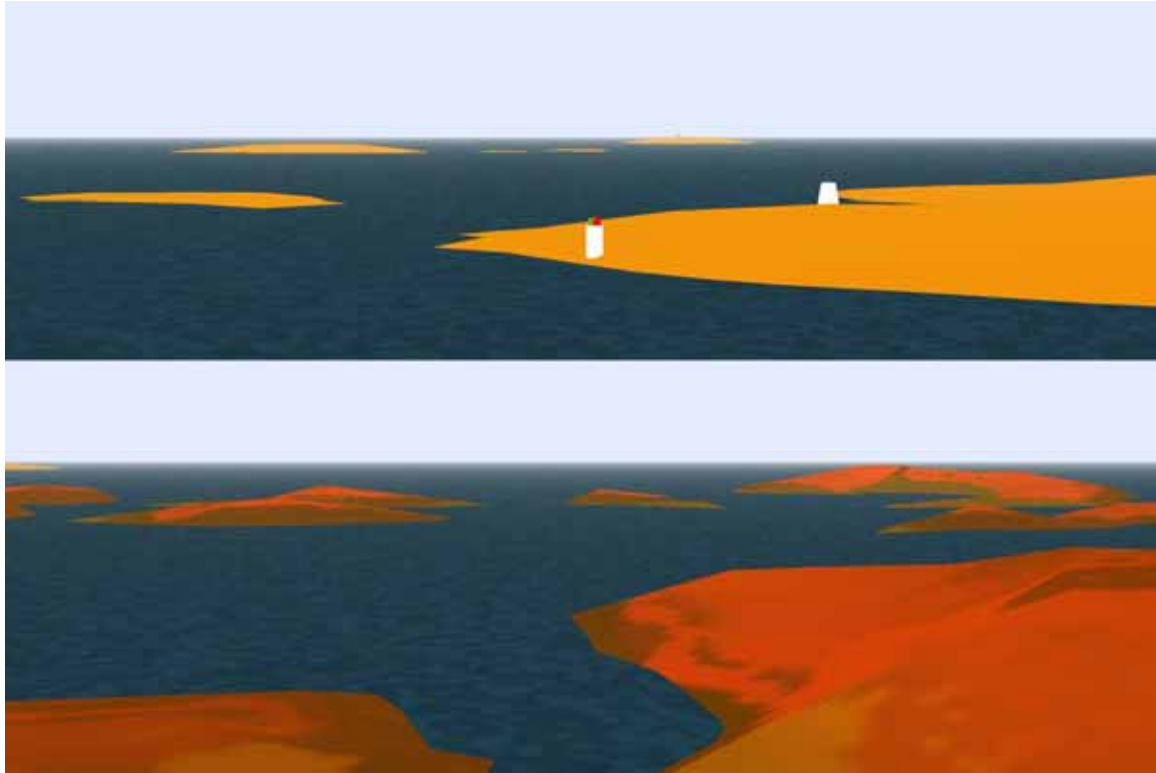


Figure 94. Untextured and hand-textured terrain surface form Prototype 3, the entrance to Mariehamn, Åland.

“Cartoon rendering” is a future interesting possibility. Using a particular rendering technique the VR software can mimic some of the techniques cartoon artists use with outlining objects and using simplified shading. This technique is used in some game software but the VR engine used in this project has not yet implemented it. However, I think that this might offer possibilities to enhance map reading in the 3-D environment, moving away from realism. Simplified colors for rock, sand and vegetation might clarify the chart. A problem when navigating in an archipelago in the real world is that islands at some distance have a tendency to merge into one another, making it difficult to see sounds and inlets. This effect is precisely the same in the 3-D chart. But with the cartoon rendering technique, which adds an outline to each island, this problem might be solved. See Figure 95 for an example of a cartoon rendered scene.



Figure 95. Example of what a cartoon rendered chart might look like. Section of Prototype 1 rendered in Cinema-4D.

The underwater terrain will also need some kind of a texture. Orthophoto is not possible to acquire except in very shallow and clear waters. Realistic, hand-painted bottom texture were tried in some early prototypes but discarded. Instead, the printed chart was used (see Figure 96).

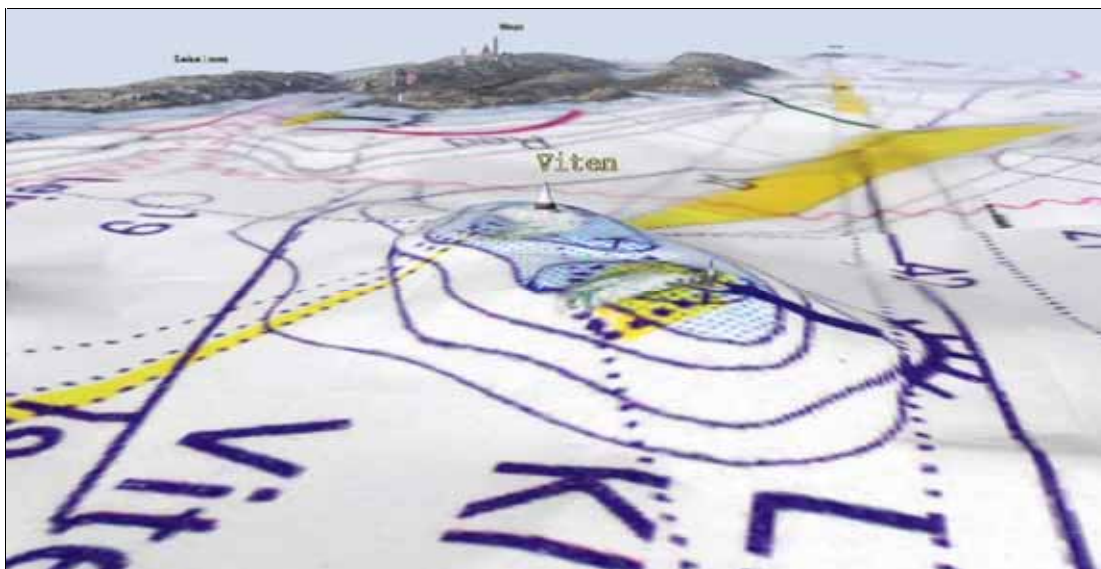


Figure 96. The printed nautical chart was used as underwater texture. Screen dump from Prototype 6.

Using the chart would serve as a check that the terrain elevation was correct and as a simple means to simulate an exocentric head-up view by letting the camera fly up and look down on the position of the own ship from above with the sea surface removed.

Tree Visualization

In coastal navigation the silhouettes of land and islands are important landmarks. The presence of forests and trees has dramatic influence on the character of an island. The bare earth elevations mentioned earlier and used in Prototype 5 strip the terrain model of features like buildings and trees. Bare earth elevations are used for flood-plane and telecommunications mapping, but for visualization purposes they seem to be problematic (see Figure 97 for an illustration of the problem). Here is a photograph and a screen dump of the same view from the bare earth terrain of Prototype 5, Ägnö,



Figure 97. Illustration of the problem of recognizing islands when the model is based on bare earth elevations. When trees are removed the silhouette changes. Bottom, a screen dump from Prototype 5; top, a photo from the same view on location in the Ägnö archipelago.

Subjects with good local knowledge of the Ägnö archipelago remarked that they could only with difficulty recognize where they were when testing the model. This was due to the absence of trees. Some islands that were “high” because of the vegetation could become very low when the bare earth elevation stripped them down to the bedrock level. For navigational purposes the loss of the tree canopy meant that the silhouette of islands was lost and with it the important factor of immediate recognition.

Recognizing the importance of correct land silhouettes along forested coasts and archipelagos, one could represent individual trees the way they are traditionally been represented in virtual environments; namely by one or two textured polygons. Figure 98 shows an example of trees visualized by two crossed, flat, polygons with a tree photo on.



Figure 98. Tree visualization from textured polygons. The representation is appealing but time consuming to make and forests use far too many polygons for real-time systems to cope with.

The result is appealing but the manual modeling is very time consuming to ensure that the islands get the right appearances. Individual trees can be automatically identified from laser data and replaced by polygon-trees. However, although it only takes one or two polygons to represent each tree, an off-coast panorama could display many millions of trees, straining also very powerful real-time systems the outmost. Ordinary polygon reduction and level-of-detail (LOD) techniques would here be of little use as they would strip far-off islands from trees, again making the silhouette incorrect.

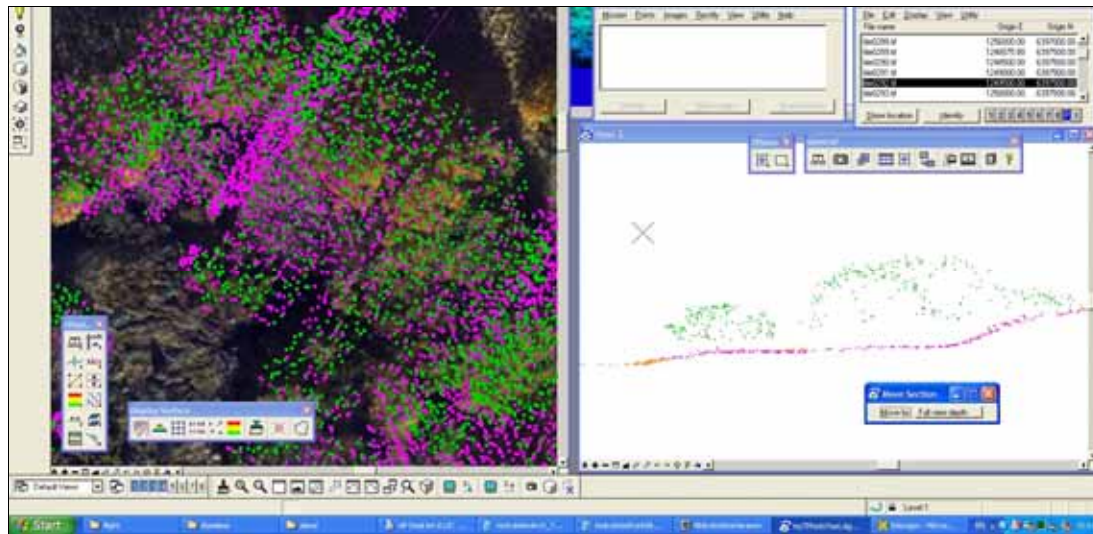


Figure 99. Classification of laser point cloud in the Terra Scan software. Left, green, purple and orange laser points on top of an orthophoto. The ground reflections under the trees are classified in purple and the top reflections from the trees in green. Single ground reflections are kept in orange. The purple ground reflections are then removed to produce a tree canopy terrain model.



Figure 100. Aspholmen in the archipelago of Gothenburg. Top is a photo from the real world. Bottom the terrain model. The air photo draping is taken at fall and the top photo in the summer which explains the color differences in the vegetation

Instead, laser scanned elevation data offer an interesting possibility. The laser beam that is thrown from the helicopter and passes through the foliage of a tree sends multiple reflections back to the receiver. The first and the last of these reflections are normally saved, thus giving a clear indication of the presence of a tree in contrast to ground hits which only return one reflection. When a bare earth elevation model is requested the first reflections are filtered away from these double reflections, but by filtering off the last (ground) reflection instead, a tree canopy can be produced. In the lower right of Figure 99 a cross-section of a tree grove can be seen. Ground reflections are classified in purple, later to be removed, and first reflections representing the tree tops are classified in green.

By removing the ground reflections in forested areas a tree canopy polygon mesh can be created. Figure 100 top is a photograph showing a grove on Aspholmen in the Gothenburg archipelago and below the terrain model where the tree canopy is kept.

To handle the enormous amount of polygons that would have to be displayed in a 3-D chart overlooking a long coastal stretch, real-time 3-D software use a technique called *Level of Detail* (LOD). The terrain is divided into blocks and each block exists in several resolutions. High resolution blocks are displayed in the foreground of the view and low resolution blocks in the distance. Terrain software like TerraVista can automatically reduce the resolution of polygon meshes and photo textures for the low LOD blocks. The important thing here is that the silhouette of forested islands in the low LOD blocks is not compromised. Tests showed that this was not the case and subjects who looked at the prototype agreed that this would be a satisfactory level of realism. Results from such a test are shown in Figure 101.

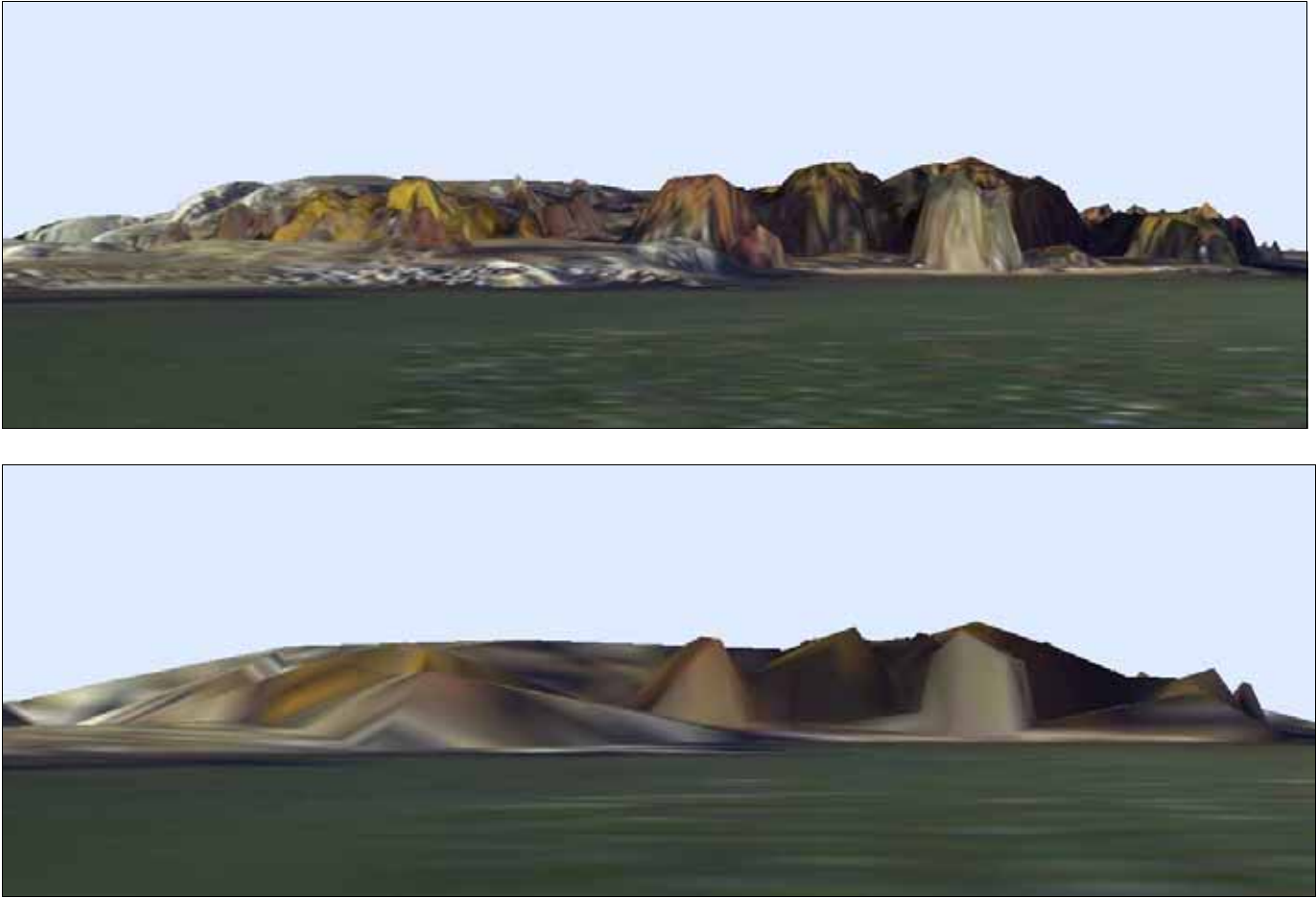


Figure 101. Test with LOD reduction of polygons necessary for the real-time system to cope with the amount of polygons. Top, a high LOD displayed at close proximity. Bottom, a low LOD displayed when the camera is at great distance. The importance here is that the silhouette is not compromised. Screen dumps from Aspholmen in the Gothenburg prototype (6).

A Flat or a Round Earth

The earth is round. This is particularly noticeable to mariners. Ships do not just fade away into a little dot as they depart, instead they sink beneath the horizon. There was an old type of cargo ship called *three-island ships* because at a distance, only the forecastle, bridge and poop decks were visible over the horizon. Already the old Greeks suspected that the fact that distant ships sank beneath the horizon must imply that the surface of the earth was curved. Then, somewhere along the line this notion was forgotten for many centuries. In Figure 102 the sequence of a

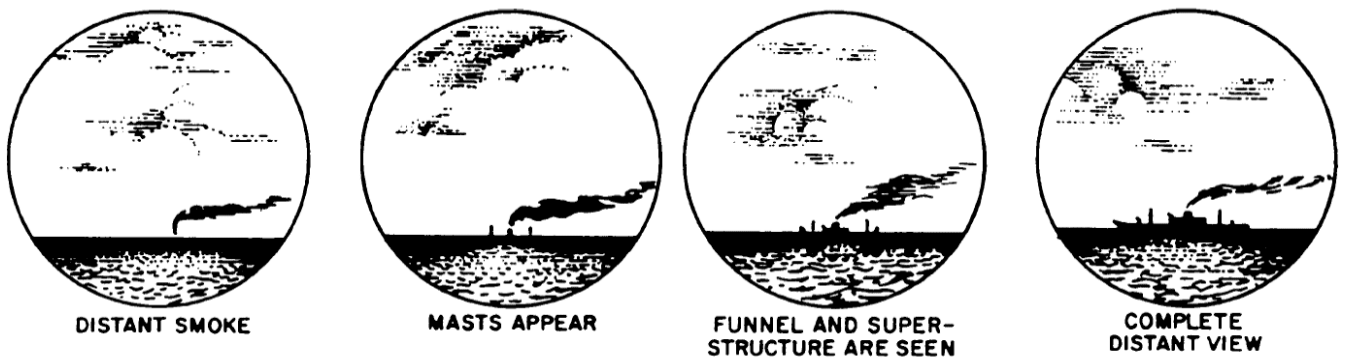


Figure 102. A sunken ship rises to the surface? Or is it just getting closer? Illustration from the U.S. Navy Lookout Training Handbook. (NAVEDTRA, 2000).

ship getting closer is illustrated, from the U.S. Navy *Lookout Training Handbook*.

If the visibility is good the distance to the horizon can be approximated with the Pythagorean Theorem knowing your height above the water. If you are 1.7 meters tall and stand on the beach with your feet in the water the horizon is about 5 kilometers away. Two swimmers will lose sight of each other at about 1,600 meters if the sea is calm and based on the equation in Figure 103³.

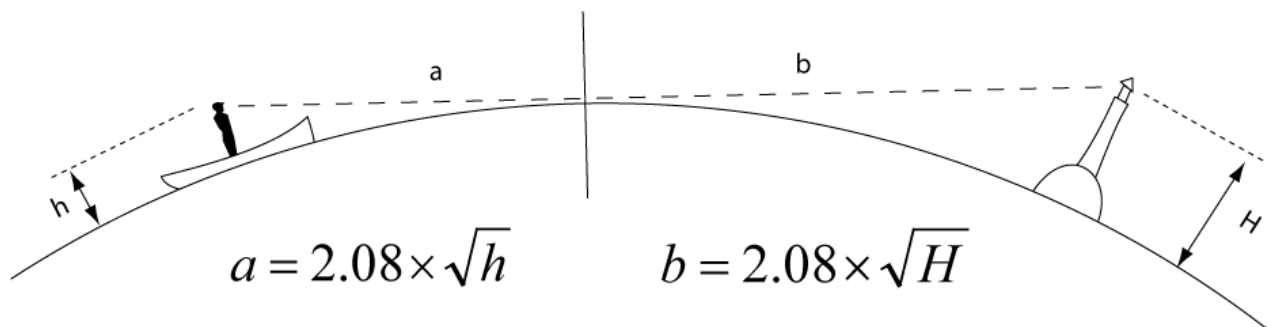


Figure 103. The formula used in navigation to calculate the distance between your boat and some object with a known height, just as it rises above the horizon. It is an approximation using the Pythagorean Theorem and the distance is given in nautical miles. (e.g. Kungl. Kommerskollegium, 1945.)

³ If one swimmer's eyes is 2 cm over the water and the top of the other swimmer's scull is 8 cm above the surface. $((2.08 * \sqrt{0.02}) + (2.08 * \sqrt{0.08})) * 1852 = 1634$.

The curvature of the earth is an evident and present fact in navigation. The point where you can expect to see an approaching coast at landfall depends on how high it is. From a low ship, in good visibility, the sight in your binoculars goes much further than to the horizon. You can not expect to see the flashing of a beacon before it is over the horizon, and then the light will suddenly be bright and clear.

So, it is evident that for a 3-D chart to properly model the physical world it will have to have the proper curvature. But in the physical world the curvature of the earth is a problem that keeps us from seeing what is beyond the horizon. Would it not be beneficial to be able to see further, particularly since, in a 3-D chart, the visibility can be infinitely good? Due to the perspective projection of the egocentric view, objects would of course be smaller and smaller, but with the mathematical possibilities of the virtual world a strong enough binocular could be provided. So, it could be beneficial to keep the 3-D chart flat, just like the map.

When you flatten the globe of the earth you get deformations. If you were to step on the half hemisphere of a squeezed orange, it would rip open along the sides before it would become flat. And so does the surface of the earth when flattened to a map, although we then allow the features to stretch out. That is why on many maps Greenland, far north on the globe, looks many times larger than Saudi Arabia, close to the equator; when both areas are about equal size, 2.2 million square kilometers. The theorem says that when projecting a curved surface on to a flat you cannot get both size and angles correct, and for the sake of compass navigation, true angles are more important.

So, for reasons of projection errors anyone who wants to build a true 3-D map of the earth will have to make it spherical (actually it is a little more complicated than that, but I will not go into that here) and the coordinate center used to measure the changing water levels would have to be at the center of the earth. It means that the mean sea level is about 6,378,137 kilometers away from the center of the earth and real-time calculations involving such large distances suffer from truncation errors and other problems. In short: the visualization system I used did not support a true geocentric coordinate system.

But you generally do not navigate with a world map, and in smaller maps, we can accept small projection errors. All my prototypes were therefore built flat using a map coordinate system (the Swedish RT 90).

Buildings, Buoys and Beacons

To anchor the display representation to the real world outside the windscreen, landmarks are needed. The term *landmark* was used by Lynch (1960) to denote buildings but can be used about any recognizable object or landform with outstanding characteristics (Golledge, 1992, p. 200). Whereas the exocentric chart shows the form of islands and coast from a view that the navigator seldom has a chance to see, the egocentric view allows direct comparison in daylight and good visibility between the map and the real world, thus facilitating the building of survey knowledge. Wickens and Hollands (2000, p. 171) stated that including distinct landmarks in a real or virtual space will help to retain user orientation, particularly if the presentation has an egocentric viewpoint.

One might ask how detailed the virtual reality of the 3-D chart should be. Purves et al. (2002) refer to the result of a survey made after testing a virtual reality mountain guide; those learning mountain navigation requested more detail to the virtual environment than the bare hill formations offered by the application. Whitaker and Cuglock-Knopp (1995) stated that landmarks are more useful if they represent artifacts (e.g. buildings and roads) than natural objects. In a coastal environment artifacts might be for example beacons, lighthouses, buoys and buildings placed in the vicinity of the beach. Another important feature would be the silhouette of islands and land. In the barren outer archipelagos of Sweden and Finland the characteristics of the low skerries are not very prominent, and so the importance of buildings and other artifacts become more obvious (see Figure 104).

Buildings and other artifacts that are depicted by the laser scan do not look real as we saw already in Figure 92. Software products for working with point data from laser scans are getting better at automatically identifying buildings and roof shapes and swap these data points for a 3-D vector model of the building. (TerraSolid, 2005) A remaining problem is that texture for the walls of buildings can not be extracted

from air photos but has to be photographed manually from the ground level.

During this project I have not had the opportunity to test building extraction techniques; instead I have manually added 3-D models of prominent buildings. With the help of the point cloud the height and size of buildings could be relatively well established. The construction of the buildings were then based on photographs and measurements made on location. It is not vital for the 3-D chart that the buildings look exactly as in the real world as long as they can be identified. A correct location is however vital. One must be able to use them in ranging in the 3-D chart as well as in the real world.

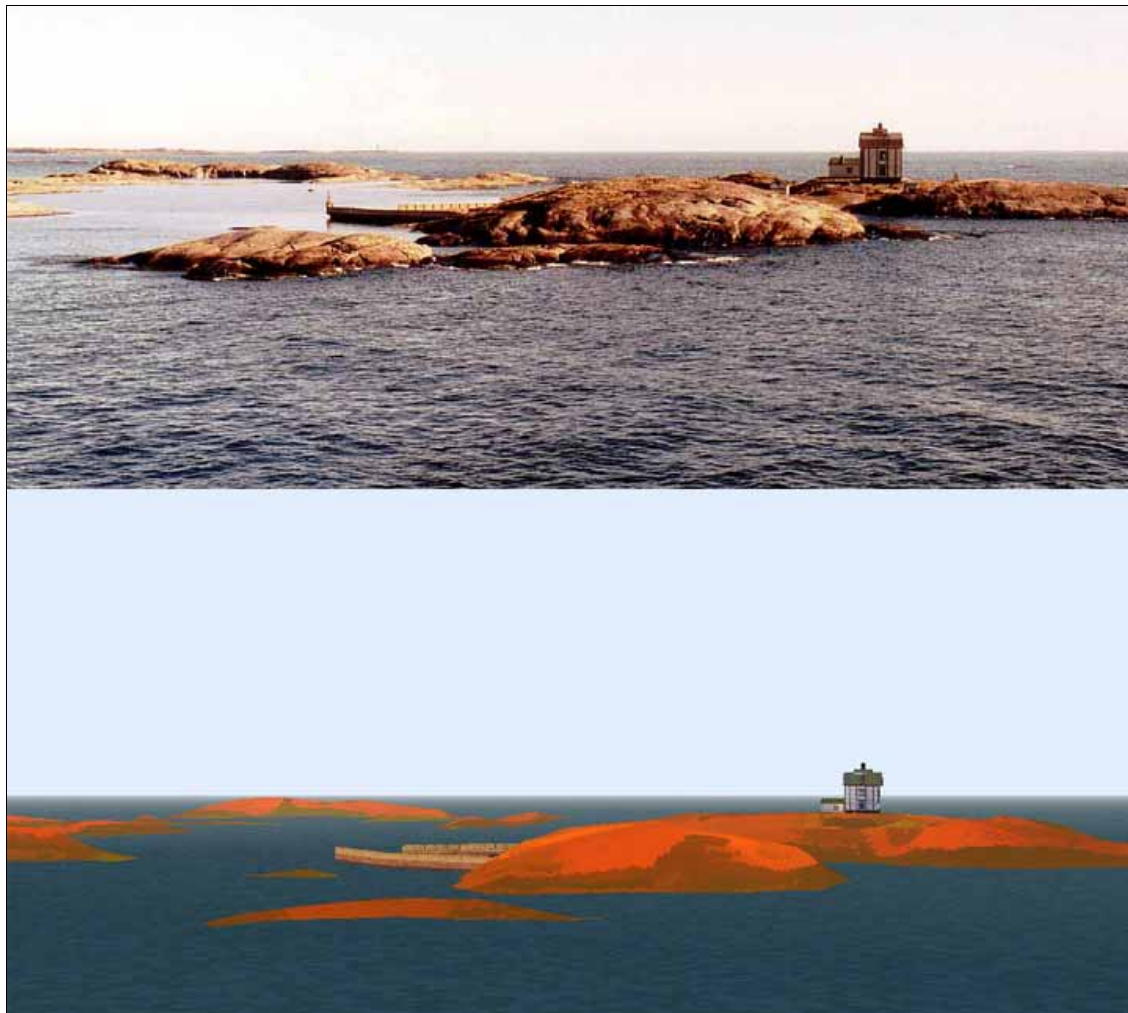


Figure 104. Kobbaklintar pilot station at the entrance to Mariehamn in the Åland archipelago (Prototype 3) shows the importance of landmarks in a cluttered archipelago of low and barren skerries.

In the top picture of Figure 105 the raw ortho-photo draped laser model is shown. The shapes of the lighthouse and the main building are caught by a few laser shots, but the little shed by the water has only got two hits on the roof and are represented by two sharp cones. A ruff 3-D model of the house and the lighthouse was made and dressed with photo texture taken on location. They were then placed and scaled on to the terrain model using the raw laser forms which afterwards were removed. The middle picture of Figure 105 shows the finished model. The bottom part shows, as a comparison, a photo from the same position in the real world. The flag pole and all of the minor buildings



Figure 105. Laser scanned elevation model. Top: the ortho-photo draped polygon model made from raw laser data. Middle, the 3-D chart with hand made buildings. Bottom, a photo from the real world. Gäveskar lighthouse in the Gothenburg archipelago.

are omitted. The question is how far it is necessary to carry the demand for realism. Comments made by several informants indicate that it is only necessary to build the characteristic landmarks that give each location its identity, and, of course, all the artifacts used for navigation. I can also imagine that in the beginning 3-D charts will be rather course, but given time and increasing demands, realism will improve. 3-D charts, as well as traditional charts, must be kept updated as, for instance, new houses will be built and forests clear-cut.

