The potential of LIDAR as an aerial antisubmarine warfare sensor

John Olav Birkeland

M.Phil – Research

Faculty of Arts

University of Glasgow

November 2009

Acknowledgements

I would like to thank my supervisors in Glasgow, Dr. Phillips O'Brien and Dr. Nigel Barltrop, for valuable discussions and important guidance in the writing process. Also, Professor Jens Hjelmstad at NTNU in Trondheim has given important backup in pointing to alternative measures of submarines search, and has functioned as a safety net for the final product.

I would like to thank my colleague and friend Major Gjert Lage Dyndal, now the dean of the Royal Norwegian Air Force Academy, for helping me into this research program and recommending me for the LIDAR project that started in 2007. Your efforts and enthusiasm as a military academic stand unparalleled.

Without the support and understanding of by commanding officers this project would not have been possible. I would like to thank Brigadier General Ole Asak as the commander of the former Joint Air Operations Center at the National Joint Headquarters in Stavanger, and my closest commanding officers Lieutenant Colonels Tore Svendsen and Odd Harald Jenssen for giving me the flexibility to write in parallel to my work at the headquarters. Also, Lieutenant Colonel Steinar Halvorsen at the Inspectorate of Air Operations provided the time and resources the final months of the writing process.

Last, but most importantly, I would like to thank Ingvild for putting up with my ambitious agenda the past year. Always encouraging and supporting, I am looking forward to new challenges together with you of whatever nature.

Oslo, November 2009

John O. Birkeland

Abstract

Traditionally, antisubmarine warfare (ASW) has been dominated by acoustic sensors, active and passive. Ending the Cold War, the ASW forces have refocused towards a theatre of war in the littorals, and the traditional acoustic sensors do not perform very well in such an environment. The sensors are working much closer to the surface, and there is a lot more surface traffic to disturb the acoustic environment. Environmental and topographic factors also play a major role. Removing or significantly reducing the acoustic capability, one forces the ASW forces to look to other technologies and sensors to compliment or replace the acoustic ones. This is where the interest of LIDAR as an aerial ASW sensor comes into play. The aim of this thesis is to evaluate "*the potential for using LIDAR technology for aerial ASW on Norwegian ASW platforms"*. In addition to this main research question, the history of LIDAR has been researched, in order to find historical and existing LIDAR projects for ASW purposes.

Antisubmarine warfare is a complicated business, but speed of reaction, flexibility to change operating areas quickly and efficiently, and the ability to deploy sophisticated buoys are all in the advantage to the aerial ASW platform. But as the submarines get quieter and quieter, new means of detection must be found to cover the complicated upper layers of the water column.

The signal components of LIDAR and the increasing processing capability have made LIDAR technology somewhat mature, but limitations such as scattering and attenuation of light in water are severely hampering.

After a decline in ASW focus after the Cold War, the Western world is finding itself in a littoral submarine threat scenario, and do not have the sensors to sufficiently meet this threat. Several LIDAR programs have been initiated and carried through, but most have been directed towards finding and neutralizing mines. Lately, a new interest of applying LIDAR-technology in the search for submarines has risen. But LIDAR itself does not seem to be able to cover the upper layers of the water column consistently enough, and other technologies might be able to compliment LIDAR in a multi-sensor solution. Synthetic Aperture Radar (SAR) and Hyperspectral Imagery seem to be the most applicable of these. A recommendation is given to military commanders to pursue a multi-sensor pod for several areas of use by Maritime Patrol Aircraft and military helicopters.

Table of contents

List of illustrations

1 – Introduction

1.1 Background

The background for this thesis lies in a constant effort to improve as an anti-submarine warfare (ASW) force. The art of hunting a submarine is not easily taught, and not easily acquired. The wish to control one's adversary's submarines is as old as the submarine force itself. From the early submersible vessels of the late 1800s, to the superbly advances nuclear attack submarines of today, the silent service has always posed a significant threat, in war as in peace time.

ASW has always demanded both state-of-the-art sensors, as well as highly trained operators. The lack of one of these has called for a raised level of the other. Technologywise, the submarine force and the ASW forces have always been in a race for constant improvement. Better sensors have called for quieter submarines, and vice versa. And traditionally, ASW has been dominated by acoustic sensors, active or passive. The passive sensors are deployed in the water to listen for sounds emitted by the submarine. Active sensors will transmit a sound themselves, and then listen out for the echo returned by the target submarine. The use of the respective sensor is obviously closely linked to the tactics being pursued by the ASW platform or force.

In World War II the German "Wolfpacks" posed a tremendous threat to allied shipping, it being convoys of merchant ships as well as transiting warships. But they hardly ever operated close to the shore, in the littoral waters. Their area of domination was the open ocean, the so-called *blue water* regions of the Atlantic and the Pacific. The submarines would hide under the surface, shadow a convoy, and attack at the right moment. Obviously, the known sea-lines of communication (SLOCs) were the most likely area to find an enemy submarine, but in principle, the entire ocean was a friendly forces' search area. Even more so than with the submarines of the Second World War, the gigantic submarines of the Cold War carrying ballistic missiles had the open ocean as their playing field. As an absolutely essential part of the mutually assured destruction (MAD) strategy, the submarines carrying ballistic missiles (SSBNs) would hide in the deep, ready to fire their deadly load from a hidden position, and thus assuring the ability for a second strike.

Ending the Cold War, the ASW forces have refocused towards a theatre of war in the littorals. This change poses challenges for both the submarine and the submarine hunter, which will be presented in detail later in the dissertation. The main point being for the ASW forces, that the traditional passive acoustic sensors do not perform very well in the littorals. One is working much closer to the surface, and there is a lot more surface traffic to disturb the acoustic environment. Environmental and topographic factors also play a major role. Removing or significantly reducing the acoustic passive capability, one forces the ASW forces to look to other technologies and sensors to compliment or replace the acoustic ones. This is where the interest of LIDAR as an aerial ASW sensor comes into play.

1.2 What is LIDAR?

"LIDAR" is an acronym for "LIght Detection And Ranging", and the technology is based on laser equipment and additional analyzing processors. Aerial LIDARs are carried by airplanes and helicopters, and are flown over the surface, be it land or ocean, that is to be analyzed. The laser emits a narrow beam of light, and the receivers send the returned signals to electronic processors that in turn analyze the different wavelengths of light. The returned signals will provide the basis for telling the operator details about ground elevation, ground conditions and structure, ocean characteristics, ocean depths and other desired surveying information. Currently the civilian world can offer LIDAR systems that perform levee profiling, dredge deposit evaluation, corridor and floodplain mapping, fish stock surveys and of course oceanographic and bathytermal surveys and mapping. Different military agencies have developed LIDARs for use in mine search, originally based on a desire to find submerged submarines by the use of lasers. Other military applications in the future can be a support to the compilation of a Rapid Environmental Picture (REP) before conducting amphibious operations.

1.3 Statement of problem

This project originally rose as a question posed to the Concept Development and Evaluation (CD & E) group at the National Joint Headquarters (NJHQ) in Norway in the fall of 2006. The discussion started between officers with a background from the Norwegian 333 squadron at Andøya in Northern Norway. The 333 squadron has a proud history of conducting aerial ASW with several different ASW aircraft along the years, and has since the late 1960s flown the P-3 Orion, with many heavy upgrades in airframe and sensor portfolio. Reading articles on researching fish stocks in the water with laser beams mounted on aircraft, one started to discuss the ability to use the same type of equipment to search for submerged submarines. But what was the reason for civilian technology coming so far, that it is able to distinguish between different families of schools of fish in the water, and known ASW-platforms do not possess a similar capability? Could this technology be placed on a P-3? And how deep will a laser beam be able to search for a submarine? The CD & E group authorized the project the following spring, with the aim of having a master thesis evaluate the following:

"What is the potential for using LIDAR technology for aerial ASW on Norwegian ASW platforms?"

In addition to this main research question, some underlying questions will be sought answered. What is the history of LIDAR research, that is, what projects have been pursued earlier? Has the question of LIDAR potential for ASW been asked earlier, and if so, what is the reason for current ASW platforms not possessing this capacity today?

1.4 Limitations

The empirical material gathered in the research for this thesis is very much based on technological and operational reports coming out of the U.S.A. This can be attributed to several factors. The U.S. has a long tradition of publicizing technological research to a greater extent than is to some degree usual in Norway and Europe. The results of civilian testing of LIDAR are no exception, and many reports have been readily available on the internet and in libraries. Based on an extensive research and as will become clear later in the dissertation, by far the most activity in the field of LIDAR research has been based out of the U.S.A. The fact that we do not have any operational aerial antisubmarine warfare platforms flying with functioning LIDAR-equipment meant for hunting submarines, and that the discussion of placing such equipment on P-3 Orions first rose several years into the 2000s in the U.S., supports the idea of looking to the U.S. first in order to see the current state of the technology.

In addition, from a Norwegian standpoint, it is always important to stay in touch with the direction and development of American warfighting capabilities, as the U.S.A. is by far the closest ally when it comes to military acquisition. Knowing the thoughts of the American politicians and the evaluation of different technologies will provide the basis for the need to perform similar processes of development and evaluation of our own. If the largest military in the world does not consider the technology cost-efficient or affordable enough to pursue, there is a significant chance of little Norway landing on the same conclusions. And if the Americans are considering a technology to be worth pursuing for whatever reasons, there is a good chance of other countries finding similar ways to put the technology to use, and maybe even additional ones.

Norwegian ASW assets work closely with other allies as well, such as the U.K., Germany and France, but open sources do not reveal any information on LIDAR programs presently being pursued in these countries. Needless to say, this does not preclude any classified programs from currently taking place.

1.5 Methodology and sources

This thesis is mainly based on literature research. For the technological details, many research reports have been studied, mostly written by the researchers themselves. Not being a technology graduate, this has at times been challenging. But it has been important for the final product, that this thesis is not a technological report, but an operational evaluation of the potential technology as a whole. The technological details have been tried reduced to a minimum, however some have been necessary to include, especially in an effort to build up some credibility in the technology chapter.

Three technology reports have been tried declassified from U.S. CONFIDENTIAL, of which only one has successfully gone through the Washington bureaucracy over the past 2 years. Hopefully, the thesis provides a credible discussion mainly based on open sources.

Several sections have been written based on the author's personal knowledge and experience as an officer in the Royal Norwegian Air Force and a Tactical Coordinator (TACCO) on P-3 Orions. Where needed, information has been sought from open sources. But due to the highly classified nature of the technical and tactical details of ASW, a more detailed discussion than the one provided here will border on privileged information. This has of course led to some restrictions, but hopefully the provided information will suffice.

There is apparently no open discussion going on as of now regarding the potential of LIDAR as an ASW sensor, other than the U.S. Navy's proposal to expand their existing mine countermeasure-program to include LIDAR on the P-3 Orion (details will follow). Not much information on this is available, and naval theorists have not been very explicit on this matter. Both Norman Friedman and Geoffrey Till have pointed to the challenge of conducting efficient ASW in the littorals, but have not gone further into details other than proposing exploring searching by non-acoustic means such as lasers. Internet forums and submarine-authors have discussed the potential of a hypothetic sensor that is able to "*see through the water*", and played it down significantly (Buff 2003). LIDAR is praised for its potential and capabilities in the civilian world, and is considered efficient enough for the U.S. Navy to carry on their mine countermeasure-program with LIDAR installed on helicopters. The potential as an ASW sensor, however, is not heavily debated apparently in any open forum. One of the challenges of this thesis have been the effort of digging into a discussion that is not really there, and thus perhaps initiate one that can be of use for the ASW-community.

1.6 Disposition

This introduction has had the goal of providing the reader with enough motivation to read the following chapters leading up to a humble recommendation. The dissertation as a whole consists of 3 parts, each consisting of two chapters.

Part I provides a background for the discussion, with two chapters with basic information. Chapter 2 gives an introduction to aerial antisubmarine warfare in order to provide an insight into the sensor portfolio usually present onboard aerial ASW platforms of today. Chapter 3 explains the basics of LIDAR technology, from the basic components of lasers to the challenge of interpreting the frequencies on light being returned form the water (and hopefully the target).

Part II lays out the historical development of LIDAR as a technology, and the changing focus on ASW. Chapter 4 discusses the different changes in tactics, doctrine and political focus that we have seen from the mid-1980s up until today. Chapter 5 gives a detailed overview of the development of LIDAR technology, both civilian and military. The civilian and military-civilian programs have mainly focused on areas of interest for both communities, mostly being hydrography and the mapping of shallow, coastal waters. This information is readily available in books, reports and on the internet. The military programs have been either entirely "black", or hidden from the public, or known to the public through congressional budget discussions. This chapter gives an idea of where the technology-development is today.

Part III is the evaluation of LIDAR for ASW, and the presentation of alternative technologies to possibly compliment LIDAR as a sensor. Consisting of two chapters, chapter 6 will first discuss LIDAR for ASW in isolation. Then alternative methods of non-acoustic detection will be discussed, calling for other technologies in addition to LIDAR. Chapter 7 is a short and humble conclusion and a recommendation for military commanders when it comes to the potential and need for LIDAR and supplementary sensors in the hunt for submarines in the littorals.

2 – Airborne ASW – An introduction

2.1 Background

The classical distinction within submarine technology is between the two main types of propulsion; diesel-electric and nuclear. Obviously, the first submarines were diesel-electric, but as the nuclear powers developed smaller and more efficient reactors, the desire to move faster and longer with bigger submarines without replenishment over an extended period of time came to the scene. Most submarines carrying ballistic missiles (SSBN) are nuclear powered, and are able to operate almost anywhere in the world for months at a time. Attack submarines can be nuclear (SSN) or diesel-electric (SSK) – the SSKs usually do not operate very far from the shore as they need to replenish diesel, a need the SSNs don’t have. The SSKs are almost without exception smaller than their nuclear sister boats, and are often likely to operate in a near-shore environment due to their size and maneuverability. In addition, some new submarines have Air Independent Propulsion (AIP), and are powered by fuel-cells that are charged without air. These submarines are also incredibly silent, and can operationally be referred to as something of a hybrid between nuclear and diesel-electric propulsion. They are, however, as quiet as the SSKs.

In World War II, airborne radar was the primary anti-submarine warfare (ASW) sensor. Boats were usually diesel driven and consequently had to surface to recharge batteries, and many submarines chose to transit on the surface where possible to achieve greater speeds (Mason 1987:103). As the nuclear technology matured, some oceangoing vessels started to be designed with nuclear propulsion. When the nuclear submarines were sent to sea, new and improved ways of detecting the submerged vessels were needed, and other technologies than radar were developed and refined. Airborne ASW is usually performed by either long-range land-based aircraft or shorter-range ship-borne helicopters. The aircraft have a long endurance of nine hours or more, with an extensive sensor capacity and a relatively fast transiting speed, at least compared to the helicopters and surface vessels. The aircraft, usually referred to as Maritime Patrol Aircraft (MPA), are fitted with sensors such as sonobuoys, radar, magnetic anomaly detection (MAD), electronic support measures (ESM), and electro-optic and infrared cameras (EO/IR), apart from the obvious visual detections made by the crew themselves. The following will give a brief introduction to the different sensors.

2.2 Acoustic sensors

2.2.1 Oceanography basics

Except under polar icecaps, where the temperature is constant regardless of depth, the sea has a layered architecture that determines the speed of sound. Sound velocities vary with water temperature, pressure and salinity. Salinity plays a role, but the biggest factors are temperature and pressure. Cooler temperatures lower speed while higher pressures increase it. Sound in water will always seek towards the area where the speed is the lowest, so initially the sound will seek towards the cool abyss, before the pressure becomes so high that the sound is bent upwards again towards the point of minimum velocity (see figure 2.1).

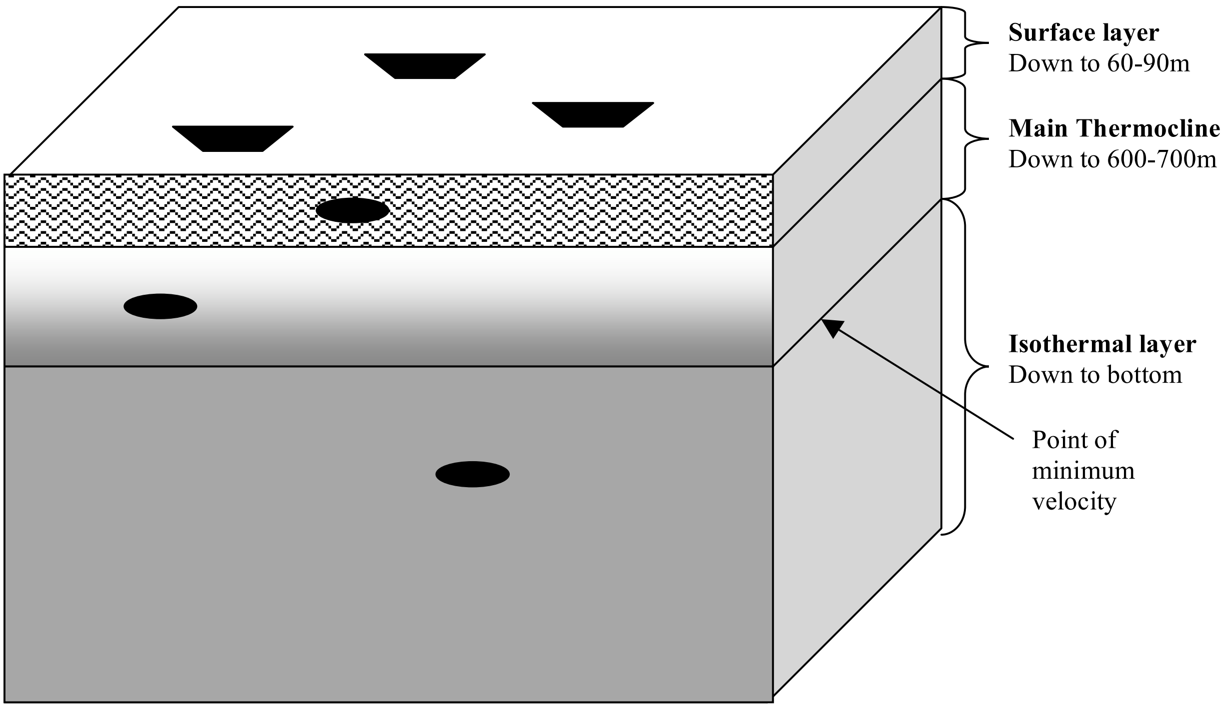

Figure 2.1

Layers in the water column

The surface layer gains and loses heat in response to influences such as sun-light and changes in season. This means that parts of the layer can be warmer than the other, leading to the common phenomenon of temperature increase with water depth. The layer can go as deep as 60 – 90 meters (> 200 feet) (Hassig 1992:67).

The next layer is called the thermocline. In this layer the temperature drops steadily reducing sound velocity more than pressure raises it. The layer stretches down to around 600-700 meters (approximately 2000 feet). At the bottom of the thermocline the velocity of sound reaches a minimum, and the water temperature stabilizes at around 4 degrees Celsius (around 39 degrees Fahrenheit).

From the thermocline to the bottom is the isothermal layer with a constant temperature. Here, the sound velocity increases as pressure increases with depth.

If a submarine is in the surface layer, much of the noise from the submarine will be confined there by reflection and upwards refraction, contributing to the loudness of the environment which is already there because of surface traffic, sea life and other environmental factors. The surface layer is, in short, a very complicated and noisy environment for acoustic sensors.

2.2.2 Sonobuoys

Probably the most distinct feature of airborne ASW is the dropping of sonobuoys in order to search for frequencies emitted by the submarine. The submarines are mechanically driven, and emit sounds from their machinery in almost all circumstances. The sounds come from external units such as the propeller(s) and hydroplanes, or they come from internal equipment such as electrical generators. The aircraft drops disposable sonobuoys into the water, which is really a floating microphone, listening for sounds from the ocean. After dropping the buoys, several factors complicate matters.

Oceans tend to be noisy, regardless of geographical position. Sea-life, shipping-traffic, surface winds, and seismic activity are examples of what is referred to as ambient noise. One of the challenges for the analysts onboard the aircraft is to distinguish between this ambient noise and the frequencies emitted by the submarine. Of course, this ambient noise is also known to the submarine commander, who in turn will try to “hide” the sounds of the sub among these ambient frequencies.

As mentioned in the previous section, oceanographic factors such as salinity, temperature and pressure have an impact on how sounds move through the water. These factors change daily, as well as in concert with the season. They also differ according to geographical factors such as proximity to lakes and fjords, in littoral waters as opposed to the open ocean, seasonal changes to temperatures and seasonal

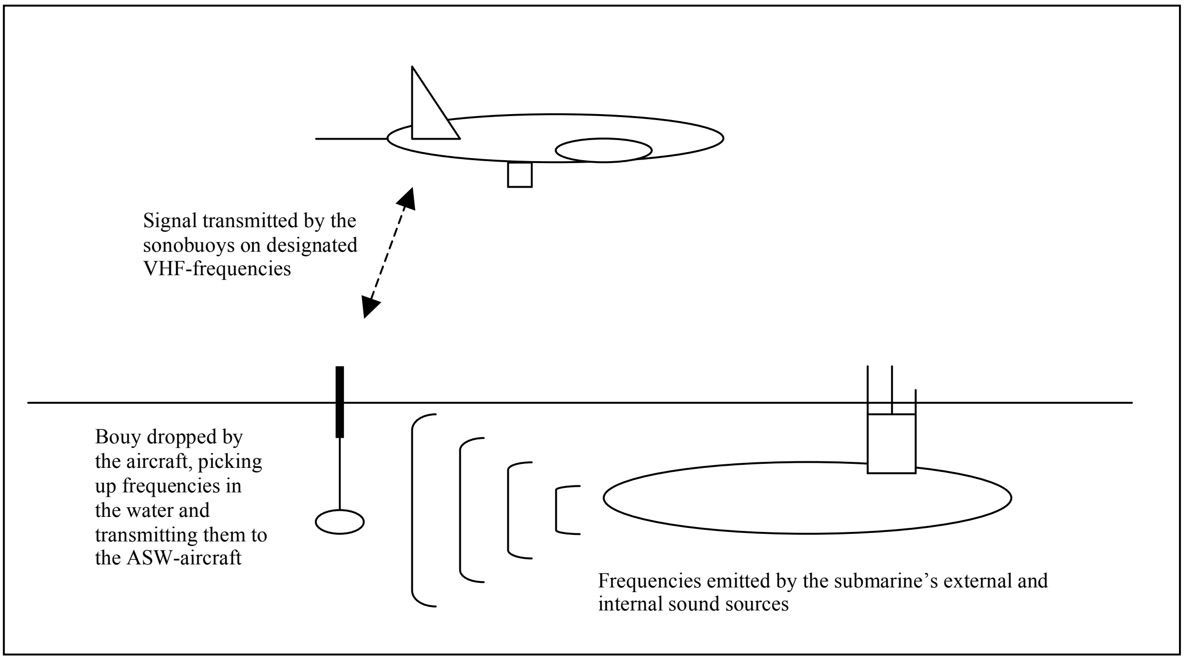

Figure 2.2

Acoustic sensors

changes to currents and winds. And as explained, these oceanographic factors and their layers determine where and how the sounds from an emitter are distributed. One example of submarine tactics is that if there is a clearly defined layer in the upper part of the water column, which the sound waves are moving away from, the submarine will try to stay beneath the layer in order "steer away" the emitted sounds that can be recorded by sonobuoys placed on the surface. In turn, the sonobuoy operator will lower the hydrophone to get it underneath the layer in its search for submarine sound waves, in case he doesn't find the submarine inside the layer. The submarine skipper is aware of this capacity, and may in turn move closer to the layer or even into the layer, in order to mask the submarine's own noise behind the sounds that are close to the surface.

In addition to these challenges to the ASW-aircraft, the submarines are becoming quieter and quieter. Diesel-electric submarines are both very loud and very quiet. When the batteries are fully loaded, the only sounds being emitted are those of the mechanical, external parts and a little of the internal machinery such as the gearboxes. The electronic components have become almost undetectable. But when the batteries need to be charged, the submarine will be on the surface and running its diesel engine. The diesel-engines have become quieter by the years as well, but have distinctive engine sounds that spread very easily through the water. However, with more and more sophisticated battery-technology, where the sub has to conduct charging more rarely during a mission compared to earlier, the noisy charging-process is likely to occur only during prolonged missions for the sub, as opposed to during the relatively short on-station period of the ASW-aircraft.

Placing small, mobile sensors in a volatile environment such as the ocean will always pose challenges. Most sonobuoys do not have any positioning equipment on them by themselves, and need to be located by the aircraft once dropped. The aircraft computer-system will note where the buoy was originally dropped, but after the drop the buoy will immediately start to drift. The drift is caused by factors such as wind, local currents, seasonal currents and sea-state. After some time in the water the buoys must be relocated, and the updated position must be entered into the aircraft computer. Some buoys have now been developed with GPS embedded into the buoy itself, which makes them able to transmit their own position together with the sound-information they are gathering. This keeps the aircraft computer updated at all times as to where the different buoys are located, obviously helping a lot in the job of locating the sounds in the water. This solution, however, is quite expensive, as the buoys are disposable and only used once.

Another challenge is the life-length of the sonobuoys, which is variable by the operator from 30 minutes to 8 hours. The life of a buoy can be set by the operators, and is usually set according to the tactical situation. When the aircraft is prosecuting a submarine the crew and their computer must keep track of the remaining life of the buoys, so that the submarine doesn't get away due to buoys not functioning any more.

The accuracy of the sonobuoys is an important factor to the operators of the ASW-aircraft. As mentioned, distinguishing between sounds emitted by the submarine and other sounds in the water will always be a challenge, but once this distinction has been made it is necessary to pinpoint where the sounds are actually coming from. The delay made by the sound moving through water at a slower speed than for example light, gives the buoys the disadvantage of pointing towards where the submarine was several seconds ago. Working "in the past" like this can be difficult. The operators of the aircraft must always try to predict the movement of the sub as a continuation of the movements just made, or place the sensors to safeguard from turns and shift in depth performed by the submarine.

If a sonobuoy is only able to listen for submarine frequencies and other sounds in the water, it is usually referred to as a passive bouy. Bouys that transmit a sonar sound around it function almost as an underwater radar, which sends out an electronic signal in order to receive an echo of the emitted sound returned by the submarine. These buoys are referred to as active sonobuoys. With knowledge of the local water conditions, and the speed of sound through it, the distance and possibly the direction of the submarine from the buoy can be instantly calculated, thereby accelerating target localization (Mason 1987:104). The downside to this is that the submarine will be warned that it has been detected.

2.2.3 The acoustic challenge

The acoustic challenge is illustrated through figure 2.3, where the sound of a submarine versus its range from a passive sonar is depicted. Both submarine curves show how the sound of the submarine radiates through the water.

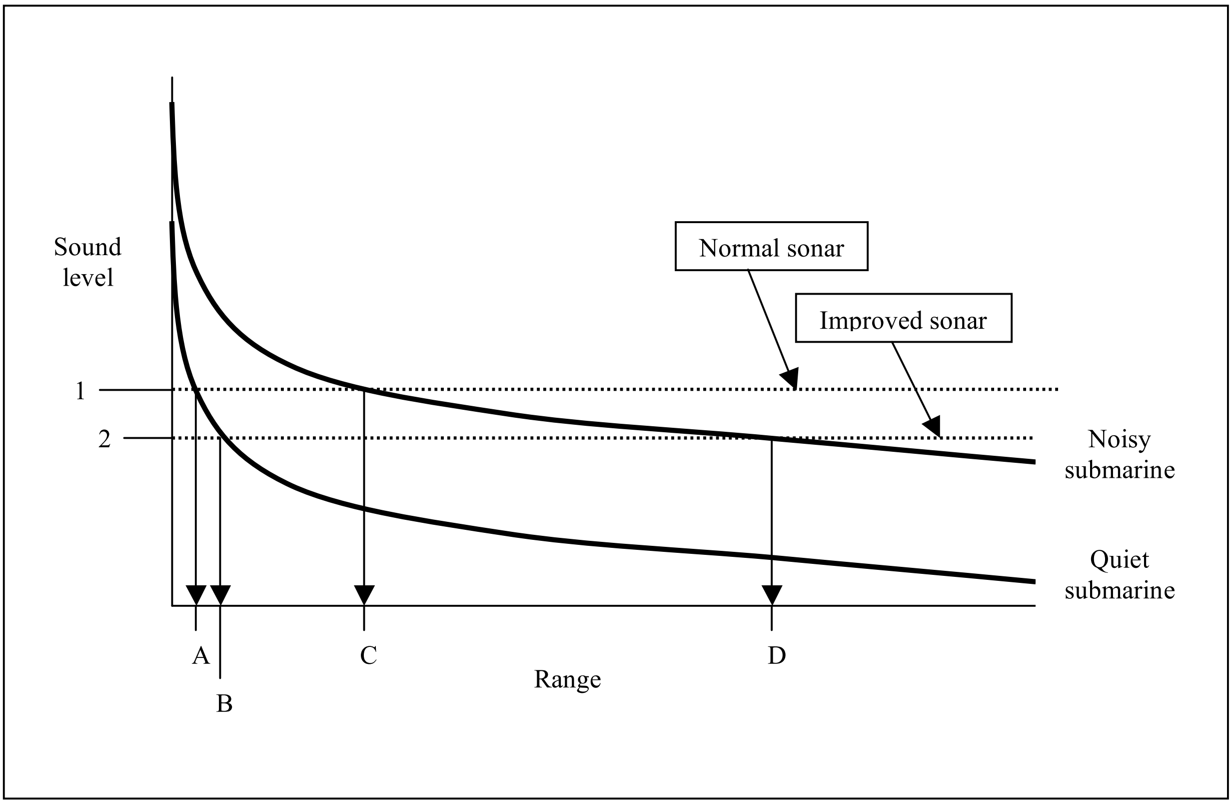

Figure 2.3

The acoustic challenge

The sound diminishes with the square of the distance, which means that by doubling the distance you cut the sound by a factor of four. After reaching the bottom, the sound expands cylindrically as opposed to spherically, and therefore diminishes directly with distance rather than by its square.

