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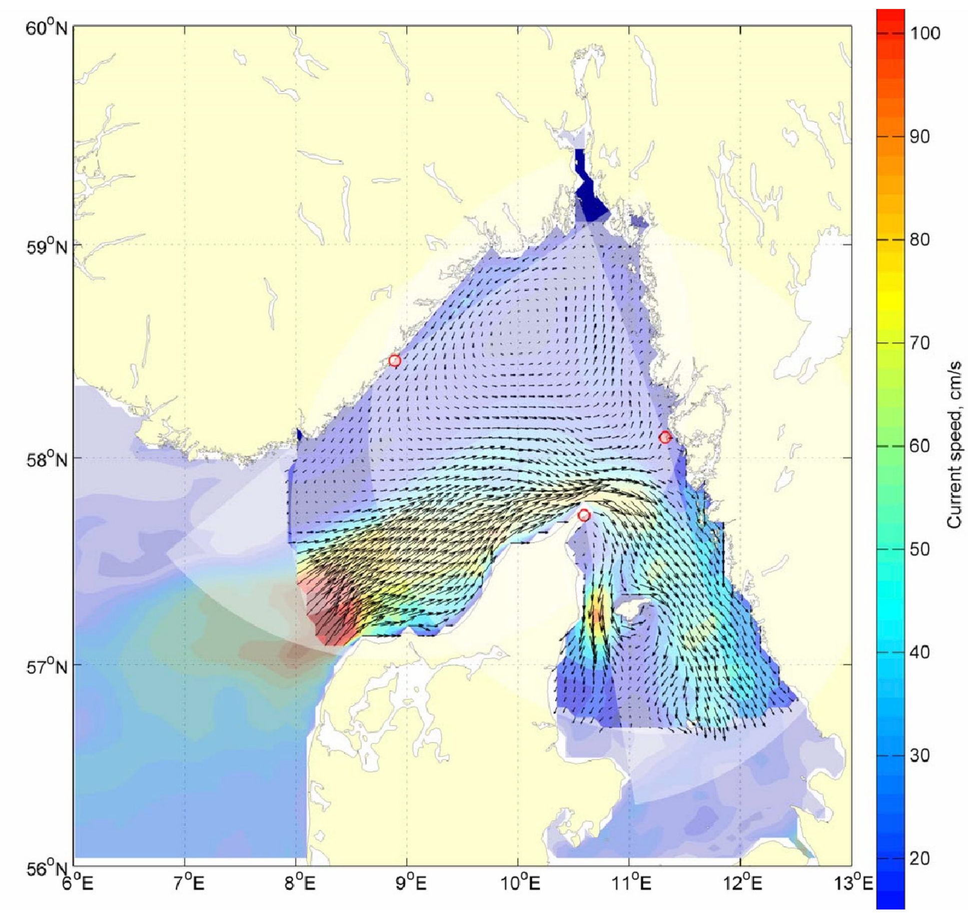
Oceanographic applications of coastal radar

Philip Axe



Cover picture.
An artist's impression of current information available from a Nordic radar network covering the eastern Skagerrak and northern Kattegat

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Report details

Uppdragstagare	Projektansvarig
SMHI 601 76 Norrköping	Philip Axe +46 (0)31 751 8901; +46 (0)31 751 8980 Philip.axe@smhi.se
Uppdragsgivare	Kontaktperson
Naturvårdsverket: Havsmiljöenheten Valhallavägen 195 SE - 106 48 Stockholm	Petra Wallberg +46 (0)8 698 1116 petra.wallberg@naturvårdsverket.se
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Contents

1 Summary

This report documents the 2010 Coastal Radar Workshop organised by the Swedish Meteorological and Hydrological Institute with support from the Swedish Environmental Protection Agency. The aim of the report is to provide background information on coastal oceanographic radar for a wider professional audience and to provide a basis for further Nordic cooperation in the field of oceanographic (coastal) radar with the ultimate aim of establishing a Nordic network covering (initially) the shared waters of the Skagerrak and Kattegat.

Information on currents in near real time is seldom available when needed by many day to day applications and services. Data are needed for safe and efficient ship routing in narrow areas of high traffic such as in the northern Kattegat, Danish Straits, Bornholm Strait and the Gulf of Finland. At the entrances of major ports and where [environmentally] dangerous cargos are carried current information can be of crucial importance. For this reason the Swedish Maritime Administration maintains current observations in critical areas. However, these are point measurements and in the waters mentioned above topography may alter currents both in strength and direction in nearby areas. Hence, complementary spatial information on the behaviour of currents is preferable.

Access to high quality, spatially resolved current information is critical both for effective oil spill containment and greatly increases the chances for successful outcomes of search and rescue operations. Combining data from models and observations will reduce the search area in rescue operations and make planning and combat of oil spill operations more efficient.

In addition, areal near real time current observations are likely to promote research and development related to fish larvae transports, the spread of alien species, improve oceanographic models and lead to the better understanding of ocean and coastal sea processes.

The present workshop highlights and extends the knowledge base on European and US experiences, user needs and available technical systems for areal current observations. Taking into account that Nordic views are usually coherent, opportunities to coordinate and cooperate in establishing and running an operational pilot system at a Nordic level seem realistic. The workshop intends to lay the foundation for carrying this work further.

Acknowledgements

This project was supported by the Swedish Environmental Protection Agency, *Naturvårdsverket*, through contract 7711 2332 32212 – 5389 (Diary number 309-1880-09 Nh). Thomas Helzel (Helzel Messteknik GmbH), John Howarth (National Oceanography Centre, UK), Chad Whelan (CODAR Ocean Sensors), Mike Moorhead (Neptune Radar Ltd), Lucy Wyatt (University of Sheffield and SeaView Sensing Ltd) and MarineTraffic.Com (University of the Aegean) are thanked for their permission to reproduce figures in this report.

Chad Whelan, Thomas Helzel and Mike Moorhead are thanked particularly for their comments on the manuscript. The contribution of the participants in making the workshop a success is warmly acknowledged, and we look forward to continuing this cooperation with the aim of establishing an operational radar network between the Baltic and North Sea.

Workshop presentations are available by anonymous ftp at ftp://ftp.smhi.se/users/naturftp

2 Introduction: Skagerrak, Kattegat & Danish Straits

This chapter describes the oceanographic characteristics of the Kattegat – Skagerrak system, before providing a brief background to the relevant social and economic activities within the region. This is followed by a discussion of user needs: activities needing near real time wave and current information.

2.1 Oceanographic background

The Kattegat/Skagerrak system is a large bay on the eastern side of the North Sea, approximately 350 km wide (north - south) by 250 km deep (east-west). It is bordered in the north by Norway, in the east by Sweden and to the south by Denmark. The Danish mainland forms a peninsular almost entirely closing off the bay, leaving the 100 km wide Skagerrak open to the outer North Sea while sheltering the Kattegat. The Skagerrak is deep: with depths of 700 metres towards the Norwegian side at the head of the Norwegian Trench. In contrast, the Kattegat is shallow, characterised by old river beds in the east, where depths can reach 90 metres outside of Gothenburg, although it is mostly covered by a broad sandy shelf only 10 – 15 metres deep. The average depth of the Kattegat is only 25 metres. Connecting the Kattegat to the Baltic Proper are the Sound and the Belt Sea (collectively known as the Danish Straits). The Sound, between Sweden and Denmark, is short (about 100 km), narrow (between 3.8 & 20 km) and straight, with mean depths of about 25 m and a minimum of 6 metres across the Drogden Sill at the southern end. By contrast, the Belt Sea is long (300 km), wider (never less than about 10 km) and shallow – with only a tortuous narrow channel reaching 30 metres in places - before opening out into the 40 m deep Arkona Basin of the Baltic Proper (Figure 1).

The south of the Kattegat is fed by the Baltic outflow, which exits the Baltic through the Sound and Belt Sea. Discharge into the Kattegat from the Danish Straits is about 800 km^3 per year. About a third of this volume enters from the Sound and the remainder from the Belt. This 800 km^3 is made up of the fresh water excess from the Baltic (about 400 km^3) mixed with a similar volume of entrained North Sea water. The outflow flows northwards from the Straits, concentrated along the Swedish coast. Salt water entrainment into the surface outflow starts in the Baltic, where the surface salinity increases from below 2 [psu] in the innermost Gulfs of Bothnia and Finland, to typically 7 – 8 in the western Baltic Proper. Surface salinity then doubles over a relatively short distance across the Drogden Sill into the Sound, and increases by almost the same amount again by the southern Kattegat (Anholt E.). Surface salinity at the northern end of the Kattegat is typically 23 while the offshore Skagerrak is effectively marine (Figure 3).

Salt enters the system from the Skagerrak. The Skagerrak/Kattegat front is usually found close to the tip of Jutland at Skagen, where the Jutland Coastal Current, which has followed the Danish coast up from the southern North Sea, meets the brackish water of the Kattegat. The exact position of the front is controlled principally by the wind, and strong, persistent north-westerlies may push the front the whole way down the Kattegat into the Danish Straits. At the front, some North Sea water dives under the outflowing Kattegat water and enters the Kattegat as a bottom current. The Jutland Coastal Current continues eastwards and coalesces with the Baltic Current. Combining with the substantial river discharges from the Swedish west coast and southern Norway, the current becomes the Norwegian Coastal Current before exiting back into the North Sea and into the Norwegian Sea. The resulting anticlockwise circulation in the Skagerrak leads to the formation of a persistent central gyre – although changing meteorological conditions do disrupt the circulation and can create more complex structures (Figure 4).

The small instantaneous length scales of oceanographic features in the Kattegat and Skagerrak makes oceanographic modelling difficult. The typical length scale (first order Rossby radius) is about 5 km, compared to about 40 km in the Baltic Proper. As a result, eddies, meanders and other chaotic features in surface currents are small. It is both difficult to observe them with buoys and ships, and difficult to describe their position and development accurately in models. Models generally describe the overall variability well, but without observations over a large area, it is not possible to exactly say where individual eddies and fronts are, while assimilating point measurements or limited spatial observations can cause false structures to be generated as the assimilated information 'shocks' the model. As a result, while existing operational models appear to give excellent results in the Baltic Proper, in the

Danish Straits, Kattegat and Skagerrak they describe only the oceanographic variability well in a statistical sense, while the instantaneous current field may well differ in reality.

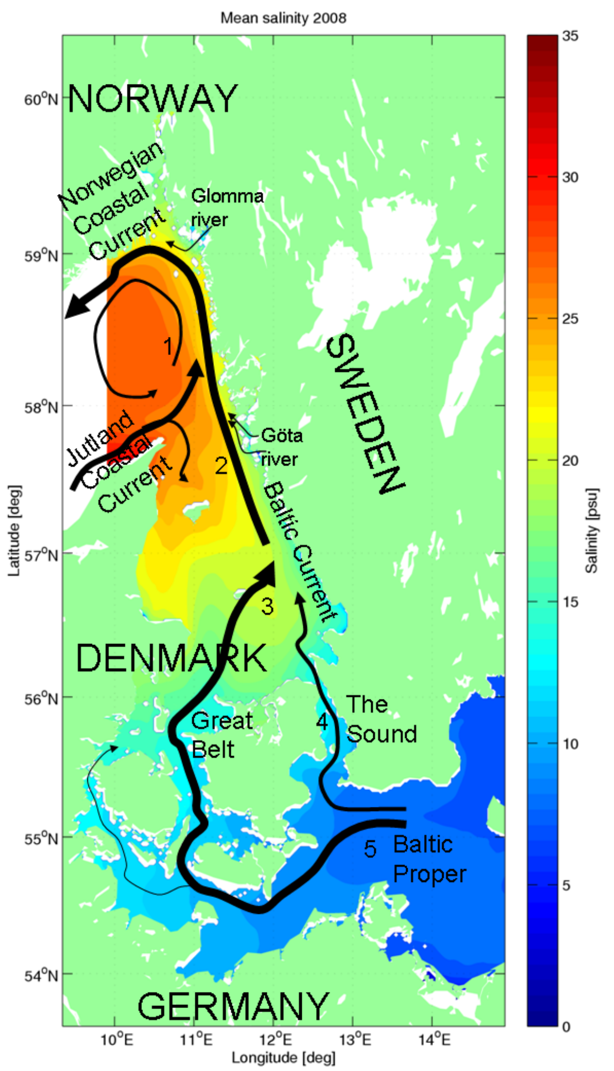

Figure 1 Typical circulation and mean surface salinity in the western Baltic, Kattegat and Skagerrak. Positions labelled 1 to 5 refer to salinity stations presented in Figure 3. Major rivers are indicated.

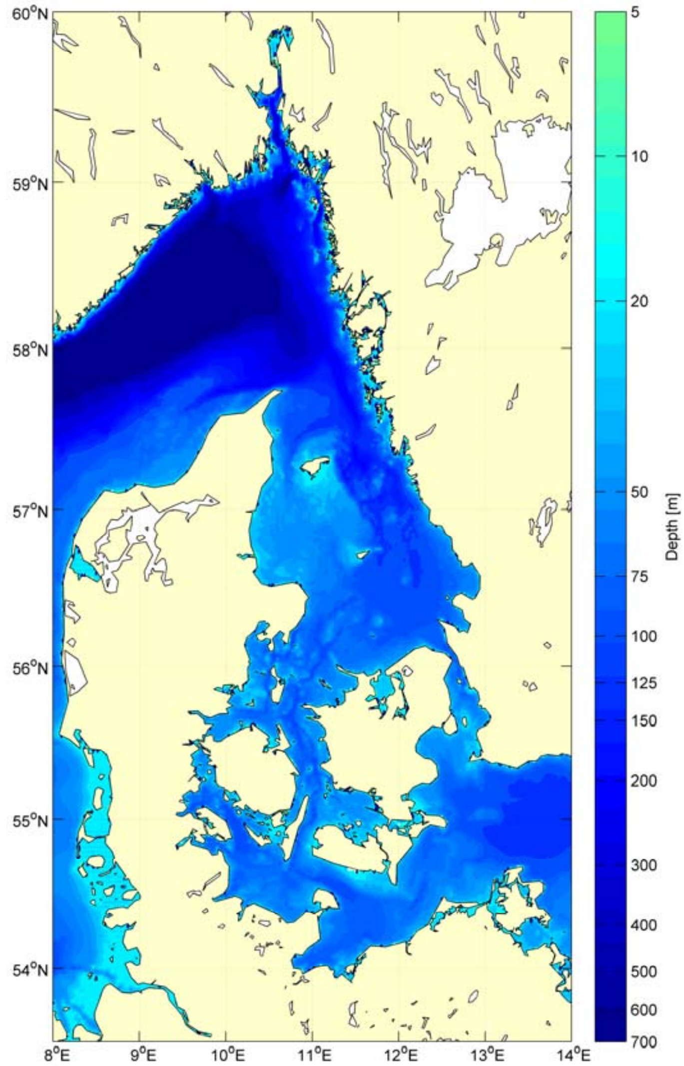

Figure 2 Bathymetry in the Skagerrak, Kattegat and Danish Straits (based on ETOPO1 dataset).

A further complication is the absence of tidal energy in these waters. In the outer North Sea, tidal currents are strong and give a large scale deterministic forcing that often dominates the wind-induced current field. From the Skagerrak inwards towards the Baltic Proper, tidal forcing becomes progressively weaker. The spring tidal range on the Swedish west coast seldom exceeds 40 cm, while the amplitude of M2 tidal component at Gothenburg is of the order of 15 cm. While surface tides are effectively negligible, the semi-diurnal internal tide displaces the pycnocline by 5 – 10 metres (Figure 5). Observations at the Läsö buoy site also show a semidiurnal pulsing of the northward flowing surface water, and a powerful shear between the surface and the halocline.

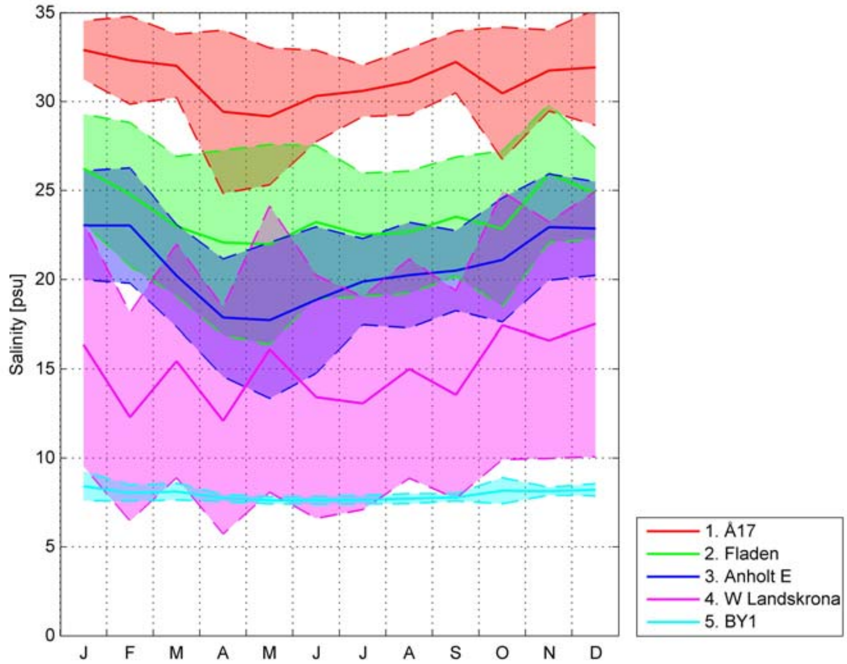

Figure 3 Annual cycles of surface salinity (mean +/- one standard deviation; 0 - 10 metres depth; data collected 2000 - 2009) at the five monitoring stations identified in Figure 1.

