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Realization of Underwater Acoustic Networks.

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Problem Description

Commit a survey to establish frameworks for realization of underwater acoustic sensor networks. The study will investigate possible research areas where underwater acoustic networks may be utilized and discuss conventional methods as opposed to the possibilities represented by underwater acoustic networks. In that way a realistic platform for further development of underwater acoustic networks towards specific applications may be found.

The study will also undertake the concept of underwater acoustic networks and assess its upsides and downsides when comparing it to other methods.

Assignment given: 15. January 2009
Supervisor: Jens Martin Hovem, IET

Abstract

This work contains a study of underwater acoustic networks. The concept of underwater acoustic networks has been presented with its benefits and drawbacks. An overview of the marine research areas oceanography, seismology, waterside security, marine pollution and marine biology has been made and a review of conventional methods and instrumentation committed. The research methods used today have been compared with the potential of underwater acoustic networks as a platform for maritime applications.

Underwater acoustic networks were reviewed as feasible within all areas with some restrictions. The fact that respectable data rate is best achieved for nodes deployed in a high density grid give limitations on the coverage area. Battery as an energy source limits the life span of an underwater acoustic network and makes it best suited for missions for short term monitoring, if not a recharging technology is applied. The energy restrictions also put constraint on the amount of sensing done and the temporal solution in measurements.

Underwater acoustic networks were found applicable for intrusion detection in waterside security to increase the range of current ultrasonic surveillance systems or realize distributed systems for passive diver detection. In oceanography and pollution monitoring current in situ sensors may enable underwater acoustic networks to do autonomous synoptic sampling of limited areas to measure a number of parameters, e.g. oxygen, turbidity, temperature and salinity. For seismic exploration this technology might save costs for permanent seismic installations in constant monitoring of producing oil fields. It might also aid marine biologists in habitat monitoring.

Preface

This master thesis in the subject Marine Acoustics is the final part of a Master of Science degree in Electronics at The Norwegian University of Science and Technology. The thesis has been written by Håkon Riksfjord during the spring term of 2009. The topic is Underwater Acoustic Networks and scenarios where this technology may be utilized.

I would like to extend my thanks to my supervisors Professor Jens M. Hovem and Professor Hefeng Dong for their encouragement and for involving me in shaping the assignment. Especially I am grateful to Professor Hovem for his initiative and patience. I would also like to thank Xueshan Bao and Svein Arne Frivik for answering my questions and giving me inspiration. Last but not least I would like to expresss my gratitude to Guosong Zhang for fruitful discussions and his general enthusiasm.

Trondheim, 1st of July 2009

Håkon Riksfjord

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Chapter 1

Introduction

Monitoring the aquatic environment and dynamical changes of the ocean is not an uncomplicated assignment. To preserve marine resources and obtain a sustainable development, changes occurring in the marine environment have to be monitored effectively. The threat of climate changes and increased water-born activity may have great impacts on oceanic life and ecosystems. More than 70 % of the Earths total area is covered by ocean and a rapid change in the marine environment may have great influence on terrestrial life and environment. One example is the effect of greenhouse gases and an increasing surface temperature, leading to melting of sea ice and as a result raised sea level.

Underwater acoustic networks as a platform for marine research have gained much attention the last years and a strategy for development towards potential applications is needed.

This study will have a close look at different research areas operating in the marine environment. Oceanography, seismology, waterside security, marine pollution monitoring and marine biology will be investigated to get an overview of what occupies scientists and engineers in the different disciplines. Next this work will give a short summary of conventional instrumentation and methods used in the different sciences and investigate if anything can be improved.

Then a discussion will be made whether or not underwater acoustic networks may be utilized to improve performance of current systems or represent a convenient research platform in the given science. The usage of underwater acoustic networks will be compared to current methods and its benefits and disadvantages taken into consideration.

An overview of underwater acoustic networks technology presented by earlier publications will be carried out to present the concept. This part will go through the applicable network architecture and topology, present challenges faced and mention applications proposed by other authors. It will also introduce a possible nodal design.

Chapter 2

Underwater Acoustic Networks

Underwater Acoustic Networks (UAN) is a generic term describing a network of different units communicating with acoustic transmission in marine environments. The network may consist of several different units like ocean bottom sensors, autonomous underwater vehicles (AUV) and surface vessels. Basic underwater networks are formed by creating two way acoustic links between the various units making up the network. Depending on the given architecture these links could span over longer ranges or one might have short range links similar to terrestrial local area networks (LAN). The usage of underwater networks provides an efficient and cost effective approach for ocean bottom and ocean column monitoring.

2.1 Applications

Several applications involving underwater networks are mentioned in the literature [2] [61] [41] [29].

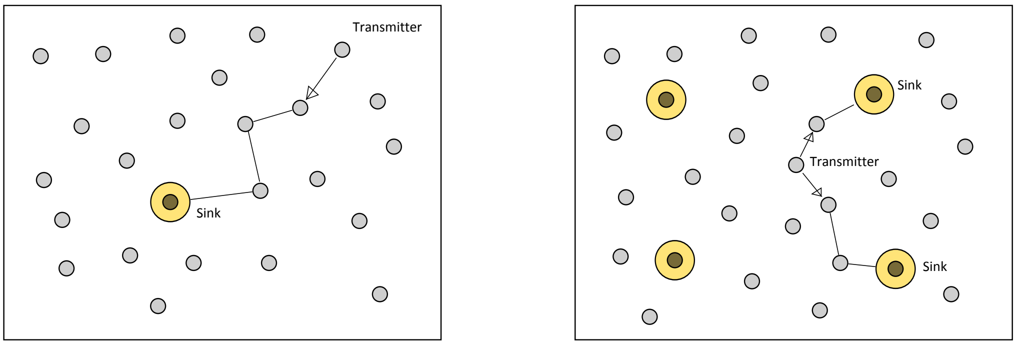
- **Ocean Sampling Networks**. Consists of both ocean bottom sensors and AUVs. Have the ability to do synoptic, cooperative adaptive sampling of the target area. Long range and full 3D coverage.
- **Environmental Monitoring**. The usage of environmental sensors in a UAN may improve the monitoring of pollution, climate changes, ocean currents and marine ecosystems.
- **Disaster prevention**. Ocean bottom sensors can record seismic activity and give important information about earthquake and tsunami probabilities in a given area.
- **Seismic exploration**. Ocean bottom sensors can be used as receivers within 4D seismic and one can avoid the time consuming and expensive process of installing permanent streamers on the seabed.
- **Tactical surveillance**. UAN alone or in connection with AUVs can give an effective monitoring of unwanted activity within a given area both for military an civilian purposes.
- **Equipment monitoring**. For short term monitoring of underwater equipment. For instance could complicated underwater installation be equipped with sensors to ensure correct deployment and failure detection.

2.2 Network Architecture and Topology

Several probable architectures are described in the literature. The advantage of having an operating network instead of several independent sensors is the possibility of real time connection with the data processing facility. This supposes the presence of one or more surface radio links within the network.

2.2.1 Topology

In [61] three topologies are mentioned: centralized, distributed and multihop.



(a) Distributed network with one underwater gateway

(b) Cluster based network with several underwater gateways

Figure 2.1: Network architecture with sensors and underwater gateways. Multihop relay paths indicated

A centralized network depends on a hub in the center of the network which distributes information from the sensors to the surface link and from the surface link to the sensors. This topology is dependent on every sensor having connection with the hub. Given the challenging marine environment this is no easy task. In addition the whole network shuts down in the case of a failure in the hub. For larger networks the presence of several hubs will increase the detection area. The hubs can be connected to the onshore control center via a surface radio link or by fiber optic cable.

In a distributed network topology the relaying of the signal is based on peer to peer connection. This topology provides point to point links between every node and eliminates the need for routing. The major disadvantage of this is interaction between nodes distributing to the same destination. A node trying to transmit to a far node might block the signal from a neighboring node, called the near-far problem. In addition to the unspecified routing approach the power consumption of having long range propagation put constraints on the lifetime of the network.

A multihop approach might be the key solution for energy savings in larger networks. In a multihop topology a node establishes connection only to its neighboring nodes. The link with the best connection will be chosen as the transmission path. Through multiple hops from node to node message from node number i to the underwater gateway/sink is carried out, Figure 2.1. [61] determines the energy consume for direct transmission and multihop strategy. It shows a decreasing energy consume with increasing number of hops. Another advantage is the robustness to system failure, if a node shuts down sensors relaying via that node select other transmission routes instead. The drawback is the trade off between energy consumes and packet delay. When the information needs to be transmitted several times it will induce a substantial time delay. Multihop peer to peer topology also requires sophisticated routing protocols.

[2] proposes a network architecture consisting of sensor nodes and a number of underwater gateways, Figure 2.3. The topology is cluster based and sensors establish connection through multiple hops with the closest sink. An option is to make it possible for nodes to enable connection with several underwater gateways, and then increase the possibility of successful transmission.

2.2.2 Ad Hoc Networks

The fundamental aspect of an ad hoc network is the lack of infrastructure. The backbone is made up of sophisticated control algorithms and the nodes make up the network for themselves. No infrastructure makes deployment both rapid, easy and cost efficient, additionally the network can be formed from whatever nodes available, which could extend the lifetime of the network[27].

The adaptive nature and high robustness makes ad hoc networks useful for many applications. In the harsh marine environment, with high probability of failure and considerable range and power limitations, ad hoc networks represent the best solution for network system.

Packets are routed to their final destination through multiple hops, for the event of UANs the final position would be the underwater gateway. The routing path is decided in accordance with the particular routing protocol. [61] proposes a weighting of best hop made by each node based on signal to noise ratio (SNR). During the initialization process every sensor rank their neighbors based on the quality of the communication link. The ranking is sent to the underwater gateway that sets up a routing tree.

2.3 Localization

The need for robust localization algorithms in underwater network technology is evident. Several publications addresses the need for accurate positioning in UANs [41] [29]. In terrestrial networks the position of a node can be resolved with the use of Global Positioning System (GPS), but since electromagnetic waves propagates poorly in water other localization methods are necessary.

Current commercial acoustic positioning systems usually presuppose the existence of an infrastructure. This opposes the usage of a centralized infrastructure and thereby limits the use of current positioning systems. [11] presents a survey on different approaches on localization in underwater acoustic networks.

2.4 Node Design

For UANs to be commercially available the cost of network nodes has to be affordable. [41] and [1] proposes unit designs for such networks including an acoustic modem, sensing unit, floating device for recycling purposes, battery and processing interface. As for terrestrial

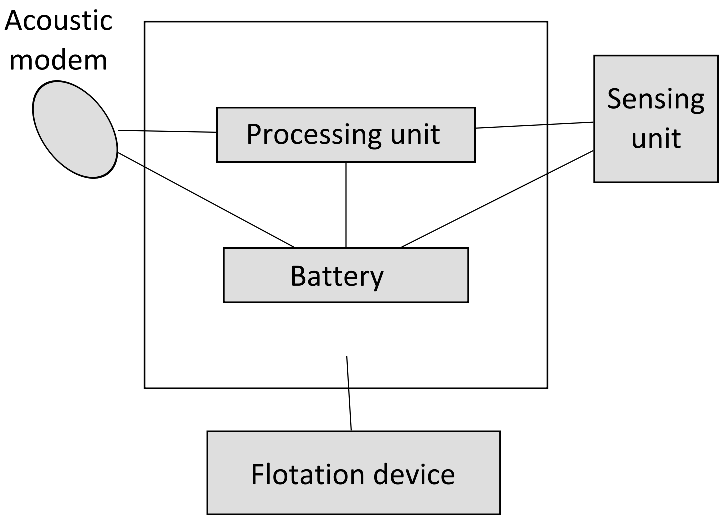


Figure 2.2: Proposed underwater sensor node with components

networks the price per node should be in the area of hundreds or thousands of US dollars for the system to be cost effective.

Another design goal is for the sensor node to be multipurpose, which means that the user has the ability to install different sensing units for different missions. The size is very much dependent on how far it's suppose to transmit, the battery lifetime and the amount of processing done locally. For the sensor to be manageable and inexpensive it should not be much bigger than sensors used in terrestrial networks. The sensor node has to be highly reliable and robust to be able to withstand heavy corrosion and fouling.

Figure 2.2 show a possible layout for a node design. The central part of the node consists of a battery and the processing unit, with a sensing unit, acoustic modem and flotation device as external interchangeable components. The processing unit is the mind of the sensor node and holds cpu, memory, power control and all protocols needed for the node to function properly.

2.5 Restrictions on Communication

The most addressed limitation on underwater communication is the available bandwidth. Strong frequency dependent absorption put constraints on the available bandwidth, thus limiting the data rate. [2] have made a table of typical bandwidth for a given range to illustrate the difficulty of long range high speed transmission, listed in Table 2.1.

Multipath propagation is another large contributer to degradation of the acoustic signal. Multipath is the source of time spread and fading of the signal. Time spread is seen as the spreading of the amplitude caused by echo components arriving at different times at the receiver. This can be the origin of intersymbol interference (ISI) in which a symbol interferes with subsequent symbols. ISI is a form of distortion, thus making communication less reliable.

Ghosting phenomena in television broadcasting is a form of time spread where the echo arriving after the direct advent duplicates the image. Fading is another word for signal interference. Interference between signals with difference in travel time, phase and attenuation

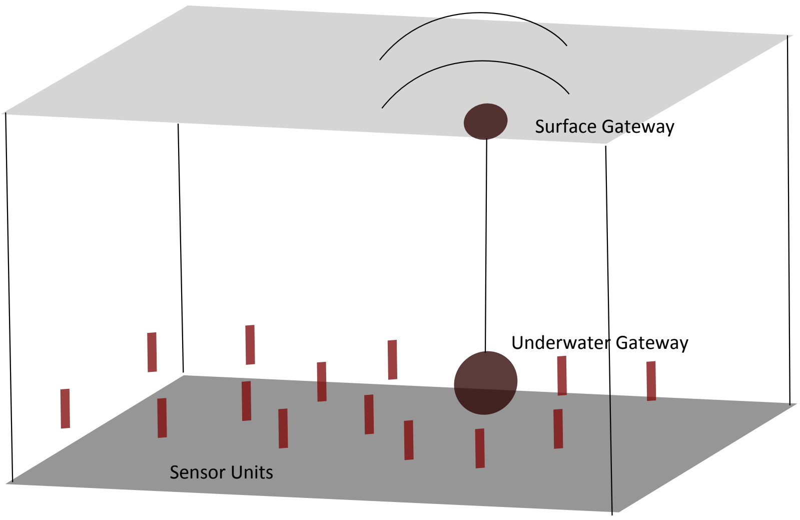


Figure 2.3: Sketch of possible network layout with randomly spread nodes connected to one underwater gateway. The underwater gateway has connection with a surface gateway through cable. The surface gateway is equipped with a radio link to maintain connection with the onshore control center

Table 2.1: Typical bandwidth for certain ranges of underwater communication

	Range$[km]$	**Bandwidth**$[kHz]$
Very Long	1000	< 1
Long	$10 - 100$	$2 - 5$
Medium	$1 - 10$	≈ 10
Short	$0.1 - 1$	20-50
Very Short	< 0.1	> 100

causes fading. Strong destructive interference is known as *deep fade* and a channel can be slow or fast fading depending on the ratio at which the magnitude and phase, influenced by the channel on the signal, changes [27]. The degree of multipath effect on the communication channel is much dependent on the channel geometry. Multipath propagation is a bigger problem in a shallow water channel than in deep water channels, and vertical sound channels may be multipath free in contrast to horizontal channels. For deep water channels the absorption may work to the channels advantage. For a source and receiver close to the bottom the travel path for surface reflections is much larger than the direct arrival, making the amplitude of the surface reflection insignificant as compared with the direct.

