UUV - Covert Acoustic Communications
- Preliminary Results of the First Sea Experiment -

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ABSTRACT

The future role of unmanned underwater vehicles (UUVs) is expected to include autonomous tasks in environmental assessment, route survey, mine hunting, and battlefield preparation. Depending on the mission, there will be a need for a robust communication link between the mother ship and the UUV, with a low probability of intercept by third parties. The overall goal of the joint European project "UUV Covert Acoustic Communications" with contributions from Denmark, Finland, Italy, The Netherlands, Germany, Norway and Sweden is to develop covert communication algorithms to enable such a communication link.

The present paper describes initial results of the project's first sea trials, conducted in the Baltic and North Sea environments in September 2006. The main purpose of these trials is characterization of the communication channel. A variety of probe signals were transmitted with a mobile projector, and recorded on a vertical hydrophone array deployed from a moored platform. The data analysis focuses on aspects relevant to acoustic communication, such as ambient noise, multi-path propagation, Doppler effects, and their time variability. The outcome of the analysis will be used for the development of a filter model, designed to model the underwater acoustic communication channel in a realistic fashion.

I. INTRODUCTION

Unmanned underwater vehicles (UUVs) will become an integral part of several fleets' surveillance, environmental assessment, route survey, and battlefield preparation capabilities such as mine hunting. They are believed to provide extensions of both sensor and weapon capability in peacekeeping and wartime missions. Basic military demands for using autonomous underwater systems such as UUVs are covert operations, reduction of risk to manned platforms, and cost reduction. They can also enhance the network centric warfare ability of the fleet. This development will require effective and reliable systems for communications to and from an UUV. The effectiveness of these vehicles will be severely restricted if not being able to communicate. Increasingly the communications capability is becoming the limiting factor in achieving viable autonomous underwater systems.

A hard wire or fiber optical link for communication purposes provides real-time data transmission and control through a high-bandwidth connection between the mother platform and UUV. However, the tether is also the primary disadvantage of this communication technique, providing a hard limit on the range that can be covered and imposing severe performance limitations both hydro-dynamically and operationally.

Therefore, wireless underwater communications is preferable for the applications mentioned above. This can be established by transmission of acoustic waves. Radio waves are of little use for this purpose because they are attenuated at short distances, while laser beams suffer from scattering and need high precision in pointing. However, also the underwater acoustic communication channel is far from ideal. It has a very limited bandwidth, and often causes severe signal dispersion both in time and frequency /1, 2, 3/.

In the field of acoustic communications one normally distinguishes between four different kinds of communication signals: control, telemetry, speech and video signals.

Control signals include navigation and status information as well as commands in order to continuously control the UUV. The required data rate is limited (in the region of 100 bit/s or less), but low bit error rates (BER) may be required.

Telemetry data is collected by the UUV sensors like a side scan sonar and may include some image data. Required data rates for this purpose are on the order of several tens of kbit/s. The reliability requirements are not so severe as for command signals. BERs of 10^{-3} – 10^{-4} are often sufficient for these applications.

Speech signals are transmitted between divers, submarines, and to surface units and installations. Available communication systems for this purpose mostly use presently analog signals based on single sideband modulation of a 3 kHz audio signal. Digital systems are under development since it is expected that digital communication provides better reliability and speech quality. A BER of about 10^{-2} may be tolerable for this application while the required data rate is on the order of several kbit/s.

Video transmission over the acoustic channel requires extremely high compression ratios if an acceptable frame transmission rate (e.g. 10 s) is to be achieved. Standards like JPEG have been applied for underwater images which exhibited low contrast and preserved satisfactory quality if compressed to few bits per pixel (e.g. 2) /4/.

II. THE "UUV – COVERT ACOUSTIC COMMUNICATIONS" PROJECT

A. Objectives

UUVs can and probably have to work autonomously in the future for the mentioned tasks like environmental assessment, or mine hunting. Operating at large distances from the mother platform (say several tens of kilometers) is a valuable option in this context. Due to the probably large time necessary for fulfilling its operation and the traveling required to traverse from the area of operation to the mother platform, the need for reliable basic communications providing continuously basic control of the UUV is obvious. For some military operations covertness of this communication is also essential.