4.4 Symbolic Features

So far I have talked about the realistic features of the 3-D chart and how to make this as similar to the real world as it takes to make a comparison between the two perspectives possible in the bridge perspective.

The other two features suggested in the introduction were however symbolic and have no correspondence in the physical world: The NoGo area polygons and the seaway network.

NoGo Area Polygons

The idea behind the dynamic NoGo area polygons is that instead of presenting all the different depths to the navigator, the water surface will be coded with two colors: areas deep enough, *free*, and areas too shallow, *NoGo*. The calculations of the under-keel clearance due to bottom topography, present draught, and present water level, are made by the system and the water is colored where it is not safe to go. The



Figure 106. Surrounded Islands, Biscayne Bay, Miami, Florida. Artwork by Christo and Jeanne-Claude, 1980-83. Photo: Wolfgang Volz, ©1983 Christo.

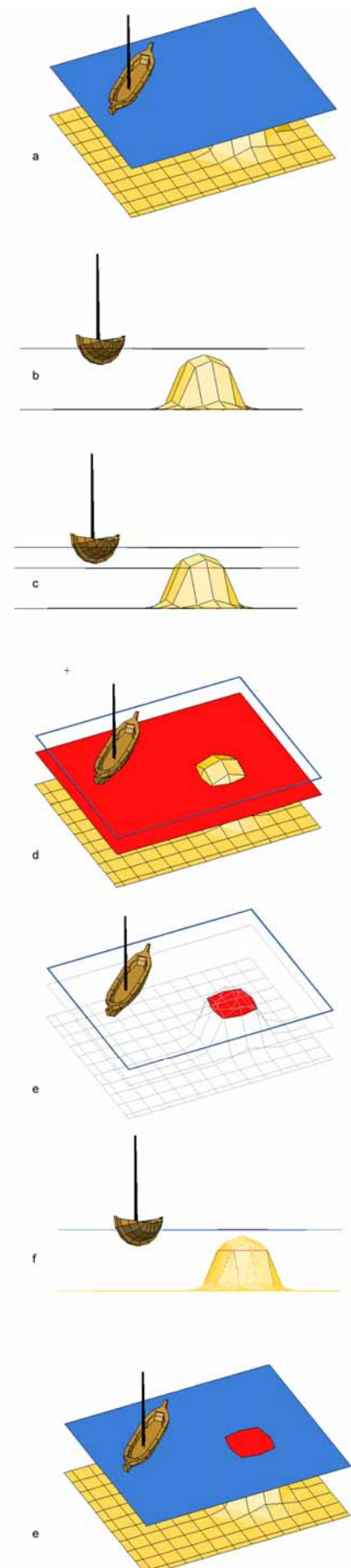
results presented in the 3-D chart will much resemble the artwork made by the artists Christo and Jeanne-Claude in Miami, Florida, 1980-83 (see Figure 106).

The dynamic safety contours could be calculated in real-time using geometrical computation directly on the 3-D TIN-model or using a raster analyses method. Both methods depend on the existence of a topographical elevation model of the sea floor and the presence of data of the ships draught and the water level.

Geometrical Computation

The geometrical computation method is illustrated in Figure 107. Simply put an intersection plane is placed parallel to the water surface at such a distance from the chart datum as described in the introduction chapter. The intersection area is then saved as a colored polygon structure and translated vertically up to be displayed on top of the water surface.

Figure 107. By intersecting the terrain mesh with a plane at the appropriate depth (a-d), saving the intersection area (e) and displaying it on top of the water surface (f), the No-Go area polygons are created.



Raster Computation

The raster method is illustrated in Figure 108. In this method the depth values (expressed as positive values) of the bottom topography (a) is saved as an attribute in a grid, like a bit map picture (b). The spatial (x, y) or (long, lat) value is saved in the position of each grid box. The resolution of the grid depends on the available data resolution or can be adapted to, for example, the size of the ship. In another grid of the same size and resolution the current water level (plus or minus) is saved (c). Then different layers can be created for the ships draught, heave, clearance and squat. Here illustrated by the single layer (d). By putting these layers on top of each other and for each grid cell making the simple Boolean query

$$b + c + d > 0$$

gives us the NoGo area too shallow for the ship. We save the result of the query in a new grid (e). The grid cells with the value *True* (colored) are where the water is too shallow and the grid cells with the value *False* (transparent) are where there is enough water under the keel. This raster layer can then be added to the water surface texture.

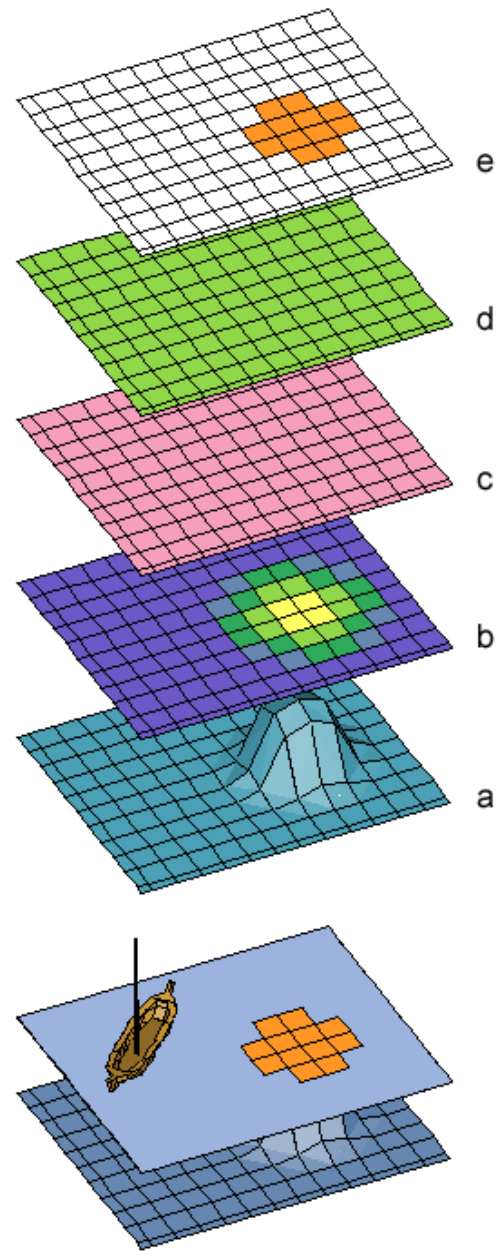


Figure 108. The raster method of creating the No-Go area polygons. See the text for a description of the procedure.

The polygons or raster image could then be displayed in both in the egocentric 3-D view and the exocentric 2-D view as the NOGo area. The system would be fed by data from tidal tables, weather service and onboard sensors. By disengaging from the current position the system could go into a simulation mode and display NoGo polygons for future positions ahead on the journey. These polygons could be calculated for the tidal situation relevant to a future time based on speed and traveled route of the ship.

Computer graphics expertise consulted ensures that this kind of computations can be made in real-time for a limited and custom sized area around the ship. For Prototype 6 I have, however used pre-computed NoGo area polygons prepared in 50 centimeters increments.

The color of these warning symbols is open to discussion. The normal warning color red is in the nautical navigation domain connected to the color of port navigation light and port side channel buoys and in this project also the port side seaway lane. In Scandinavia, very shallow water can be discriminated by a light, yellowish green color, due to the bottom vegetation. This color would naturally serve as a warning color for mariners, so it was chosen for the NoGo polygons in the prototypes. For an example of how the safety contours could look, see the screen dump in Figure 109 and Figure 110.

The water surface is also raised and lowered according to the current water level. In Sweden this might not be of major interest but in areas affected by large differences in tidal water this might be of greater interest. This feature is illustrated in Figure 110.

Future research on this feature would involve monitoring the whole voyage ahead against the tidal situation. Delays might for instance lead to other tidal levels than was originally planned. Monitoring speed against depths ahead is also necessary to be able to issue warnings for possibly dangerous suction effects when passing, for instance, thresholds in the navigation channel.

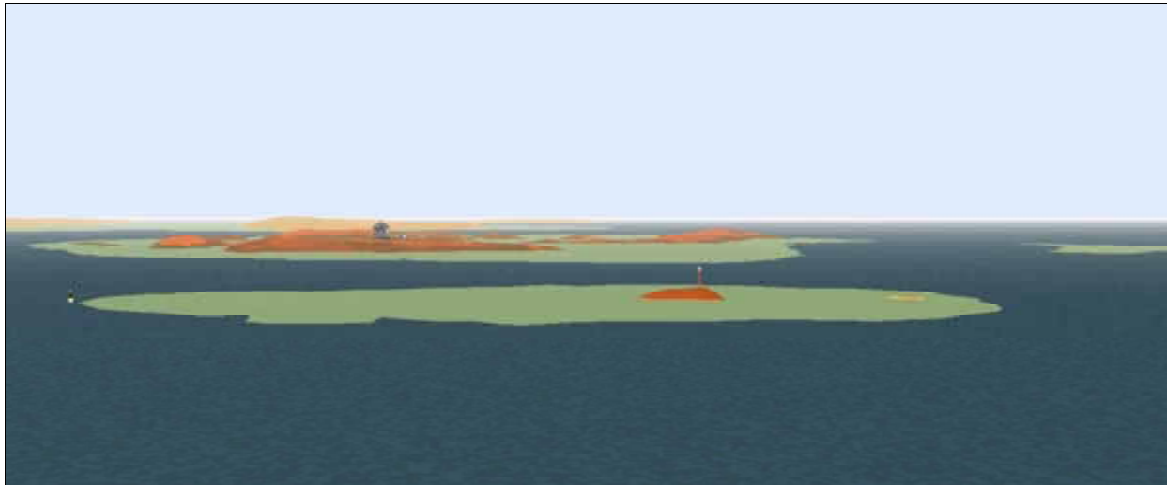


Figure 109. Dynamic No-Go area polygons in the egocentric 3-D mode. Here the polygons are set at 10 meters. Screen dump from Prototype 3 over the Mariehamn entrance in the Åland archipelago.



Figure 110. Dynamic No-Go area polygons in Prototype 6, the entrance to Gothenburg. Here Vinga Ungar lighthouse. In the top picture the polygons are set for a draught of 2.5 meters and 1 m high water. In the bottom picture the draught is still 2.5 meters and the water level is 1 meter low water.

Seaways and Track-lines

The suggestion is to construct a network of seaways with separate shipping lanes for traffic in opposite directions. It would be like the separation schemes that exist in some places of dense traffic, like the English Channel. The network could be based on the fairways of today which in the charts are marked with a single line. Figure 111 shows a design suggestion.

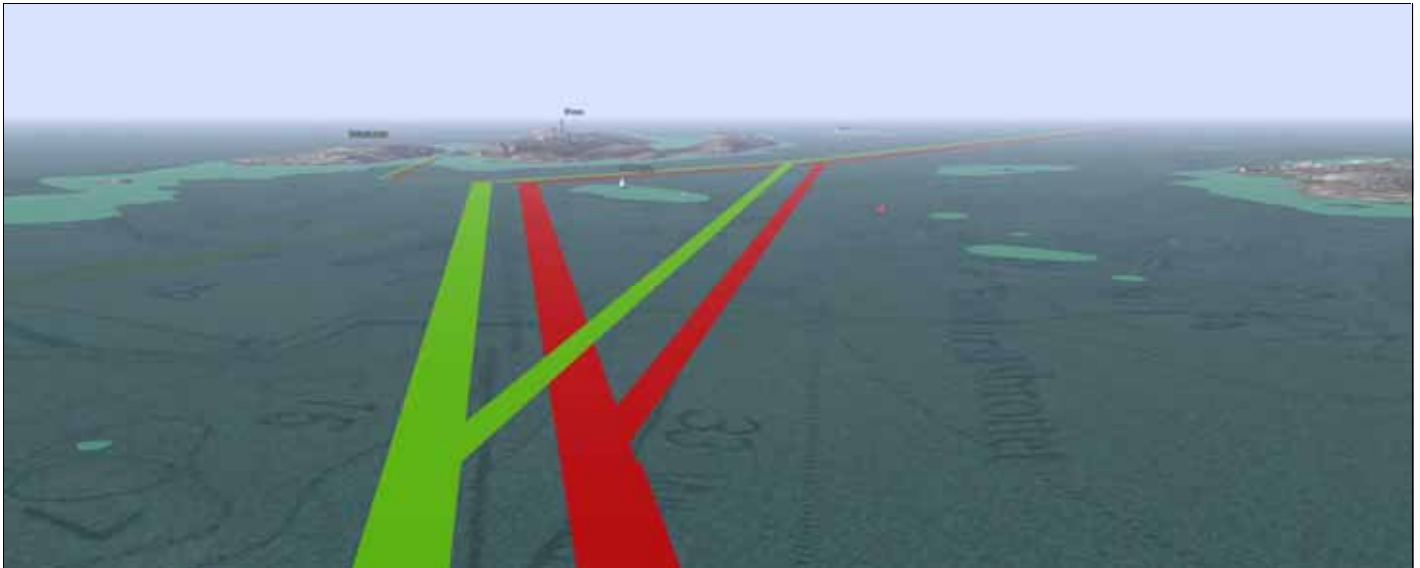


Figure 111. Sea-ways for the north-western entrance to Gothenburg harbor passed Vinga lighthouse. Screen shot from Prototype 6.

The two tracks are colored based on the IALA-A system according to which all fairways have a direction. The general rules for the direction is that it goes from the sea towards harbor, and, in Sweden counter clockwise around the coast, south on The West Coast and north on the East Coast. Generally in the archipelagos you will need a chart to know the direction of the navigational channels. When going in the direction of the channel you will have green buoys on your starboard side and red buoys on the port side.

The effect of the system is that you might have to pass through channels with different directions during a journey and that you may sometimes have green buoys on your starboard side and sometimes red. In Figure 112 the Swedish chart 624, previously shown, illustrates the different

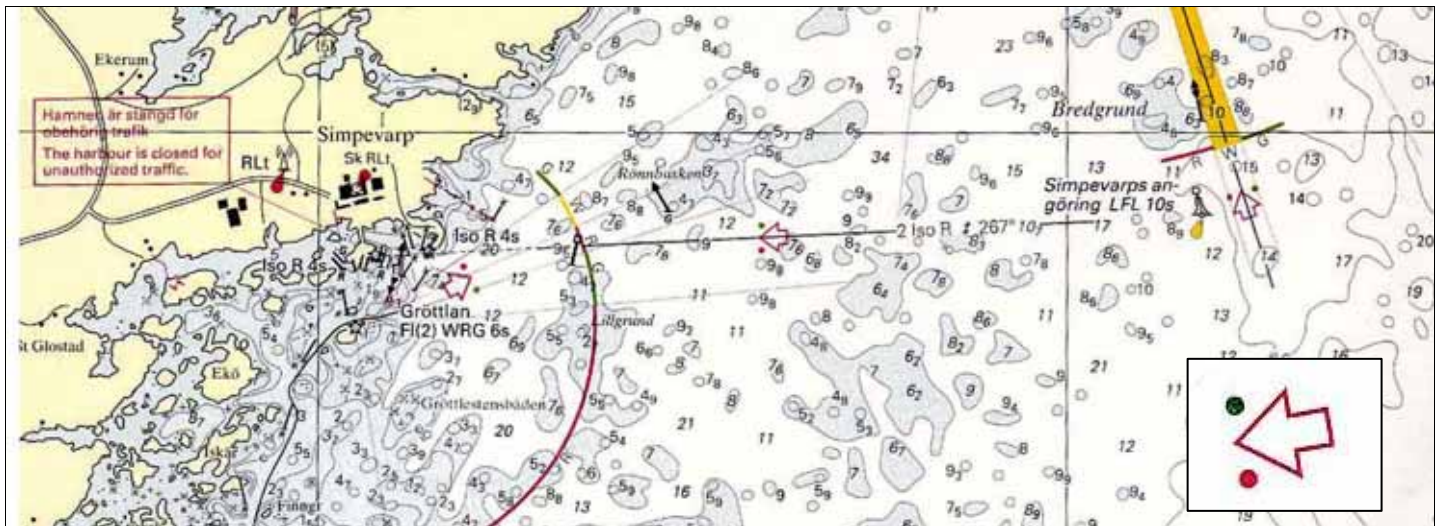


Figure 112. The direction of the fairways are marked with a red arrow and the colors of the lateral marks. Swedish Maritime Administration, chart no. 624, 1988. 1:50.000

directions of the fairways. The red arrow with the red and green dots marks the direction.

Imagine that you come from the north in the yellow sector against the direction with green marks on your port and then turn starboard going east towards Simpevarp. You will now have red marks on your port side. Approaching the harbor you turn port to continue your voyage along the narrow and troublesome inner channel passed Göttlan lighthouse, you will again have green marks on your port side.

A dual-lane network of colored “carpets” would not only serve as a track line, it would also serve as a reminder of the colors of the physical buoys. In Figure 113 an example of how it may look when going along the seaway in the Ägnö archipelago of Prototype 5.

Own Track Line

On the sea you are mostly free to go wherever you want (as long a depth and regulations let you). When you use the public seaways you will have to go in the proper lane, but sometimes you may want to take a short cut over “wild” water. An *individual track-line*, showing you own ship’s planned route, will then guide the ship. Officers piloting the large

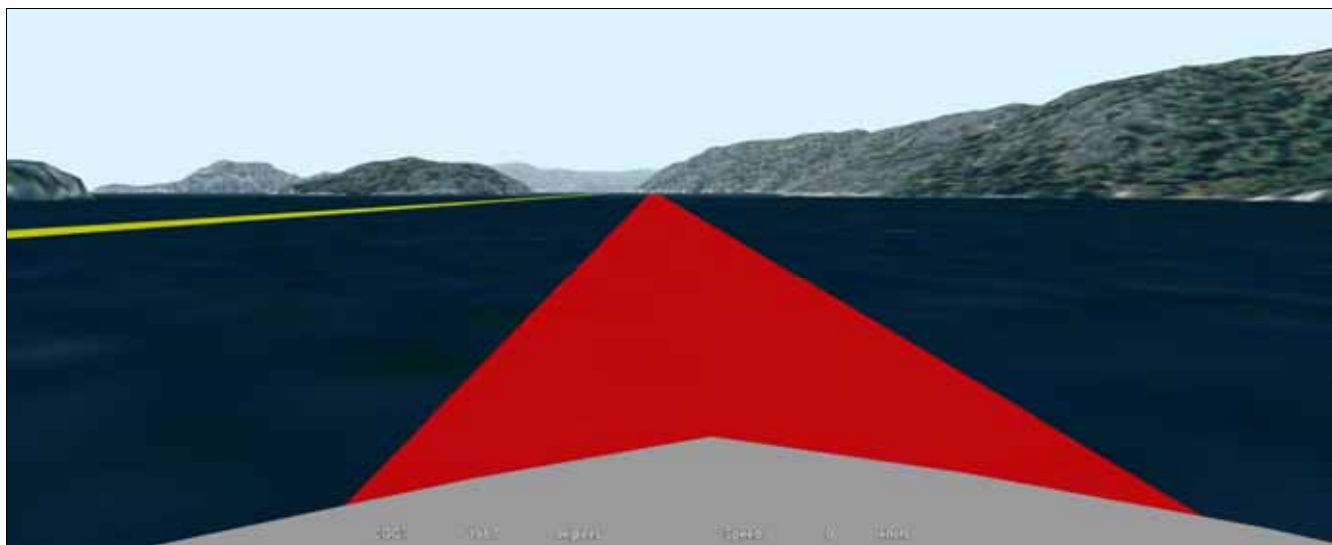


Figure 113. Seaways, in the starboard lane, going against the direction of the fairway with red marks on your starboard and green on your port. From Prototype 5, SW course, Ägnö on starboard.

Baltic ferries through the dense Swedish and Finnish archipelagos have, during their training for a pilot's exemption, to construct a *course book* to learn to know their way through the archipelago. After finished exam many of them still preferred to use the track line programmed into their route plan, and visualized on the radar screen, as an ideal course (Lützhöft, 2004, p. 25).

In Figure 114 the suggested white, *individual track-line*, is shown. This line is the same track-line that connects way-points programmed into the GPS navigator and which is displayed in the traditional electronic chart or, optionally, on the radar screen.

In this project the seaways and the track-lines were manually placed on top of the water in Prototypes 5 and 6 just to demonstrate their purpose. No actual connection to programmed way-points of the GPS was tested. See also future research in chapter 6 for a concept of *automatic wayfinding*.



Figure 114. Seaways. We are leaving Napoleonviken heading S in the starboard lane following the own individual (white) track. From Prototype 5.

Signs

On the land-based road network a signage system helps the motorist along the way. The same principle could be used on the sea. Much information, now stored away in pilots and other publications, could be made available in a timely fashion through a virtual signage system in the 3-D chart. In Figure 115 show some examples of such possible signs.

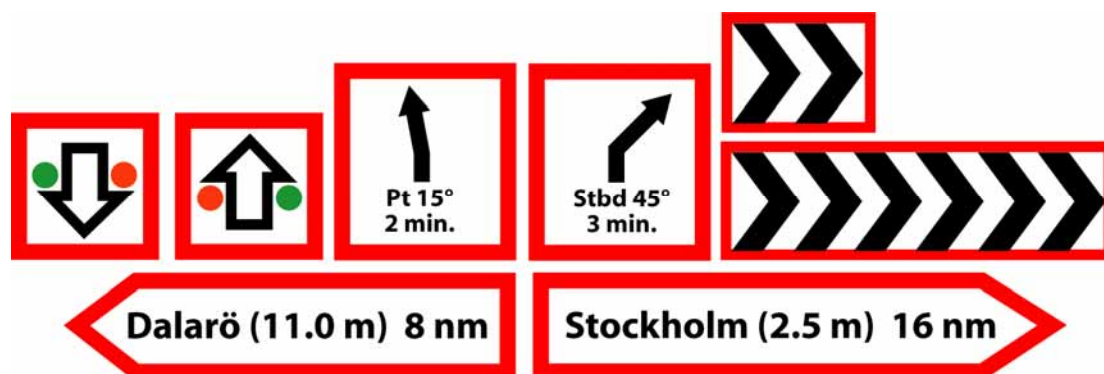


Figure 115. Some examples of suggested signs in the charts. Signs could be dynamic (e.g. turn warnings can appear for instance 3 minutes ahead of wheel over and follow the ship while counting down).

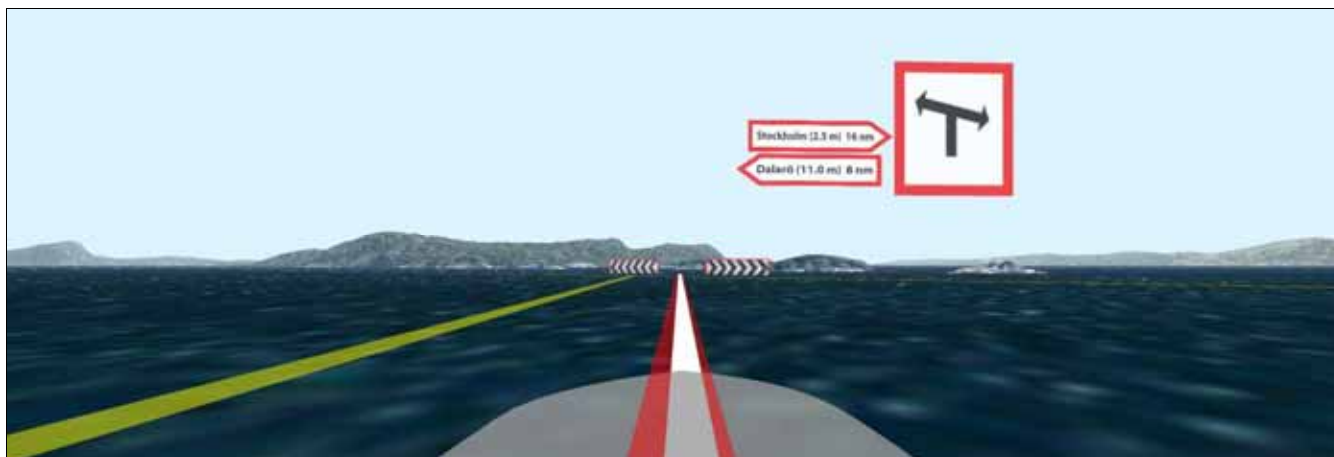


Figure 116. Road signs at sea. A seaway crossing in the Agnö archipelago. Screen dump from Prototype 5.

Augmenting Distant Objects with Pointers

One downside of the egocentric view, as we all know from our daily life, is that distant objects become very small and eventually impossible to see. When navigating a pair of binoculars is a necessary tool. Still, one often has to search for distant ships, buoys or cairns. In a 3-D chart this problem can be addressed in many ways. One way would be to enlarge distant objects and in that way make them visible. But this could lead to ambiguity as to the distance to the object because size is a distance cue. Another way which I have tried in my prototypes is a virtual pointer. It could be used for certain objects such as ships, lateral marks, buoys, lighthouses, and so forth and displayed when they are at large distances (see Figure 117).

Turn-warnings

One navy officer interviewed requested alerts of upcoming turn-points ahead of time and also an indication of the extent of the turn. One informant said he used to set the angle of the alidade on the pelorus to that of the upcoming new course to remind him of the magnitude of the turn. For small and easily maneuverable boats turns can be approximated to a singular spot, but for larger boats and ships a more complex turn model must be used involving a turn center and a turn radius, a point of wheel over, with an individual rudder angle and a turn rate indicator to keep track of the turn. The turn radius could also

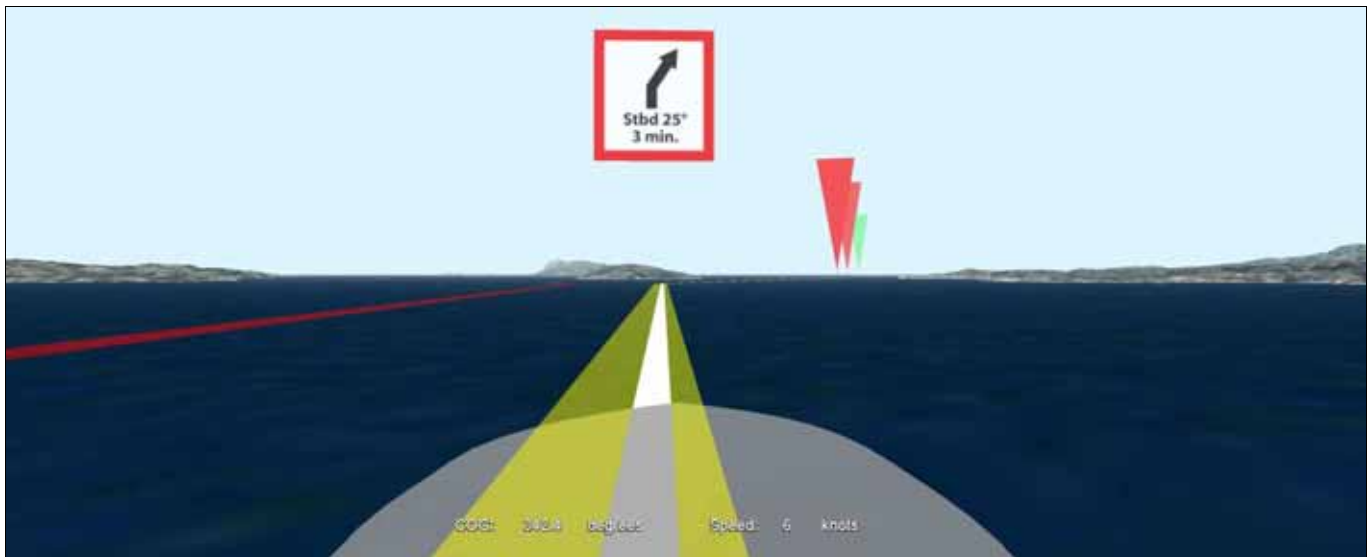


Figure 117. Three distant lateral marks are augmented with virtual pointers. Also a warning for an approaching turn, 3 minutes to wheel over. The sign follows in front of the boat counting down.