Looking at the graph, the normal sonar will detect the noisy submarine at the range of point C, and an improved sonar will be able to detect the noisy submarine all the way out to point D. Now the quiet submarine starts much lower on the graph, and quickly drops to the point of detection for both the normal sonar as well as the improved one.

In plain terms, this means that more passive sonar equipment is needed in order to cover the same area acoustically than was the case before. Another thing to read out of the graph is that further improving the sonars will not do very much with the problem. The solution seems to be either converting to an active sonar or sonobuoy at an earlier point in the tactics deployed by the ASW forces, or using non-acoustic sensors in the search for the target. This refocusing on non-acoustic sensors, and the research being done to meet the acoustic challenge has been called one of the greatest technological challenges facing the Department of Defense (Congressional Hearing 1989:62).

2.2.4 The littoral challenge

Anyone who has been involved in the cat-and-mouse game that is an ASW-operation or exercise, will report that littoral waters and the archipelago is a navigational nightmare for the submarine and a oceanographic nightmare for the surface and airborne ASW-forces. The navigational factors playing against the sub have already been mentioned. The oceanographic factors working against the sensors deployed by the ASW-forces are small islands, sticks, floating devices and marine life on the surface confusing the radars. The same problem is working against the visual lookout by the crew. Looking for electronic emissions done by the submarine such as the sub emitting radar signals or radio communication is like searching for a needle in a haystack, with all the other electronic signals flying through the air from emitters on land. Acoustically, the traditional search method for looking for a submarine, the near-shore environment is immensely complex, with an increased amount of dense surface traffic (as opposed to the open seas), the shallow water providing more noise from sea life, and currents and weather factors creating an unpredictable path for the sound waves. Magnetically one is working with a shallower water column, having ship-wrecks and other items on the bottom providing false hits for the magnetic anomaly detector (MAD). In short, the littorals and the archipelago is incredibly complex and challenging for the ASW-forces to search for the submarine in, and can be very challenging for the submarine to navigate through.

But the new SSKs are tremendously efficient in littoral waters. Examples of efficient SSKs are the German produced Dolphin-class, the Russian produced Kilo-class and the Chinese produced and heavily Kilo-influenced Yuan-class. Being smaller than the nuclear boats, they can more easily operate in the littorals. Their stealth factor is increased by the fact that a ship's sonar or an MPA's passive buoys' effectiveness is degraded in these waters. Reasons for this include the fact that in shallow waters the sonar signals can bounce off the bottom and thus send confusing signals back to the operator. The sound-search is also disturbed by the general clutter of sounds in the littorals. More sea-life, more shipping traffic, more wrecks at the bottom and more general ambient noise interfere with the signals. Sounds are also refracted and reflected by the different layers in the water column that are more clearly distinguished from each other in coastal waters. This phenomenon is especially noticeable in areas where there is little storm activity, such as in the Persian Gulf, and thus little mixing of the cold and warm layers in the water. Strong currents and fresh-water run-off from rivers also create confused layers of salinity, which again degrade sonar effectiveness (Thornton 2007:112). Simply put, an SSK operating in the littorals can be very hard to find.

The characteristics of the littorals actually enhance the SSK's offensive capabilities. It becomes hard for the surface ships to protect themselves, given that any incoming torpedoes fired from submarines will be difficult to pick up on sensors, again because of coastal clutter. The lack of maneuvering room close inshore will also hinder evasive tactics for the attacked unit. These factors lead up to a situation, where powerful navies are being dragged into littoral waters where they may have to face the asymmetric threat of better SSKs in an environment which enhances the SSKs capabilities while degrading those of their notionally more powerful opponents
(Thornton 2007:113). The naval battles between Iran and the U.S. Navy in April of 1988 taught the hopelessly outclassed Iranian forces that large vessels are vulnerable to air and missile attacks, and led Iran into an official doctrine of asymmetric naval warfare (Haghshenass 2006). They have consistently acquired and developed small, fast weapons platforms in the form of lightly armed small boats and missile-armed fast-attack craft, and midget and diesel-electric attack submarines. In 1999 Admiral Cebrowski, the head of the Naval War College and the Naval Warfare Development Command directed broader littoral aspects to be explored in the annual Global War Game held at the Naval War College (Work 2004:48). Naval exercises and war games have consistently addressed near shore issues since the turn of the century, in order to try to meet these challenges.

A Norwegian submarine commander discussed littoral challenges in 1994, and looking at the (at the time) current state of ASW technology somewhat pessimistically exclaimed that "*there is nothing yet to indicate that we are facing a technological breakthrough with regard to coastal or inshore ASW*" (Till 1994:159). With the development of non-acoustic technologies in the past decade, there might be some hope for the fjord-navigating ASW commander. But there is no single technology, including LIDAR, that stands out as the salvation for littoral ASW forces.

A common tactic for submarines is to deliberately move into a position closer to the shore, in order to complicate the search for the ASW-forces.

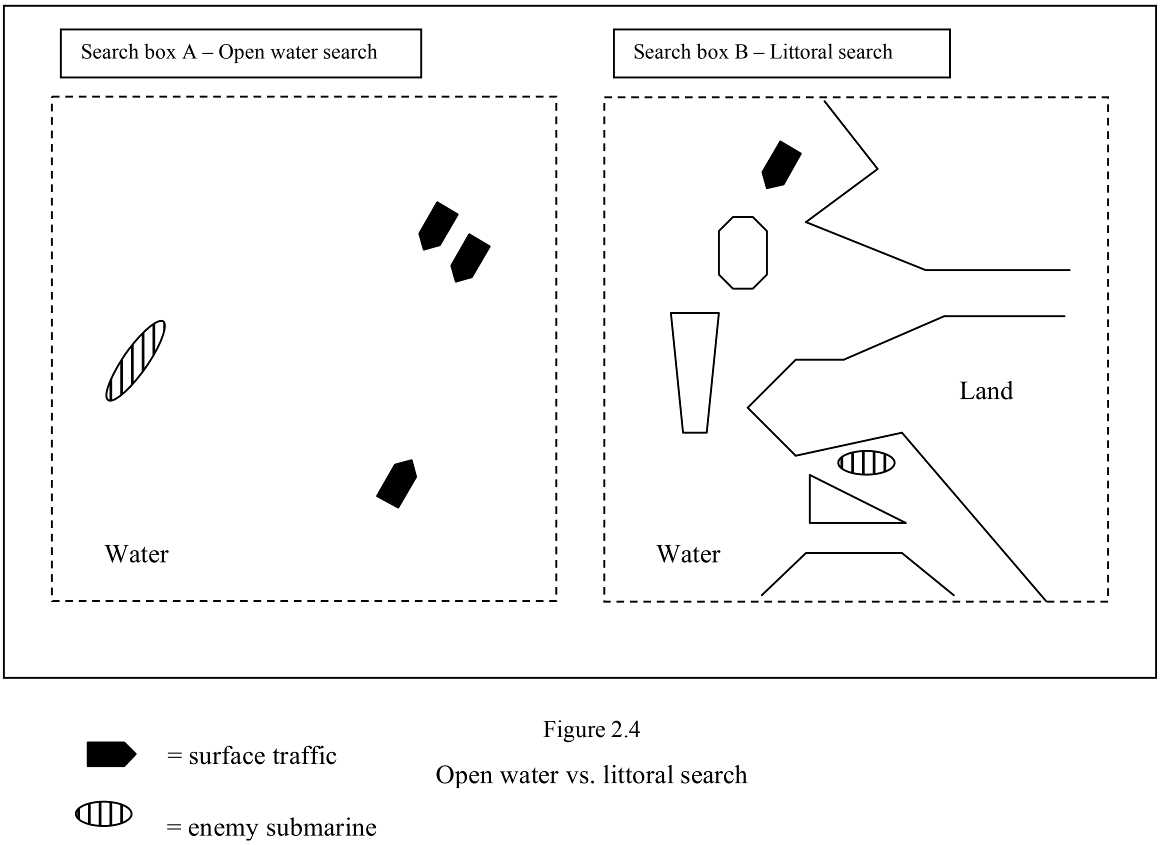

Figure 2.4
Open water vs. littoral search

Not only is the environment more intense and the sound-sources more dense, but the ASW-assets are forced to work physically more close to each other, which necessitates a strict coordination of deployment of sensors. This is much more easily coordinated further from the shore, where one is able to draw up lines for each asset's search-box. In a fjord, or close to the archipelago, this becomes much more complicated as the entire area of interest may be the fjord itself or the inlet to one or several fjords. The complexity of integrating ASW forces in near-shore environments were shown through exercises as early in the mid- and late 1980s, and is still a challenge (Grove 1991:120).

The open water search in search box A (figure 2.4) might be the classic transit along sea-lines of communications (SLOCs) away from the shore, like in the case of transiting between continents, from an island country to a mainland continent and so on. This search environment will always be relevant, however, it has been toned down somewhat in the later years. Several submarine types have been specifically designed to track and target big aircraft carrier groups (Pike et al. 2000). Sailing from its homeland into a theatre of war, such groups consist of an aircraft carrier ship with supporting frigates, submarines and logistic vessels. To meet such an extensive force out at sea demands a significant amount of logistics, not to mention training and sophistication of equipment. Few nations are able to meet this challenge with their peacetime organization of their military forces.

The submarine in search box B (figure 2.4) must navigate through narrow straits and fjords, but can do so slowly and in established shipping lanes. A proficient submarine skipper will mask the noise being emitted by the vessel into the water behind merchant ships and fishing vessels. This will make it even harder for the ASW-forces to single out the enemy submarine from a friendly fisherman. The task usually being intelligence gathering, sabotage or letting on and off agents and special forces, the smaller submarines necessarily have to get close to the shore due to the nature of their mission. Instead of meeting their target out at sea, or patrolling the oceans waiting for the executive order to fire a missile, the small attack submarines are forced to approach enemy territory in order to accomplish their mission. In other words, many submarines are forced into a challenging environment to navigate through, however one that provides plenty of opportunity to hide and lurch their way towards their goal.

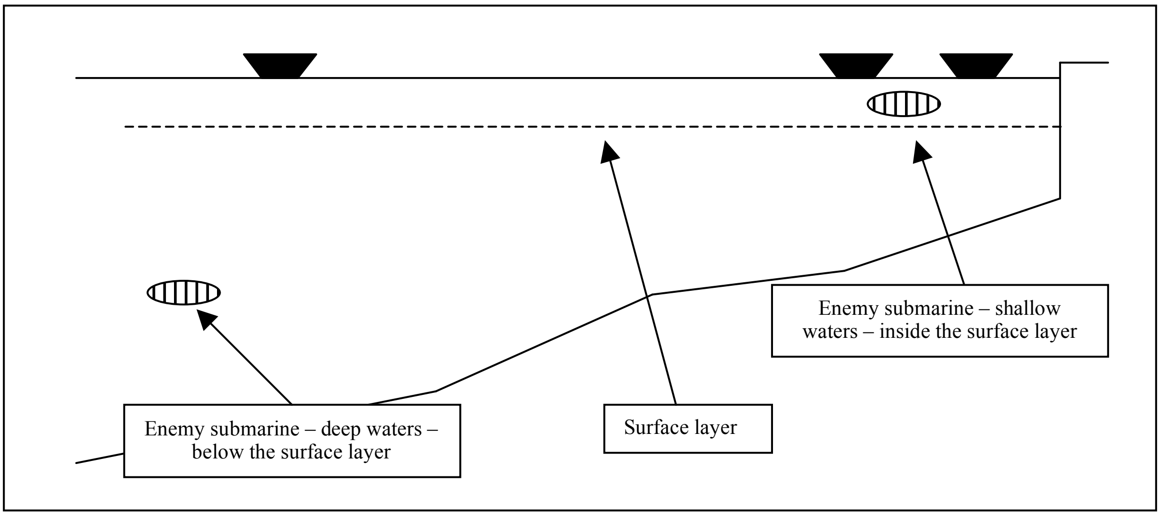

Figure 2.5

Deep vs. shallow search

Both offensively and defensively, the dense environment of search box B (figure 2.4) is preferable to the submarine. Although a challenge to the navigator, the submarine is able to hide both behind physical hinders such as small islands, and oceanographic factors such as the noise from shipping and other activity.

Acoustically, the littoral environment is enhancing the submarine's ability to operate covertly. Figure 2.5 shows two submarines, one out to sea and one close to the shore. The submarine close to the shore is able to hide acoustically behind the noise from surface vessels nearby, and together with ambient noise the surroundings are often masking out the sounds from the submarine altogether. The submarine that is out to sea is operating deeper and is much more free to navigate with much less obstacles and surface traffic disturbing her mission. However, operating below the surface layer lets the sonars of surface ships and MPA sonobuoys function optimally, and the traditional acoustic advantage of the ASW forces comes into play. This advantage is removed when the submarine is working close to the shore.

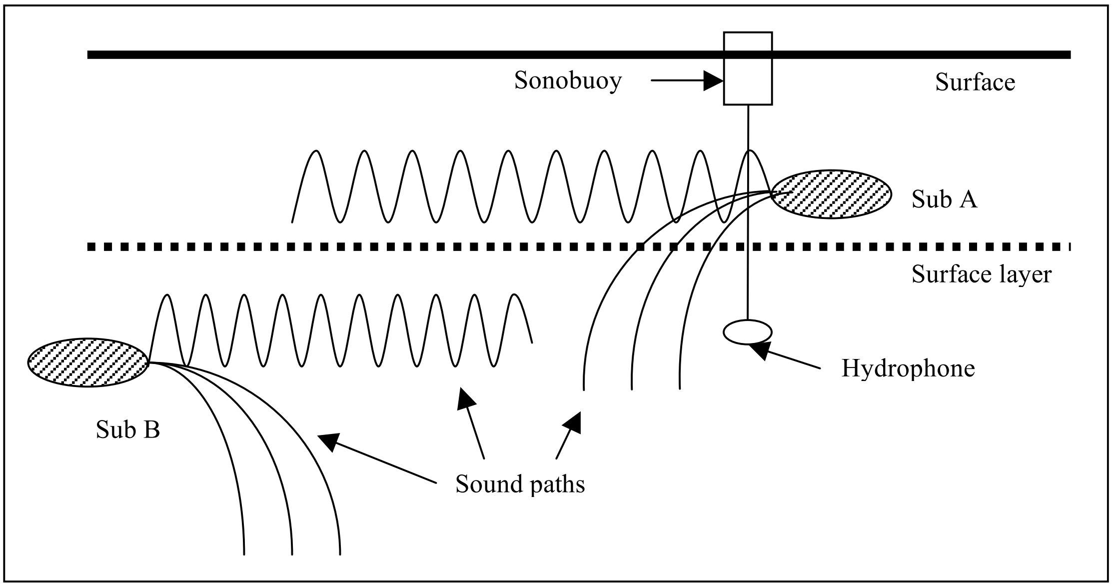

Figure 2.6
Acoustic tactics

In figure 2.6 the two submarines are in two different acoustic situations, although they are geographically close to each other. Submarine A is inside the surface layer, close to the surface, moving in an environment where it is very noisy and difficult for the hydrophone dropped by the aircraft to operate efficiently. Some of the sounds emitted by submarine A escape the layer, but this is very little and is hard to pick up. Submarine B is below the layer, more free to maneuver but is also more likely to be detected by traditional acoustic sensors. The paths of the sounds being emitted by the submarines belong to an oceanographic discussion, but suffice it to say, most of the sound follows a direct path, and some of the sound is bent downwards towards the bottom with cooler, more saline water where the sound moves slower, before being bent upwards again because of the pressure, as was mentioned in section 2.2.1.

The challenge of the littorals lies in the fact that most of the submarines will work closer to the noisy upper sound layer, where traditional means of acoustic detection are less effective.

2.2.5 Multistatic systems

In order to meet this challenge acoustically, multistatic systems have been developed that will search for a submerged target under difficult acoustic conditions. Monostatic acoustic systems consist of one active buoy that sends out a sound, or a ping, which reflects off the target submarine and returns to the buoy. The system is very much like an underwater radar, and is usually just referred to as "*active buoys*". Bistatic systems consist of two platforms, for example two ships or two separate buoys, where one platform is the active one and the other is the passive. Figure 6.1 shows monostatic and bistatic examples.

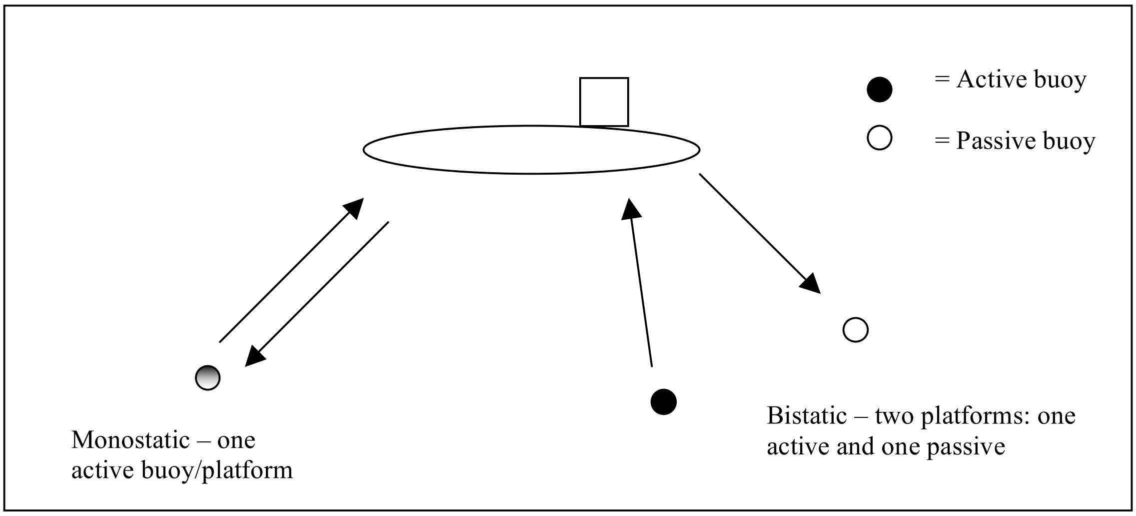

Figure 2.7

Monostatic and bistatic systems

But when using active sensors, it's the use of multistatic systems that provides the real benefits. Low frequency multistatic systems have been under development for at least

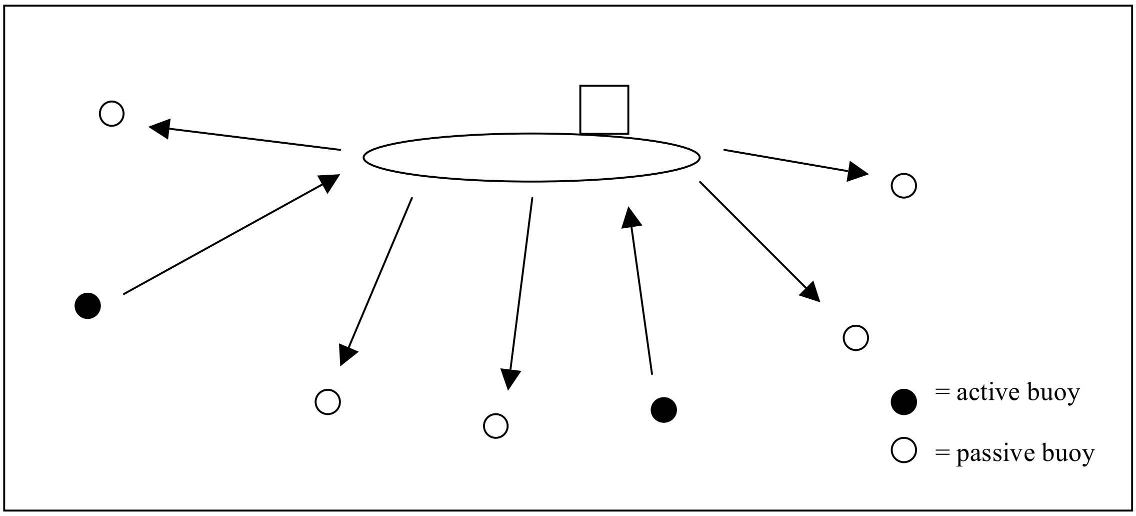

Figure 2.8

Multistatic system

10 years, and have focused on the active parts of the system that can be deployed wherever the ASW forces need them. Multistatic systems have several passive platforms or buoys, and often more than one active pinger or explosive buoy. The system will note the timing of the transmitted pings or explosions, and then record the returns on all the passive sensors. This will give the computer the opportunity to triangulate the position of the enemy submarine.

There are operational multistatic sonar systems in use by MPAs, and several systems are under development. These are capable systems, but they have their limitations. The multistatic systems are active and very revealing when it comes to letting the enemy submarine know about the presence of the ASW force. And the multistatic systems are not as efficient in littoral waters, due to the proximity to the bottom, the shore and the archipelago. These factors will provide many false and confusing returns. Also, fresh water, differences in temperature, turbulence and currents in the littorals will create layers in the water, which complicate all sorts of acoustic searches, no matter how efficient they are.

2.3 Non-acoustic sensors

2.3.1 Radar

With the technology constantly improving, the ASW radars of today have an impressive portfolio of features. They offer multiple-target tracking and a classification capability, giving the outlines of targets at long ranges. The radars are able to give a high detection and tracking performance despite high sea states. Several radars also have an Identification Friend or Foe (IFF) capability, as well as an air-to-air and a weather mode. ASW radars of today can be expected to detect large ships out to 150 nautical miles (nm) or more, vessels under 100 tons at 40 nm, surfaced submarines at 75 nm and snorting submarines at 20 nm (Laite 1991:51).

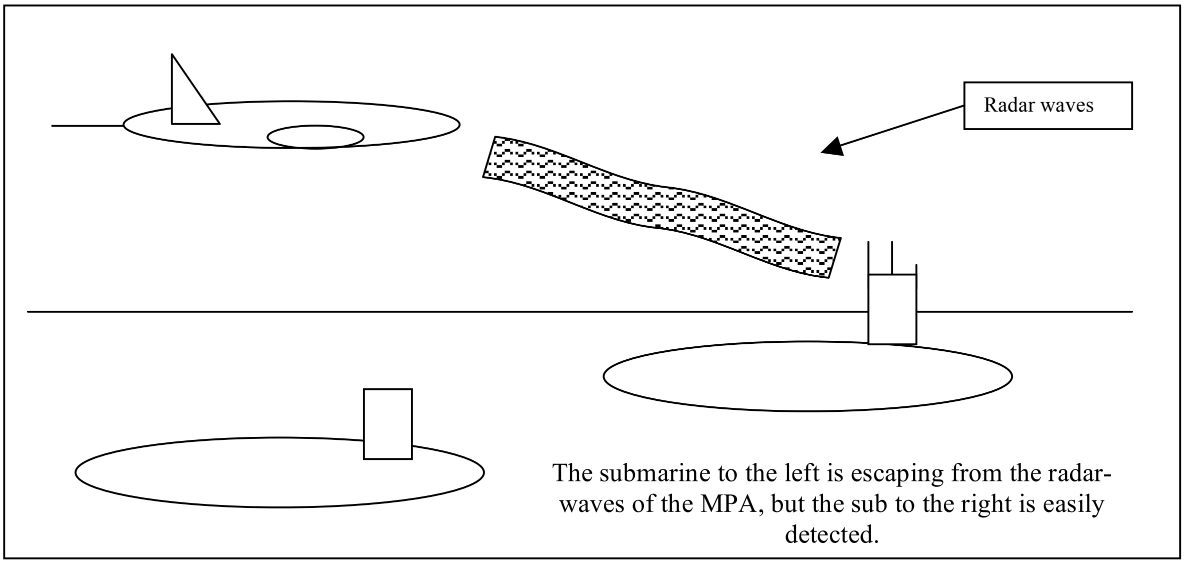

Figure 2.9

Radar

More accurate numbers presenting performance are classified, and are constantly improving. Newer radars have the ability to provide a visual reproduction of the radar profile of the target ship, called Inverse Synthetic Aperture Radar (ISAR). This is an important feature for a cost-efficient surveillance mission.

The proper way to use radar tactics is a science in itself. But regardless of operator efficiency, the sub can easily escape the MPA radar by staying submerged. The wavelength of radars does not penetrate water, making the operator only able to see what is on the surface.

2.3.2 Electronic Support Measures (ESM)

The ESM-equipment gives the operator the ability to search for, locate and classify electronic transmissions made by the adversary. New systems have a wide radio frequency (RF) bandwidth, and are able to search for a wide range of electronic transmissions. The classification is based on comparisons of the features of the intercepted signal with a computer memory store of many of the transmissions likely to be heard. Military intelligence also provides frequencies and other electronic parameters for the operator to look for. Although most navies are imposing severe restrictions to the electronic transmissions allowed to be made, some transmissions have to be made regardless. Examples include vital communications, occasional sweeps of area-defence radars, and the concentrated aiming of live-fire-control radars (Laite 1991:52).

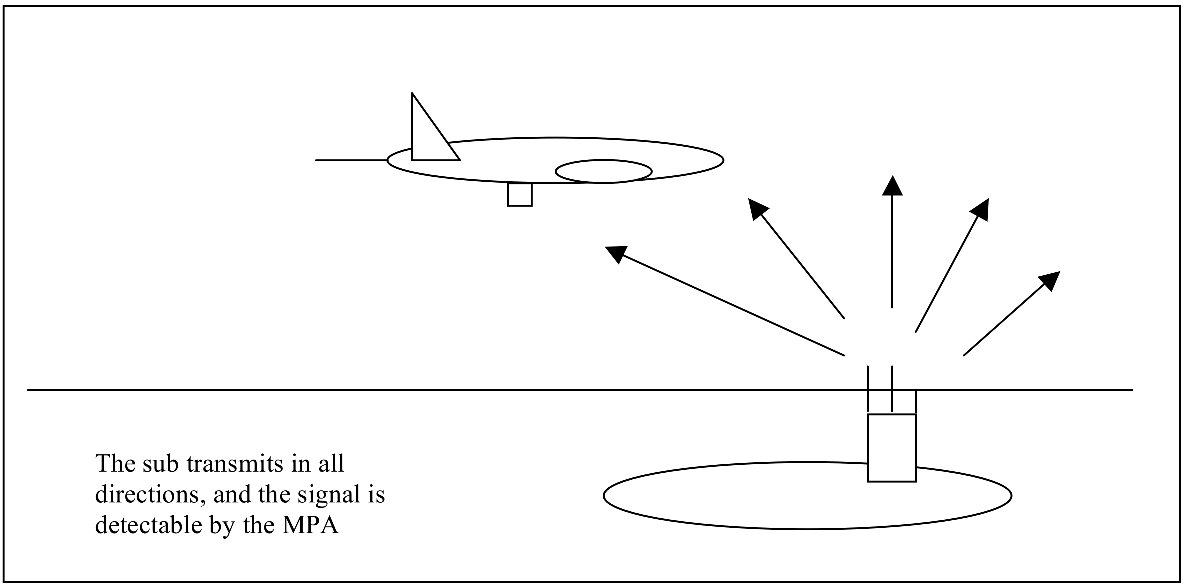

Figure 2.10

ESM

The downside to this sensor is the same as with radar, and has one in addition: First, the submarine has to be surfaced, or at least have to expose her radar mast. Second, the radar antenna has to be emitting. Simply put, the submarine is undetectable by the MPA ESM-equipment if it is submerged or has the radar turned off while on the surface.

2.3.3 Magnetic Anomaly Detection (MAD)

Most MPAs have a boom-shaped tail which easily distinguish them from other types of aircraft. The equipment inside the boom consists of magnetic sensors, and is used to detect changes in the background magnetic induction that are associated with submarines. In other words, the sensors pick up disturbances in the earth's magnetic field. The Earth's magnetic field usually varies slowly over distance, but when a submarine is present the field changes rapidly and may de detected by a low flying aircraft carrying MAD equipment. Submarines contain a large amount of metal that becomes magnetized in the course of normal operations. Large metal objects will always disturb the magnetic field that is distributed between the North and South Pole, and in the case of ASW, the submarine functions as a large chunk of metal in the water. When the aircraft flies at a low altitude, this disturbance is noticeable, and will be recorded by the operator inside. The disturbance is not nearly significant enough to provide an efficient means of searching for the submarine, but it functions as a tool for confirming the presence of the submarine.