The project "UUV – Covert Acoustic Communications" under the EUROPA MoU is addressing the problem of communicating covertly between an UUV and a mother platform for ranges up to several tens of kilometers in littoral waters with data rates up to (about) 100 bits/s. The aim of this joint project with contributions from Denmark, Finland, Italy, The Netherlands, Germany, Norway and Sweden is to demonstrate a covert transfer of data, typically short messages and instructions of a few tens of bytes, from a surface ship or submarine towards an UUV and vice versa. The project draws upon the existing national programs of work and has the following global objectives:

- Quantification of operational constraints.
- Quantification of environmental constraints at test sites by investigating the acoustic channel during sea trials.
- Establishment of a common filter model of the channel for testing the investigated / developed communication schemes under simulated, predefined conditions.
- Comparison, development, and evaluation of acous. methods for covert communications
- Implementation of software and required hardware on existing platforms.
- Evaluation of communication sub-systems on existing UUVs.
- Quantification of the practical, achievable range-rate product.

In the course of the European project "UUV – Covert Acoustic Communications" three sea trials will be carried out at two chosen test sites. The first sea trial aims at acquiring noise and channel data for investigating the acoustic channel and establishing a common filter model of this channel. Main goals of the second sea trial one year later are to further collect acoustic data that provide insight in the specific acoustic conditions, which will determine the communication possibilities. At the same time communication signals will be transmitted and recorded for laboratory analysis to test the communication schemes developed so far. The third and last sea trial is a field demonstration for the developed algorithms using a surface vessel and an existing UUV equipped with the developed software and hardware modem.

B. Preliminary Experiments

Taking advantage of the sound channel, which exists in summer, FOI was able to decode 4000 bps at a transmission range of 38 km, without bit errors for data recorded during the BAROC experiment in the Baltic Sea in 2002 /5, 6, 7/. Bandwidth efficient modulation of the quadrature phase-shift keying type (QPSK) was used in this case. In order to combat the multi-path distortion, FOI employed a multi-channel adaptive receiver involving several hydrophones and an adaptive decision feedback equalizer.

Using a towed array or a flank array as receiving system and taking advantage of the beam forming gain for these systems, FWG was able to establish a simplex link from a surface vessel to an underwater recipient for transmission ranges up to 25 km during a bi-static sonar experiment in the Celtic Sea in 2002 /8/. In this example for a mobile acoustic communication link a full GPS-string was transmitted each minute within 4 seconds.

III. FIRST SEA TRIAL

The first UCAC I – 2006 sea experiment took place in September 2006 at three sites, one close to Bornholm in the Baltic Sea (Fig. 1.a) and the other two west of Bergen in the open sea (Fig. 1.b) and in the Björna Fjord. The main goal of these trials was characterization of the communication channel.

A. Experimental Sites

Two different vessels were involved in the experiment at each site. FS Planet (FWG) anchored at centre positions and served as platform for the receiving systems (vertical array III and NESSY hydrophone chain with calibrated omni-directional broad-band spherical hydrophones). The Swedish vessel S/V Ocean Surveyor (FOI) or the Norwegian vessel R/V HU Sverdrup II (FFI) sailed away from FS Planet along outbound tracks and returned on inbound tracks for probing the acoustic channel towing an acoustic source.

Source depths of 12 or 35 m in the Baltic Sea and 15 or roughly 60 m in the North Sea were used. A variety of probe signals were transmitted (e.g. LFM sweeps, cw and PRBS sequences) covering the medium frequency range from 2100 to 5600 Hz. In order to get high SNR ratios source levels from 200 to 210 dB were applied. The reader is referred to /9/ for further details.

The site in the Baltic Sea exhibits a water depth of 60 – 90 m, while the water depth at the site off the coast of Norway shows depths from 200 to 300 m. At the beginning and end of a track, which typically took about 3 to 5 hours, CTD-profiles (Conductivity Temperature Depth) were taken from both source and receiver platform. In addition, currents were monitored continuously with an Acoustic Doppler Current Profiler on board FS Planet. Finally, surface conditions were measured in the North Sea with a deployed wave rider buoy and variations in the temperature profile of the water column with a deployed thermistor string.