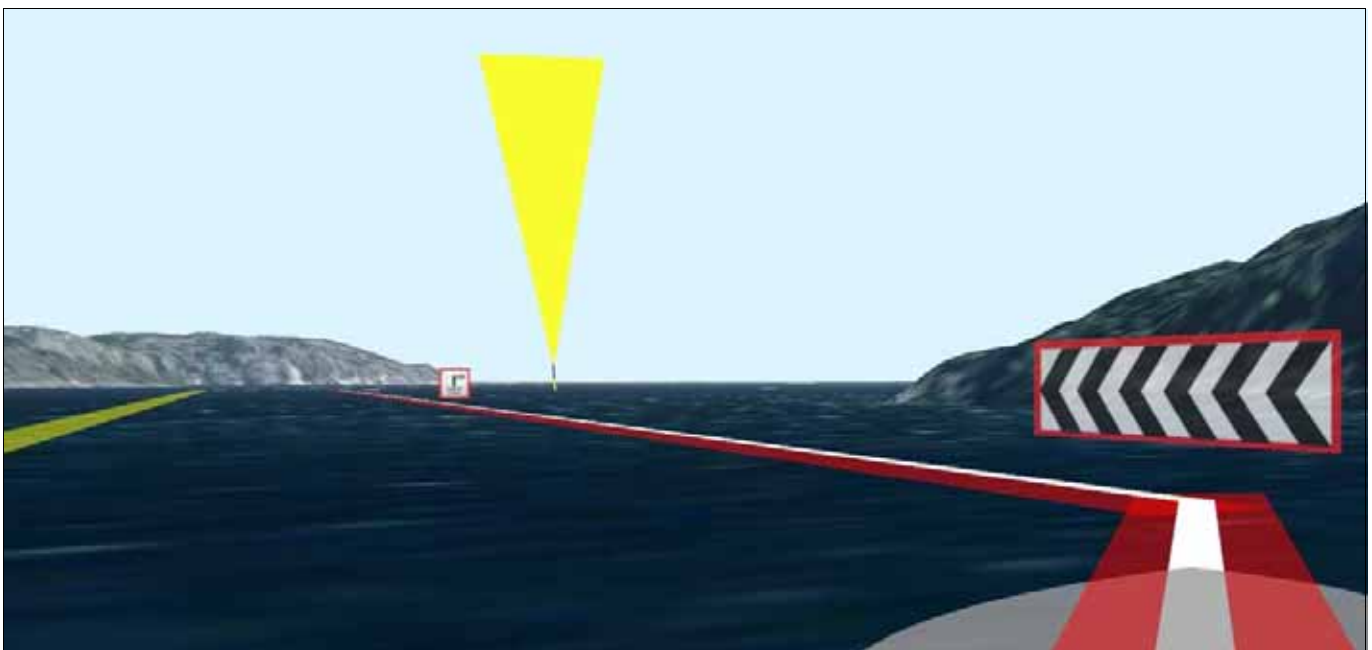


Figure 118. In the present prototypes seaway turns are visualized as sharp turns on the position of waypoints. In reality a turn has a smooth curve using a curve radius and a point of wheel over. This will be implemented in the future.

be visualized in the 3-D chart. This technique is used in electronic charts and ARPA radars.

One thing that differs compared to a signage system in the physical world is that virtual signs do not have to be present all the time. Instead, signs can be shown depending on vessel type and task, and at distances from their targets dependent on the vessel speed, just to mention a few parameters that can influence sign display.

Other Vessels

With the new Automatic Identification System (AIS) approved by the International Maritime Organization (IMO) all ships larger than 300 tons must have an AIS transponder in international traffic since 2004 and in national traffic by 2007. The AIS transponder is sending a number of data to vessels in the vicinity. Some of this data is programmed into the transponder by the ship, like name, type, destination and so forth. Other information is added automatically, like course, speed, turn rate and so on. The position of vessels in the vicinity can then be plotted on the electronic chart display and/or radar screen, tagged with, for example, the name or call sign of the ship. Before the AIS there could be a problem identifying a blob on the radar screen and communication over the VHF radio often started with “Ship on my starboard...” or “Northbound ship 12 miles east Gotska Sandön, this is...” In crowded places there could be difficulties clearing out who you were communicating with, which could lead to dangerous situations. The AIS system solved this by letting you call a ship unambiguously.

As the 3-D chart is based on the idea of picture realism, it follows that vessels in the vicinity should be visualized with a proper 3-D model. A library of ship models could accompany each chart. Some of these models could be individual, identifiable ships like ferries that traffic the area of the chart (see Figure 119 and Figure 120), other could be an anonymous standard bulk carrier or chemical tanker resized to the length and width of the AIS information and clearly marked as to be a stand in prop.

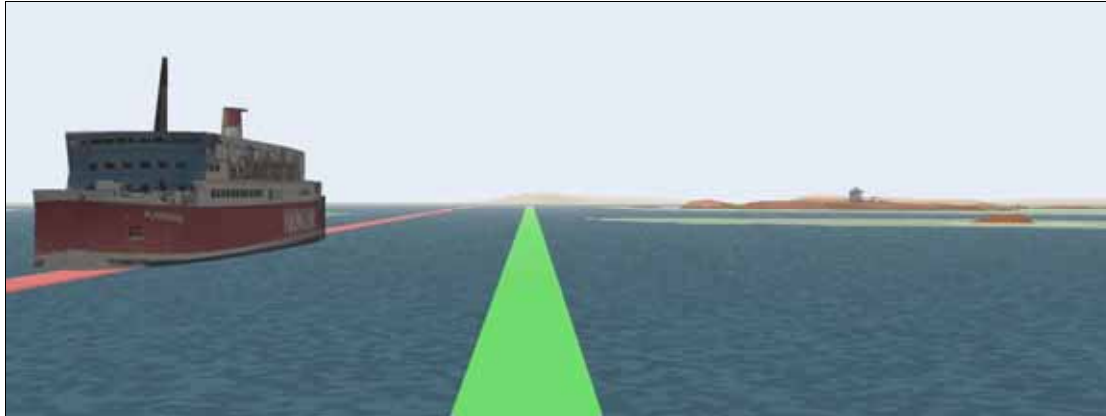


Figure 119. An example of a 3-D model of a ship positioned by AIS transponder data. Here Ålandsfärjan on her regular route between Kapellskär and Mariehamn on Åland.

Other Ships' Intended Track

While the *own ship's track* is based on waypoint programmed into the GPS navigator and only displayed on your own chart, the *other ships' intended tracks* are based on waypoints broadcast through the AIS transponders. It will show the intentions of approaching ships.

In the civil aviation domain there is an obvious need for keeping track of air traffic. For this the Air Traffic Control Radar Beacon System (ATCRBS) was developed. Apart from normal surveillance radars the system uses a secondary surveillance radar (SSR) to send and receive transponder information from the aircraft. Due to radio frequency congestion an enhanced Mode S will be implemented in the near future by some nations civil aviation, where also the intended future route of the aircraft is transmitted (Civil Aviation Authority, 2004).

In the AIS, transponders send information about the ship's position, name, call sign, MMSI number, speed, course, heading, navigational status, type of ship, position sensor indication, antenna location, rate of turn, rudder angle, maximum draught, air draught, length, breadth, angle of heel, angle of roll, list of ports of call, list of hazardous cargo, and some extra slots for customizable information but no waypoints ahead for the intended route are sent.

A suggestion to the IMO for a future enhancement of the AIS is to send two or three waypoints ahead of the present position, so as to allow the visualization of approaching vessel's *intended* track. One then has to bear in mind that this is only the intention programmed into the vessel's navigator and that a ship might at any time deviate from this track just like cars might not always turn when flashing their turn lights or driving in a turn lane. Figure 120 shows an egocentric and a tethered view of seaways with *own track* (white line) and *approaching vessel's intended track* (black).

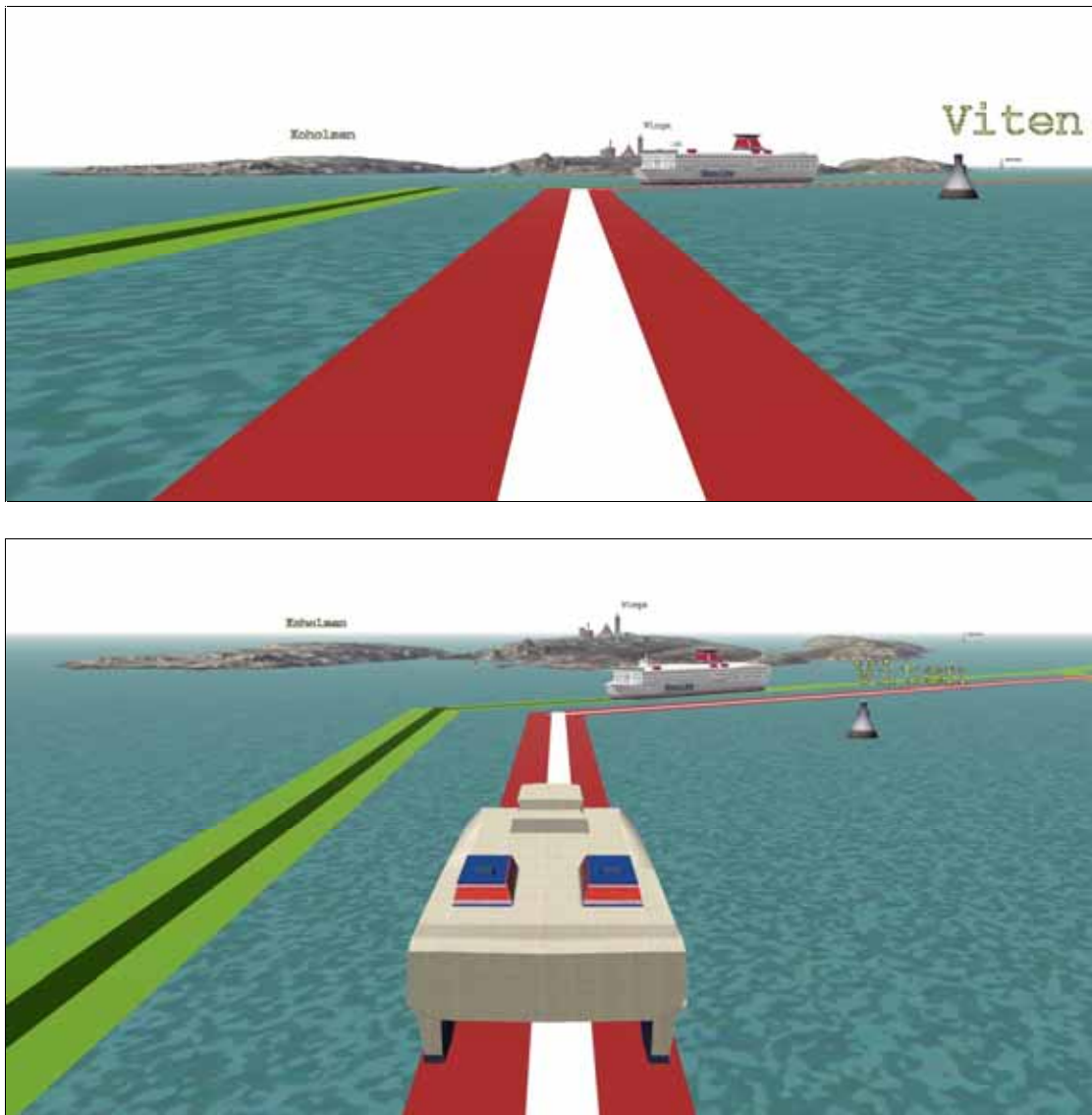


Figure 120. Own track (white) and approaching vessel's intended track (black) on top of the seaways. Here *Stena Germanica* entering by Vinga northern passage. Top, an egocentric view, bottom, a tethered view (own ship being HSC *Stena Carisma*).

Wave Pattern and Optical Flow

The size of the wave pattern on the water surface is important. This pattern creates the optical flow which gives an intuitive sensation of speed and direction. This is important when traveling in darkness. More research in field experiments is needed to establish the relationship between the sensation of speed in the chart, the size of the wave pattern and the actual speed of the ship.

Chart in night mode

The whole point of the 3-D chart is to be able to provide a daylight view also at night and in low visibility. There could, however, be situations in which the ability to provide a *night mode* could be valuable. Such situations could be training or a wish to be able to check the light beacons in the chart view against the real world. In this mode you could dim the light to a custom level and turn on light characteristics of beacons for the current position (see Figure 121).



Figure 121. Prototype 6 in night-mode. Lighthouses and light characters are shown, and by dimming the daylight to dusk conditions the terrain will still remain visible. This mode could be useful for training and comparison with the physical world.

4.5 The Prototypes

Six prototypes have been constructed during the course of this project. The first two are fantasy archipelagos made to test the usability of the idea. The remaining four have been made to test how to create realistic 3-D charts, and how realistic a 3-D chart needs to be. The prototypes are here briefly presented. Details in the models that have been of general interest have already been addressed above.

Prototype 1. Small Fantasy Archipelago, 1999

Real world size:	About 0.15 square-kilometres
Type:	Over- and underwater model
Height data from:	Elevation curves
Texture:	No texture
Validation:	No real world comparison

Very early, before the doctoral research project had started I made the first prototype. To quickly make an environment to test the idea I used Cinema 4D on a Macintosh to create a small fantasy prototype with just a short narrow navigation channel (see Figure 122).

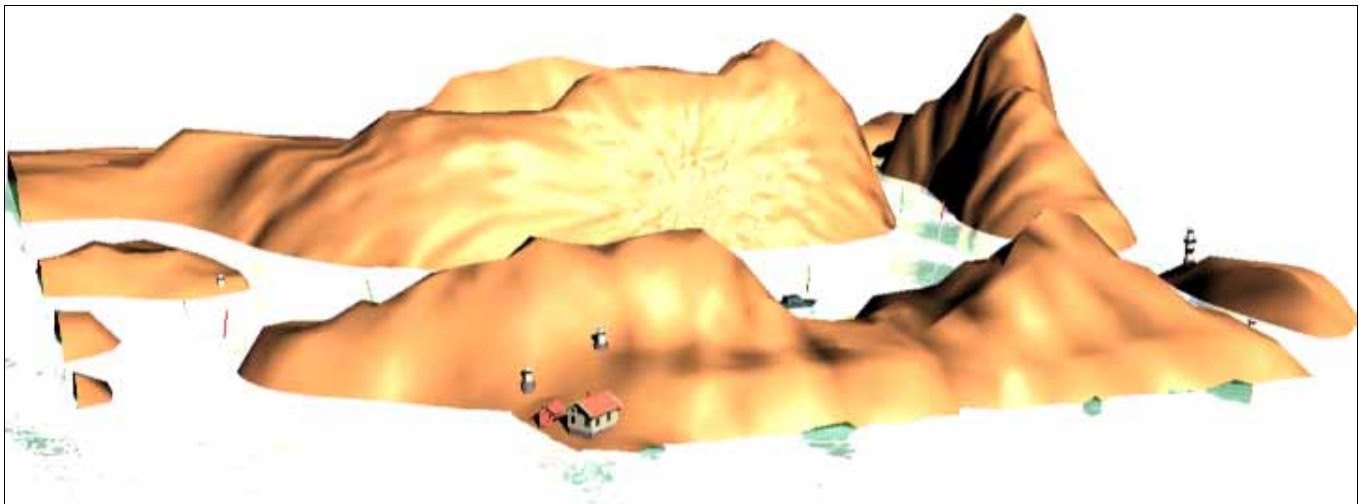


Figure 122. The extent of the first prototype containing but a short and narrow fairway.

At first I had no real-time platform so pre-rendered video sequences in Director were used to visualize the first concepts of training and learning applications. A radar training and simulation environment was tested (see Figure 123) and later an application for navigation training (see Figure 124).



Figure 123. One of the first tests using three inter-connected pre-rendered video films (egocentric view, chart and radar) to visualize the concept.

The first real-time platform tested was Multigen-Paradigm's Vega. A very competent VR software, but expensive and with a demanding programming interface.

The first concepts started to take form and in Figure 125 many features is already conceptualized. The archipelago with its one navigation channel was however too small to allow any wayfinding so a larger model had to be made.

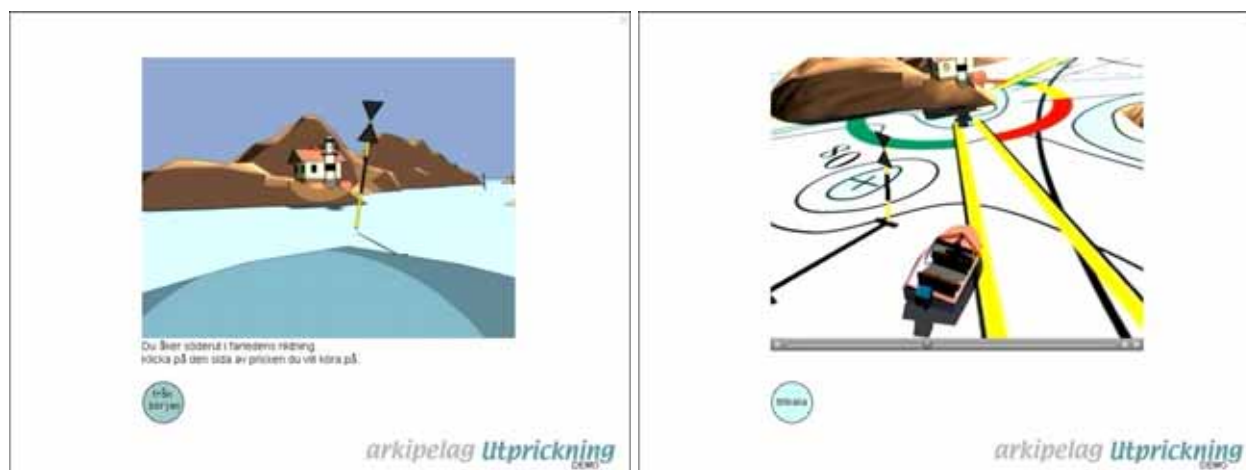


Figure 124. Screen dumps from a navigation training application.

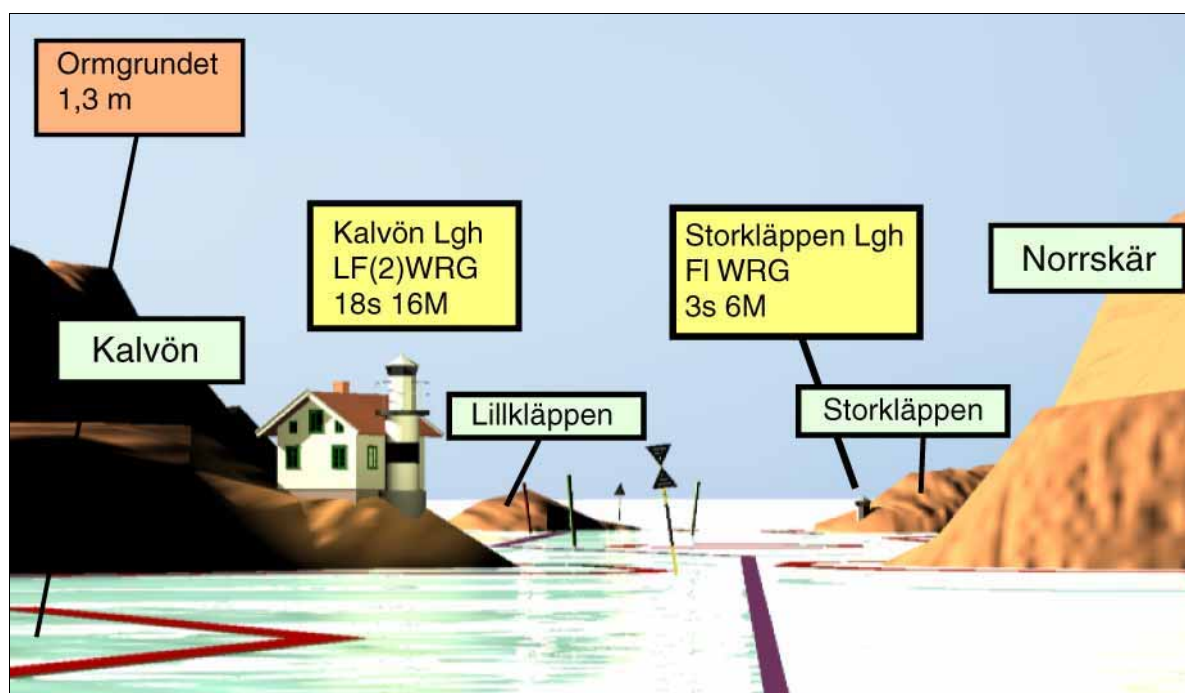


Figure 125. The first fantasy archipelago prototype model from 1999.

Prototype 2. Large Fantasy Archipelago, 2000

Real world size:	About 30 square-kilometres
Type:	Over- and underwater model
Height data from:	Elevation curves
Texture:	No texture, cartoon rendering
Validation:	No real world comparison

A much larger fantasy archipelago was produced this time with some 30 islands and both an outer and an inner archipelago. The archipelago contained a fairway network with a number of buoys and lighthouses so that full scale navigation could be tested.

To start with video films were pre-rendered from the Cinema 4D environment. A *cartoon rendering* technique was tested with simplified shadowing and contour lines on objects. With this type of rendering technique it will be easier to separate distant islands from each other. Unfortunately this rendering technique was not supported by the real-time software and could only be tested in pre-rendered videos.

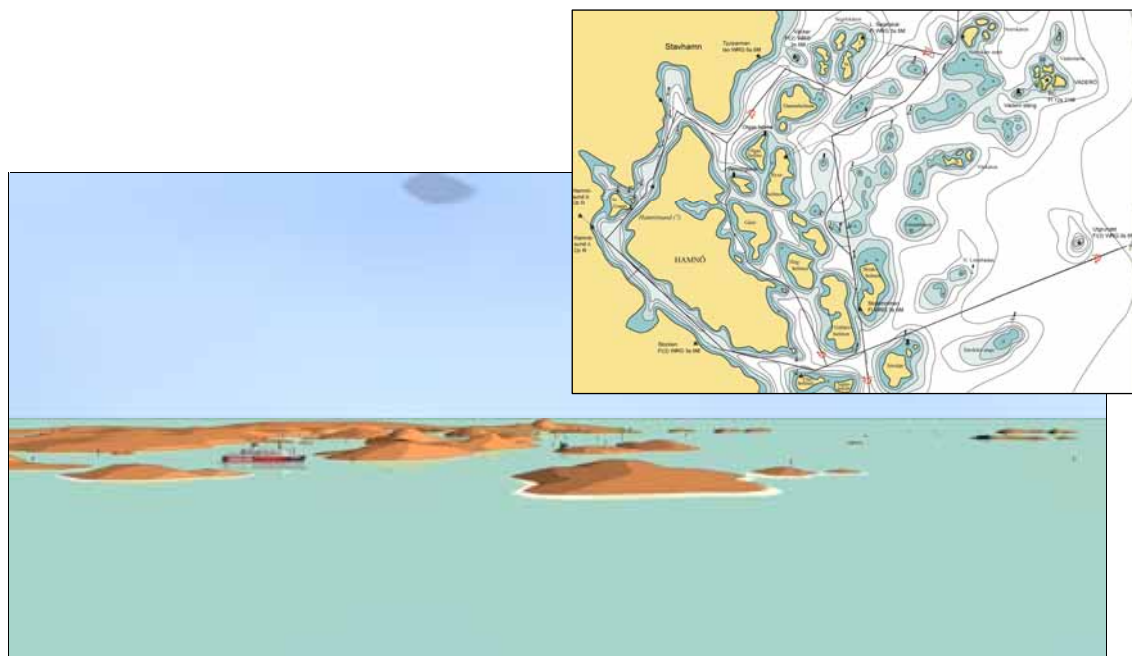


Figure 126. The extent of the second prototype.

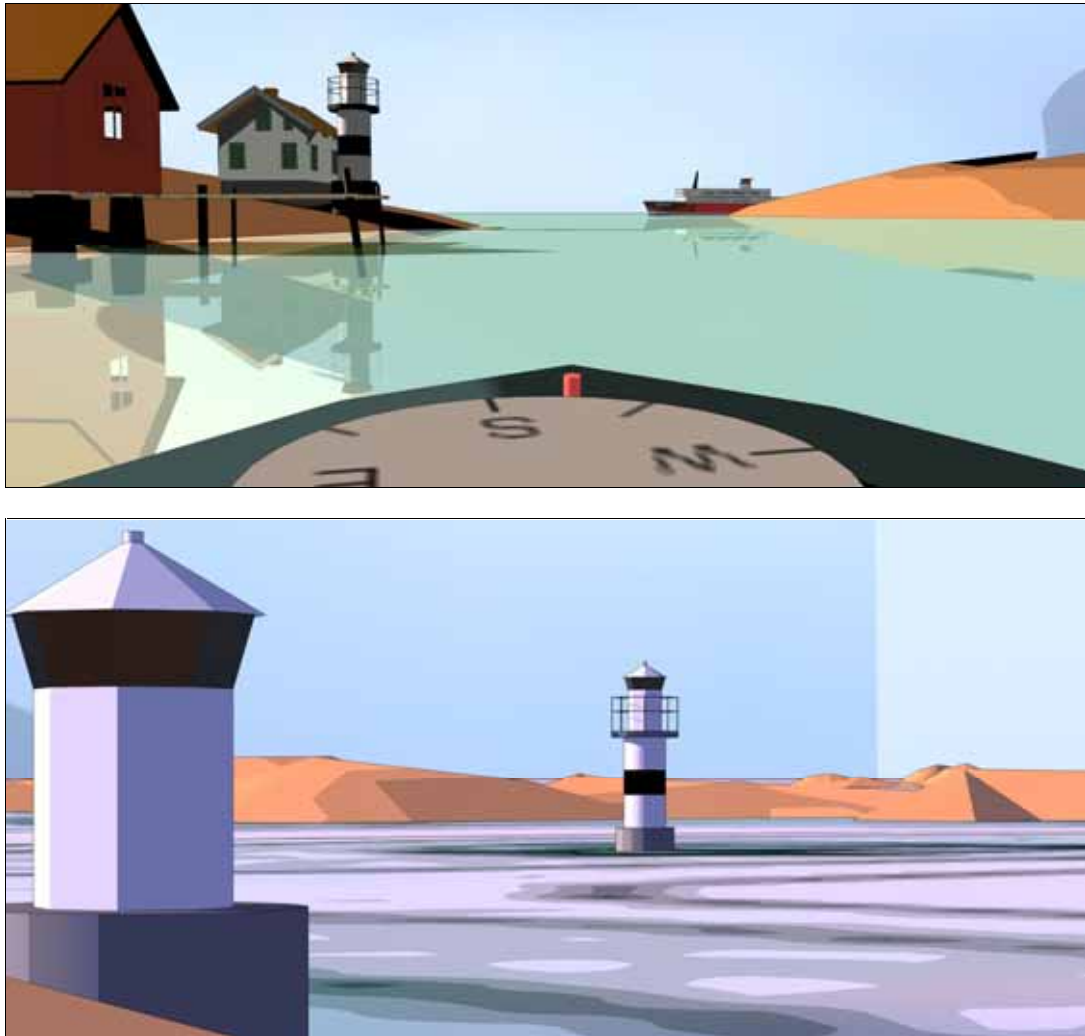


Figure 127. Test renderings using cartoon rendering technique.

This archipelago was the first one tested with the new VR platform EON Studio. The real-time performance was not as high as with Vega, but the programming interface a lot easier and allowed me to test different feature in a simple way. A navigation training application with collision detection to detect groundings and a web interface was build and tested with satisfying results.

The time had however come to test pictorial realism against a geographic reality, as the study now had become part of a doctoral research project.

Prototype 3. Åland, 2001

Real world size:	About 5 square-kilometres
Type:	Over- and underwater model
Height data from:	Elevation curves and spot soundings
Texture:	Hand painted
Validation:	On location, from photographs, interviews

I now started working on an archipelago to test the possibility of achieving pictorial realism of a real geographical area. I chose the barren outer islands of the Mariehamn approach on Åland, because it was easy to travel to Åland on the ferry and the islands could be easily reached with a rented speed-boat from Mariehamn. Something that was needed to get the photographic material needed to texture buildings and to evaluate the pictorial realism. The model was based on elevation and depth curves from the Åland topographical map that was scanned and vectorized. A TIN model was then created in ArcView and exported and tried both in Vega and in EON Studio. The extent of the model can be seen in Figure 128.



Figure 128. The extent of the prototype over Kobbaklintar and surrounding islands at the entrance of the fairway to Mariehamn, Åland.

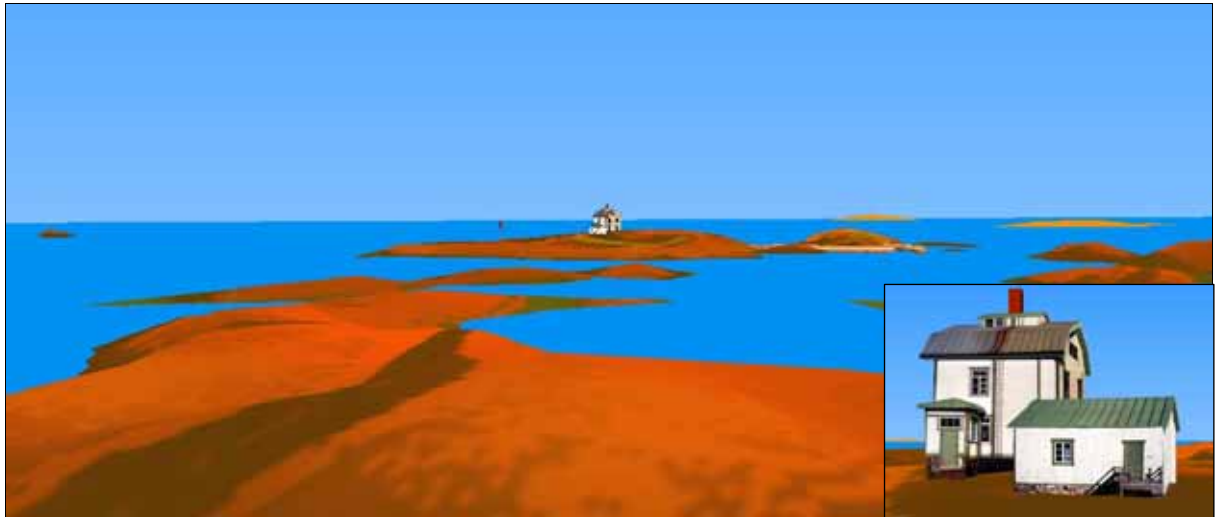


Figure 129. The old pilotstation at Kobbaklinter from the 3-D chart.



Figure 130. Kobbaklinter old pilot station. The ferry från Sweden is approaching in the main fairway to Mariehamn. Comparison between the 3-D chart (right) and a photograph from the physical world (left).