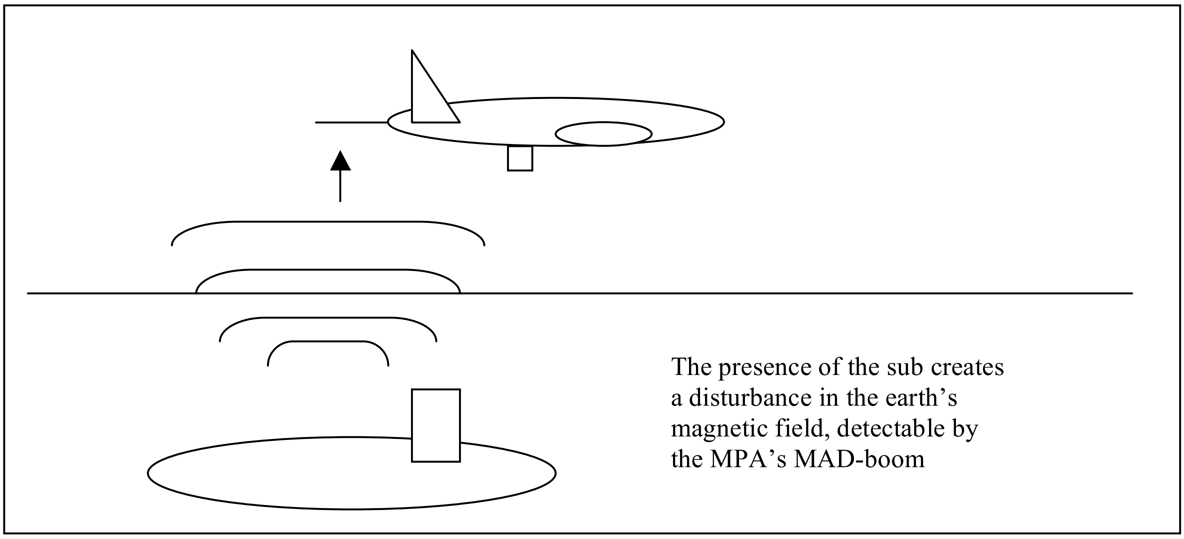

Figure 2.11

MAD

The immediate downside to this sensor is that one cannot use the MAD to perform a blind search for a submarine. It is, however, a valid and good complementary sensor. Also, it performs poorly when it comes to a littoral search, as the sensor will react far too easily on false targets, such as ship-wrecks and cables on the bottom.

2.3.4 Electro-Optic/Infrared Cameras (EO/IR)

Cameras have always been important sensors for the MPAs in their gathering of intelligence of all sorts. Starting with handheld cameras almost as early as the first airplanes, moving on to cameras integrated with other sensors and built into the airframe itself today, they provide details for further analysis either in-flight or post landing. The new EO/IR cameras of today do not function very well as a search asset, but they give an extraordinary opportunity to zoom in on a prospective target from a distance and classify it without having to fly all the way up to the target only to have the eyes of the aircrew do the same thing. In addition, one is also able to study a target or an activity from a distance, safe from possible hazards such as gunfire or portable rocket propelled grenades (RPG).

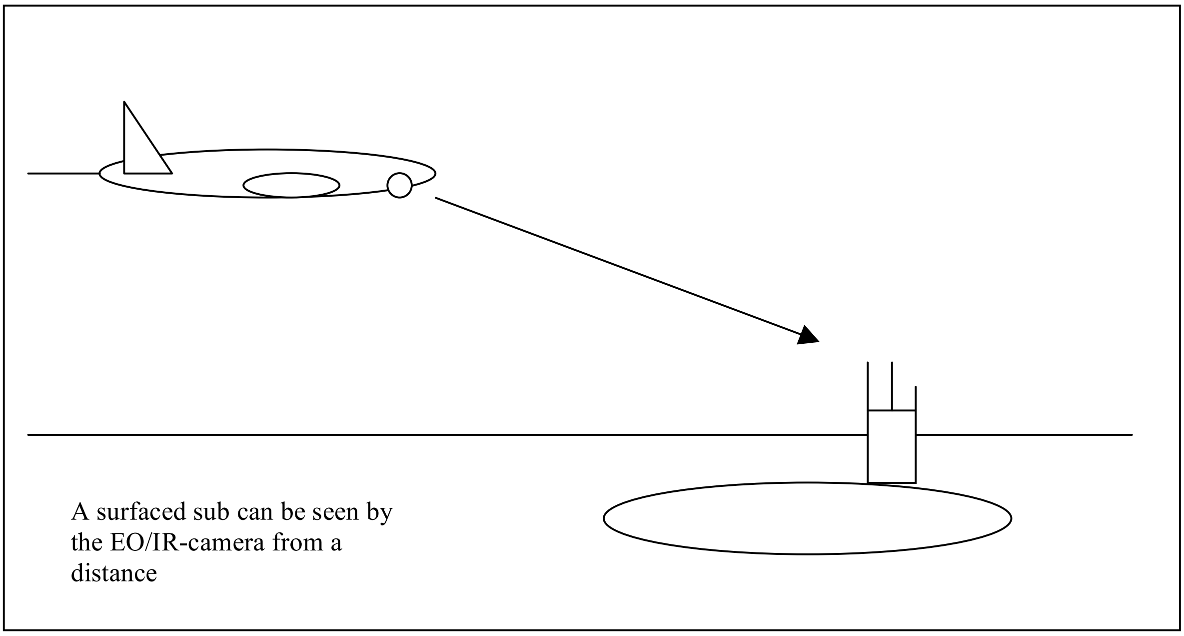

Fig 2.12

EO/IR

An obvious downside to this sensor is that the submarine has to be surfaced if the camera is to be able to classify and provide further details for the aircrew. Because of this simple fact, the modern cameras are of little use when it comes to actually searching for a submerged submarine.

2.4 Summary

Antisubmarine warfare (ASW) is a complicated business. The flying crew needs to understand the environment they are working in and they need to have a working knowledge of the particular equipment they use and how well it might function. Those who are involved in ASW need to have a wealth of material available at all times. Speed of reaction, flexibility to change operating areas quickly and efficiently and the ability to deploy sophisticated buoys are all in the advantage to the aerial ASW platform. They have an array of sensors in addition on board that will help them accomplish their mission, be it covertly following the enemy submarine or hunting it down in order to neutralize her. But as the submarines get quieter and quieter, the aerial ASW sensors are lagging behind, and moving the operational area into littoral waters certainly complicate matters for the aircraft, as well as for other ASW platforms. The existing sensors do not perform as well close to the shore as they might do out to sea, and in order to stay on top of the game one has to investigate additional methods for detecting the adversary submarine and stay in control of it. This thesis seeks to explore the potential of one such method, and recommends in the end a way forward for meeting the current littoral challenge.

3 – LIDAR technology explained

3.1 Background

The term "*LIDAR*" is an acronym for LIght Detection And Ranging, and the technology is in effect based on laser equipment and additional analyzing equipment. LIDAR systems in use are all based on laser technology. The laser is used as an active sensor, emitting light with known characteristics and comparing the transmitted light with the returned signal from the object which it illuminates. Timing of pulses, wavelengths and angles of the returned signals are all part of the analysis of returns that the LIDAR system processes, in order to describe the shape, presence or structure of the illuminated object. Systems that for example measure the depths of coastal waters and lakes from low-altitude aircraft use a scanning, pulsed laser beam. The LIDAR system transmits laser pulses into the water, and analyzes the pulses of light when they return.

The laser – an acronym for "*Light Amplification by Stimulation of Radiation*" – was invented in the late 1950s, initially for scientific purposes and industrial applications, and the invention is credited to the two scientists Schawlow and Townes for publishing the article "*Infrared and Optical Masers*" in 1958 (Schawlow & Townes 1958). A laser has a narrow beam that does not diverge as it travels from the transmitter, and many applications take advantage of this feature for heating, cutting (for instance surgery), etching and illumination (Campbell 2007:239). The further development has exploded in all directions, and in modern times one can hardly get through a normal day without encountering a device relying on laser technology. Further examples of everyday technology that is based on laser are pointers, CD players, printers, scanners and bar code readers.

In the 1970s several agencies including National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA) and the Defense Mapping Agency (DMA) began developing LIDAR-type sensors for measuring topographic and oceanographic properties (USACE 2002:11-3). Over the past decades, developments in lasers, optics electronics and computers have contributed in making it easier to construct airborne LIDAR systems with varying purposes, and an increasing number are being constructed (Guenther 2006:254).

Airborne LIDAR bathymetry is an accurate and cost-effective alternative to traditional, waterborne sonar systems, given the appropriate depth and water clarity. LIDAR systems usually perform better in relatively shallow waters where sonar is less efficient (see figure 3.1 below). Airborne LIDAR systems can also survey in areas where sonar cannot, like structures above water and over land (Guenther 2006:254). LIDAR has become an essential part of coastal surveying, and large-scale nautical charting has been the main focus for most of the deployed systems. Like the Swedish Maritime Administration puts it: "*the use of a helicopter-borne laser-beam system is essential, especially in shallow waters and narrow waters in the archipelago*" (Nordstrom 2000:37).

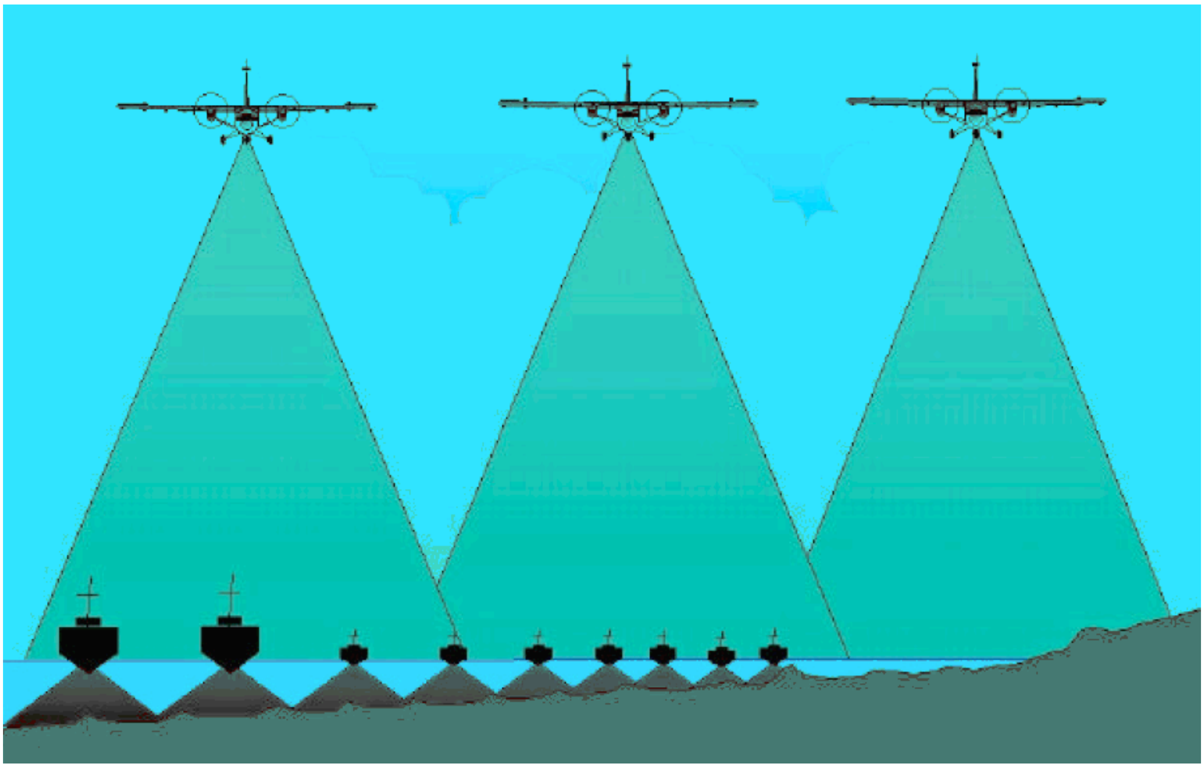

Figure 3.1
Airborne vs. surface based surveys

However, as will become clear through this chapter, the technology applied through water has its inherent limitations. Water clarity, attenuation and scattering of the light beam give a fairly shallow working depth in ASW terms. The presented systems at the end of the chapter will show mixed results, and not very impressive ones, even when functioning properly, submariners might claim. Submarine commanders themselves, knowing about the evolving non-acoustic sensors, are eager to point out that a submarine "*can only be detected one way – by sound – and by going slow it puts out very little sound*" (Gelantin 1995:273). And submarine forums and magazines play down the prospect of developing technologies that "see" through the water, taking the attenuation and scattering of light into account (Buff 2003).

In any circumstance, civilian airborne LIDAR systems are accurate and have a high coverage rate for their purposes. The systems are flexible and mobile, and have a relatively low cost per unit area. Although LIDAR-systems are usually used alone, they are generally complementary with other surveying systems, such as sonar (Calder & Penny 1980:1-21). This will be discussed later with regards to the usage and potential of military airborne LIDAR-systems.

To get an understanding of the basic technology that lies behind the LIDAR systems, and look at the factors which play a role in constructing such a system for the desired use, an introduction to LIDAR technology will be presented in this chapter. The performance of existing and future LIDAR capacities will be discussed, as well as factors limiting this performance.

3.2 LIDAR hardware

3.2.1 Laser light

The laser unit applies an electrical current to a "lasable" material, such as carbon dioxide, argon, helium-neon, rubies, and other less familiar materials. These materials have atoms, molecules or ions that emit light when they return to their normal state after being excited by a stimulus such as electricity. Electricity start the laser, but the key property is that light itself stimulates the lasable material to emit more light and that this light is coherent - it is in phase with the light that stimulated it and composed of a narrow range of wavelengths. Light with these attributes can travel long distances and only diverge slightly, as opposed to "normal" light.

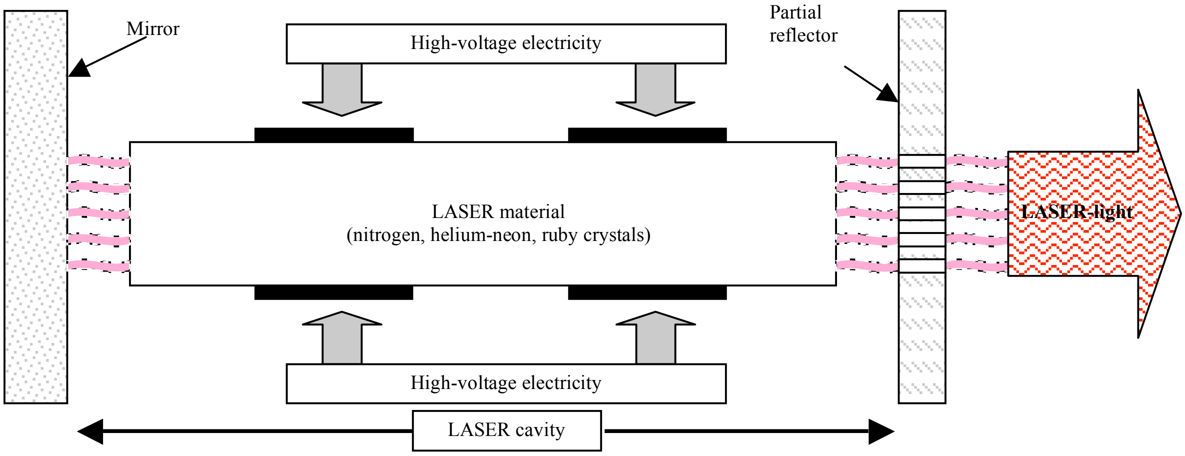

Figure 3.2
Laser in principle
(Campbell 2007:240)

Each separate material provides a specific laser-beam with distinctive characteristics when it comes to wavelength. The laser uses mirrored surfaces to accumulate many pulses in order to increase the intensity of the light beam before it leaves the laser (Campbell 2007:239-249). By knowing the characteristics of the light-beam and timing of the pulses it is possible, with the proper receiving equipment, to record, measure and analyze the returns from different objects. This is what is done by police-officers measuring the velocity of passing cars. They utilize a very simple piece of equipment to illuminate the car with a laser beam, and measure the return based on the known characteristics of the transmitted beam. The calculated result is the speed of the car. The police speedometer is one of the simplest forms of LIDAR usage.

Getting a bit more advanced, one can integrate the laser with the proper electronics, which in turn will arrange laser-pulses in the proper timing-sequence, as opposed to a steady beam, and thus give the transmission the form of incredibly fast pulses of light. Combining this with the appropriate processing of the returned pulses of light, one can start to record and analyse the received bits of information.

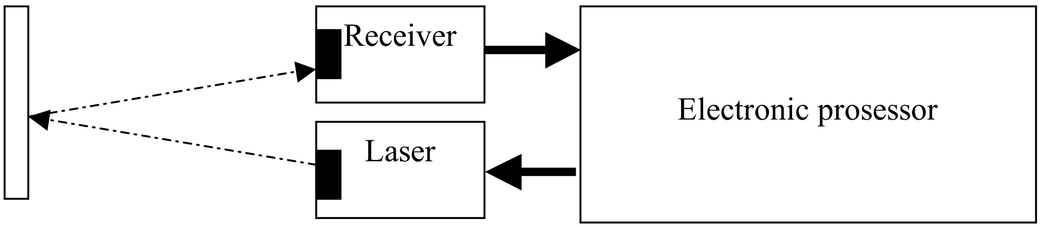

Figure 3.3
Basic LIDAR

The next step would be to feed the light into a system of mirrors, which will redistribute the pulses as a scanning beam like the simplified diagram figure 3.4 shows.

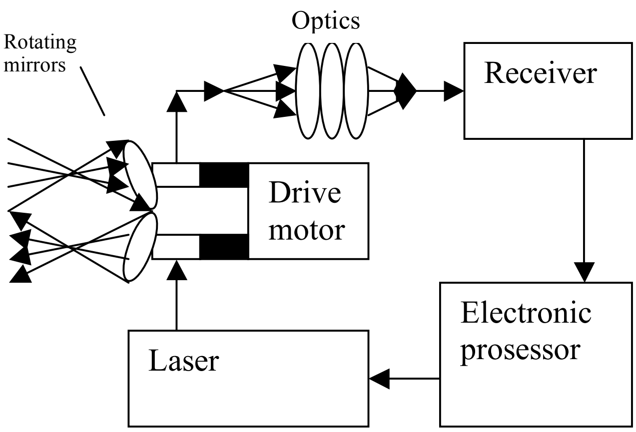

Figure 3.4
Advanced LIDAR
(Campbell 2007:242)

There are several different designs within laser technology, and the above diagram shows only one of these, and in principle. To go into detail of the technology of the laser and the LIDAR themselves is both outside my competence and the scope of this dissertation. I will, however, try to point to some physics factors that affect the usage and further development of such technology. To design a reliable LIDAR system it is necessary to have a thorough understanding of the characteristics of the laser and optics, of the data collection and electronics and as many as possible of the different interactions between the light beam and the environment.

One of the biggest problems that must be solved involves the accurate and reliable determination of the air/water interface for each of the laser pulses. Separate wavelengths within the same scan must be used for this. At least two, widely separated, non-green wavelengths, such as red and infrared (IR), should be used, in order to achieve the highest degree of accuracy for every laser pulse.

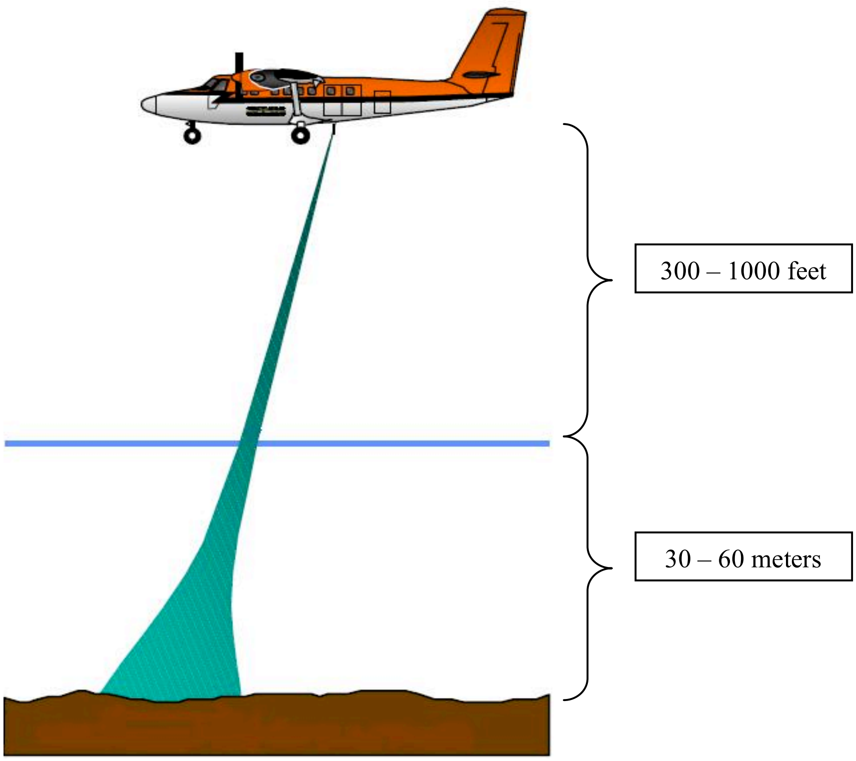

Figure 3.5
Spreading of laser light

A second problem is the immense difference in magnitude of amplitude dynamic range between the very strong water interface returns and the very weak bottom returns – the difference is often more than six orders of magnitude of amplitude dynamic range (Guenther et al. 2000:7). This difference occurs in the course of tens of hundreds of nanoseconds, and must be handled by the detector and further relayed to the digitizer in accordance with the latter's input range, after compressing the signals without distorting them.

These complicating factors create great demands to the laser transmitter, as well as the processing equipment. Unfortunately, the pulse energy, pulse-repetition rate, pulse width and reliability under field conditions for laser transmitters have made slow process after the laser was invented (Guenther et al. 2000:7).

The laser pulse repetition rate is a key factor in developing an efficient LIDAR-system. The faster the repetition rate, the better, as the LIDAR will be able to process a greater area in less time. Over the coming years, faster lasers will be needed and likely available, and repetition rates should approach 10.000Hz, with 5mJ/pulse and 1-2 ns pulse widths (Pope et al. 2001:6). The size, weight and power requirements of the laser equipment must decrease in order to facilitate smaller LIDAR-systems. Also, lasers which are tunable according to the given environmental conditions would increase the portfolio of a given system. The processing challenges will be discussed in the section "*3.3 LIDAR software - Processing the returns*".

3.2.2 Imaging LIDARs

The first airborne LIDARs were profiling lasers, which were pointed directly beneath the aircraft, and would thus be able to map out the elevation profile directly beneath the aircraft. When used primarily to acquire topographic data, or measure the height of the aircraft above ground, these instruments are primarily known as airborne laser altimeters.

In the past decades several technologies have matured, such as data processing equipment and positioning devices, and with these capabilities in place several LIDAR systems are used as remote sensing instruments for collecting detailed information about the Earth's surface and subsurface environment.

The further development of several technological elements has been crucial, of which three stand out.

Inertial Measurement Units (IMU)

The inertial measurement unit measures the attitude of the aircraft, or the orientation in roll, pitch and heading. Combined with the GPS positional data this information provides an accurate positioning of each point collected of the laser returns (USACE 2002:11-6). Precise control and recording of the orientation of the aircraft has been developed initially as a tool for the pilots, but is invaluable to airborne surveying equipment as well. The development of laser gyro-stabilized IMUs have made this technology mature during the 1980s and 1990s.

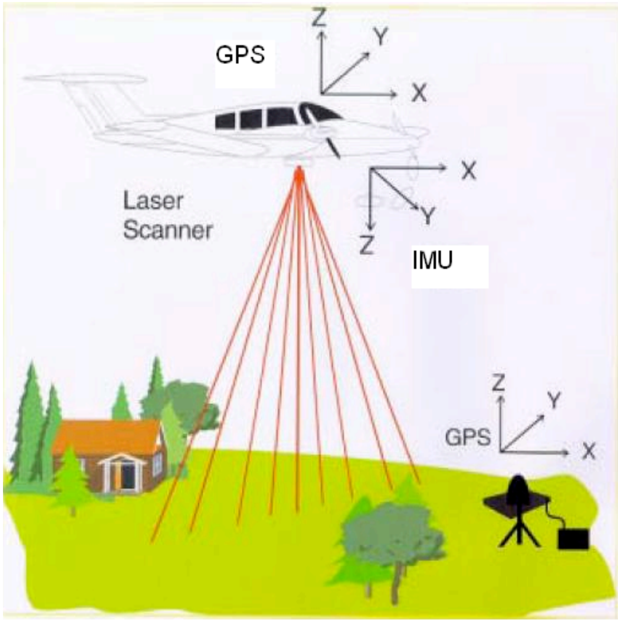

Figure 3.6
Inertial Measurement Units

Global Positioning System (GPS)

An accurate recording of the geographic location of the aircraft is essential to be able to place each recording geographically. The development of the GPS system gives military units as well as civilians an accurate account of their position, and with the system including an accurate time-indication as well the GPS has become absolutely necessary in the design of an accurate LIDAR system.

Using what is known as differential GPS (DGPS) one can input the local error in GPS-positioning (ranges to the satellite derived by an iterative process) and thus generate corrections (see the stand-alone GPS-equipment in figure 3.6). DGPS positioning is used by almost all LIDAR systems, and has an accuracy of better than 3 meters (Pope et al. 2001:6, Guenther 2006:293). The development of carrier-phase, or kinematic GPS techniques in 1997 eliminated the need to collect concurrent tide measurements (Wozencraft & Lillycrop 2002:4). This further gives an accurate position both in altitude as well as geographically.

Clocks

The always improving science of measuring time has led to highly accurate clocks for precise timing of the laser pulses in the LIDAR systems. As the pulse repetition rate desirably will increase, the development of even quicker and more accurate timing devices has kept pace and must continue to do so in order to achieve the proper processing of every transmitted ray of light.

The accuracy of these three units is paramount for the performance of a LIDAR scanning system. With the units properly integrated, the returned signals into the system can be associated with specific points on the Earth's surface. The timing capability permits accurate assessment of distance and elevation, which further leads to a detailed image of the environment that is being surveyed (Campbell 2007:241).

3.2.3 The Processor

The pace of the improvements made by the computer industry has been tremendous over the past decades, and these have had an impact on the development of LIDAR systems as well. One of the biggest challenges of the early systems was the lack of capability to process the returned signals. With the computer technology reaching new heights by the week over the last decades, the technology needed to have a thorough processing of the signals have finally reached a point where one is talking about a "mature" technology or science. The algorithms required to analyze each wavelength have been modified and become increasingly more advanced over the years. This has been done after experiencing new factors in light going through water and air during surveying processes (Wozencraft & Lillycrop 2002:4).
In addition to analyzing the returns the processor merges the positional information with every signal being returned, thus providing an actual position for every single return. This makes LIDAR-mapping possible.

3.2.4 Design philosophies

Different design philosophies are employed for full-capability systems. They differ in their scan patterns, the power of the laser, the spread of the beam or spot size, swath angle, pulse repetition rate, surface detection strategies, and means of handling the signal-amplitude dynamic range (USACE 2002:11-4, Guenther 2006:263). NASA has deployed a system with very short, low-energy laser pulses and a very small receiver field of view in order to achieve good resolution and accuracy. These factors provide enhanced performance in very shallow waters, but lead to a limited depth capability.

What is important for the design of an aircraft-borne LIDAR system is that the area that can be covered per unit time depends on the laser pulse-repetition rate. Higher rates permit faster aircraft speeds and higher altitudes, in addition to higher survey densities important for small-object detection (Guenther 2006:5). This combination of pulse energy and width is not an easy set of requirements for laser manufacturers to meet at such high pulse repetition rates.

To increase operational flexibility it is beneficent that the LIDAR system is small, portable and modular in design. In addition it is important to lower the threshold of technological insight needed to operate such a system. The level of automation for the system should increase and thus provide the operator with an understandable and flexible system (Pope et al. 2001:6).

All these factors have to be incorporated in the design of new LIDAR systems: faster pulses, quicker processing and a more flexible and portable module.

3.3 LIDAR Software - Processing the returns

3.3.1 Wavelength

In classical bathymetry one seeks to establish the depth of the water column. To distinguish the returns of the radar-pulses from each other and analyse them it is important to know when and where each pulse enters the water – that is when the change from travelling through air to travelling through water occurs. To know this, it is important to have a designated, steady beam of transmission that will give you this information.

Taking advantage of what we know about the electromagnetic spectrum and the characteristics of water, experience has shown that the best type of laser light for water penetration is a green, or blue-green laser. This light will actually penetrate the water surface, as opposed to the infrared (IR) beams that are reflected off of the surface. Using these two, different characteristics in the beams simultaneously, one can examine the returns from the top and bottom of the water-column and from within the water column itself, with the knowledge of where the green laser hit the water in mind.

The wavelength typically used for IR-beams in LIDAR-equipment is 1064 nm, which is a wavelength that has proven itself suitable for surface detection. What is exceptionally nice with this wavelength is that is it possible to use the same beam to divert fractions of it and double the frequency of that diverted fraction. The diverted light will then be sent out as a beam in itself. This gives us a wavelength of 532 nm which is the green light needed to penetrate the water-surface (Guenther 2006:265). This feature of splitting one, original beam is playing its part in keeping the hardware small and light.

The wavelength issues of LIDAR for use in water are not as clear-cut as indicated. In an optimal world the equipment would have transmitted two beams, and received two beams. However, the receiver detects several different wavelengths as a result of the original transmission. Some of the green light is reflected immediately as the beam hits the water surface, although most of the light penetrates the surface. Inversely, some of the IR-light penetrates the surface, although most of the IR-beam is reflected off of the surface once the beam hits the water. In addition, the water-column splits the original green-light (see fig. 3.7) and produces in this way several different wavelengths which are returned to the receiver. This process is known as scattering. Lasers are usually thought of as being highly collimated with a small cross section, as they are in space or over short distances in air. This is not the case in water. Scattering causes even the narrowest beam to expand into a cone with an angle and cross section that increases significantly with depth (Guenther 2006:262).