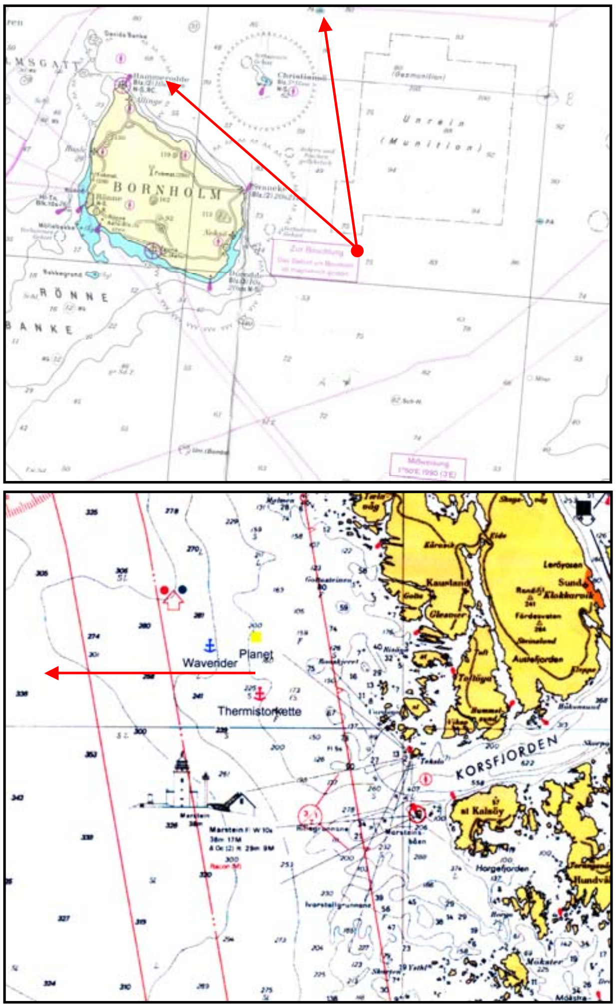


Fig.1: Tracks close to Bornholm a) and off the coast of Norway b).

B. Environment

During the measurements weather conditions were rather rough. For all sites typically observed wind speeds were in the order of 10 m/s resulting in a swell of typically 1 m or more. Currents in the Baltic Sea were negligible, while in the open sea off the coast of Norway the tidally induced currents bended the deployed antennas. Magnitudes of this tidal currents system varied between about 0.0 and 0.5 m/s within 12 hours.

Baltic Sea **15E33.11 55N04.66**

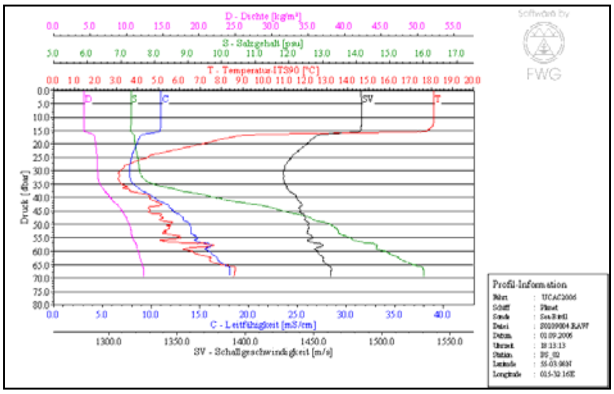


Fig.2: Typical observed sound speed profile observed close to Bornholm.

North Sea **004E52.63 60N12.10**

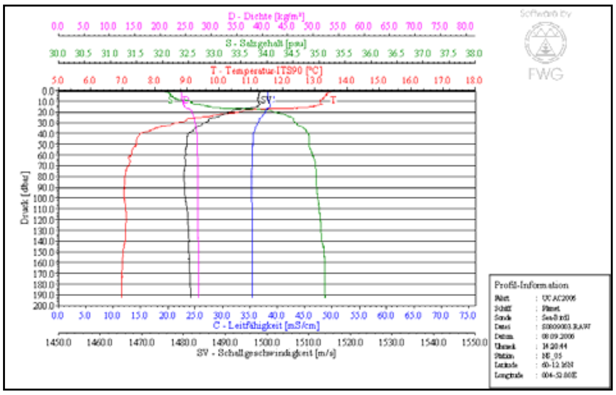


Fig.3: Typical observed sound speed profile observed close to Bergen of the coast of Norway.

In the Baltic Sea a typical summer sound speed profile exhibiting a sound channel was observed. This channel reaching from about 15 to 40 m was formed by a surface layer of warmer water and a bottom layer of water with higher salinity (Fig. 2). In comparison, the sound speed profiles taken off the coast of Norway show only a surface layer of 10 to 15 m thickness, which is caused by higher water temperatures and a reduced salinity (Fig. 3) . This surface water originates from the fjords, which carry the melt water from the Folgefond – Glacier. The measured sound speed profile in the Björna Fjord is comparable to the profiles observed in the open sea.

IV. CHANNEL CHARACTERISTICS

To achieve the objective of covert acoustic communication over long ranges in shallow water, precise knowledge of the influence of the environment, which will determine the communication possibilities, is required. The available bandwidth and transmission range in an underwater acoustic channel depend on the signal-to-noise ratio which is primarily determined by transmission loss and noise level. System performance and its information throughput depends on signal distortions caused by reverberation, multi path propagation and the influence of Doppler spreading as well as Doppler shifts for moving platforms. Channel characteristics are time varying and depend on the system location.