A comparison between the model and the physical world is seen in Figure 129 and in Figure 104, earlier in this chapter. The importance of textures was tested in this prototype and has already been described above.

The Kobbaklinter prototype was shown on several occasions at presentations in Mariehamn and was successfully received. It was obvious that although simple, the pictorial realism was sufficient for

navigation in the fairways. For mooring and navigation close to land the low polygon model was however too coarse. And a simple test with crossed-polygon trees on one of the inner islands failed. To create any kind of realism very many tree polygons had to be added straining the real-time environment and being very labor consuming.

The quality of the underwater data was also very poor depending on the quality of the Finnish charts used at that time. I started too look for an area where I could acquire better bathymetrical data.



Figure 131. Approaching Kobbaklintar on Åland. Prototype 3 was first tested in a real-time environment (Multigen-Paradigme's Vega) allowing a dynamic ocean state (wave height that could be altered). But no users indicated that incorporating sea state in the 3-D chart could be of any value.

Prototype 4 Stora Nassa, 2002

Real world size:	About 3.2 square-kilometers
Type:	Over- and underwater model
Height data from:	Elevation curves and spot soundings
Texture:	Generated pseudo color from height
Validation:	From photographs, interviews

The Åland prototype was the first one made depicting a geographical area. The pictorial realism was in parts OK, but it was all manual labor and the underwater data was poor. I now needed to investigate more automatic methods of creating the terrain model and I needed better underwater data.

I contacted Hydrographica AB and Lars Granath who was surveying and making beautiful and very detailed nautical charts over parts of the Stockholm outer archipelago. From Hydrographica I acquired digital elevation and depth curves as well as spot soundings of very good accuracy over the Stora Nassa, Gillöga and Svenska Högarna areas of the Stockholm archipelago. From this data I made a model of about 3 square kilometers in the northern part of Stora Nassa (see Figure 132).

The focus was now at testing automatic methods to produce a terrain model from elevation contours. The original spline and point data was brought into MicroStation. The number of anchor points in the splines was reduced and the file exported in Shape format and fed into ArcView where a TIN surface was generated. The surface were then converted to an ASCII grid and brought into TerraVista which produced the OpenFlight files used by the real-time software. As texture I let TerraVista generate pseudo colors based on terrain height: blue colors are under water and green to red is on land.

Although the data was of very high quality, the prototype turned out to be a disappointment. I have already in section 4.3 mentioned the terracing problem when making terrain models from elevation curves and also the problems of using un-textured models. Several users said

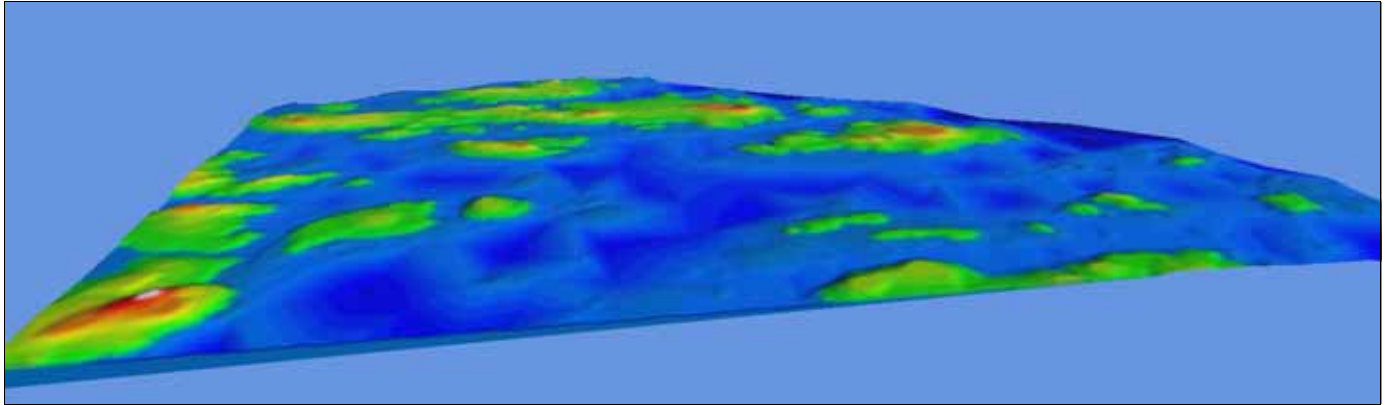


Figure 132. The OpenFlight model with the extent of the northern part of Stora Nassa in the outer Stockholm archipelago.

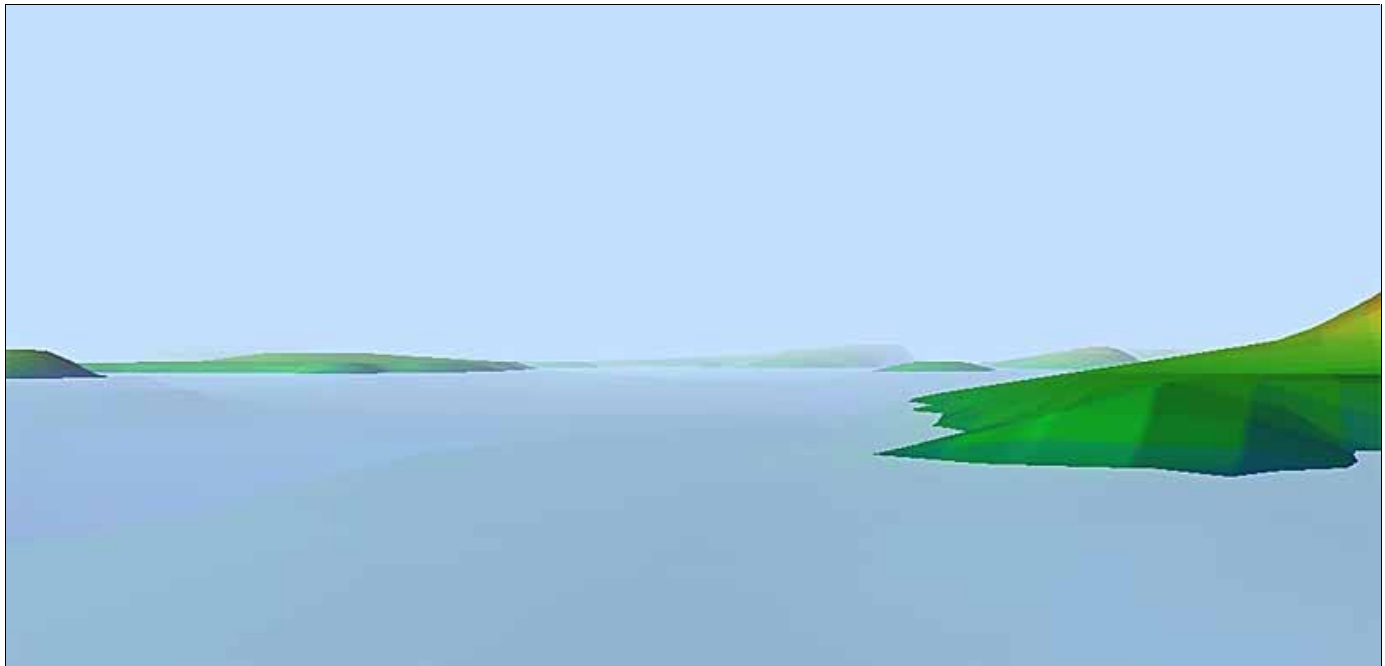


Figure 133. The northern part of Stora Nassa in the Stockholm archipelago looking south. Norrhamnsskäret is to the right and Joffskärs Långkobbar to the left. Gubben and Gumman is visible in the distance.

that they could not get a feeling for the scale of the archipelago and one respondent who was well acquainted with the area, said “I cannot directly say that I recognize the islands” (e-mail, 2002, December). The effect is visible in Figure 133 and also in Figure 87, earlier in this chapter.

The Stora Nassa prototype was a failure as far as pictorial realism went. The problems had to do both with the type of elevation data used (contours) and the lack of proper texture. I had tried hand painted texture in Prototype 3 with acceptable result, but this type of texture required manual labor, and would not be possible if large areas were to be produced. I needed elevation data in grid format and photo texture. Both could be got from air surveying.

Prototype 5. Ägnö, 2002

Real world size:	About 18 square-kilometres
Type:	Over- and underwater model
Height data from:	Photogrammetrically measured elevation points
Texture:	Orthophoto, 25 cm per pixel
Validation:	On location, from photographs, interviews

I first tried with the Swedish Land Survey (Lantmäteriverket) but soon realized that archipelago data that could be obtained from them had way too low resolution (height grid 50 m resolution and orthophoto 1 m per pixel). I then tried the air surveying company Blom Info who happened to have data for an 18 square-kilometers area of the Ägnö archipelago in Ingaröfjärden, an area of some 20 islands mostly covered with forest in the inner archipelago of Stockholm (see Figure 134).

The elevation data they could offer was photogrammetrically measured from stereo photos in a 2 by 2 meter grid, and the ortho-rectified airphotos had a resolution of 25 cm per pixel. The area can be seen in Figure 135.

As mentioned earlier the data acquired was bare earth elevation and did not reflect the tree canopy of the area but the aim of this prototype was to test automatic methods of handling height grids and orthophoto textures.



Figure 134. Map of the Stockholm archipelago. The Ägnö area marked.

The height data was delivered as x,y,z coordinates in columns in ASCII text format and read into ArcView. In ArcView a TIN model was generated and converted to grid format and exported as ASCII text grid. This grid was then imported into TerraVista and draped with the orthophoto. From TerraVista terrain blocks were generated in OpenFlight format that later could be imported into EON Studio for the prototype application. After having tested different resolutions for the texture and the terrain the real-time engine managed to handle the 18 square-kilometers fairly well and tests with the new chart features commenced.

In 3ds Max intersection areas for different depths were generated as NoGo area polygons. Buoys and distance markers as well as seaways and sign systems were also constructed and demonstrated during presentations.

Comments on the seaways, signs and buoy marks were positive. Some comments were made that it would be very easy to navigate this way, “like car driving.” As mentioned above some users who knew the area well commented on the pictorial realism that from an oblique bird’s eye view (Figure 135) the model looked very realistic, but from the bridge view (Figure 136) the lack of tree canopy made it very difficult to recognise geographic features in this forested archipelago. It was evident

that in this respect the prototype did not answer to the demands of enough pictorial realism to allow immediate recognition of geographic features.

Finally an application with a GPS connection was prepared for to do a field test. The objective was to test how the chart behaved in field conditions.



Figure 135. The Ägnö archipelago. Top, a screen dump showing an overview of the 3-D terrain model . Bottom, a perspective view of a Transas electronic nautical chart of the same area.

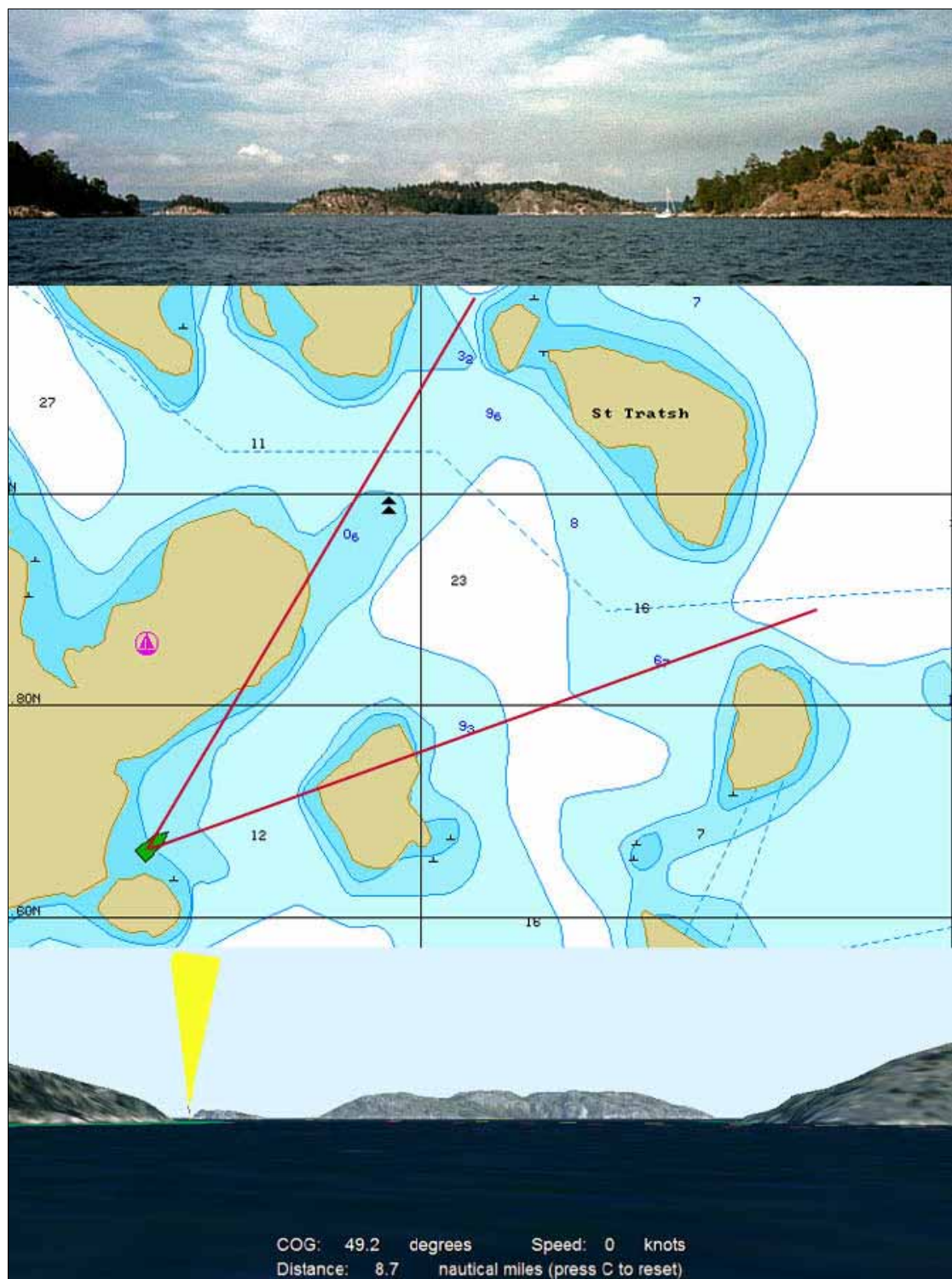


Figure 136. A comparison between the 3-D chart (bottom) and a photograph (top). In between a screen dump from a Transas electronic chart with an overlay of camera position and view angle of the egocentric view.

Field Test

The prototype system described above was tested under practical conditions in the Ägnö archipelago in October 2004.

The 3-D chart was used inside a shell application (Direcor 7.0) which through a plug-in (Communication Xtra) could receive the NMEA code from a GPS navigator through the com port. The longitude and latitude of the NMEA code were converted into the x and y coordinates used by the Eon application running the 3-D chart. The shell program also had two 2-D nautical charts of the same area, one overview map displayed in a north-up mode and a detail map displayed in a head-up mode. See Figure 137 for an overview of the system used.

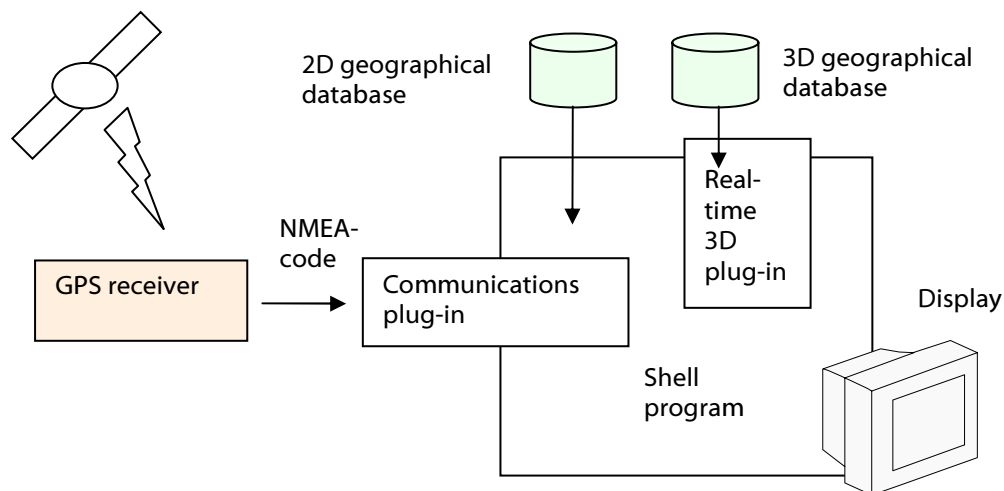


Figure 137. A block schedule over the navigation visualization system being described in this article.

The GPS-receiver used was a non-professional *Garmin 12 Personal Navigator* with 12 parallel channels. The position accuracy is stated as 15 m and velocity accuracy to 0.1 knots. The GPS devise was set up to show speed in knots and position in degrees and decimal minutes instead of in degrees, minutes and seconds to facilitate the calculations needed for the transformations to the 3-D x, y grid. The communication interface was NMEA 0183 version 2.0 and the position update

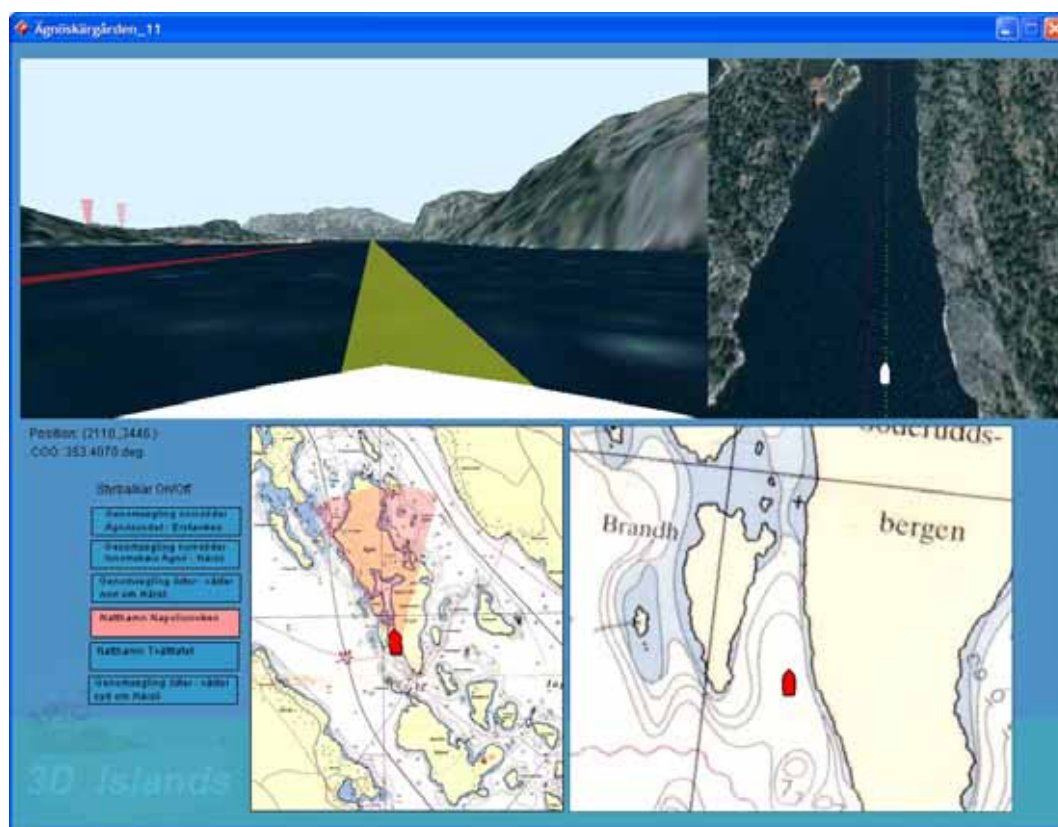


Figure 138. The interface of the test application. Top, the 3-D chart, left, the egocentric view and right in an exocentric head-up view corresponding to the 2-D head-up view shown directly below it. Bottom left, an exocentric 2-D chart in a north-up mode. The red boat symbol is moving and the pink sector marks the view of the egocentric 3-D view above.



Figure 139. Prototype 5 tested on location at Ägnö. The interface of the test application is seen on the authors computer screen. The inserted picture to the right is a close-up of the 3-D view at the top of the computer screen.

frequency was 1 second. The interface of the test application is shown in Figure 138.

The system worked as intended but showed performance weaknesses. There was a considerable lag in position updates, in certain cases amounting to 20 – 30 seconds. The lag was due to a number of factors: a) internal delays in the Garmin 12 GPS unit that were out of our control, but also b) communication delays in CommunicationXtra, reading data from the com port. c) ineffective programming of the interface filtering the longitude and latitude from the NMEA code and then transforming it into EON coordinates.

The lag in the system was a drawback and prevented serious testing of the system. It could not be used as a steering aid even at low speeds. Even if enhancements in the programming can optimize the performance of the application there is still the low update rate from the Garmin unit. One Hertz is much too slow for the application to be used at speeds of 40 knots or more. Judging from recommendations valid for game applications, update frequency of 30 Hz will be needed to avoid self inflicted oscillations due to over compensating course errors. Better GPS update rates will come and professional equipment today offers 100 Hz (e.g. Javad LGG100). The new NMEA 2000 code being implemented will hopefully mean a faster communication interface. To remedy the risk of a freeze in chart updates due to signal loss in bad places (e.g. under high cliffs), the ideal devise will probably be a satellite receiver combined with an *inertial navigation system* (INS).

To conclude, the field test showed that the chart did work as intended but that the update frequency was too low to really evaluate its functions from a human-factors perspective.

Prototype 6. Gothenburg, 2004

Real world size:	About 7 square-kilometres
Type:	Over- and underwater model
Height data from:	Overwater: from LIDAR, underwater: depth contours
Texture:	Ortho-photos 25 cm per pixel
Validation:	Tested on location, from photographs, interviews

Although Prototype 5 was successful in many respects it was evident that the tree canopy was needed to convey the necessary realism needed. I had been interested in the new laser scanning technique for some time and had made contact with TopEye in Gothenburg which was an air scanning company. The prices for a commercial air scanning was way out of reach, but by waiting for the moment a helicopter and a crew had some hours over I managed to get a 100 square-kilometer large area along the main fairway into Gothenburg harbor scanned in November 2002. Figure 140 shows the extent of the scans. During the scans air photos were taken as well.



Figure 140. Gothenburg and the approach through the archipelago. Overlaid is the LIDAR data scanned by TopEye in November 2004. The data is pseudo colour based on height. Dark is the 0 m level and lighter is increasing height. No scanning was needed over open water areas; that is why there are “holes” in the scan path.

The raw data were delivered as point cloud and un-rectified air photos. The resolution of the point cloud varied from very dense (typically 1 hit per dm) in areas where flight tracks crossed to relatively scarce in some areas in the outskirts of the track (less than 1 hit per m), but an estimated average was 1 hit per 0.5 m.

Software from the Finish company TerraSolid was used to handle the raw data. First the air photos had to be rectified in TerraPhoto, then the point cloud had to be classified and converted to a mesh models in TerraScan and TerraModeler. Figure 141 shows a mesh model of the raw laser data. Note the “mast” in the water on the far side of Vinga island. This could have been a laser hit on the back of a flying sea gull because no construction is at this place. (The construct in the upper right-hand corner is, however, the Viten lighthouse.) The point cloud had to be checked this way for the whole area. From the point of view that this prototype was specially aimed at testing tree visualization the barren Gothenburg archipelago was not the best but it was what was available, and one island, Aspholmen, had a small forest and the work with the tree canopy has already been presented in section 4.3, Tree Visualization.

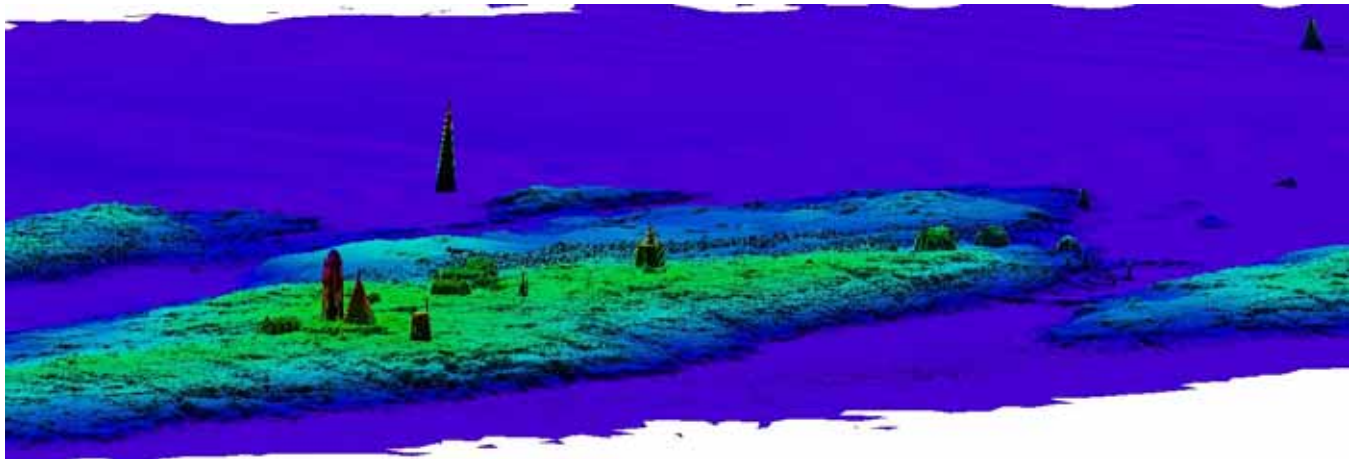


Figure 141. A mesh model of the raw unclassified point data cloud of Vinga island. In the upper right-hand corner Viten lighthouse can be seen. In the water above the island, somewhat to the left of the middle there is a high “mast.” This is a defect because there is no construction there, possibly the laser scan has hit the back of a sea gull. These kinds of defects has to be removed in the classification process. Screen dump from the TerraModeler software.

The laser scanned overwater terrain was exported from TerraModeler as xyz ASCII grid into ArcView and merged to the underwater line and point data traced from a nautical chart. A texture that consisted of orthophotos for the overwater areas and the raster chart for the underwater areas was prepared. The TIN model was imported as before into TerraVista and the new texture draped on top to produce the final OpenFlight blocks. Figure 142 shows the extent of the Vinga block (about 7 square-kilometers) prepared in this way.



Figure 142. The extent of the Vinga block of the Gothenburg archipelago.

The NoGo area polygons were prepared as before using 3ds Max intersection feature. I had contacted computer graphics programmers to make sure that the intersection polygons could be created in real-time for a reasonable large area around a ship, but at this stage I only needed a limited number of polygons for to be able demonstrate the feature, and these polygons could be prepared before hand. I generated NoGo area polygons for every 0.5 meters of depth in the Vinga block.

A number of important buildings and lighthouses were hand-made in a way previously described as well as seaways and name tags for islands and lights. Lighthouse characters were programmed for the night vision model. Then the model was taken on a field test in connection to an interview made by the University TV (2005).



Figure 143. A view from prototype 6 and a photograph of the same view. As can be seen pictorial realism is OK, but islands merge into one land in the 3-D view as well as in the physical world. Can this problem be solved with cartoon rendering methods in the future?

Field Evaluation

The realism of the prototype was evaluated in January 2005 by two members of the maritime police in Gothenburg. The evaluation was done in connection with a TV presentation of the research project. The inefficient GPS from in the field test at Ägnö was not used but funding for a professional solution was not available. Instead, the chart was evaluated in terms of pictorial realism and how the policemen thought the NoGo area polygons and seaways worked. Figure 143 presents a photo and a screen dump of the same view. The policemen were positive to the chart and regarded it as an improvement compared to the charts of today. The TV journalist asked one of the policemen if he thought the 3-D chart would allow them to drive faster and he answered, “Not faster, but safer, maybe” (Universitets-TV, 2005).

In summary, I thought the 3-D chart well passed the critical eyes of practitioners in the field and I am quit happy with this model. The next step in the development of a 3-D nautical chart will be field tests with the Gothenburg prototype and a fully working GPS connection.

Chapter 5

Field Studies and Interviews

In this chapter the findings of six field studies onboard ships of different sizes are presented. During these studies interviews have been made and experts have commented on prototypes presented to them. First some comments on the methodology.

5.1 Field Studies, Participant Observations and Heuristic Interviews

“Field studies are nonexperimental scientific inquiries aimed at discovering the relations and interactions among sociological, psychological and educational variables in real social structures” (Kerlinger & Lee, 2000, p. 585). Kratz (1953) divides field studies into two broad categories: *exploratory* and *hypothesis testing*. The exploratory type seeks *what is* rather than *predicts relations to be found*. My purpose in the following field studies has been twofold: to explore the environments onboard different types of ships and to present the 3-D chart to the bridge crew for an expert evaluation.

In chapter 2 I discussed the notion of *situated cognition*. Hutchins (1995) has, for instance, stressed the importance of making observations in the proper context on the bridge – a method he calls *ethnographic* – to make sure navigation can be understood as a team-work and use all its cognitive tools distributed over the ship and the environment around

the ship. Lützhöft (2004) argues that “to understand the operators, the researcher must understand their circumstances, which also implies being where the operators are and participating to some degree in the practice, everyday as well as in unusual circumstances” (p. 20). See also the discussion in chapter 6.