Spreading of the signal is another obstacle. For uniform distribution geometrical spreading increases the transmission loss as a consequence of the *inverse square law*. Refraction generates shadow zones that would make certain areas unsuitable for transmission. Because of time variations shadow zones could expand over time and infer with communication abilities [31].

The speed of sound in water is five orders of magnitude lower than the speed of electromagnetic waves in air. Making transmission speed in underwater communication much lower than in Radio Frequency (RF) terrestrial network. Propagation delay complicates the idea of real time connection between nodes in the network. In combination with limited bandwidth the bit rate of underwater communication becomes severely restricted.

Ambient, man made and thermal noise in combination with considerable transmission loss reduces the signal to noise ratio(SNR) with increasing range.

2.6 Energy Limitations

Sensor networks in general are made up of independent nodes relying on battery power to execute their monitoring duties and communicate. Methods to prolong lifetime of sensor networks are a great concern for scientists working with terrestrial sensor networks as well as underwater sensor networks. Optimization of energy dissipation and consume are related to all network layers and will not be undertaken in great detail in this study. A study on lifetime estimation and battery optimization for underwater networks is presented in [37].

UAN as opposed to terrestrial networks do not have the benefit of solar energy for recharging purposes. In addition to this UAN distributed in subsurface terrain require large resources for recharging or replacement of battery packs. Some ideas to extend the lifetime of UAN may be the utilization of AUVs with solar panels drifting between nodes transferring energy, and recharging themselves at the surface, so called energy replenishment. Scientists within network technology is also occupied with energy harvesting by e.g. transforming mechanical vibrations into energy [68].

For the purpose of this study it's sufficient to acknowledge that the energy capacity is very limited and applications for UAN should adapt to this fact by not using energy demanding sensing equipment, keep the temporal sampling at a minimum and limit local data processing.

Chapter 3

Oceanography

3.1 Introduction

Oceanography as a discipline refers to the study of the oceans. As a relatively new science the study of oceanography began in the late 20th century and was pioneered by scientists like Sir Wyville Thomson and Fridtjof Nansen. Oceanography is conveniently divided in terms of the basic sciences into physical oceanography, biological oceanography, chemical oceanography and geological oceanography. Scientists of oceanography usually devote themselves to one of the categories, but the different areas are closely related. The basic goal of oceanographic studies is to gain an understanding of the world's oceans and hopefully be able to predict changes.

Physical oceanographers are occupied with the study of temperature, density, hydrostatic pressure and the behavioral of light and sound in ocean environments. From all the physical properties of the sea, temperature is the most important one. Water has, after ammonia, the greatest heat capacity of all liquids, meaning that it warms up and cools down very slowly. Pressure is fairly predictable and increases with depth. Together with temperature and salinity the hydrostatic pressure decides the speed of sound in seawater.

Biological oceanography or marine biology is seen as the study of ocean life and ecosystems. This will be treated in Chapter 7.

Chemical oceanography involves the study of chemical processes within the ocean. Scientists within this field are devoted to investigate the different substances which make up the salinity of seawater. Seawater is not just river water added salt; the chemical processes defining the total salinity of a sample are numerous. 99.9 % of the dissolved inorganic components in seawater are made up of only 11 ions, the rest being trace constituents such as nitrogen and phosphorous. This is fairly strange considering all the different minerals and sediments found in the sea. Chemists in oceanography are seeking to isolate the processes taking part in deciding the salinity at different geographical regions. The North Atlantic Ocean contains the highest concentration of salinity, mostly owed to the forming of sea ice. Evaporation is another effect increasing salinity in regions with higher surface temperatures. The salinity is also more constant in deep water than at the surface. Chemists also study the constituents necessary for life in the sea and their role in marine ecosystems. With increasing ocean pollution by anthropogenic activity chemical analysis of water to monitor and predict polluting contaminants is growing in importance. Marine pollution and monitoring strategies will be treated in Chapter 6.

Geological oceanography concentrates on the study of sediments and bathymetry of the ocean bottom and movement of continents. It is closely related to seismology and the techniques used in exploration seismology presented in Chapter 4.

Another thing attracting the interest of scientists is the disseverment of carbon dioxide in the sea. A lot of the carbon dioxide released by the burning of fossil fuels ends up in the sea where it reacts with water molecules to form carbon acid. The ocean actually contains 60 times as much carbon dioxide as the atmosphere. The absorption of carbon dioxide is greatest in warmer seasons when the carbon dioxide is less soluble, with the opposite taking place during cold periods. Monitoring of aquatic CO_2 level is briefly presented in Chapter 6.

The superior objective of most ocean property measurements is to gain an understanding of the great ocean movements, dynamical oceanography. To make in situ measurements with current meters at all relevant positions all over the ocean is both time consuming and expensive. Instead one may apply Lagrangian method, which describes the movement of one fluid particle as a function of time. Still, the approximations should be verified by surveys to measure temperature, salinity and density. The distribution of these factors tells us a lot about the changes occurring within the ocean as a result of atmospheric influence.

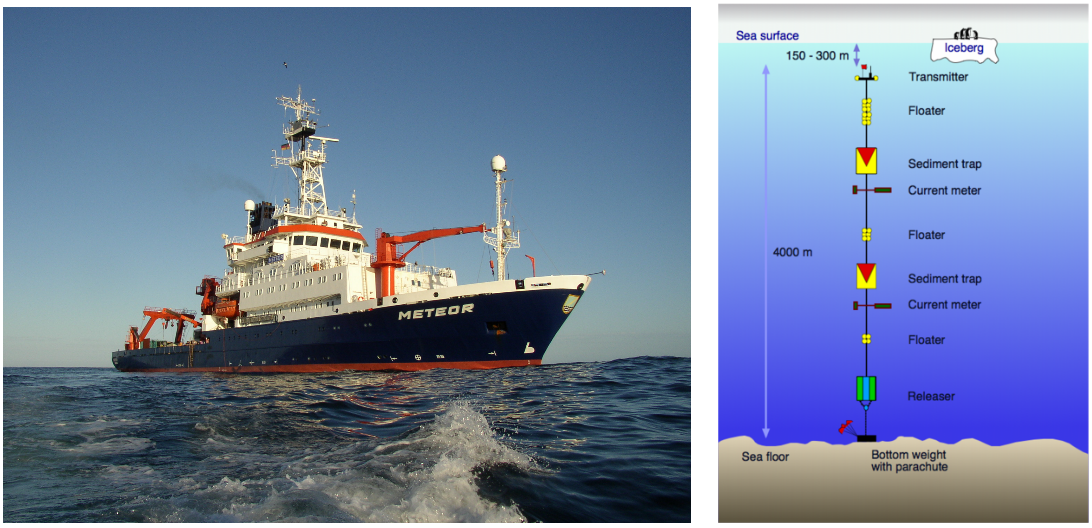
General information about oceanography as a dicipline is found in [34].

3.2 Instruments and Methods

The most important tool for oceanographic research is the research vessel. These types of ship are usually custom-built to serve the purpose of oceanographic research. They may hold onboard laboratories for biological, chemical and geological studies and carries scientists all over the world to perform oceanographic studies. A good example of a research vessel is the R/V Meteor managed by The Operations Control Office of the University of Hamburg. The vessel is owned by Ministry of Research and Technology in Germany and constantly holds scientists from several countries [8]. The Meteor is a large vessel compared to standard research vessels with its 97.5 m compared to standard 50-80 m. It's depicted in Figure 3.1a.

The research vessel carries tool for oceanic measurements. Multibeam echo sounders are used for bathymetric measurements as the ship moves, when the vessel holds at a position to carry out measurements a Global Positioning System (GPS) sensor logs its position. It's important to keep the ship from drifting while the measurements are done and modern vessels have a dynamic positioning system that controls the thrusters to hold it at the exact same spot during testing.

Research vessels used to be the only way to obtain information about the oceans, but the advent of deep sea moorings, autonomous vehicles, drifters and satellites have reduced their importance. Still, some measurements may only be carried out by research vessels. Within all degrees of oceanography the existence of nutrients and tracers as well as the composition of seawater at different locations is valuable information. For these measurements water samples has to be obtained and analyzed at a laboratory. The early methods of taking water samples was with a group of Nansen bottles attached at appropriate intervals along a line lowered into the water. The Nansen bottle, developed by Fritjof Nansen, is now out of production and has been replaced by the modified Niskin bottle. The principle is still the same. When the bottles reach the desired depth a weight is dropped along the wire triggering the closing mechanism on the first bottle. When this closes it releases a new weight to trigger the next bottle and so on. That system have many places been replaced by multiple sample devices



(a) R/V Meteor [21].

(b) Example of deep sea mooring [56].

Figure 3.1

which are triggered at certain depths by remote control, the sample bottles are still of the Niskin type.

For continuous monitoring of a specific area over time moorings are a valuable tool. A typical design is an anchor, wire or rope to which the instruments are attached and buoyancy to keep it as vertical as possible. Moorings are used for both deep sea and shallow waters, with varying designs. The most used design is the deep sea mooring used at water depths down to several thousand meters. For this design the top buoyancy is kept about 50-300 meters below the surface to avoid damage from ship traffic and the effects of surface waves. Instrumentation is mounted at desired intervals along the rope or wire together with small float elements to compensate for the weight of the instruments. To gather the moorings after a mission an acoustic release is applied above the anchor point, when triggered the mooring is unfixed from the anchor and floats to the surface. A typical mooring design is depicted in Figure 3.1b

For use in shallow waters and in missions where meteorological data is gathered a surface buoy may be attached. The surface buoy holds all the instrumentation for meteorological research and may also be equipped with a radio link to transmit data. In shallow waters a design called u-type mooring is often used. This holds two moorings, a surface marker and a separate mooring with a subsurface float that contains the instruments. The idea is for the instruments to move with the current.

The advent of satellite technology opened up for remote sensing from space. To obtain information about ocean surface properties satellites equipped with a wide span of sensing tools have the ability to do synoptic research of a fairly large water mass in a short time frame. To measure sea surface temperature radiometers in the infrared spectrum may be used. This includes the Advanced Very High Resolution Radiometer (AVHRR), which measures surface temperature close to an accuracy of 0.2 °C. A multi spectral radiometer operating in a wide selection of frequency bands is able to measure ice coverage, chlorophyll content, sediment load and particulate matter. In addition a SAR (Synthetic Aperture Radar) may be used to measure dynamic properties, such as internal waves affecting surface water and the effect of bottom tomography on currents and waves. Satellites may also measure sea level at an accuracy of 5 cm with modern altimeters. The vast coverage provided by satellites supplies very useful information about tidal motion and increase in total sea level, important characteristics in climate research.

For the purpose of retrieving geological samples of the sea bed submersible vehicles are often used. In the beginning of geological oceanography scientists used specially designed sieves to obtain information about sediments in the sea bed, a time consuming and not very accurate method. Employment of remote operated vehicles or manned submersibles simplifies the process of obtaining samples from the sea bed or deep sea ecosystems. Another category of submersibles is autonomous vehicles or towed vehicles. When a research vessel is travelling a towed vehicle may retrieve information about surface water, such as conductivity, temperature and depth (CTD) and some chemical properties. Towed vehicles are a good instrument for measurements that requires high spatial resolution, but may also be replaced by autonomous vehicles.

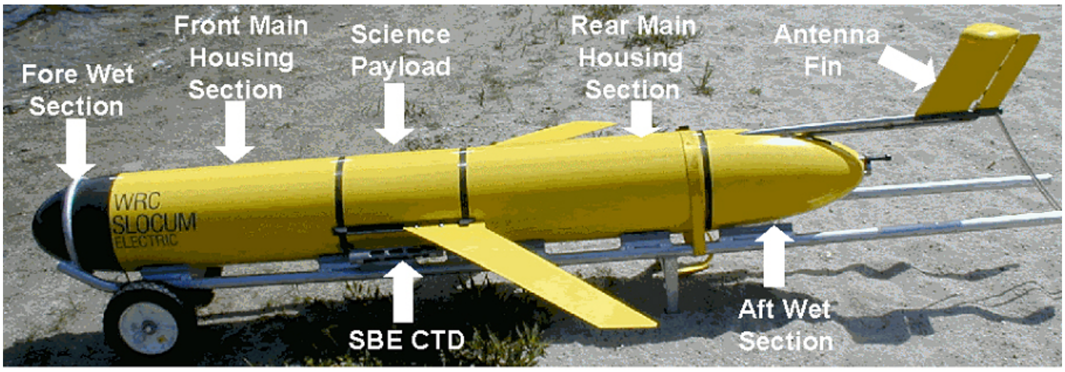


Figure 3.2: Autonomous Underwater Vehicle [78].

Autonomous Underwater Vehicles (AUV) are unmanned submersibles travelling along preprogrammed routes recording data at specific waypoints or on the go. They may be equipped with solar panels and radio link alongside with advanced instruments. When the AUV surface and holds at a position it may recharge its batteries and transmit the data it has recorded since the last stop. AUVs have the ability to replace the role of research vessels for oceanographic measurements. Figure 3.2 show a typical AUV for scientific use.

Another platform much used for constant monitoring is the drifter. Drifters take on many shapes and can float on the surface and do meteorological measurements as well as surface water measurements. The common quality of all drifters, or floats as they are sometimes referred to, is that they follow the currents at their location. Some drifters have the ability to sink and rise at given intervals, transmitting data when surfaced and carry out measurements when submerged. Other subsurface drifters are equipped with acoustical modems and transmit their data acoustically. The latest most ambitious project is the Argo drifter. The Argo programme is scheduled to have 3000 drifters localized all over the worlds oceans constantly measuring CTD down to depths of 2000 meters. After deployment an Argo drifter submerge to a preprogrammed depth while measuring CTD and drifts with the current for a given time interval. When scheduled to surface it measures CTD while surfacing and transmits the data via satellite at the surface. The Argo cycle is shown in Figure 3.3. Surfaced it is also possible to reprogram the drifter. The measurements are made public just hours after they are received by the base station. More about Argo on the project homepage [62].