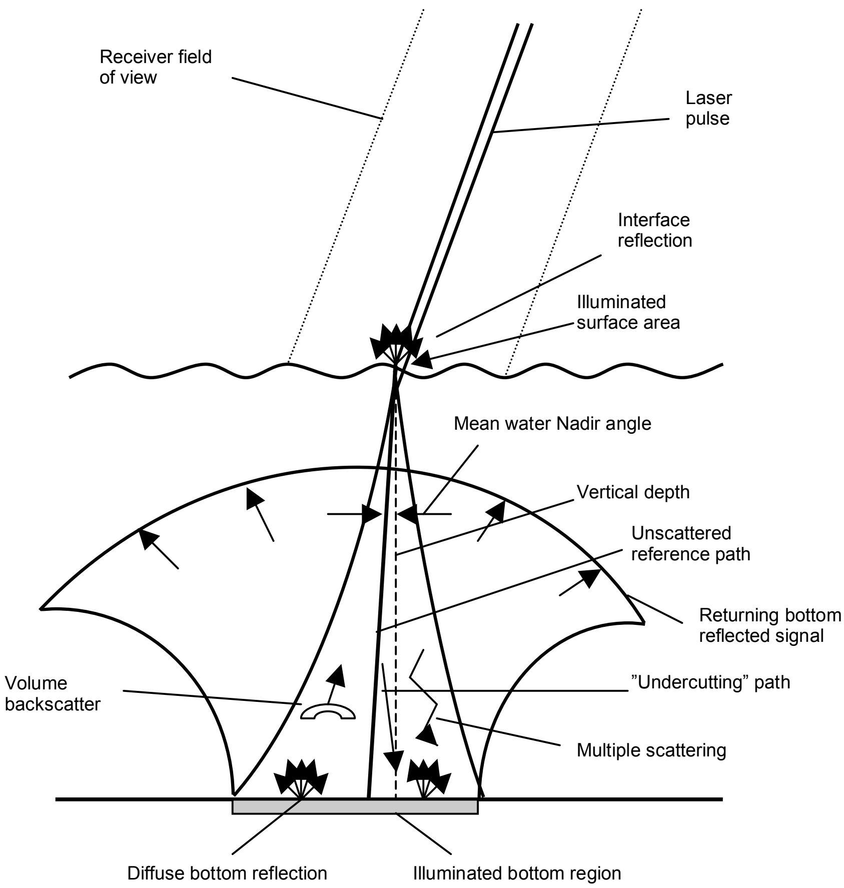

Figure 3.7
Scattering of the light beam
(Guenther et al. 2000:10)

This dictates the receiver to be able to handle and analyze different wavelengths for every transmitted beam of light. After the reception the different wavelengths are separated into specific channels for detection and timing (Guenther 2006:265).

The returns from the water-column are a complex mixture of wavelengths of light, and the faster the platform (e.g. an airplane), the faster pulse-repetition rate of the light-pulses and the more we want out of the information coming back as a light-return, the more powerful a processor is needed to handle the immense amounts of information which are accumulated. The advance in computer-technology in the past two decades has undeniably played an important role in the current and further development of LIDAR as a potent sensor for bathymetry. However, the laser energy lost due to refraction, scattering and absorption at the water surface and the sea bottom significantly limits the strength of the bottom and object return, and therefore limits the maximum detectable depth (Smith et al. 2007:3).

3.3.2 Finding the water surface

Establishing where the laser beam enters the water serves as a reference point for the other returned signals because of the difference in transmitting light through air and water. Knowing the characteristics of light moving through water it is possible to put the different wavelengths through algorithms which will tell us from where and what they have returned. But, as mentioned, all of the green light does not penetrate the surface, and all of the IR-light does not reflect off of the surface immediately.

Green surface returns are a problem. These surface returns can be actual returns from the interface between air and water, but can also be returns from particulate materials in the water column just below the surface. The interface component signal amplitudes have a huge standard deviation (Guenther et al. 2000:8-9). They vary from pulse to pulse, and may be much stronger or much weaker than typical volume backscatter returns. Generally, the green surface returns fall between a pure interface return and a pure volume backscatter return, and is termed the "*surface uncertainty*" problem (Guenther et al. 2000:9). The time difference between the inseparable components of volume backscatter just beneath the surface and actual interface returns is far too large to permit the use of this combined green return of ambiguous origin for surface timing and detection. Discussions on solving this problem with an extremely short laser pulse have been put aside, as a minimum laser spot diameter of 2-3 meters is needed for eye-safe operation and to provide satisfactory surface return probability.

In addition, a beam nadir angle of 15-20 degrees is needed for an economically sound swath width (Guenther et al. 2000:9).

In the case of the infrared the surface returns from the interface reflections dominate the backscatter returns. The IR-signals are a lot weaker because of much higher attenuation in the water due to its wavelength, and consequently the returns come from a region much closer to the surface. This means that they don't present the timing error that the green returns do. But the IR-signals being reflected so easily also create challenges. IR-returns can come from sea spray, birds and low-lying mist, and due to these factors the IR-returns cannot be used for surface detection alone.

One can also have a receiver-channel tuned to the green-excited Raman backscatter wavelength of the red portion of the spectrum (Guenther et al. 1994:422-430). This is an inelastic scattering process that arises from a vibrational mode of the O:H bond in water molecules (Walrafen 1967:114-126). Compared to the green and the IR-returns the Raman backscattering is relatively weak, but because this return arises solely from volume excitation under the interface there is no surface component, and its origin is unambiguous. With the proper bias corrector to translate its arrival time to the predicted location of the interface, the surface may be detected. One of the major benefits of this backscattering is that it is present regardless of wind-speed and sea-surface slopes, which may affect the green and IR-returns. On the other hand, Raman backscattering can be contaminated by bottom reflected red energy in shallow water. In addition to this, the designated receiver will pick up broad-band, green-excited fluorescence which will be a disturbance if it comes from the sea bottom, but may be beneficial as a signal enhancer if it is from the water column itself (Guenther et al. 2000:10).

Finally, detecting the surface will demand a strategy for prioritizing between the different surface returns. In order to handle all environmental circumstances and provide fully reliable, accurate, false-alarm free surface location for every pulse, a receiver should be able to handle both IR and red (green excited Raman) wavelengths. The receiver may follow a "R-I-G"-logic, in treating the different returns: The Raman returns will be prioritized first due to their insensitivity to the surface condition and immunity from false targets. If the Raman returns do not exceed the pre-selected threshold, the processor starts looking for an IR-return. If neither the Raman nor the IR-returns qualify, the system will default to the green returns (Guenther et al. 2000:10).

3.4 Operational systems

3.4.1 The SHOALS-system – a hydrographical example

An example of applied LIDAR-technology is the U.S.Army Core of Engineers (USACE) SHOALS-system. Carried onboard an aircraft like figure 3.8 shows, it is considered one of the most versatile LIDAR survey systems in the world today.

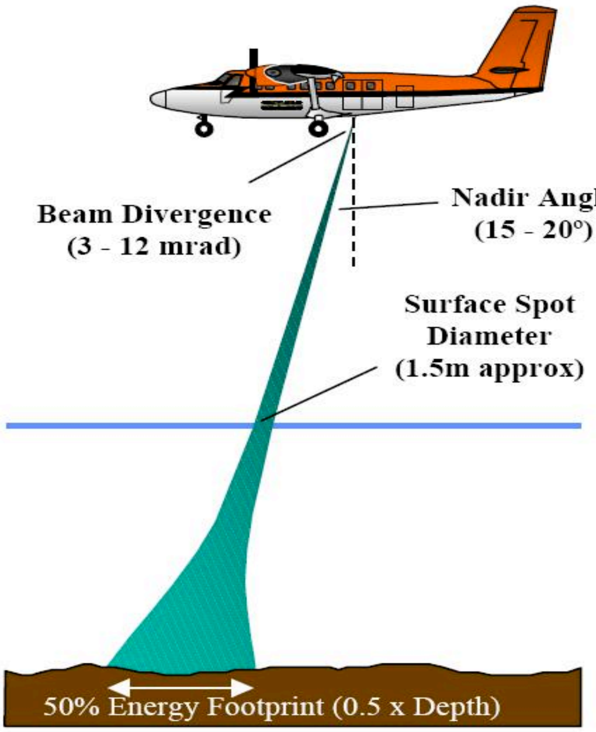

Figure 3.8

SHOALS performance

With a beam divergence of 3-12 mrad the laser spot on the sea-surface becomes about 1.5 meters in diameter. 90% of the energy is contained within a footprint with a diameter approximately equal to the depth of the water column. However, due to the spreading and scattering of the laser light, much of the returned energy is returned with a significant time lag and is insignificant for measurement purposes. The consequence is that only 50% of the energy emitted is regarded effective for analysis. A footprint with a diameter of ½ the water depth is normally regarded as the effective footprint of a LIDAR system (West & Lillycrop 1999:2). As already mentioned, the infrared channel is usually used for surface detection, but the blue-green channel will also detect the surface. The generic waveform has, as figure 3.9 shows, two distinct returns form the air/sea interface and the bottom. With such a large footprint the asymmetry of the bottom return is inevitable, but the "tail" is mainly from outside the 50% diameter footprint (West & Lillycrop 1999:2).

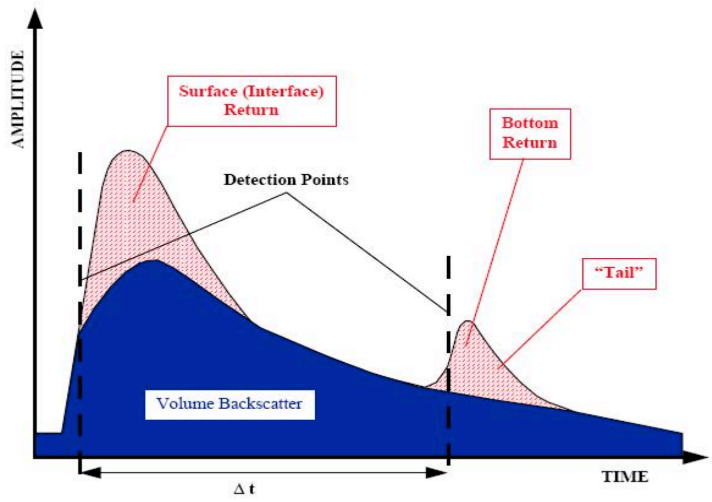

Figure 3.9

Surface vs. bottom return

(West & Lillycrop 1999:2)

The inherent challenge in analyzing the returns becomes clear when looking at figure 3.9. The surface (interface) return is much stronger in amplitude compared to the bottom return. A return from in between the two mentioned detection points, which will be weaker than the surface return but stronger than the bottom return, will pose a challenge in distinguishing between the different returns. Also, the volume backscatter comes into play, which also may be stronger than that of an object lying close to the bottom. Using two channels, the infrared channel and the blue-green channel, to compare the returns shows its value when looking at the results from a SHOALS-diagram:

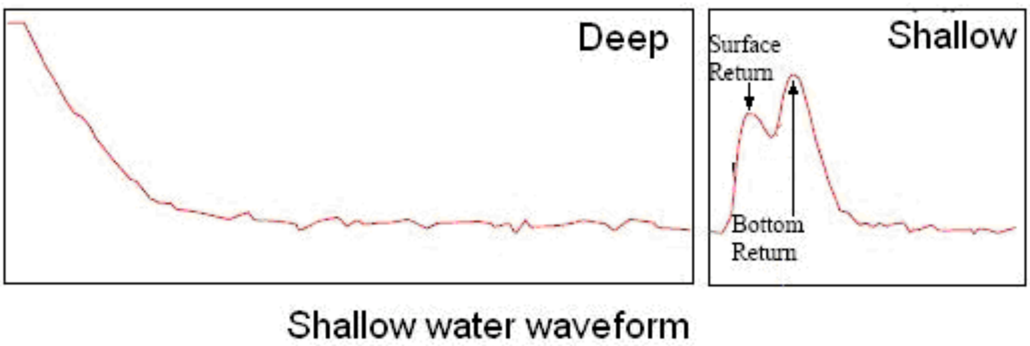

Figure 3.10

(West & Lillycrop 1999:3)

The diagram above is a typical shallow water waveform. With the bottom being saturated in the deep channel, the advantage of using two channels becomes clear. In figure 3.11 the returns are distributed between the deep and the shallow channels, as the bottom return falls outside the maximum depth of the shallow channel.

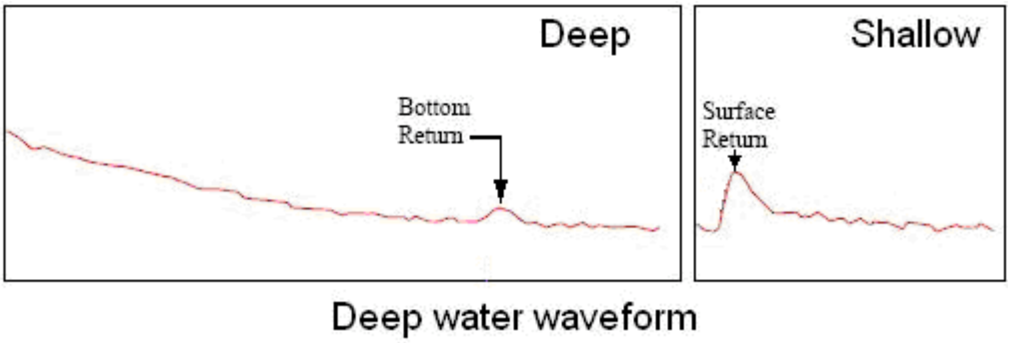

Figure 3.11

(West & Lillycrop 1999:3)

The following two diagrams show returns from objects close to the seabed. This is where the characteristics of LIDAR for target search come in to play. The distinction between bottom illumination and target detection is a challenge, and is important for the operator to make out. Looking at figure 3.12 below there is evidence of a return above the bottom (deep channel), but the shallow channel shows this as a separate return, so this is probably fish (West & Lillycrop 1999:3).

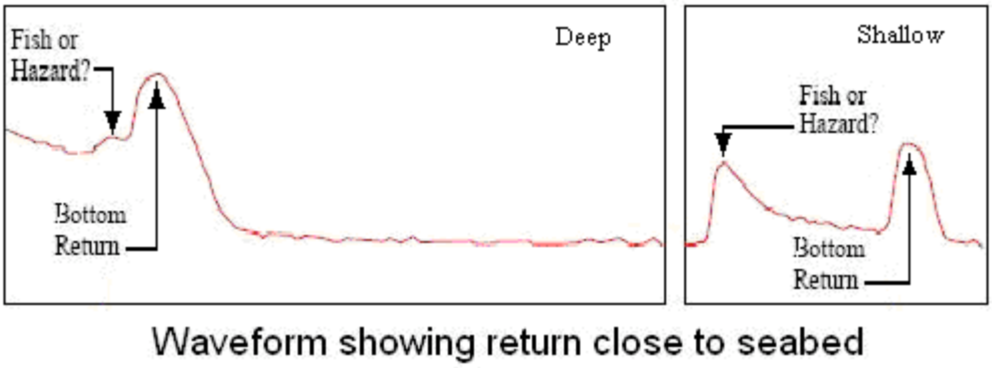

Figure 3.12

(West & Lillycrop 1999:3)

The next diagram has both the deep and the shallow channels showing a separate return in mid-water column, which clearly indicates the presence of fish or some other object.

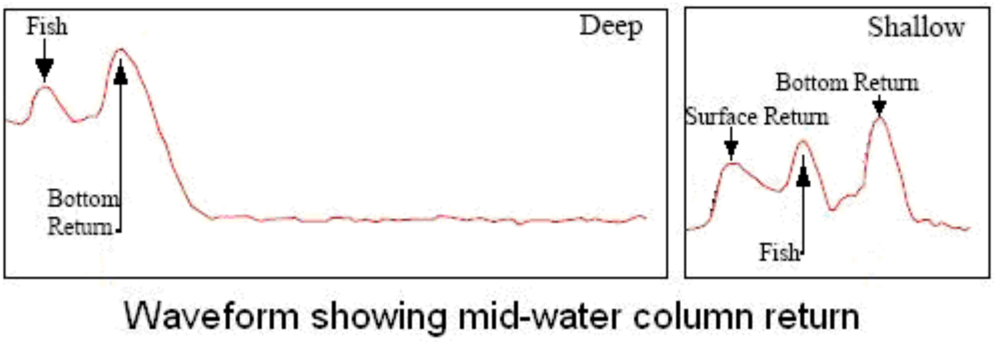

Figure 3.13

(West & Lillycrop 1999:3)

Although the technology has come a long way, the role of the operator as an interpreter is very much still a factor. The situation becomes more difficult in deep water, where small objects will be illuminated by a decreasing proportion of the total energy transmitted, so they become more masked by the "up" ramp of the bottom return (fig. 3.9) (West & Lillycrop 1999:4). The SHOALS-system was initially developed as a tool for monitoring the near shore bathymetric environments. The system has, among many other things, been used to assess the underwater performance of sand placed as part of beach fills. The high density data gathered also allow hydrographers to accurately position navigation hazards. SHOALS-operators report a maximum depth for surveying of 60 meters (Irish et al. 2000:3).

The reliable detection of small objects on the sea bottom depends on a properly designed LIDAR transceiver, sophisticated automated pulse-processing software, a well-designed survey strategy, knowledge of system hardware and software capabilities, and well-trained and experienced human data processors. All these challenges have to be met in order to perform a successful survey, and the consequences of not meeting them can be a large object in the ocean or at the bottom being missed (Guenther 2006:270). This thesis focuses on the ability to detect large metal objects in the water, such as submarines. The mentioned interpretation is most likely somewhat less needed to detect a submerged submarine, but the challenges to the operator are nevertheless present. Other factors that come into play are the probability of hitting at least part of the object with the scanning laser beam, the probability that the target return is resolvable and strong enough to be detected given the illuminated fraction of the target, the specific location of the target within the illuminated area and the water clarity, and the ability to discriminate the target return and accurately measure its location in the waveform. The Office of Coast Survey has provided depth determination algorithms for the SHOALS-system, that have the capability to recognize and report a small target return in the presence of the much stronger bottom return (Guenther et al. 1996).

3.4.2 Amethyst – a Russian example

Soviet scientists researched LIDAR technology parallel to their Western counterparts, and managed to place a system, although fragile, on some of their Bear F Mod 4 ASW aircraft. The system is called "Amethyst", and uses a blue-green CO_2 laser. It scans from side to side as the aircraft moves forward covering a 100m wide swath. The pilot must maintain constant altitude and speed (100m altitude, 100m/sec = 200 knots speed), and the system has to be shut down whenever the aircraft turns.

Each line in the display represents one scan, and deviates up and down to indicate range, in effect depth. The lines are scaled one meter apart, and very high projections or deep troughs extend over adjacent lines creating a shadow effect. The back-and-forth scan forms a green line on a standard Russian 525-line screen, measuring 20x25 cm, with a frame rate of 100Hz. Because the screen is relatively short, the image is compressed vertically, and is somewhat distorted toward the sides because the beam slants so deeply there. The system is calibrated to 50m depth, but it is said to be ineffective below 30m. The system requires interpretation by the operator, which in many cases can be difficult. Some operators never learn to interpret, but others do in a relatively short amount of time.

The limitations on aircraft motion suggest that the system is mechanically range-gated, probably by a disk rotating in front of the receiver. The sensitivity of the receiver dictates that the aircraft must fly steady with no turns, as the change in angles and ranges to the sea surface most likely will burn out the receiving equipment. The system processes only one pulse at a time, and hence the strict limitations to aircraft speed as well. If the aircraft moves too quickly, part of one line is inserted into the next (Friedman 1997:663).

Due to the strict limitations and the fact that the system has been installed on a Bear F and not the Russian primary ASW Aircraft, Il-38 May, one can speculate that the Russian armed forces has not pursued the technology further after the implementation of the Amethyst.

3.4.3 ATD-111 and April Showers – an American example

After the revelation of the black program "April Showers" and the technical details of the ATD-111 system (see chapter 5), some information on the system is available in open sources. The American technology seems to have developed significantly further than the Russian. The two mentioned American systems have been competing for the final ASW/MCM LIDAR contract, but seem to be of somewhat the same specifications.

The sensor uses a multi-wavelength laser that can emit blue (475 nm) or green (532 nm) light at power levels of 7 and 40 W, respectively, with a selectable polarization. The pulse width is approximately 10 ns, and a faceted prism forms a 3.3 x 3.3 deg bream. There are two interchangeable sensor heads. One has a pair of intensified charged coupled device (ICCDs) receivers, and is used for wide area search in shallow water. The other has an imaging time-resolved receiver (ITTR) using photomultiplier tubes, and is used for deep water search. The ICCDs offer better resolution, the ITTR greater sensitivity.

For both sensor heads, the aperture is quite large (427 and 1430cm², respectively). The production company Kaman claimed that the large apertures and better signal processing enabled the system to see much deeper than had previously been possible.

In particular, April Showers could register very faint details in the scene it observed, improving the possibility of target detection significantly (Friedman 2006:708).

The systems are not reported as having equivalent limitations to aircraft motion as the Russian Amethyst, although some restrictions do apply. The further development of the system must aim to allow for more aircraft motion and less operator interpretation. With the working environment and warfare platform already being as complex as they already are, the more technologically specified and less intuitive the system is to the operator, the harder it will be to implement as a supplementary sensor for ASW operations.

Specific performance related numbers in relation to the ATD-111 and April Showers systems have not been released, but one can assume that the technology allows for target detection for antisubmarine warfare (ASW) and mine countermeasures (MCM) purposes at least the equivalent to the SHOALS system, which is around 60 meters.

3.5 Performance

3.5.1 Operating environment and performance

When applying LIDAR technology to a water environment, a lot more energy gets lost compared to when operating by sending the light beam only through air. Laser energy is lost due to refraction, scattering and absorption of the water surface, the sea bottom and the water itself. These effects are the most limiting factors for operating a light system through water, and therefore limit the maximum operating depth for the beam.

The mentioned SHOALS-system is reporting an accuracy over a depth range of 7 to 50 meters of 0.30 meters with a 95% confidence level (Guenther 2006:266), although measurements have been made down to 60 meters (Irish et al. 2000:3, Wozencraft & Lillycrop 2002:4). The renowned Swedish LIDAR system "Hawk Eye II" reports a depth range of "*over 30 meters*" in Swedish coastal waters (Karlsson 2006:6).

Current hydrographical surveys are conducted over a range of speeds and swath widths, the two factors most affecting the coverage rate. At the low end, a system with a 100 knots speed and a 110 meter swath width will give a gross survey rate of 20.4 km²/hour. On the high side, a 175 knots speed with a 240 meters swath will give a rate of nearly 78 km²/hour (Guenther 2006:265). In ASW planning terms this is converted to 6.5 nm² (nautical miles) and

24.5 nm^2, respectively. With P-3 Orions working with a speed of roughly 240 knots, the numbers increase more. Increasing the swath width even more gives an estimated coverage rate of 45 nm^2/hour, and calculating conservatively with the same swath width as the 175 knots-aircraft one will get roughly 33 nm^2 of ocean investigated by the P-3 LIDAR per hour. Several systems have been upgraded with a higher pulse repetition rate, which allows the flying platform more flexibility when it comes to accuracy of the survey (Wozencraft & Lillycrop 2002:3). The capability then arises to decrease altitude and flying speed in order to decrease measurements spacing when required, and do the opposite when the latter is not.

When it comes to hydrography, a field traditionally dominated by surface vessels, the well established systems (LADS, Hawk Eye, SHOALS) have all reported significant savings over conventional acoustic methods (Axelsson & Alfredsson 1999). Operating airborne LIDAR in coastal waters has been proven very cost-effective, with littoral waters being among the most costly, hazardous and time-consuming areas for ship and boat operations. LIDAR has long been considered to be a tool that will open up new opportunities in fields as diverse as regional sediment management and warfighting support (LaRoque & West 1999:12).

3.5.2 Limitations

The Secchi depth can be explained by lowering a 45 cm diameter disc with alternating white and black quadrants into the water – the depth at which the disc becomes invisible is known as the Secchi depth. Typically, current LIDAR bathymeters operate down to three times the Secchi depth (Smith et al. 2000:3).

The most significant limitation for airborne LIDAR systems is **water clarity**, which limits the maximum surveyable depths (Goodman & Guenther 1978, Guenther 2006:268). For a typical eye-safe system, the maximum surveyable depths range from greater than 50 meters in very clear offshore waters to less than 10 meters in murky near-shore waters. In extremely turbid conditions, surveying may not be possible (Guenther 2006:268). Light energy is lost in water due to the inherent characteristics of water, but the amounts of additional particles that the light will reflect off of is the most hampering of all factors for LIDAR operations (Wozencraft & Lillycrop 2002:4).

Heavy sea mist and fog will reduce green signal strength, although tropical clouds can often be circumnavigated by flying below 500 meters. **High winds** can cause whitecaps and large waves which in turn can cause false detections and degrade system penetration and accuracy. They also create a spray of drops above the surface that can cause false returns. **Low winds** can also be a factor, when they do not provide enough roughness on the surface for the IR-beam to be reflected. **Sun glint** can, if sufficiently strong, effectively blind the receiver. Because of this, most LIDAR surveys are usually not scheduled around noon. Underwater masses and ocean vegetation can be a factor in near shore environments. When dense, the vegetation is nearly impossible to penetrate with the LIDAR beam, and can thus cause false returns and impact accuracy (Guenther 2006:271).

3.6 Summary

This chapter is by no means sufficient for a detailed technical discussion on LIDAR as a technology. It has, however, sought to give an insight into what LIDAR is, and the basic components of the technology. We see the use of laser light in appliances every day, and LIDAR is simply put an advanced laser pointer where the returned signals are being analyzed a bit more than is common in other laser appliances. The signal components, and the ability to process the returns are the two factors that have eventually made this technology as mature as it is now. Civilian companies are offering details mapping of near shore waters, which is a sought-after capacity nearly everywhere in the world. The development of inertial measurement units and GPS for exact positioning have provided more and more accurate mapping through the use of airborne LIDAR. The inherent challenge of transmitting light through water is the scattering, and the returned signals to the LIDAR processor contain a vast amount of different wavelengths that must be analyzed in an instant. Thorough knowledge of the water environment and the characteristics of light is required at all levels, and even after all the digital processing has been carried trough, the operator still has to evaluate the signals in order to make sense of the returned signals.

There are many limitations when it comes to the use of LIDAR in water, and water clarity is the most prominent of these, putting the scattering in the water itself aside. Other factors that come into play are mist and fog, high winds and sun glint – all factors that are very much present for long periods during the year, especially in the northern parts of Norway. In short, the limitations of aerial LIDAR systems when operating over and through the ocean are severe. The limitations of LIDAR through scattering and absorption of light will most likely be, and has been until now, the most hampering factor for pursuing this technology for ASW purposes. This problem will be discussed together with other complimenting technologies in the final chapter. When discussing LIDAR in isolation, one can see that the technology most likely will be insufficient alone as an efficient ASW sensor. The next chapter will provide some historical insight into the decline in ASW-focus after the end of the Cold War, and the refocusing in the mid-1990s towards the turn of the century.

4 – Antisubmarine Warfare – A shift in focus

4.1 Background

The submarine force has a long and proud tradition dating back to the 19^{th} century, but was really made famous by their impact on the two world wars in the 20^{th} century. The submarine campaigns of the First World War played a decisive role in its outcome. The U-boats deployed to attack both convoys and independent shipping, and monthly losses to submarine attacks were often in excess of 300.000 tons (Till 1994:110). Traditionally, the submarines have operated alone, relying on individual stealth for both their protection and operational effectiveness. Sea denial and the attack on trade have tended to be their main focus, although the submarines have always been used for many more assignments than this. One example is the Gallipoli campaign of 1915, where British submarines attacked Turkish shipping, and then proceeded to land small parties ashore and shelled railway lines and other land targets (Till 2004:123). By the end of World War II submarines from Great Britain, Holland, Poland, Norway, France and Greece, had sunk 2 million tons of enemy shipping and 57 major war vessels, out of which 36 were enemy submarines (Edmonds 2001:55). German U-boats formed the largest submarine fleet during World War II, but it is often forgotten that American submarines sunk almost 1.000 Japanese merchantmen as well as a third of all the Japanese warships lost in action (Grant et al. 2001:165). Naval historian calls the Pacific Ocean submarine campaign "*American mayhem*", pointing to the sinking of 84% of the Japanese merchant fleet accomplished by the American submarines (Owen 2007:188).

After the Second World War the world entered the era of the Cold War, which saw a phenomenal development of submarines, especially in the case of the USA and the Soviet Union. A quantum leap within the development of naval warfare came with the commissioning of the first nuclear submarine, the USS Nautilus in 1954, and her importance cannot be overstated. The submarine's high speed over great distance would change the way naval commanders planned and acted forever (Edmonds 2001:75).

The roles of the submarines during the Cold War varied, but by far the most prominent was that of the ballistic missiles that could be fired from big, submerged submarines. From a doctrinal point of view the submarines carrying ballistic missiles provided a pivot point for the Cold War, as these machines helped the two nuclear superpowers in assuring their ability for a second strike. As the missiles fired from one side towards the other might take out the ground based systems, the undetected submarines would lurk in the deep and always be ready to fire back, regardless of what happened on the shore. The role of the strategic submarines has been elaborated on in a previous dissertation, and is outside the scope of this one. Their important role in the Cold War does, however, provide the easiest explanation for how far the submarine technology has come today.

After the Cold War, both the U.S.A. and Russia have continued their development of submarine technology, although not to the same scale as before. Both nations have cut down on the number of operational submarines in their respective fleets. The importance of the role of the submarines, regardless of the situation in macro-politics, is recognized to be so important that the submarine branches of the two nations seem to be among the few sacred posts when the military budget is discussed.

Other nations are also building and operating submarines. The British, French, and the Germans are all building their own boats, in addition to Sweden and Japan and several other countries. The Russians are famous for their export of military equipment, and submarines are no exception. The most prominent buyers of Russian submarines have been China, India and Iran (RIA Novosti 2009).