The validity and reliability of qualitative research is debated. These terms do not have the same significant meaning as in quantitative studies. Cook and Campbell (1979) describe two types of validity: *internal* and *external*. The internal validity concerns the question if other factors, apart from the observed, might be responsible for the result. The whole point of making observations on the bridge is to bring the tasks into context, and my own navigation experience is useful as to ensure that I have understood the task being preformed. I have also asked questions whenever I have wondered about something, and the situation has been appropriate. But one has to realize that observation necessarily means interpretation, which opens the possibility for misinterpretation as well. External validity concerns the possibility to make generalizations from findings. Here too, one has to realize the limitations of the method at hand: the situations and people observed are unique and interpreted through a unique observer. However, realizing their limitations, field studies and interviews can answer many questions that quantitative research may fail to answer, most notably in seeking explanations to why things are the way they are.

The field studies have been made by participant observation and heuristic interviews. That is, I have been present on the bridge during navigation and voyage (except for the navy corvette which was moored), my intentions as a researcher were known to all on the bridge. Whenever possible I asked questions about the doings of the bridge crew. The visits were short (in the time scale of one to a couple of hours) except for the product tanker on which I stayed for five days. On this ship the observations were also made partly by more un-intrusive observation. The interviews were conducted based on what happened on the bridge and no enquiry form was used (*heuristic*). After the visits notes were taken and later written down in full. No recordings or note taking were made on the bridge during the observation so as not to unnecessarily remind the participants of my observation. (With the exception of the combat boat where a sound recording was made).

The environments visited were: one larger, open sea, slow-going product tanker, one huge Baltic passenger ferry, one smaller, mid-speed archipelago ferry, one fast police patrol boat and two fast naval vessels, a coastal corvette and a combat boat. A seventh environment studied was three land based Vessel Traffic Service (VTS) centers.

I have chosen not to reveal the names of interviewed persons or the ships visited. The maritime community is relatively small and although I have not asked or written about any controversial subjects I have concluded that names are not necessary.

Below follow in brief some findings relevant to this study made during these field studies and the expert evaluation of the interviewed officers to whom the prototype chart application was showed.

5.2 Product Tanker

During five days in July 2001 I was onboard a 20.000 ton and 164 m long, product tanker during a voyage from Muuga in Estonia to Hamburg in Germany. The ship carried Norwegian flag, the captain and the first officer and chief engineer were Swedish while the second and third mates and the 9 remaining members of the crew were all Russian speaking Latvians. During the voyage a cargo of 20,000 tons of gasoil was carried, destined for Rotterdam “for orders”. (The expression “for orders” meant that the cargo was not sold at the time of departure and that the brokers would be selling the oil during the voyage, if not, we would have to wait outside Rotterdam until the cargo was sold. As it turned out we would end up in Hamburg.

The purpose of participating in the voyage with the tanker was to get some first hand experience with professional navigation early in this project. Through my brother, who was the captain of this tanker, I got the opportunity to join this voyage. My strategy was to observe without interfering with the life onboard. Holme and Solvang (1996, p. 110) caution the investigator to be very clear about loyalty and interference problems that might arise. My position as being the captain’s brother



Figure 144. The 20,000 ton product tanker visited during a 5 day period in 2001.

made my situation very special. The sociological configuration onboard was also special with the three Swedish senior officers and the rest of the crew, including the second and third mates, being Latvians. My area of interest was concentrated to the bridge and the navigation procedures which meant that I only was engaged with the bridge crew, captain and the three mates as well as different pilots coming and going. Mainly I stood by and watched, once in a while asking questions. On board I was presented as the captain's brother on a vacation trip, but also as doing research in maritime navigation. Most of the time onboard I spent on the bridge. The two Latvian officers treated me very respectfully as the captain's brother and I had the feeling that my presence on the bridge during their watches was somewhat uncomfortable for them and probably influenced their normal doings. Therefore I spent most of the time on the first mate's watches. (The captain was normally not watchstanding.)

The Bridge and the Bridge Crew

The bridge was situated at the top of the six-store-high superstructure and was a so called *built in* bridge, which meant that the bridge crew could access the bridge wings overhanging each side of the ship

without having to go outdoors. This gave a very spacious bridge with a width of about 30 m (see Figure 145).

The maneuvering consol was placed amidships at the front part of the bridge with a minor console at each bridge wing for berthing maneuvers. In the center was the helm console with the wheel for hand steering and the auto pilot controls on top. To the right of the steering console were the engine controls. The engine was during voyage maneuvered from the bridge, but during harbor maneuvers manned and sometimes also run from the engine control room. To the left of the steering control was the main radar set, a 10 cm Atlas ARPA radar. And to the left of that a monitor for the Transas electronic chart display.

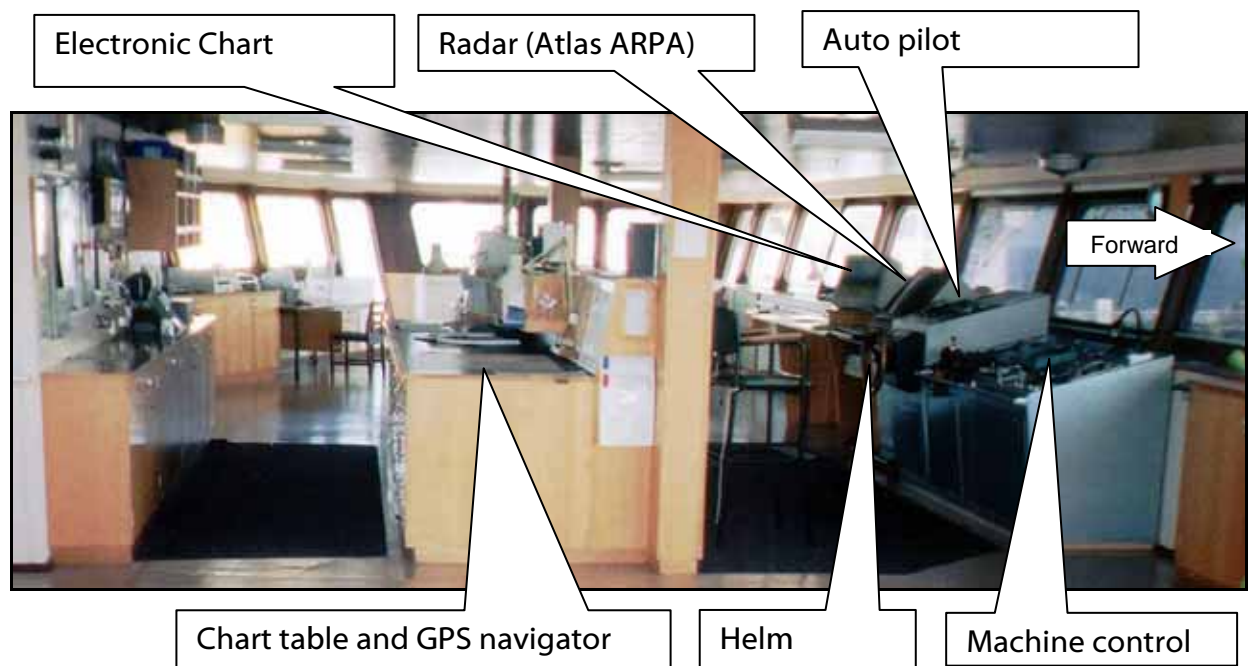


Figure 145. The built-in bridge of the 20.000 ton tanker. The bridge is a huge area about 30 by 7 meters with windows in all directions. On the front end amidships, to the right in the picture, is the manoeuvring place overlooking the ship through the front windscreens. The major navigation method is using paper charts from the chart table behind the manoeuvring station (in the middle of the picture). At the back of the bridge amidships is the toilet and the staircase down into the super structure. The bridge also contains a desk for working with the Inmarsat-C and a visitor's sofa.

Behind the maneuvering consol was the navigational workstation with the chart table and the GPS navigator. The navigation area was open to the rest of the bridge and the chart table was facing forward and equipped with a white adjustable light that could be dimmed.

During sea watches the three bridge officers worked around the clock. The first mate had the 8 to 12 watch both in the mornings and in the evenings, the second mate had the 12 to 4 watch and the third mate the 4 to 8 watch. The captain was not watch standing but could and should be called on the bridge whenever anything out of the ordinary happened. (This did not happen during my stay.) During harbor and docking maneuvers the captain took command on the bridge and the officers went to their docking stations. During harbor stays the sea watches were broken off by another system where, for example, the first mate was in charge of cargo handling. Standard procedure was also that the second officer was in charge of navigational equipment and charts. He was responsible for correcting the charts with the latest updates and navigational warnings. He was also responsible for the passage planning of the coming voyage, making sure all necessary charts and pilot books were onboard, preparing the charts with courses and waypoints.

The Passage Plan

The *International Chamber of Shipping* (ICS) is a London based international trade association for merchant ship operators. They publish the standard work *Bridge Procedures Guide* (BPG), a guide to watch keeping practice. A copy of this guide must be on the bridge of every ship. The BPG prescribes that certain navigation routines are followed by all ships. This standardizes to a large extent the navigational procedures in a large part of the world's maritime traffic. Different organizations, classification societies and port state authorities controls that these procedures are followed. For part of the oil tanker industry, like the tanker I visited, the vetting inspectors of Intertanko (The International Association of Independent Tanker Owners) make constant unannounced inspections onboard and checks on all things relevant to shipping safety, including preparations and execution of navigation procedures.

BPG states that every ship is to make preparations in the chart for the coming passage. This is called a *passage plan* and it should be prepared before departure. In the passage plan every course must be drawn into the chart, course to steer and distance to the next turn be marked on the chart and the waypoints connecting the courses be programmed into the GPS navigator. “At any time during the voyage, the ship may need to leave the planned route temporarily at short notice. Marking on the chart relatively shallow waters and minimum clearing distances in critical sea areas is but one technique which will assist the OOW when having to decide quickly to what extent to deviate without jeopardizing safety and marine environment” (ICS, 1998, p. 18). In Figure 146 the preparations of a British Admiralty chart over the Sound (Öresund) is shown. The courses are drawn into the chart using a pencil that can be erased after use (in accordance with the BPG), the shallow waters, dangerous to the fully loaded tanker are marked with a red marker. This is not in accordance with the BPR, because these markings cannot be erased, but they are certainly more visible, and would probably be more helpful to a stressed officer of the watch needing to make a quick decision about an evasive maneuver. But we may note here that these markings take no notice of water levels (which in the Sound can be about ± 1.5 m), sea states and squat effects. For more explanations of the chart preparations, see Figure 146.

The preparations shown in Figure 146 were made on the paper chart, which was situated on the chart table in the rear of the bridge (see Figure 145). At the conning station a Transas electronic chart was used as reference. On this chart the waypoints and course tracks were visible, but not the NoGo area warnings.

Comments on the 3-D Nautical Chart

The captain and the first officer of the tanker were shown prototype 3, the Mariehamn approach on Åland. Their comment was that they found it interesting and useful, but probably more so for smaller and faster crafts. For a tanker like theirs, the value of a 3-D chart would be very limited during operation. Carrying dangerous cargo they always had a pilot onboard when traveling in confined waters where a 3-D chart might be most useful, and the pilot would then be the one conning the ship. They said, however, that during passage planning to new



Waypoints connecting the different courses of the voyage. The numbers in the red circle accompanying each waypoint is the ID number in the GPS navigator's library for longitude and latitude of the waypoint.

Line with arrow and the (true) compass course of the course leg.

Course line, drawn into the chart using a pencil

NoGo areas. Shallow waters dangerous to the ship. (In this case the 10 m depth curve is marked; the draught of the tanker, fully loaded, was 10 m.

Figure 146. Photo of a prepared British Admiralty chart no. 2594 1990, *The Sound – northern part*, from the tanker visited.

areas, like a new harbor never visited before, it would be valuable to be able to get a visualization of the approach and the berth. During docking maneuvers a large ship is dependent on winds and currents, and the maneuverability of each ship is individual. The captain here often must take over maneuvering as the pilots may not know the individual differences of the ship as well as the bridge crew.

5.3 Midsize Archipelago Ferry

In July 2003 a visit was made on the bridge of a 40-meters-long archipelago ferry. The ferry had a standard speed of 24 knots and took 450 passengers. A number of these ferries traffic the inner archipelago of Stockholm and particularly during the summer traffic is very dense. There are great numbers of passenger to and from the many populated islands and the ferries have many dozens of stops at landings on each trip. In the summer the traffic with leisure craft is also very dense and the bridge crew of these ferries has a tough job navigating the ship.

The boat is conned by a driver seated in a chair at bridge center with all controls around him. The ship has no bridge wings instead rear mirrors is utilized to look astern when backing out from the landings. The bridge crew consists of a captain and a mate. During the voyage I visited the ship was conned by the mate and he was assisted by the captain. The two members of the bridge crew are very well familiar with the route they are driving but the high traffic intensity of leisure craft in the summer, and the un-predictable behavior of inexperienced



Figure 147. A midsize archipelago ferry visited.

drivers, lead to a high cognitive strain. A certain preparedness for evasive maneuvers always has to be kept. The main navigation method was optic, looking out of the windows, on the daylight trip I joined. Backup method was radar, which was displayed in a head-up mode. The ship had no ability to run the display in north-up. An electronic Adveto chart was also used for reference; this was displayed in a north-up mode. None of the officers found navigation with the two different display modes problematic. They found the head-up mode of the radar useful as the relative bearings to islands and other ships was preserved by the display mode. The chart was seldom used, except for a check, because they knew their routes very well.

No chart prototype was shown to the bridge crew in this study.

5.4 Police Patol Boat

In January 2005 I visited a Maritime Police patrol boat in the Gothenburg archipelago (see Figure 148). The boat had a crew of two police officers, a standard cruising speed of 30 knots and was equipped with radar and an electronic chart (Transas). The radar was used in a head-up mode as gyro support for north-up mode was missing. The chart was used in a north-up mode.



Figure 148. The police patrol boat visited in January 2005 in the Gothenburg archipelago.

The police boat was patrolling up and down the coast and had a very large area to cover. It was not possible for the officers to learn the whole area by heart so references to both paper charts and the electronic chart had to be made relatively often. The two police officers sometimes found it useful with the radar in a head-up mode because it preserved the relative directions, but that it sometimes made it more difficult to compare the radar picture to the chart as they were in different modes. This would typically be in a situation when they were trying to establish from which islands different radar echoes derived. In well-known areas they often knew the area from the radar picture, but in lesser known areas, some interpretation work was needed.

Comments on the 3-D Nautical Chart

During this visit I had the opportunity to show the police officers Prototype 6 over the same waters we were traveling in. A comparison between the chart and the physical world was possible to make. The officers agreed that based on their local knowledge it was possible to recognize the locations in the 3-D chart, without any problem. The police officers thought the system could be useful and that it might lead to safer navigation. “This could mean



Figure 149. The interior of the police patrol boat. The driver in the starboard seat. In front of him a screen that can either show the radar or the electronic chart. In the middle (in front of the journalist) is the radar screen and to the left, in front of the police assistant, the electronic chart.

better and safer shipping” was the comment of one of the officers. Asked if it would allow them to drive faster, he answered “Not faster, but safer” (University-TV, 2005).

5.5 Navy Combat Boat

In January 2005 I also visited the training center of the west coast amphibious battalion. Here the drivers of the Swedish-made Combat Boat 90 were trained and I had the opportunity to interview an experienced high-speed navigation instructor and join a trip in the archipelago with two conscripts that had been trained as combat boat drivers for one year and now were about to go back to civilian life. The navigation of a combat boat at more than 30 knots zigzagging in the narrows of the archipelago is a very delicate task described in the following section.

During the voyage a sound recording was made of the communication between the driver and the navigator. Due to technical failor this recording came out empty. Annotations have been used instead.



Figure 150. The starboard seat (the driver) of the combat boat. The port, navigator, seat is shown in Chapter 1, Figure 6. In front of the driver a slave screen that can either show the navigators radar or chart screen.

Navigating a Combat Boat at High Speeds

The following section on the methodology of combat boat navigation is a compilation of information from the interview with the navigation instructor (personal communication, January 2005), the navy methodology manual *Bryggjtjänstinstruktion för Marinen* (Försvarsmakten, 1998) and the Swedish Accident Investigation Board's report of the combat boat accident in April 2003 described in appendix A (SHK, 2004). (See also the introduction on mental rotations in chapter 1.)

The navigation technique of a combat boat is a two-person teamwork, the navigator, seated in the port side seat and the driver, seated in the starboard seat. Either one of them can be in charge of the boat; this does not affect the navigation methodology (see Figure 151).

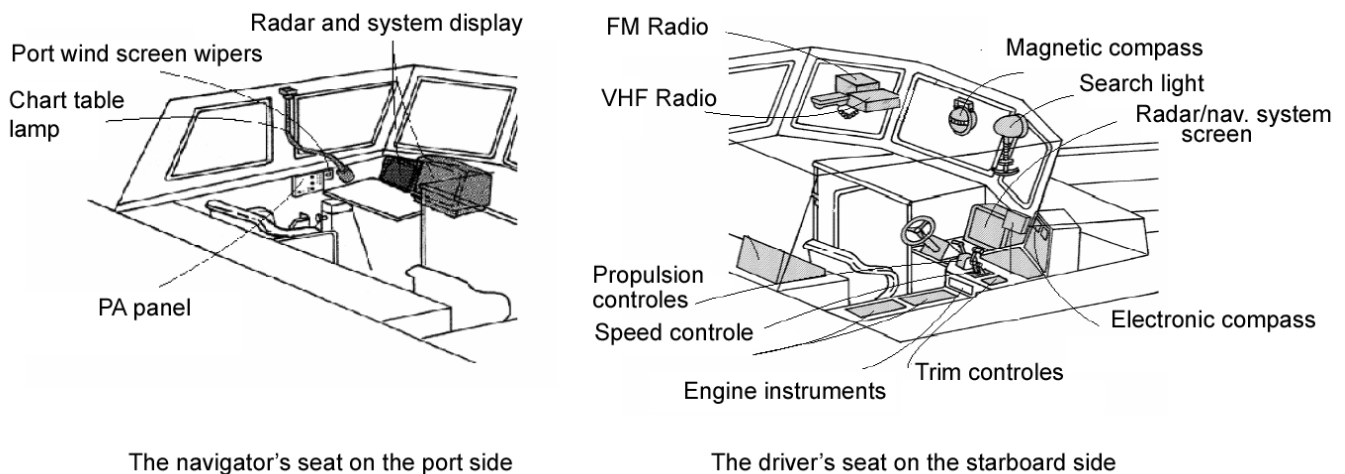


Figure 151. The interior of the cockpit of a combat boat 90H. Adapted from the Swedish Accident Investigation Board's report (SHK, 2004)

The technical navigation equipment of the boat consists of a magnetic compass, an electronic compass, radar (with *ARPA* functions), distance log and a navigation system with plotting functions connected to a *DGPS*. In the electronic chart on the display of the navigation system, the position of the boat is plotted every 10 seconds. (See the section on the combat boat accident in appendix A.) The accuracy of the *DGPS* is between 1 and 2 meters. For all practical purposes the error is so low that the position of the boat can be regarded as correct in the coordinate system; the problem is instead the position error of the chart. Electronic

charts of Swedish waters are produced by different companies (both *private*, like the Transas system used in the 881, and *official* like the S-57 from the Swedish Maritime Administration). In the major fairways the depths and positions of the shore line can be said to be accurate, but outside the major shipping lanes the measurements often rely on manual soundings and triangulations from the 19th century. Thus the accuracy of the DGPS positions can be of little value and the system must be used with great care considering its limitations. (However, the screen dumps of the recordings from the navigation system in appendix A, show that the accuracy in this part of the archipelago was fine.) When navigating in darkness outside lanes equipped with beacons, the main method is radar navigation and the electronic chart system is only used as a backup.

In front of the navigator are both the electronic chart and the radar displays and the controls used to operate these. (See Figure 6 in Chapter 1.) In front of the driver there is a repeating display that can be switched between either the electronic chart or the radar display of the navigator.

Navigation of a combat boat is based on verbal communication between driver and navigator, preparations in the chart and a structured methodology. According to instructions in the manual used to teach combat boat navigation, the following preparations are to be made in the charts prior to a voyage (marked with a non-permanent marker on the plastic chart protection). See Figure 152.

Courses: lines representing the route the boat is to take. Compass headings are to be put out. Each straight course leg is delimited by *break points* (*brytpunkter* - BP).

Turning points (*girpunkter* - GP): a well defined point in the terrain used as reference for when to start a turn. The GP has to be chosen so that the turn is completed before entering the new course leg. The turning rate is individual for each boat which affects the choice of the turning point. A GP for visual confirmation can be abeam but turning points that are to be used with radar must be situated afore or astern of the boat because of technical limitations in the radar system. (The high speed of the boat together with the relatively low revolution rate of the radar antenna

make abeam echoes unreliable.) Then the distance to the GP, called *girpunktsavstånd* - GPA, is used.

Passage distance (*passageavstånd* - PA): the distance to well defined points in the terrain; used with radar to check the lateral position of the boat.

Free lines and *leading lines* (*frimärke/frilinj*e -FM/FL): ranges to well defined points in the terrain used to determine the position of the boat in relations to, for example, dangerous shoals or reefs.

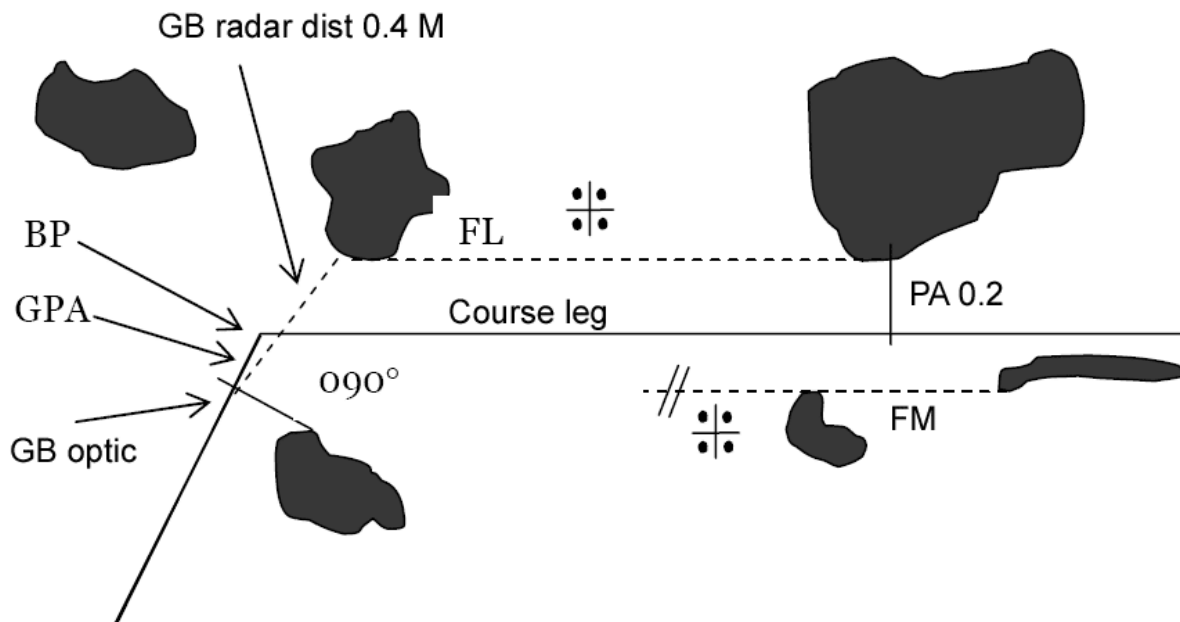


Figure 152. Illustration of the chart mark up technique used in the methodology of combat boat navigation. Adapted from the Swedish Accident Investigation Boards report (SHK, 2004)

The navigation procedure is a loop consisting of four phases:

Transport/Acquisition phase. In this phase the driver is maneuvering the boat according to the instruction given to him by the navigator in the previous phase. He is actively asking the navigator about approaching objects. In the meantime the navigator collects information about the

next course leg, the turning points, passage distances, leading lines and possible dangers, plus available space for evasive or combat maneuvers.

Relay phase. The navigator is verbally communicating information about the next course leg, turning points, radar and optical references etc. The language used is a formalized command language designed to be unambiguous and time efficient.

Turning phase. The driver turns on command or after having reported that he is on the turning point. During the turn the navigator constantly watches the position and heading of the boat.

Control phase. After the turn the navigator controls the position and heading of the boat on the new leg, using visual and radar references and navigation system.

Comments on the 3-D Nautical Chart

The navigation instructor was very interested in the 3-D chart and thought it could be most useful in navigating combat boats. He also thought that the 3-D chart could convey the important spatial terrain knowledge necessary to soldiers operating in the archipelago (personal communication, January 2005).

5.6 Navy Coast Corvette

In April 2005 I visited a navy coast corvette moored at Berga naval station outside Stockholm. I was shown onboard by an experienced navy officer who had served onboard in several functions, the last as the ship's commander. The coast corvette is a 50-meters-long ship with the capacity of an official standard speed of 27 knots.

The ship is navigated by a navigation team of four persons: the conning officer, the navigator/plotter, the helmsman and the look-out. The conning officer and the helmsman are seated on the bridge, the navigator/plotter is seated in front of the navigation radar in the Combat Information Center (CIC) in the interior of the ship and the look-out is stationed on the open top bridge. The team is communi-



Figure 153. The bridge interior of a navy coast corvette. In the port/left seat sits the conning officer, in the middle the helmsman's and in the starboard/right seat the commanding officer. The third member of the navigation team is seated in the CIC, in the interior of the ship.

cating on a designated navigation channel through their head-sets. Recently the corvettes have been equipped with electronic charts which was not the case before. The navigation process is conducted so: the plotter in the CIC suggests a new course along the prepared route to the conning officer; the conning officer approves and give orders to the helmsman. Like in combat boat navigation the process depends on information verbally communicated between persons. As I see it: as ships go faster, and in a noisy and (in combat situations) possibly chaotic environment verbal communication becomes a weak link to navigation.



Figure 154. A navy corvette leaving the mountain at Muskö naval station. Photo from <http://www.huvudbas.kajen.com/fakt/berget.html> [March, 2006].

Comments on the 3-D Nautical Chart

Prototype 6 over the Gothenburg area was shown to the commander. He was very supportive and believed that such a chart would facilitate navigation in the narrow and confined waters of the Swedish archipelagos. He added that it also would be useful to incorporate passing distances to islands (for cross-checking with radar) and a visualization of upcoming turns (for more on this, see chapter 4, on Seaways). (Personal communication, January 2005.)

5.7 Large Baltic Passenger Ferry

A number of huge passenger/car ferries traffic the Baltic Sea between Sweden, Finland and Estonia. I visited one of the largest in March 2006 and could study the bridge work during a couple of hours in the early morning as the ferry approached Stockholm through the archipelago. The ship was 200 meters long and had a capacity of more than 2,600 passenger and 450 cars. Standard speed in the open sea was 21 knots, but in the archipelago the speed was mostly limited to 12 knots, and in some passages even slower. The draught was 7.1 meters. Such a huge ship gets close to the limits as to what can be maneuvered in the

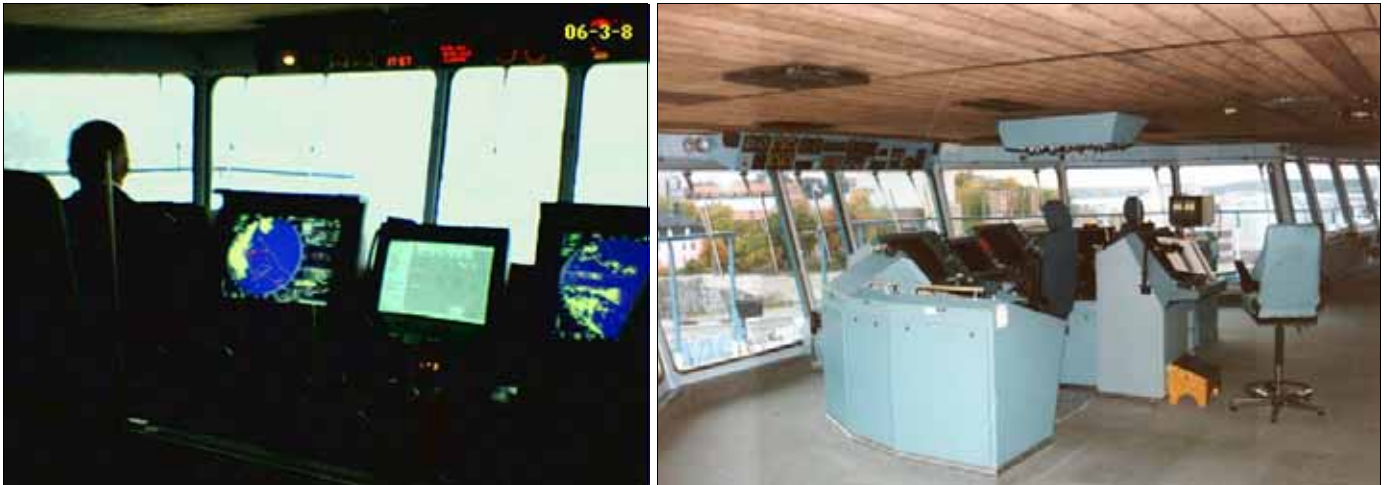


Figure 155. The bridge onboard the large Baltic ferry visited in March 2006.

narrows of the archipelago. Some passages are so tight that they have only 10-15 meters clearance on either side (Lützhöft, 2004).