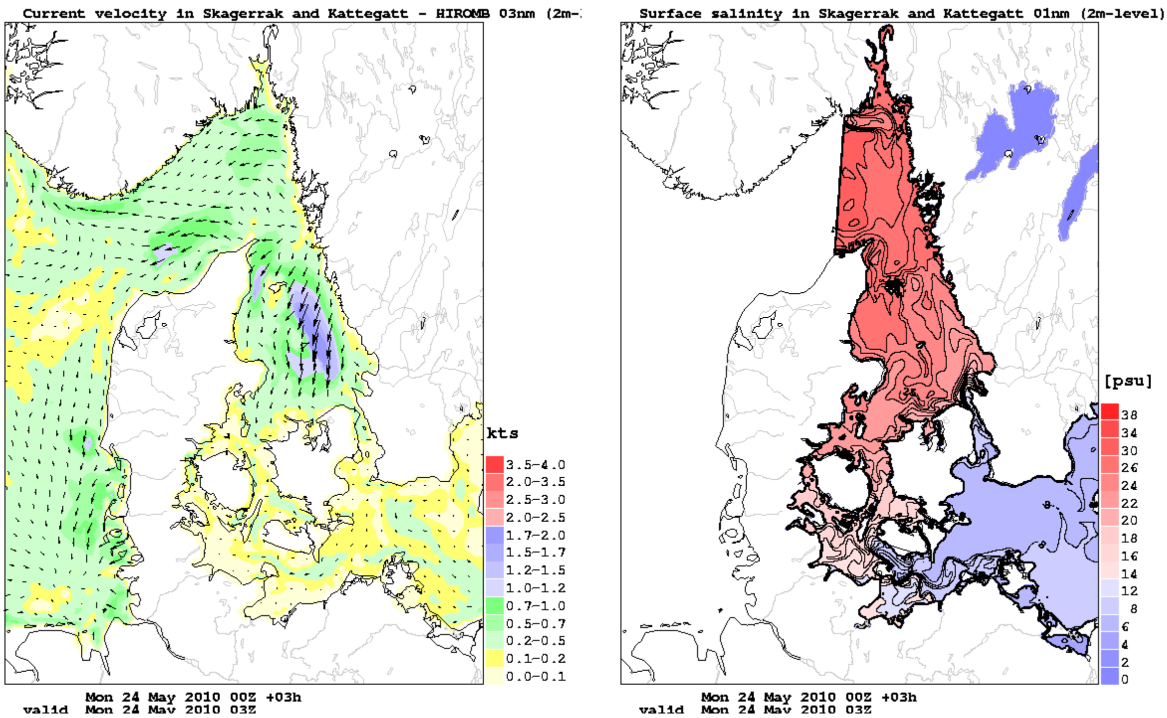

Figure 4 Instantaneous image of modelled current velocity (left) and sea surface salinity (right) in the Kattegat and Skagerrak. Note presence of small scale features not clear from the annual picture (Figure 1).

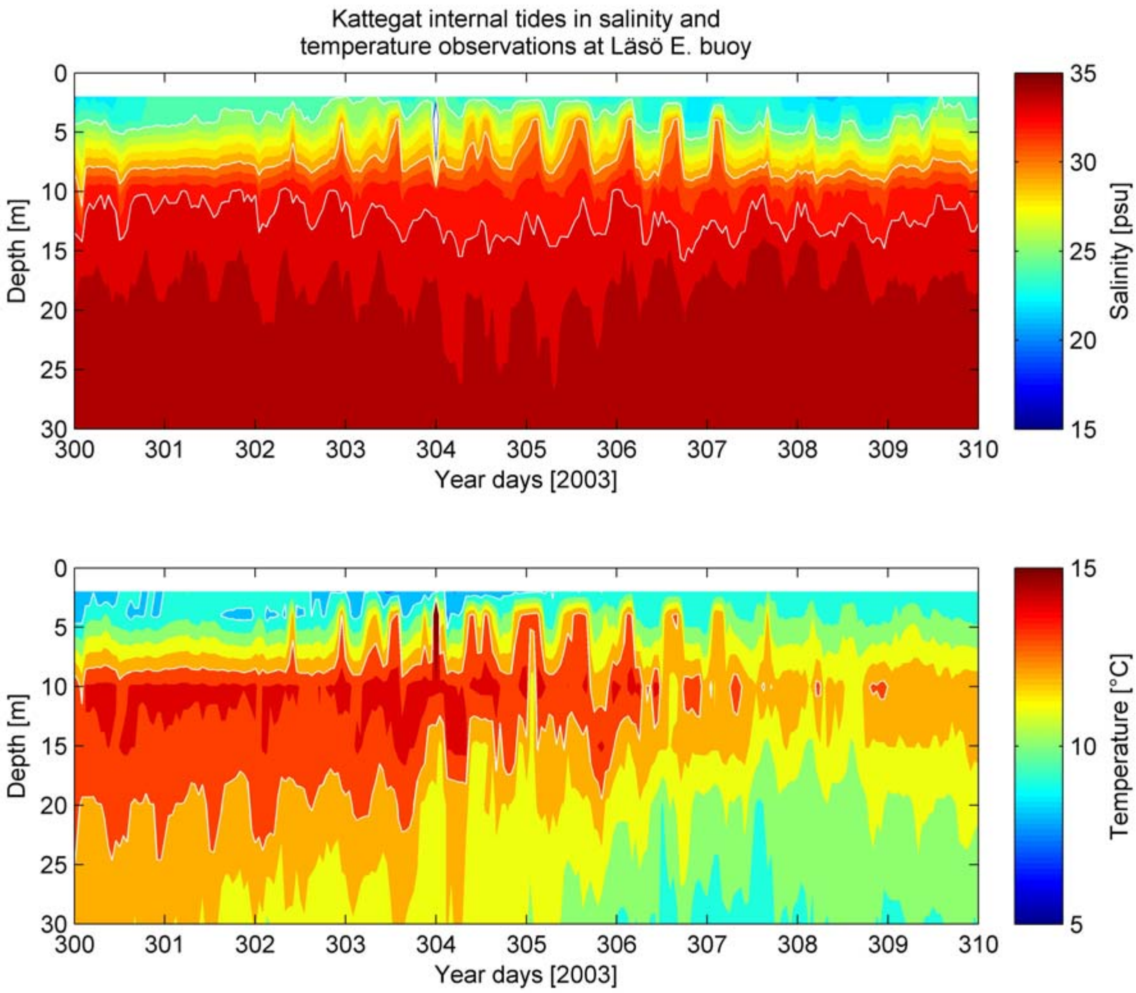

Figure 5 Internal tides visible in the salinity (upper) and temperature (lower) observations from east of Läsö in the central Kattegat.

2.2 Societal pressures

In addition to being oceanographically dynamic, the Skagerrak – Kattegat region has economic importance as a major shipping route, both for goods in transit through the region and for those being handled by the region's ports. Figure 6 shows an instantaneous picture of shipping traffic in the Skagerrak and Kattegat: around one hundred vessels, including fifteen oil tankers, were underway at this one time. Annual ship movements collated by HELCOM for 2008 indicate more than 60 000 ship movements crossing the line from Skagen to Marstrand at the northern entrance of the Kattegat.

Oil tankers may be in transit to or from one of the region's oil terminals (Brofjorden, west of Uddevalla and Göteborg being the largest) or to one of the Baltic terminals, such as Fredericia & Kalundborg (Asnaes) in Denmark, or Primorsk in Russia. Göteborg is the single largest port in Scandinavia, handling 2500 shipping movements, including 22 million tonnes of liquid goods (oil, oil products and chemicals) per year[1], Brofjorden is almost as large, with a turnover of 17.3 million tonnes per year. The three terminals in the Danish Straits handle a further 23.2 million tonnes although these are all dwarfed by Primorsk, which handles more than 70 million tonnes per year. Figure 7 shows both how Baltic marine traffic is concentrated along the route to St. Petersburg, but also how the traffic is concentrated between the Kattegat and the Danish Straits. Both the volume of oil and the number of tankers transiting the Great Belt have more than doubled since 2000 (HELCOM, 2009a; Figure 8 and Figure 9).

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[1] Source: www.portgot.se, web site of the Port of Gothenburg

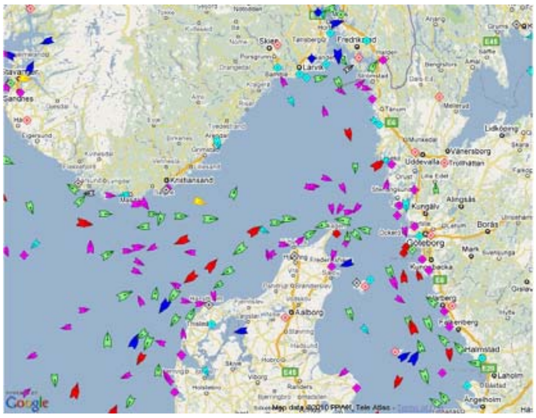

Figure 6 Instantaneous screen shot from MarineTraffic.com, showing shipping traffic in the Kattegat and Skagerrak. Ships in red are oil tankers, cargo vessels are green, passenger ferries blue or yellow. Published with kind permission of MarineTraffic.com, University of the Aegean).

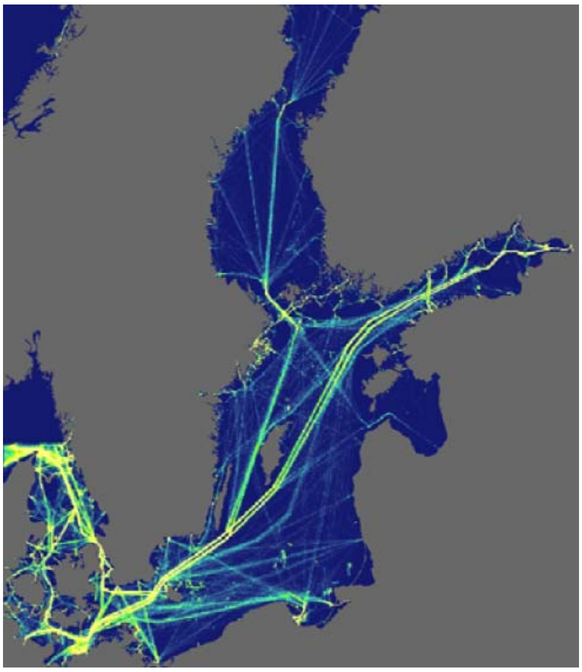

Figure 7 Baltic shipping density observed by HELCOM AIS during one week in 2008. Busiest routes highlighted in yellow (HELCOM, 2009).

An unfortunate result of the maritime traffic is the frequency of accidents (Figure 9) and illegal oil discharges observed in the Baltic and surrounding seas (Figure 10). Successful prosecutions following increasing aerial and satellite surveillance, coupled to better management tools, have reduced the total number of observed slicks in the HELCOM area to less than 180 per year, from a maximum of more than 700 per year in 1989 (HELCOM, 2009b). While the large increase in maritime accidents in 2003 is attributable to a change in reporting methodology, the number of accidents remains of concern. According to HELCOM (2008) approaches to ports and the Danish Straits are the regions most susceptible to collisions, although the introduction of AIS has reduced their frequency.

In addition to being a dynamic physical environment and an important thoroughfare, the Skagerrak – Danish Straits system is also a valuable habitat. The Sound region (Öresundsregion) is home to 3.8 million people (2008), while the regions around Göteborg and Oslo are home to almost a further 2½ million (source: Göteborgs Region 2008; Wikipedia). The shallow waters of the Kattegat and Belt Sea also make it a significant breeding ground for seabirds and the region's importance is recognised through the designation of substantial marine areas as Baltic Sea Protected Areas and Natura 2000 areas. The region is also the boundary between marine administrative districts: the Helsinki Convention area covers the Baltic and the Kattegat, while the OSPAR region includes the North Sea and Kattegat. The proposed Marine Strategy boundary between the North East Atlantic and Baltic regions is also at the southern end of the Kattegat. These conventions and Directives aim to achieve 'Good Environmental Status' throughout their respective regions.

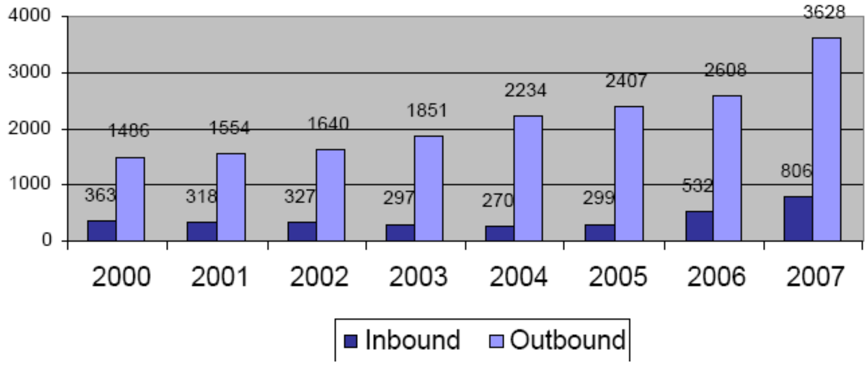

Figure 8 Number of laden tankers in transit to/from the Baltic via the Great Belt (HELCOM 2009a).

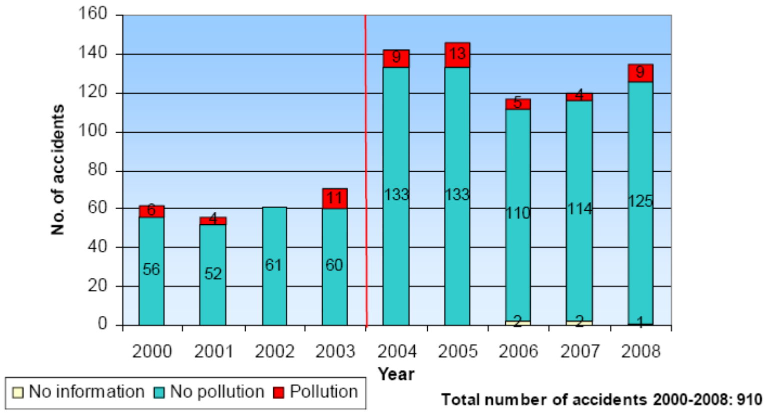

Figure 9 Reported shipping accidents in the Baltic Sea (HELCOM 2008; the jump in 2003 is due to a change in reporting methodology).

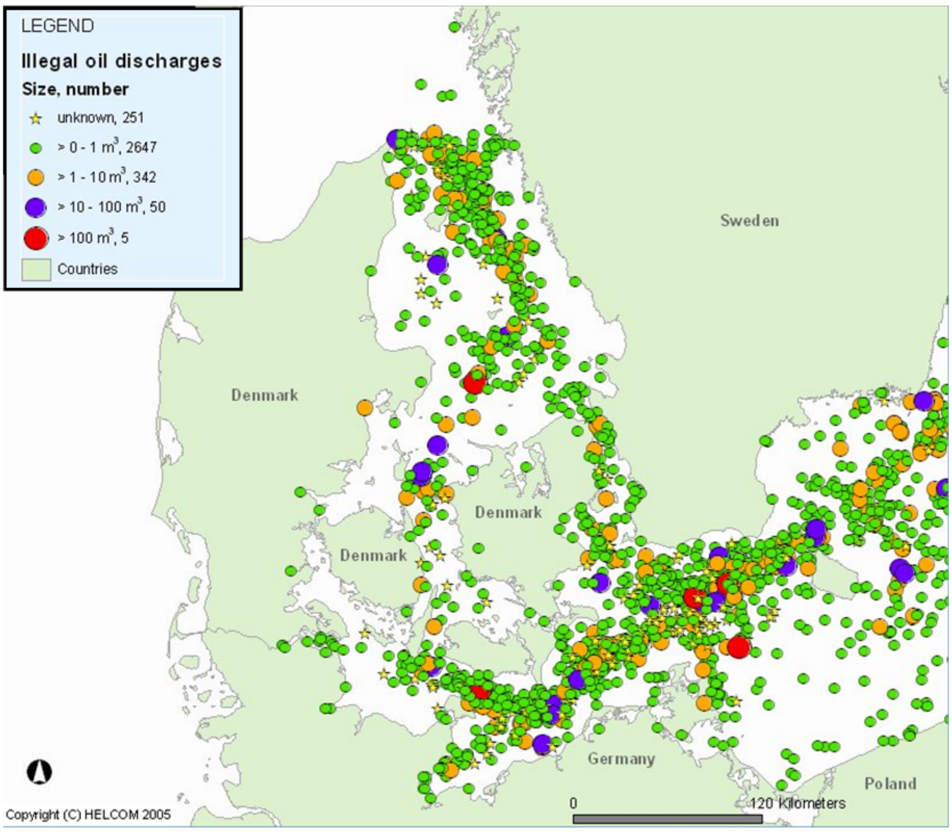

Figure 10 Observed oil spills in the western Baltic, Danish Straits and Kattegat. Data from HELCOM MARIS.