Submarines of so-called "*rogue states*" have long played the role of the enemy in war-games for the Western powers, and as we distance ourselves from the chilling era that ended in 1991 with the Soviet downfall, one has started to include the use of submarines by organizations not necessarily representing a state when discussing potential enemy naval power. There are several examples of cocaine cartels trying to smuggle illegal drugs across borders by the use of submarines, although not as sophisticated as the ones being used by nations (Aftenposten 2008). These facts together with the export of naval assets to the mentioned countries bring to the table the possibility of terrorist organizations getting a hold of submarines with the capability to do significant damage. Quite simply, it boils down to recruiting trained personnel who are willing to work for such a cause, and having the money to purchase such an expensive weapon as a submarine with the necessary support elements.

Not only submarine technology has improved since the end of the Cold War. Maritime Patrol Aircraft and helicopters are carrying sophisticated radars, their ESM-equipment is constantly improving and so is the sonar equipment presented in chapter 2. The acoustic sensors have made significant improvements, both within active and passive technologies, and the most offensive and prominent feature of ASW that has been pursued is the ongoing development of multistatic acoustic systems. However, as chapter 2 pointed out, the acoustic challenges inherent in working in littoral waters will only partly be met by multistatic systems, and only through an active offensive posture. This chapter seeks to explore the background for the apparent decline in ASW focus in the militaries of the world after the Cold War, and what challenges are present when learning that ASW, through proliferated technology and a changed warfare scenario, has become even harder to perform.

4.2 Changes in political focus

4.2.1 The decline in ASW focus

During the Cold War the two superpowers were still working with a great deal of emphasis on submarines and antisubmarine warfare (ASW) technology. The importance of this focus can be exemplified by a statement from a 1989 Congressional hearing on the subject, where the Chief of Naval Operations "*directed this action in making the ASW our number one warfighting priority*" (Congressional Hearing 1989:7). There was also a concern, that being a product of foreign technology, many types of submarines could become available to third-world nations entering the following decade (1990s). The possibility of small but radical powers being able to threaten the ships of the much bigger U.S. and Soviet navies was an issue being discussed in political circles. One scenario included the prospect of a stealthy submarine under the Libyan flag, for example, entering New York harbour undetected and carrying out its mission (Congressional Hearing 1989:60). Thus with nations quieting their nuclear submarines and the prospect of even quieter non-nuclear submarines with considerable submerged endurance but of unknown nationality, several nations, especially the U.S., started to evaluate their cornerstone of ASW, the passive sonar systems. The passive sonar system technology-lead was being threatened by new and proliferated submarine technology.

However, after the end of the Cold War, the clear-cut enemy picture disintegrated. From having one arch-enemy that stood out with no introduction needed, it was now necessary to establish a new world order, with new potential enemies and threats. Related to this, it became important to justify details in defence spending in a way that did not seem necessary up until then. Without the obvious submarine-threat lurching in the oceans providing one's enemy with the ability to carry out a second strike, the justification for the enormous amounts of money being spent on antisubmarine warfare seemed obsolete. A decline in ASW-focus became a reality in the beginning of the 1990s. ASW forces were being used to eliminate land threats, and platforms such as MPAs were increasingly being used for intelligence, surveillance and reconnaissance (ISR) and as missile delivery platforms.

Especially moving aircrew over land took away important ASW operational experience and training – knowledge that it takes many years to build up and a persistent focus to maintain. With new threats rising, and the war in the Gulf in 1991 demanding its resources and focus, the decline in ASW-focus was hardly noticeable to anyone but the ASW-forces themselves. In 1996 the dangerous cuts in ASW-assets were explicitly addressed for the first time in the United States Congress, leading to the Senate in 1999 calling the state of the national ASW-portfolio at the time to be at "*historically low levels*" (Congress 1996, Senate 1999). Bearing in mind that learning to perform antisubmarine warfare is not comparable to learning how to fire a gun due to the complexity of the tasks, several years may pass before one is back on a satisfactory level of assets and expertise given the appropriate funding and resources. A computer algorithm has not yet been developed that can replace a skilled acoustic intelligence (ACINT) operator, although more routine classifications can be accomplished by computer algorithms. ASW requires skill and experience. The U.S. National Research Council stresses this fact by saying that "c*lassification is now best done passively by highly skilled ACINT-operators who have nearly 10 years of training before being ranked in this specialty*" (NRC 2007:3).

ASW is assessed as being one of the most challenging areas in the years to come for the maritime nations of the world. Putting the art of hunting submarines aside when the Cold War ended, several nations are rechanneling their focus now that they find their ASW-forces have been somewhat neglected for the past decade or two.

Again, the National Research Council evaluating the U.S. Navy in 2007: *"The Navy's capability for broad-area search of sufficient accuracy for cueing for antisubmarine warfare has been badly eroded with respect to diesel electric submarines, and especially the newer high-end types*" (NRC 2007:7).

In the Indian Ocean one finds that India has 16 conventional submarines and just set to sea their first nuclear submarine in the summer of 2009, aiming for four nuclear submarines by 2015. Indonesia sails her two to three submarines, Iran has three conventional and more than ten midget submarines, and Pakistan has five conventional and three midget submarines under commission.

In the Mediterranean Ocean Israel sails her three state-of-the art Dolphin-class submarines, Algeria has two conventional subs and Egypt sails four somewhat outdated submarines.

In the Far East China is by far the largest operator of submarines, with 55-60 conventional submarines, seven nuclear attack submarines and two to three ballistic missile submarines. North Korea sails at least 20 conventional submarines, and up to 60 midget submarines among other things being used for covertly inserting agents on foreign soil (Global Security 2009).

Given these numbers it is somewhat paradoxical to see the decline in ASW focus after 1991. Naval experts have always pointed to the necessity of a robust and modern ASW capability. Just before the closure of the Cold War, a congressional armed forces committee in the U.S. stated that a "*failure to deal adequately with quiet submarines under the control of our adversaries could have profound effect on our national security; and [...] the Navy needs to improve its strategic vision for dealing with ASW as a prerequisite to developing the ASW system needed for the future*"

(Congressional Hearing 1989:1). Military commanders started to focus more on political processes and the impact many military platforms could have over land, as opposed to over sea. An example of this is the use of tactical aircraft and Maritime Patrol Aircraft to fire missiles into the Balkans during the Kosovo-campaign, in stead of keeping them in their original domain (Friedman 1999:15, Work 2004:52). And as the political focus changed to be more over land, Western ASW capability went into a steady decline for more than a decade after the end of the Cold War. The prospect of submarine technology being proliferated to third world nations was not a hot topic. The technology and the manpower to proficiently operate it are expensive, but in the right hands, a powerful submarine is a very potent weapon. As the Iraqis and the Argentineans have learned the hard way, owning expensive technology does not necessarily lead to victory. The failure of Argentina's Type-209 submarines to launch a successful attack on the British during the Falklands campaign shows how demanding modern submarine operations can be (Till 2004:125). And as the naval expert Anthony Preston warned in 2001, "*as the once mighty Soviet Navy shows, proficiency can vanish through neglect and underfunding. No navy can be complacent about the lessons of the Cold War, particularly not the 'winners'*" (quoted in Edmonds 2001:80). One frustrated, Canadian submariner said that the Canadian fleet's overall ASW capability declined due to "*a fatal combination of potential indifference, tight budgets and the inability of the Naval Staff to push shipbuilding to the forefront of the Defense Program*" (Edmonds 2001:160).

Quiet diesel electric submarines and increasingly sophisticated mines available to potential enemies are a threat to the thought of conducting military operations where and when they are needed worldwide. This is especially true for missions involving entering and exiting of ports, fast transit through choke points, and operations in deep as well as shallow littoral waters. Approaching the end of the century, the U.S. Navy's new operational focus was the littoral waters, and its key operational requirement was clear – to ensure "*the guaranteed safe delivery of goods and services during joint campaigns*" (Work 2004:46). But this mission did not sound as attractive or as meaningful as *sea control* to most naval officers, and the picture of the status of the worldwide naval capabilities and potential was not shared by all. The lack of a clear cut enemy picture led the ASW priorities into a decline. The United States Senate explicitly addressed this problem in 1999, when stating that "*the lack of consensus on a submarine threat and competing naval warfare priorities, combined with mounting pressure on the overall defense budget, have put the Navy's ASW program at historically low levels*" (Senate 1999). And as the naval strategist Norman Friedman points out, the main European NATO navies had all "*committed themselves to a fairly narrow sea control mission. At a stroke their fleets became obsolescent*" (Friedman 1999:2). Without a clear enemy picture one started to use *deep water ASW* frigates as cruise-missile platforms against land targets. What Friedman has coined as "*mission obsolescence*" for the deep water ASW force has been very real for many navies after the end of the Cold War (Friedman 1999:15). What was needed at the turn of the century, and is needed now, is a new type of flexibility as the battle scenario has moved into the littorals.

4.2.2 Refocusing on ASW

Five years after the Cold War ended some politicians started to warn about the trend of downscaling the nations ASW capabilities. In 1996 the House of Representatives in Washington, D.C., addressed the "*apparent decline in priority of the Navy's anti-submarine warfare (ASW) program*" (Congress 1996). Calling for an assessment of the nation's overall ASW program, the Secretary of Defense was directed to assess the current and future U.S. ASW capability in light of the continuing development of quieter nuclear submarines, the proliferation of increasingly capable diesel submarines, and the declining trend in allocating budget resources to ASW programs. Already at this time, politicians wanted the Navy to look deeper into the evolving littoral threat in addition to the open ocean threat. The following year the House pursued the matter, discussing increased capabilities of advanced nuclear submarines, the proliferation of new, quiet diesel submarines and advanced non-nuclear submarine technology such as Air Independent Propulsion (AIP), and efforts to improve their submarine operational proficiency being made by several Third World navies (Congress 1997A). Analyzing the budgets together with looking at what the Navy was asking for over several years, it is interesting to see that the politicians actually were willing to set more money aside for submarine warfare than was asked for by the Navy. This was done over several years starting in 1996, and was probably done in order to put the focus back on ASW and the evolving submarine threat, and to accelerate the development of advanced antisubmarine warfare technologies. Detailed discussions occurred at very high levels, calling for items such as "*anti-submarine warfare (ASW) signal processors and algorithms for detection and classification of submarines in high cluttered shallow water environments*" (Congress 1997B). This shows a surprisingly deep insight into the challenges facing their ASW forces. Specific background for these discussions is not available, although one can speculate that experience from naval situations in the 1990s, and proliferation scandals such as the bust of the Walker-Whitworth spy ring in 1985 might have driven the desire for further refinement of own capabilities by the politicians. The Walker-Whitworth spy ring had for twenty years provided the Soviets with detailed information on American submarine capabilities, shortcomings, tactics and movements (Hassig 1992:62). Knowing in advance about the U.S. submarines' movements and positions allowed the Russian to pre-plan positioning of own units in order to record American system transmissions and weaknesses, which they would not have been able to do if they did not know the American positions.

Scholars such as Geoffrey Till and Norman Friedman, and military commanders such as the Head of the Naval War College in 1999, Admiral Cebrowski, all pointed towards the likeliness of future combat occurring in the littorals and not out to sea. Friedman, when presenting thoughts on new technology for future navies, emphasized that *"surface forces will almost inevitably find themselves operating in littoral areas. That may mean seizing control of an area of littoral to support an amphibious operation, or it may mean operating in shallow water for a sustained period*" (Friedman 1999:25). He went on to say that "*there may be a considerable payoff in deploying countermeasures such as periscope-detection radars and even lasers*". Knowing about the acoustic challenges inherent in operating in the littorals, he pointed to non-acoustic sensors that we are still exploring for these purposes.

The politicians felt that the Navy itself was not prioritizing the matter at a high enough level, and wanted to end the "*apparent decline in priority of the Navy's ASW program [that has] been echoed by the Chief of Naval Operations and by the Chairman of the Joint Chiefs of Staff"* (Congress 1997b). It is interesting to see that cutting the resources for ASW going into the 1990s, it seemed hard to turn the Navy back towards prioritizing ongoing and new ASW programs. The Navy might have been channeling their resources more towards meeting threats from land, such as supporting the land operations during the first Gulf War, and the following presence in the area. In 1997 the Congress stated a concern with "*the Navy's slow* *progress in planning for and funding organic battle group airborne antisubmarine warfare systems suitable for countering the existing and projected littoral ASW threat*" (Congress 1997b). The politicians recognized the Navy's difficulty in modernizing existing systems within budgetary constraints, but demanded a plan, supported by adequate resources, in order to "*meet the evolving littoral ASW threat*" (Congress 1997b).

Approaching the end of the decade, several ASW programs, both acoustic and non-acoustic, had been started (for details see chapter 5). And the discussions regarding the status of the ASW forces had lead to some core guidelines that the politicians wanted the military to follow.

First, that antisubmarine warfare is one of the Navy's most fundamental core competencies. Regardless of the decline in budget allocations and competency, this is laid down as the fundament for future discussions.

Second, that ASW must remain a core competency in the face of a submarine threat that will increase in the 21st century to become the dominant threat to naval missions. The thought of being able to project military power and presence worldwide demands an understanding of the local submarine threat and naval scenario.

Third, that the continuing draw down in naval forces and the current de-emphasis on ASW have seriously eroded the Navy's ASW capabilities, and that this "*erosion of capabilities comes at a time when potential future adversaries are rapidly acquiring advanced quieting techniques and other offensive submarine capabilities*". Starting in the 1980s, the Soviet Union had exported the conventional but very capable "Kilo"-class submarine to countries such as China and Iran (Grant et al. 2001:202). And in 1986, to the embarrassment of Norway, the Soviets scored a major coup by purchasing vital technology from Toshiba Machine Company in Japan and Kongsberg Vaapenfabrikk in Norway. Going against an international agreement aimed at restricting the flow of high-tech devices to the Soviet bloc, the two companies sold to Soviet four room-sized precision milling machines with computer-guided cutting heads of the kind used to manufacture incredibly smooth propellers for American submarines (Hassig 1992:62). According to U.S. intelligence, the machines where used not only to cut flawless, ultra quiet propellers for new submarines but also to make replacement propellers for the old ones. However, after the end of the Cold War, American politicians agree that there has been a lack of consensus regarding the submarine threat, and that this has had an impact on where the direction of a national ASW capability has gone.

And fourth, that advances in ASW capability only come as a result of dedicated, long-term research and development based on at sea operations, testing, measurements, and experimentation. Years of decline in competency and technological ability will take many years to build back up (Senate 1999).

Approaching year 2000, the focus was seriously back on ASW, trying to rechannel the resources being allocated elsewhere. P-3 Orions were being used for missile firings and special operations over land, but were more and more being wanted back to flying over water meeting evolving submarines threats. The Senate called for a "*stable and focused ASW program under appropriate oversight"*, emphasizing that ASW is a "*critical enabler for naval operations in the world's littoral regions*" (Senate 1999).

4.3 Changes in doctrine and tactics

It is important to discuss the shift in naval doctrine and tactics that we have seen in the later years. The world has definitely moved away from the gigantic naval battles of the early and mid-1900s, where entire fleets maneuvered across the oceans with the mission to destroy one's adversary. The battles of the Russo-Japanese war of 1904-05 and the submarine warfare conducted by the German "Wolfpacks" in the Second World War are more likely to be reading for historians and not for students of future naval tactics (Jukes 2002:27, Kaplan & Currie 1997). Geoffrey Till emphasizes this, and states that "*there is no one to challenge Western maritime supremacy and it is hard, at least at the moment, to imagine a situation in which there could be a sustained conflict at sea*" (Till 1994). Likewise, the enormous resources allocated to support the development of submarine technology and tactics of gigantic strategic submarines carrying ballistic missiles that were seen during the Cold War is very unlikely to occur again at the same scale in the foreseeable future.

The shift has been towards smaller submarines with less weaponry, conducting tactical intelligence, surveillance and reconnaissance (ISR) missions, giving support to special forces crossing or leaving the shoreline, or conducting missions to sabotage enemy territory and assets. These are all missions with a great deal of a strategic aspect to them, keeping the submarines important to own forces, and thus very desirable to find by the adversary. But diesel submarines no longer serve in the U.S. Navy or the Royal Navy, and there is a sense of difference stressed by naval strategists when discussing smaller nations' diesel tactics and operating procedures. These larger navies seem to be attracted by the "*seven deadly virtues*" that is achieved by having nuclear propulsion: flexibility, mobility, stealth, endurance, reach, autonomy and punch (Till 2004:124). But the SSKs' capacity to approach an enemy shore without being detected facilitates the delivery and extraction of special forces or agents, and shorter flight time of cruise missiles fired just offshore speeds up the target-identification-and-attack cycle. More and more navies around the world are acquiring submarines for just these reasons. The U.S. Navy has converted four former submarines built as platforms for ballistic missiles (SSBNs) into submarines carrying cruise missiles of a more tactical character, so-called SSGNs (O'Rourke 2004:6). This has been done in order to meet the change from being a nuclear deterrent to functioning in a theatre of war closer to the shore in a joint effort with other forces.

The pluses of nuclear-powered boats are obvious. They can stay submerged for months, are fast, and have a great range. This makes them ideal for use in the ballistic missile (SSBN) role or in the attack role (SSN). Diesel-engined boats are slow, and were traditionally, by comparison, unable to remain long under water. Their diesels needed air to run, and thus the motors could only operate under water using battery power. These batteries would soon run down, limiting speed and time submerged.

However, there have always been certain positives with the SSK submarines. They are cheaper and easier to operate than nuclear boats, and are quieter and thus harder to detect with sonar. But although nuclear boats are more vulnerable to sonar because of the noise from their reactor, the U.S. and the U.K. navies came to prefer them because they could always find a lot of deep ocean to lose themselves in. Range and speed has never been a problem.

Recent years, however, have witnessed technological advances in terms of diesel submarine technology that have enhanced the potency of the SSKs. Battery power has increased significantly, leading to the diesel-electric submarines being able to sail faster and stay submerged longer. This is contributing to making them ideal for littoral operations. The diesel submarines are becoming stealthier, with quieter engines and propellers that make them even harder to find. The diesel engines are obviously very noisy, but the submarines are often able to mask the noise from their diesel engine when recharging their batteries by hiding behind a big, noisy fishing trawler, for example. The electric engines have always been very quiet compared to their nuclear sister ships, and new technology is making them even quieter. Nuclear submarines have to cool their reactors regardless of position, speed or circumstances, and as the electric engines have become quieter over the years, the new diesel-electric SSKs are actually considered quieter than the nuclear boats. The new diesel submarines are in addition cheaper to build, and thus cheaper to buy. The availability and increasing ability of modern diesel submarines make them attractive to smaller and "weaker" states (Thornton

2007:113). These factors were also mentioned several times by concerned American politicians above.

In the post-Cold War era, the U.S. Navy has placed increased emphasis on "*missions that contribute to U.S. military operations in littoral area against regional adversaries other than Russia*" (O'Rourke 2004:7). The turn away from heavy ships out to sea towards smaller ones operating close to the shore, both technologically and doctrinally, shows that more and more emphasis is being laid on the littorals. This turn in focus is further emphasized by the fact that the U.S. Navy is acquiring 55 vessels of the new Littoral Combat Ship (LCS). The LCS is a fast, agile and flexible surface-combatant with a module based sensor and weapon set-up, giving the combatant commanders flexibility in the littorals. The ships will be able to transit faster than 40 knots, and will cost around USD 460 million apiece. The total LCS acquirement will most likely pass USD 12 billion (Work 2004, O'Rourke 2009:2)

4.4 A geographical change

When the Soviets quieted their submarines in the 1980s, the response of the U.S. Navy was to develop short-range passive, acoustic arrays for deployment on the ocean bottom in the most important operational areas. The Fixed Distributed System (FDS) connected a number of distributed nets of sensors by cable with another, and then to a signal-processing and communications centers on land (NRC 2007:ix). For obvious reasons, the FDS' locations are necessarily limited to areas which are accessible for friendly submarines and support vessels. The smaller submarines operating today are sailing closer to the shore, and usually have most of their mission objectives in littoral waters. In plain terms, submarine warfare has moved from *blue-water operations* to *littoral operations*. Several strategy documents in the U.S. Navy have addressed this change from the blue-water, war-at-sea focus of the "*Maritime Strategy*" (1986), through the littoral emphasis of *"…From the Sea*" (1992) and "*Forward…From the Sea*" (1994). In 1997, the Chief of Naval Operations in the U.S. stated that "*we will have to merge our sea control seamlessly into control of the littorals and fully integrate our capabilities into the land battle*" (Johnson 1997). The new thoughts evolve around a wider strategy in which naval forces are fully integrated into global joint operations against regional and transnational dangers, now with more of a littoral focus (Clark 2002). A comprehensive approach is leading the way for an integrated force structure with maritime patrol aircraft, ships, submarines and unmanned vehicles that will provide comprehensive situational awareness with regards to the new evolving asymmetric threats.

Today the United States is recognized as the sole superpower, with its global reach often dependent on the capability of the U.S. Navy to put ships close to or into the ports of virtually any country in the world. The National Research Council recognized in 2007 that this global reach is threatened by the widespread acquisition of quiet, diesel electric submarines and inexpensive mines that can be very effective weapons in an adversary's littoral waters, whether shallow or deep (NRC 2007:1).

Bringing the submarine mission closer to the shore usually means that the submarine has to operate in waters that are more shallow. Consequently, the submarine will be closer to other surface traffic, it will be more prone to unwanted detection and it has to navigate through straits and sounds which are naturally present in littoral waters and the archipelago. All these factors call for a smaller and more maneuverable submarine, as opposed to the 160 meters long strategic submarines of the superpowers (Genat 1997:32, Mills 2003:28). Regardless of its mission, the submarine must first accept all these factors in its disadvantage, and possibly try to make them into factors playing on its own side for preventing detection, as laid out in chapter 2, "*The littoral challenge*".

4.5 Summary

The submarine force has during its entire history played a major role in world military affairs. From the operations of the First and Second World War to the strategic movements of the gigantic strategic submarines of the Cold War, naval commanders and the political leadership were given a truly strategic tool at their disposal with the introduction of submarines in the late 1800s. The Cold War saw a phenomenal development of high tech submarines, based on the need for a strategic deterrent and the second strike ability. The technological race to quieten the submarines themselves, and improving sonars to detect them brought the world to a very high level of sophistication in a relatively short amount of time. The submarine technology today is highly advanced, and is becoming more and more available. Smaller nations are acquiring small and sophisticated submarines and are thus building a credible naval force, be it for offensive of defensive operations. The decline in ASW-focus after the end of the Cold War lead to a problematic gap between the availability of small and advanced submarines, and the explicit ambition of being able to find and control these submarines. At the turn of the century most naval strategists and politicians recognized the need to further develop and refocus on ASW, and realized together with this refocusing that the arena for submarine operations to a great extent had moved from blue-water operations to operations in the littorals. This is a demanding change, and requires a heavy focus on new sensor technology and ASW platforms. The next chapter will discuss the development of one such sensor technology that might be worth pursuing in this regard, and the final chapter will look at the potential of combining LIDAR technology with other technologies in order for the ASW force to be able to perform better in the littorals.

5 – Historical Development

5.1 Background

The history of remote sensing began with the experimentation with photosensitive chemicals in the early 1800s, when different scientists conducted trials and experiments with the goal of permanently recording a photograph. L. Daguerre is historically credited with the first photography in 1839, and already during the decade between 1850 and 1860 the first occurrence of aerial photography was registered from balloons (Campbell 2007:7). All amateur photographers can relate to the problem of acquiring a satisfactory picture of an object when either the object or the photographer is moving. With the photographer moving at until then unprecedented speeds when sitting in an aeroplane, aerial photography presented a new challenge. Further development and research within the science led to aerial photography being conducted from aeroplanes already in 1909. The explosive development of aeroplanes from the beginning of the 20th century towards the big wars, and obviously during them as well, allowed for World War I marking the beginning of aerial reconnaissance on a routine basis. With photographers leaning out of an open aeroplane with big, hand-held cameras, reconnaissance of this sort was not only challenging but dangerous as well. It did, however, provide invaluable intelligence about hostile activity and distribution of forces that, until then, military commanders could only dream about.

The economic depression in the 1920s and 30s gave way to not only economic and financial challenges, but it also led to an environmental crisis. Concerns about the consequences regarding rural economic development (or lack thereof), erosion of the soil, the quality of water-supplies and similar issues led to governmental applications of aerial surveys to record and monitor rural development. This tradition has been continued and further refined, as can be seen from the wide range of non-military use of aerial surveillance presented later in this chapter.

Experimentation led to the first attempts in the 1930s to measure air density profiles in the upper atmosphere by determining the scattering intensity from searchlight beams, and in 1938 cloud base heights were measured with pulses of light (Weitkamp 2005:2). Such experiments required thorough examination of the behaviour of light, and awakened the interest in possibly exploiting the entire electromagnetic spectrum. This led the way to further exploration of the non-visible portions of the electromagnetic spectrum.

During the inter-war years one sought to integrate the cameras and the aeroplanes so as to develop a somewhat seamless platform for aerial reconnaissance. Reconnaissance airwings and squadrons were established, with designated tasks of conducting intelligence gathering, reconnaissance and surveillance. As the technology was further developed, these squadrons became more and more integrated as an invaluable tool in the decision-making chain-of-command.

World War II saw almost an explosion in the use and need for aerial photography and surveillance, and technological development led onto the exploration of the non-visible portions of the electromagnetic spectrum. This can in many ways be seen as a natural path from the development of radars in the 1930s in Germany, the United States and the United Kingdom. Up until the outbreak of the war one was almost exclusively focused on the visible spectrum, but as operations evolved, especially the infrared and microwave regions became increasingly interesting and explored.

One of the positive sides of the events of war, is the incredible speed at which technological development takes place. One of the most frustrating factors of military research and development in peace-time, for developers as well as the military itself, is the slowness of the entire process. One has to justify the development and, most of all, the costs to the civic authorities. The researchers have standard peace-time, often union-decided work-hours to comply with, and the number of people and institutions involved in the project can be, and usually are, overwhelming and process-slowing. Military acquisition is very resource consuming. Every step of the process must be justified, and the acquired technology must be up to military specifications and standards. Once a project has been started, the technology must be developed, tested and evaluated, and there is a chance of the entire project being scrapped in order to pursue some other investment instead if the results are unsatisfactory. Then the process starts all over again.

Of course, in a democracy where the people of the nation demands thorough insight into the process that leads to the acquisition of a new military capacity, the spending of their hard-earned tax-money, and where often daily discussions regarding the military and the use and need for it occur in the media and elsewhere, this encompassing process is in many ways necessary. These factors are, however, slowing for the development of new capacities. During wartime, on the other hand, such process-slowing factors as working-hours and budget-justification get played down, and this allows for an incredible speed of research and development of military capacities. As Vernon Ruttan argues, it is "*difficult to overemphasize the importance of the historical role that military procurement has played in the process of* *technology development*". Knowledge acquired from making weapons was an important source of the industrial revolution. And during almost every year since World War II, defense and defense-related research and technology development expenditures have accounted for at least two thirds of all U.S. federal government research and development (R&D) expenditures (Ruttan 2006:3)

Research combined with recent operational experience provides the invaluable combination of theoretical and practical experience needed for the rapid progress in technical knowledge accumulation, in this case within remote sensing and the non-visible portions of the electromagnetic spectrum (Campbell 2007:10). World War II provided such a realm for research and development.

The Cold War that followed also created an environment for relatively rapid progress within this science, with the daily request for up-to-date intelligence about the movements of the adversary on the other side of the Iron Curtain. The refinement of reconnaissance techniques in addition to a rapid sequence of developments in the 1960s released several bits of technologies to the civilian market. And, as will become clear in the following section on civilian development, the interaction between the civilian and military world creates a synergy effect that both sides take advantage of. Advances in defense-related technology can induce technology development in the commercial sector, and feedback from advances in the commercial sector can induce technology development in the defense sector (Ruttan 2006:164).

With photographic technologies and remote sensing that manipulates other ranges of the electromagnetic spectrum taking their own courses, this dissertation will focus on LIDAR and its historical, current and potential applications.

5.2 Open and civilian research

The rapid development and success of the early lasers of the 1960s and 70s led to researchers building LIDAR-systems meant to be installed on aircraft, as opposed to the "traditional" ground based systems. The initial wish for aircraft instalment of these kinds of systems came out of the need to place the LIDAR in the exact area of interest and not just examining any body of air passing the stationary equipment that was being used at the time (Weitkamp 2005:356). In the mid-1960s, the concept of Airborne LIDAR Bathymetry (ALB) was developed through the efforts to use laser in the search for submarines (Guenther 2000:3). Antisubmarine Warfare (ASW) was a highly prioritized branch for both sides of the Cold War, and measures to improve one's ASW-sensors were always interesting. The topic of further research on LIDAR for military purposes will be discussed later. The course of development of lasers in the 1960s and 70s is an example of what Ruttan calls a "*spin-on*". As a field of commercial technology that initially drew heavily on military R&D or military and defense-related procurement matures, its dependence on military and defense-related sources tends to decline. The flow of knowledge and technology may then reverse – "from spin-off to spin-on" (Ruttan 2006:5).

In 1967 the first airborne LIDAR measurement took place over Williamsburg, Virginia (USA) when the NASA Langley Research Center T-33 aircraft flew together with simultaneous measurements being conducted from the ground by stationary equipment. The objectives of these measurements were to detect clear air turbulence (CAT) (Weitkamp 2005:356). The idea of using a pulsed laser for underwater ranging was first proposed in the late 1960s, and the Syracuse University Research Institute was the first institution to put such a system into testing for underwater purposes in 1968 (Kim et al. 1975:1). The first LIDAR-measurement of the atmosphere done from the air independent of any ground-observations was with an airborne LIDAR built by the Stanford Research Institute, and took place in 1969 with the objective of measuring lower tropospheric aerosols (Weitkamp 2005:356).