A. Bandwidth and Range

Transmission loss is caused by energy spread and sound absorption. While the energy spreading losses depend on the propagation distance and in shallow water on the boundary conditions (e.g. type of sea floor), absorption loss increases not only with range but also rapidly with frequency, thus setting the limit on the bandwidth that is available for communication over long ranges.

Ambient noise observed in the ocean over a broad frequency band consists of man-made and natural ambient noise. In the deep ocean, natural ambient noise dominates, while near shores and in the presence of shipping lanes, man-made noise significantly increases the noise level. Since ambient noise depends on wind speed, rainfall, shipping and off-shore activities, marine life and so forth, it is highly dependent on location, direction and time. Self-noise due to for example noise of engines on the receiving platform or water flow along the acoustic sensors also contribute to the total noise level.

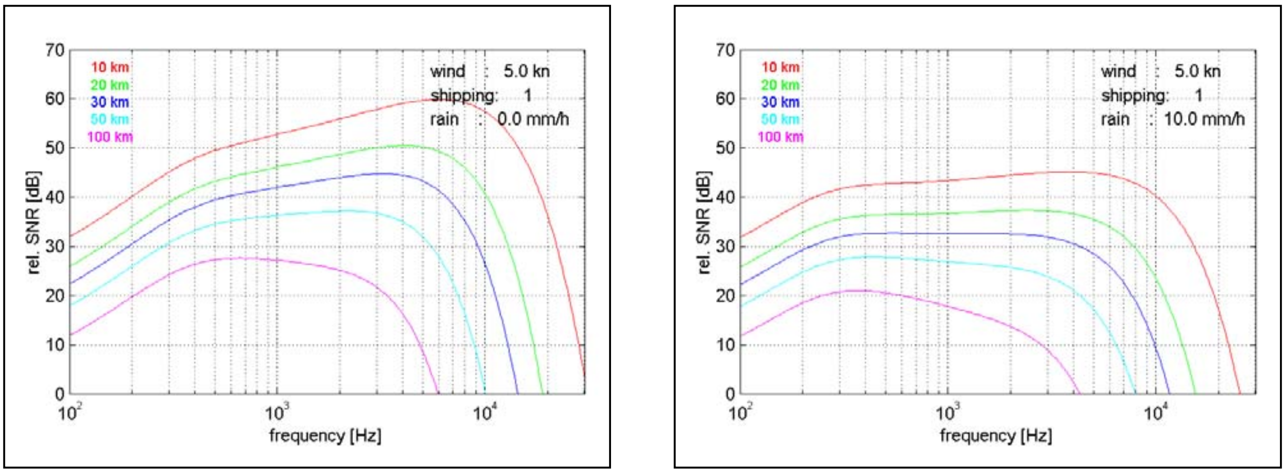


Fig.4: Frequency-dependent portion of SNR calculated for a range of 10 (-), 20 (-), 30 (-), 50 (-) and 100 (-) km assuming spherical spreading and absorption loss according to Francois-Garrison as well as a Knudsen spectrum for wind generated noise (5 knts) and noise curves for heavy shipping (1) and rain (0, 10 mm/h) according to Navel Undersea Warefare Center (NUWC-NL TM No. 931116) .

Transmission loss and total noise level determine the relationship between the possible transmission range, available bandwidth and achievable SNR at the receiver input for acoustic underwater communication links. Fig. 4 shows the estimated frequency dependent relative SNR level for blue waters and several transmission ranges (10, 20, 30, 50, 100 km). Obviously, this dependence influences the choice of a carrier frequency and determines the available frequency band for the desired maximum transmission range. For a long-range system, operating over 10 - 50 km, the available bandwidth falls below a few kHz. This determined the frequency band used during our experiments.

B. Impulse Response Function

Multipath propagation occurs if several propagation paths connecting the source and the receiver exist. It is highly dependent on the location of the transmitter and receiver and changes with time, if the sound velocity profile in the water column shows a time variability /10/.

Multipath propagation leads to time-spreading of the communication signals, which is especially troublesome if the time-spread exceeds the symbol duration. In the first place, the time spread depends on the link configuration, which is primarily designated as vertical or horizontal. While vertical channels exhibit little time dispersion, horizontal channels may have extremely long multipath spreads.