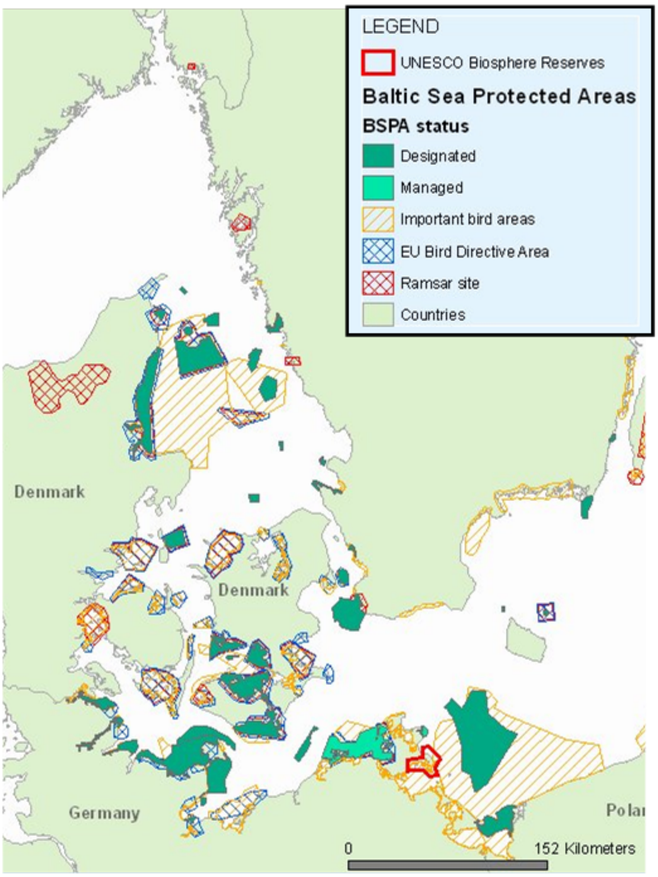

Figure 11 Nature reserves and protected areas in the western Baltic, Danish Straits and Kattegat (from HELCOM MARIS).

The Skagerrak - Kattegat - Belt Sea region is:

- Home to more than 4 million people
- Of international ecological significance
- Has ports handling more than 60 million tonnes of bulk chemicals per year (including oil)
- Is a transit zone for rapidly increasing numbers of oil tankers
- Is oceanographically complex:
    - several current systems interact
    - weak tides & small first-order baroclinic Rossby radius => fronts & eddies which are difficult to model accurately

3 Uses of oceanographic radar in the coastal zone

The previous chapter described the dynamics of the Skagerrak – Danish Straits region, its role as a natural habitat, and some of the pressures on the system from shipping and other human activities. This section describes examples of tools used in the region to protect life and property.

3.1 Improving oil spill tracking in hydrodynamically complex waters

Oil spill response teams in the HELCOM area, and now also in the North Sea, have access to a web based oil spill tracking and forecasting tool called Seatrack Web. Seatrack Web enables clean-up coordinators to predict the path of oil spills, taking into account the current fields and the physical properties of the oil. Operators input oil-slick observations (using observations from ship, aeroplane or satellite) and a description of the oil type into a web interface. This interface connects to a server which in turn is coupled to an operational oceanographic model run at either at SMHI, the Royal Danish Maritime Administration or at the Bundesamt für Seeschifffarht in Germany. The operational model at SMHI is run four times a day using atmospheric conditions (wind, heating/cooling), river inflows and tidal forcing. The model predicts currents, temperature and salinity throughout the water column, as well as sea level and sea ice.

Using the model predictions, Seatrack Web determines whether the oil floats or sinks, and then how it is dispersed by the wind and currents. The chemical decay of the slick is reproduced, describing evaporation and natural decay processes. Seatrack Web provides a forecast for where the slick will be over the next five days, including whether it will be stranded during this time. The system even includes GIS layers describing protected areas, to see whether these would be affected by the slick. This allows clean-up coordinators to make best use of often limited resources to protect high value areas. The system currently has 150 users around the Baltic.

In addition to providing forecasts, the system also includes a backtracking facility, allowing the source of an observed spill to be predicted up to a month prior to initial observation. Data from the HELCOM AIS system are combined into the system, allowing for the identification of likely ‘suspects’. These suspects can then be boarded by the coastguard and oil samples taken for chemical matching against the oil in the slick. This has contributed to the successful prosecution of shipping operators, and may well be a factor in the reduction in illegal spills observed over the past 20 years. Seatrack Web is under constant development, and is now even used for predicting the spread of harmful algal blooms, fish eggs and larvae.

Seatrack Web users in the Baltic report that they are extremely satisfied with the system, as it is simple to use, fast and accurate. The HIROMB model that lies behind the system has been developed over many years by a large consortium in a Baltic wide cooperation and includes advanced assimilation of sea level, sea surface temperature and salinity as well as CTD profiles. A recent (as yet unpublished; Antoni Staśkiewicz, *Maritime Institute in Gdańsk*, *pers. comm.*) independent validation exercise shows the forecasts to be of surprisingly high quality both in surface waters and in the deep water around rough topography.

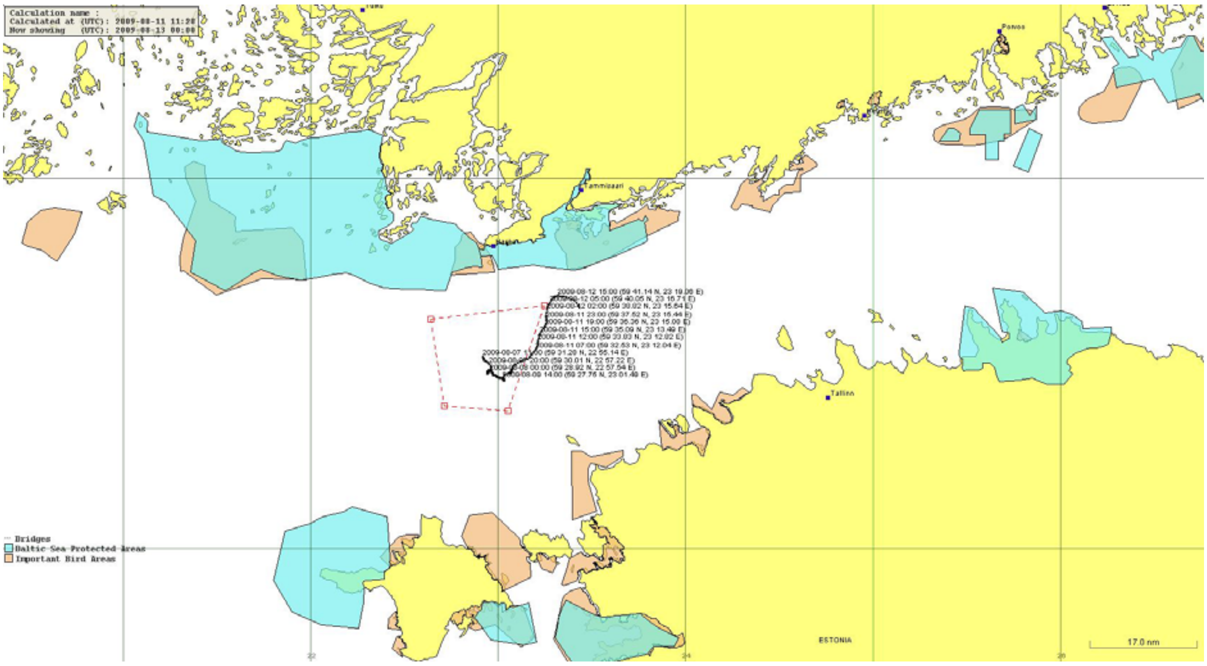

Figure 12 Example of an oil spill in the Gulf of Finland, tracked in Seatrack Web also showing Baltic Sea Protected Areas and other bird reserves.

The Danish Straits are difficult for the model however. The bathymetry is particularly complex and shallow, and the Sound is only one grid cell across at its narrowest point. In the Kattegat, the outflow from the Baltic, controlled by the Skagerrak – Kattegat front, is chaotic and meandering, such that the exact westerly extent of the current is difficult to predict (while the eastern limit is usually close to the Swedish coast). The interaction of the Baltic Current with the Jutland Coastal Current, the large rivers and the atmospheric inputs are difficult to reproduce exactly – particularly as the first order Rossby radius in the Kattegat is equal to roughly three grid cells, so eddies are difficult for the model to describe. The result of this is that forecasts of oil spread in the Kattegat and Skagerrak are reasonable on the larger scale, but it is unreasonable to rely on the model completely for exact forecasts over the five day period. With four major oil terminals between the Belt Sea and the Skagerrak, this is a serious shortcoming.

3.2 Reduction of search areas in Search and Rescue operations

The Swedish Maritime Administration has a similar problem to solve when predicting the trajectory of objects in the water such as life rafts, small boats, containers or bodies in the water. On average (2007 - 2009), there are about 440 search and rescue missions each year in the Skagerrak (180) Kattegat (140) and Sound (120) SAR regions. To increase the chance of a successful outcome, rescue actions need to be able to minimize the search time, which means having confidence in where a floating object will drift. A reduction in the size of the potential search area increases the chance of finding a casualty alive and reduces the time of rescue units need to spend at sea or in the air, with consequent improvements in their safety, and in fuel consumption.

The BADIS system is an adaptation of the Norwegian Leeway model (Breivik and Allen, 2008) implemented by SMHI on behalf of the Swedish Maritime Administration. It includes a database of 63 different objects and their leeway coefficients, which describe their relative response to wind, currents and waves. To predict the likely position of an object, the start position is seeded with 500 particles, half of which have a tendency to veer to the left of the wind, and the remainder to the right. These are allowed to drift, based on their own inherent characteristics, while driven by the surface current and wind fields from numerical models. Around Sweden, HIROMB is used for currents and HIRLAM for the winds, as in Seatrack Web. BADIS allows the search object to be washed up against the coast, but to continue drifting along shore. Predictions can be produced at a range of time steps.

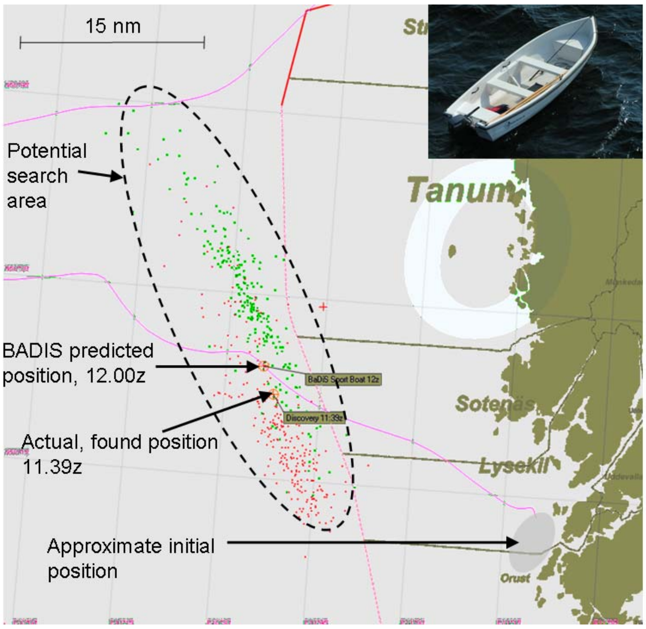

Figure 13 Example of a successful application of BADIS, to recover a small sports boat in the eastern Skagerrak adrift for up to 22 hours.

The system appears to work well in the Baltic. While it has helped in a number of cases between the Skagerrak and the Danish Straits, in other cases and in validations against current measurements and drifting buoys during SAR training exercises indicate significant room for improvement. Given the success of the system in the Baltic, it suggests that improvement needs to come in the modelled current fields presently used.

During the workshop, Glenn reported on field experiments made during 2009 on the US East Coast. A surface drifter was tracked for up to 96 hours, and their trajectory compared both with predictions from an operational oceanographic model used in SAR operations, and also with HF radar-observed currents. After 48 hours, the drifter was on the periphery of the region the model identified as the likely drifter position, while after 96 hours the drifter was well outside the search area identified by the model. Using current fields from HF radar, the drifter position remained at the centre of the 'highest probability' zone. After 96 hours, the recommended search area from the model was 154 x 232 km (36 000 km^2) compared to 100 x 123 km (12 300 km^2) using HF radar. Hagmark, from the Swedish Sea Rescue Society showed a typical search pattern, which starts at the centre of the area most likely to contain the target. The ability of HF radar fields in the US experiment to maintain the drifter within the 'highest probability' region implies that search duration is significantly reduced using HF radar fields rather than numerical models. The presentations of Glenn (slides 30 - 36) and Hagmark are available online at
ftp://ftp.smhi.se/users/naturftp/Presentations/User_experiences/Sweden_Glenn_Final.pptx and
ftp://ftp.smhi.se/users/naturftp/Presentations/User_needs/Thore kort presentation 2010.pptx.

Even without the numerical integration of HF radar fields into the SAR system, knowledge of the actual current fields across the search area during a rescue would help rescue coordinators know if they can trust the output from BADIS. Alternatively, the current fields could be used in manual drift calculations or to accurately hindcast an object's movements to give a better estimate of the initial position, and thus a smaller search area. This suggests that initial benefits from HF radar monitoring could be achieved immediately after monitoring starts.

3.3 Improved safety and security for shipping and construction

Wave and current fields are used in several ways to optimise maritime operations. Some of these are obvious, such as weather constraints on surface vessels involved in marine construction and underwater operations. This need is growing, particularly in the southern Kattegat where there is a planned expansion of the wind generation capacity, while the proposed Scanled pipeline across the

Skagerrak into and across the northern Kattegat is a further example of infrastructure being established in this coastal zone.

Wave forecasts can be considered good: Meteorological services in the region run prediction systems which take input from meteorological models. These predicted wave fields are continually validated against point observations, although these observations are from relatively deep water (60 – 70 metres). Fully directional wave fields in the near coast region are lacking. Even the current generation of operational wave models has trouble in areas of complex bathymetry and where reflection and diffraction processes occur. This difficulty is only partly due to the relatively coarse resolution that is used in the forecast models. It is possible to envisage an increased need for near-coast wave information in support of wind farm construction (where wave height is often a limiting factor during the construction phase) or if the presently experimental wave power generation devices currently under test offshore of Lysekil[2] prove economic. These needs are in addition to the existing recreational and safety needs of the general public.

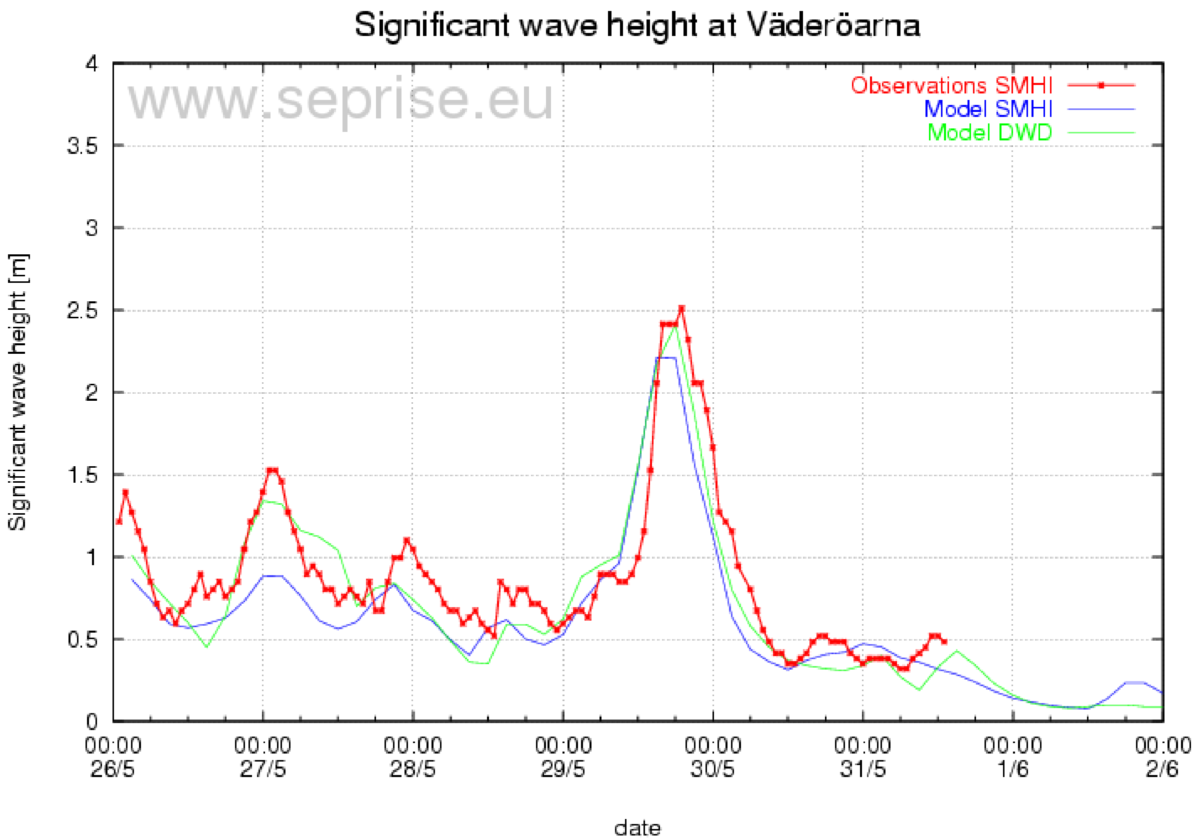

Figure 14 Example time series showing a comparison of observed Skagerrak wave heights with model predictions from operational wave models run by two different institutions. Image from http://www.seprise.eu

Ship routing is a competitive commercial sector, with consulting companies offering products and services to ship operators to optimise fuel use and berth availability at the port of arrival. In the open ocean, operators use meteorological forecasts and whatever oceanographic information is available to enable operators to exploit currents and avoid storms. In coastal waters, such as the Kattegat, the density of shipping is such that marine traffic must be managed. This is achieved by Vessel Traffic Services (VTS) in a way analogous to air traffic control. In the narrow waterways of the Danish Straits, it is particularly important to maintain safe distance between vessels. Fluctuating currents and eddies can slow one vessel relative to another and given the length of time required for a large oil tanker to change course or slow down, it is important for VTS to able to warn vessels of these hazards as early as possible. This in turn enables optimum use of a limited resource: space.