In the early 1970s several early LIDAR-systems were tested by the U.S. Navy (1971-76) and NASA (1975) in the USA. Between 1971 and 1972 the Naval Oceanographic Office in Washington, D.C., deployed a system known as Pulsed Light Airborne Depth Sounder (PLADS) and conducted a series of field tests. However, both the projects of Syracuse University and the Naval Oceanographic Office were considered not to guarantee either the performance of the system nor its cost effectiveness, compared to other available depth sounder means (Kim et al. 1975:1).

In 1974 NASA flew a C-54 aircraft over the Chesapeake Bay and around Key West, both in the USA, at low altitudes measuring water depths in clear water. From then on and up until present time different LIDAR-systems onboard different platforms have been used, mostly for environmental investigations and measurements of the layers of the atmosphere, including temperatures, fluorescence and mineral density.

In addition, agencies in Canada (1975-78) and Australia (1975) started the testing of their own systems (Guenther 2000:3). By the mid-1970s several LIDAR altimeters and bathymeters were installed in aircraft both for flight safety and environmental measurements.

In the mid-1970s we see a profound increase in interest from both military institutions as well as from civilian ones as to the need and potential of using LIDAR for several purposes. The ASW-aspect has already been mentioned, but hydrographical measurements for amphibious troop landings as well as peacetime geological surveys were being more and more discussed.

In 1975 and -76 the National Oceanic and Atmospheric Administration (NOAA) and NASA co-hosted several symposia, with the aim of establishing user requirements and design goals for the NASA Airborne Oceanographic LIDAR (AOL). A natural step forward was to develop a scanning feature as opposed to the "conventional" profiling mode. The AOL was a joint effort by the NASA, NOAA and the U.S. Navy, and was to become the first scanning airborne LIDAR (LaRocque & West 1999:1). Successful hydrographical testing of the NASA AOL was conducted in 1977. Similar systems were built and tested in Canada, Australia and the Soviet Union in the late 70s – early 80s.

At the 4th Laser Hydrography Symposium in 1981 in Australia several breakthroughs were reported. Following this, Optech Incorporated in Canada started the development the LARSEN-system for the Canadian Hydrographic Service and the Canada Centre for Remote Sensing to support nautical-charting missions in the Arctic during the time of year when the region is ice-free (Guenther 2006:259). By the mid-80s the LARSEN-500 had been fully developed, and by 1984-85 the Canadian system was declared the world's first operational ALH-system.

Testing of the Australian WRELADS II was completed by 1988 under the Weapons Research Establishment (WRE) (LaRocque & West 1999:1), and it did not take long before the operational version Laser Airborne Depth Sounder (LADS) was being built for the Royal Australian Navy. The Americans continued their research and development on systems such as the U.S. Navy Hydrographic Airborne Laser Sounder (HALS), and in Sweden the Defense Research Establishment (FOA) continued their work on their FOA Laser Airborne Sounder for hydrography (FLASH), which flew in 1988 (LaRocque & West 1999:1, Steinvall & Koppari 1996). From the mid-80s and into the 90s both the Soviet Union/Russia and China tested systems, the GOI/Chaika/Makrel-II and the BLOL respectively (Steinvall et al. 1996:1). The U.S. Army Corps of Engineers (USACE) began the well-known Scanning Hydrographic Operational Airborne LIDAR Survey (SHOALS) program in 1988, which is still ongoing with regards to testing, operational hydrographical activity and field measurements (Guenther 2000:3).

In the early 90s the Australian LADS became operational with the Royal Australian Navy, the USACE started flying their SHOALS-system and the Swedes deployed their Hawk Eye-system operationally from helicopters. There has been significant speculation surrounding the use of the Hawk Eye-system for hunting submarines, but no open sources seem to be able to confirm this. The Canadian LARSEN-500 continued its work from the mid-80s. As the pulse repetition rate increased because of both hardware development as well as increased processing capacity for the computers, several systems were moved from helicopters to fixed-wing aircraft, and from slow aircraft to faster aircraft (Guenther 2000:3, Guenther 2006:259). This increased the amount of square kilometers surveyed, and hence the cost effectiveness of every system.

Airborne LIDAR Bathymetry (ALB) was proving itself more and more to be an accurate, rapid, flexible, cost effective and less expensive system for surveying than ship-borne systems in given locations (Guenther 2006:259). It must be pointed out that the mentioned systems were tested for hydrographical/bathymetrical purposes and environmental measurements, and not for ASW-purposes *per se*. This distinction in focus can possibly be attributed to the decline in ASW-focus after the initial thoughts on the use of such systems in military circles, and an increase in the environmental focus with respect to surveys of coastal and/or iced areas, and nautical charting. The decline in ASW-focus was discussed in the previous chapter.

In 1991 Optech Incorporated, Canada, delivered the ALARMS-system to the U.S. Defense Advanced Research Projects Agency (DARPA) for the purpose of mine detection during the Gulf War (Driggers 2003:10, Optech 2008). Further development of LIDAR-technology has led to advances in military applications for mine countermeasures (MCM), which will be discussed in the next section.

As part of a project for conducting sea ice mapping (on and around the North Pole), terrain mapping (Nevada & Arizona), and chlorophyll measurements (the Christmas Islands) the NASA utilized a P-3B Orion with LIDAR-equipment installed. But even in the early 90s

LIDAR was by this renowned institution considered a "*relatively new field of data acquisition*" (Berry 1993:2).

In the course of the 1990s surveys were conducted by government agencies in Australia (LADS) and Sweden (Hawk Eye), and the LARSEN, SHOALS and LADS were contracted for surveys by a variety of agencies and governments. Canada, Mexico, New Zealand, Norway, Indonesia, Barbados, Puerto Rico, the United Arab Emirates and Finland are nations that purchased LIDAR ALB/ALH services, as well as NATO and commercial organizations such as gas, oil and ocean engineering companies (Guenther 2006:259).

The world's first operational ALB, the LARSEN, was retired in 2001, but several new systems have come to the scene after this. One of these is the NASA Experimental Advanced Airborne Research LIDAR (EAARL) with several unique design-features (Guenther 2006:259).

In the course of the early part of this decade the American SHOALS has been going through a heavy update-program, keeping up-to-speed with the ever improving technological features available, and in the early 2000s the Japanese Coast Guard purchased the upgraded SHOALS-1000 to augment their existing sensors (Guenther 2006:259).

As of this writing, one of the latest milestones regarding operational LIDAR development was reached early in 2007, when Northrop Grumman delivered the first of 45 LIDAR pods to be installed on the U.S. Navy helicopter MH-60S for mine-detection (Defense News 2007). This program will be discussed in detail in the next section.

5.3 Black programs and military development

The research for this thesis has very much focused on revealing the military aspects of LIDAR development and technology. However, most programs aimed at improving submarine capacity or ASW technology is conducted covertly, in so-called "*black programs*". Needless to say, information on these is not available or is very scarcely scattered in open sources. Naval magazines and publications have sometimes provided some insight into what programs are being funded, but they hardly ever provide any details on technical functionalities and specifications. But as the programs are converted into deployable technology and equipment, or come to the surface due to among other things congressional discussions, the development within a field is revealed.

Early in the age of the laser one started to talk about the potential of using a laser beam to search for submerged submarines. This can very likely be attributed to what can be called the first boom of interest for the new technology. In the early 1960s the laser technology was establishing itself as a viable science, but talk of using lasers efficiently to search for objects in the oceans was calmed due to the fact that the technology required to process the immense amounts of information returning from the ocean was not available. Neither the positioning equipment for the platform being used, nor the processing technology was mature enough to pursue lasers as a non-acoustic means of detection for submarines. Further development within most fields of the technology had to be made.

There is very little to no information available on what was being done in military research establishments around the world in detail, except for the open programs already mentioned. This builds up the argument that the military recognized the technology not to be mature enough to be pursued for ASW-purposes in the 1960s and 70s, and the civilian world was left to take the lead in further development. Data processors were being used more and more and saw a tremendous development during the 70s and the 80s. Looking back, the military may have saved a significant amount of money for research and development when civilian companies, aiming to build sensors for oceanographic and environmental surveying, led the development of technologies such as LIDAR hydrography and oceanography. Looking at the previous section of this chapter, there have been a significant amount of civilian and military-civilian projects within the mentioned fields. Geoffrey Till discusses this phenomenon, and points to the U.S. Naval experience with torpedo and anti-torpedo technology in the 1920s. This example shows that navies that rush into new developments seem often to get their fingers burnt. The reason for this is what he refers to as the *"Learning S-curve*", in which a steep period of technological advance is followed by a flatter period of consolidation.

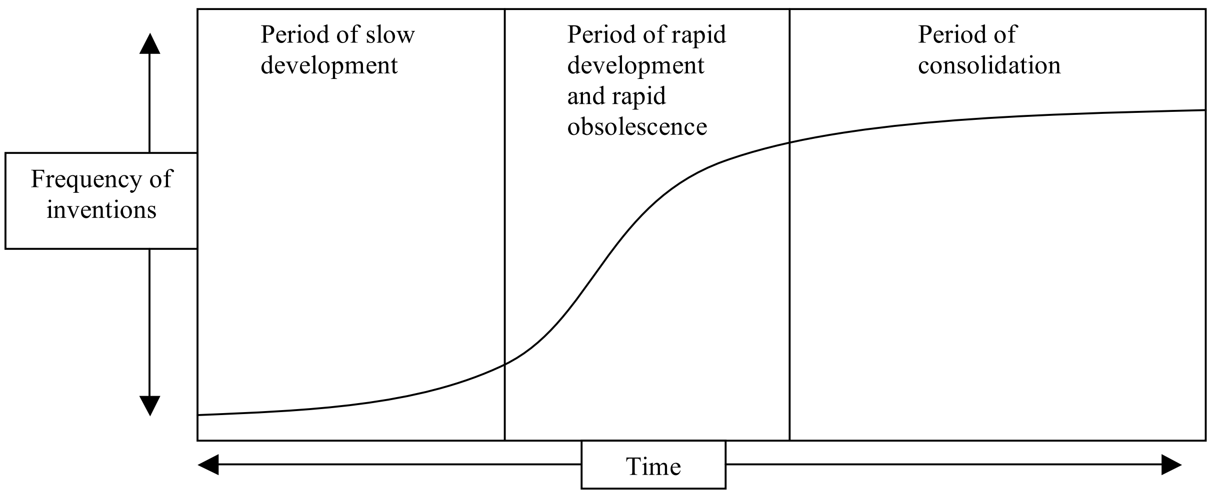

Figure 5.1

The Learning S-curve

"*Investing heavily in the early stages of development will produce equipment that is quickly rendered obsolete; better to wait until the dust has settled before plunging into large-scale procurement programmes. Just behind the leading edge is a good place to be*" (Till 2004:142). Norman Friedman points out the same phenomenon, and claims that *"all technologies are subject to S-shaped development curves. For part of their lives they look exponential [...] but ultimately all other curves have levelled out*" (Friedman 2008:14). Looking at the development of LIDAR both on the civilian and the military side as a whole, it seems as if the military has somewhat waited for the technology components to mature, before really pursuing the technology for military purposes.

In the 1980s, however, Soviet defectors created a second boom of interest within the American military research establishment, when they indicated that Russian scientists and intelligence branches where able to follow and track American submarines using lasers and radars placed on satellites in space. Pointing towards the great oceans, the satellites provided information on the whereabouts of the strategic, top-secret, ever-changing American SSBN-positions (Hjelmstad 2009). Reports from unnamed sources suggested that synthetic aperture radar was being used by the USSR from aircraft and the Salyut space station to detect submerged Delta-submarines in the Northwest Pacific (Andrews 1984a). The U.S. Defense Department denied the report (Andrews 1984b). Investigating the claims further they were found to be false, and that the Soviets were several years behind the West in computer-technology and signal data processing capability. However, a statement was released in a Soviet newspaper in July of 1981, saying that "*soon the range of electromagnetic waves exploitable for surveillance will be expanded. [...] Internal waves are very widespread in the ocean. It is possible to register their manifestations at the surface from satellites and to judge what is taking place in that upper layer of hundreds of meters which is of the utmost importance to us*" (Nelepo 1981).

The U.S. Navy conducted their own experiments with radar from a space shuttle trying to detect internal waves in the ocean. The Navy seemed optimistic about the progress of the technology, although not expecting any breakthroughs before the turn of the decade (1980/90) or some time into the next (1990s) (Stefanick 1987:201). A congressional hearing held in 1989 in the U.S. also revealed similar thoughts on the other side of the Iron Curtain: "*If we can discover how to detect submarines remotely – by space-radar, for example – then we will have a surveillance capability with entirely new characteristics that could have a substantial impact on anti-submarine warfare. We do not know yet whether such a capability is possible, but we and others are doing the research to find out*" (Congressional Hearing 1989:22).

Nevertheless, the indications of Soviet progress provided the grounds for research projects conducted by American universities, with Johns Hopkins University in Baltimore taking the lead. Several experiments were conducted with radar technology, with the expertise and help from among others Swedish and Norwegian scientists, who had good knowledge of the Scandinavian fjord environment. The experiments were initiated due to an interest in investigating alternative methods for detecting submerged object in the water. Out of this came the idea of observing internal waves in the water caused by the object, instead of necessarily aiming for a direct detection of the target. The Scandinavian fjords are usually strongly stratified, and provide optimal conditions for scientific experiments of this kind. Several experiments were conducted between 1988 and 1992, with the purpose of identifying internal waves caused by an object moving through the water. The experiments did succeed in proving the estimates of the scientists when it comes to algorithms and calculations, but did not provide any breakthroughs needed to call these new non-acoustic methods of detecting submerged submarines mature (Wickerts & Källen 1990, Källen & Dahlquist 1992, Hanson et al. 1992). Some of the technical details will be discussed in chapter 6, in relation to alternative and supplementary technologies and LIDAR.

The developments within LIDAR-technology in Russia were during the Cold War comparatively little known by the West and Western scientists. In the USSR the progress was independent of the results achieved by Western counterparts. One helicopter system in particular, flown onboard the KA-32S, had a reported performance of conducting oceanography and bottom mapping up to a depth of 80 meters in 1993, although performed in a hovering position above the water surface for a long time, and with the aid of submersible measuring devices (Feigels & Kopilevich 1993:128). Comparative analyses between Russian and Western LIDAR-systems have shown the Russian systems not to possess the same processing capacity and carrier positional control as the Western systems do. However, the independent Russian scientists of the Cold War pursued a series of optical elements with no comparative approaches in other countries, so it is anticipated that future cooperation between scientists who have previously been working separately will enable the creation of a new generation of effective LIDAR-systems.

With coalition forces entering the Persian Gulf in 1991, the mine threat was very much present. Most of the focus being on air supremacy by the coalition forces, the small Iraqi navy was allowed to mine its coastal waters almost without opposition (Cordesman 1996:860). The U.S. Navy had significant problems dealing with mine threats. Although the Americans had begun to improve its mine warfare capabilities as a result of its experience in dealing with

Iranian mines in 1987-88, the mine countermeasures (MCM) capabilities were still relatively limited. The United States Defense Advanced Research Project Agency (DARPA) ordered the delivery of a laser system able to detect submerged items in near-shore waters, with the aim of adding to the U.S. Navy MCM-portfolio in the Persian Gulf. Optech Inc. in Canada was selected, and developed and delivered the ALARMS-system for successful field trials in less than seven months, based on their previous experience (Optech 2008). Incorporating the system into U.S. Navy helicopters together with other aircraft systems created the Magic Lantirn. The Magic Lantirn mine detection system underwent evaluation trials in 1988, where it was used to find, classify and locate sea mines under real conditions. After conducting successful trials, an advanced version of the system was deployed aboard helicopters and used during the Desert Storm Operation (Driggers 2003:10, Jane's 2009). Six MH-53E helicopters and the smaller SH-2F helicopter were equipped with the, at the time experimental, Magic Lantirn laser mine detection system (Cordesman 1996:891, Optech 2008). The system includes an automated target recognition capability and multiple receivers to focus on many depth levels simultaneously. Integration and flight demonstration of the system on an MH-53E helicopter started in early 2002, and 8 SH-2G Seasprite helicopters of a U.S. Naval Reserve squadron have been modified to carry Magic Lantirn. The Seasprite is now the primary carrier of this system (Jane's 2009). As the Magic Lantirn was decommissioned as an operational sensor for the fleet in early 2000, the system was placed on the mentioned reserve SH-2G helicopters.

The lessons of the Gulf War led the U.S. Navy to further pursue LIDAR technology for MCM and submerged target detection. In the beginning of the 1990s, U.S. Congress started to fund several programs to develop non-acoustic sensor technology for anti-submarine warfare and mine detection applications under the non-acoustic ASW program (NAASW). ATD-111 was one of these programs, but the program apparently came to a halt after a few years. In 1995 the Lockheed Martin ATD-111 program was alive, but only barely so. The U.S. Congress set aside more money, but needed results (Congress 1996). Based on studies and experiments, for example the ones conducted in Sognefjorden, Norway, by Johns Hopkins University, a report was written by Johns Hopkins for the Secretary of the Navy that was delivered to Congress in mid-1995. Here, the technology professionals found no other program or technology to be more mature, more promising and more capable, relative to stated Navy mission requirements, than the ATD-111 (Congress 1996). U.S. Congress wanted the Navy to continue the ATD-111 program and pursue LIDAR-technology as a means for filling the increasing holes in advantages in acoustic ASW-technology. Based on the promising LIDAR-reports given to Congress, an overarching LIDAR-program was established, and named Airborne Laser Mine Detection System (ALMDS). Congress also directed the Navy to conduct a competitive evaluation of the mentioned Magic Lantirn deployed during the Gulf War and the newer ATD-111, in order to help in the decision as to which system to acquire under ALMDS (Congress 1996, Flight International 1997). The comparison of systems would provide a basis for establishing a firm requirement for systems to come.

U.S. Congress also mandated the CIA to study non-acoustic detection, in a program called Tsunami. As with the halting of the ATD-111 program, U.S. Congress feared that the Navy was unenthusiastic about technologies that might challenge or even extinguish its sea-based deterrent. Congress wanted an entirely independent audit of non-acoustic technology (Friedman 1997). The Tsunami-program was, however, reportedly entirely unsuccessful.

In addition to the ATD-111, work began on a black basis on another program in about 1991-1992, called April Showers. The Space and Naval Warfare Command (SPAWAR) sponsored it, and issued an upgrade contract in 1995 (Friedman 2006:708). Kaman Aerospace was given the contract, but encountered problems. Only mentioned in the official records in vague terms, funding for the program was given steadily, but April Showers did not reach its goal of a complete prototype by 1998. The program had just stopped about a year short of completion, due to lack of funding – SPAWAR reported that no funds were available for additional work (Jane's 2000). The black program was revealed partly because Kaman hoped to find another sponsor willing to spend USD 3.4 million to complete the upgrade. The program was revealed at Navy League 2000, with the aim of possibly having the warfighting commanders-in-chief provide at least interim support.

U.S. Congress ordered two fly-offs, first between Kaman's Magic Lantirn and Lockheed Martin's ATD-111 in 1996, and later between the ATD-111 and Kaman's April Showers in 1998 (Congress 1997b). The ATD-111 showing itself to be the better of the two first systems, the Magic Lantirn was decommissioned in early 2000. Now the system flies on reserve helicopters.

The second fly-off reportedly did not produce any clear results, and Kaman Aerospace and Lockheed Martin later teamed for the significant ALMDS-contract. In the spring of 2000 Northrop Grumman, considered the outsider of the MCM-community compared to the more experienced Lockheed Martin and Kaman, won the USD 40 million ALMDS-contract (Flight International 2000).

Since the early 1990s the U.S. Navy has been evaluating electro-optics as a method of locating sea mines. Improving technology has allowed LIDAR-systems so provide accurate information on the characteristics of targets at various depths. The idea rose out of a need to provide the fleet self-protection when travelling through choke points and confined straits, as well as rapid reconnaissance of minefields in support of amphibious operations. The overall concept was called Airborne Laser Mine Detection System (ALMDS) and was, and still is, a LIDAR-system designed to detect and localize drifting and floating shallow-water moored mines.

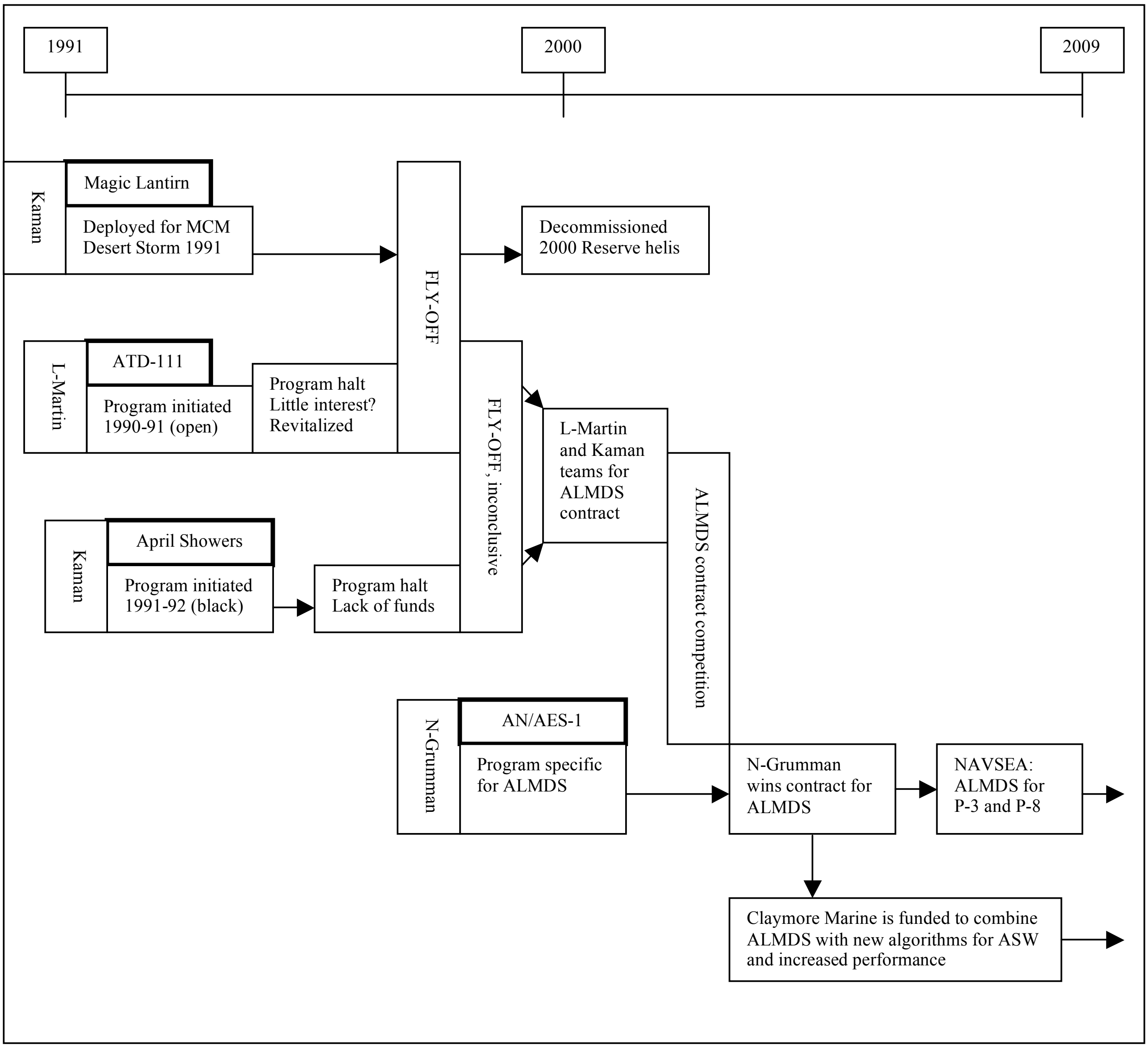

Figure 5.2

U.S. military LIDAR development

The system was operationally assessed in 1995 with a planned deployment onto the SH-2G helicopters in 1997 (U.S. Navy 1997). Delays led to a revised plan of installing the system onboard CH-60 helicopters with an Initial Operational Capability (IOC) in 2005 (U.S. Navy 1999). Due to further delays in the program, Northrop Grumman delivered the first production ALMDS-pod to the U.S. Navy in the beginning of 2007. The full-rate production of the pods will start in 2010, with a total delivery of 45 pods within 2018 (Defense News 2007).

Within the ALMDS a project started called Rapid Airborne Mine Clearance System (RAMICS), which integrated the LIDAR-detection system with a supercavitating 30mm Tungsten projectile. The projectile is specially designed for travelling tactical distances in air and water through a casing, causing a low-order deflagration of the mine (Global Security 2002). The gun is controlled by a fire-control system with targeting algorithms coupled with the LIDAR-system, and shows how far the technology has come, and how confident the LIDAR-developers have become when it comes to system accuracy. In addition, the need to distinguish between harmless objects in the water and mines have lead to work being done to create a 3D-model of the target in the water, helping the operator to make this distinction. Current technology allows this to be done, albeit from hovering helicopters (Drost & Singer 2004). However, for the sake of the ASW discussion carried out in this dissertation it is important to differentiate between mines on or skimming the surface and submarines operating at tactical depths. Mines will mostly lay much closer to the surface than will a submerged submarine, and will thus be easier to find by a LIDAR system than a submarine further down.

Having every LIDAR-program established since the Gulf War mostly focusing on mine countermeasures, a more submarine-directed program was established in 2003-04 called Claymore Marine. U.S. Congress directed the funding and further development of this specific ASW-system, with testing reportedly commencing in 2005-06. Claymore Marine is meant to be a new littoral ASW system, which integrates the previously developed ATD-111 airborne ASW and mine hunting system with new signal processing algorithms to achieve a significant increase in performance (Congress 2004). The system is a non-acoustic, environmentally friendly, airborne laser, submarine detection system specifically used for shallow water and harsh environments where acoustic detectors do not work well. Congress specifically asked the U.S. Navy to build a new state-of-the-art prototype system to support additional target testing and performance validation in 2005. The Committee on Armed Services has been optimistic about the program succeeding, and has continued to fund the development of the system (Congress 2005).

Reportedly, as of 2008 the U.S. Naval Sea Systems Command (NAVSEA) was seeking to expand the role of ALMDS into other missions including ASW, surface warfare and U.S. Coast Guard missions. NAVSEA has stated that the current configuration could be integrated on fixed-wing ASW platforms such as the P-3 Orion and the future P-8 Poseidon (Jane’s 2008). One is optimistic about the system being able to stay efficient despite the increase in altitude and forward air speed.

5.4 Summary

As a sensor, either military or civilian, the LIDAR has a short but relatively eventful history. NASA proclaimed in the early 90s that “LIDAR is a “*relatively new field of data acquisition*”. One question that must be answered is whether the technology itself and the need for this technology have matured enough to pursue further development into a cost effective sensor for future use, be it military or civilian. The civilian LIDAR establishment has come a long way in refining the technology for oceanographic and hydrographical purposes. The need for naval mapping for shipping, the oil industry and other off shore parties will most likely be a driving factor for years to come. The military potential for LIDAR has been pursued by the military, especially after the early 1990s, and we are starting to see operational and developing systems on board military aircraft for both mining countermeasures and antisubmarine warfare.

Although the initial thoughts on military LIDAR surrounded ASW, most programs have been directed towards finding mines (MCM). Military mines are usually laid in shallow waters and near shore environments where LIDAR actually works at its best. During the past five years, actual testing and implementation of LIDAR as an ASW-sensor have started to materialize, although none of the operational Western MPAs or ASW helicopters are carrying designated ASW LIDAR-pods. The NAVSEA-discussion regarding putting LIDAR on P-3 Orions and the future P-8 Poseidon is one that will be followed closely, especially by allies flying similar platforms in similar environments.

The next chapter will discuss whether LIDAR alone is a capable enough technology to be used for ASW, whether it should be put aside, or whether it possibly should work together with other potent non-acoustic technologies for hunting submarines.

6 – The need for LIDAR as an ASW sensor

6.1 Introduction

After the Cold War we saw a steady decline in ASW focus from many of the major powers, and this can very likely be attributed to the disintegration of a clear enemy picture. Other military projects and capabilities became more prioritized, and the defense against enemy submarines was placed further back in the budget line. In the mid-1990s and approaching the turn of the century one started to point out the need to keep the focus on the proliferation of advanced submarine technology and the existing and future submarine threat. Several naval experts and politicians alike emphasized that so-called Third World navies could match state-of-the-art submarine technology quite easily, and thus pose an uncomfortable threat to friendly forces worldwide.

As the focus came back to ASW, the geographical focus shifted as well, from blue-water operations to littoral scenes of action. This brought several challenges to the forefront of the tactical discussion. Blue-water navies consisted of ships that were too big to comfortably maneuver close to the shore when opposing an enemy submarine. The weapons and sensors were not built for working as close to the shore as was being projected in the exercises of the late 1990s and after 2000. There is a need for a sensor that can work under conditions where acoustic sensors do not work as well as they do out to sea. We are searching for a non-acoustic sensor of some kind. This chapter seeks to explore the potential of LIDAR alone as an ASW sensor. From the technology chapter we have seen that there is an uncertainty related to LIDAR penetration depth, and thus an inherent uncertainty in the probability of direct detection of a submarine. These weaknesses will be commented. But submarines can also be detected indirectly, and techniques in this regard will be discussed as well. The chapter then goes on to investigate two more technologies that can support LIDAR in a comprehensive non-acoustic search for a submerged target.