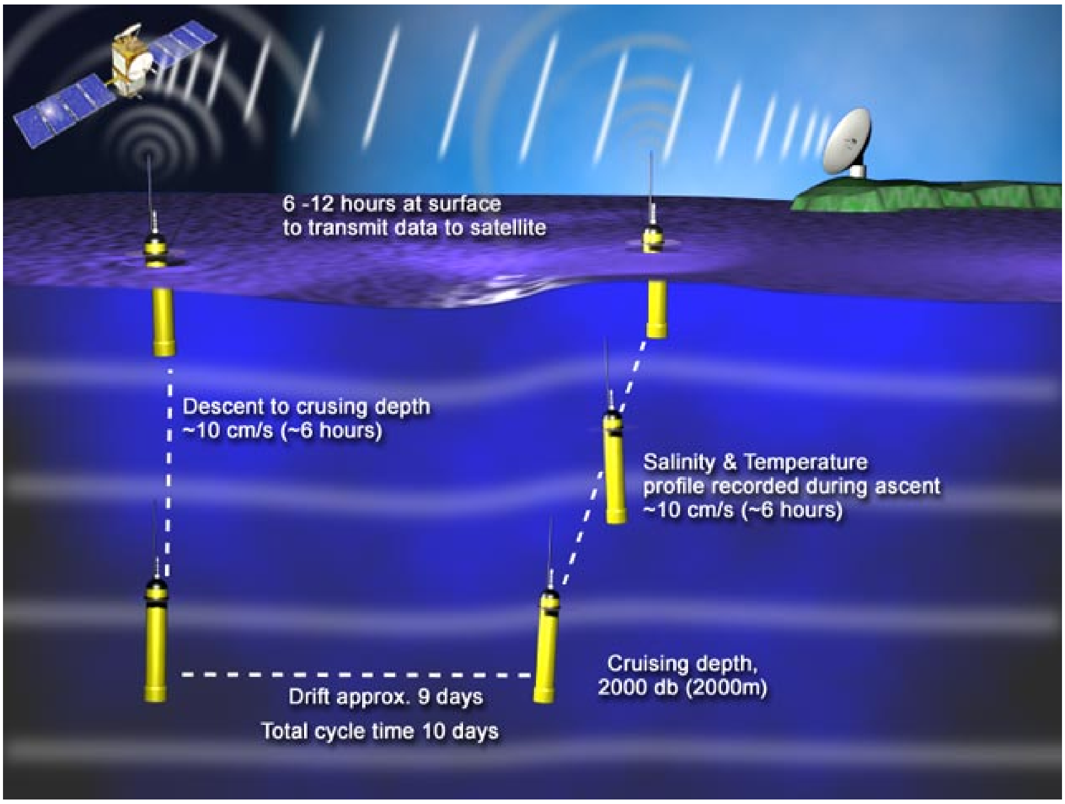


Figure 3.3: Cycle of the Argo drifter [62].

The drawback about CTD measuring devices is that they should be calibrated regularly because the calibration changes with time. They are often used with reversing thermometers and water samples to ensure correct measurements. Reversed thermometers are a type of mercury thermometers specially designed for oceanographic use. When the temperature can't be read at the spot the measurement has to be locked to prevent it from being influenced by the warmer surface water. This is done by inverting the thermometer at the measuring depth; as a result a short side-arm above the bulb in the capillary of the thermometer breaks and stops the mercury flow. The exact temperature, down to an accuracy of 0.01 K, may be read at deck. Modern research vessels usually employ a rig containing multiple Niskin bottles with reversing thermometers and a CTD measuring device.

To gain a complete understanding of oceanic changes, dynamic properties are utmost important. The composition of currents, tidal motion and surface waves yields the total movement of the ocean. Several techniques may be used and varies from near shore use to offshore use.

To measure currents current meters may be applied. There exist four different classes of current meters. The common denominator is that they measure the strength and direction of the current at the given position and are divided into electromagnetic current meters, mechanical current meters, acoustical current meters and acoustic Doppler current profilers (ADCP). The different current measurement instruments are listed below.

- Mechanical current meters rely on a propeller to measure current speed and a vane to measure direction. Some are constructed with two propellers arranged at 90° and resolve current vectors without the use of a vane. They have a low time resolution and are unfitting in surface waters. Widely used in deeper waters because they are easy to use, robust and relatively cheap.

- Electromagnetic current meters use the conductivity in sea water measuring the water flow through a magnetic field. With two sets of measurement vectors arranged correctly at each other the speed and direction of the current is determined.

- Acoustic current meters use compression waves to measure current speed and direction. A transmitter placed between two receivers emits an acoustic pulse and the difference in arrival time at the two receivers make up the currents direction and speed. Acoustic current meters have a high sampling rate and may thus be used for surface wave measurements as well as current measurements.

- Acoustic Doppler current profilers use reflection of acoustic waves from moving particles in the ocean. This enables the device to make measurements at different depth intervals based on travel time and consequently construct a current profile instead of a recording at a certain point. ADCPs may be installed in moorings or on ships for continuous measurements.

Surface waves may be measured by current meters at shallow depths, wave riders or a stilling well gauge. When measuring surface waves, information about wave period, wave height and wave direction is retrieved. A wave rider is connected to a mooring and may be fitted with an accelerometer in three orthogonal directions which registers period, height and bearing of waves or just one accelerometer to measure height and period. The stilling well gauge measures mostly wave height and to some extent the period. It consists of a water filled cylinder with a float at the surface connected to a wire and a tube where surface waves may pass into the cylinder, thus increasing the water level in the cylinder measured by an accelerometer in the wire. By measuring the varying water level in the cylinder height and period may be established.

A more advanced type of stilling well gauges is often used to measure tidal movements. They have a slightly narrower tube, functioning as a low pass filter suppressing surface waves. Since tidal waves have known period it's only necessary to measure the actual height of the tidal change. Another way of doing this is by a pressure gauge, fixed at the bottom. The pressure gauge measures the amount of water above it given by the hydrostatic pressure. The information is stored in the device until it's retrieved. Pressure gauges may also be applied for tsunami warning systems detecting giant wave formations.

Information about instruments and methods within oceanography has been found in [59], [77], [73] and [56].

3.3 Implementation of Underwater Acoustic Networks

With the swift temporal and spatial fluctuations in properties of the world's oceans new measurement techniques are called for to increase resolution in oceanographic measurements. An increase of todays conventional methods for oceanic sampling would be both time consuming and cost ineffective and demand large amounts of resources. The threat of climate changes caused by greenhouse gases is already starting to show with changing ocean temperatures and currents, and prediction of these effects demands an increase in synoptic sampling of oceanic properties. Autonomous Ocean Sampling Networks (AOSN) with in situ sensors may be utilized to do rapid environmental assessment and increase the resolution of oceanographic measurements in time and space [81].

AOSNs may be realized by many different applications, with varying cost and time consume. The development of AUVs for scientific use has made these applicable for adaptive sampling of vast areas in a fairly short timeframe. AUVs may be equipped with a long range of in situ sensors and passive sampling devices, giving them a strong position as a convenient platform [13], [70], [85]. Another advantage with AUVs are the potential to sample e.g. oxygen, CTD and current properties in a three dimensional space. The clear disadvantages with AUVs are the fact that they may malfunction and be lost during a mission, something goes wrong and the data obtained in between surface rests is lost, rather expensive, even though technology is improving, and requires a fairly large amount of manpower for deployment/retrievement, monitoring and service.

The Argo project show a way of using drifters for monitoring of large water masses and are receiving good reviews. Drifters deployed by many regional observatories are relaying data towards a central data acquisition centre and a total image of global dynamic properties may be acquired in almost real time. The drawback is clearly the unpredictable sampling points, given that the drifter is following the current with alternating speed and surfacing only at certain time intervals. In this way the drifter is a good instrument for continuous monitoring of large area, but unsuited for high resolution sampling of a specific region.

Moorings represent another platform for continuous monitoring of a water body. They are reliable, fairly low cost and may be deployed in dense or low density grid configurations. The fact that they have the ability to carry a long range of instrumentation and sample in three dimensions, while in a grid structure, is overshadowed by the fact that they are costly to deploy and can't be monitored. At least for subsurface moorings the data may not be analyzed until the mooring is recovered and a malfunction could make the mission unsuccessful since all of the stored data may be lost. A way around this predicament is by meteorological buys on the surface relaying data in real time or by cabled subsea ocean observatories with a central infrastructure, and moorings arranged in a sensor network connected to the backbone [32], [33]. Ocean observatories using cabled nodes, offshore installations, ROVs and gliders represent a rather good approach for monitoring purposes, but are a very expensive alternative. The cost of instrumentation, installation, maintenance and information gathering is making this alternative a high-end solution not applicable for cost effective research. The alternative of using gliders to relay information is proposed in [33], introducing the use of acoustic communication and saving the trouble and cost of using cables over long distances.

UAN employing low cost nodes represent a reasonable way of achieving a high spatial and temporal sampling of limited areas, with restricted costs. It's to expect that these kinds of network should take into use generic sensors with limited size and consequently not a large battery pack to achieve easy deployment strategies by airplane or fast moving vessels.

The limited battery and general complexity of acoustic communication would then encourage a dense deployment with an internode distance below 3 km and does not allow it to be interchangeable with ocean observatories with a node spacing of maybe 100 km. This approach with 100 nodes and 3 km node spacing would be able to cover an area of approximately 900 km^2 with uniform distribution. The use of UAN presupposes good localization algorithms to get the necessary geographical metadata required in oceanographic measurements. The maybe greatest advantage of UAN is the ability for nearly real time monitoring by acoustic communication links, making them far more reliable than moorings.

The limited lifetime and the restricted coverage of an UAN does not make it as good as other platforms in continuous monitoring of immense areas with few sampling points. Of course with a large amount of nodes the coverage may be extended, but this would again complicate deployment and increase instrumental costs. The limited battery life does also put constraints on the sensing equipment put on one node. Increased amount of equipment means increased battery consume and decreased network lifetime, also limiting use of power consuming measurement tools such as ADCPs. UAN used for oceanographic measurements is then perfect for use in missons where a limited region where rapid changes are occurring is monitored over a limited time span. UAN nodes may hold equipment for measurement of dissolved oxygen, CTD and current properties, dependent on the power required to operate the equipments.

Chapter 4

Seismology

4.1 Introduction

Seismology is the study of earthquakes and elastic waves in the earth. It is a branch of geophysics dedicated to studying seismic sources such as volcanoes, tectonic and earthquakes as well as the physical properties of the earth. If we want to look into the Earth's interior, measurement of seismic waves is the most accurate and preferred method. Scientists often use artificial sources such as explosions and study reflected and refracted waves at certain areas to picture the geological structure, e.g. in search of hydrocarbons.

The branches of seismology may be summarized accordingly:

- Earthquake monitoring and analysis.
- The study of the Earth's structure and physical properties.
- Usage of artificial sources to obtain information about sedimentary basins in the search for hydrocarbons and minerals, and measurement of ice thickness in sea ice and glaciers.
- Shallow surveys for hydrology and construction purposes.
- Theoretical seismology and data processing.

The early research in seismology was driven by the study of earthquakes, which led to the realization that transmission of waves occurred through the Earth, founded by such as Hooke in 1668. In the 19th century mathematicians developed the theory of elastic waves in a solid body, Poisson proved the existence of two types of body waves, shear waves and compression waves, and Rayleigh introduced the surface waves. By the end of the 19th century seismographs had been put into use and the study of seismographic records form great earthquakes led to the discovery of faulting as the main reason of earthquakes and gave evidence of the Earth's core.

During the 20th century more accurate seismographs and research on seismic travel-times drove the development of a distributed network of seismographs. During the cold war the need to study nuclear explosions financed the development of more sensitive seismographs and led to the establishment of the Worldwide Standard Seismograph Network, which became important to accurately study fault motion and develop the theory of plate tectonics. During this period the first seismic surveys at sea was carried out to explore the oceanic crust and gain a more complete understanding of the lithosphere. Through the study of reflection and refraction surveys and surface wave dispersion a complete model of mantel and crust structure could be made. And computer technology enabled the construction of total Earth models.

Also in the 20th century military research on ground waves and the advent of tomography pioneered exploration seismology. Scientists measured seismic velocities and studied travel times in surveys with artificial sources to create maps of geological structures. The common technique is the reflection method where near vertical reflections are measured with a distributed net of seismometers or geophones. Like seismometers geophones record the movement of the ground as an effect of seismic waves, and convert the movement into voltage. In surveys at sea hydrophones are most commonly used, they are placed in long cables named streamers dtowed behind the survey vessel and converts pressure into voltage. Another possibility in marine seismic surveys is to drag streamers along the seabed with both geophones and hydrophones to record shear waves as well as pressure waves, so called ocean bottom seismic.

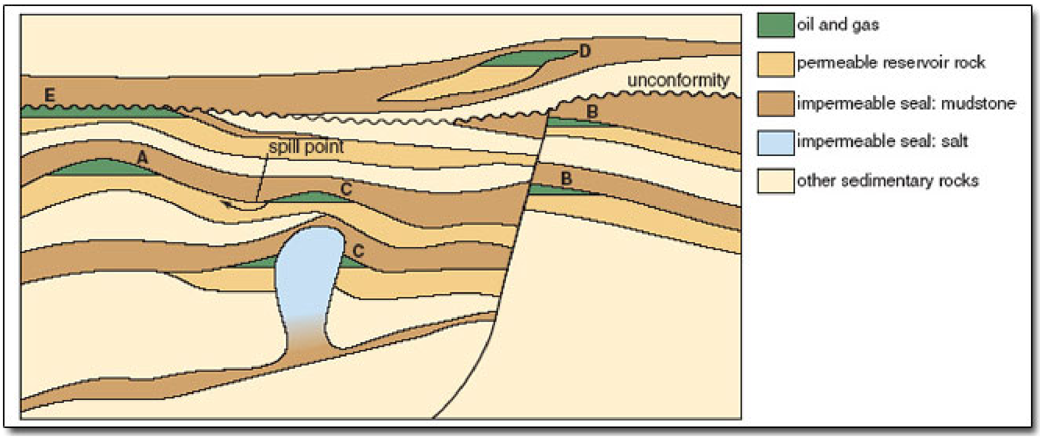


Figure 4.1: Animation example of a seismic section [79]

In addition to the reflection method one may measure refracted waves bent back from deep layers. In refraction surveys the geophones are placed at a longer distance from the source and the method give a bit more accurate velocity information than reflection surveys. In both methods the recorded data are processed to make two dimensional or three dimensional seismic sections; a seismic section contains information about the thickness and physical properties of the sediment layers. Matched with lab measurements of expected sediments like sand stone or lime stone this may give a very accurate geological map for the search of hydrocarbons and minerals. Figure 4.1 shows an animated example of a seismic section.