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[2] See http://www.el.angstrom.uu.se/forskningsprojekt/WavePower/Lysekilsprojektet_E.html

The oil terminal and refinery at Mongstad, Norway lies about 12 km from the entrance of the Fensfjord. The refinery handles about 10 million tonnes of crude oil per year, while the crude oil terminal is the second largest in Europe after Rotterdam. Crude oil is transported to the refinery by ship, which must enter the fjord by first crossing perpendicular to the Norwegian coastal current. Ships must start their turn well upstream of the fjord entrance, and make a good estimate of the current strength so that they exit the current at the fjord mouth. To complicate matters further, the current is not steady but, like the Baltic current, both meanders and sheds eddies. To facilitate their approach, VTS Fedje at the mouth of the fjord use three HF CODAR SeaSonde radar to give real time wave and current observations, allowing them to advise approaching vessels. The difficulty of entering the fjord was highlighted by the loss of the Cypriot registered cargo vessel ‘Server’, which ran aground while trying to enter the fjord in January 2007. The vessel broke up in high waves, leaking 650 tonnes of bunker oil. Entry to the refinery at Brofjorden in the Skagerrak bears some resemblance to the entrance to Fensfjorden, with vessels also required to cross perpendicular to the northward flowing, unsteady coastal current.

A parasitic use of coastal radar currently under development is for ship detection and tracking. While all international voyaging ships over 300 gt and all passenger vessels are required to use AIS (Automatic Identification System) the system does not include all vessels, and does not prevent vessels from turning off their transmitters. A typical AIS message contains information on a vessel’s identification, navigational status (such as ‘underway’ or ‘at anchor’), position, speed, course, dimensions and destination (among others). The information is transmitted frequently on VHF channels. The typical range of an AIS transmission over sea is about 40 km, although the use of coastal repeater stations can extend this up to 120 km. During the workshop, methods of ship detection and tracking were presented by teams from the UK, Germany and the US, using Pisces, WERA and CODAR systems. The Technical University of Hamburg demonstrated a system operating on the Portuguese coast, capable of detecting large (200 metre long) vessels up to 200 km from the coast, while small vessels were detectable up to 50 km from the coast. In order to determine dynamic information, such as position, course and speed over ground, a tracking algorithm was developed to predict the ship position at the next time step within a certain probability. If the ship was detected within the predicted area at the next time step, it was considered to be tracked. Glenn (Rutgers University) presented work by a consortium funded by the US Department of Homeland Security, which had expressed an interest in being able to use HF radar to monitor shipping in the coastal zone and in particular in approaches to ports. This group was able to detect and track two vessels at a range of about 10 km with uncertainties of about 300 metres, and to determine target position, speed and course as well as the rate of change in these parameters. The UK team described the problems of distinguishing between false echoes and those from vessels, and the development of tracking routines to solve these problems.

3.4 Support to ecosystem management

The Kattegat is considered the outermost region of the Baltic Sea system by HELCOM, and the limit of the North East Atlantic / North Sea region by OSPAR. Achieving the goal of ‘Good Environmental Status’ requires detailed knowledge of the pressures on the region, including the nutrient (and toxic substance) inputs from adjacent sea areas. Previously, estimates of nutrient loading from the outer North Sea and Baltic have been made using simple box models, where each basin is described as a horizontally homogenous area, allowing the use of one dimensional solutions in each box. Ideally, estimates made by these methods should be improved, for example by the use of validated three dimensional coupled ecosystem models. The physics in these models is the same as that used in oil spill and search and rescue models, with the same limitations. Using observed currents to constrain and validate the models would increase the reliability of the (nutrient) flux estimates.

A better understanding of the drift of harmful algal blooms, or the larvae of invasive species would also facilitate regional ecosystem management. In recent years, fish farms in Denmark have suffered major fish kills due to blooms of organisms such as *Psuedochattonella* and *Karenia.* being taken up. Similarly on the Swedish west coast, the presence of *Alexandrium spp* , *Dinophysis acuminata* and *Pseudo-nitzschia spp.* leads to the closure of mussel farms. The ability to trace and predict the spread of these organisms should lead to improved early warning of potential problems and may help shellfish producers optimise harvesting. In the case of land-based fish farms, this may even allow managers to close water intakes in good time to avoid contamination.

3.5 Improved meteorological now- and forecasting

Given the difficulty of measuring wind speed and direction at sea – let alone in a standardized manner – the principle source of marine wind data is from satellite mounted scatterometers. QuikSCAT was launched in 1996 and provided data for 10 years. These data were considered reliable by NOAA up to wind speeds of about 17 m/s (34 kts) even under clouds and through light rain. A principle problem with QuikSCAT was its inability to retrieve wind data within 20 km of the coast. This created a data gap covering the greater part of the Skagerrak and almost all the Kattegat. User requirements for the QuikSCAT replacement mission would accept a coastal mask of 5 km. Wind speed accuracy (rms) was 2 m/s up to 20 m/s, while 10% accuracy was required beyond this. The European ASCAT, flown on the ERS and MetOp satellites, gives a horizontal resolution of up to 25 km while WindSat / Coriolis was launched in 2003 and also has a horizontal resolution of 25 km

It is also possible to retrieve wind information from SAR (Synthetic Aperture Radar) and also from satellite altimetry. Altimetry suffers from a similar problem to scatterometry, in that the radar footprint is large, and the system is unable to function within about 5 km of the coast. Mourad et al. (2000) demonstrate that wind speed retrieval from SAR is possible, giving horizontal resolutions of perhaps 100 metres. SAR wind direction may be determined by looking at the direction of foam streaks on the sea surface, or by using in-situ calibration measurement. It is not likely however that such data could be routinely available with sufficient latency for use in meteorological production.

Wind observations over the sea are available from the Scandinavian rainfall radar network. These are microwave radar (5.5 cm wavelength) used primarily for rainfall observation and measurement. They are capable of producing spatial wind fields with 1 – 2km resolution at a range of up to 120 km, and at a coarser resolution up to 240 km from the source. Wind speeds are determined from the Doppler shift (phase difference) obtained from primarily rain, but also from pixels with large insect or bird concentrations. Wind estimates up to 24 m/s are achievable. Velocity ambiguities are minimised by using alternating pulse repetition frequencies, while aliasing problem are minimised by software processing techniques.

Weather radar suffers from interference and blocking from structures and topography. While this can usually be modelled or processed away, returns from wind farms cause particular problems, as the rotating blades give spurious returns on the Doppler measurements. Other moving targets, such as ships, can also cause contamination. Sea clutter is also a problem, and at present cannot be used as an information source for oceanographers. An independent means of measuring wind speed at sea – not dependent on backscatter from the atmosphere, would provide a useful reinforcement and validation of the existing weather radar network and would strengthen existing meteorological production processes.

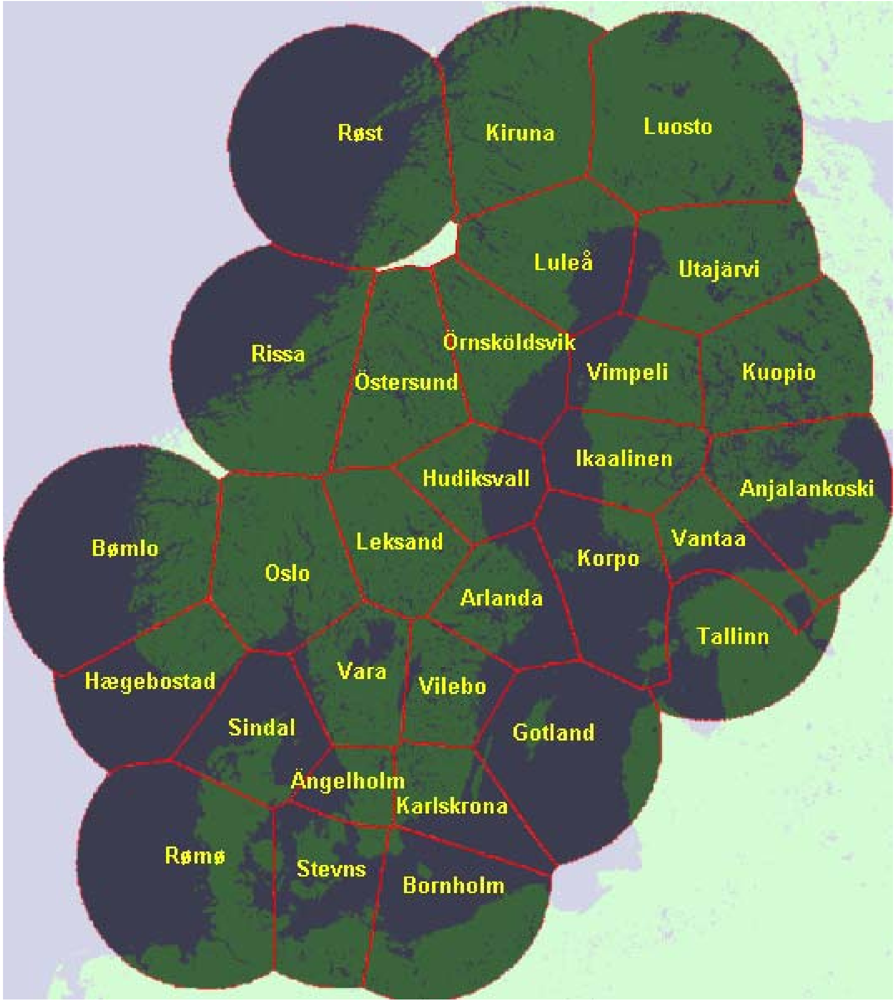


Figure 15 Distribution of meteorological radar stations in the NordRad2 network.

User needs summary

There is a pressing need for improved current information in the Skagerrak / Kattegat / Belt Sea region. The density of marine traffic, in particular the density of oil tankers, and the complexity of both the navigation channels and the current regime mean that near real time current fields will facilitate traffic management with a subsequent improvement in safety.

Both search and rescue and oil spill containment activities require a minimum of uncertainty in the current fields. Presently, current fields are obtained from numerical models which, because of the hydrodynamics of the Skagerrak/Kattegat/Danish Straits, struggle to give reliable current fields – although the tools presenting the information to users are appreciated. Current data assimilation into models is problematic where there are long open boundaries and energetic mesoscale features. Whether current data assimilation into models is viable in Skagerrak – Danish Straits system remains to be seen (and could be expected to become more successful as coverage improves). In the mean time, direct use of the observed current fields offers advantages including quality checks on model predictions. Experiments on the US east coast indicate that having radar-observed currents can reduce the search area for a drifter by 2/3 over 96 hours.

Additional uses are primarily based on the improved wave and current fields available from radar compared to operational models. Principle beneficiaries are marine construction industries, marine environmental managers and the operational meteorological institutes themselves, where wind observations provide independent validation of other observing techniques.

4 Introduction to coastal radar

4.1 Background

The influence of ocean waves on HF radar backscatter was reported by Crombie in 1955. He examined the backscatter of a 13.56 MHz signal, and noticed the peak energy in the reflected signal was constant at 0.38 Hz. He proposed that this dominant reflected component was probably due back scattering of the radar signal by water waves with a wavelength equal to half that of the radio waves. The secondary peak he observed he considered due to water waves of the same wavelength as the radio waves. He proposed to use variable frequency radar to scan the sea surface to determine the frequency spectrum of water waves.

In 1969, Munk and Nierenberg reported their observation that the -23 dB backscatter cross-section of HF radar from the sea surface bore a resemblance to the coefficient proposed by OM Philips to describe the slope of the wave number spectrum. These authors were aware of backscatter being caused by Bragg scattering and also refer to the work of Barrick, who had studied the scattering of radar signals from a variety of rough surfaces. Development continued with contributions by the likes of Barrick and Hasselmann, focussing mainly on sea waves and winds. In 1974, Stewart and Joy reported on using HF radar for measurements of ocean currents.

Work in the US started with phased array systems, using long beam forming receiver arrays. A requirement from NOAA for a smaller footprint system led to the development of direction finding methods such as those used by CODAR. University of Hamburg (DE) also required a small-footprint system, as they wished to use it on board ship. The US developments eventually led to the use of the crossed-loop antenna that forms the basis of the modern CODAR SeaSonde system.

In Europe, OSCR (Ocean Sensing Current Radar) was developed by the Rutherford Appleton Laboratory (RAL) and by Marine Exploration (MarEx) Ltd during the 1980s. OSCR was an HF radar system using a phased-array receive antenna. It was further developed into OSCR II, which was also available as a VHF system. It was used in the Fluxmanche experiments looking at fluxes through the English Channel, for studying the flow through the North Channel of the Irish Sea and along the Holderness (eastern UK) coast, where it was also used for wave measurement (Wyatt et al., 1999). The system was also tested in the US in 1991 at Cape Hatteras and Miami Beach (Jendro, 1992). OSCR systems are no longer actively marketed.

Since the mid-1990s, the University of Hamburg has abandoned direction finding systems and has developed the WERA system, based on the phased array. WERA is now manufactured and marketed by Helzel Messtechnik GmbH.

In the 1980s the University of Birmingham (UK) introduced the Pisces system for wave measurement in parallel with the RAL OSCR system for current measurement. In the light of initial results Neptune Radar further developed this into a dual radar system with the median wave measurement range increased from 90 km to 130 km. This system is commercially available from Neptune Radar Ltd.

For current measurements, the direction finding approach of the CODAR SeaSonde has become the market leader.

4.2 Advantages, Limitations and Validation

Current fields from HF radar are particularly attractive in comparison to those obtained by ADCP or electromagnetic current meter. HF radar fields cover large spatial areas synoptically. The surface current vectors produced reflect water movement due to both wind stress and Stokes' drift – which is not possible to determine from an ADCP, and is not well represented in numerical models. Perhaps the principle advantage of HF radar monitoring is that the equipment stays on land: There is no need for waterproof housings (except for the data processing computers); equipment is accessible for servicing, while power supply and data transmission are less problematic. The equipment typically has a lifetime of at least a decade. This results in a reliable system (examples during the workshop often achieved better than 90% data return) and running costs are lower than those associated with oceanographic buoys.

The antennas of the phased-array systems (WERA, Pisces) require access to a longer stretch of the beach or cliff top for the array (40 to 200 m). This may affect the choice of site. The SeaSonde is a more compact system and can be mounted for example on a scaffolding tube attached to a pier.

The range of these ocean radar systems depends on the operating frequency, the transmitted radio-frequency (rf) power and the signal to noise performance. The three commercial systems provide different ranges for a given operating frequency. If a high transmitted power is not critical, the Pisces systems provide the longest ranges.

Phased array systems such as those from WERA and Pisces are considered to offer better temporal resolution than direction finding systems (such as the CODAR SeaSonde and the WERA DF), although CODAR do say that radial data are produced at intervals from 18 minutes (at low frequencies) to 4 minutes (higher frequency systems). These data are usually averaged however, to produce hourly current maps.