6.2 A littoral ASW sensor

6.2.1 Current use of LIDAR

As for civilian use of LIDAR as a sensor, we find that the number of LIDAR vendors grew from 5 in 1995 to 50 worldwide in 2000 (USACE 2002:11-1). LIDAR vendors offer solutions for a wide array of applications for the use of their technology:

- Levee profiling
    - LIDAR provides cross sections and identifies floodwall structures near the levees and areas on the levee needing repair.
- Dredge deposit evaluation
    - LIDAR is used to provide the basis to plan and monitor areas for depositing dredge material.
- Corridor mapping
    - Through LIDAR technology one can collect elevation data along long corridors and linear parcels of land, and thus contribute in the planning of for example high-speed rail corridors and long-distance highways.
- Floodplain mapping
    - LIDAR applications help through providing various models for floodplain modeling.
- Environmental studies
    - LIDAR is used to examine beach erosion and for land resource management.
- Oceanographic surveys and mapping
    - The mapping of shallow, coastal waters is a sought after resource worldwide, and LIDAR provides a cost efficient procedure for this type of mapping.

As for military applications there are already several systems in place, conducting different types of missions. Combining already existing applications with potential areas and thinking somewhat out-of-the-box we find several areas, in addition to the just mentioned civilian products, where LIDAR can be used alone as a sensor for military reconnaissance and surveillance.

- Rapid Environmental Assessment (REA)
    - Sending military assets to collect data to characterize potential landing sites for amphibious forces, where data may be outdated or non-existent, is an area with high potential for using maritime air assets such as MPAs for joint operations. REA will contribute in the compilation of a Rapid Environmental Picture (REP), which provides the backbone of an amphibious landing by surface and naval forces (Hammond 2001). The need for such a resource as a whole, and the potential for LIDAR in this context is undeniable. Pre-landing operations like this is referred to as "*shaping the littoral battlespace*", and are vital in mounting a successful amphibious operation (Speller & Tuck 2001:55). Also, environmental information is giving higher military authority an improved basis for planning and decision regardless of type of operation, and LIDAR will be able to contribute most significantly.

- Mine Countermeasures (MCM)
    - The Airborne Laser Mine Detection System (ALMDS) in the U.S. Navy and the continuation of this program shows how LIDAR is making MCM-warfare more efficient and safe. From the success of Magic Lantirn during the first Gulf War to the Rapid Mine Clearance System (RAMICS) installed on SH-60s currently flying operationally for the U.S. Navy, LIDAR has come to stay and will only help naval forces in clearing straits and coastal waters from mines in a more efficient manner than before.

- Antisubmarine Warfare (ASW)
    - The thought of using LIDAR in the search for submerged submarines is almost as old as laser technology itself. But the initial processing capabilities of the 1960s and the 1970s did not allow the ideas to fully develop into operational systems. But the potential for LIDAR as an ASW sensor is absolutely present. The most obvious application for LIDAR in the hunt for submarines is by direct detection of the submerged vessel. However, due to the scattering, attenuation, and absorption of light by water, the laser beam will not penetrate as far as one would wish. But the presence of LIDAR still might deter the submarine commander from working close to the surface for his own situational awareness or mission completion, and force the submarine below

the comfort of the noisy upper layers in the water column. Now the acoustic sensors take over. These ideas will be discussed in the coming sections.

6.2.2 LIDAR tactics – the littoral challenge

The active, multi-static systems presented in chapter 2 (section 2.2.5) are good systems for a more offensive agenda, where an area is to be continually covered by the ASW forces through an active posture. The goal in such cases will be to find and to stay in control of the submarine's movements, and neutralize her when this is deemed necessary. This is the strategy of "*hold at risk*". The U.S. Navy defines this strategy as "*to deny enemy submarines an offensive capability by maintaining the ability to destroy them, if and when required, at a time and place of our choosing*" (U.S. Navy 2009). This strategy is ambitious, but it seems necessary in an asymmetric environment. If one is to wait until it is necessary to know where the enemy submarine is, it is usually too late. The ambitious goal calls for a more offensive posture than is traditionally the case with ASW. The National Research Council points out that new technology must ensure "*the ability to detect and hold at risk adversary submarines and of shortening the detection-to-engagement time line in both deep and shallow waters*" (NRC 2007:vii).

Knowing from the technology chapter that the LIDAR beams will not penetrate sufficiently deep for the sensor to be able to detect the submarine at medium and great depths, the LIDAR system will still be able to contribute in ASW tactics, especially in the littorals.

As for *direct detection*, the system will be able to detect submarines operating in the upper layers of the water column. The submarines in the littorals will be forced to operate close to the surface for several reasons: for navigation, for message handling, for electronic and visual surveillance, and to create a good surface picture for her own mission. Staying close to the surface will always give the submarine the best picture of what is going on at the surface and in the air above her. The obvious downside to the tactic of LIDAR direct detection is that the submarine must be working fairly close to the surface in order to be detected.

But the area in which LIDAR contributes in a not such an obvious way, is through *deterring* the submarine from working close to the surface. Through this point, the capability of LIDAR direct detection still has an effect. The submarine commander, knowing about the MPA's LIDAR capability and its ability to detect submarines close to the surface using this technology, will aim to spend as little time as necessary in the upper layers of the water column. The submarine is very capable of calculating the effects of her environmental surroundings, be it salinity of the water, pressure or temperature. Her sensors will also make her able to estimate the local LIDAR detection depth. With these calculations in mind, the submarine commander will operate more below this depth, with the obvious goal of not being seen by the adversary's LIDAR system. But by lowering her depth, the submarine leaves the safe and protecting noisy upper layer which is making things hard for the ASW forces to conduct an acoustic search. Now the passive sonars and sonobuoys can do what they do best.

In addition to being detected directly, the submarine can also be detected *indirectly*. A submarine will always leave a trace, a clue, for the ASW forces to exploit. Decades ago several ASW aircraft had a "*sniffer*" system that would investigate the air that the airplane flew through, looking for traces of diesel exhaust. The contaminated air would reveal if a diesel submarine had been charging her batteries in the area lately (Burgess 1982:14). Unrelated to this, regardless of propulsion a submarine will leave behind clues as to her position and course. The main phenomenon is the wake that evolves behind the submarine. This wake is present just behind the vessel, and then proceeds to float up towards, and eventually to, the surface. When the wake is still submerged, it can be detected through the presence of turbulent water that should not be turbulent. LIDAR will be able, given the appropriate algorithms, to detect such turbulence behind a shallow-transiting submarine. In addition, the turbulence will excite microorganisms in the water, which in turn will emit bioluminescence. This bioluminescence might be too weak to be seen by the human eye, but the microorganisms will be further excited by the LIDAR beam, and thus create the basis for detection by an electro-optic/infrared camera (Hjelmstad 2009). The wake will also create a roughness on the surface of the ocean, and this small anomaly will be detectable by a Synthetic Aperture Radar. The experiments conducted in the Sognefjord and elsewhere between 1988 and 1992 showed that this is feasible. These alternative methods of detection will be further discussed in the coming sections of this chapter.

6.2.3 Pros and cons - summarized

Chapter 2 described how LIDAR works in principle, and three examples of LIDAR systems were presented. The Russian Bear F has had a system on board called the "Amethyst", which reportedly worked under some conditions, and under severe limitations. The laser beam did not penetrate effectively below 30 meters, and the current status of the sensor is unknown. The American ATD-111 and SHOALS systems can be assumed to base their technology on technology similar to each other, and can thus work down to somewhere between 50 and 60 meters under good conditions. Evaluating the technical reports that are being released by civilian scientists, and talking to experts with thorough knowledge of using laser-based water-sensors, one is forced to emphasize the inherent limitations which come into play through scattering, attenuation, absorption, water clarity, bottom and surface conditions and other environmental factors. The limitations are severe enough for several documents to report down to 10 meters effective depth range for the LIDAR equipment in poor conditions. With this in mind, it is hard to recommend the use of LIDAR as a single ASW sensor for direct detection in the littorals. The light simply does not penetrate deep enough to have a sufficiently deterrent effect.

This said, one should point to other fields, in addition to ASW, for the use of eventual LIDAR sensor onboard a surveillance aircraft, such as the P-3 Orion or the future P-8 Poseidon for that matter. The potency of the technology is evident through the current civilian use of LIDAR, in addition to the already operational MCM LIDAR-systems. If the sensor can be used for ASW and MCM and REA, the flexibility in operational portfolio is clear and the sensor becomes much more attractive. The answer of the potential of LIDAR as an ASW-platform by itself has been given: it has too uncertain a penetration depth to be relied on as a stand-alone direct detection ASW-sensor. The potential is there if it would be possible to guarantee a penetration depth of, say, 40 meters or more, but this is simply not the case. The limitations are not a function of technology not being mature enough – it's the characteristics of water as a medium that limits the potency of the sensor. Now, the LIDAR will penetrate the upper layer of the water column in the right conditions, so it is unfair to discredit the technology from being a relevant ASW sensor altogether. In the right conditions, and probably more often than not, LIDAR will be applicable as a non-acoustic sensor for the uppermost layer in the water column. LIDAR will be able to perform direct detection when the conditions are right, it will have a deterrent effect to the submarine (unless the water conditions make light penetration nearly impossible), and the system will be able to contribute through indirect detection. The latter will be further discussed in the following.

Looking at other technologies, we might be able combine sensors in our search for a potent, littoral non-acoustic sensor. The following section will present two such systems, and one more method of detection, which can be directly combined with LIDAR onboard the aircraft.

6.3 Alternative means of detection

The need for the ability to locate submarines in the littorals has been elaborated on. So have the difficulties of conducting submarine hunting in these waters. New sonar systems will be required to find and track the small and advanced diesel-submarines in the littoral waters, and operators must be taught new techniques. Multistatic systems were presented in chapter 2, and might be the active acoustic answer to the littoral challenge. R. Thornton, when discussing submarines and asymmetric warfare, states that "*navies might consider putting sonar to one side altogether and look to detect SSKs through the use of lasers, temperature-measuring devices, or even by tracking the bioluminescence of any vehicle that is under water"* (Thornton 2007:114).

In the following section, one more method and two other means of submarine detection will be presented, building on the thought that they might be able to compliment LIDAR as a littoral ASW sensor.

6.3.1 Detection of submarine-induced bioluminescence

The primary source of ocean bioluminescence is certain species of the plankton dinoflagellates. The mechanical stimulus of a moving submarine hull and its turbulent wake will produce light or bioluminescence, from organisms being disturbed or killed by the submarine. The intensity and duration of this light is a function of the population density, species, environmental conditions and submarine speed.
Luminescence is the strongest in the turbulent regions associated with the submarine, which are the water close to the hull, and the wake being created by the submarine.
The typical length scales for surface ship luminescent wakes are several ship lengths, but the physical wakes of submarines may be shorter (Stefanick 1987:190).

The population density of bioluminescent organisms varies with location and depth. The density of organisms will also vary according to the season, as well as the time of day. Under natural conditions, bioluminescence is at its highest around midnight and at its lowest around midday. Most bioluminescence is found between 50 and 150 meters and is associated with dense plankton populations in continental shelf areas up to 60 degrees north latitude. Levels in the Norwegian Sea and the GIUK gap area remain low (Stefanick 1987:191).

Observing the plankton disturbances created by a submarine is not common, and will most likely require advanced electro-optical instruments. If the submarine wake is by itself going to create a surface bioluminescent disturbance, the wake of the submarine must reach the surface. Tests have, however, already shown that submarine wakes generated below 50 meters are unlikely to do so (Stefanick 1987:190). However, if a LIDAR beam reaches the already somewhat excited microorganisms, they will be further excited, and this will enhance the possibility of detection by the mentioned advanced electro-optics (Hjelmstad 2009). Placing a camera beside the LIDAR equipment in a pod can be the needed electro-optic equipment, and this will facilitate indirect detection of the submarine through bioluminescence.

6.3.2 Submarine-generated turbulent wakes and internal waves

As a submarine moves through the water, some of the energy of propulsion goes into generating a turbulent wake behind the hull. Typical wake lengths associated with submarines below 125 feet are on the order of 100 yards at 6 knots and 30 yards at 2 to 3 knots, based on actual measurements (Stefanick 1987:199). When the turbulent wake collapses, it can drive an internal wave in the density-stratified layers of the ocean, in what is referred to as the *pycnocline* (see fig. 6.1 below). The pycnocline is defined as a rapid change in water density with depth. An object moving through the water, such as a submarine, will excite the pycnocline, and in areas where freshwater and saltwater meet, there are often well defined pycnoclines. This is often the case in littoral waters. Warmer and less saline freshwater will be on top of cooler and more saline saltwater, and with little mixing of the two water types, the difference in density will be significant. When excited by an object moving through it, the layers will seek back to the state they were in, and the internal waves that are created will be accentuated, and cause disturbances on the surface. Submarines also generate internal waves by the movement of the hull alone, without consideration of the wake collapse effect.

The internal waves cannot be seen directly as roughness on the surface. But the internal wave will generate horizontal currents near the surface that modulate existing surface ripples. The wavelengths of these ripples are on the order of centimeters or tens of centimeters. The modulation of the surface takes the form of changes in the ripple wavelength and steepness, which will change the radar scattering properties of the surface. The modulation of surface waves can in principle reveal the pattern of underlying internal waves. Synthetic Aperture Radar (SAR) can be tuned so that the radar backscatter depends on the wavelength of the short surface waves (Stefanick 1987:199). Detecting submarine-generated turbulent wakes

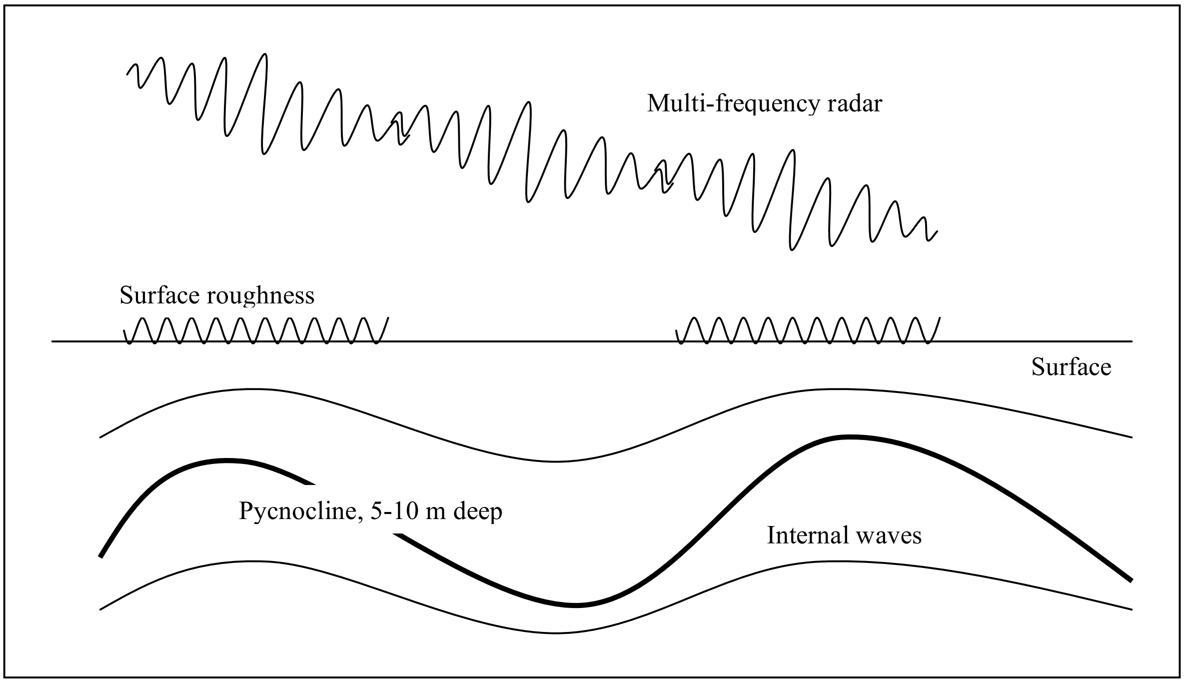

Figure 6.1

Multi-frequency radar matching the surface roughness

and internal waves is possible due to the concept of matched illumination of targets using coherent multi-frequency radars. If two coherent electromagnetic waves are transmitted they will develop a spatial interference along the transmission path.

The distance between nulls in the interference pattern can be made to vary over a wide range of scales with relatively small changes in transmitted frequencies. A target, whose characteristic longitudinal dimensions include sizes near the result of the interference formula, will backscatter the incident radiation resonantly (Apel & Gjessing 1989:295). Looking at figure 6.1 above, the internal waves modulate short gravity waves, and the resultant roughness scales scatter electromagnetic radiation when the interference scale matches the roughness scale. Experiments conducted in Norwegian fjords in the late 1980s and early 1990s showed the radars to be able to pick up the roughness on the surface in wind speeds up to 10 m/s, roughly 20 knots, and in light to moderate rain (Apel & Gjessing 1989:305). Further research has been done and can be done in this area, leading to a capable sensor for examining submerged objects in the littorals.

6.3.3 Hyperspectral imagery

Imaging spectrometers are passive sensors that measure reflected sunlight from objects on the earth's surface. All objects have unique spectral footprints that can be registered in wavelengths invisible to the human eye. A hyperspectral imaging sensor that operates across hundreds of wavelengths simultaneously makes it possible to analyze the object or surface in a different way.

The sensor is designed to collect radiation with a lens and to divide it into spectral regions that are then recorded on film or measured electronically (Campbell 2007:414). The sensors are coupled with processing algorithms that remove disturbances such as sea-surface glint, the atmosphere, water column radiance and bottom reflectance from the signatures. And as Durey et al. explains, "*when combined with in-situ measurements of inherent optical properties, solution for the bottom reflectance using these techniques can be allowed*" (1997:17). This *in-situ*
measurements can be done by a LIDAR system, and Estep et al. (1994) has suggested a technique which consists of using SHOALS water optical information and depth information to compute the diffuse optical depth at each calibrated point in an image for the hyperspectral sensor.

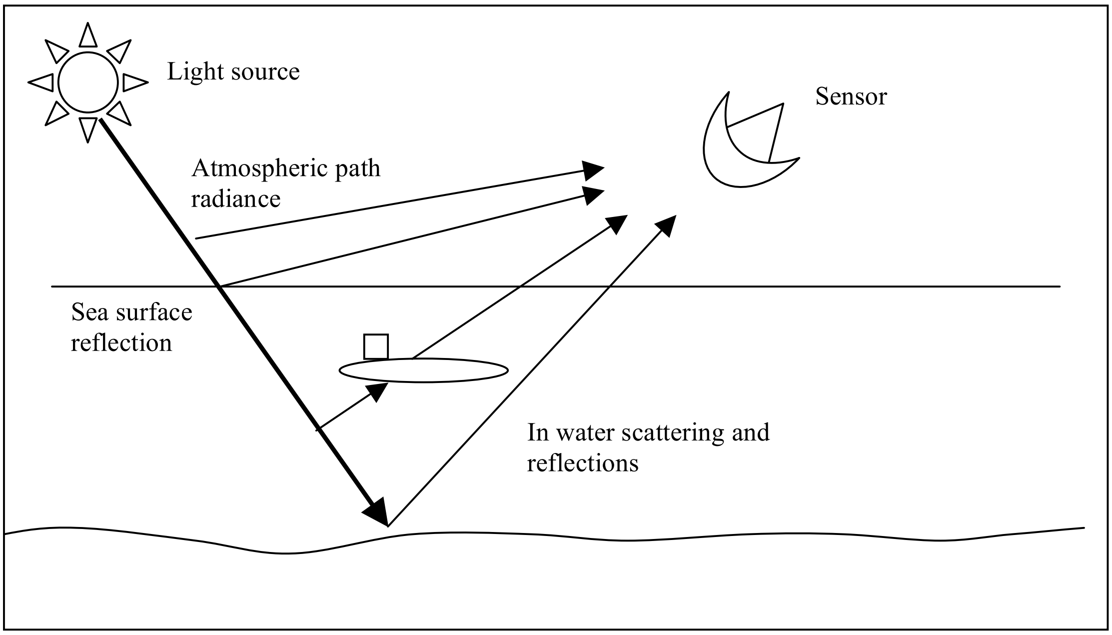

Figure 6.2
Water optics

Based on spectral properties, a hyperspectral system can provide information and detailed mapping of the distribution of nearshore sediments as well as marine vegetation. A combination of LIDAR and hyperspectral imaging can provide environmental data, greater depth resolution, and water optics (Estep et al. 1994). A fusion of SHOALS data and hyperspectral imagery allows the LIDAR depths to be used for calibration of the imagery (Smith et al. 2000:8). Combined with the capabilities of a LIDAR-system to determine depth accurately, a more complete hydrographic survey can be achieved more efficiently than through traditional surveys. Hyperspectral imagery will in this way be able to compliment LIDAR technology and provide a more comprehensive means of target detection in water.

In December 1999 the U.S. Office of Naval Research (ONR) awarded Science and Technology International (STI) a contract of USD 50 million over five years to develop a family of imagers under the Littoral Airborne Sensor – Hyperspectral (LASH) program. This was initially focused on ASW, but has since expanded to include Mine Countermeasures (MCM) and other applications.

The LASH consists of two Charged-Coupled Device (CCD) cameras that build up an image, one line at a time, in the direction of flight. A spectrometer splits the incoming reflected light into different colors (wavelengths) containing spectral information in the visible range of the electromagnetic spectrum. The values recorded are used to discriminate and classify objects of interest, exploiting characteristics not discernible by the human eye (Jane's 2006). The spatial and spectral resolutions can be changed in software, depending on the specific needs for the application.

Extensive testing in the ASW role has taken place aboard the P-3 Orion Maritime Patrol Aircraft (MPA) and Seahawk helicopters. The imager has demonstrated its ability to detect, geolocate and classify submerged submarines at tactical depths in littoral waters.

Passive optical remote sensing of shallow water and the littorals poses several challenges. The signal received at the sensor is a combination of that from the water itself, surface irradiance reflected off bottom features, glint and inherently complex in-water optical effects. One of the largest sources of non-target signal is surface clutter in the form of glint from foam, objects on the surface and wave action. In an effort to solve this problem, hyperspectral algorithms have been developed, in which disturbances such as glint is subtracted from the scene before image segmentation and anomaly detection.

The ONR seems optimistic about the further development of the technology for ASW purposes, and hyperspectral imagery seems to be a capable and potent complimentary sensor in addition to LIDAR.

6.4 A multi-sensor ASW-pod?

As presented in the previous chapter, NAVSEA in the U.S.A. is considering expanding the role of ALMDS to include ASW, and potentially placing LIDAR-technology on P-3 Orion MPAs. This can mean several things. The Americans are content with the uncertainty of the depth performance by LIDAR in the ASW role. They are satisfied with aiming to deter the submarine commander from operating close to the surface. Or, they have accomplished a technological breakthrough, not known to the rest of the world, and they are able to consistently penetrate at least the upper layers of the water column, more than 100 meters.

LIDAR systems today that we know about are not able to penetrate very much further than 60-80 meters under optimal conditions. And due to oceanographic factors, even the best systems can be reduced to an effective 10 meters in depth range. The inherent characteristics of water and light will hamper the further expansion of range in the future, almost regardless of technological breakthroughs. A consistent 100-meter penetration depth might be seen in the future, although this is not very likely (Hjelmstad 2009). However, combining LIDAR with other non-acoustic sensors might take advantage of the physical giveaways present when a submarine is covertly sailing through the littorals.

6.4.1 Combining three technologies

Discussing the different technologies available, combining LIDAR with a tactical Synthetic Aperture Radar (SAR) to detect roughness on the surface and a hyper-spectral camera to investigate light reflected from the ocean seems to combine the three most potent littoral sensors. Combining these into a pod for mounting on aerial ASW-platforms such as MPAs and frigate helicopters will provide more robustness than comes out of the technologies working by themselves.

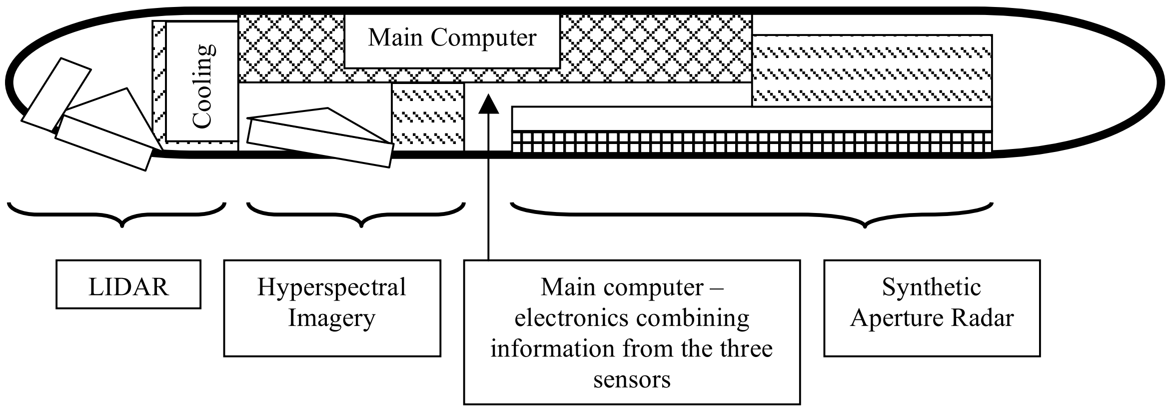

Figure 6.3

Multi-sensor ASW-pod

Building on the thought of using LIDAR as an *in-situ* measurement for the hyperspectral imagery, the two technologies could be placed in front of the pod. LIDAR will be able to work by itself as an active sensor aiming for direct detection of the submarine. In addition, the LIDAR information will give the necessary information of the water-conditions that the receiver of the hyperspectral imagery needs. And the LIDAR beams will excite the microorganisms in the wake behind the submarine, and create bioluminescence that the hyperspectral imagery can detect. In the back of the pod the Synthetic Aperture Radar will be placed, working to identify the potential roughness on the ocean surface created by the excited pycnocline in the wake of a submerged submarine.

6.4.2 Multi-sensor tactics

A multi-sensor pod like the one presented above can be utilized as follows. Entering the search area the radar portion of the pod will be searching for disturbances on the surface. These have been created by the wake behind the submarine that has floated up to the top of the water column. The radar plot will indicate which direction the submarine is headed, based on the formation of the wake disturbances (see fig. 6.4). These calculations were established and carried through in the late 1980s, so they can be and have been further refined today (Hjelmstad 2009).

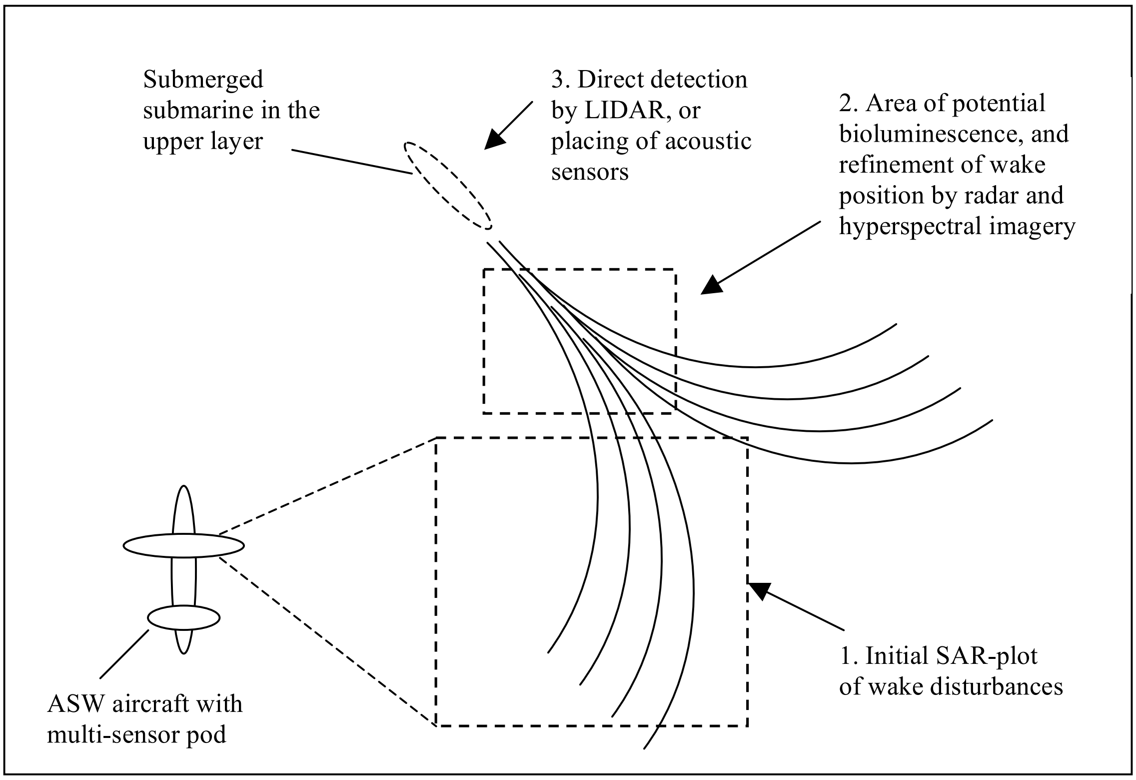

Figure 6.4

Multi-sensor tactics

Once the wake formations have given a rough estimate as to the position of the submarine, the ASW aircraft will descend closer to the surface, in order to have the hyperspectral imagery perform better. In addition to the hyperspectral cameras investigating passively by themselves, the LIDAR beams will look for disturbed water below the surface, and also try to excite microorganisms that in turn will be detected by the advanced cameras placed just behind the LIDAR system. These processes will aim to confirm what the radar already told the system regarding the wakes and the initial positioning of the submarine, and closing in on this position the LIDAR will try to make a direct detection by itself.