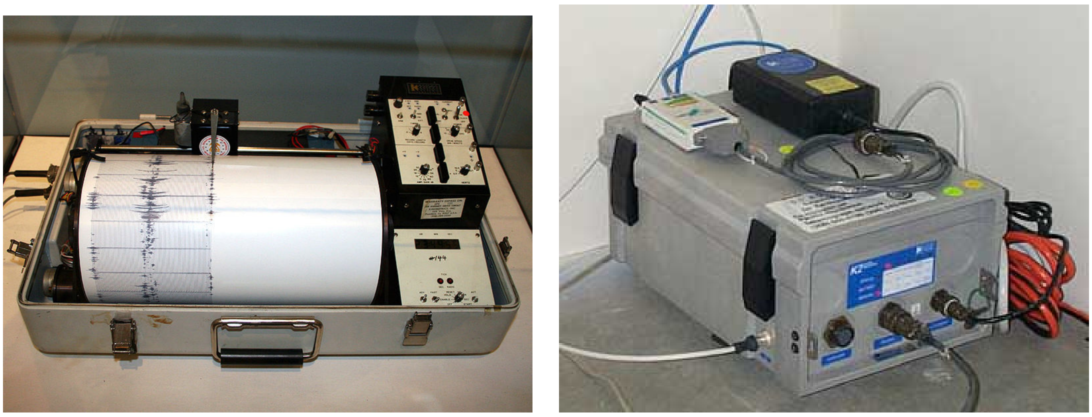
General information about seismology is found in [17]

4.2 Instruments and Methods

4.2.1 Earthquake Measurments

In Earth science the seismograph is as important as the telescope in astronomy [17]. The seismograph is a tool to measure earth movement and hence the spread of elastic waves. The resolution spans from one hundredth to a few hundred hertz depending on the range of the instrument. With the ability to record waves with a wavelength of thousands of meters seismographs can detect the presence and magnitude of earthquakes or other sources on the other side of the globe, but with very little accuracy. Broadband seismographs introduced in the last half of the 20th century consequently made the predictions of epicenters more reliable.

The basic concept of a seismograph is to record ground motion relative to a stationary point above the ground. In early instruments ground movement was recorded by a pendulum tracing in sand, on smoked glass or on paper. As technology developed the damped horizontal pendulum proved to be more accurate. This design includes a heavy weight mounted on the point of a long triangle hinged at its vertical edge. When the ground is moving, the weight stays motionless and the gate on the hinge is swinging. The oscillation of the pendulum may be adjusted and it obtains very low frequencies.



(a) Analog Seismometer.

(b) Digital Seismometer.

Figure 4.2: [4]

The ideal seismograph will convert relative ground motion to electrical current. In modern instruments this is done by either a vertical pendulum that generates electrical current by movement of two capacitor plates or a mass connected to a spring. In the latter, often referred to as inertial seismometers, movement of the casing will induce current in coils attached to the mass caused by magnets surrounding them. Another way of measuring the relative motion between the casing and the mass is to apply an electronic feedback loop to keep the mass in equilibrium. The electrostatic force used to keep the mass motionless is the output of the seismograph and is recorded digitally. Examples of an analog and a digital seismograph is shown in Figure 4.2.

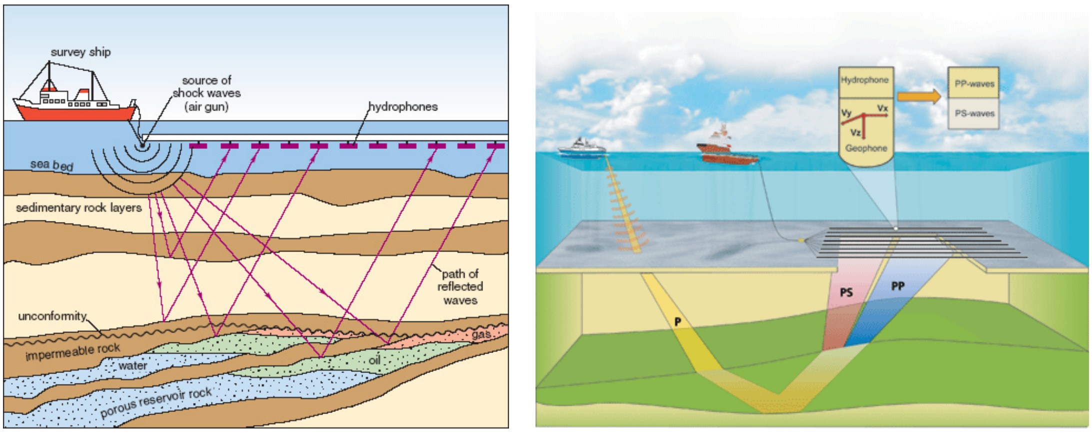
State of the art seismographs use electronic sensors, amplifiers and filters to obtain a very high resolution and broadband spectrum. They are commonly divided into classes of sensitivity and frequency as geophones with sensitivity of hundreds of V/m, geological seismographs with sensitivity in the area of 1500 V/m and teleseismographs with sensitivity of 20000 V/m. Related to frequency they are further divided into short period, long period and broadband.

A way of precisely deciding the location of any source in three dimensions is to employ interconnected seismographs spaced in an array. Much like the methods used in exploration seismology, but with a much larger spacing interval. To gain a complete picture of the Earth's interior scientists early developed a worldwide network of seismographs. At first in the

1960s the World Wide Seismic Network (WWSN) helped scientists cooperate in imaging the Earths deeper layers, supplied by the US National Seismic Network with a bit more advanced instruments and better coverage on the American continent. During the last decades the WWSN has been replaced by the Global Digital Seismograph Network (GDSN), increasing the sensitivity, frequency range and coverage. In addition, experiments with subsea seismographs is currently looking to increase the spatial resolution of seismic recordings [66].

4.2.2 Seismic Exploration

Methods and instrumentation in seismic exploration differ from terrestrial surveys to marine surveys, both related to applied sources and detectors. About fifty percent of terrestrial surveys carried out globally use explosive sources, the rest use vibrating sources (Vibroseis). Explosive sources are quite simply charges of ammonium nitrate or similar explosives placed in shallow shot-holes and triggered electronically. They emit a short pulse with an almost flat frequency spectrum and are regarded as producing best results. The Vibroseis method is a very different approach and consists of a vibrating element mounted on a specifically designed truck. To launch a shot the truck is lifted by an enormous pad such that the pad is the only connection to the ground, then on-board hydraulic pumps or electronic vibrators sets the pad in motion. Usually it vibrates for about 7 - 20 seconds doing a frequency sweep from about 15 - 90 Hz. The Vibroseis method saves money from consume and logistics regarding explosives and is usually preferred in easy terrain.



(a) Conventional marine survey [79]. (b) Ocean bottom seismic survey with streamers [72].

Figure 4.3

In terrestrial surveys the detecting is done by simple accelerometers grouped together to reduce noise. The accelerometers, or geophones, may be oriented along one, two or three axis. The common instrumentation today is the three component geophone with accelerometers in the vertical direction, horizontal north - south direction and horizontal east - west direction. In that way it detects both vertically and horizontally polarized shear waves. Geophones are also employed in marine surveys, so called ocean bottom seismic where streamers are towed along the seabed, buried in the seabed for long term monitoring or distributed through Ocean Bottom Nodes (OBN).

Conventional marine surveys started out with several experimental sources like TNT and imploding light bulbs, which proved impractical and hazardous. Explosives may still be used despite the fact that they represent a large threat to environment and safety. Explosives are still banned in some areas and limited to use in daylight, which make them very expensive and rather unpopular. Other possible sources in marine seismic surveys include a water jet type of source called *water gun*, a source named *Vaporchoc* which uses a steam bubble and a high energy source called *Sparker* used in shallow surveys with good resolution but many multiples.

The common source in marine surveys though is the *air gun*, which utilize a chamber of compressed air to obtain a short low frequency pulse. Air guns are towed behind the survey vessel in front of the recording streamers and fires constantly at a certain rate. The source array usually contains air guns of different size to obtain different frequencies, and is divided into two different groups, to be fired at different intervals typically. The grouping also prevents noise caused by bubble oscillations when an air gun is triggered.

Recording at sea is usually done by long arrays of hydrophones towed behind the survey vessel, streamers. The conventional configuration involves the air-gun array towed a few hundred meters at the rear of the vessel with the streamer cables following close behind, see Figure 4.3a. Both the source and receivers are kept at a few meters depth to avoid surface waves and keep the source at an antinode, the depth of the equipment may be remotely operated from the vessel.

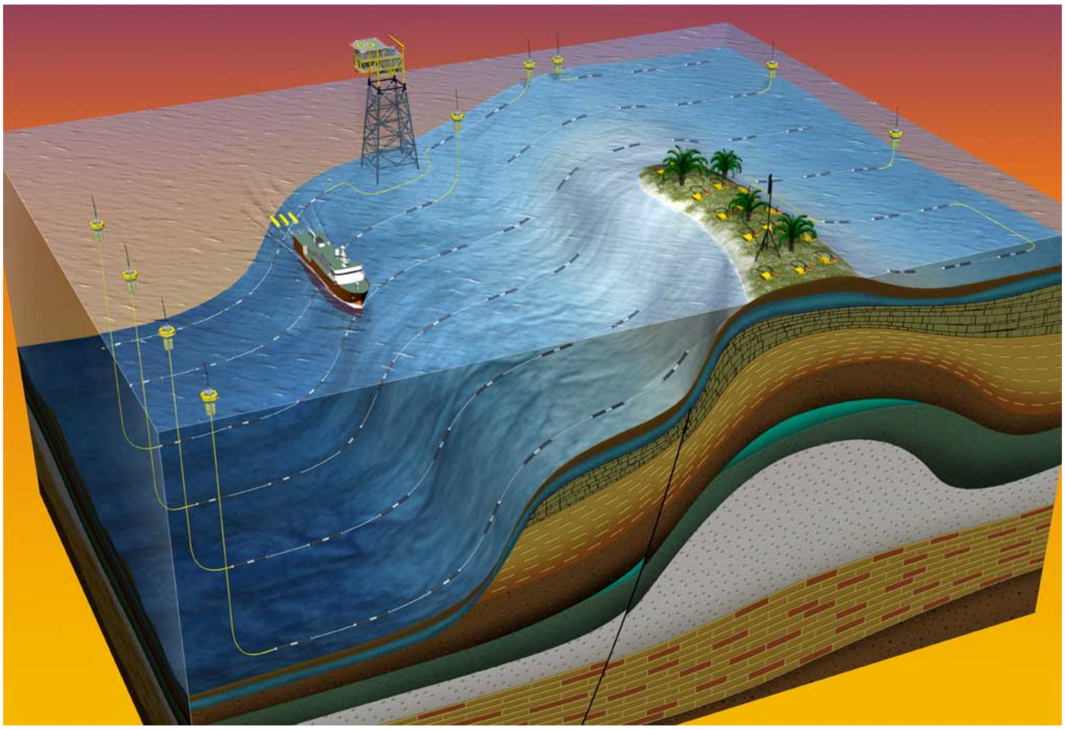


Figure 4.4: Bottom mounted seismic cables [25].

Another way of doing marine surveys is by so-called ocean bottom seismic, Figure 4.3b. The receivers in this configuration are geophones coupled with hydrophones to detect shear waves as well as pressure waves, since shear waves does not propagate in fluids the recordings has to be done at the bottom. This method also involves a dedicated source vessel to gain a longer distance between source and receivers. The receivers used in ocean bottom streamers are often four component receiver stations (4C) consisting of a three component geophone and a hydrophone. The same kind of receiver is used in OBN as well. OBN is a rather new approach to be used in areas with a fairly immense infrastructure where towed seismic may not give good coverage. OBN also make possible the use of wide azimuth for better resolution [63].

A rather new application for seismic surveying is so called four dimensional seismic (4D) or time-lapse seismic. This involves three dimensional (3D) seismic surveys to be applied at certain temporal intervals over a reservoir to monitor fluid movement and pressure effects over time. The common way of 4D seismic is to run a conventional seismic 3D survey maybe once a year to monitor changes in the reservoir and do the necessary changes in well intervention. But since marine surveys are rather expensive the time intervals may be reduced to every second or third year. A way of reducing costs per survey and increase temporal sampling is by installing permanent streamers into the ocean bottom in the reservoir area, so called Permanent Seismic Installations (PSI), as illustrated in Figure 4.4. For this to be cost effective the reservoir have to be of a decent size and so complex that it requires rapid monitoring to obtain a good recovery factor [29].

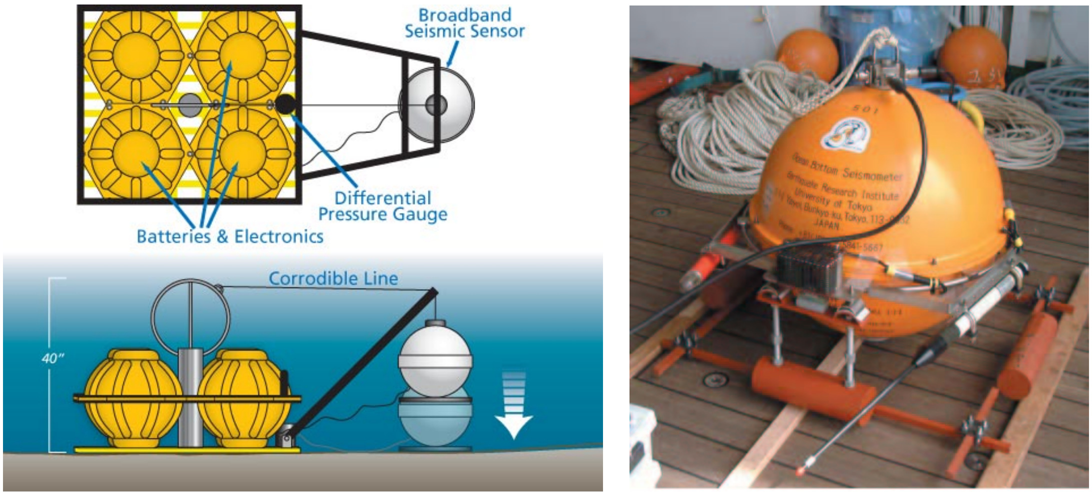
Information about instrumentation in seismology has been found in [17] and [48].