The angular field of view, resolution and accuracy depends on the kind and number of antennas as well as the signal processing techniques employed. A compromise to reduce array length is a 12 antenna array, but even 8 antennas can provide reasonable ocean current data. The field of view of these shorter phased array systems is limited to ±60° (±70 with curved array). The compact SeaSonde can provide a 360° field of view.

For all systems the range resolution is dependent on the available bandwidth. The required bandwidth is a function of the spatial resolution such that bandwidth (kHz) = 150 / required resolution (km) i.e. bandwidths of 20 kHz to 100 kHz give resolutions of 7.5 km to 1.5 km respectively This has implications for radio licensing of the system, as a very fine resolution (e.g. 300 m) requires a large bandwidth (500 kHz in this example) which is hard to get for a low frequency (long range) system. In consequence the long range systems will always provide a coarser resolution than a short range system.

One radar site allows the radial velocity vectors to be determined while two sites are needed to obtain the full two dimensional current field. Site spacing is determined by the maximum range offshore. The space between adjacent radar systems should be about 40 to 60 % of the range: thus ranges of 210, 150 or 90 km require radar baselines of 120, 90 or 55 km respectively. If only current vectors are required, then spacing is determined by the current mapping range. If wave data are required then the reduced coverage (or higher power requirements) necessary to obtain wave data must be considered.

A further limitation on all HF radar systems is that caused by brackish water. Jendro (1992) reported on French experiments with VHF radar monitoring. He suggested that the system might be useful for tracking the plumes of rivers, by looking at the limits of signal propagation. More recently, both WERA and SeaSondes have been used in the Baltic, and the effective range has been found to be reduced by about 50% where the surface salinity is 7 psu. Outside of St. Petersburg, Gorbatskiy and colleagues (workshop presentation) were able to produce only 4 – 6 beams from their SeaSonde, and reached a maximum of 10 km out from the shore, because the low salinity (0.3 – 0.5 psu) hindered radar propagation. If a 50% the range reduction can be accepted at 7 psu, then there is no reason why a permanent network could not be established in the Baltic Proper. Range problems in regions of low salinity can be reduced by using a high power system such as Pisces. Assuming a linear decrease in range with salinity, a system operating over typical Kattegat surface salinities of 20 [psu] might be expected to have 70% - 75% of the expected oceanic (35 [psu]) range.

There has been extensive validation of each of the three commercially available radar systems. Comparisons have been typically been made between radar current fields and point ADCP observations, between radar and buoy-mounted current meters and also between drifters and radar to validate the spatial component of the current fields. It was not clear whether or how the arrays were calibrated after installation, and what benefits this gave. Neptune Radar states however that all types of antenna need some calibration on installation. If the calibration degrades with time, then direction finding systems produce directional errors while beamforming systems suffer directional sidelobe responses. In both cases it is sometimes possible to mitigate effects in post processing if up to date calibration factors can be measured. Regular maintenance is needed as all systems suffer from long-term environmental damage, which degrades calibration. Phased arrays of more than 16 elements have lower sidelobes; arrays with fewer than 16 elements have intrinsically high sidelobes and are less suitable for wave measurements. According to Helzel GmbH, neither the WERA phased array nor the WERA direction finding system needs any post installation antenna calibration as, since 2000, they have implemented a solution in the data processing that does away with this need.

Validation exercises give confidence in all of the available systems – though the intercalibrations do not give guidance as to whether one radar system is superior to another. Differences between radar and in-situ observations appear to be due to sub-grid scale phenomena that the radar cannot resolve, or vertical shear (particularly close to the surface) that cannot be measured with an ADCP. CODAR report typical raw rms differences of up to 10 cm/s, while rms differences in the harmonic components of tidal currents are less than 2 cm/s. Comparison with drifters also inspire confidence in the radar generated current vectors.

The intercomparisons are illustrated by the results presented in Figure 16, Figure 17 and Figure 18, which show results of various intercomparisons for CODAR, WERA and Pisces respectively.

Wave measurement is based on analysis of the 2nd order signal, which is typically 15 dB lower than the 1st order used for currents. A wave measurement radar therefore requires 15dB greater performance than a current measurement radar for the same data return at the same range. Pisces600 has 15dB higher performance than SeaSonde or WERA. For low prevailing sea states the 1st to 2nd order ratio is greater requiring higher performance to maintain the measurement range.

For directional current measurement (not radial) and all spectral wave measurements, two radars are needed. Site spacing is determined by maximum range offshore, ranges of 210, 150 or 90 km require the radar baseline of 120, 90 or 55 km respectively.

4.3 Coastal radar today

Coastal radar systems are now well established components of coastal monitoring systems and observatories. In the early and mid-1990's they were principally used in relatively short deployments during specific experiments, such as during the MAST 2 project FluxManche (1990 - 1991) and at Holderness on the UK east coast (Prandle et al., 2000). This is in part because systems are now more affordable, but also because computing power makes online data processing and near real time data delivery realistic.

The market is dominated by the CODAR SeaSonde range, with particularly impressive coverage along 2000 km of the US west coast, and large parts of the east coast covered as well. There is diversity however, with some US institutions opting for the WERA system. As a result, NOAA have developed guidance in the form of common data management standards for both WERA and CODAR systems (NOAA, 2007). The motivation for this is to optimise data quality and facilitate data flow in the US Integrated Ocean Observing System (IOOS, http://www.ioos.gov/hfradar/). In Europe, the requirements for data flow from CODAR, WERA and Pisces systems, and the solutions, are likely to be similar, using a combination of netCDF and ASCII data files making data accessible to all through OpenDAP servers, in much the same way that numerical model data are made available now.

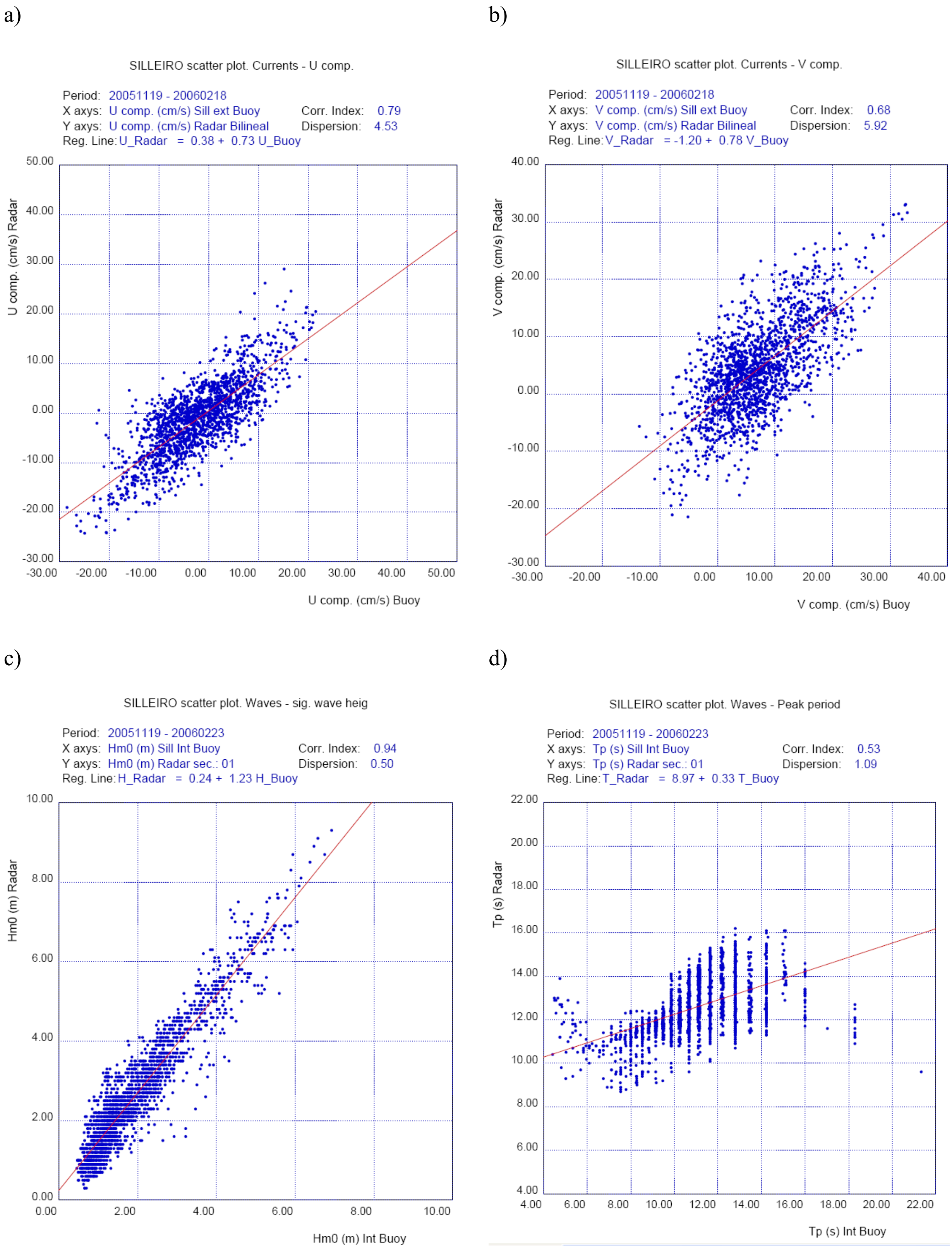


Figure 16 Comparisons between CODAR data and observations from a Spanish buoy. Figures show a) u & b) v velocity components of the current, c) Hs and d) Tp (from Alfonso et al., 2006)

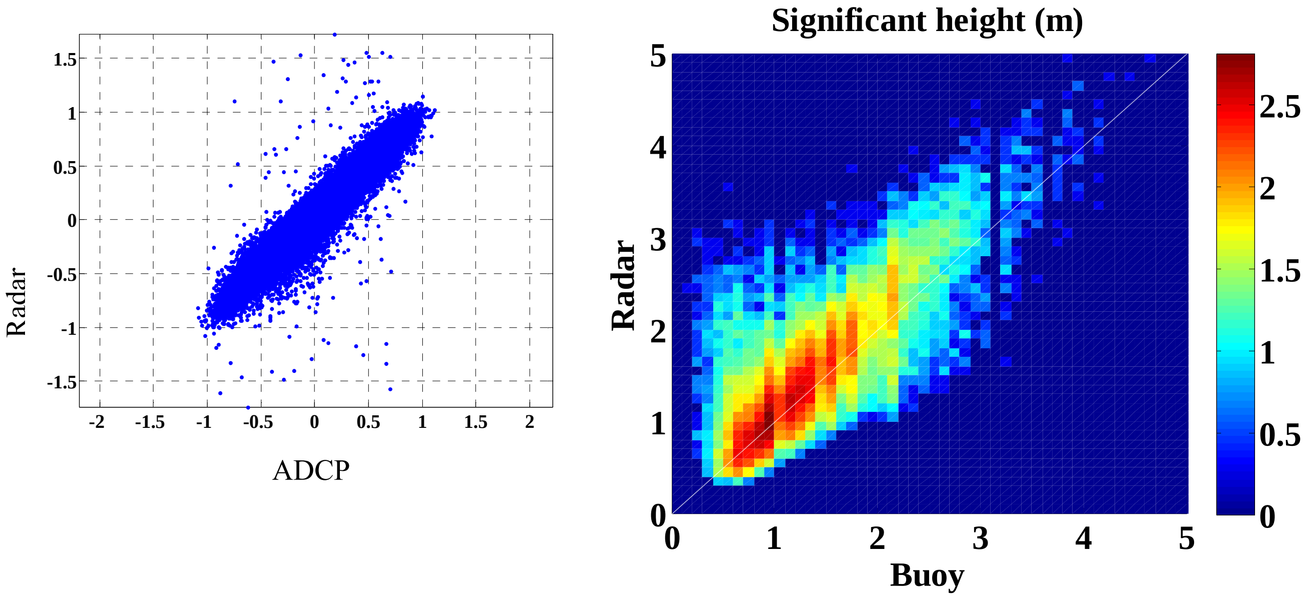
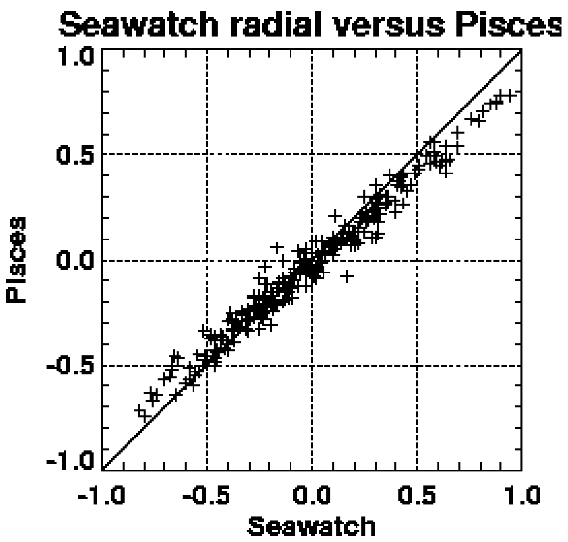


Figure 17 Comparisons of WERA and ADCP measured currents (left) and WERA wave height vs. buoy wave height , both Liverpool Bay (Howarth's workshop presentation: smhi_howarth.ppt)



Correlation coeff.: 0.99

Rms difference: 8 cm/s

Figure 18 Comparison of a radial velocity measured with Pisces with that observed from a Seawatch buoy (from Wyatt's workshop presentation: skagerrak2010-2.ppt) at a range of 150 km from the radar site

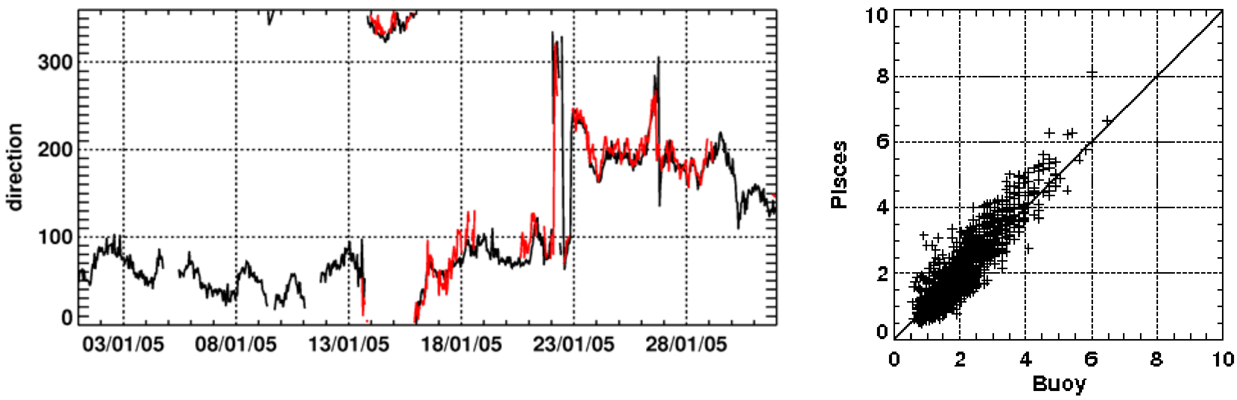


Figure 19 Comparison of short wave observations from Pisces radar and a Seawatch buoy at 150 km range.

4.4 Commercially available systems

4.4.1 CODAR

CODAR Ocean Sensors (http://www.codar.com) manufacture the SeaSonde (and RiverSonde) system of current-measuring radar. The company claims about 85% of the world market for ocean surface current radar, and can justifiably claim to have pioneered the development of this observing technique. Barrick D. was responsible for much research into HF radar reflections and subsequent development of current measuring technologies from the 1960's onwards and remains as president of the company. SeaSondes are in operation in at least 24 countries, and the parent company has affiliates 7 countries, including Norway and Spain. Presently, 2000 km of the US West coast is covered by a network of 50 or so SeaSondes, with low frequency units supplemented by higher resolution systems to provide a nested grid of current fields where appropriate. This system may be viewed at http://www.sccoos.org/data/hfrnet/oi.php, or by Googling 'CORDC'.

The basic SeaSonde is a single aerial, about 7 m long, carrying out both transmit and receive tasks. The single antenna is connected to a shed or instrument cabinet containing control and processing hardware, including a GPS for time control. The single antenna system works at the 12 – 50 MHz band (although recently CODAR claims frequencies down to 5 MHz are possible) so is suitable for short to mid ranges and standard to high resolution applications. Longer range systems use a separate transmit aerial (10 metres long) mounted maybe 200 metres from the receive aerial. Greater range may be achieved by using two transmit aerials (e.g. Vermillion oil platform, Gulf of Mexico). Typical radiated power output from a SeaSonde is of the order of 80 Watts, with an average of 40 Watts. Marketing literature provided by the company shows systems powered by wind generators, with about 200 Watts needed to operate a system including computers, dependent on how much energy is required for cooling the system.

A single system (i.e. a transmit and receive aerial or aerials at a single site) can only estimate current velocities towards or away from the system's position. In order to obtain current vector fields, another transmit/receive station must be set up such that the fields from each station overlap. With radials from the adjacent stations crossing 90° it is easy to exactly decompose the two radial components into Cartesian components. This constraint is not so strict however, and a wide range of crossing angles permits the current field to be determined. This is illustrated in Figure 20 and Figure 21. The recommended distance between adjacent radars is 60% of the offshore range.