For ships of this size it is mandatory to have a marine pilot onboard. A marine pilot is a licensed captain with local knowledge employed by the Swedish Maritime Administration (SMA). The captain of the ship is still in charge, but in practice the pilot is the conning officer. It is possible for bridge officers to train for a pilot's exemption for a particular ship and for a particular route. It is long and hard training which is described by Lützhöft & Nyce (2006). The large Baltic ferries on regular route between Sweden and Finland often have bridge officers with a pilot's exemption.

The ship is conned from a central console on the large indoor bridge (see Figure 155). The console uses the cockpit-layout from the aviation domain with two parallel seats from where the ship can be conned. Two officers are constantly on duty during the long tracks through the archipelagos. One officer, *the pilot*, is the one conning the ship, and the other, *the watch officer*, monitors the navigation. The navigation team uses a formal closed-loop-communication. Before any course changes the pilot will report for example "Starboard to 168 degrees" and the watch officer will confirm the course change. Then the turn is executed. If the pilot needs to be relieved, he will *hand-over* to the watch officer, which is confirmed by pressing a button switching the steering to the

other seat. Often the watch officer also have a pilot's exemption or is in training for one.

The routes are very well-known to the pilots, to the extent that they can be said to know them by heart. Navigation is then monitored by radar. The 10 meters' depth curve is displayed on the radar screen and acts as a border between free and NoGo areas. (The ship's draught is 7.1 meters) The track line for the journey is also displayed and acts as an optimal track as well as the ship's position with a true relative size and predicted track and position one to three minutes into the future (see Figure 156).

The navigation of such a huge ship in the narrow archipelagos for extended periods of time is a meticulous job and the safety standards are high. Even if the speed is low and currents in the region are minimal, the inertia of the ship and the influence from winds and bank effects make navigation complex.



Figure 156. The radar display with additional chart information. Here the ferry is still in port and the traffic limitation borders represent the quays. Photo Margareta Lützhöft.

Comments on the 3-D Nautical Chart

The captain, the first mate and the chief engineer were shown Prototype 6 during a meeting in the mess; the second mate later on the bridge. The three main features, the bridge perspective, the NoGo area polygons and the seaways, were shown to them. All four were supportive of the

idea and thought that it could work as intended. The first mate commented that it might be difficult at first, “being set on thinking in cardinal directions, like a bird”, but he thought that once you got used to it, it could be good (personal communication, March 2006).

5.8 VTS – Vessel Traffic Service Centers

On three occasions I have visited VTS centers (Vessel Traffic Service). The VTS centers are the equivalent of the Air Traffic Control in the aviation domain, but they do not lead the traffic, they only monitor it. The object of the VTS centers is to provide information service to the ships, such as the presence of other vessels in the vicinity, approaching, crossing or proceeding in the same direction. “In addition information will be provided on possible faults to safety gear, passage limitations, ice conditions and other relevant information” (Sjöfartsverket, chart 9313, 2004). The reason for my interest in the VTS centers is that they use nautical charts to visualize the traffic situation in their areas. What I wanted to find out was whether it would benefit them to use 3-D charts. My idea was that if they were guiding individual ships it could be beneficial to “step on to the bridge” of the ship, giving guidance from the same perspective as the bridge officer.

VTS Stockholm

In February 2003 the VTS center in Stockholm was visited. The center is situated on the shoreline on southern Djurgården. The center at that time still used an old method of visualizing the sea traffic going to and from Stockholm through the long fairways of the archipelago. At a number of reporting points ships over 300 GRT are required to report to the VTS center over the VHF radio. When a report was received the VTS watch-stander moved a magnetic ship symbol on a metallic board on the wall of the VTS center (see Figure 157).

The regular ships plying the archipelago, like the Baltic ferries, had magnets with their name painted on them. Other ships had magnets with a number on it, and on a slip with the number beside the board, their name was written. By this system the watch-stander would know about where the ships would be, by extrapolating from the times they



Figure 157. The VTS Stockholm in February 2003. Plotting of ships coming into and leaving Stockholm was at that time still made by boat-shapes magnets moved over a metallic chart on the wall. A simple and functional devise.

had reported s/he could report to the ships of expected meetings in the next fairway section ahead. The device was simple and functional.

For their comments on the 3-D chart, see the end of this section.

VTS Gothenburg

In January 2005 I visited the VTS center in Gothenburg. The center is housed in an office building in the container harbor on the northern shore of the river Göta Älv. There are three command posts in the center. One watch-stander is monitoring the ships coming and going to and from Gothenburg harbor, about 10,700 ships per year (BolagsFakta, 2006). See Figure 158.

Of the other two command posts, one monitored the traffic on the rest of the west coast and the other is the booking center for pilots. The VTS center monitored the whole west coast from Båstad in the south to the Norwegian border in the north. They have electronic chart screens where ships are displayed by symbols based on AIS data and radar responses from a number of radar stations along the coast. Ships destined for Gothenburg have to report to the VTS when they enter the mandatory reporting area starting 6 nautical miles outside Vinga lighthouse.



Figure 158. The Gothenburg VTS which is monitoring the Swedish west coast. Left is the command post watching Gothenburg harbour. Right is a close up of the rightmost screen.

VTS GOFREP, Helsinki

In March 2006 I visited the VTS center in Helsinki. The center is monitoring the traffic in the Gulf of Finland, an area with increasing oil traffic from the Russian harbors in the eastern part of the gulf. The center represent the next generation of visualization techniques with large screen monitors on the walls (see Figure 159). In other respects the center functions like the Gothenburg VTS.



Figure 159. The GOFREP VTS in Helsinki monitoring the Gulf of Finland.

Comments on the 3-D Nautical Chart

The VTS personal on the three stations visited were presented to or told about the 3-D chart and asked if this could be something useful in their work. My suggestion was that if they were to give piloting instructions to ships in an incident of some sort, would it be useful to “climb down

on the bridge” of the ships to see the situation from the ships point of view. The personal spoken to all said that they never gave that type of instructions because the ships usually had a pilot onboard and their job was to monitor the traffic not to pilot. From their point of view they could not see any use of the 3-D chart on the VTS centers.

However, the Finnish VTS said that they sometimes had to guide ships to their rendezvous’ point with the pilot cutter, especially when the weather was bad and the pilot needed to board on a more protected location.

5.9 Two Marine Pilots

I was interested if marine pilots would have any use for the 3-D chart and I have received feed-back from two pilots. One Gothenburg pilot was interviewed during my visit to the Gothenburg VTS in January 2005. He was presented to Prototype 6 and found it interesting; but he could see no use for it from a pilot’s point of view. “We know our fairways by heart,” he said (personal communication, January 2005).

However, a Tasmanian marine pilot who had found my project on the internet mailed me and told about his environment, piloting ships up a river with strong tidal currents and heavy fog during the winter months. He said that the radar and electronic charts he used were “a long way from perfect as the river was narrow and the tidal flows could be strong. --- I have been searching for a system/navigation aid that could provide a bridge-eye view as a pilot would normally see if the visibility was clear, as this would be far more useful to a pilot. One only needs to look at the value of simulators in replicating the natural environment for the training of marine pilots.” (e-mail communication, October 2005).

5.10 Harbor Master

In June 2005 I visited the harbor master of one of Sweden’s largest ports to show him Prototype 6 and get his comments on if this type of a chart would be of any value to a port authority. The port has more than 10,000 calls every year. For each call a ship is designated to particular

berth or actually a section of a quay, as long as needed for the ship to fit. The administration and designation of berths is done using a computer program at the port authorities. The pilots that bring the ship into harbor know the general quay where to take the ship, but for the final mooring the harbor boatswains take over, because they know exactly where to the ship is designated. If the 3-D chart could be connected to the ports designation program and the pilots could take the ship directly to its designated berth efficiency could be improved. My idea here is that this could be done by letting a calling ship, on approach download an individual track line leading to its designated berth.

The harbor master was carefully positive and my impression was that the 3-D chart could be an interesting possibility to improve effective port handling.

5.11 Presentations

During the five years that this project has been conducted more than 36 presentations have been made in front of different types of audiences. More than 600 persons have been presented to the 3-D chart. More than 200 of these had some connection to maritime life, either as seagoing personnel or as maritime administrators or manufacturers of marine equipment. After these presentations many people have come up to me to discuss the project. This feed back has been very valuable.

During these presentations I have never received any negative comments to the effect that someone does not believe in the feasibility of the project, not during the questions after the presentation nor by someone approaching me afterwards. The value of such a sign is of course limited as it is less likely that people make negative comments, than positive, but it has never the less been very inspiring.

5.12 Concluding and Summarizing This Chapter

During these field studies I have been most interested in finding out how radars and charts are used on craft of different sizes and speeds and if professional navigators experience any problems with mental rotations. To summarize my findings on this subject, I find that the

product tanker, the navy corvette and the large Baltic ferry always used north-up on both charts and radar.

However, the captain of one Baltic ferry said that “about half the bridge crew” used head-up on the radar southbound through Kustaanmiekka (Gustavsvärdsundet), a very narrow passage at Suomenlinna (Sveaborg) south of Helsinki (personal communication, March 2006). One navy commander also told me that when he had been navigating in unknown archipelagos in high speeds he had turned the paper charts head-up to facilitate navigation. He did not think anybody else did it as this was not the way it was done in the navy. He did think it was sensible, “but would not say so aloud.” He said that this was an absolute “no-no” among mariners (personal communication, April 2005).

The smaller ships visited, the midsize passenger ferry, the combat boat and the police boat always used head-up on the radar and north-up on the chart. However, there seemed to be technical reasons for this as the boats visited lacked support from a gyro compass, which is needed to keep the radar in north-up.

One pilot that I had an e-mail conversation with said that head-up was often used on small fast boats in narrow waters because the radar picture then “agreed with what was visually seen”, but the downside was that the land contours were not fixed on the screen. The boatswains driving the pilot cutters could be using head-up on their way out to the rendezvous” point but once onboard the ships which they were piloting, the pilot would always use north-up. He had “never heard of anybody using but north-up” (e-mail communication, February, 2005).

Chapter 6

Discussion and Conclusions

This chapter contains a brief discussion on two important objections to the 3-D chart. First the notion that new technology causes new problems, then the fact that there are downsides with the egocentric perspective. A concluding summary of the project and finally, a look on future research brings the chapter to an end.

6.1 Discussion

In this dissertation I have suggested and tested a new egocentric display mode of nautical charts. Findings have been very positive, which will be summarized in the conclusions in a later section. I will, however, start this chapter by bringing up two reminders to carefulness: new technology causes new types of accidents and that there are problems with the egocentric view as well.

New Technology Causes New Problems

In October 1995, coast guard vessel KBV 302 grounded at 18 knots on a rock in daylight and calm weather in the Stockholm archipelago. A very experienced coast guard assistant was on watch while the captain and the other crew member were below making a report. Before the accident the boat was on autopilot which was connected to the integrated navigation system and following a pre-programmed track. At each waypoint the navigation system sounded an alarm which the coast guard assistant acknowledged by pressing a button and the ship then automatically turned to the new course. This evening everything was well and under control. Right before to the accident the coast guard

assistant wanted to look at an upcoming part of the voyage. As the electronic chart screen is small he had to scroll ahead along the track with the trackball which is used instead of a mouse. He could now no longer see the position of the boat, nor did he look out through the window. After about half a minute the assistant clicks the picture back to present position and then notices that the boat has left the preprogrammed track and is now in a slow port turn heading for a small rock just in front of the vessel. A quick glance out the window confirms that the collision is imminent and that there is no time to reverse the waterjet propulsion as the reversing buckets will take some time to come into position. Then he stops the engines and shouts out a warning to the other in the crew before the boat hits the rock at full speed. Luckily no one is hurt and the boat gets only limited damage (see Figure 160).



Figure 160. Coast guard vessel *KBV 302* grounded in October 1995. Photo from the police investigation.

So, what happened to the autopilot? Somehow the assistant with the sleeve of his arm must have happened to touch the button that turns off the autopilot. The button is placed unprotected on top of the joystick used to steer the boat manually. There is a sound alarm going off when the autopilot mode is changed, but it is very faint and difficult to hear above the noise of the engines. (Ekblad, 2001)

The paradox is that if no modern technology had been used, and the helmsman had been minding the helm in the old-fashioned way, this accident would never have happened. New technology causes new types of accidents. We have seen this before, for instance in the Honda Point disaster 1923, when seven American destroyers ran aground in darkness and fog because they did not trust the signals of the new radio direction finder (Dep. of the Navy, 2002), in the radar assisted collision between the passenger ships *Stockholm* and *Andrea Doria* outside Nantucket Islands in 1956 (Nordling, 2006) and in the grounding of the *Royal Majesty* in 1995 due to a GPS failure (Lützhöft & Dekker, 2002).

When presenting the 3-D chart for the head of a large Scandinavian boat insurance company I was told that the company had a rising number of accidents with small leisure boats going full speed in the dark of night with the help only of a GPS connected to an electronic chart. Some of them did not even carry navigational lights or bothered to keep watch. The results were in some cases collisions with other boats or strandings. He said that some people did not seem to realize that other boats were not presented on the electronic chart displays or realizing the positioning delay caused by the limited update frequency of the GPS signal and computation delays in certain systems. This CEO said that there was a risk that this type of accidents could become even more common with my kind of system, which he otherwise endorsed and thought could mean an improvement to safety among the leisure crafts that were his customers (personal communication, June 2005).

In her dissertation titled *Technology is great when it works* Lützhöft (2004) discusses the problem of new technology in cooperation with people on the ship's bridge. She starts out by saying: "Several recent maritime accidents suggest that modern technology sometimes can make it difficult for mariners to navigate safely" (p. iii). Lützhöft has spent several years studying a number of ships using an ethnographical method of participant observation. Herself a holder of a master's certificate with many years of sea practice, she sees a problem with the fact that the majority of studies on bridge work are made in a simulator environment using questionnaires. These experimental methods tend to give one kind of answers. In order to find out how people make sense of the situation they find themselves in, you also need to study them in their factual situation on the bridge. This will better focus the human

factor. “Using methods designed to quantify behavior or to write laws will not yield the richness and complexity of the work situation and will seldom tell technology designers or manufacturers what they need to know about the ‘human element’” (p. 18).

What Lützhöft found during her study was that many ostensibly technically integrated maritime systems are not integrated at all. Instead, mariners themselves have to perform “human integration” to bridge the gap between technology and man (p. 88). The strange thing was that often this kind of knowledge never reached the designers and the manufacturers.

This shows the importance of contextual experience and the need to bring the users into the design process as much as possible. During this project I have used both experiment and observation as methods and that way I hope to benefit from the best of both worlds. But one must bear in mind that there might be effects of the new 3-D display mode that I have not anticipated and particular attention must be paid to mode switching between egocentric and exocentric modes and the effect of these switches on situation awareness.

One also has to bear in mind that the everyday egocentric perspective also has its drawbacks.

Naïve Realism

In research at the Pacific Science & Engineering Group in San Diego, Smallman, St.John, Oonk and Cowen have investigated the advantages and disadvantages of the 2-D and 3-D perspective views (PSEG, 2006). They ask questions like “Do 3-D displays really improve situation awareness and task performance, or do they actually hinder performance and place people at risk?” Their answers are published in a number of articles and they are critical to, what they call, the “misuse” of 3-D displays. Their findings are collected in a theory called *Naïve Realism*. Generally they have found that 3-D views are very good for understanding 3-D shapes and scenes. However, for making precise spatial judgments the 2-D views are to prefer.

Errors in distance judgment derive from the fact that *depth* into a perspective view compresses much faster with distance than does *width*. Their explanation is that psychologically the brain assumes that depths compress the same as widths which they call *cross-scaling* from width estimates to depth estimates. “Though a reasonable approximation for nearby distances, cross-scaling results in progressively underestimated distances and thus in large errors, particularly at the back of 3-D scenes” (Smallman & St. John, 2005, p. 8). The concept is illustrated in Figure 161.

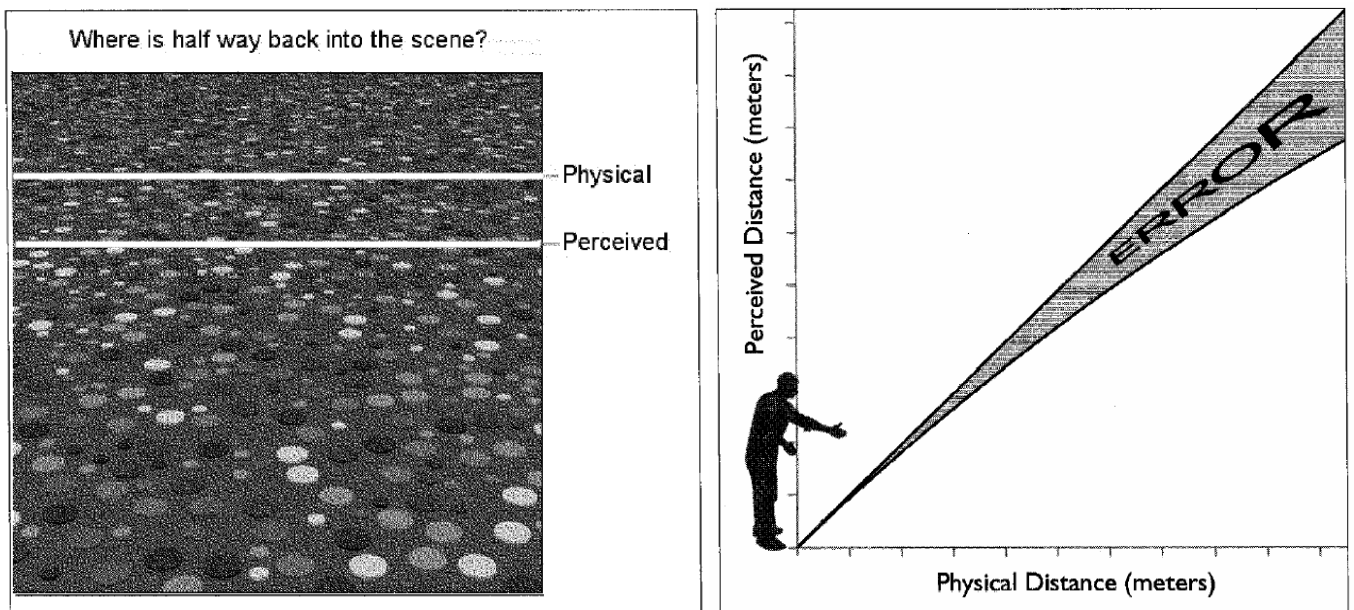


Figure 161. The compression of distance in 3-D views cause an error of distance judgment that grows larger with distance from the viewer. Illustration from Smallman & St. John (2005).

Smallman et al. have also looked at the use of 3-D icons in command and control displays and found that 3-D symbols are often preferred by users but that they can lead to poor identification performance when they represent objects that are visually similar. In Figure 162, top, a suggested command and control display for battle space visualization is shown. This display was thought to be able to provide “at a glance” situation awareness. However, experiments by Smallman et al. showed that icons were named slower than standard military 2-D icons (see Figure 162, bottom). The reason for this would be that airplanes and ships might be visually similar and distinctions become more difficult to see in the increasingly smaller size of icons towards the back of the

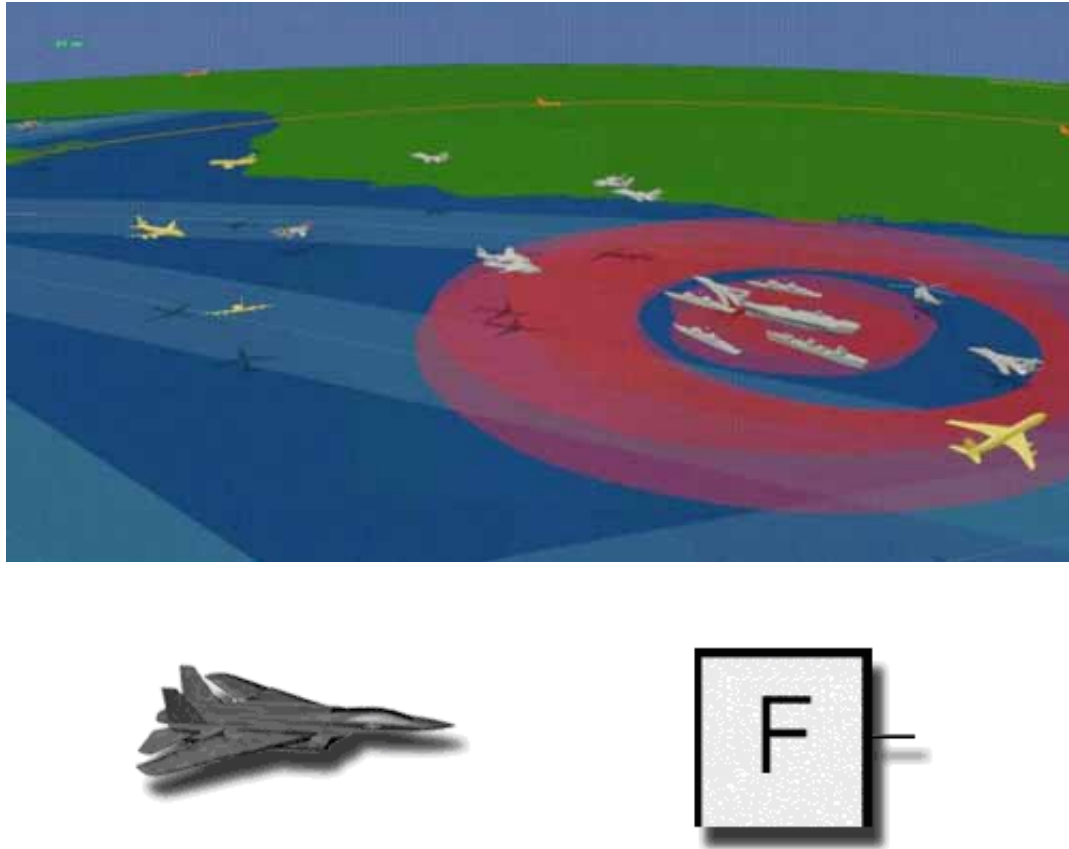


Figure 162. Top, an example of a 3-D Command and Control display of a battle-space populated with realistic icons of ships and airplanes. Bottom example of two 3-D aircraft icons, one realistic 3-D and one stylized 2-D icon. Illustration from <http://www.spawar.navy.mil/sti/publications/pubs/tr/1854/tr1854.pdf>

scene. In contrast abstract 2-D icons can be designed to be as dissimilar as necessary to promote rapid identification (Smallman et al., 2001).

The objections by Smallman et al. are important to the idea of the egocentric bridge perspective. The problem of distance compression is not only a problem for 3-D views displayed on computer screens but very much so also in the everyday egocentric view of real life. We have all experienced the difficulty to make true distance judgments in environments that lack objects of known sizes to compare distance with, for instance in the mountains or at sea. Air humidity can add to this deception making nearby objects feel distant on a foggy day, or by making distant objects appear close on a clear one. In my childhood I was often warned by adults to never try to swim over a lake or a strait

with the explanation that “it is much further than it looks.” And I believe that many a drowning accident depends on misjudgment of the true distance to a distant shore.

The distance compression effect is known at least since the renaissance painters started to investigate techniques to convey depth and perspective in flat canvases. The VR technique gives us this effect for free, but also the problems that comes with it. It is important not to be ignorant to these problems. Further studies have to be made on when it is beneficial to use the egocentric mode and when the traditional (2-D) exocentric mode should be used and if there are problems when changing between the two modes. One suggestion from a naval officer was that passing distances to close by islands, used in radar navigation, should actually be displayed in the 3-D chart. Another possibility is displaying dynamically decrementing duration times to upcoming turns or ship meetings. The problem with that 3-D ships become very small and indistinguishable at long distances has been addressed in short in chapter 4 with the suggestion of *pointers*, or nametags, to buoys, lighthouses or ships.

It is now about time to conclude this work and summarize what has been achieved so far.

6.2 Conclusion

The title of this dissertation is *Safe Navigation*. By that, I do not mean that navigation today is unsafe. Shipping today is probably safer than ever. Still accidents happen, and as I showed in the introduction, the great majority of accidents are blamed on *human error* and problems with *situation awareness*.

The context of this study is the ship’s bridge. Underway the main concern of the Officer of the Watch is to monitor the progress of the voyage and make decisions about the future course due to other ships, effects of wind and sea state and so on. His main tools are the view out of the window and the radar, which informs him about obstacles above the surface, and the nautical chart, which informs him about obstacles under the surface. On occasions decisions have to be made under strong

time pressure, this is particularly true in modern high speed vessels. If time-consuming and mentally demanding tasks like mental rotations and depth calculations can be facilitated by a more intuitive design, safe navigation can be made even safer.

In this project three conceptual ideas have been presented and investigated: the *bridge perspective*, the *NoGo warning polygons* and the *seaway network*. Based on these three concept three research questions were formulated:

Research question 1: *Does the use of an egocentric display of a 3-D chart lead to better wayfinding (faster decision-making, fewer errors) than a traditional map in the conning situation?*

Research question 2: *Does the marking of free as well as forbidden water areas with dynamic NoGo area polygons ease the cognitive workload of the navigator*

Research question 3: *Do double-lane seaways and sign systems, like road network on land, simplify wayfinding and enhance safety at sea?*

To answer these questions a number of different methods were used, both quantitative and qualitative. In a laboratory experiment I sought the answer to the first research question, if navigation in an egocentric bridge perspective lead to faster decision-making and less errors. The results here clearly showed: yes, the subjects did better using the egocentric 3-D map compared to using the other three traditional map types. The generalization opportunity of this experiment can of course be discussed. How well does a 6 by 6 meters maze work as a stand-in for ship navigation in general? For combat boats zigzagging in the inner archipelagos of Scandinavia in 40 knots (soon to be 60), I think there is a large relevance; for a bulk carrier on the open seas, less. Still, the object of the experiment was to see if there was any positive effect in using a map type that removed the need to make mental rotations, and that effect was clear.

Qualitative observations were also made during the experiment and they, too, supported the notion that the bridge view worked as intended. The ease with which the subjects navigated with the 3-D map was most striking. Although the level of abstraction and the fact that the 3-D view was not quite an egocentric point of view but rather a tethered one, with a camera virtually hanging a few meters behind the driver, there seemed to be no difficulty to translate the screen representation to the physical world. One way of noticing this was through the comments from the subjects while conducting the tests. While driving with the 3-D and head-up maps they were more talkative than with the paper and the north-up maps and I interpreted this as the cognitive workload was higher navigating with the north-up and paper maps, than with the 3-D and the head-up; overall many subjects seemed to drive in a relaxed and comfortable way when using the 3-D map.

For the other two research questions I did not design experiments, instead I used qualitative methods like interviews, observation and expert evaluations. The reason for this was that I considered it important to meet real users. However well a laboratory experiment is designed there might always be important features in the bridge context that, when missed, lead the experimenter astray. One such example given to me by an instructor at an American maritime academy ship simulator was that after the *Exxon Valdez* accident in 1989, the Alaskan authorities wanted to make a thorough analysis on how piloting to and from the port of Valdez was really done. Therefore local pilots were brought into a ship simulator where the Prince William Sound area had been modeled and while they were performing their piloting tasks their behavior and technique were monitored. At one such time the pilot suddenly stopped and said: “I cannot go any further, I cannot see the waterfall on...” and he mentioned the name of a mountain many miles inland that the simulator constructors had not bothered to model believing it had nothing to do with Valdez navigation (personal communication, 2000).

The importance of studying navigation in its proper context is stressed by many cognitive scientists. Hollnagel & Wood (2005) highlight, for instance, the study of how people and technology can work together to achieve specified goals. Their concept of *joint cognitive systems* (JCS) differs from traditional Human-Machine Interaction (HMI) and

Human-Computer Interaction (HCI) by focusing on how people work through an artifact rather than with it. This study is best done in the proper context on the bridge. I have also mentioned Lützhöft's (2004) investigation above.

So, the research questions were also answered in a qualitative fashion. I have shown the prototypes and their interface to a large number of users. Between 2001 and 2006, at 36 occasions, more than 600 persons, 200 of whom were mariners or had maritime related occupations, have had the 3-D nautical chart demonstrated to them. It has been done either on conferences or workshops or during field studies onboard. During or after the demonstration many of them have given me personal feedback. I have had a some hesitating comments on parts of the suggested systems (mainly the display of waypoints ahead of ships to visualize a planned route) but no one has ever told me that they do not believe the system will work as intended.

Almost all people have been positive and encouraging, saying they believe this system will work and facilitate navigation. One navy officer even commented that with this system "anyone can conn a ship," (implying that it made acquired knowledge and experience superfluous).

I take these answers, both the directly positive ones, and the absences of protests, as a qualitative answer to all three research questions. Yes, a large number of mariners, having seen a prototype demonstrated, believe this system will work as intended.

6.3 Future research

Visors and HUDs

In the navy navigation is often a teamwork where navigational information is communicated verbally from a navigator to a driver (see chapter 5). Verbal communication is sequential and takes time. Full concentration is needed from both the navigator delivering the conning instructions as well as from the driver listening to them. This type of communication is sensitive to disturbances and if the courses are short, the time to read the instructions may not be sufficient. By presenting the

navigational information directly to the driver an erroneous work task might be removed and driving facilitated. If “anyone can conn a ship” as one navy officer commented the 3-D chart, the vulnerability of navy operations because of short supply of key personnel, may be reduced as well.