4.3 Implementation of Underwater Acoustic Networks

4.3.1 Earthquake Measurements

After the Indian Ocean megathrust earthquake in 2004 and the devastating tsunami following it, research on subsea earthquakes and tsunami detection has gained more attention. Monitoring of deep sea plate tectonics has for many years been a focus area for seismic scientists. More than 80 % of all earthquakes around Japan occurs on the seafloor by plate subduction, which may be devastating for the mainland in case of a tsunami incident. The focus on seafloor earthquakes has increased after the disastrous earthquake in Kobe in 1995 and The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) has a high priority in developing seafloor observatories to monitor seismic activity along mid-ocean ridges. JAMSTEC currently has several seafloor monitoring networks in operation around the Japan islands. These networks consist of a Real-time Seafloor Observatory (RSO) and a Mobile Seafloor Observatory (MSO). Each consisting of several pressure gauges for tsunami detection and ocean bottom seismometers. Two examples of OBS are displayed in Figure 4.5. The RSO is connected to the onshore control centre through cables and transmit data constantly. The MSO has got several pop up buoys which store data for different periods and one pop up every month to relay the latest data to a satellite. The purpose of these networks is of course to report any precursor seismic activity or slip between plates giving good indications about forthcoming earthquakes [53], [23]. [83] is also proposing a configuration for a long term monitoring network of seismic activity near the Juan De Fuca mid-ocean ridge.

This type of applications contains rather energy demanding instrumentation, requires transmission with high data rate and has few spatial sample points. UANs may then not be to suitable for this field, but deployment could be made less complex and expenses saved by the use of acoustic modems to relay data. Considering the temporal sampling points can be reduced to adapt to the low data rate of the acoustic channel. Real-time monitoring would also be difficult owing to high latency in acoustic communication.



(a) Ocean Bottom Seismometer configuration presented by [35].

(b) Example of a Ocean Bottom Seismometer [20].

Figure 4.5

4.3.2 Seismic Exploration

The oil and gas industry is always looking for new technology to save money. Usage of PSI is today quite expensive and limited to bigger projects, but the demand for more hydrocarbon recovery from producing fields may make this technology a must have. British Petroleums Valhall field in the North Sea is a good example of increased recovery factor by the use of PSI. The Valhall field is spanned with 20 km of cable spread over 35 km^2 of seabed, involving 9500 sensors at a cost of 40 - 50 million USD. The life-of-field installation is reported to give more accurate images and has extended the lifetime of the reservoir by many years [40], [16].

A requirement while doing time-lapse seismic is the position of the sensors. For the repeated shot to be comparable to the last survey the receivers has to be in the exact same place. For PSI with mounted cables this is given and technology in steering of towed streamers is improving, another way is to employ OBN which may be placed at their last position after guidance from underwater localization equipment. OBN systems have been developed mainly to increase resolution by covering blind spots, related to conventional marine surveys, near offshore infrastructure and use of wide-azimuth. The increased resolution and high level of repeatability make OBN systems well suited for use in time-lapse seismic [63]. The question is how dense the nodes should be distributed on the seabed, given the cost of deployment per node. OBN may be compared to the use of Ocean Bottom Streamers (OBS) where the spacing between receivers varies among 25m, Western Geco, or 50m, RXT. For a typical oil field covering an area of 64 km^2, [29], a node spacing of 50m would mean deployment of 25600 nodes to cover the entire field, which would be quite expensive. To obtain nearly the same resolution an increased receiver spacing may be compensated for by more rapid source points and Seabird Exploration, [18], with their CASE system states they can cover an area of 17 km^2 with 250 nodes. That would mean a node distance of approximately 250m in a uniformly distributed grid. The node spacing and the grid formation would of course be dependent on the field geometry and the terrain. The nodes would be deployed at the beginning of the survey and recovered at the end. The basic drawback is then that the nodes store the received data locally and some data might be lost due to failure. In addition the deployment of current OBN systems require divers or ROVs to install the equipment, which is rather complicated and exspensive.

UANs with good localization algorithms may be a good approach to reduce costs and simplify deployment of OBN systems by their ad hoc strategy. According to [29] a seismic event transforms into about 8-10s of received data in four channels, geophones along three axis and hydrophone, to be converted by a 24 bit D/A converter with a 500 Hz sampling frequency [29]. This results in about 60 kB of data to be transferred over the acoustic channel per event. With about 250 meters inter node spacing a relatively good data rate may be expected on the acoustic channel making UANs for seismic exploration a highly relevant application. A concern regarding battery is still present, as for all applications involving UAN. For UAN to be applicable for 4D seismic they should have a fairly long life span leading to a technique for battery changing or in field charging techniques. A solution to this challenge may be using AUVs or ROVs to charge the nodes in field, mentioned in Section 2.6. Since the receivers have to be in the exact same spot for each survey redeployment is not an option unless the nodes can be steered into the previous positions by automated or remote control.

Chapter 5

Waterside Security

5.1 Introduction

The technology is heading towards more unmanned self operating subsea structures in the field of offshore exploitation of natural resources and other types of maritime infrastructure like wave power plants or fish farms. These kinds of installations are very complex and consist of many different underwater constructions spread over a large area. The security situation of today's society makes those rigs highly vulnerable to terrorist attacks and unconventional warfare. Another potential target is busy harbours taking care of hundreds of shipping vessels every day. A strike against any such marine infrastructure may have a large economic and environmental effect. This makes the area of waterside security (WSS) no longer a unique military concern [7].

Military installations are in general under high end security and well protected both under and over the surface. Port security has gained a lot of attention recent years and the introduction of Autonomous Underwater Vehicles (AUV) for commercial use has enabled cost effective underwater patrolling of large harbour areas. [6] presents several concepts of AUVs for waterside security use. In combination with coast guard patrols and strict routines the security situation within a port facility is manageable. To uphold complete coverage of all arriving and departing traffic and isolate any security threat is still a very difficult task and requires vast adaptive sampling of the total area under protection and short reaction time for

Table 5.1: Typical functions for a waterside security system

Function	**Land example**	**WSS example**
Prevention	Locks, fences, access control	Barriers, access control, lighting
Detection	Fence sensors, ported coax, video motion detection	Sonar, radar, video motion detection
Assessment	Closed circuit television (CCTV)	CCTV, underwater vehicles
Deny/Delay	Fences, barriers	Floating barriers
Response	Mobile security forces	Mobile security forces

countermeasures.

Potential threats include divers, unmanned underwater vehicles, speed boats, divers with scooter and AUVs. All possible threats have different signatures and possible approach trajectories, which require an advanced system to detect all kinds of threats [7]. One of the biggest challenges is to be able to identify covert threats hidden within the daily activity, potentially disguised as a small cargo vessel. Protection of sea infrastructure is further complicated by the relatively easy public access.

A security system for protection of sea installations need to serve several functions to reach the same level of security as important land installations [45]. Table 5.1 give an overview and examples.

Harbour areas have the advantage of being located at the shore and consequently easy access to security personnel and other land resources. The security situation becomes more complicated at installations far at sea with limited resources. Still, this challenge has not been addressed in detail, yet. Civilian marine security systems seem to concentrate mostly on harbour protection, inspired by military applications for the same purpose.

The continous demand for hydrocarbons does not seem to lead towards a decrease in offshore activity. In addition the technology for utilization of renewable energy offshore is developing. Wave energy plants and possible offshore windmills are a examples of applications demanding waterside security systems in the future.

5.2 Instruments and Methods

5.2.1 Threats

After the September 11th attacks in 2001 the terrorist threat has increased in intensity as seen in the Madrid train bombings in 2004 and the London bombings in 2005. The simplest form of attack against seaside high value targets (HVT) as well as terrestrial targets is a bomb outrage. An Explosive Motor Boat (EMB) was effectively used in the attack against USS Cole in the Aden Harbour in Yemen in 2000 leaving 17 sailors dead and the destroyer severely damaged [55]. An EMB may be compared to a car bomb, simply consisting of a boat filled with explosives. Such threats might act fast and be difficult to discover caused by their ability to blend into the regular activity. Once the attack is initiated the response time of security forces has to be down to minutes to prevent the attack from being completed, owed to the potential speed of a motorboat and the challenge of confirming hostile intent.

According to [55], [52], [7], [3] the most relevant threat is that of underwater attacks. Post 9/11 security measures are increased and ship traffic highly regulated. The hindering of EMB attacks is much in the hands of coast guard patrols and radar surveillance making sure no unwanted traffic enters the harbour area. Underwater threats have the ability to be far more covert and operate outside of the reach of conventional port security.

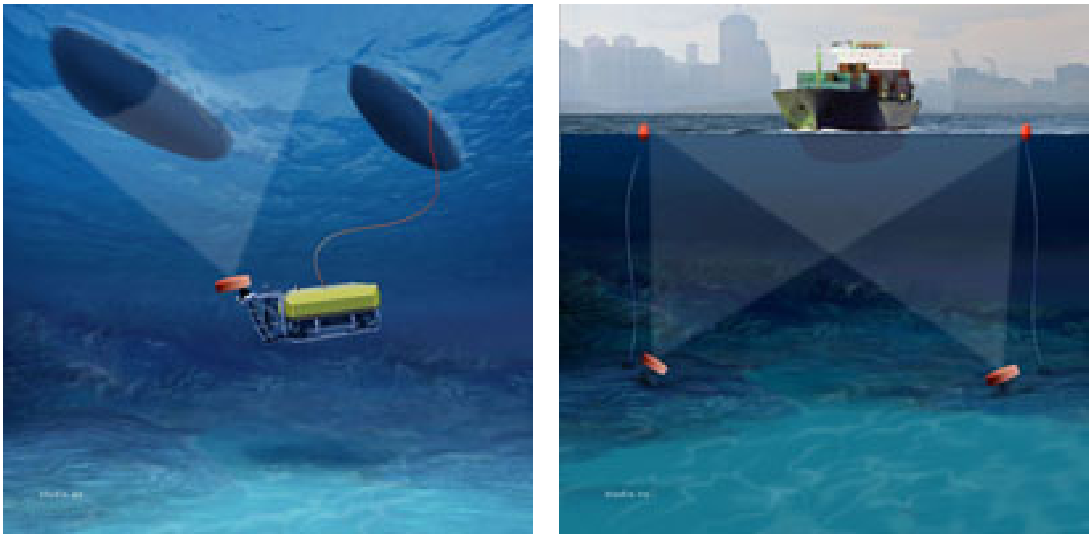
The simplest underwater threat may be the frogman. A single or several swimmers with off the shelf scuba gear have the ability to move freely at shallow depths and carry explosives or other kind of weaponry. The usage of air-recovery circuits to avoid bubble dispersion makes them almost impossible to discover from the surface [7]. The biggest limitation for a diver is the anticipated range and requires him to be deployed a distance to the target relative to his supply of oxygen or mixed gas. A form of Swimmer Delivery Vehicle (SDV) may be used to extend the range and double the speed, but produces more noise to be picked up by underwater surveillance systems.

The more complex variant of underwater intrusion is represented by a submersible vehicle. The advancement in technology and consequently cost effectiveness of such kind of vehicles for scientific use has labelled them as a security threat [7]. Terrorist may get a hold of mini submarines or AUVs and use them in unconventional attacks. Submersibles can obtain a higher speed, lowering the detection and reaction time from a security point of view, and operate close to the seabed, along shorelines or other trajectories with low detection probability.

5.2.2 Surveillance

In disclosing underwater threats sonar is the preferred tool. Sonar systems may be active or passive. Active sonar systems use one or more transmitters and receivers while a passive sonar system only uses receivers. The transmitters of an active sonar system emit a short pulse and analyze the received echo to identify any ship, submarines or obstacles. A passive sonar system on the other hand only listens to noise emitted by potential targets and identifies the target based on distinct noise signatures. Most sonars are mounted on the hull of a vessel or towed behind it.

High frequency and multibeam sonar systems employ one or more frequency bands in the ultrasonic range and achieve a very high resolution. In WSS this is a handy feature given the complex situation and small covert threats. Low frequency military sonars aimed at detecting large ships and submarines are of little use against swimmers or small submersible vehicles. With the development recent years several sonar system manufacturers, like Kongsberg Maritime [50] and Sonardyne [47], have come up with products aimed specifically at diver detection. Some integrated systems include additional detection sensors based on CCTV thermal camera imaging [69]. But most advanced diver detection systems appear to rely solely on acoustic detection [14].



(a) ROV with upward looking sonar.

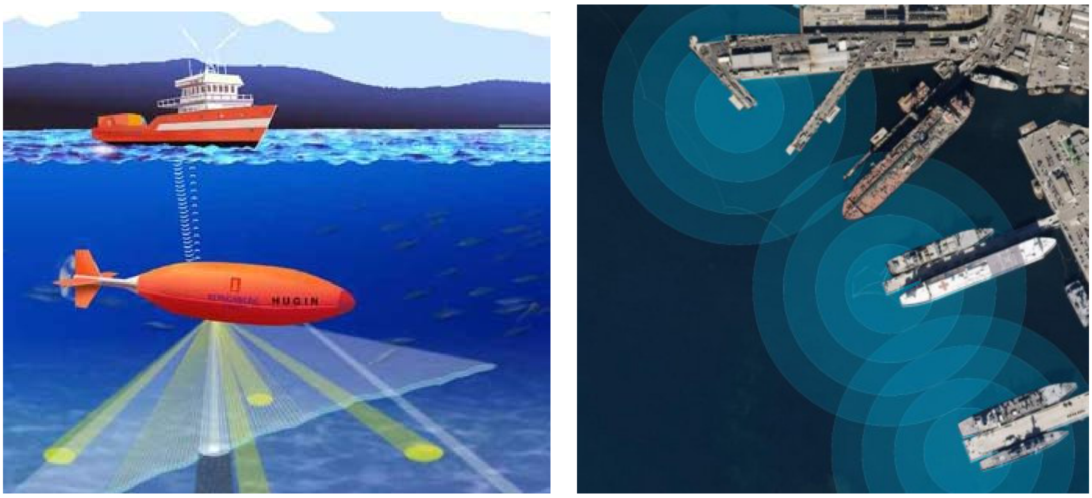
(b) Multibeam echosounders for hull detection.

Figure 5.1: [51].

Even though the majority of commercial WSS security systems for advanced applications are based on active sonar for detection of underwater threats there exists an approach involving passive sonar technology for diver detection [74], [12]. Passive acoustic diver detection relays on that the primary sound produced by a diver using scuba gear is his or her breathing, at a rate of about 0.3 Hz. The breathing sounds, which occupy a wide frequency spectrum, may be detected very clearly in a prominent ultrasonic frequency range. By utilizing this characteristic a diver may be discovered by a passive acoustic system owed to these distinct breathing sounds [76].