6.4.3 Flexible use

Every military organization in the world is experiencing funding cut-backs, and politicians and military commanders are together seeking more efficient ways of running their organizations. This includes a desire to use every military platform in more than one way, which is easily seen through the use of for example an antisubmarine warfare platform such as the American P-3 Orion or the British Nimrod for use over land in Time Sensitive Targeting (TST). In effect, they are reduced to very expensive targeting pods, performing tasks that Unmanned Aerial Vehicles (UAV) are doing more and more. To suggest the development of a sensor that can search for one type of target, in one way, by one exclusive platform indicates a lack of understanding for the mentioned need for flexibility and efficiency. A suggestion for a rigid sensor like this would be to put a LIDAR-pod capable of looking for submarines only, hardmounted onto a Norwegian P-3 Orion.

The mentioned pod should be able to perform more than one task, for example ASW *and* MCM, from more than one platform, for example the P-3 Orion *and* the new NH-90 frigate helicopters. This will call for two things.

1. *Multitasking*

   Instead of just focusing on one, single operational task, such as hunting for submarines, the pod should be able to look for mines and debris, in addition to conducting environmental surveys for troop landings and compiling a comprehensive environmental picture. The advance in technology should provide the basis for a pod being able to conduct all of these tasks, and thus giving the military commanders a flexible tool and not just another designated sensor meant for one thing only.

2. *Flexible mounting and cabling*

   The pod must have a generic mounting system, so that it can easily be moved from one airplane to another, and from one platform to another. This means that it must be fitted to comply with existing military standards for mounting on military platforms. It also must have the ability to hook onto existing cabling laid out in the wings of the MPAs and the helicopters, so that the pods can easily be interchangeable between the aircraft. New wings with digital cabling on the MPAs and the new pod-mounting system for the helicopters enable sensor-pods of different kinds to be mounted, with the receiving computer on-board the aircraft working with whatever is mounted on the wings or the helicopter.

6.4.4 Affordability

LIDAR-technology is often referred to as a cost-efficient surveying method, compared to other surveying systems available. It is important, however, that the suggested sensor-pod does not lead into a severely advanced, costly and time-consuming technology development process. The process of military acquisition is costly and time-consuming enough as it is, and the suggested pod should be based on existing programs such as the ALMDS technology being pursued for mine hunting and the hyperspectral LASH-system that is being tested on P-3 Orions. SAR-technology has been available since the late 1980s, and has been flown on Maritime Patrol Aircraft since the late 1990s. The further advance of these technologies during the past decade should provide for an integration of the three sensors in one single pod, with an affordable price.

6.5 Summary

This chapter has presented the current applications of LIDAR technology in both the civilian and the military world. Almost every system mounted on military platforms has been designated mine countermeasures (MCM) systems, with the speculation of some systems being used specifically for hunting submarines. Using LIDAR for Rapid Environmental Assessment (REA) in order to contribute in the compiling of a comprehensive environmental picture will benefit the military planners significantly. The early stated wish to use LIDAR for submarine hunting did not materialize into any operational systems, but NAVAIR in the U.S.A. is currently considering expanding the ALMDS-program to include LIDAR as an

ASW-sensor for MPAs. Although the light beams do not penetrate very deep, and although they might be reduced to only 10-20 meters of penetration in demanding conditions, an ASW LIDAR-system might have a deterrent effect to the submarine commander, and thus make him choose a deeper route of sailing. This makes the submarine more vulnerable to existing active and passive acoustic systems.

Other non-acoustic technologies have been tested against submarines, and have shown their ability to detect dark and submerged objects in the upper layers of the water column. This has led to a thought of combining LIDAR with Synthetic Aperture Radar (SAR) and Hyperspectral Imagery in order to take full advantage of the physical conditions present when a submarine is transiting through the littorals. A merging of three technologies like this might be the way forward for a littoral ASW-pod to be mounted on Maritime Patrol Aircraft and frigate helicopters, and should only demand a modest amount of funding for development and production.

7 – Conclusion and recommendation

7.1 Conclusion – What has been done until now?

The aerial ASW-platforms are fast, flexible and are able to apply advanced sensors in the hunt for the enemy submarine. An array of sensors are aiding them in accomplishing their mission, be it covertly following the enemy submarine or hunting it down in order to neutralize her. But the submarines are getting quieter and quieter, and now the aerial ASW-sensors are lagging behind. Many of the existing ASW-sensors were made for a blue-water search, and do not perform as well close to the shore. Experience has shown the need to investigate other technologies in order to be able to meet the emerging challenges inherent in a littoral ASW-campaign.

The maturing of signal processing equipment and laser components has made LIDAR into a somewhat mature technology, although it has mostly been used for civilian research. Exact positioning equipment has also provided the basis for exact measuring services provided by several civilian contractors. The biggest challenge of transmitting light through the water is the scattering of light once the light beams enter the water, and the immense amount of information that has to be processed by the receivers. The computers have to distinguish between the large difference in magnitude between the different returns, based on advanced algorithms and thorough knowledge of the characteristics of water. Due to this, the most prominent limitation to laser beams being sent through water is the water clarity, and thus the scattering of light. These limitations have very likely contributed to the fact that no Maritime Patrol Aircraft or designated ASW-helicopters are presently flying with LIDAR as an ASW-sensor.

The world saw great advances in submarine technology during the Cold War, and the proliferation of such technology has given even small nations the ability to appear as a credible naval force in isolated operations. As a paradox from the early 1990s, the major nations in the West have not prioritized ASW as much as they did before, due to a changing world picture. Approaching the turn of the century, they found that much advanced submarine technology had been proliferated, and the move had been made from blue-water operations to more likely scenarios in the littorals. However, the acoustic sensors that most ASW-forces had been relying on are not as efficient close to the shore, and the need for supplementary technologies became apparent.

The development of LIDAR started in the early 1960s with the aim of hunting submarines from the air with lasers. The technology, however, was not ready. Much effort was put into several early programs, but more robust and quicker processors were needed in order to take care of the information that returned to the receivers. The U.S. Navy has been using LIDAR since the first Gulf War in 1991, and has improved the technology since then. NAVAIR in the U.S. Navy is now considering expanding the ALMDS-program to include designated ASW-sensors to be put on MPAs such as the P-3 Orion and the future P-8 Poseidon.

7.2 Recommendation – The way forward

LIDAR systems of today do not seem to penetrate sufficiently deep to provide the aerial ASW-platform a credible search sensor for exclusive ASW use. Militaries are building up experience with LIDAR for use in mine countermeasures, and this might give a better sensor in the future. However, LIDAR will have an important effect doing more than hunting for submarines. The technology will aid in providing a Rapid Environmental Picture, and most certainly in the hunt for submerged mines. MPAs have historically also been used in mining operations, and they will through LIDAR be able to assist in a most efficient manner. Also, the fact that the MPA is carrying LIDAR might in itself be able to deter the submarine commander from working close to the surface, and thus force him down to a depth where the traditionally efficient acoustic sensors can perform better.

As for a designated ASW-sensor, LIDAR does not seem to suffice. But knowing about the effects of other technologies that will aid in the search for submerged objects in the upper layers of the water column, a combined sensor might be able to provide a much more stable set of results for the operator. The recommendation will be to combine LIDAR with a Synthetic Aperture Radar (SAR) and a Hyperspectral Imagery camera in order to take full advantage of the physical conditions present when a submarine is transiting through the littorals. The merging of three technologies like this might be the way forward for a potent littoral ASW-pod, and by taking advantage of published science reports and the running experience of LIDAR being used for mine searches, such a multi-sensor will be an affordable solution to a complex problem.

Abbreviations

ACINT	Acoustic intelligence
AIP	Air Independent Propulsion
ALB	Airborne LIDAR Bathymetry
ALH	Airborne LIDAR Hydrography
ALMDS	Airborne Laser Mine Detection System
AOL	Airborne Oceanographic LIDAR
ASW	Antisubmarine Warfare
ATD	Advanced Technology Demonstrator
CAT	Clear Air Turbulence
CCD	Charged-Coupled Device
CD & E	Concept Development & Evaluation
DARPA	Defense Advanced Research Projects Agency
DGPS	Differential Global Positioning System
DMA	Defence Mapping Agency
EAARL	Experimental Advanced Airborne Research LIDAR
EO/IR	Electro-Optic/Infrared
FDS	Fixed Distributed System
FLASH	FOA Laser Airborne Sounder for Hydrography
FOA	Swedish Defense Research Establishment
GPS	Global Positioning System
HALS	Hydrographic Airborne Laser Sounder
ICCD	Intensified Charged-Coupled Device
IFF	Identification Friend or Foe
IMU	Inertial Measurement Unit

IOC	Initial Operational Capability
IR	Infrared
ISAR	Inverse Synthetic Aperture Radar
ISR	Intelligence, surveillance and reconnaissance
ITTR	Imaging Time-Resolved Receiver
LADS	Laser Airborne Depth Sounder
LASH	Littoral Airborne Sensor - Hyperspectral
LIDAR	Light Illumination Detection and Ranging
m	Meter
MAD	Mutually Assured Destruction
MAD	Magnetic Anomaly Detection
MCM	Mine Countermeasures
MPA	Maritime Patrol Aircraft
NAASW	Non-Acoustic Antisubmarine Warfare
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NAVAIRDEVCEN	Naval Air Development Center
NAVSEA	Naval Sea Systems Command
NJHQ	National Joint Headquarters
nm	Nanometer
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
ONR	Office of Naval Research
PLADS	Pulsed Light Airborne Depth Sounder
RAMICS	Rapid Mine Clearance System
REA	Rapid Environmental Assessment
REP	Recognized Environmental Picture
RF	Radio Frequency

RPG	Rocket Propelled Grenade
SAR	Synthetic Aperture Radar
SHOALS	Scanning Hydrographic Operational Airborne LIDAR Survey
SLOC	Sea-Lines of Communication
SPAWAR	Space and Naval Warfare Command
SSBN	Submarine carrying ballistic missiles, nuclear propulsion
SSN	Attack submarine, nuclear propulsion
SSK	Tactical/attack submarine, diesel-electric propulsion
STI	Science and Technology International
TACCO	Tactical Coordinator
TST	Time Sensitive Targeting
UAV	Unmanned Aerial Vehicles
USACE	U.S. Army Core of Engineers
W	Watt
WRE	Weapons Research Establishment

Bibliography

Aftenposten (2008)

- http://www.aftenposten.no/nyheter/uriks/article2544453.ece
- 29 June 2009

Alfredsson, R., Alfredsson, M. (1999) '*Capacity and Capability for Hydrographic Missions*'. Proceedings 1999 U.S. Hydrographic Conference, April 26-29, Mobile AL.

Andrews, W. (1984a) '*Soviets Said Able to Target U.S. Subs from Space by Radar*'. Washington Times, 16 August 1984, p.6A.

Andrews, W. (1984b) '*Soviet Ability to Target Subs Denied*'. Washington Times, 17 August 1984, p.12A.

Apel, J.R., Gjessing, D.T (1989) `*Internal Wave Measurements in a Norwegian Fjord Using Multifrequency Radars*`. In "Johns Hopkins APL – Technical Digest", Volume 10, Number 4 (1989). Laurel, MD (USA): The Johns Hopkins University Applied Physics Laboratory.

Berry, R.E. (1993) `*Modifications of Airborne Oceanographic LIDAR for the Long Range P-3 Missions*`. Final Report Grant No.NAG5-689, March 1 1992 to September 30 1993, St.Vincent College, Latrobe, PA.

Buff, J.J. (2003) `*So what if the Seas Were Transparent*?`. Article in "The Submarine Review", July 2003 issue.

- http://www.joebuff.com/essay26.htm
- 18 October 2009

Burgess, R. (1982) ´*P-3 Orion – 20 years young*`. Published in "Naval Aviation News", August 1982 issue, p.14.

Calder, M., Penny, M.F. (1980) `*Australian overview*`, Proceedings 4th Laser Hydrography Symposium, ERL-0193-SD, Defense Research Centre Salisbury, Sept.30-Oct.3, 1980, Salisbury, South Australia, 1-21.

Campbell, J.B. (2007) `*Introduction to Remote Sensing*`. 4th edition, New York: The Gilford Press.

Clark, V. (2002) ´*Sea Power 21 – Projecting Decisive Joint Capabilities*´. United States Navy, Proceedings, October 2002

- http://www.navy.mil/navydata/cno/proceedings.html
- 09 February 2009

Congress (1996) ´*NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 1996*´. 104TH CONGRESS - 1st Session - REPORT - 104–406, CONFERENCE REPORT TO ACCOMPANY H.R. 1530, DECEMBER 13, 1995.

- http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=104_cong_reports&docid=f:hr406.pdf
- 24 September 2008

Congress (1997a) ´*NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 1997*´. 104TH CONGRESS - 2d Session - REPORT - 104–724, CONFERENCE REPORT TO ACCOMPANY H.R. 3230, JULY 30, 1996.

- http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=104_cong_reports&docid=f:hr724.pdf
- 24 September 2008

Congress (1997b) ´*NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 1997*´. 104TH CONGRESS - 2d Session - REPORT - 104–563, REPORT OF THE COMMITTEE ON NATIONAL SECURITY HOUSE OF REPRESENTATIVES ON H.R. 3230 together with ADDITIONAL, SUPPLEMENTAL, AND DISSENTING VIEWS, MAY 7, 1996.

- http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=104_cong_reports&docid=f:hr563.pdf
- 24 September 2008

Congress (2004) `*NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 2004*`. 108TH CONGRESS - 1st Session - REPORT - 108–354, CONFERENCE REPORT TO ACCOMPANY H.R. 1588 NOVEMBER 7 (legislative day, NOVEMBER 6), 2003.

- http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=108_cong_reports&docid=f:hr354.pdf
- 24 September 2008

Congressional Hearing (1989) ´*Advanced Submarine Technology and Antisubmarine Warfare*´. Hearing before the Seapower ad Strategic and Critical Materials Subcommittee, the Research and Development Subcommittee and the Committee on Armed Services. House of Representatives, One Hundred First Congress. Honolulu, Hawaii: University Press of the Pacific.

Cordesman, A.H**.** (1996) '*Lessons of Modern War: the Gulf War volume IV'*. Boulder, CO (USA): Westview Press.

Defense News (2007)

- http://www.defensenews.com
- 05 February 2007

Defense News (2009) `*China Defense Minster: We Can Compete With the West*`. Agence France-Presse in Defense News, 21 September 2009.

- http://www.defensenews.com/story.php?i=4287428&c=SEA&s=ASI
- 12 October 2009

Driggers, R.G. (2003) `*Encyclopedia of Optical Engineering*`. Vol.II, Marcel Dekker Ltd. Boca Raton, FL: CRC Press.

Drost, R.J., Singer A.C. (2004) *'Factor graph methods for three-dimensional shape reconstruction as applied to LIDAR imaging*'. Optical Society of America, vol.21, no.10/October 2004/J.Opt.Soc.Am.A 1855.

Durey, L., Gregory, T., Arnone, R., Martinez, A.B. (1997) *´Bottom Reflectance Maps form Hyperspectral Sensors: An Application to AAHIS Data´*. In Proceedings, ERIM Fourth International Conference on Remote Sensing for Marine and Coastal Environments. Orlando, FL.

Edmonds, M. (ed.) (2001) `*100 years of the trade – Royal Navy Submarines: Past, present and future*`. Centre for Defence and international Security Studies (CDISS). Lancaster: CDISS.

Estep, L.L., Lillycrop, W.J., Parson, L.E. (1994) *´Sensor Fusion for Hydrographic mapping Applications´*. In Proceedings, U.S. Army Corps of Engineers 1994 Training Symposium, Surveying and mapping, Remote Sensing/GIS. New Orleans, LA.

Feigels**,** V.I., Kopilevich, Y.I. (1993) `*Russian Airborne LIDARs for Oceanography*`. Symposium on Russian Airborne Geophysics and Remote Sensing, Proceedings vol.2111, p.127-141, 1 Nov 1993, SPIE Digital Library.

Flight International (1997) '*U.S. Navy plans mine-detector fly-off'*. U.S. Navy League Magazine, Flight International 19 – 25 November 1997.

Flight International (2000) '*Laser mine detector goes to EMD'*. U.S. Navy League Magazine, Flight International 25 April – 1 May 2000.

Friedman, N. (1997) `*The Naval Institute Guide to World Naval Weapons Systems*`. Illinois: Naval Institute Press.

Friedman, N. (1999) `*New Technology and Medium Navies*`. Royal Australian Navy, Maritime Studies Program, Working Paper No.1, August 1999. Jervis Bay: National Library of Australia.

Friedman, N. (2006a) `*Warship Propulsion – The Alternatives*`. Testimony Prepared for the Power Projection Subcommittee, House Armed Services Committee, 6 April 2006.

Friedman, N. (2006b) `*The Naval Institute Guide to World Naval Weapons Systems*`. Illinois: Naval Institute Press.

Friedman, N. (2007) `*The Future Surface Combattant*`. Royal United Services Institute – The Shape of the Future Surface Combatant, published in "RUSI Defence Systems", October 2007.

Friedman, N. (2008) `*Some Global Naval Trends*`. In ´Six Perspectives on Naval Strategy´, conference on naval strategy and maritime issues held in Karlskrona and Stockholm, Sweden, 22-23 October 2008. FOI report FOI-R-2655-SE.

Frost, R.J., Singer, A.C. (2004) `*Factor graph methods for three-dimensional shape reconstruction as applied to LIDAR imaging*`. Optical Society of America, vol.21, No.10, October 2004.

Gelantin, I.J. (1995) `*Submarine Admiral – From Battlewagons to Ballistic Missiles*`. Chicago: University of Illinois Press.

Genat, R. & R. (1997) ´*Modern U.S. Navy Submarines*´. Osceola, WI (USA): MDI Publishing.

Global Security (2002) '*AN/AWS-1 Rapid Airborne Mine Clearance System (RAMICS)*'.

- http://www.globalsecurity.org/military/systems/aircraft/systems/an-aws-1.htm
- 01 October 2007

Global Security (2009) `*World Military Guide*`

- http://www.globalsecurity.org/military/world/index.html
- 21 September 2009

Goodman, L.R., Guenther, G.C. (1978) '*Laser applications for near-shore nautical charting*'. Proceedings, SPIE Ocean Optics V, vol. 160. pp.174-183.

Grant, G., Konstam, A., Marriott, L. (2001) `*Warships – From the Galley to the Present Day*`. New York: Gramercy Books.

Grove, E. (1991) `*Battle for the fjords – NATO`s Forward Maritime Strategy in Action*`. Annapolis: Naval Institute Press.

Guenther, G.C., LaRocque, P.E., Lillycrop, W.J. (1994) `*Multiple surface channels in SHOALS airborne Lidar*`. Proceedings SPIE Ocean Optics XII, vol.2258, pp.422-430.

Guenther, G.C., Eisler, T.J., Riley, Perez, S.W. (1996) `*Obstruction detection and data decimation for airborne laser hydrography*`. Proceedings, 1996 Canadian Hydrographic Conference, Halifax, N.S., p.51-63.

- http://shoals.sam.usace.army.mil/downloads/Publications/9Guenther_Eisler_Riley_Perez_96.pdf
- 17 October 2007

Guenther, G.C., Grant Cunningham, A., LaRocque, P.E., Reid, D.J (2000) `*Meeting the accuracy challenge in airborne LIDAR bathymetry*`. Proceedings of EARSek.SIG-Workshop LIDAR, Dresden/FRG, June 16-17, 2000.

- http://las.pysik.uni-oldenburg.de/eProceedings/vol01-1/01_1_guenther1.pdf
- 04 January 2008

Guenther, G.C. (2006) `*Airborne Lidar Bathymetry*` in "*Digital Elevation Model Technology and Applications: The DEM User`s Manual*", 2nd edition, D.Maune (ed.), American Society for Photogrammetry and Remote Sensing, ch.8.

Haghshenass, F. (2006) `*Iran's Doctrine of Asymmetric Naval Warfare*´. The Washington Institute for Near East Policy, 1179, 21 December 2006, 1-3.

Hammond, N.J. (2001) `*Revolution in Military Affairs – Does Hydrography have a part to play?*`. U.S. Hydrographic Conference 2001, May 22-24, 2001.

- http://www.thsoa.org/hy01/11_1.pdf
- 20 September 2008

Hanson, J.M., Hughes, A.S., Marcotte, F.J. (1992) '*1992 Sognefjord Experiment'*. FS-92-142, September 1992. Fleet Systems Department, The Johns Hopkins University – Applied Physics Laboratory. Laurel, MD (USA).

Hassig, L. (ed.) (1992) `*Hunters of the Deep – The New Face of War*`. Alexandria, VA: Time-Life Books.

Hjelmstad, J. (2009) Interviews conducted at the professor's office in Asker, Norway, February and October 2009.

Irish, J.L., McClung, J.K., Lillycrop, W.J. (1999) '*Airborne Lidar Bathymetry: The SHOALS system*'. Joint Airborne Lidar Bathymetry Technical Center of Expertise.

- http://shoals.sam.usace.army.mil/downloads/Publications/Irish_McClung_lillycrop:00.pdf
- 27 January 2009

Jane's (2000) '*Clouds lift over April Showers ASW-pod sensors'*. Jane's Weapons and Equipment, 25 May 2000.

Jane's (2006) '*Littoral Airborne Sensor – Hyperspectral Programme (LASH)*'. Jane's Information Group

Jane's (2008) '*Northrop Grumman AN/AES-1 Airborne Laser Mine Detection System (ALMDS)*'. Jane's Information Group

Jane's (2009) '*Magic Lantirn (United States), Mine warfare – Mine Warfare Laser Systems'*. Jane's Underwater Warfare Systems, 10 February 2009.

Johnson, J. (1997) `*Anytime, Anywhere: A Navy for the 21st Century*`. Proceedings, November 1997, p.48-49.

Jukes, G. (2002) ´*The Russo-Japanese War 1904-1905*´. Oxford: Osprey Publishing Limited.

Källen, E. Dahlquist, H. (1992) '*Measurements and Modelling of Internal Waves in Sognefjord*'. FOA Report, C 20901-2.6, September 1992. ISSN 0347-3694.

Kaplan, P., Currie, J. (1997) ´*Wolfpack – U-boats at war 1939-1945*´. Annapolis, MD (USA): Naval Institute Press.

Karlsson, H. (2006) '*Hawk Eye II – a repeatability study of an airborne bathymetry LIDAR sysmem*'. Proceedings, World Map Forum.

- www.gisdevelopment.net/proceedings/mapworldforum/tm/MWF_Terrain_134.pdf
- 06 February 2009

Kim, H.H., Cervenka, P.O., Lankford, C.B. (1975) `*Development of an Airborne Laser Bathymeter*`. NASA Technical Note, NASA TN D-8079, Wallops Flight Center, Wallops Island, VA., 5 October 1975.

Kristensen, H.M. (2009) `*Chinese Submarine Patrols Doubled in 2008*`. Published by the Federation of American Scientists, February 2009.

- http://www.fas.org/blog/ssp/2009/02/patrols/php
- 12 October 2009

Laite, B.C. (1991) *'Maritime Air Operations'*. London: Brassey's Defence Publishers.

LaRoque, P.E., West, G.R. (1999) `*Airborne Laser Hydrography: An Introduction*`. Proceedings, ROPME/PERSGA/IHB Workshop on Hydrographic Activities in the ROPME Sea Area and Red Sea, October 24-27, Kuwait City.

Mason, R.A. (1987) '*Air Power – An overview of Roles*'. London: Brassey's Defence Publishers.

Mills, A. (ed.) (2003) ´*Submarine – Discover the secret underwater world of submarines and submersibles*´. New York: DK Publishing.

Nelepo, B. (1981) quoted in McConnel, J.M. (1985) '*New Soviet Methods for Antisubmarine Warfare?*'. Naval War College Review, July/August, 1985, pp.16-27.

Nordstrom, G. (2000) `*The Swedish Hydrographic Service on the eve of a new millennium*`. Integrated coastal zone management, Spring Edition, 37-40.

NRC (2007) - National Research Council of the National Academies (2007*)* `*Distributed Remote Sensing for Naval Undersea Warfare*´. Washington, D.C.: The National Academies Press.

Optech (2008)

- http://www.optech.ca/shoalsprodhistory.htm
- 03 February 2008

O´Rourke, R. (2004) `*Navy Attack Submarine Force Level – Goal and Procurement Rate – Background and Issues for Congress*`. CRC Report for Congress, Order Code RL 32418.

O'Rourke, R. (2009) `*Navy Littoral Combat Ship (LCS) Program: Background, Oversight Issues, and Options for Congress*`. CRC Report for Congress, Order Code RL 33741.

Ott, L.M. (1965) "*Underwater ranging measurements using blue-green laser*", NAVAIRDEVEN Report No. NADC-AE-6519. Naval Air Development Center, Warminster, PA (CONFIDENTIAL, declassified to UNCLASSIFIED)

Owen, D. (2007) `*Anti-Submarine Warfare – An Illustrated History*`. Annapolis, MD.: Naval Institute Press.

Pike, J., Vick, C., Jacubowski, M., Garrett, P. (2000) `*Weapons of Mass Destruction Around the World*`.

- http://www.fas.org/nuke/guide/russia/theater/949.htm
- 17 August 2009

Pope, R.W., Johnson, P., Lejdebrink, U., Lillycrop, W.J. (2001) `*Airborne Lidar Hydrography: Vision For Tomorrow*`. U.S. Hydrographic Conference 2001, May 22-24, 2001.

RIA Novosti (2009)

- http://www.globalsecurity.org/wmd/library/news/russia/2009/russia-090624-rianovosti02.htm
- 29 June 2009

Ruttan, V.W. (2006) '*Is War Necessary for Economic Growth? – Military Procurement and Technology Development*'. New York: Oxford University Press.

Schawlow, A.L., Townes, C.H. (1958) `*Infrared and Optical Masers*`. Physical Review, vol.112, pp.1940-1949, December 15, 1958.

Senate (1999) ´*DEPARTMENT OF DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 1999*´. 105TH CONGRESS - 2d Session - REPORT - 105–189, REPORT [TO ACCOMPANY S. 2060] ON AUTHORIZING APPROPRIATIONS FOR FISCAL YEAR 1999 FOR MILITARY ACTIVITIES OF THE DEPARTMENT OF DEFENSE. COMMITTEE ON ARMED SERVICES, UNITED STATES SENATE, MAY 11, 1998.

- http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=105_cong_reports&docid=f:sr189.pdf
- 24 September 2008

Smith, R.A., Irish, J.L., Smith, M.Q. (2000) `*Airborne Lidar and Airborne Hyperspectral Imagery: A Fusion of Two Proven Sensors for Improved Hydrographic Surveying*`. Proceedings, Canadian Hydrographic Conference 2000, Montreal, Canada.

Stefanick, T. (1987) '*Strategic Anti-submarine Warfare And Naval Strategy*'. Cambridge, USA: Institute for defense and disarmament studies.

Steinvall, O., Koppari, K., Lejderbrink, U., Winell, J., Nilsson, M., Ellsen, R., Gjellan, E. (1996) `*Depth Sounding Lidar-perfomance and Models*`. SPIE, vol.2748, 1996, p.18-38.

Steinvall, O., Koppari, K. (1996) `*Depth Sounding LIDAR – An Overview of Swedish Activities and with Future Prospects*`. SPIE, vol.2748, 1996.

Speller, I., Tuck, C. (2001) '*Amphibious Warfare – The theory and Practice of Amphibious Operations in the 20th Century*'. London: Amber Books Ltd.

Thornton, R. (2007) ´*Asymmetric Warfare*´. Cambridge: Polity Press.

Till, G. (ed.) (1994) `*Seapower – Theory and practice*`. Essex: Frank Cass & co., Ltd.

Till, G. (2004) ´*Seapower – A Guide for the 21st Century*´. London: Frank Cass.

USACE Manual (2002) `*Engineering and design – Photographic Mapping*`. U.S. Army Core of Engineers, EM 111-1-1000, ch.11.

U.S. Navy (1997) '*United States Naval Mine Warfare Plan*'. Third Edition, fiscal year 1996-1997 Programs.

- http://www.dtic.mil/cgi-bin/GetTRDDoc?AD=ADA321292&Location=U2&doc=GetTRDoc.pdf
- 09 September 2009

U.S. Navy (1999) '*United States Naval Mine Warfare Plan*'. Fifth Edition, fiscal year 1998-1999 Programs.

- http://www.exwar.org/Htm/ConceptDocs/Navy_USMC/MWP4thEd/appendix_c.htm
- 01 October 2007

U.S. Navy (2009) ´*Anti-Submarine Warfare - Concept of Operations for the 21st Century*´

- http://www.navy.mil/navydata/policy/asw/asw-conops.pdf
- 19 September 2009

Vego, M. (2009) `*No Need for High Speed*`. United States Naval Institute magazine ´Proceedings´. Issue: September 2009, vol.135/9/1,279.

Walrafen, G.E. (1967) `*Raman spectral studies of the effects of temperature on water structure*`. Chem.Phys., 47, 1, 114-126.

Weitkamp, C. (2005) `*LIDAR - Range-Resolved Optical Remote Sensing of the Atmosphere*`. New York: Springer.

West**,** G.R., Lillycrop, W.J. (1999) `*Feature Detection and Clasification with LIDAR – Practical Experience*`. Report to Joint Airborne LIDAR Bathymetry Center of Technical Expertise, Mobile, AL.

- http://shoals.sam.usace.army.mil/downloads/Publications/29West_Lillycrop_99.pdf
- 17 October 2007

Wickerts**, S.,** Källen, E. (1990) '*Observation and Modelling of Internal Waves in a Strongly Stratified Ocean*'. FOA Rapport, C 20784-2.7, February 1990. ISSN 0347-3694.

Work, R.O. (2004) `*Naval Transformation and the Littoral Combat Ship*`. Center for Strategic and Budgetary Assessment, February 2004. Washington, D.C.: CSBA.

Wozencraft, J.M., Lillycrop, W.J. (2002) `*Total Shallow-water Survey Through Airborne Hydrography*`. Proceedings, Oceanography International 2002, London, England.