In special environments like navy vessels chart information could be shown superimposed directly on the surface of the water instead of on a screen. Thus the *not-looking-out-the-window-problem* would be solved. One way of doing this is by using a semitransparent visor or even writing with low energy laser directly on the retina! (Viirre et al., 1998; Turner, 2002; HITLab, 2006). NoGo areas, seaways and other symbols could then be superimposed on the physical world at daytime. At night the synthetic terrain could be turned on, still allowing navigation lights from approaching ships to be seen. This technique is called *augmented* or *mixed reality*. A problem here is that the information will only be available for the driver, no second opinion can be offered by fellow mariners on the bridge unless they also have visors.

Studies have also been made (Olsson et al., 2002) on how to display chart information directly on the windscreen of ships similar to the way fighter aircrafts have their so called head-up displays, HUDs (here in the meaning that they are looking out the window – head up – as opposed to down on the instrument panel – head down). The benefit of this technique is that no intrusive visors or helmet need to be worn by the navigator. When a wind-screen a few yards in front of the navigator is used to show information that has to be aligned with the physical world hundreds or maybe thousands of yards ahead of the ship, great care has to be taken to compensate for parallax effects. If the navigator moves his head ever so little, the information also has to move. This can be done by head tracking. One only has to realize that the same problem as with the visor remains: the information is only valid for the navigator wearing the head tracker. If another person enters the bridge standing beside the navigator, s/he will see the chart information in the wrong place.

Automatic Wayfinding

In the prototyping chapter (chapter 4) three different types of seaways were mentioned. A *general network* of red and green carpets, a white *own ship's track* and a black *other ship's intended track* based on broadcast waypoint from the AIS transponders. The own track would in the present case consist of the waypoints programmed into the navigation system during passage planning.

However, the generation of Go and NoGo areas for the individual ship based on present water level etc. opens a possibility to automatically generate passage plans. If the system knows where you are and where you are going and what waters that are free for you to pass through, relatively simple geometric computations could generate a route. By adding constraints to the computation, the route could be generated to satisfy particular needs, like shortest route, most economical route considering wind, sea state and currents, most weather protected route, most sheltered route based on radar signature, and so forth.

Such a route could then be constantly updated in real-time so that if you for some reason should leave your course, the guiding system would always update the white *own track*.

It should, however, be pointed out that automation in itself may lead to new problems, e.g. boredom, decreased competence on non-automated ways of performing tasks, maintenance requirements.

Radar Integration

The radar is often considered as the primary navigation tool, prior even to looking-out-of-the-window visual navigation. Yet, there might be situations when information from both radar and chart need to be integrated and the time is too short. Remember the accident with the high speed ferry *Baronen* mentioned in chapter 2. The ferry hit a rock because the captain was monitoring only the radar and not paying attention on the shoals marked on the electronic chart, saying in court that "he could only do one thing at a time" (Bergenavisen, 2000).

If unidentified radar echoes could be reliably integrated into the 3-D chart, such time could be won. By comparing radar returns and the chart, removing all echoes that belong to terrain or artifacts represented in the chart (and even correcting drift in the GPS positioning), the remaining unidentified echoes could be represented in the chart. Because one would not know what such an echo was, one would need to be careful as to how it was represented. A simple solution, with a gray cube with a side length the same as the width of the radar echo is shown in Figure 163.

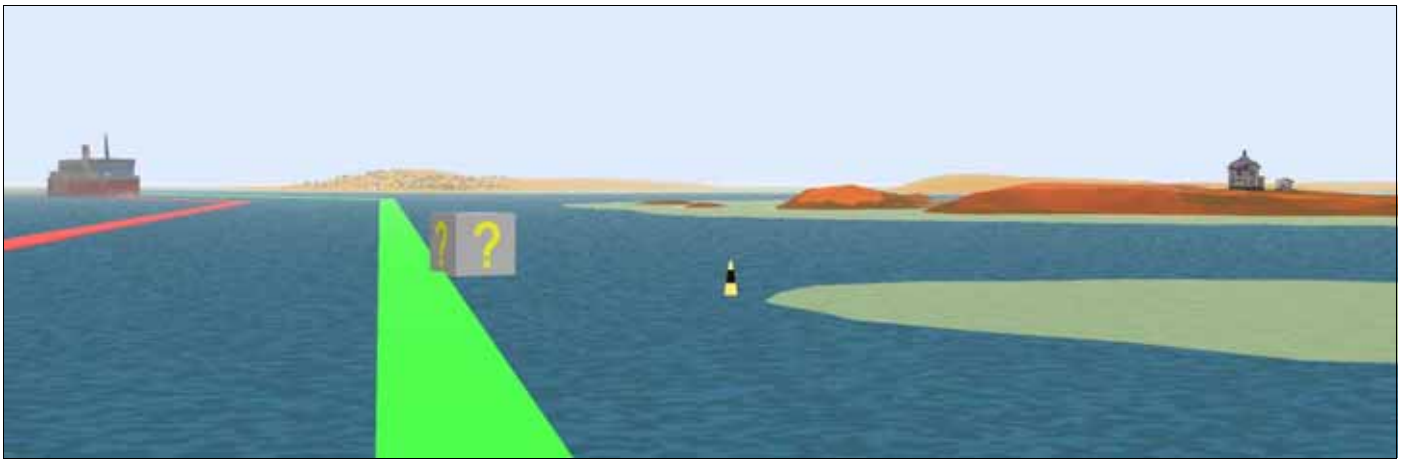


Figure 163. A simple visualization of radar integration into the 3-D chart. The radar returns are compared to the 3-D chart and only echoes that are not accounted for are shown. Here visualized by a grey cube with the size corresponding to the width of the radar echo. Some hint as to the origin of the object is given by its pattern of movement.

Because interpreting radar returns is difficult and much of an art in itself, I think that for a while one would like to be able to see the “raw” data in the traditional way. But future radar equipment possibly using scanning techniques may eventually be able to visualize the raw data in 3-D space right in a chart, addressing both the integration aspect and the wish to take part in the analysis.

A True Nautical GIS

The international IHO standard format for nautical chart data is called S-57 edition 3.1. The format is a vector, chart format where, for example, depth contours are tagged with an object class code and the depth as an

attribute. This type of data modeling with attributed point, line and polygon elements is often called *map spaghetti* (Laurini & Thompson, 1992, p. 399). This approach limits certain types of spatial analyses.

The intention of a Nautical Geographical Information System (N-GIS) would be to allow chart data to be displayed from an exocentric bird's eye perspective, but also allow for the same data to be looked upon from an egocentric surface view. This could as a provisional method be accomplished by combining the S-57 vector charts and a 3-D (actually 2.5-D) terrain database.

But a much better and more flexible solution would be to store all elevation data (both over and under water) in a true 3-D voxel based database allowing modeling of currents, temperature and salinity differences as well as bottom sedimentation. The database should allow for different resolutions, so that newly sounded areas could have a very high resolution and old areas maintain a low. The traditional chart look in the exocentric view would then be accomplished by creating depth curves for the displayed area in real-time.

A N-GIS would have simulation capability for predicting tidal currents and wave patterns, and could in advance warn mariners about extreme wave height of some areas under certain conditions. More reliable tidal predictions could also be made including effects of winds and air pressure as well as tidal table data. We are not quite there yet, but I am sure it will not take long.

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Appendix A

Three Shipping Accidents

In this appendix I will examine three shipping accidents in which the loss of orientation plays an important role. This in order to convey an understanding of the context in which some minor slip or mistake can cause an accident later to be identified as “human error.”

A.1 Case Study

“A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context” (Yin, 2003, p. 13). We have here the same motivation that was used to motivate ethnographic participant observation in the field studies chapter: that we needed to study applied navigation in its proper *context*. This project is about *safe navigation* so an important source of information is of course accidents. Schramm (1971) emphasizes that the case study tries to illuminate a decision or a set of decisions, “why they were taken, how they were implemented and with what result” (Yin, 2003, p. 12).

At the beginning of this project I searched the archives of several accident investigations boards. I did this hoping to identify accidents that were caused by the mismatch of directions originating in mental rotations that I so often had experienced onboard my own boat, but then with amateur navigators. I did not manage to find such an accident. Although several interview sources have talked about incidents of that kind no one has been willing to supply any precise

data as to vessel and time. One reason for this might be that if nothing happened there would be no need to report the incident, but another reason might be stigmatization connected to this kind of “unprofessional” mistakes.

I have chosen three accidents for a closer study in this chapter. They all in some sense depend on the loss of orientation or situation awareness and they give insight into human behavior when something goes wrong. They encourage the reader of case studies to ask questions about why certain actions were taken and, particularly, why in some cases actions were not taken. What decision-making tools were used, which were not used and why? And they have given me as a researcher insights into what possible measures could be taken to aid decision-making in complex situations.

The three case studies in this chapter are based on secondary data: accident, reports, court protocols and newspaper articles; no interviews of first-hand sources have been used. Never the less I believe that these case studies have been valuable for this project, and that they serve as evidence that although we are better equipped than ever to perform safe navigation today, there is still some way to go.

In the following will be told the story of the grounding of combat boat 881 in 2003, where a Swedish high speed combat boat stranded on an island at full speed with 20 soldiers onboard; the *Sleipner* accident 1999, when a Norwegian high speed ferry hit a rock and sank, killing 16 passengers; and the *Exxon Valdez* in 1989, when a 200,000 ton tanker grounded in Alaska with large environmental damages as a result.

A.2 The Grounding of Combat Boat 881 in 2003

The Accident

The account of this accident and the technique of combat boat navigation are based on a report by the Swedish Accident Investigation Board (Svenska Haverikommissionen, 2004). The reader is expected to have read the section on the navigation environment of Swedish combat boats in chapter 1 and 5.

On the night between 25 and 26 of April 2003 ten Swedish combat boats were transporting soldiers in an exercise on the Swedish west coast. The soldiers had been picked up outside the city of Uddevalla, and at 23.15 hours the loading was finished and the boats set course south along the fairway leading towards Gothenburg. It was dark but the weather was fine with moderate wind and surge along the track in the inner archipelago. It was partly cloudy and some mist in the air and the contours of islands could be distinguished against the sky. Combat boat 881 had 20 soldiers onboard, now seated in the amidships transport cabin. In the wheelhouse the crew of three conscripts, all trained as combat boat drivers, were strapped to their seats. The conscript serving as chief officer was driving the boat, another one was serving as navigator and the third as mechanic.

A combat boat is a light transport vehicle; about 16 meters long built in aluminum and weighing about 20 tons fully loaded. It is capable of speeds above 40 knots. It has a water jet propulsion system and very good maneuverability allowing sharp precision turns even at full speed (see Figure 164 and Figure 165).



Figure 164. A combat boat type 90 H in the archipelago outside Gothenburg. Photo by the author.

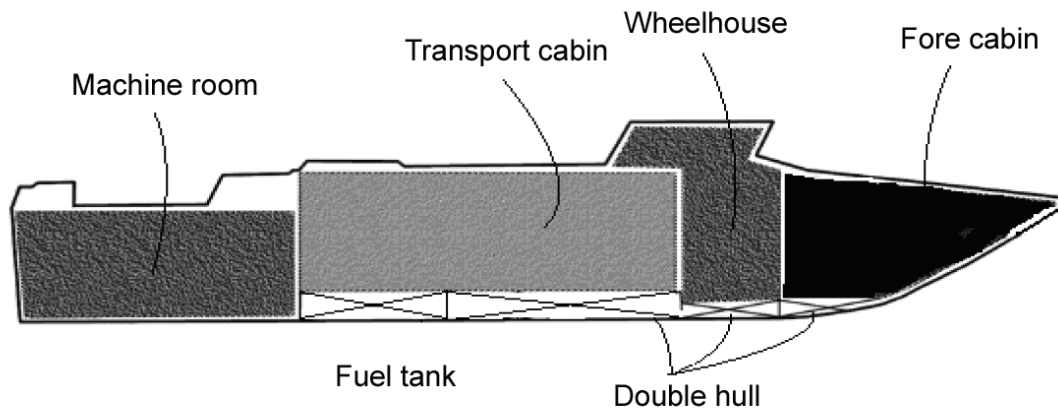


Figure 165. A cross-section of a combat boat type 90 H. Picture adapted from the Swedish Accident Investigation Board (2004).

The navigator had not fully prepared the chart for the voyage. The course lines with their break points (BP) were drawn but nothing else; no turning points (GP), turning point distances (GPA) or passage distances (PA). (For an explanation of these terms see the section on combat boat navigation in chapter 5.) The crew had driven the route before and according to interviews by the investigation board they felt confident with their task. During the first 45 minutes of the voyage the track went southwest along the main fairway leading from Uddevalla. It is wide and well lit with lighthouses and flashing buoys. Ten combat boats were traveling in pairs with about 200 meters between them and at a speed of about 30 knots.

At around fifteen minutes past midnight the *881* was passing Älö with the little rock Lorten on port side. Having passed Lorten, *881* made a hard port turn and came to course 133 degrees (about SE). They were now leaving the main fairway and entered onto a small and narrow track with only daylight marks and no lights.

The new course was leading towards the narrow sound between the islands Lilla Brorn and Stora Brorn. (See Figure 166.) Their heading was for the northern tip of the small skerry NE of Stora Brorn and the speed was now 32 knots. After having passed the green starboard buoy NE of

Lilla Brorn, 881 was supposed to have made a 116 degrees starboard turn to course 249. The navigator informed the driver that their next turn would be to starboard after having passed the buoy, “*turning point*: the north eastern tip of Lilla Brorn abeam on starboard.” (The term *turning point* is explained in chapter 5.) Shortly before the turn the navigator shifted radar range from 0.75 to 0.5 nautical miles. At the same time he pressed the push button to change radar pulse length from “medium pulse” to “short pulse.” A shorter pulse length augments the resolution of the radar, making it possible to see narrower straits between islands that otherwise risk merging. However, the picture quality did not improve. The navigator later stated that he might have pressed the wrong button or not pressed the button hard enough. The 881 was now on the decided turning point and commenced the turn. (About 00:20:12, see Figure 166.)

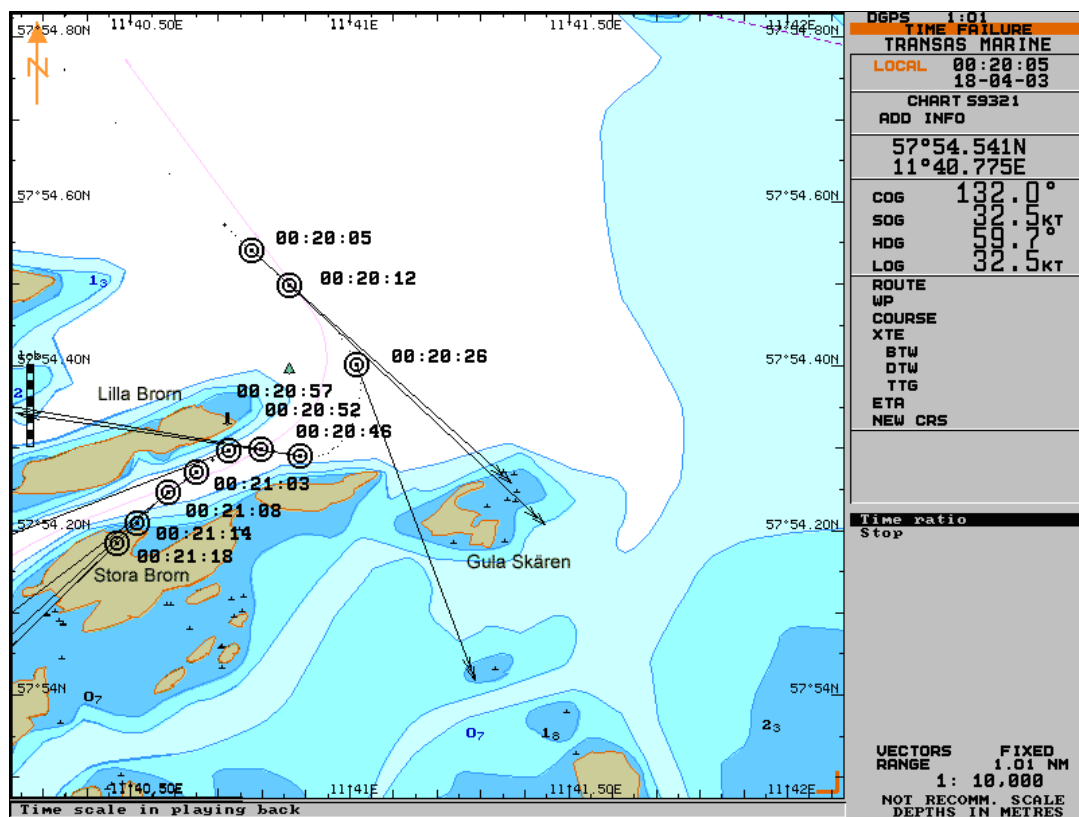


Figure 166. Consecutive screen dumps from the replay of the 881's electronic chart and navigation system merged into one to describe the boat's final movements before the grounding. Adapted from the Swedish Accident Investigation Board's report (2004). The date in the navigation system is wrong due to an insertion error onboard, but the times are right. The data to the right refers to the first location at 00:20:05 hours.

During the turn both the driver and the navigator suddenly saw land straight ahead in the light from the top navigation light. It was the skerry north east of Store Brorn (about 00:20:36). The navigator commanded "Come starboard!" at the same moment the driver gave hard starboard rudder. The boat escaped land (00:20:46) and the driver returned to midship rudder (00:20:52). Almost immediately land was observed ahead on starboard bow. The navigator called out "Port rudder!" and the driver applied hard port rudder and once again avoided land.

The driver then asked the navigator to reduce the gain on the radar display. (The driver only had a slave display in front of him; the navigator had the instrument controls for the radar display.) The navigator turned down the gain knob without any effect, the driver and the navigator could still not see the extent of the sound on their displays. However, the navigator thought the boat was now heading in the right direction through the sound (about 00:21:03).

After a couple of seconds land was once again observed afore. Another evasive maneuver was applied but this time too late. The boat hit a shoal close to the beach and bounced up on land stopping some 30 meters from the shore. See the newspaper photo in Figure 167. The time was now 00:21:18.

Two of the crew and one of the soldiers suffered light injuries. The bottom of the boat and the propulsion system were damaged but later repaired and the boat was put back into traffic.

The *Swedish Accident Investigation Board* (SHK) found no technical reasons for the accident. The direct cause was, according to SHK, that the crew did not stop the boat after having lost orientation. SHK comments that this is remarkable as the drivers are trained to stop immediately as soon as there is any uncertainty about the position. SHK continues in their concluding remarks by saying that the crew had traveled that route several times, in daylight however, and with an instructor onboard, and never with a full load of passengers. But the



Figure 167 From *Göteborgs Posten* April 26, 2003. The heading reads: Military boat ran ashore. Photo: Bengt Christiansson, *Göteborgs Posten*.

task this night was not considered a difficult one which induces the investigation board to comment that the crew might have felt a false confidence facing the task. The uncompleted chart preparation points in this direction.

Discussion

The investigation board concluded that the direct cause of the accident was that the crew did not stop the boat after having lost their orientation. One might further infer that the reason for losing orientation was that the radar was not tuned the right way and could not show a clear picture of the strait between the islands. Thus, as far as radar and optical vision go, the navigator and the driver were in effect blind when they entered the sound. The electronic chart system did, however, show a very accurate picture of the boat and its position (see the logged screen dumps in Figure 166). But the update frequency of this system is normally around 1 Hz and this makes it difficult to use it as steering guide at speeds as high as in this case (risk of oscillations). Although not mentioned in the accident report, it seems that the maneuvers prior to the crash bear the sign of what in the aviation domain is called *pilot induced oscillations*; a mistaken course is

overcompensated, leading to overcompensation in the other direction and so on. Because of the lag in the control instruments the closed loop is amplified. Although the electronic chart is said not to have been used during the accident, it is well-known that low GPS update frequencies and high speeds open for pilot induced oscillation patterns. The solution is probably the use of inertial navigation systems (INS) which allow very high update frequencies.

One might ask why the compass was not used to find the new course through the sound after the turn. Traditional procedures for navigation in darkness would rely heavily on keeping compass course and time intervals on each leg. But even so, passing the narrow strait at a speed of 32 knots would be a very risky business.

The malfunctioning radar was according to the investigation board not a technical failure. Instead, it was what might be called an operator error. The navigator pressed the wrong button, or he pressed the right button, but not hard enough. These kinds of errors are often called *human errors*, which we discussed in chapter 2.

The most surprising thing about this accident is, of course, that the driver did not stop, or at least slow down when he lost his orientation. He might have been concerned about the whereabouts of the combat boat that followed behind, afraid that it might crash into the stern of his boat if he suddenly stopped (such an accident happened in 2004 where two conscripts died).

It is evident that navigating a combat boat at over 30 knots in confined waters is a very complex task. A weakness in the methodology above seems to be that when navigating in very complex archipelagos where each course leg is short, there is not enough time to verbally inform the driver about the situation. In this case the navigator had much more information (the position plotted on the electronic chart) which he never gave the driver, either verbally or by linking the picture to the drivers display.

This accident foregrounds the need for a navigation aid on the intuitive level that will work also when preparations are missing and time is too short to communicate orders.

Conclusion

Radar navigation was the primary navigation method onboard this night and the radar was used in a head-up mode, which was the normal mode. The radar could, according to the SHK, be used in a north-up mode as well, but according to personal communication with the responsible instructor (January 2005) the radar did not function well north-up due to problems with gyro support. When the radar failed to give a proper picture shortly prior to the accident, the electronic chart should have been used for positioning. This was never done according to the testimonies presented by the SHK. But even if it had been used it would have been a risky venture driving the boat at over 30 knots on a southerly course in the narrow, considering the problems with mental rotations. And the problem of system lag will remain.

Using the compass to ensure they were on the right course after the turn would have been a third possibility that was never used. Chart preparations were very limited and courses were not written down on the chart according to SHK, so the navigator had not taken out a new course to head. This would have taken a couple of seconds and that time was not available at the time.

The last and most obvious action, which the crew were trained for, would have been to stop, or at least, reduce speed. Why was this not done? One reason might be indecisiveness and lack of initiative to take actions that might cause commotion and worry among the 20 conscripts that were transported.

This is an example of how high speed leads to short decision time and stress; an example also of technically complicated systems that are not functioning for different reasons, and other systems that are not used, possibly because there is not enough time to “think of it”. This is a situation where a 3-D chart would serve well showing a simple and unambiguous picture of the situation.

A.3 The *Sleipner* Accident in 1999

The following account is based on the official accident report (Norges offentlige utredninger, 2000), protocol from court hearings (Gulating lagmanrett, 2003) and newspaper articles.

The Norwegian Westland is mountainous and the mountains go all the way to the coast which is cut through by deep fjords. This makes road transportation time consuming, with many ferries and tunnels. The high speed ferry route is therefore a convenient way of traveling between Bergen and Stavanger, Norway's second and fourth largest cities. The HSD shipping company runs this route, called Flaggruten, with several high speed ferries.



On November 26, 1999 one of them, the high-speed craft (HSC) *MS Sleipner* left Haugsund on the Norwegian Westland at 18:47, two minutes after scheduled time. As she left the harbor of Haugsund on northerly course she entered a notorious stretch of the coast named Sletta, open in the west to the whole North Atlantic. It was dark and the weather was bad: SW gale, force 8-9 Beaufort (21 m/s) and showers of haile. Between the showers the visibility was good. On the bridge was the captain, an experienced mariner with 27 years as a bridge officer and 11 years on HSC the last seven of which on this route. He was normally the captain of *MS Draupner*, an almost identical HSC, but was this day standing-in as captain on *Sleipner*. With him on the bridge was also the first mate with 6 years of experience as an officer on HSC and the chief engineer. With the rest of the crew and the passengers *Sleipner* hosted in all 85 persons this evening.

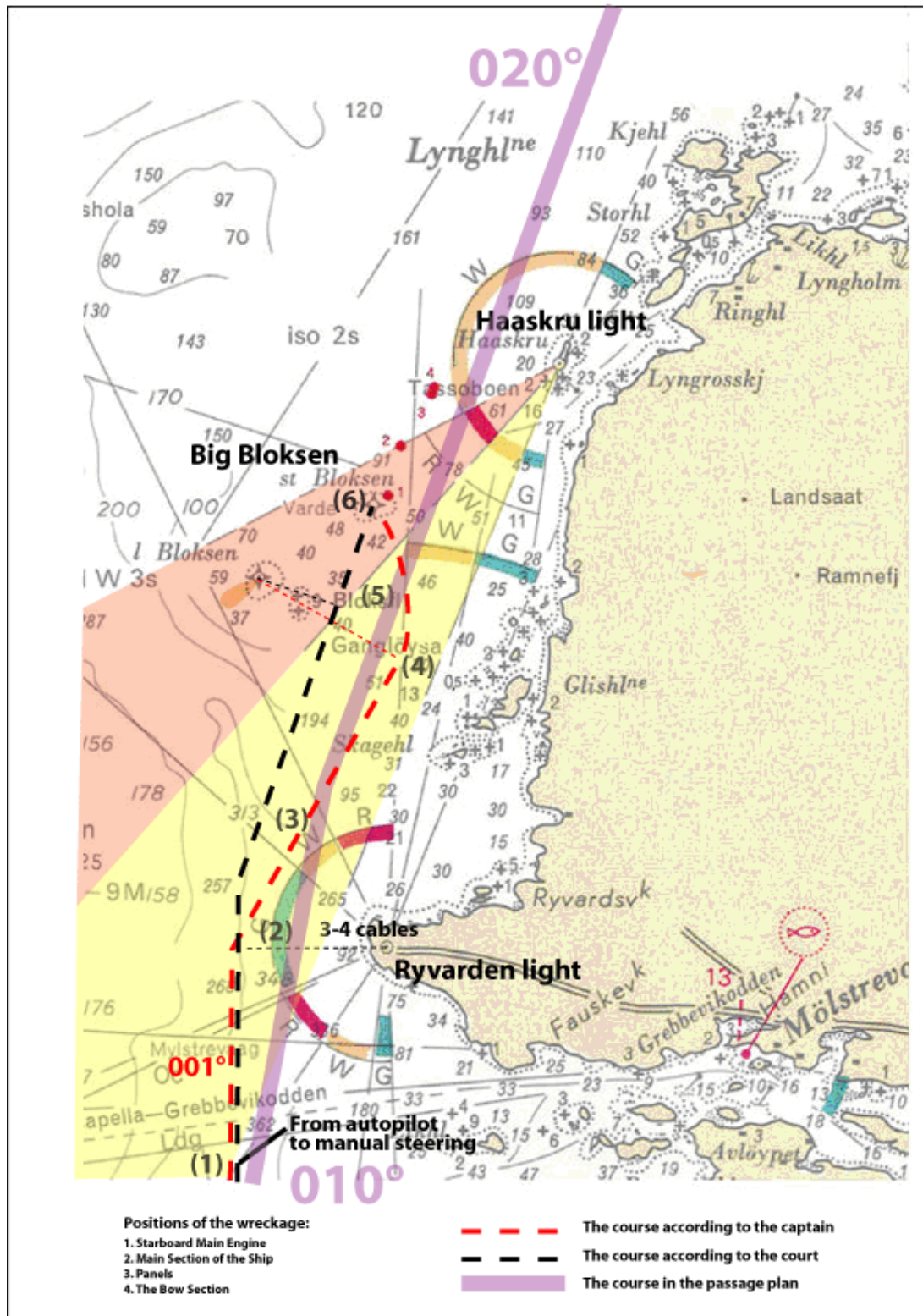


Figure 168. Adapted from the accident report. Detail from chart no. 17, Statens kartverk, Sjøkartverket.

The captain and the first mate had embarked on the *Sleipner* in the morning and done one trip north to Bergen and then back south to Stavanger again. They were now on their way north for the second time that day. Earlier in the day, as *Sleipner* passed Sletta on southgoing, the wind had been S force 8 (18 m/s) but had in the evening begun to shift towards SW and increase. *Sleipner*, newly delivered from an Australian ship builder, had still not had her hard-weather-test done and was not allowed to operate in weather with a significant wave height⁴ above 1 meter. If the waves were higher the route was to be canceled over Sletta and the passengers to be bussed. The wave height on Sletta was dependent on wind force, but also on the distance to windward land. Southerly winds meant calmer sea state in lee of the Røvær islands and westerly winds opened Sletta to the North Atlantic. In the morning *Sleipner* had passed Sletta without problems and on the way back north the captain was talking to the sister-ship *Draupner* on the telephone, and they were also passing Sletta without problems, so he decided to carry on. Afterwards the Norwegian Metrological Service estimated the significant wave height on Sletta this night to have been between 2 – 4 meters.

Sleipner was a brand new ship. She had a modern wheel house with a 360° view out of the windows. The captain and the first officer were seated in a cockpit arrangement at the front of the bridge, the captain in the starboard seat and the mate in the port (see Figure 169). The captain had a 10 cm, S-band, radar screen in front of him and the first mate a 3 cm, X-band radar the controls of which were on the port armrest of respective chair. On the starboard armrest were the steering controls, the rudder being maneuvered by a small turn knob. On the captains chair a spring on this knob was broken, a faint click-stop giving haptic feedback that the rudder was in amidships position was missing. There was also an electronic chart (ENC) fitted to the DGPS system. The electronic chart was displayed on a screen in the center between the two drivers. The screen was a LCD display and the observation angle of each officer was about 45° which made the screen very hard to read, and in darkness, to read without being dazzled. This devise was therefore seldom used, and was not so this night either.