For the task of hull inspection and other operations involving inspection of specific areas Remotely Operated Vehicles (ROV) represent a flexible and cost effective solution [52], [69]. ROVs may be equipped with a number of different sensing equipment such as acoustic, video and thermal cameras, side scan sonar and upward looking sonar. ROVs equipped with grabbers may also remove parasitic objects on ships or identify foreign objects in the operating area. Still, they do not represent a threat against divers with hostile intent. The thrusters make loud noise, which give away their presence, and with the limited movement ROVs may easily be outmanoeuvred by a diver and incapacitated by a knife or other simple weapons.

Hull inspection may also be performed by bottom mounted upward looking multibeam echosounders placed in the shipping lane or at random positions within a harbour area. Hull detection techniques are illustrated in Figure 5.1



(a) AUV equipped with several sonar systems [51].

(b) Detection range for Sonardyne diver detection system [47]

Figure 5.2

Another platform that may be utilized for inspection purposes is the AUV, Figure 5.2a. [6] mentions the resource represented by small inexpensive AUVs equipped with a range of optical, magnetic and acoustic sensors for rapid search of potential targets. AUVs are programmed to follow certain trajectories and may not be utilized for target classification or pinpoint inspection like ROVs. But equipped with side scan sonar they are effective in mapping the seabed or search for small covert threats out of range of high frequency sonars positioned closer to the marine installation. The Kongsberg Maritime anti intrusion system [50] for instance operates with a range of 400 to 800 meters depending on physical properties, a probable detection range for port use is illustrated in Figure 5.2b.

Several studies propose the usage of several dynamic and fixed platforms to gain complete coverage of the area under surveillance. Both with regards to prevention, detection and assessment [5], [45], [46]. One can imagine the usage of bottom mounted echosounders in combination with ROVs for hull inspection, response divers and ROVs for threat assessment and close inspection, AUVs and patrol boats with sonar systems for random search and fixed diver detection systems mounted at various installations for additional intrusion surveillance.

5.3 Implementation of Underwater Acoustic Networks

Surveillance systems for protection of waterside and offshore installations is commonly based on an integrated approach [3]. This involves the use of several sensing systems and sensor platforms. For surveillance above the surface radar and patrol boats are common, and various sonar systems are employed under the surface. Often surveillance systems are combined with floating barriers and control points for prevention purpose.

Sonar systems employed are, as discussed in Section 5.2, usually made up of active solutions with various frequency resolutions. These acoustic sensors may be installed on existing constructions, such as piers or platforms, or positioned at predetermined points on specific structures to yield better coverage or create sonar fences [3], [45]. For hull inspection seabed sensors might be an effective approach, as mentioned in Section 5.2.

Trade-off between cost and coverage is usually a dilemma when implementing underwater surveillance systems [84], [69]. Basic systems for diver detection use, which is most appropriate for protection against asymmetric attacks, utilize higher frequency bands. Higher frequencies suffer higher absorption loss, [31], thus limiting the range. This calls for a large amount of instrumentation distributed to achieve good coverage, which is increasing the cost. A proposed approach is then to combine diver detection systems close to the installation and AUVs or towed sonars for random patrolling further from the installation [46]. Even though this solution doesn't offer full coverage it might increase the probability of detection quite a bit.

A ad hoc network approach for good coverage in marine surveillance of high risk areas is presented in [5]. The sensor network consists of a number of receiver nodes capable of analyzing acoustic signals, some source nodes with acoustic transmitters and a few gateway nodes with satellite links. The nodes are represented by buoyancy elements with short distance radio for internal communication, an acoustic receiver and a processing unit to analyze received signals. When detection is done a report is sent to an onshore control centre to analyze the alarm.

For the use of UAN a similar approach can be made, only changing the floating nodes by subsurface nodes.The advantage gained by installing it on the ocean bottom instead is that the network is out of the way of ship traffic, and it may also be used for hull inspection by detecting reflections of passing ship emitted by a central source. The battery consumption is more of a challenge for UAN. Positioned on the seabed changing of battery may not be as easy as for floating nodes. On the other hand the system is deployed close to infrastructure and a mechanism involving the node to pop up to the surface when it reaches a critical battery level might represent a solution. In this way a node with need of battery change may be located quickly by a radio beacon, battery changed and the node redeployed.

For the use of an active sonar system the node is working regularly, depending on the shot intervals of the source, analyzing received signals. To prolong network lifetime a passive acoustic solution may be more feasible. In that way the node may only react to distinct acoustic signatures, saving energy on processing. Another way of attacking this challenge is by having no onboard processing and relay the data directly to the onshore control centre, which would require a fairly high data rate not necessarily present in an UAN.

[75] proposes a sensor network for passive diver detection and gives a good discussion on sensor placement versus probability of detection. This network configuration presupposes processing done locally and the initiation of an alarm in case of intruder detection. The power required to do this processing is not given, and a trade-off between probability of detection and energy consume is to be expected.

Chapter 6

Marine Pollution

6.1 Introduction

The ocean is the end station for large amounts of land based refuse. Most of the marine pollution originates from land based sources including household waste, sewage, agricultural runoffs and different toxic chemicals. Toxins may origin from e.g. wind carried pesticide or polluted rivers. In the ocean they get dissolved into many small particles and absorbed by benthos and plankton. Once in the ecosystem the pollution concentrates within the food chain and contaminates all parts of sea life. Many chemical particles carried with rivers and streams may combine chemically in a way that makes estuaries anoxic, exterminating all aquatic life. Since marine resources are used for food heavy metals and dangerous chemicals may eventually end up with humans or otherwise spread to terrestrial animals. In addition to the spread of toxics and mortality, pollution may cause mutations or change in biochemistry, tissue matter or reproduction ability [57].

The increasing ship traffic and deep sea oil and gas extraction is a great concern. It seems that the biggest part of pollution within the ocean origins from operative discharge from ships and accidents on ships and platforms. The amount of oil spilled annually worldwide is estimated to more than 4.5 million tons, equal to two super tanker accidents every week. But oil discharges and spills are going down. Since the 1980s it has been reduced by 63 % and still progressing. In some respect owed to the advent of double hulled tankers and political initiative [39].

Another global concern is the reduction of Persistent Organic Pollutants (POPs). A great deal of serious toxic pollution on marine life is caused by POPs. POPs are organic compounds resistant to environmental degradation, due to this they tend to stay in the environment and are capable of long range transport and accumulate in organisms far from the area of initial exposure. POPs have multiple origins like raw sewage, industrial processes, pesticides or natural processes. Although some of the POPs may be caused by natural reactions the larger quantity origins from artificial processes or by-products. Good efforts have been made to reduce the spread of POPs, but they still remain a serious threat to the environment [9], [67]. Examples of POPs are PCB, DDT, furans, dioxins and phenols.

The most dangerous effect of marine pollution may be eutrophication, meaning an increase in nutrients caused by i.e. agricultural runoffs. This effect is mostly limited to coastal waters, given the shorter distance to polluting sources. Eutrophication causes an increase in so called primary production, provided by the lowest level of the food chain, which in marine ecosystems refers to algae. This in turn causes several ecological effects such as decreased biodiversity, changes in species composition and dominance, and toxicity effects [34].

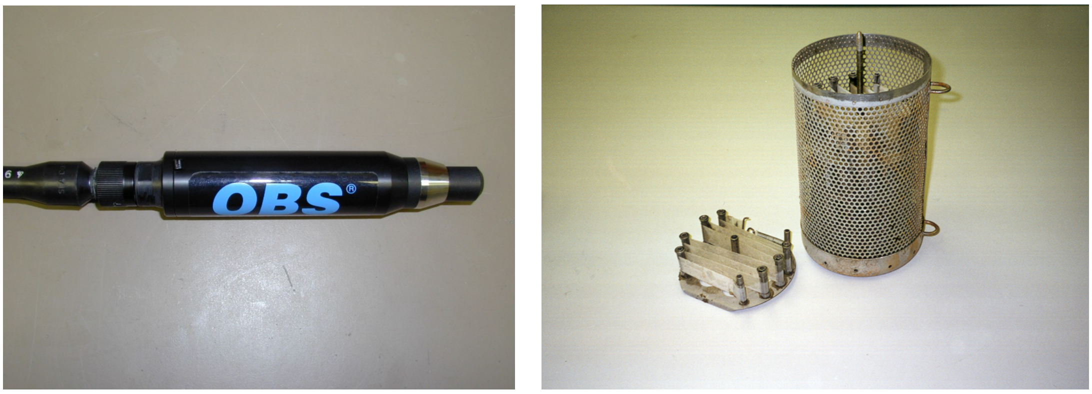
6.2 Instruments and Methods

In marine pollution studies research vessels are the prime tool to gather information about spreading of pollutants and assess water quality by active sampling. The lack of instrumentation to do in situ measurements of all possible POPs, toxins and nutrients leads towards water sampling as being the dominant way to analyze the abundance of pollutants in the oceanic environment. Analytical chemistry is the preferred way in looking for pesticides, nitrate and phosphorous, pH, oxygen demand and metals [58]. Research vessels with an onboard chemical lab is able to analyze water samples rapidly and consequently manage to cover a wide area, but swift sampling of large areas for monitoring purposes require specific instrumentation or methods to be employed [60].

Sources of marine pollution can be divided into point and non-point sources (NPS). Monitoring of point sources can be made very effectively by isolating the source and measure the volume of pollutant discharge, e.g. flow measurement on the end of sewage pipes, reporting from industrial waterside facilities and measurement of drainage from storage sites. Point source effect on the nearby water volume can further be calculated with models for spreading and disintegration. For NPS on the other hand the volume of pollutants entering the ocean is not that easy to decide and due to numerous transport paths the area of exposure may be immense.

A way of analyzing the water quality is by measuring the turbidity of a water body. Turbidity is the cloudiness of a fraction of water caused by small particles present. These particles may be phytoplankton, dust or unsettled sediment particles as well as contaminants, and causes the water to look muddy. Consequently the turbidity level gives good indications on the number of undissolved particles and thereby the polluting components in the sample space. Turbidity, measured in Nephelometric Turbidity Units (NTU), may be calculated by attenuation or scatter of light by a Nephelometer, shown in Figure 6.1a. A Nephelometer consists of a light source and a light detector positioned 90° relative to the source beam. The amount of light reflected to the detector is then a function of the density of particles in the water, thus giving the turbidity. The reflected light though is dependent on the size, colour and reflectability of the particles and the correlation between the measured turbidity and the amount of particles has to be decided independently by e.g. empirical tests. Nephelometers may then be designed to trace particles with specific properties depending on wavelength and scatter orientation. Fibre optic technology is also advancing the work on specific sensors to measure dispersion of certain pollutants [24].

The Nephelometer has furthermore proved useful regarding oil pollution and monitoring of oil spills. The most dominant technology for detection of oil in water however has been Fluorometry, since it is more accurate in detecting just oil relying on electromagnetic spectroscopy or absorption spectroscopy. The concept of Fluorometry is that a beam of light excites the electrons of specific compounds, causing them to emit light of lower energy. The frequency spectrum of this light emission, which is recorded, may then be used to identify the compound. Fluorometry is the best technique to analyse oil in water when the oil is partly dissolved, but its sensitivity is reduced when larger particles are considered. The bigger particles in the sample, the more sensitive is the Nephelometer causing the two technologies to be complementary. Used in parallel they may be very accurate, but this is fairly impractical. New design of Nephelometers and appropriate signal processing may give these an advantage in future applications [28].



(a) Nephelometer for ocean turbidity measurements [43].

(b) Semi permeable membrane device [71]

Figure 6.1

To do time integrated sampling of larger water volumes passive sampling techniques has to be employed. Passive sampling devices are deployed into the ocean and are equipped with a variety of filters to catch particles drifting in the water mass. After some time they are collected and their exposure to different pollutants may be decided. Examples of passive sampling instruments are semi permeable membrane devices (SPMD), shown in Figure 6.1b, and polar organic chemical integrative samplers (POCIS). Passive sampling devices have proved highly effective in monitoring of e.g. organochlorine pesticides, polycyclic aromatic hydrocarbons, organophosphate pesticides, waterborne ionic metals and polychlorinated biphenyls (PCB) [58], [15].

The concern of CO_2 level in the atmosphere trouble many climate scientists. Given that the largest quantity of excess CO_2 ends up in the ocean, as mentioned in Chapter 3, measurement of this level in the ocean may give good indications on the portion of increasing discharge ending up in the atmosphere. Since the rise in atmospheric content of CO_2 is half of what predicted, the question is if the ocean absorbs more than what initially expected [65]. To be able to make future predictions on atmospheric level of CO_2 the net transfer to surface waters have to be decided. This may be done by measuring the partial pressure of CO_2 (pCO_2) and calculate the difference from the pressure in the overlying atmosphere, which is rather constant. This difference in pCO_2 decides the gas transfer coefficient and enables us to calculate the net transfer of CO_2 to surface waters. Measurements of pCO_2 in surface waters is currently done by research missions globally, but this approach does not have the ability to do the detailed monitoring in both time and space that is needed. To commit the necessary spatial and temporal sampling fibre-optic sensors capable of long term autonomous measurements have been developed [65].

6.3 Implementation of Underwater Acoustic Networks

The need for vast adaptive sampling of pollutants in specific maritime areas is definitely present. The lack of effective methods for detection, monitoring, analyses and prediction of marine pollution is of great importance. The current methodology of active and passive sampling may not be applicable to monitor the future spreading of marine pollutants. To assess the forthcoming threat of marine pollution, methods for vast adaptive sampling should be developed.

Monitoring of pollutants in the ocean may be compared to the challenges of monitoring of physical oceanic parameters as presented in Section 3.3. The platforms available for in situ sensing of pollutant are almost the same as those for oceanographic use. A large drawback about pollution monitoring is that many pollutants may only be detected by use of analytical chemistry; consequently their presence may not be detected by sensors mounted on e.g. AUVs or moorings.

The sensors available for in situ sensing, as presented in Section 6.2, are limited. The measurements of turbidity by a Nephelometer and oxygen level by oceanographic sensors may still be applicable for a general impression of the quantity of contaminants in an area. Especially to monitor rising levels of nutrients, which might make the water volume hypoxic, measurement of oxygen level is fairly useful. For the concern of measuring pCO_2 level on a global scale, this may be solved by integrating a pCO_2 sensor into the Argo drifter for instance.

As for monitoring of limited coastal areas and estuaries UANs may be a good solution. UANs are expected to work best with short nodal spacing and rather simple sensing equipment, which would make them ideal for measuring turbidity or oxygen level of smaller areas. Equipped with custom designed Nephelometer or fluorometry equipment, a UAN may be deployed swiftly to be used for tracking of oil spills in case of an emergency. Monitoring of discharge from offshore installations or waterside facilities is another well suited application. UANs ability to do synoptic sampling of a limited area for monitoring purposes in almost real-time represents a great resource to investigate marine pollution in high risk areas. Additionally their low cost prognose and easy deployment may encurage increased monitoring.