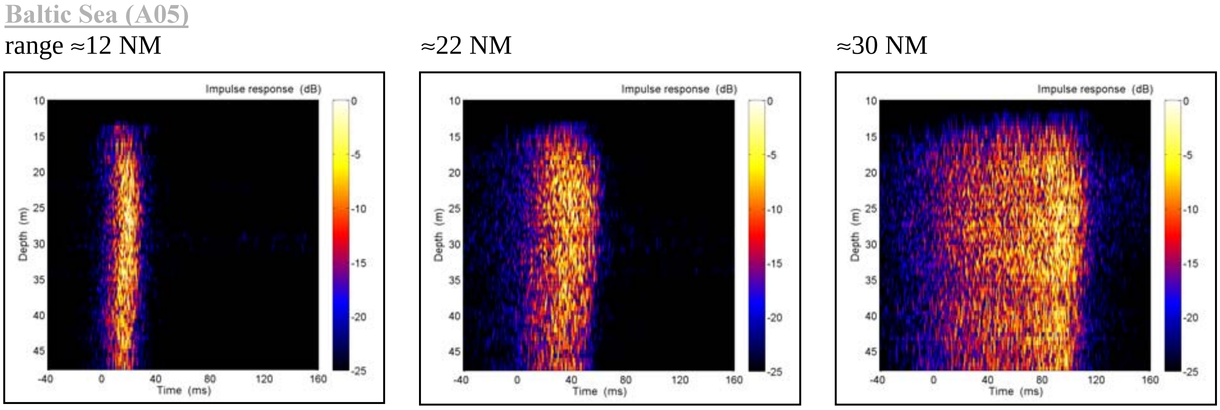


Fig.5: Impulse response functions measured with VA III over depth for a source towed at 35 m in the sound channel in the Baltic Sea for ranges of roughly 12, 22 and 30 NM.

In the Baltic Sea the acoustic section of the vertical array III covered roughly the portion of the water column between 10 and 50 m. Therefore, the most upper hydrophones of this array were located in the warm surface layer (see Fig. 2), while the greater part of the array was placed in the sound channel. This position of the array is directly reflected in the shown three impulse response functions for all 128 hydrophones for a source towed in 35 m depth close to the sound channel axis. In particular hydrophones in the sound channel display received signal energy. The observed features of the impulse response function were more or less the same for all hydrophones in the sound channel.

These first results suggest that for the chosen site close to Bornholm and the observed weather conditions time spread increases with range. For long ranges (e,g. ≈30 NM) and the described source-receiver geometries time spread was in the order of 100 ms (for a reduction in energy compared to the maximum received energy of 10 to 15 dB). Most of the energy was received at the end of the impulse response function.

Off the coast of Norway the observed time spread was smaller (Fig. 6). For the longest range of 16 NM a maximum width of about 30 ms for the impulse response function was determined. In this case the source was located beneath the surface layer at 60 m and the receiving array covered roughly the portion of the water column between 20 and 60 m. Due to the measured sound speed profile, which was of the downward refracting type (see Fig. 3), the highest values for the received energy are observed for the deepest hydrophones. This gets more pronounced for longer ranges.

North Sea (B07)