⁴ The significant wave height is the amplitude from top to bottom of the highest one third of the waves.



Figure 169. Left, *Sleipner* Right, the blueprint of the wheel house arrangements. From the report of the accident commission.

The voyage north over went without problems. The visibility was good outside the showers (1.5 – 2 nm) and the lighthouses up along the coast were clearly seen. The sea state was calm to begin with, but as they came more north on Sletta the waves became higher. *Sleipner* was conned by the captain using visual sight (the colored sectors of the lighthouses) and the radar was set on the 3 nm range and temporarily changed to 6 nm to check on a course in the southern part of Sletta. No range rings or parallel indices were used to control the distance to the coast. Standard speed (30-35 knots) was used.

The captain had *Sleipner* on autopilot on course 001° as she approached Ryvarden light in the northern section of Sletta (see Figure 168). Here the fairway became narrower and also the waves, which *Sleipner* now had on the port quarter, had become high enough to cause some swaying, so the captain decided to switch over to manual steering (see point (1) in Figure 168). To steer he now used the turn knob on his starboard armrest, the one which did not have a click-stop to indicate midship rudder. When Ryvarden light was about 3-4 cables abeam on starboard side the captain turned starboard in the white sector of Haarskru light (2). He did know exactly how many degrees he turned but he states he was steering with Haaskru light as much as possible straight ahead on the stem. The captain now turned his radar down to

1.5 nm. The ship was swaying about 10-15° to either side due to the seas from the aft quarter. He states that he never saw either Little or Big Bloksen on his radar screen, even after he had seen the light of Little Bloksen pass abeam on the port side. He usually used Haaskru light, the radar land behind Haaskru, the small island of Glisholmen and the light on Little Bloksen as reference points for visual navigation in this area and he meant that he from experience could say that he was about in the middle of the white sector heading for Haaskru. He had not used the radar since departing from Haugsund, except for the short course check mentioned earlier. But as he did not see Big Bloksen on his radar when passing Little Bloksen he decided to set the range rings at 0.25 nm intervals. He states that he was busy doing this for a couple of seconds. In the report the commission here remarks that the distance between Little and Big Bloksen is 0.22 nm which with 35 knots takes 23 seconds to travel. While doing this the captain was interrupted by the mate who shouted "You are on the wrong way!"

This is the course of events reported by the accident commission in 2000. In the court hearings before Gulating lagmansrett in 2003 the court found that the last turn must have been executed later, approximately at (3), when Ryvarden light already was aft of abeam. They also concluded that *Sleipner* must have had the white sector of Haarskru more on the starboard bow than dead ahead. The mate testified before the commission that he saw Haarskru clearly in the white "close to starboard bow" up until they had Little Bloksen abeam, which he saw both visually and "as a big rose" on his radar screen. This is the point (4) or (5) depending on which route *Sleipner* took. At this point the captain and the mate had a conversation. To the commission the mate reported that the captain said: "There is Bloksen abeam, there should be a radar reflector on her, so she would be easier to see." The mate answered: "There should be a reflector on the other." He meant Big Bloksen, he saw no logic in what the captain said as there was a light on Little Bloksen. At this moment the mate started to look for Big Bloksen on his radar screen. He had much clutter and tried to adjust the Gain and Sea Clutter controls but without success, he did not see Big Bloksen. The mate thinks he spent about 20 seconds adjusting his radar. When he looked up he did not see Haaskru light on the starboard bow as expected. Instead he saw it in the red through the first window on the captain's side. He states the ship must have turned 20 - 30° to the port. He got really afraid because he knew they had not passed Big

Bloksen and shouted “You are on the wrong way! You will hit Bloksen!” The captain turned on the bow headlights and the cairn of Big Bloksen became visible straight ahead. The captain gave full port rudder, pulled the throttle handles fully aft but *Sleipner* almost immediately hit the rock (6). In Figure 170 is a photograph from the accident commissions report showing Big Bloksen in fine weather. In a force 9 gale she would be quite a different sight, an inferno of braking waves and with showers of foaming water towering over her.



Figure 170. The small skerry Big Bloksen in fine weather. From the report of the accident commission

At 19:08 *MS Sleipner* hits Big Bloksen at not far from full speed, 35 knots, and with the cairn close on the starboard bow she got stuck. The grounding crashed both hulls of the catamaran and soon both engines died, preventing the captain from further attempts to back off the rock. After a short time the bow of *Sleipner* broke off and the ship was pushed off the rock by the seas. Without a bow and the remaining of the two hulls perforated *Sleipner* only remained afloat for a short time and

finally went down about 30 minutes after the grounding taking 16 people with her to the bottom. The remaining 69 were saved by ships coming to assistance.

The accident commission's report was published in 2000 and came to the conclusion that

- The wave height at Sletta was over the allowed 1 m and that *Sleipner* should not have sailed.
- The event that triggered the accident, the sharp end, was that faulty navigation by the navigators (read the captain as the conning officer) who did not know their position. This because they did not use all available equipment onboard, and because they, in the critical time frame, were inattentive to the navigation.

After having been freed in the lower court, Guleting higher court in 2003 convicted the captain to 6 months imprisonment, conditional, for reckless conduct. He had entered confined waters in darkness and bad weather and did not use all available navigation instruments onboard to fully establish the position of the ship. The court found that *Sleipner* must have headed toward Big Bloksen on a relatively straight course because none of the witnesses on the bridge or among the passengers had felt the side-forces of any sharp turn after the passage of Little Bloksen. The court found that such a large course change needed if the track had been the one suggested by the captain should have been noticeable (see Figure 168). The court concluded that the main reason for the grounding was the captain's inattentiveness and faulty navigation. The Supreme Court the same year refused an appeal.

Discussion

On the chart in Figure 168 I have inserted the two different tracks as I have plotted them based on the statement of the captain and presented in the report of the commission, and the track the court later decided must have been the most probable based on witnesses. We will never know which of these or, more probable, which mixture of them was the actual track. And frankly, it is of no importance. We know that *Sleipner* ended up where she should not have been, so we know something went wrong. Neither the commission nor the court found any natural reasons

for the course change (hull, propulsion, currents, broaching⁵, etc.) so the faulty navigation is the only reason left.

In the critical part of the journey, just before *Sleipner* was to pass Big Bloksen, none of the officers were looking out of the window. For a couple of seconds, we do not know how many, both of them were occupied making adjustments to their radar sets. This is of course not acceptable, human, but not acceptable in such a situation. Formalized communication on the bridge of HSC was also among the recommendation made by the commission. A formal hand-over would have ensured that the helm was not left unattended: “Take over!” “OK, I have the conn.”

In the Norwegian maritime journal *Skipsrevyen* the handling of the radar equipment was criticized by a naval officer (Garvik, 2000). Being a radar expert and after having read the print-outs of the hearings with the officers he concluded that the radars would probably not have been of much use trying to detect Big Bloksen in the sea state of the night of the accident. The 10 cm S-band radar of the captain would probably not have seen the small echo of Bloksen and the disturbing echoes from the waves would probably block out the 3 cm X-band radar of the mate. He also stated that the mate seemed unfamiliar with how to make the proper adjustments on the radar set. Both officers also stated that they had no proper training on the radar sets besides what they had learned themselves on the job and were not familiar with all the functions. Several other articles have also stated that there are detection and real-time problems with radars and HSC (Garvik, 2000 and 2001; Isaksen, 2000; Strønen, 2005).

Both the commission and the court criticize the captain for not using all means to establish his position. He should have used the radar as a secondary means to check his navigation, with for example, having the range rings turned on to measure the distance to land on his starboard side. When he could not detect Big Bloksen on his radar, he could have turned his head and checked Ryvarden light on his starboard quarter which would switch from red to white when he was passed Bloksen.

⁵ Broaching is a term used for the incident when a ship is thrown sideways by braking waves from behind.

Both officers had been in service for 9,5 hours at the time of the accident. The court acknowledges this but says that it played no role in the accident. I disagree. Can it really be ruled out that fatigue has a part in this accident?

When going downwind in heavy seas a ship will sway from side to side. The court acknowledges that *Sleipner* swayed 10 - 15° to either side. If amidships rudder is kept the ship will keep the same course although she is swaying, but it is reasonable to think that the captain used the rudder to keep the ship on a more steady course upon entering the narrow water on the inside of Bloksen. The absence of the click-stop on the steering-knob to mark amidships rudder could have played a fatal role when he was not looking at his visual steering mark, Haaskru light, but instead was adjusting his radar. Do we not all know how it is to try to find a radio station while driving a car at the same time?

The ship was fitted with an electronic chart. It was not used because it was placed in a bad position, difficult to see and not used. But according to the commission it was turned on during the evening. On a northerly course there would have been fewer problems with mental rotations. An eye on the chart would have told the officers what was going on.

The captain looked up from his radar set at the shout from the mate. It was then maybe already too late to do anything. But when the mate looked up from his radar screen it must have taken him some second to realize that Haaskru was not white on the stem (Iso 2 s = one 1 s flash every 2 s) but instead red on the bow. Valuable seconds and fractions of seconds passed as the mate tried to orientate himself. It is this situation the 3-D chart is addressing.

A.4 The *Exxon Valdez* Accident in 1989

The following overview is based on the Alaska Oil Spill Commission's final report of the Exxon Valdez accident. (1990) The numbers in bold in the text refer to the characters in red on map in Figure 171.

In the evening of March 23, 1989 the 210,000 ton tanker *Exxon Valdez* left the Alyeska Marine Terminal loaded with 53 million gallons of crude oil for Long Beach, California. On her way out through the Valdez Narrows she was attended by a marine pilot and a tug boat but once in the Prince William Sound she was on her own and began to increase speed. On the bridge were the captain, the third mate, the helmsman and a lookout. At 23:24 (1) the pilot was dropped off at the entrance to the Traffic Separation Scheme (TSS) and at 23:25 the captain radioed to the Valdez Vessel Traffic Service (VTS) that he on his radar had detected ice from the nearby Columbia Glacier drifting in the sound and that he intended to divert from the outbound lane of the TSS and take a more easterly course through the inbound lane "if there is no conflicting traffic". The traffic center indicated concurrence; there was no reported traffic in the inbound lane. This was evidently a routine maneuver; two outgoing tankers had done the same deviation from the TSS the same day for the same reason. It would save some time in reaching the open sea, not having to push her way through the ice at low speed; instead *Exxon Valdez* could continue to ramp up her engine to sea speed and at the same time cut a corner for a faster exit.

At 23:30 (2) the captain informed the VTS that he was changing course to 200°. At 23:39 (3) the mate plotted a fix in the separation zone in the middle of the TSS and the captain ordered another change of course, now to 180°, due south. According to the helmsman, the captain also ordered the ship to be placed on autopilot. This second turn was not reported to the VTS. For a total of 19 to 20 minutes the ship now sailed diagonally through the eastern, inbound lane of the TSS and crossed its eastern border with approximately 12 knots at 23:47 (4). At approximately 23:53 the captain left the bridge after having told the mate to change course when abeam Busby Light (some 2 minutes ahead).

At 23:55 (5) the third mate plots a fix in the chart abeam Busby Island but he does not order a turn. For another 5 minutes he continues to take *Exxon Valdez* on her southerly course towards disaster. At midnight (6) the lookout reports Blight Reef light buoy broad off the starboard bow. Now the mate orders 10 degrees right rudder. Two minutes later, at 00:02 (7), the mate orders increased right rudder to 20° and at 00:04 (8) hard (35°) right rudder. At 00:07 (9) *Exxon Valdez* strikes Blight Reef at

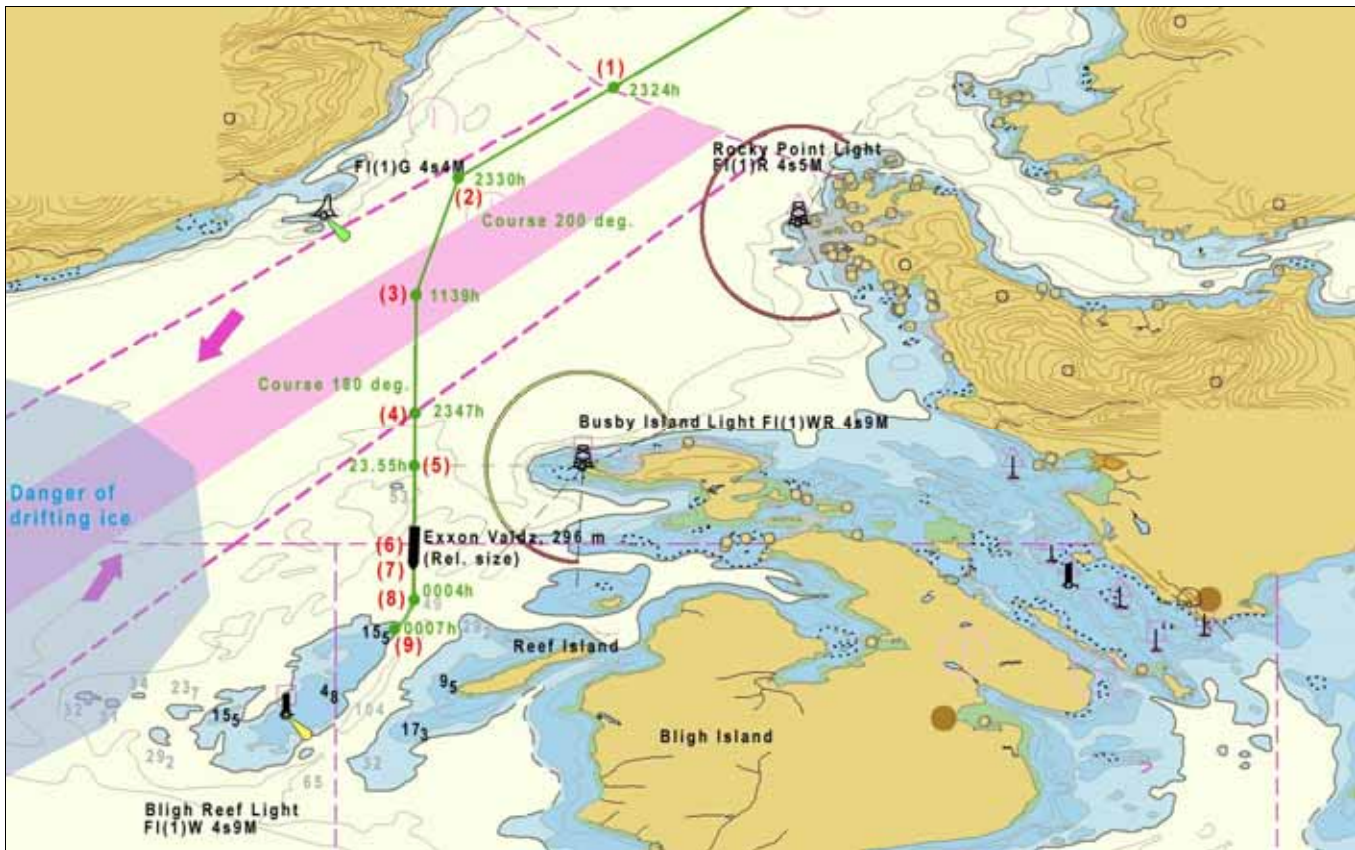


Figure 171. The route and times of the Exxon Valdez the night of March 23, 1989 in green. The numbers in red correspond to numbers in the text. NOAA ENC US5AK11, 24 and 25M over Prince William Sound, Alaska.

a speed of approximately 12 knots, ripping open 8 of 11 cargo compartments (see Figure 172).

The National Transportation Safety Board (1989, p. 170) investigated the accident and determined that the probable causes of the grounding were:

1. The failure of the third mate to properly maneuver the vessel, because of fatigue and excessive workload.
2. The failure of the master to provide a proper navigation watch, because of impairment from alcohol.
3. The failure of Exxon Shipping Company to provide a fit master and a rested and sufficient crew for the *Exxon Valdez*.
4. The failure of an effective Vessel Traffic Service because of inadequate equipment and manning levels, inadequate personnel training, and deficient management oversight.
5. The lack of effective pilotage services.



Figure 172. *Exxon Valdez* grounded on Blight Reef in March 1989 causing the spill of 11 million gallons of crude oil into the Prince William Sound and the Alaskan Gulf.

As far as the first point goes it is evident that the third mate was too late in initiating rudder and when doing so, he gave too little rudder. In a rare interview with the captain in the *Outside Magazine* in October 1997 (Coyle, 1997), eight years after the accident, the captain is conning a somewhat larger tanker going the exact same route in a full-scale simulator in Seamen's Church Institute in New York, a training center for merchant mariners. The simulator has been set up to replicate the conditions at midnight, March 23, 1989. When abeam Busby light the captain orders: "Give me right 20." In the simulator the ship nicely turns and passes the reef with a two mile margin. "That's all you'd have to do. That's all anybody would have had to do," the captain is quoted saying.

It is clear that this accident, like many others is part of a big system where rules and regulations, often at high administrative level, contribute to a situation where an accident is only a question of time. But in the specific case, like in the *Exxon Valdez* accident, there is often a small human error that is the direct cause. Why did the, possibly overtired, third mate Cousins wait for 6 minutes to make the turn, when he was ordered to do it when the lighthouse was abeam? The hearings give no clear answer. There was no doubt about the ship's position. Was his mental picture of the position and extent of the reef distorted? Or did he misjudge the turning capabilities of the tanker? We will never know. Research shows that although individual actions may be

performed well the overall organization of these actions seem to suffer from fatigue (van der Linden et al.,2003).

In this situation I think that a simple intuitive decision aid like the 3-D chart with a bridge perspective of the world and a single track to follow will improve safety. Using computer predictions showing the would-be course lines of maximum starboard and port rudder maneuvers in the chart would at the same time give the navigator a visualization of his decision space (Porathe, 2004b).



Figure 173. Visualizing the decision space of a ship's maneuverability in a real-time 3-D nautical chart. The red area on both sides of the ship is area out of bounds; the trumpet form in front of the ship predicts the borders of maximum turning angle (Porathe, 2004b).

A. 5 Concluding This Chapter

From a number of reports I have chosen to convey the story of three shipping accidents. They were all caused by lack of proper situation awareness. In the accident statistics presented in the introduction chapter we saw that somewhere around 80 percent of all shipping accidents were due to human error, in chapter 2 I discussed the concept of the *sharp* and the *blunt end*. If we look carefully there is a large chance that we find a human error at the sharp end. (But if we continue to look, there is also a large chance that we would find faults in instrument design or other human factor issue.) In the three accidents presented here we have such a human error: we have the driver and the navigator at combat boat 881 who did not stop although they were virtually

blinded by a wrongly adjusted radar and lost orientation in close proximity to land; we have the captain and the first mate of the *Sleipner* who lost orientation in close proximity to land because no one had their eyes “on the road”; and we have the third mate on the *Exxon Valdez* who did not execute a turn in time, “possibly due to fatigue” the accident report says, possibly because he did not properly judge the slow maneuvering properties of the 200,000 ton tanker, what we call *level 3 situation awareness* (see chapter 2).

In stressful and complex situations, decisions may have to be made quickly. Not acting can have disastrous results (which are shown in these three accidents). Decisions have to be based on apt situation awareness. Not knowing basic facts about what is going on might lead to hesitations in decision making (which we have seen here, too). The *881* and the *Sleipner* accidents would definitely not have happened in daylight, possibly not the *Exxon Valdez* accident either. The radar, a tremendously useful instrument as it is, has certain drawbacks: it has to be properly handled and it has to be properly interpreted.

What I hope to have shown in this chapter is the need for a simple chart view showing a synthetic daylight out-of-the-window-view. A chart view that is always there and crystal clear, independant on the knowledge, stress fatigue or proper handling and interpretation by the bridge crew. I hope that the proposed 3-D chart can be such a device.

Appendix B

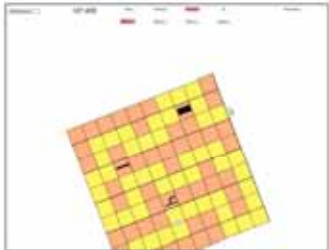
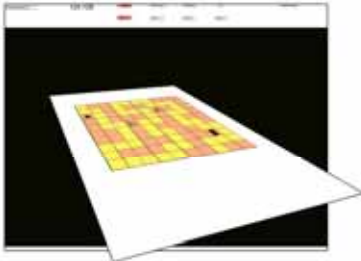
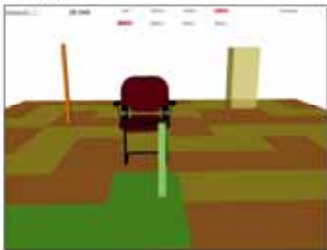

Experiment Results

The form the subjects were asked to fill in after the four tests:

Försöksperson.....

Vilken karta tyckte du var enklast att navigera efter?
Rangordna de fyra kartorna genom att skriva siffrorna 1 - 4 i rutan under respektive karta.

1 är lättast och 4 är svårast.

<p>Kurs-upp (pilen still, kartan rör sig)</p>  <input type="text"/>	<p>Papperskartan</p>  <input type="text"/>
<p>3D</p>  <input type="text"/>	<p>Nord-upp (kartan still, pilen rör sig)</p>  <input type="text"/>

Vad har du för erfarenhet av navigering med karta, sjökort, ritning?

(Fortsätt på baksidan om inte platsen räcker.)

Appendix B

Research experiment data: MAP DISPLAY MODES 2005-02-13

Subj. (#)	Paper map			North-up map		
	Time (s)	Errors	Track #	Time (s)	Errors	Track #
1	372	15	4	303	16	2
2	276	10	4	172	5	2
3	232	3	2	132	1	3
4	115	17	3	132	11	4
5	347	14	1	377	3	3
6	194	1	4	170	1	1
7	199	16	4	80	7	3
8	194	3	3	199	1	4
9	192	11	1	147	1	3
10	224	2	2	139	1	1
11	159	3	3	137	2	4
12	403	12	3	196	2	1
13	425	17	4	246	7	1
14	309	MD	1	154	MD	4
15	266	4	3	229	0	4
16	266	7	1	208	4	1
17	540	20	3	206	9	1
18	263	8	3	167	2	2
19	333	10	2	179	2	1
20	126	8	2	124	6	1
21	182	9	1	146	2	3
22	109	11	1	71	7	4
23	103	9	2	85	8	4
24	199	4	1	108	1	3
25	219	8	4	304	5	2
26	208	4	4	226	1	3
27	153	5	1	185	4	2
28	141	8	1	150	3	2
29	284	5	2	160	0	4
30	102	6	1	142	2	3
31	258	15	2	135	7	1
32	77	5	4	78	6	2
33	217	6	3	137	10	1
34	157	4	3	168	2	1
35	555	16	3	186	6	1
36	134	3	3	146	14	2
37	251	4	4	195	1	3
38	187	2	3	210	1	2
39	212	4	4	192	0	3
40	182	4	3	118	0	1
41	164	5	4	136	1	2
42	197	12	4	145	14	2
43	159	2	2	109	0	3
44	196	13	3	124	6	4
45	289	15	1	180	3	3
Mean:	230.4	8.2	2.60	167.4	4.2	2.38

MD = Missing Data

Research experiment data: MAP DISPLAY MODES 2005-02-13

Subj. (#)	Head-up map			3-D map		
	Time (s)	Errors	Track #	Time (s)	Errors	Track #
1	105	5	3	111	4	1
2	138	3	1	96	2	3
3	116	3	4	106	1	1
4	69	6	2	84	6	1
5	406	9	2	230	0	4
6	151	4	3	127	1	2
7	73	4	1	63	2	2
8	151	2	1	139	1	2
9	124	3	4	126	1	2
10	190	2	3	99	2	4
11	137	0	2	116	0	1
12	183	2	4	155	2	2
13	191	1	3	140	2	2
14	157	MD	2	67	MD	3
15	167	0	1	184	0	2
16	190	3	2	206	6	4
17	175	11	2	146	7	4
18	165	6	1	123	0	4
19	169	0	3	151	0	4
20	96	4	3	88	0	4
21	133	0	2	101	0	4
22	53	4	3	56	1	2
23	96	14	1	77	9	3
24	84	0	2	75	0	4
25	116	3	3	83	4	1
26	214	3	2	154	1	1
27	127	2	4	82	0	3
28	128	3	4	76	1	3
29	92	0	3	76	0	1
30	101	3	4	99	4	2
31	142	4	4	93	1	3
32	67	2	1	55	3	3
33	123	1	4	109	3	2
34	117	0	2	106	0	4
35	203	4	4	158	3	2
36	95	2	4	86	2	1
37	249	2	1	144	0	2
38	159	1	4	152	1	1
39	223	6	1	201	0	2
40	114	0	2	69	0	4
41	99	1	3	86	2	1
42	145	19	1	78	0	3
43	95	0	4	81	0	1
44	75	4	2	55	1	1
45	193	11	2	106	0	4
Mean:	142.1	3.6	2.53	111.4	1.7	2.44

MD = Missing Data

Appendix B

Research experiment data: MAP DISPLAY MODES 2005-02-13

Subj. (#)	Gender	Age	Sense of	Subjective rank ease of use				
			Direction	Nav.exp.	Paper	North-up	Head-up	3D map
1	2	35	2	2	3	4	2	1
2	2	33	2	2	4	3	2	1
3	2	30	2	3	4	3	2	1
4	2	52	2	3	2	4	3	1
5	2	32	2	2	3	4	2	1
6	2	28	2	2	3	4	2	1
7	2	43	2	3	4	3	2	1
8	2	63	2	2	3	4	2	1
9	2	59	2	3	4	3	2	1
10	2	61	2	3	4	2	3	1
11	2	37	2	3	4	3	2	1
12	1	55	2	2	4	3	2	1
13	1	MD	2	2	4	3	2	1
14	2	44	1	2	2	3	4	1
15	1	27	2	1	4	3	1	2
16	1	32	2	1	4	3	1	2
17	1	54	1	1	1	4	3	2
18	1	27	2	2	2	4	3	1
19	1	27	2	1	3	4	2	1
20	1	24	2	2	4	2	3	1
21	2	57	2	3	4	3	2	1
22	2	31	2	3	3	4	2	1
23	1	23	2	2	2	4	3	1
24	2	46	2	2	4	3	2	1
25	2	51	2	2	3	4	2	1
26	2	63	2	2	4	2	3	1
27	2	23	1	2	2	4	3	1
28	1	24	2	2	4	3	2	1
29	2	29	2	2	4	3	2	1
30	1	45	2	2	1	4	3	2
31	1	24	1	2	4	3	2	1
32	2	45	2	3	4	3	2	1
33	1	26	2	1	4	3	2	1
34	2	29	2	3	3	4	2	1
35	1	50	1	1	4	3	1	2
36	2	48	2	2	2	4	3	1
37	1	26	2	2	4	3	2	1
38	1	25	1	2	2	4	3	1
39	2	36	2	2	4	2	3	1
40	2	26	2	3	4	3	2	1
41	1	24	2	1	4	3	1	2
42	1	25	2	1	3	2	4	1
43	1	21	2	3	3	4	2	1
44	1	16	2	2	4	3	2	1
45	1	55	2	1	4	2	3	1
Mean:	1.5				3.33	3.24	2.29	1.13

MD = Missing Data; Gender: 1 = Female, 2 = Male; Sense of Direction: 2 = Good, 1 = Bad; Navigation Experience: 3 = Large, 2 = Average, 1 = Little; Ranking: 1 = The Easiest, 4 = The Most Difficult.

Research experiment data: MAP DISPLAY MODES 2005-02-13

Subj. (#)	Objective ranking based on time on track				Figure rotations	
	Paper	North-up	Head-up	3-D map	Raw pt.	Stanine
1	4	3	1	2	11	3
2	4	3	2	1	42	5
3	4	3	2	1	53	8
4	3	4	1	2	39	6
5	2	3	4	1	45	6
6	4	3	2	1	50	7
7	4	3	2	1	48	8
8	3	4	2	1	52	9
9	4	3	1	2	34	6
10	4	2	3	1	24	4
11	4	2.5	2.5	1	38	6
12	4	3	2	1	33	6
13	4	3	2	1	25	4
14	4	2	3	1	46	7
15	4	3	1	2	51	7
16	4	3	1	2	27	5
17	4	3	2	1	31	5
18	4	3	2	1	53	8
19	4	3	2	1	47	8
20	4	3	2	1	52	9
21	4	3	2	1	54	9
22	4	3	1	2	49	7
23	4	2	3	1	49	8
24	4	3	2	1	23	4
25	3	4	2	1	53	9
26	3	4	2	1	37	5
27	3	4	2	1	53	8
28	3	4	2	1	50	8
29	4	3	2	1	52	7
30	3	4	2	1	46	7
31	4	2	3	1	44	7
32	3	4	2	1	50	8
33	4	3	2	1	39	6
34	3	4	2	1	50	7
35	4	2	3	1	25	4
36	3	4	2	1	54	9
37	4	2	3	1	48	8
38	3	4	2	1	39	6
39	3	1	4	2	53	8
40	4	3	2	1	52	7
41	4	3	2	1	52	9
42	4	2.5	2.5	1	51	9
43	4	3	2	1	50	8
44	4	3	2	1	48	8
45	4	2	3	1	34	6
Mean:	3.69	3.02	2.13	1.16	43.5	6.87

Ranking: 1 = The Easiest, 4 = The Most Difficult; Figure Rotations: Raw Points
 Max 54 p. Stanine: 1 – 9;