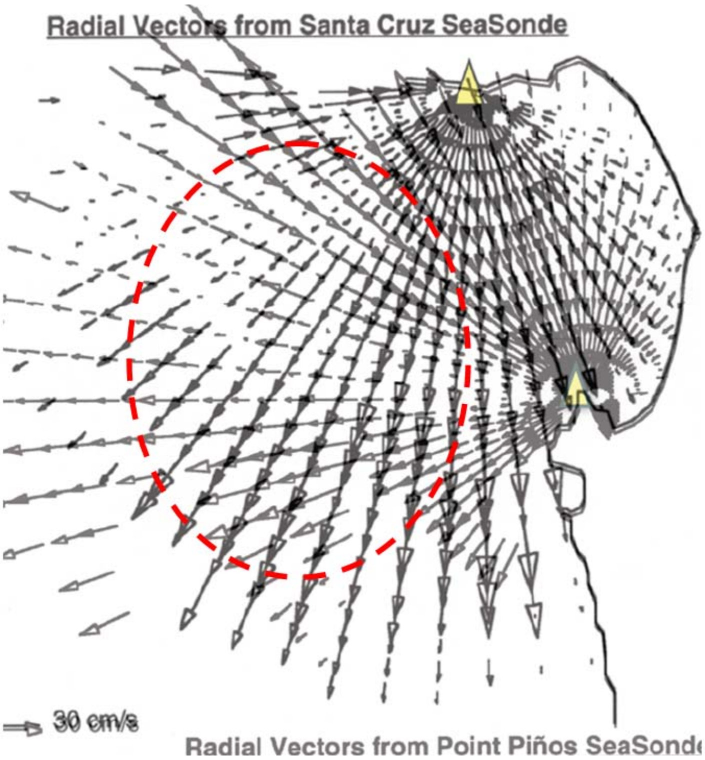


Figure 20 Radial velocity vectors from two adjacent SeaSonde systems (from Whelan's workshop presentation CODAR_SMHI_2010_May.pdf). Dashed red oval indicates approximate region where best current vectors should be attainable

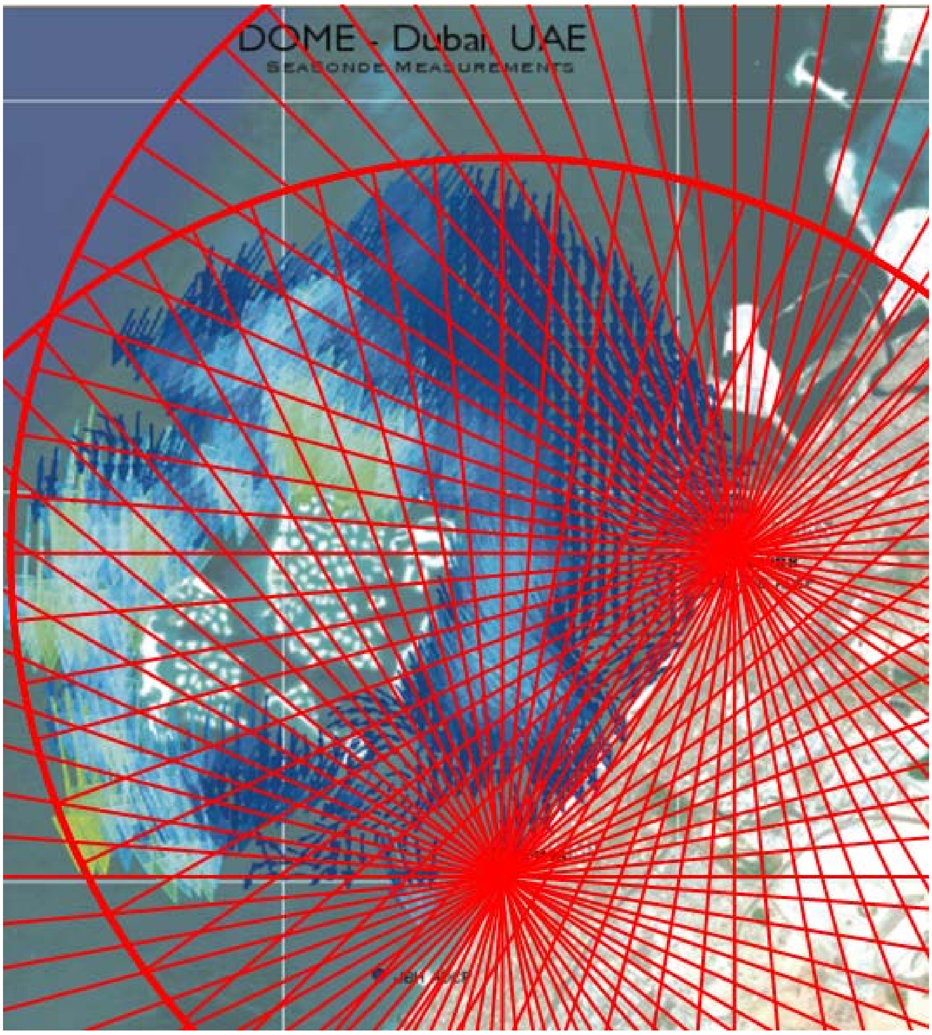


Figure 21 Sketch of overlapping radials from adjacent CODAR stations (~5° between radials). Sketch overlain onto a slide from Whelan's presentation (CODAR_SMHI_2010_May.pdf) showing currents observed by two SeaSondes off 'The World', Dubai

The SeaSonde uses a three element directional cross-loop and dipole antenna design to identify the relative phases and amplitudes of the received signal. This means that the SeaSonde aerial can resolve signals from all directions which avoid the directional limitations of a beam-forming array. A possible advantage of the SeaSonde approach is when the aerial is mounted on a spit or island, with the sea on more than one side. The SeaSonde is able to discriminate between reflections coming from all directions, whereas a beam-former array may 'fold' the reflected signal energy from 'behind' the array onto the energy coming from in front, giving misleading results. This drawback of classical beam-former arrays may be avoided by using two rows of aerials (as in the Pisces system) although the improved beam-former will now be blind to the signal coming from behind.

Various configurations of SeaSonde are available. As with all systems, there is a trade-off between frequency, range and resolution. Maximum range achievable is 220 km, at about 4 MHz. This can be extended by the use of either twin transmitters and/or by making the system bi-static. In its simplest form, this involves an additional receiver deployed towards the limit of the radar domain and can enhance the system range by 30%, or more if a more complex system of transmitters is used. This system is patented and unique to CODAR. The specifications of the various CODAR systems are listed presented in Table 1.

CODAR's bi-static and multi-static modes depend upon a frequency modulation multiplexing technique (called GPS Sync). This allows multiple radar stations (more than 100 working at 150 kHz, according to Barrick et al., 2005) to transmit and receive simultaneously on the same frequency, without interference. This releases operators from the need to have permission to operate on multiple frequency bands and reduces the risk of having to share a frequency band with another user (which would restrict observations to pre-arranged time slots). This GPS synchronisation facility allows CODAR to coordinate large radar networks, such as those along the US East Coast. CODAR have patented this technique (Barrick et al, 2005) and it is available under license to other manufacturers.

Type	Frequency	Range	Resolution
Hi-Res	40 – 44 MHz	10 – 15 km	200 – 500 m
Standard	24 – 27 MHz	30 – 50 km	500 m – 2 km
Mid-range	11.5 – 14 MHz	60 – 90 km	1 – 3 km
Long-range	4.3 – 5.4 MHz	150 – 220 km	3 – 10 km
Dual transmitter with twin TX antenna		280 – 340 km	3 – 10 km
Multi static long-range with offshore bistatic buoys	4.3 – 5.4 MHz	300 + km	6 km

Table 1 Manufacturer's general specifications for current measurements from the principle SeaSonde systems

The SeaSonde is a fairly low power system. Under most conditions, waves can be measured by SeaSondes out to 25% - 35% of the range for current measurements. For example, a 12 MHz system that typically gets 75 - 80 km range, would measure wave parameters out to about 25 km under most conditions. Wave measurement range increases with higher sea states, and decreases with lower. Flags indicate when waves are too low to measure at each range. Presently obtainable wave parameters are significant wave height, dominant direction and dominant wave period.

Typical Range:	Significant waveheight accuracy	Dominant onshore direction accuracy	Dominant onshore wave period accuracy
Approx 25 km for a 12 MHz system (25 – 35% of current measurement range)	7 – 15%	typically 5 – 12°	typically 0.6 seconds

Table 2 Manufacturer's general specifications for wave measurements with SeaSonde

No problems have been reported due to ice formation on the aerials during winter, while salt deposition is usually short lived.

4.4.2 WERA

The WERA system is manufactured by HELZEL Messtechnik GmbH, of Kaltenkirchen, Germany (http://www.helzel.com). It was developed in the mid-1990s by the University of Hamburg (Gurgel and Antonischki, 1997) with hardware development by Helzel. The motivation for developing the system was to obtain spatial descriptions of the wave field: hence the name WERA, an abbreviation of the German *We*llen (wave) *Ra*dar. Helzel is an industrial electronics company specialising in RF systems and sensors.

A WERA installation can take two forms. Both use a transmit array of four aerials. The simplest set up uses a direction finding receive array also made up of four aerials. The standard approach uses a linear beam-forming array of 8 to 16 aerials. These two options have differing capabilities (Table 3).

Type	Parameters	Range	Resolution
Direction finding (4 poles)	Currents & wind	270° field of view	Temporal resolution > 15 minutes
Beam forming (8 – 16 poles)	Dynamic currents, wind & waves	120° field of view (more for a curved array) Range resolution 250 -3000 m depending on the allocated bandwidth, it is identical for all systems	Temporal resolution 3 – 10 minutes

Table 3 Array options with WERA

The transmit array is a rectangular array made up of four aerials typically spaced ½λ apart in the alongshore direction, and 0.15λ apart in the across shore, where λ is the radio wavelength. The transmit antenna needs to be isolated from the receive antenna. This is achieved by a physical separation of at least 50 to 100 metres, but also by ensuring alignment of the transmit and receive arrays, such that the null point in the transmit array is aligned with the receive array.

The receive array uses one of two principle configurations. The simplest and most compact is a square array of four aerials, where aerial spacing is governed by the radio wavelength. This is a direction finding array similar in principle to that used by CODAR that can be used when wave data are not required. The more usual WERA configuration is a linear beam forming array. This is typically made up of 16 aerials in a line (although sometimes 8 or 12 are used with some resolution loss). The spacing between each aerial is typically 0.45λ where the wavelength λ is that associated with the highest frequency the system is expected to operate on. Depending on the intended frequency, the receive array can extend from 40 to 250 metres. The receive array should be installed within +/- 15° to the coast, to minimize differences in propagation length between the water and the array. The receive array using beam-former (linear) construction has a field of view +/-60° around the cross shore axis. This field of view can be extended to ±70° by using a slightly curved array configuration. WERA systems typically transmit 30 Watts continuously.

The separation of the transmit and receive arrays should be about 10λ, although experience has shown that the separation need not exceed 250 metres. This results in a system length of just less than 200m for the 27.65 MHz system, and allows free access to the beach in front. Total site dimensions for various frequencies, and the achievable ranges and resolutions are listed in Table 4. Other environmental considerations are that the site should be as high as possible, and as close to the shoreline as possible or located on a cliff top. Metal fences, cables and other conductors should not be located between the antennas and the waterfront. A new, WERA-unique noise and interference reduction method (for beam forming systems only) allows to operate the systems even near industrial noise sources. External noise sources within the field of view (buoys, platforms, etc.) are eliminated as well.

WERA can be used at lower frequencies than those shown in Table 4, but for applications on the Baltic this is not recommended as the corresponding long Bragg waves won't be available all-the-year. WERA also offers functionality such as a multi-frequency option to increase data availability. This is claimed to improve wave detection, minimize uncertainty in ship tracking and minimize day/night range variation.

Figure 22 View through the WERA transmit array deployed behind a public beach at Tannum Sands, Australia. 12 channel long range (200 km) system operating at 8.34 MHz

Figure 23 WERA 16 MHz receive array at Key Biscane (Florida). Photograph courtesy of Thomas Helzel, Helzel Messtechnik

Type	Frequency	Range	Possible Resolution	10λ Separation between transmit and receive antennae	Total installation length (including transmit & 16 channel receive arrays)
Short range	48 MHz	15 km	50 m	62 m	108 m
Intermediate	27 MHz	*55* km	300 m	111 m	192 m
Long range	8.3 MHz	180 km	3 km	*250* m	*490* m

Table 4 Frequency, range, resolution and array size for WERA assuming full 16 channel linear array. Total array length given by Σ(0.5λ transmit array length)+(10λ separation)+(0.45 x 15λ receive array length). Low power and 'compact' array configurations are also possible.

Despite the potentially large bandwidth requirements, Helzel claim that the WERA generates very small amounts of radio frequency noise, so is unlikely to disturb users of adjacent frequency bands. Furthermore the WERA system operates in a "listen-before-talk" mode. The systems scan the allocated band prior to the next acquisition cycle and can adjust its frequency to fit into a "quiet" gap.

Given that WERA was initially developed due to the need for wave measurements, it is unsurprising that this is a system strength. Both significant wave height and directional spectra are available up to a range of 100 km, while wind direction is available up to 200 km. Both wind speed and wave spectra are available through software systems provided by SeaView Sensing. Howarth reported results from validation exercises using the Liverpool Bay WERA system. Wave periods were measurable down to 2.8 seconds, and wave heights down to 1 metre. A correlation of significant wave height between a buoy and radar returned correlation coefficients of 0.90. Wind speeds up to 31.4 m/s were recorded, although agreement between these and observations from a nearby mast was poor. Wind direction agreed well.

Statistics from the WERA systems installed near Brest in France, operated for SHOM, demonstrated the reliability: within the last 2.5 years, all of the current vectors within 40 km range were provided every 12 minutes for 98.7% of the time.

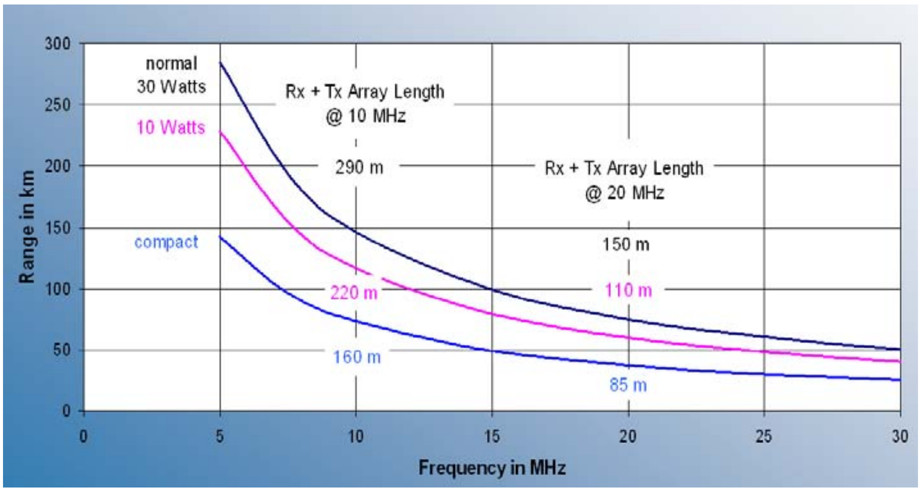


Figure 24 Spacing of WERA beam forming transmit and receive antennas for different power and space constraints, and the effect on the resulting range. Assumes standard oceanic salinities (low salinity reduces range). From: Helzel's workshop presentation: WERA-G~1.PPT

Site	Array description	Parameter	Frequency	Power	Sweep time & sampling period	Range cell size	Range
Fedje / Lyngoy[3] - (No) *EuroROSE project, Feb – Apr 2000*	16 antennae	Currents, Hs and wave direction	27.35 MHz	*30 W*	0.26 s / *5.3 mins*	1 km	45 km
St. Catherine East Coast (USA)	12 antennae	Currents + Hs and direction	8.35 MHz	30 W	0.5 s/ 8.5 mins (1024 samples)	3 km	240 km
Florida's W. Coast (USA)	16 antennae	Currents	16.04 MHz	28 W	0.3 s/ 10 mins	1.5 km	*85* km
Florida's E. Coast	16 antennae	Currents + directional wave spectra	16.3 MHz	28 W	0.3 s / 5 mins	1.5 km	100 km
Brest (Fr.)	2 x 16 antennae arrays	Currents + directional spectra	12.4 MHz	*30 W*	*0.26 s* / 12 mins	1.5 km	120 km
Liverpool Bay (UK)	2 x 16 antennae arrays	Currents, waves, winds	12.5 MHz (Formby point); 13.4 MHz (Llanddulas)	30 W	*0.26 s* / 9 mins	4 km	*65 km*
Limnos Island (Gr)	2 x 4 antenna arrays (Direction finding arrays)	Currents	13.544 MHz			3 km	*40 km*

Table 5 Examples of actual WERA configurations

4.4.3 Pisces

Neptune Radar (http://www.neptuneradar.net) was founded in 1983. The company demonstrated a real time metocean data collection system in 2001, while in 2005 the system was shown to meet contracted requirements for data return. The radar systems are sold under the name Pisces. Systems are based on standard off-the-shelf components to facilitate local maintenance. A design lifetime of 10 years is specified (excluding computers). The system on the south west coast of the UK has been in operation for 9 years.