range ≈2 NM ≈10 NM ≈16 NM

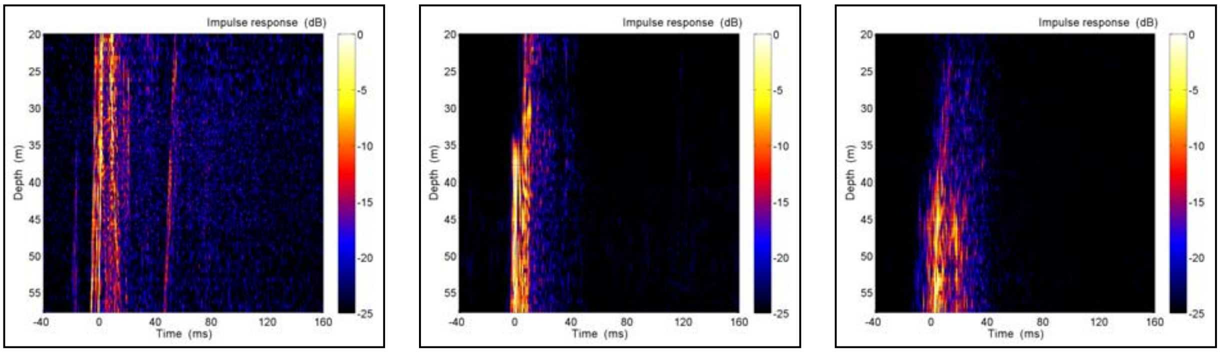
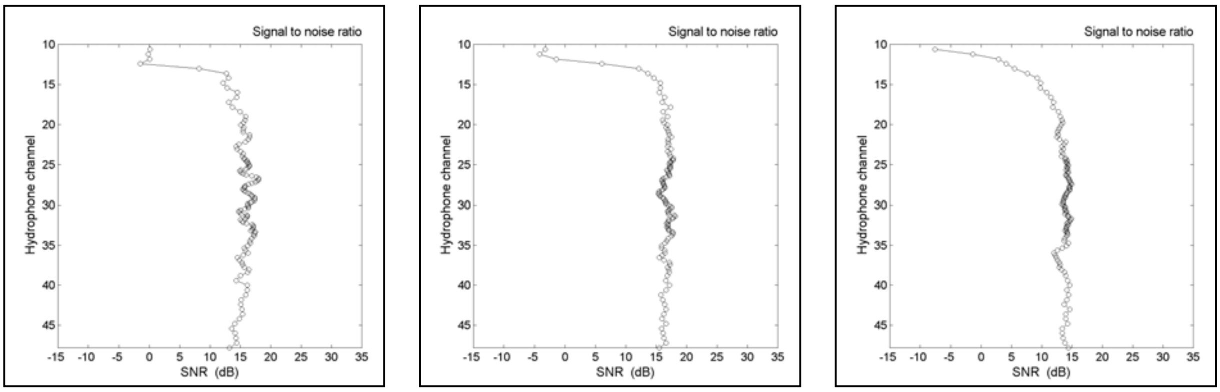


Fig. 6: Impulse response functions measured with VA III over depth for a source towed at 60 m beneath the surface layer in the North Sea for ranges of roughly 2, 10 and 16 NM.

The displayed measured impulse response functions for both sites correspond to different signal to noise (and reverberation) ratios. In case of the Baltic Sea quite good values for this ratio measured for the PRBS probe signals in the order of 15 to 18 dB were observed for all ranges and all hydrophones in the sound channel. In comparison, this measured signal to noise ratio dropped from about 25 dB for short to about 0 dB for long ranges (≈16NM) off the coast of Norway (Fig. 7).

Baltic Sea (A05)

range ≈12 NM ≈22 NM ≈30 NM



North Sea (B07)

range ≈2 NM ≈10 NM ≈16 NM

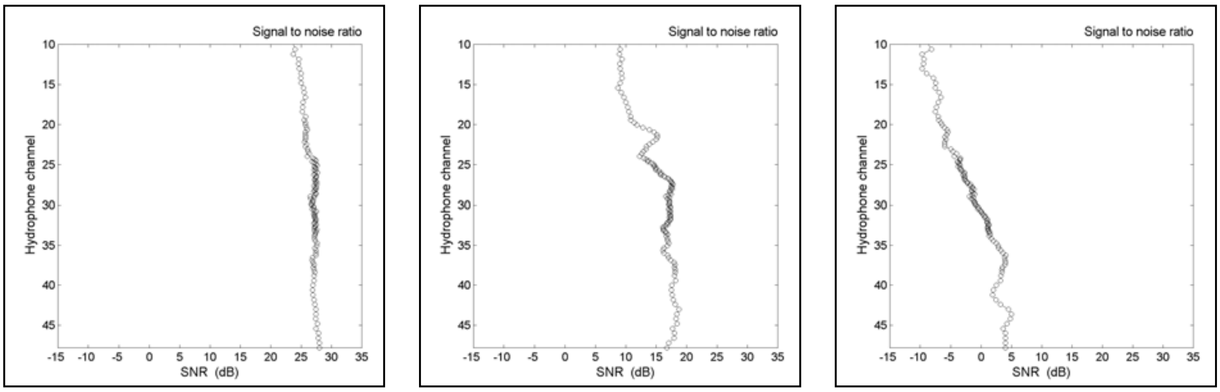
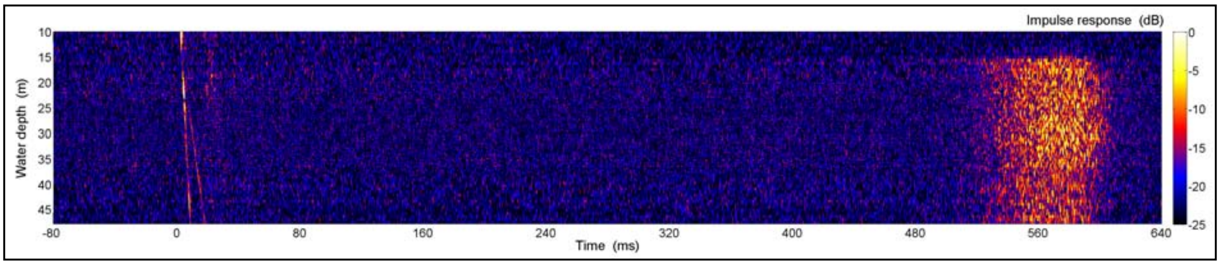


Fig. 7: Measured SNR for three ranges in the Baltic Sea close to Bornholm and the open North Sea close to Bergen.