UANs for the purpose of pollution monitoring is discussed to some extent in [39].

Chapter 7

Marine Biology

7.1 Introduction

Marine biology is the study of living organisms in the sea or other marine environments. In addition to studying the different organisms making up the cast in the sea, biologists study the effect of different substances on sea life. It is consequently much related to oceanography and the study of sea salinity, temperature and dynamic changes.

Like oceanography marine biology is a relatively new science and originated from the study of terrestrial creatures. An important motivation for studying life in the sea is the hypothesis that this is where life started. Marine biology spans from the study of one celled organisms and bacteria via photosynthesis in deep water to migration of large marine mammals.

Scientists believe that life in the sea tells us a lot about the evolvement of the Earth and give good indications about changes occurred in the past and changes occurring now. The relationship between life in the sea and important changes happening in the atmosphere and to life on land is not yet fully understood. Large parts of the ocean still remain unexplored and may contain new information about evolution and future resources.

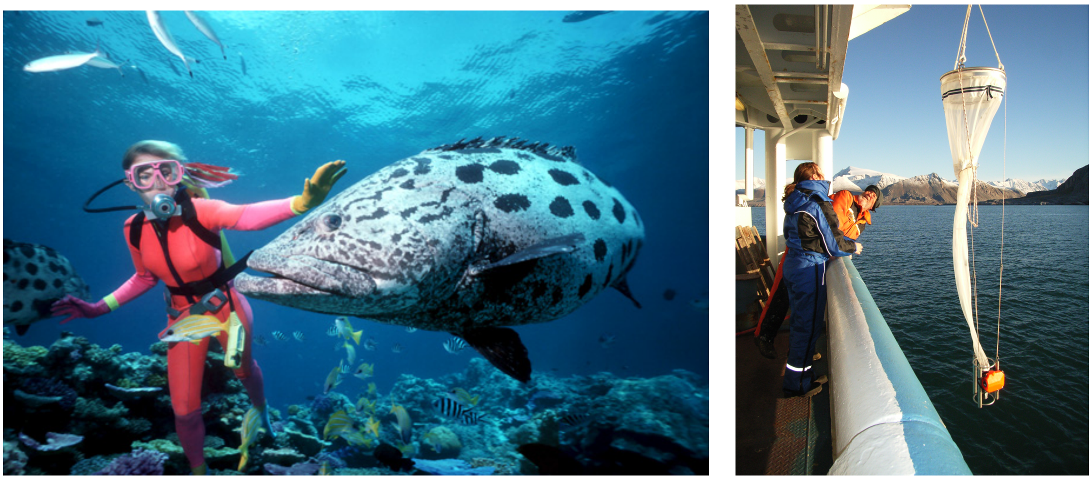
Marine resources are of a great significance for our lifestyle and for the life on Earth in general. Oceanic resources provide us with food, medicine and minerals and even helps out tourism. 71 % of the Earth's surface area is covered by water and the total water volume sees to that marine environments encompasses many times more habitable area than terrestrial habitats. Consequently marine life influences all aspects of the biology on Earth and effects e.g. climate and oxygen cycle.

A vital part of biology is the study of habitats and ecosystems. The change in physical or chemical properties in a specified area could have a vital impact on the quantities of life there. Monitoring of a habitat may supply good data regarding abundance of species and conditions for life or reproduction. Habitats to be monitored includes layers of surface waters suffering rapid changes in properties, reefs with a rich environment containing hundreds of species and deep sea trenches at depths of several thousand meters and no sunlight [34].

7.2 Instruments and Methods

Marine biology is a branch of oceanography, and oceanographic research mission by specifically designed vessels usually also carries out biological sampling as mentioned in Section 3.2. In the search for algae one may investigate water samples obtained at different depths and phytoplankton may be gathered with a fine-meshed trawl. Most modern research vessels contain a biological lab and collected samples can be analyzed in field.

Methods to obtain information about abundance, habitat use, spawning and feeding usually involve invasive techniques, Figure 7.1. Either by using divers to observe and collect information or by harvesting samples and going through e.g. stomach content. To assess the biodiversity surrounding a habitat scientists may dive down and note the populating species in different seasons. In this way any new species may also be described. For the purpose of population assessment some marine biologists may identify each and every animal in a given habitat after size and certain characteristics gathered with in situ enclosures, but of course this is only possible for small populations in a limited area [80]. Like missions with oceanographic research vessels this is both a time consuming and expensive affair.



(a) A diver at the Great Barrier Reef outside of Australia [30]

(b) Marine biology work during research cruise at Svalbard [22]

Figure 7.1: Examples of invasive methods to obtain information about aquatic life.

A more discrete way of estimating abundance and habitat use is by remote sensing with acoustic equipment. Echosounders in the ultrasonic frequency range may give high resolution echograms to be analyzed. Not to be compared with echosounders used for sport fishing, these supply a rather insensitive output and only detects the presence of fish nearby. [44] presents an instrumentation platform and an algorithm to detect and analyze fish shoals. This requires rather extensive signal processing but yields a reliable output containing shoal cross sectional area and density to estimate abundance. The goal is to be able to detect spawning and aggregation sites (SPAGS) and categorize coral fishes for preservation of coral reefs.

To estimate more sensitive parameters such as size distribution and abundance of smaller targets advanced processing have to be employed. For the detection and classification of zooplankton [42] proposes an inversion model to analyze the target strength of backscattered signals. Presence of zooplankton may further give good indications on biological processes in a given area. Inversion is the technique used to solve inverse problems and is done by fitting a model to known data. In this particular problem the goal is to find a model describing size and abundance of zooplankton as a function of target strength. When measurements are done one may optimize the model equation to the given results by guessing on a number of parameters. By finding the global maximum, or minimum for some optimization techniques, the best fit is found.

Different sonar technologies represent a great resource in remote sensing. In search for benthic habitats, parameters like sediment grain size, shear strength and sediment dynamics are very important. These parameters may be obtained through seabed mapping, even though not by a single technique. By applying different type of technologies, like side-scan sonars, multibeam echosounders or acoustic ground discrimination systems, one may decide a range of characteristics helpful in habitat classification and monitoring in the benthic zone [38].

Conventional methods in acoustic remote sensing rely on active sonar systems to obtain their results, which may disturb the life they are suppose to map and require a lot of energy. Research has been done to discover different sonic signatures made by fish, mammals or other animals in the sea. That opens up for passive acoustic detection techniques for assessing biodiversity and activity in a marine habitat. By listening to their specific noise signature habitat requirements and behaviour of fish may be monitored [64].

In search for and classification of marine habitats environmental data is of great importance. Animal life requires nutrients and a tolerant water quality to live, feed and reproduce. Knowledge of basic oceanographic properties as salinity, temperature and oxygen level may give good indications of any ecosystem present in the area [80], [86]. Many scientists are dedicated to ecosystem health assessments, studying dominant factors for life in certain habitable areas and contaminants with the ability to influence the biodiversity [54], [36]. The effect of climate change and perturbations made by anthropogenic sources may have great impact on the quality of marine ecosystems and monitoring of these systems is thereby important to uphold the stability of oceanic life.

The advent of the United Nations initiative the Water Framework Directive and the Marine Strategy Directive have called for an effort to reach good marine environmental conditions. This inspires the work towards a general reference on water quality and trophic status in aquatic habitats as well as tools for quality assessment. Since few habitats are equal one must decide on determining parameters in different classes of ecosystems, in deeper areas the presence of phytoplankton give good indications on life while other methods must be utilized in shallow coastal waters and transition waters [26], [19].

7.3 Implementation of Underwater Acoustic Networks

Ecosystem health assessment and habitat monitoring share concerns with both oceanographic research and pollution monitoring. Oceanic life is dependent on many factors to act, live, breed and develop. Climate changes, which may alternate physical properties in the ocean, may disrupt the natural processes taking place and effect oceanic life a great deal. Additionally human activity is affecting marine ecosystem by spreading inorganic contaminants and disturbing the natural level of nutrients.

Methods for habitat monitoring in the ocean today consist of active sampling and field work to decide biodiversity and species abundance. For terrestrial habitats this work is partly taken over by distributed sensor networks [49], [10]. A way of discriminating and classifying targets is by acoustic recognition of distinct calls [82]. The same can to a certain degree be done in underwater habitats, according to [76] and [64].

Utility of passive acoustic detection in UAN may simplify and limit costs of marine habitat monitoring. The fact that oceanic habitats are limited in size makes them a proper platform for use of UAN. Passive acoustic detection is considered not as energy demanding and the temporal sampling points can be reduced to further limit power consume. One can imagine different sensors sampling at different intervals and submitting raw data to the control centre for assessment. A small reef, lagoon or other habitats of interest does not have to be bigger than to be covered by 10 - 100 nodes. Making the network easy to manage and control. The life-time of such systems is dependent on the temporal sampling and consequently the power related to recording, processing and communication. It's hard to believe UANs for habitat monitoring lasting more than a full year without being recharged or redeployed. For UAN systems there are still many variables to be decided regarding battery capacity and energy required by passive acoustic sensors is not documented to the author's knowledge.

Conventional acoustic remote sensing equipment may also be utilized by UANs, in a configuration with several receiver nodes recording backscattered signals and one or more source nodes to initiate an event. This approach can supply the same sort of data achieved by remote sensing done with modern applications today.

For UAN applications in assessment of ecosystem health by pollution and environmental parameters this is covered by Sections 3.3 and 6.3.

Chapter 8

Conclusions and Further Work

In this study the concept of Underwater Acoustic Networks (UAN) has been researched to discuss the feasibility for different applications. Some area of interest has been investigated to gain an understanding of the demands made by the research community and an overview of current research applications, which have been compared to the use of UAN.

UANs have great potential in committing vast adaptive sampling of underwater environments, applicable for all of the applications analyzed. The UAN technology is still facing many challenges within underwater communication, sensor management, energy optimization and sensor design. These challenges has not been tried solved in this work, only acknowledged as restrictions and further involved in the discussion.

This study has assessed the research areas oceanographic environmental research, seismology, waterside security, marine pollution and marine biology and given an overview of common instrumentation and methodology. Then the possible implementation of UANs has been discussed in order to simplify field work or increase resolution of measurements.

In oceanographic research UANs were found feasible for monitoring a fair range of environmental parameters by in situ sensors currently mounted on other platforms, e.g. moorings or AUVs. The limited power capacity and inter node distance put constraints on the networks lifetime and coverage area. Consequently UANs for oceanographic use is best utilized in limited areas over a short time span with dense spatial sampling points.

UANs were not found feasible for earthquake monitoring, owed to the high time resolution of current measurements and the fact that the spatial sampling points are very few. Still, the current platforms could be optimized with high speed acoustic modems.

The effect of 4D seismic exploration has increased the demand for cost effective Permanent Seismic Installations. UANs were compared to Ocean Bottom Streamers and Ocean Bottom Nodes (OBN) currently applied for high resolution repeated seismic over hydrocarbon reservoirs. A further development of OBN for permanent installation with acoustic modems may transform this technology into an UAN application. The drawback is then the network lifetime, which should be high for PSI, and requires technology for energy replenishment. Still, PSI turns out to be a very relevant application for UANs.

For the case of waterside security UANs may be utilized to increase the coverage of ultrasonic diver detection systems. Current instrumentation mounted on waterside or offshore installations suffers from limited range and consequently late detection. By employing UANs with receiver nodes and source nodes the range of anti intrusion systems might be increased. Another technology to be used with UANs for underwater surveillance is passive diver detection. The latter is less energy demanding than an active system and may simplify maintenance and prolong lifetime. The spatial sampling points and deployment area for WSS applications make UANs a suiting platform for underwater surveillance.

Marine pollution monitoring is dependent on advanced chemical analysis to detect most dangerous contaminants. This lack of direct in situ sampling instrumentation leads to the conclusion that UANs may not commit advanced pollution monitoring. By applying some specific instrumentation UANs may still aid monitoring of toxic effects of limited areas for a certain time span, as for oceanography. Equipped with a Nephelometer UANs may also be effective in monitoring of oil spills in case of an emergency. The rapid deployment time and adaptive nature would in this area make them a great asset.

Marine biology is characterized by many cumbersome methods for field research. For species classification biological samples has to be obtained and habitat monitoring to decide biodiversity over time is as a result a time consuming effort. UANs utilized for acoustic remote sensing in field may simplify habitat monitoring. By employing passive detection the effectiveness may be further increased. Networks for oceanographic environment assessment and UANs for pollution monitoring may also assist in investigating water quality and ecosystem health.

This study does only give an overview and further work should be done to create complete frameworks for UANs in each research area. One wishes to establish the effectiveness of the proposed sensing equipment and involve relevant research institutions to get well assessed customer specifications. This may further boost the development of possible sensing platforms to be directly assembled on UAN nodes. It is also necessary to gain a more thorough understanding of the amount of processing a network node is able to do and possibly rule out applications dependent on a larger amount of onboard processing.

Bibliography

[1] Ian F. Akyildiz, Dario Pompili, and Tommaso Melodia. Underwater acoustic sensor networks: research challenges. *Ad Hoc Networks*, 3(3):257 – 279, 2005.

[2] Ian F. Akyildiz, Dario Pompili, and Tommaso Melodia. State-of-the-art in protocol research for underwater acoustic sensor networks. In *WUWNet '06: Proceedings of the 1st ACM international workshop on Underwater networks*, pages 7–16, New York, NY, USA, 2006. ACM.

[3] A. Asada, F. Maeda, K. Kuramoto, Y. Kawashima, M. Nanri, and K. Hantani. Advanced surveillance technology for underwater security sonar systems. pages 1–5, June 2007.

[4] Absolute Astronomy. `http://www.absoluteastronomy.com`.

[5] L. Benmohamed, P. Chimento, B. Doshi, B. Henrick, and I.-J. Wang. Sensor network design for underwater surveillance. pages 1–7, Oct. 2006.

[6] E. Bovio. Autonomous underwater vehicles for port protection. NATO Research and Technology Organisation, 2006.

[7] A Caiti. Underwater acoustic networks scenario description. *Preliminary draft from ISME to UAN partners*, 2009.

[8] Carbon Dioxide Information Analysis Center. `http://cdiac.ornl.gov/oceans/met.html`. Read May 11th 2009.

[9] UNEP World Conservation Monitoring Centre. `http://www.grida.no/publications/rr/our-precious-coasts/page/1292.aspx`. Read May 20th 2009.

[10] Alberto Cerpa, Jeremy Elson, Deborah Estrin, Lewis Girod, Michael Hamilton, and Jerry Zhao. Habitat monitoring: application driver for wireless communications technology. *SIGCOMM Comput. Commun. Rev.*, 31(2):20–41, 2001.