[3] This installation was an short-term deployment by the University of Hamburg as part of the EuroROSE experiment, and should not be confused with the permanent operational CODAR SeaSonde installation at Fedje described on page 13

There are three principle Pisces models, the 500, 600 and 700. The Pisces 500 is intended for frequencies of 12.5 MHz, giving median effective ranges of about 65 km for waves and 130 km for currents. The 600 model works at 10 MHz, covers 140 km for waves and 240 km for currents. The Pisces 700 can achieve a range of 190 km for waves and 275 km for currents at 8 MHz. This system also achieves better spatial resolution than the others. The frequencies described are not prescriptive: each system can be operated anywhere from 5 to 35 MHz and this is instantaneously variable. As with WERA, range resolution is a function of bandwidth. Bandwidths of 8 to 250 kHz are possible, giving range resolutions from 20 km down to 750 m.

Like WERA, Pisces uses a phased array. It differs from WERA in using use doublet elements (two rows of aerials in the receiver array) so is not corrupted by signals from the rear. The doublet elements are wideband and high gain contributing to radar performance and frequency flexibility. A typical Pisces 600 installation is about 600 metres long (including the transmit array). It requires a clear offshore field of view, without any islands more than 1 km across. Pisces installations can cover between 300 and 500m of coastal aperture. A transmit to receive antenna separation of 100m is designed to provide great flexibility in siting. The transmit antenna can be beside or behind the receive array, which can be particularly effective with a sloping coastal site. There is no dependence on antenna pattern for isolation and the receive channels have robust power dissipation capability.

While WERA uses a Frequency Modulated Continuous Wave signal (FMCW), Pisces, like the SeaSonde, uses FMICW that is to say an interrupted continuous wave. FMICW has advantages in ensuring the isolation of the transmission system from the receiver. The system design appears to be unusually robust, with lightning protection allowing the system to survive single lightning strikes to individual aerials without damage.

The Pisces radar systems were designed primarily for measurement of the directional wave spectrum. Successful and reliable wave measurement demands better signal to noise characteristics than are needed to detect currents alone. The signal to noise ratio is improved by using high power transmitter – typically 1000 Watts. The Pisces performance is partly delivered by the transmitter power but equally by high gain antenna systems, which tend to be larger than those of low powered systems. Where tests have been made in the Western Approaches (Celtic Sea, off the south west United Kingdom) mean wave heights of about 2.7 metres were found. Compared to this, the Skagerrak is a low wave height environment, and so a high power system would be required to reliably return wave spectra. The level of wave information possible from the Pisces system makes it suitable for research into wave-current interaction – which is still a problem in operational oceanographic models.

Data return is normally expressed as a long-term percentage of observations that yield required data. It is different for different metocean parameters and it varies with waveheight, time of day, season, radio frequency, radar power and site configuration. Table 6 shows the actual data return from the PISCES 600 system.

Parameter	50% (median) availability	>80% availability
currents	240 km	180 km
wind direction	180 km	140 km
single radar waveheight	140 km	60 km
dual radar wave spectral data and wind speed	140 km	60 km

Table 6 Demonstrated data return from the PISCES 600 (source: M. Moorhead, Neptune Radar)

Ship surveillance is possible with SIREN. Identifying echoes from ships is not straightforward when there is so much backscattered noise from the ocean surface. Large ships are more easily detected than small ones, although small vessel detection is of interest for both for fishery and security reasons. Small vessels are likely to be masked by the Bragg peaks, sea resonances, land echoes etc. Chances of detecting vessels are increased by a high signal to noise ratio. The SIREN system uses ship tracking to filter returns from vessels from background noise. The system is expected to become operational during 2010.

4.4.4 Seaview Sensing

Both WERA and Pisces allow users the choice of using software from Seaview Sensing to enable them to extract directional spectral wave information and wind parameters as well as the more usual current parameters from the radar backscatter. The Seaview Sensing software suite also includes data management and presentation routines. Seaview Sensing was founded in 2004 and specializes in data processing for phased array systems.

The company's principle product is a software suite, consisting of three parts: Seaview Realtime, Seaview Data Viewer and Seaview Offline. Seaview Realtime is installed on a server to receive, process and archive the radar data (using a MySQL database) and to deliver the processed metocean data fields to the (same) database. Seaview Viewer is a web interface to the metocean database, allowing users to view maps and time series, to download data and to perform quality control. Seaview offline allows users to process archived radar data. The programs form the main production chain for delivering real time and delayed mode data.

The programs are written mainly in C, and provided as compiled routines for use on a Debian or Ubuntu server (although these could be run through a virtual machine). Plotting and most post-processing is done by means of Perl and GMT, so is user modifiable. Input data are stored in HDF5 files, while output data are provided as text or GRIB files.

Comparison of wave parameters measured by buoys with those obtained by WERA and Pisces, and processed using Seaview software, are generally satisfactory: wave heights agree with correlation coefficients of between 0.83 (WERA 12 MHz) to 0.97 (WERA 25 MHz). Peak directions between 5 and about 20 seconds were generally in good agreement. Frequency spectra were not always in agreement. The WERA wave fields were not always available, because of the higher minimum wave height condition with WERA compared to Pisces.

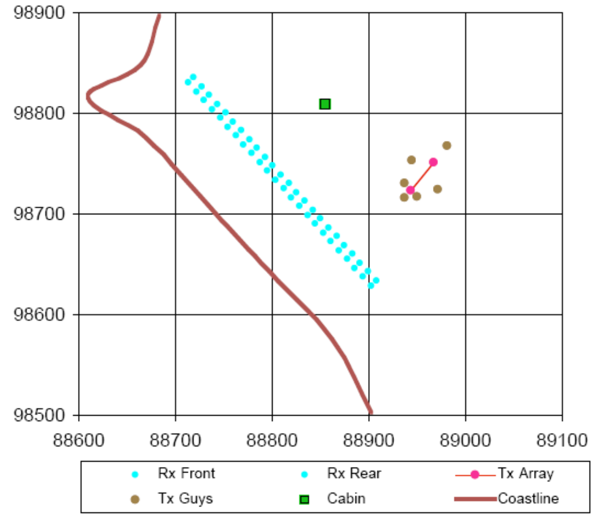


Figure 25 Pisces site configuration on a coastal slope (sea to the bottom left of the picture). The array aperture is limited by the available land, but the transmitter is mounted behind the receiver, up the slope. The total site extent is 300 x 250 metres.

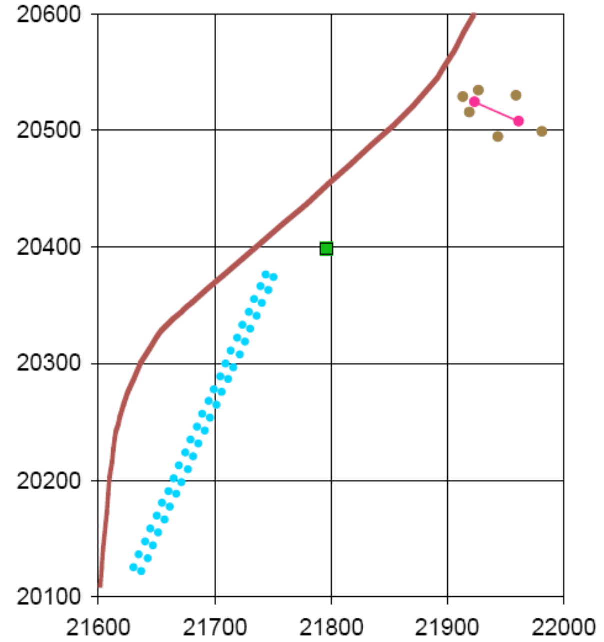


Figure 26 Pisces installation on flat ground along a cliff. Transmit array is situated north west of the receive array. Total site extent is 500 x 125 metres.

Figure 27 Back row of Pisces receive array (foreground, to the right) with transmit array in the distance (background, left).

Figure 28 Pisces transmit array. Tops of receive array are just visible further down the slope.

Figure 29 Double rows of antennas in the Pisces receive array.

4.4.5 X-band

X-band marine radars work at frequencies of 8 – 12 GHz. This is in the centimetre range of the spectrum, with wavelengths of the order of 3 cm. These radars are small and light weight, typically with a rotating aerial only a couple of metres across and are standard on commercial vessels. While a commercial operator will adjust the radar to filter out ‘sea clutter’, X-band radar easily generate images showing the surface wave field as alternating dark and light bands. As with HF radar, this type of image is formed due to the backscatter of the radar energy from the surface wave field through Bragg scattering. Unlike HF radar, the X-band radar signal is generally scattered by capillary waves on the back of the gravity wave field rather than the gravity wave field itself (although some direct reflection may occur from breaking waves). As a result, X-band radar has trouble producing an image during still conditions (typically wind speeds below 2 m/s).

By assembling a series of radar images based on each scan of the aerial, a frequency spectrum can be determined for each pixel. Each pixel’s frequency spectrum is a description of the actual wave spectrum at that point, although the actual wave energy density cannot be determined without a validation point. Studying an individual frequency bin allows the wave direction in that bin to be determined, and in this way the directional wave energy spectrum can be determined across the radar domain.

In linear wave theory, the wave length and frequency are related through the dispersion relation:

$$\sigma^2 = gk \tanh kh$$

where σ is the angular frequency (equal to $2\pi f$), k is the wave number (equals $2\pi/\lambda$), g is acceleration due to gravity and h is the water depth .Thus if both s and l are known, then the water depth can be determined. The dispersion relation is subject to modification however: if the waves are propagating on a current, it becomes:

$$\sigma^2 = g\bar{k} \tanh \bar{k}h + \bar{u}.\bar{k}$$

where the $u.k$ is the vector cross product of the current vector and the wave number vector. Thus if depth is known, or if the water is sufficiently deep that the tanh kh term tends to 1, then the equation can be solved to obtain the current vector.

X-band radar have been used for many years, initially for research purposes (e.g. Bell et al., 2004), but have more recently become commercially available, for example the WAVEX system from MIROS (http://www.miros.no). Typical horizontal resolutions from an X-band system are of the order of 8 – 10 metres, while an effective range of 200 metres (Bell suggests 800 metres may be possible) make them ideal for monitoring beaches, harbour approaches and narrow channels rather than the extended coastal areas covered by HF radar.

5 Summary and Conclusions

5.1 User communities and needs

The workshop identified a range of users that could make a possible reference group to guide the development of a current monitoring network. Primary users appear to be the Joint Rescue Coordination Centres, the Coastguard and Vessel Traffic Services. These organisations all require better current information than can presently be delivered between the Danish Straits and the Skagerrak. Whether this data comes from improved models or from direct observations is not as relevant to them.

Hydrometeorological institutions in Denmark, Sweden and Norway produce current forecasts, and are also engaged in supporting the primary users in the event of accidents. They also run operational wave models, but appear to be rather satisfied with the performance of those models without assimilation. This could be fortunate, as spectral wave parameters require more powerful systems for reliable data production. Hydrometeorological institutes can also be counted as research users of such information, as they are actively engaged in the improvement of operational forecasts, and a better representation of Stokes' drift and wind induced currents should lead to better model products. These institutions already have the responsibility to provide their respective societies both with warnings and with the basic environmental information needed by other agencies and organisations to operate.

Security and border agencies have an interest in ship tracking, although like the wave application, it is not completely apparent that a robust detection system can be built without a high power radar system. It appears to be an active area of research however.

The fourth group of users is more diffuse, and includes the general public, either as recreational water users or simply as interested individuals. This group also includes the construction sectors. Both the public and the construction industry have a strong interest in the spatial wave fields.

In addition, coastal radar systems can provide information and data for the GMES GISC (GMES *In Situ* Co-ordination) process in Europe presently under coordination at the European Environment Agency.

5.2 Suitable resolution

Operational models in this region have a resolution of between 0.5 and 3 nautical miles. Given the first order Rossby radius is of the order of 5 km (due to the shallow halocline) it is no surprise that the models have difficulty describing the mesoscale activity in these seas. For the velocity fields to add value, they should also be fully eddy resolving, and so a resolution of say 0.5 nm (900 metres) would be most desirable.

This would require a 166 kHz bandwidth from WERA. The 27 MHz system used during Scawvex at Fedje in Norway had a cell range size of 1 km, and a total range of 45 km. The 16 MHz system could deliver a resolution of 1.5 km over 100 km range, making a typical eddy 3 – 4 cells across. CODAR suggest an initial network of 6 mid-range sensors, all deployed along about 260 km of the Swedish coast. This suggests a sensor separation of about 43 km. Assuming that the separation is 60% of the offshore range this would make the offshore range about 70 km. This would require a 12.5 MHz system and could maybe deliver a 1.5 km grid resolution.

A Pisces 500, working at 12.5 MHz could cover 130 km for currents and 65 km for waves. Assuming the 24 element array was used, this would give a beam width of 6°. Over 65 km this would give a cross range horizontal resolution of 7 km, while the along range resolution is determined by the system bandwidth.

All systems have worsening cross range resolution with increasing distance due to radial spreading of the transmitted signal. To maintain a cell size of around 1000 x 1000 metres over the entire Kattegat (for example) would require a 150 kHz bandwidth (as bandwidth in kHz = 150 / range in km) to give the 1000 metres along track resolution, and a beam width (or angular resolution) of about 9½° at 30 km (which would require radar systems on both sides of the Kattegat) or just under 5° for radar along one coast only, measuring out to 60 km. These limitations may be relaxed if multistatic radars are used.

5.3 Geographic coverage

Initial discussions concentrated on the Skagerrak and possibly the northern Kattegat. In part this was driven by a desire to share costs between the three countries. It is hoped that a system covering this region would significantly improve the modelled current fields from numerical models. The position of the Kattegat – Skagerrak front would be on the edge of this region, however and might cause problems.

This region is ideal from the point of view of trans-boundary inputs. Monitoring just this region would cover the coastal current from the North Sea, the northward flow of the Baltic Current along the Swedish coast, and the Norwegian coastal current as it re-entered the North Sea.

Workshop contributions from the Joint Rescue Coordination Centre indicated that their interest was much more in the southern Kattegat and Belt Seas. This is because of the congested shipping lanes, the stronger and more variable currents and population pressures. This would suggest a different consortium to the Skagerrak, with Sweden and Denmark cooperating to cover the Sound and southern Kattegat, and Denmark and Germany covering the southern Belt Sea. Much of the region consists of Danish internal waters however

JRCC also indicated that they needed much more inshore data than had previously been considered. This could be obtained along the Swedish coast from sites located in Denmark (range permitting). Similarly, the Swedish network would be suitable for describing Danish coastal waters. This illustrates an added value in establishing this type of cooperation.

Funding is unlikely to be sufficient to establish six radar sites along the Swedish west coast with complementary sites in Denmark and Norway. Such a network is more likely to grow piecemeal, by first establishing a small network, and then expanding it. This requires some areas to be prioritised ahead of others – for example the entrances to the Danish Straits, or the area outside of Gothenburg. This prioritizing may need to consider the final form of the network: can the network be optimal at all times during development, or should equipment purchases only consider the final (desired) form?

Experience with the NORDRAD2 meteorological radar system suggests that interference from wind farms could be a significant source of noise. Reflections from the moving blades of wind turbines give a Doppler-shifted echo, which may be interpreted by the radar as a persistent rain shower. Given the expected increase in offshore wind energy production, particularly in the Kattegat, this may be a factor that affects the design of a monitoring network. It will be necessary to assemble further experience from existing users.

5.4 Radio licensing

Radio licensing is potentially problematic: Obtaining high spatial resolutions to satisfy the needs of data assimilation into models requires a high bandwidth from phased array systems. This may cause problems with the licensing authorities. There may also be issues surrounding the permanent broadcasting of radar signals into an adjacent country's economic zone.

An additional concern on the Swedish west coast is how far away should a transmitter be from the radio telescopes at Onsala. The Onsala observatory is engaged in activities such as space geodesy with VLBI, which involves listening to pulsars. The area around the observatory is 'quiet': no mobile telephones are permitted within a kilometre or so. How far away need radar transmitters be kept?

Neptune Radar has operated a Pisces system within 500 metres of microwave radar (used for tracking cannon shells) and an operational microwave communications link with no apparent interference between the systems. The very large frequency difference appears to adequately isolate both systems from each other. The Pisces transmitter has been cleared for common use of the mast for TETRA communications (mobile radio standard used by emergency services and other critical agencies). Some interference was initially expected to occur between the 40th to 50th harmonics of the HF radar signal (a 10 MHz radar signal generates low level harmonics at 400 to 500 MHz) but the combination of signal filtering to reduce the harmonics, and the poor performance of the respective antennas away from their designed operational frequencies allowed both the Pisces transmitter and the TETRA receiver to be mounted on the same mast.