While towing the source frame in the surface layer an interesting effect was observed for the PRBS probe signals in the Baltic Sea, which requires further investigations. The received energy was recognizable as a first short signal in the surface layer as well as the sound channel.

Additionally, the impulse response function for the sound channel displayed a delayed signal portion, which bears most of the received energy. The delay of this drop-in signal increases with range and amounts to about 500 ms for the given example with a source – receiver distance of more than ≈11 NM. It may be caused by source energy leaking into the sound channel in combination with multi-path propagation.



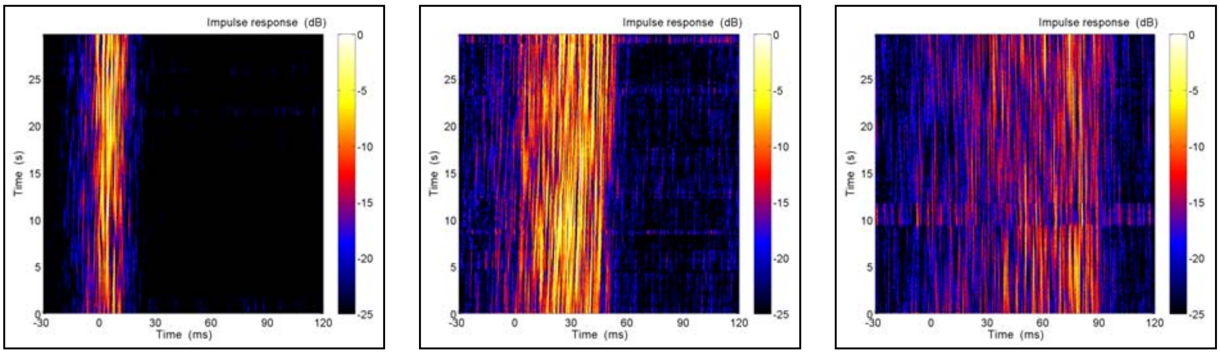
Baltic Sea (A04)
source depth ≈12 m

Fig.8: Impulse response functions measured with VA III over depth for a source towed at 12 m in the surface layer in the Baltic Sea for a range of more than 10 NM.

Time spread caused by multipath propagation results in inter-symbol interferences (ISI). An important figure in this context for a single carrier system is time spread in terms of symbol intervals. While typical time spreads in the commonly used radio channels are on the order of several symbol intervals, in the horizontal underwater acoustic channels they may increase to several tens, or a even hundreds of symbol intervals for moderate to high data rates. For example, ISI would extend over 10 symbol intervals for a system operating at a rate of 100 symbols per second for the observed time spread in the Baltic Sea (Fig. 5) or 100 symbol intervals for a system operating at a rate of 1000 symbols per second. Especially the observed drop-in signal for a shallow source and a receiver in the sound channel (Fig. 8) would result in a difficult situation for a standard underwater communication equalizer since ISI would extend over 50 or 500 symbol intervals, respectively. For such channels the use of a sparse equalizer should be considered.

C. Channel Variability

Time-variability of the acoustic channel is related to random signal fluctuations caused by (micro) multipaths associated with each of the main deterministic multi paths. These fluctuations include surface scattering due to waves. In shallow water this is the most important contributor to the overall time variability of the channel, while in deep water, internal waves additionally contribute to the time-variation of the signal propagating along each of the deterministic multipaths.



Baltic Sea (A05)
range ≈12 NM
≈22 NM
≈30 NM

Fig.9: Evolution of the impulse response functions over 30 seconds for a single VA III hydrophone at the lower side (100) for a source towed at 35 m in the sound channel in the Baltic Sea for ranges of roughly 12, 22 and 30 NM.