[11] Vijay Chandrasekhar, Winston KG Seah, Yoo Sang Choo, and How Voon Ee. Localization in underwater sensor networks: survey and challenges. In *WUWNet '06: Proceedings of the 1st ACM international workshop on Underwater networks*, pages 33–40, New York, NY, USA, 2006. ACM.

[12] Kil Woo Chung, Hongbin Li, and A. Sutin. A frequency-domain multi-band matched-filter approach to passive diver detection. pages 1252–1256, Nov. 2007.

[13] P.G. Collar. The autosub project-autonomous underwater vehicles for data collection in the deep ocean. In *Monitoring the Sea, IEE Colloquium on*, pages 3/1–3/4, Dec 1990.

[14] A.M. Crawford and D. Vance Crowe. Observations from demonstrations of several commercial diver detection sonar systems. pages 1–3, 29 2007-Oct. 4 2007.

[15] Arthur David, Hélène Fenet, and Elena Gomez. Alkylphenols in marine environments: Distribution monitoring strategies and detection considerations. *Marine Pollution Bulletin*, 58(7):953 – 960, 2009.

[16] Norwegian Petroleum Directorate. `http://www.npd.no/English/Emner/Ressursforvaltning/Undersokelse˙og˙leting/livstidsseismikk˙valhall.htm`. Read June 2nd 2009.

[17] Hugh Doyle. *Seismology.* John Wiley and Sons, West Sussex, 1995.

[18] Seabird Exploration. `http://www.seabird.no/`.

[19] Dirk Fleischer and Michael L. Zettler. An adjustment of benthic ecological quality assessment to effects of salinity. *Marine Pollution Bulletin*, 58(3):351 – 357, 2009.

[20] Japan Agency for Marine-Earth Science and Technology. `http://www.jamstec.go.jp/`.

[21] Max Planck Institute for Marine Microbiology. `www.mpi-bremen.de/en/Research˙Projects˙Ferdelman.html`.

[22] The Svalbard Science Forum. `http://www.ssf.npolar.no/`.

[23] N. Fujiwara, H. Momma, K. Kawaguchi, R. Iwase, and H. Kinoshita. Comprehensive deep seafloor monitoring system in jamstec. In *Underwater Technology, 1998. Proceedings of the 1998 International Symposium on*, pages 383–388, Apr 1998.

[24] A. Garcia, M.A. Perez, G.J. Grillo, and J. Tejerina. A new design of low-cost four-beam turbidimeter by using optical fibers. In *Instrumentation and Measurement Technology Conference, 2005. IMTC 2005. Proceedings of the IEEE*, volume 1, pages 592–596, May 2005.

[25] ION Geophysical. `http://www.iongeo.com/`.

[26] G. Giordani, J.M. Zaldívar, and P. Viaroli. Simple tools for assessing water quality and trophic status in transitional water ecosystems. *Ecological Indicators*, 9(5):982 – 991, 2009.

[27] Andrea Goldsmith. *Wireless Communications.* Cambridge University Press, New York, NY, USA, 2005.

[28] D. A. Green, R. Naimimohasses, P. R. Smith, and H. Thomason. In-situ measurement and classification of oil pollution. *Environment International*, 21(2):245 – 250, 1995.

[29] J. Heidemann, Wei Ye, J. Wills, A. Syed, and Yuan Li. Research challenges and applications for underwater sensor networking. *Wireless Communications and Networking Conference, 2006. WCNC 2006. IEEE*, 1:228–235, April 2006.

[30] The Sydney Morning Herald. `http://www.smh.com.au/`.

[31] Jens M. Hovem. *Marine Acoustics Part I.* Norwegian University of Science and Technology, Trondheim, 2008.

[32] B.M. Howe and T. McGinnis. Sensor networks for cabled ocean observatories. In *Underwater Technology, 2004. UT '04. 2004 International Symposium on*, pages 113–120, April 2004.

[33] B.M. Howe, T. McGinnis, and M.L. Boyd. Sensor network infrastructure: Moorings, mobile platforms, and integrated acoustics. In *Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, 2007. Symposium on*, pages 47–51, April 2007.

[34] Dale E. Ingmanson and William J. Wallace. *Oceanography : an introduction.* Wadsworth, San Diego, 1995.

[35] Woods Hole Oceanographic Institution. `http://www.whoi.edu/`.

[36] Emma L. Johnston and David A. Roberts. Contaminants reduce the richness and evenness of marine communities: A review and meta-analysis. *Environmental Pollution*, 157(6):1745 – 1752, 2009.

[37] R Jurdak, C. V. Lopes, and P. Baldi. Battery lifetime estimation and optimization for underwater sensor networks. *IEEE Sensor Network Operations*, 2004.

[38] A.J Kenny, I Cato, M Desprez, G Fader, R.T.E Schuttenhelm, and J Side. An overview of seabed-mapping technologies in the context of marine habitat classification. *ICES J. Mar. Sci.*, 60(2):411–418, 2003.

[39] A. Khan and L. Jenkins. Undersea wireless sensor network for ocean pollution prevention. pages 2–8, January 2008.

[40] Jan H. Kommedal, Olav I. Barkved, and Dave J. Howe. Initial experience operating a permanent 4c seabed array for reservoir monitoring at valhall. *SEG Technical Program Expanded Abstracts*, 23(1):2239–2242, 2004.

[41] Jiejun Kong, Jun hong Cui, Dapeng Wu, and Mario Gerla. Building underwater adhoc networks and sensor networks for large scale real-time aquatic applications. In *In Proceedings of IEEE Military Communications Conference (MILCOM'05), Atlantic City*, pages 1535–1541, 2005.

[42] AAge Kristensen and John Dalen. Acoustic estimation of size distribution and abundance of zooplankton. *The Journal of the Acoustical Society of America*, 80(2):601–611, 1986.

[43] NOAA Earth System Research Laboratory. `http://www.esrl.noaa.gov/`.

[44] J. Lotz, L.M. Zurk, J. McNames, T. Ellis, and J.-L. Ecochard. Coral fish shoal detection from acoustic echograms. In *OCEANS 2007*, pages 1–7, 29 2007-Oct. 4 2007.

[45] J.H. Lougheed and R.W. Clifton. C3a design for a waterside security system. pages 39–43, Oct 1988.

[46] A. Lovik, A.R. Bakken, J. Dybedal, T. Knudsen, and J. Kjoll. Underwater protection system. pages 1–8, 29 2007-Oct. 4 2007.

[47] Sonardyne International Ltd. `http://www.sonardyne.com/Industry/Defence/Maritime˙Security/index.html`. Read June 2nd 2009.

[48] S.J. Maas and I. Buchan. Fiber optic 4c seabed cable for permanent reservoir monitoring. In *Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, 2007. Symposium on*, pages 411–414, April 2007.

[49] Alan Mainwaring, David Culler, Joseph Polastre, Robert Szewczyk, and John Anderson. Wireless sensor networks for habitat monitoring. In *WSNA '02: Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, pages 88–97, New York, NY, USA, 2002. ACM.

[50] Kongsberg Maritime. `http://www.km.kongsberg.com/KS/WEB/NOKBG0240.nsf/AllWeb/31A785B964682F57C12573DB004AFC3D?OpenDocument`. Read June 2nd 2009.

[51] Kongsberg Maritime. `http://www.km.kongsberg.com`.

[52] Marianne Molchan. The role of micro-rovs in maritime safety and security. Molchan Marine Sciences, 2005.

[53] H. Momma, N. Fujiwara, K. Kawaguchi, R. Iwase, S. Suzuki, and H. Kinoshita. Monitoring system for submarine earthquakes and deep sea environment. In *OCEANS '97. MTS/IEEE Conference Proceedings*, volume 2, pages 1453–1459 vol.2, Oct 1997.

[54] Monica Montefalcone. Ecosystem health assessment using the mediterranean seagrass posidonia oceanica: A review. *Ecological Indicators*, 9(4):595 – 604, 2009.

[55] Naval-Technology.com. `http://www.naval-technology.com/features/feature46248/`. Read Feabruary 2nd 2009.

[56] Matthias Tomczak Flinders University of South Australia in Adelaide. `http://www.es.flinders.edu.au/~mattom/IntroOc/newstart.html`. Read April 13th 2009.

[57] Richard Owen, Carys Mitchelmore, Cheryl Woodley, Hank Trapido-Rosenthal, Tamara Galloway, Michael Depledge, James Readman, Lucy Buxton, Samia Sarkis, Ross Jones, and Anthony Knap. A common sense approach for confronting coral reef decline associated with human activities. *Marine Pollution Bulletin*, 51(5-7):481 – 485, 2005. Coral Reef Ecotoxicology and Health.

[58] J. D. Petty, J. N. Huckins, D. A. Alvarez, W. G. Brumbaugh, W. L. Cranor, R. W. Gale, A. C. Rastall, T. L. Jones-Lepp, T. J. Leiker, C. E. Rostad, and E. T. Furlong. A holistic passive integrative sampling approach for assessing the presence and potential impacts of waterborne environmental contaminants. *Chemosphere*, 54(6):695 – 705, 2004.

[59] George L. Pickard and William J. Emery. *Descriptive physical oceanography : an introduction.* Pergamon Press, Colorado, 1990.

[60] R. Prien. Technologies for new in situ chemical sensors. In *OCEANS 2007 - Europe*, pages 1–6, June 2007.

[61] J.G. Proakis, M. Stojanovic, and E.M. Sozer. Underwater acoustic networks. *Oceanic Engineering, IEEE Journal of*, 25(1):72–83, Jan 2000.

[62] The Argo Programme. `http://www.argo.ucsd.edu/l`. Read April 2009.

[63] Amal Ray, Bertram Noltem, and Don Herron. An experimental nodal obs acquisition from the thunder horse field, gulf of mexico. *The Leading Edge*, 24(4):410–412, 2004.

[64] Rodney Rountree, Francis Juanes, and Cliff Goudey. Listening to fish: Applications of passive acoustics to fisheries. *The Journal of the Acoustical Society of America*, 119(5):3277–3277, 2006.

[65] S.I. Rubin and H. Ping Wu. A novel fiber-optic sensor for the long-term, autonomous measurement of pco2 in seawater. In *OCEANS 2000 MTS/IEEE Conference and Exhibition*, volume 1, pages 631–639 vol.1, 2000.

[66] S. Saito, K. Moriwaki, and Y. Yamada. Jma's new ocean bottom seismographs (obs) using marine cable installed at the sea of enshu to the sea of kumano. In *Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, 2007. Symposium on*, pages 639–646, April 2007.

[67] Takeo Sakurai, Jun Kobayashi, Yoshitaka Imaizumi, and Noriyuki Suzuki. Non-food-chain transfer of sediment-associated persistent organic pollutants to a marine benthic fish. *Marine Pollution Bulletin*, In Press, Corrected Proof:–, 2009.

[68] S. Sherrit. The physical acoustics of energy harvesting. In *Ultrasonics Symposium, 2008. IUS 2008. IEEE*, pages 1046–1055, Nov. 2008.

[69] M.S. Smookler, B.G. Clark, and J.M. Ostrander. Underwater detection and surveillance technology for commercial port and vessel security. who is going to pay for it? In *OCEANS, 2005. Proceedings of MTS/IEEE*, volume 1, pages 935–940, 2005.

[70] J. Sousa, N. Cruz, A. Matos, and F. Lobo Pereira. Multiple auvs for coastal oceanography. In *OCEANS '97. MTS/IEEE Conference Proceedings*, volume 1, pages 409–414 vol.1, Oct 1997.

[71] Pacific Southwest Research Station. `http://www.fs.fed.us/`.

[72] StatoilHydro. `http://www.statoilhydro.com/no/TechnologyInnovation/OptimizingReservoirRecovery`.

[73] Robert H. Stewart. *Introduction To Physical Oceanography.* Texas A and M University, Texas, 2008.

[74] R. Stolkin and I. Florescu. Probabilistic analysis of a passive acoustic diver detection system for optimal sensor placement and extensions to localization and tracking. pages 1–6, 29 2007-Oct. 4 2007.

[75] R. Stolkin and I. Florescu. Probability of detection and optimal sensor placement for threshold based detection systems. *Sensors Journal, IEEE*, 9(1):57–60, Jan. 2009.

[76] R. Stolkin, S. Radhakrishnan, A. Sutin, and R. Rountree. Passive acoustic detection of modulated underwater sounds from biological and anthropogenic sources. pages 1–8, 29 2007-Oct. 4 2007.

[77] Harold V. Thurman and Elisabeth A. Burton. *Introductory oceanography.* Prentice Hall, New Jersey, 2001.

[78] Rutgers University. `http://rucool.marine.rutgers.edu/`. Read April 2009.

[79] The Open University. `www.open.ac.uk/openlearn`.

[80] Nisikawa Usio, Rui Kamiyama, Azumi Saji, and Noriko Takamura. Size-dependent impacts of invasive alien crayfish on a littoral marsh community. *Biological Conservation*, 142(7):1480 – 1490, 2009.

[81] Ding Wang, Pierre F.J. Lermusiaux, Patrick J. Haley, Donald Eickstedt, Wayne G. Leslie, and Henrik Schmidt. Acoustically focused adaptive sampling and on-board routing for marine rapid environmental assessment. *Journal of Marine Systems*, In Press, Corrected Proof:–, 2009.

[82] Hanbiao Wang, J. Elson, L. Girod, D. Estrin, and Kung Yao. Target classification and localization in habitat monitoring. In *Acoustics, Speech, and Signal Processing, 2003. Proceedings. (ICASSP '03). 2003 IEEE International Conference on*, volume 4, pages IV–844–7 vol.4, April 2003.

[83] W.S.D. Wilcock, P.R. McGill, E.E.E. Hooft, D.R. Toomey, H.M. Patel, D.S. Stakes, A.H. Barclay, T.M. Ramirez, and R.T. Weekly. The deployment of a long-term seafloor seismic network on the juan de fuca ridge. In *OCEANS 2007*, pages 1–6, 29 2007-Oct. 4 2007.

[84] W. E. Wilhelm and E. I. Gokce. Branch-and-price decomposition to design a surveillance system for port and waterway security. *Automation Science and Engineering, IEEE Transactions on : Accepted for future publication*, pages 1–10, May 2009.

[85] S. Wood, T. Allen, S. Kuhn, and J. Caldwell. The development of an autonomous underwater powered glider for deep-sea biological, chemical and physical oceanography. In *OCEANS 2007 - Europe*, pages 1–6, June 2007.

[86] Bin Zhang, G.S. Sukhatme, and A.A. Requicha. Adaptive sampling for marine microorganism monitoring. In *Intelligent Robots and Systems, 2004. (IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on*, volume 2, pages 1115–1122 vol.2, Sept.-2 Oct. 2004.

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