Figure 30 Pisces system co-sited with microwave radar and communications system.

CODAR's patented frequency modulation multiplexing capability 'GPS sync' allows many radar sites to operate on the same frequency, reducing the overall radio spectrum requirements. Helzel GmbH state that multiple WERA systems can also operate on the same frequency bands, as they do not use interrupted frequency modulated continuous wave.

CODAR also reported briefly on efforts to designate international permanent frequency bands for HF radar worldwide.

5.5 Data management and integration into production

Oceanographic radar stations produce fundamental environmental data which is intended primarily to improve predictions and increase the ability of society to avoid or deal with emergencies. In that respect, coastal radar stations are similar to sea level stations or weather stations, and so form a natural part of the observation networks administered and maintained by the respective hydro-meteorological institutes. As part of the warning and monitoring network, they are typical components of a GMES (Global Monitoring for Environment and Security) Core Service. The implementation of GMES is administered by the EC/DG Enterprise GMES IG and presently the marine core service is under development in the EU FP7 project MyOcean. The hydrometeorological services are experienced in maintaining such networks, and cooperating in data sharing. The NORDRAD2 network, of meteorological radars is a similar venture, and demonstrates that meteorological services around the Baltic can share data and resources to produce products for the common good.

Data received from the radar to the site computer should be considered as Level 0 data. Quality control of radar data should be automated as far as possible. The various system manufacturers deliver data processing tools and NOAA have published guidance on quality assurance of radar measurements. After initial processing (integrating observations from the various units in the measurement network) and automated quality control, results can be disseminated directly via, for example, OpenDAP as is currently done with both model data fields and point observation data. Individual institutions and organisations can then disseminate results further, for example as maps on a web server. This should be considered the Level 1, or basic, dataset which can be made available directly and compared with model-predicted current fields. Observed current fields in GRIB format should be easily readable by SeaTrack Web and BADIS (oil spill and SAR support systems, respectively) in the same way as model data, quickly giving tangible improvements in backtracking oil spills and determining initial search positions for SAR operations.

The next level of data processing would come with integration into numerical forecasting models (data assimilation). This will give a more detailed quality control – using model physics to validate the observed fields, and generating estimated error fields in the observations. This is also likely to spin-off model improvements – for example the better representation of Stoke's drift in numerical modeles. The combined model/observation fields should then be the best representation of the actual current fields. These data will also be made available via OpenDAP as part of GMES, probably with a latency of up to 12 hours.

Final level processing involves integrating Level 2 combined model/radar fields into products and information. This may be done by the hydrometeorological services (for example, for back tracking the path of oil that has sunk below the surface) but may also be done by external organisations, such as engineering consultancies, environmental protection agencies, recreation and tourism organisations. A wide user base is likely to detect problems and require service improvements that otherwise go unnoticed.

Data levels 0 to 2 should be archived and managed by the hydrometeorological services. A relational database may be useful for handling metadata and facilitating searches, and possibly even for managing the binary files. It is to be expected that improvements in data recovery, processing and gap filling will allow the reanalysis of the observed fields (Level 0 to 1), while progress in data assimilation and modelling methodology will lead to the production of improved Level 2 products. These archived data will form the basis of climate data sets, and be used for scientific and technical research, for engineering and environmental management applications. To maximise societal value, datasets need to be freely available with easy access.

It is likely that the various hydrometeorological services will have differences in their archived data products. While each service must have the same Level 0 data (and have access to or copies of the entire Level 0 archive) it is likely that different institutes will choose different processing routines, based on their particular geographical interests and the particular characteristics of their numerical forecasting models. This diversity should be considered positive: there will be discussions about the 'best' product, but it should be possible to choose the most suitable product for the user's application, and possibly even build 'intelligent ensembles' to provide even better information.

5.6 Funding possibilities

Current monitoring by radar in the Skagerrak, Kattegat and Danish Straits addresses clear societal needs, which cannot presently met by alternative oceanographic modelling or observation technologies. Coastal radar monitoring provides fundamental oceanographic and meteorological information that is both complementary to and independent of existing observation systems. It has been argued that data from these systems would be part of the standard hydrometeorological information production chain. As such, coastal radar systems should be part of the standard observing networks operated by the hydrometeorological institutes, and it can be argued that as such, their acquisition, operation and maintenance should be paid for through central institutional funding. Societal benefit exists however on both national and regional scales, and as such both national and regional funding organisations should be approached.

Within Sweden, SMHI receives an annual grant directly from the Ministry of the Environment, which covers roughly half the organisation's costs, with the remainder coming from research grants and commercial activities. While radar appears to be a cost effective way to produce fundamental observations (for example when compared to the purchase and operation of buoys) competing calls on central institute funding make it more likely that system purchase can be supported by external funds, for example from Research and Development activities. A national (and international) consortium approach is also possible: with the development of the buoy network around Sweden, funds for the Kattegat buoy were forthcoming from the National Environment Research Agency (NERI/DMU) in Denmark, as well as the Swedish Environmental Protection Agency (Naturvårdsverket) and SMHI. The Baltic Proper buoy was funded by SMHI and the Swedish Defence Agency (*Försvarsmakten*).

The Swedish Science Council (*Vetenskapsrådet*) makes contributions to expensive equipment (costs greater than 2 Mkr). Since 2009, these grants have not been available to individual researchers or groups, but are instead for buying research equipment of national interest. Items costing between 0.5 and 2 Mkr are considered to be ‘fairly’ expensive, and are covered in normal research grant applications. The council web page does not presently show an open call for proposals for research infrastructure.

The research council *FORMAS*, responsible for environmental, agricultural and spatial planning research can support applications for moderately expensive equipment, in the 0.5 to 2 Mkr range. Developing the monitoring network fallsinto *FORMAS*’ remit both in terms of their stated research aims to improve knowledge of natural resources and their sustainable use, and sustainable societal development.

The third possible national funding agency in Sweden is *Vinnova,* the Swedish Government Agency for Innovation Systems. The stated aim of this organisation is to support ‘needs-driven research’ including in the transport sector. It remains to be seen whether it is possible for a government agency, perhaps as part of a consortium including commercial actors, can apply for this support.

Regional support could be forthcoming from European institutions and programmes, or from regional cooperation.

At a regional level, the Nordic Council of Ministers (NMR) supports Nordic cooperation through funded projects, Possible relevant funding programmes operated by the council include ‘Climate’, ‘Environment’ and ‘Sustainable Development’. Since 1990, the Nordic Environment Finance Corporation has loaned money to infrastructure projects in the region, often supported by grants at a national level. The NMR is also active in adjacent regional programmes. Of particular relevance is the *North Sea Region Programme 2007 – 2013*. Germany, Denmark, Sweden and Norway are all involved in this programme. Existing project ideas include the maritime sector, with requested budgets of over a million Euros.

The Interreg IV A project *Öresund – Kattegat – Skagerrak* also runs from 2007 – 2013. The aim of the fuunding is to support international cooperation between partners from Norway, Swedn and Denmark. The geographical area suits this application perfectly, as it includes even the Danish Great Belt (on the Sjaelland side). Projects with budgets of the order of 1 million Euros are supported.

Another suitable forum for project support is the NordMet cooperation. This is a cooperation between the meteorological services in Denmark, Finland, Iceland, Norway and Sweden. An aim of NordMet is to provide an example of how to ‘share responsibilities in order to create mutual benefits’. The organisation also prioritises ‘better coordination and use of resources with other disciplines including hydrology [and] oceanography’.

The BONUS 169 programme is a joint activity under the EU Framework Programme 7. It has a regional focus on the Baltic Sea, and as such appears to exclude Norway. It may be possible to include capital investment costs as part of a proposal, for example where information on exchanges through the Belt Seas is required.

5.7 Proposal for activities to realise the network

Operational oceanography is supported in the region by two umbrella organisations: BOOS and NOOS. The coastal radar activity should be proposed to both groups (as it covers the transition waters between them). This could permit grant applications to both Baltic and North Sea focussed organisations. There is no reason why, if the BOOS application was supported before the NOOS one, that network development shouldn’t start from the south of the region, in the Danish Straits or southern Kattegat.

Considering the network as research infrastructure, the regional BALTEX project, which is a continental scale study into energy, water and carbon cycles coordinated by the World Meteorological Organisation (WMO) stands to be a major beneficiary, as the project will finally have observations of water exchange in the Kattegat. BALTEX has supported the development of the NORDRAD system of meteorological radars, and is a natural partner in this work. Ideally, BALTEX could support research grant applications, develop data use and provide a scientific user forum.

A suitable work plan could be the following:

- Working groups are formed by NOOS and BOOS, comprising representatives of the interested hydrometeorological and operational marine institutes
- Working groups coordinate respective user requirements
- Recommend geographic coverage and resolution
- Initiate / participate in funding proposal
- Optimize technical and financial specifications, together with location of proposed base stations
- Pilot network construction and operation
- Responsibility for operational management handed over to relevant institutions

Subsequent, smaller scale projects should then be attractive to develop products and services based on the radar data.

6 References

Alfonso M., E. Álvarez, J. López, 2006,"Comparison of CODAR SeaSonde HF Radar operational waves and currents measurements with Puertos del Estado buoys: Final Report", Puertos del Estado report, available online at: http://www.puertos.es/export/download/puertos/1162197763930.pdf

Barrick D.E, P.M. Lilleboe and C.C. Teague, 2005, 'Multi-station HF FMCW radar frequency sharing with GPS time modulation multiplexing', Codar Ocean Sensors, Ltd. (Los Altos, CA, US), US Patent No. 6,856,276 B2, available online at http://www.codar.com/images/about/patents/Patent_2005_GPS_granted.pdf

Bell P.S., Williams J.J., Clark S., Morris B.D. & Vila-Concejo A. 2004. 'Nested radar systems for remote coastal observations'. Journal of Coastal Research, SI 39 (Proceedings of the ICS 2004): in press.

Breivik and Allen (2008). "An Operational Search and Rescue Model for the Norwegian Sea and the North Sea." Journal of Marine Systems, 69(1/2), 14.

Crombie D.D., 1955, "Doppler spectrum of sea echo at 13.56 Mc./s", Nature vol 175 no 4459, pp 681 – 682

Gurgel K.-W. and G. Antonischki, 1997, "Remote Sensing of Surface Currents and Waves by the HF Radar WERA", in Seventh IEE Conference on Electronic Engineering in Oceanography, Proceedings, ISBN 0 85296 689 X, pp. 211...217,

Göteborgs Region, http://www.gr.to/download/18.4586cab911bbca70e89800084/Pressmeddelande+-+Inv%C3%A5nare+G%C3%B6teborgsregionen+2008-08-14.pdf, accessed 2010-05-18

HELCOM 2008, 'Report on shipping accidents in the Baltic Sea area for the year 2008', available online at: http://www.helcom.fi/stc/files/shipping/shipping_accidents_2008.pdf, Accessed at 2010-05-18

HELCOM, 2009a, 'Overview of the shipping traffic in the Baltic Sea', available online at http://www.helcom.fi/stc/files/shipping/Overview%20of%20ships%20traffic_updateApril2009.pdf Accessed 2010-05-17

HELCOM 2009b, 'Annual 2009 HELCOM report on illegal discharges observed during aerial surveillance', available online at http://www.helcom.fi/stc/files/shipping/Oilspills2009.pdf, accessed 2010-05-17

Jendro, L., 1992, "Survey of European Surface Current Radar Systems", in ESN Information Bulletin 92-05 p 207 - 217

Mourad P.D., D.R. Thompson and D.C. Vandemark, 2000, 'Extracting fine-scale wind fields from synthetic aperture radar images of the ocean surface', Johns Hopkins APL Technical Digest, vol 21 nr 1 pp 108 – 115; available online at: http://sd-www.jhuapl.edu/fermi/symposium99/articles/Mourad.pdf, accessed 2010-05-31

Munk W.H., and W.A. Nierenberg, 1969, "High frequency radar sea return and the Phillips saturation constant", Nature vol 224, p 1285

NOAA, 2007, "Data management standards for high frequency radar", Version 1.0, available online at http://www.oceandatastandards.org/index2.php?option=com_docman&task=doc_view&gid=29&Itemid=99999999 accessed 2010-10-22

Prandle D., J.C. Hargreaves, J. P. McManus, A.R.Campbell, K. Duwe, A. Lane, P. Mahnke, S. Shimwell and J. Wolf, 2000, "Tide, wave and suspended sediment modelling on an open coast — Holderness", Coastal Engineering, Volume 41, Issues 1-3, September 2000, pp 237-267

Stewart R.H., and J.W. Joy, 1974, "HF radio measurements of ocean surface currents", Deep Sea Research vol 21, pp 1039 - 1049

Wikipedia, 'Oslo', http://en.wikipedia.org/wiki/Oslo, accessed 2010-05-18

Wyatt L.R., S.P. Thompson & R.R. Burton. 1999. "Evaluation of HF radar wave measurement". Coastal Engineering, 37,259-282.

7 Appendix 1: Workshop Participant List

Name of participant	Organisation	Mail adress
Scott Glenn	Rutgers University	glenn@marine.rutgers.edu
Chad Whelan	CODAR Ocean Sensors	chad@codar.com
Anton Kjelaas	CODARNor	akjelas@online.no
Lucy Wyatt	University of Sheffield	lucywyatt@seaviewsensing.com, l.wyatt@sheffield.ac.uk
Henrik Lindh	SMHI	henrik.lindh@smhi.se
Andres Alonso-Martirena	CODAR Europe	andres@codar.com
Vincent Mariette	ACTIMAR	mariette@actimar.fr
Simone Cosoli	Istituto Nazionale di Oceanografia e Geofisica Sperimentale OGS, Trieste (ITALIA)	scosoli@ogs.trieste.it
Gorbatskiy Vladimir	Krylov Shipbuilding Research Institute, Saint Petersburg, Russial	gorbatsky@infopro.spb.su
Andreev Alexander	Krylov Shipbuilding Research Institute	gorbatsky@infopro.spb.su
Jon Albretsen	Institute of Marine Research, Norway	jon.albretsen@imr.no
Karin Borenäs	SMHI	karin.borenas@smhi.se
Ole Krarup Leth	Danish Meteorological Institute, Denmark	okl@dmi.dk
Anna Dzvonkovskaya	Hamburg University of Technology	anna.dzvonkovskaya@tu-harburg.de
Bruce Hackett	Met.no	bruce.hackett@met.no
Matthias Kniephoff	Helzel	kniephoff@helzel.com
Thomas Helzel	Helzel	Helzel@helzel.com
Dr. Christian Senet	BSH - Bundesamt Für Seeschifffahrt und Hydrographie	christian.senet@bsh.de

Jonas Ringsberg	Chalmers University of Technology	Jonas.Ringsberg@chalmers.se
Wengang Mao	Chalmers University of Technology	Wengang.Mao@chalmers.se
Zhiyuan Li	Chalmers University of Technology	Zhiyuan.Li@chalmers.se
Dr Patrik Strömberg	SMHI, Bpo	patrik.stromberg(a)smhi.se
John Howarth	National Oceanography Centre, Liverpool	mjh@pol.ac.uk
Igor Rychlik	Chalmers University of Technology	rychlik@chalmers.se
Anna Rutgersson	Uppsala University	anna.rutgersson@met.uu.se
Martin Krogager	DHI - Institut for vand & Miljø	mkh@dhigroup.com
Pia Andersson	SMHI	pia.andersson@smhi.se
Bertil Håkansson	SMHI	bertil.hakansson@smhi.se
Philip Axe	SMHI	Philip.axe@smhi.se
Örjan Bäck	SMHI	Orjan.Back@smhi.se
Cecilia Ambjörn	SMHI	cecilia.ambjorn@smhi.se
Thore Hagman	Sea Rescue Society	thore.hagman@ssrs.se
Mike Moorhead	Neptune Radar	mike@neptuneradar.com
Janette Reading	Neptune Radar	janette@neptuneradar.com
Sverker Evans	Swedish Environmental Protection Agency	sverker.evans@naturvardsverket.se
Signild Nerheim	SMHI	signild.nerheim@smhi.se
Maria Boman	Swedish Maritime Administration, Maritime Rescue Coordination Centre	maria.boman@amrcc.sjofartsverket.se

Leif Eriksson	Chalmers University of Technology	Leif.Eriksson@chalmers.se
Gisela Carvajal	Chalmers University of Technology	Gisela.Carvajal@chalmers.se

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Haven runt Sverige 1991. Rapport från SMHI, Oceanografiska Laboratoriet, inklusive PMK - utsjöprogrammet. (The conditions of the seas around Sweden. Report from the activities in 1991, including PMK - The National Swedish Programme for Monitoring of Environmental Quality Open Sea Programme.)

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Sveriges meteorologiska och hydrologiska institut
601 76 NORRKÖPING
Tel 011-495 80 00 Fax 011-495 80 01