North Sea (B07)

range ≈2 NM ≈10 NM ≈16 NM

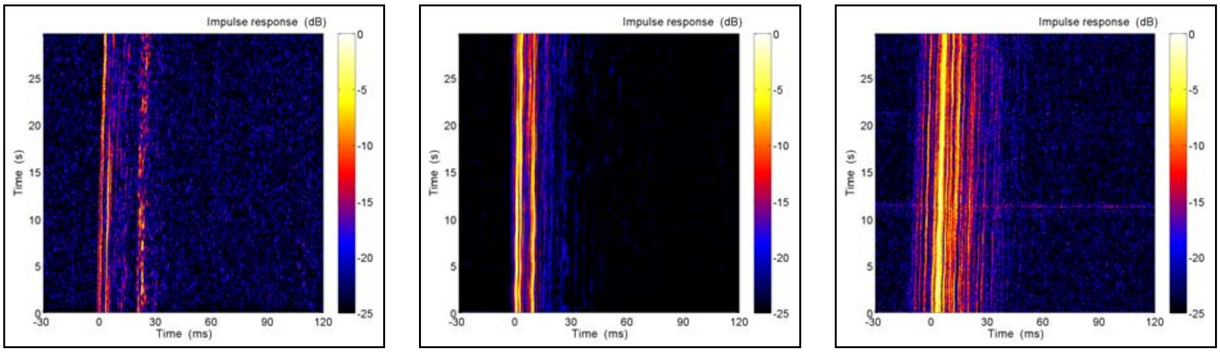


Fig.10: Evolution of the impulse response functions over 30 seconds for a single VA III hydrophone at the lower side (100) for a source towed at 60 m beneath the surface layer in the North Sea for ranges of roughly 2, 10 and 16 NM.

While the length and structure of the impulse response function reveal the multipath propagation situation the evolution of this function over time for a single hydrophone gives information about the short term stability of the acoustic channel. The shown examples for the Baltic Sea (Fig. 9) and North Sea (Fig. 10) indicate that the acoustic channel in the Baltic Sea changes within a couple of seconds while the acoustic channel in the North Sea shows a short term stability in the order of ten seconds.

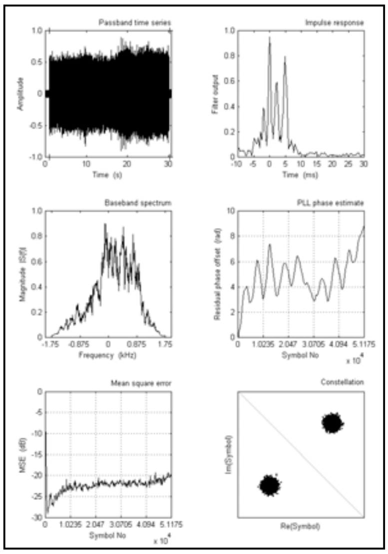
D. Doppler Effects

The relative motion of the UUV with respect to the mother platform leads to a time dilation of the communication signals, resulting in a shift and broadening/compression of the signal spectrum.

Motion of reflection points for the propagating acoustic wave at moving surfaces (e.g. waves) results in Doppler spreading of the surface reflected acoustic communication signals. Due to relatively high frequencies, highest Doppler spreads (lets say up to about 10 Hz) may be found in short and medium range acoustic links.

First impressions indicate, that despite the observed weather conditions for the data gained during the UCAC I – 2006 sea experiment the Doppler influence was mainly linked to sea state induced motion of the vessel towing the source frame.

V. OUTLOOK



Analyzing of UCAC I – 2006 data has just started. The given examples came from the quick look analyses during the sea experiment. We think that these data will allow us to gain understanding of the acoustic channel at the chosen sites concerning noise, transmission loss, SNR, time spread, Doppler effects and channel variability. In addition the used PRBS sequences for probing the channel are bit sequences which can be decoded, as the last example shows for a short range of about 1 NM for the Baltic Sea.

VII. ACKNOWLEDGMENTS

The work described in this publication was done under a multinational, three-year project aimed at developing and demonstrating long-range covert acoustic communication with unmanned underwater vehicles (UUVs) in coastal waters. This project under the EUROPA MoU ERG No1 is known under the name RTP 110.060 “UUV - Covert Acoustic Communications”. The project partners are: Kongsberg Maritime AS (Norway); Fincantieri (Italy); Reson A/S (Denmark); TNO Defense, Security and Safety (Netherlands); Patria Systems (Finland); and Saab Underwater Systems AB (Sweden). The Federal Armed Forces Underwater Acoustics and Marine Geophysics Research Institute (FWG) has been tasked by the Federal Office of Defense Technology and Procurement (BWB) (Germany). Subcontractors are the national defense research establishments of Sweden (FOI) and Norway (FFI), as well as Cetena (Italy) and the University of Genova (also Italy).

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