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Characterization of Long-Range Time-Varying Underwater Acoustic Communication Channels

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We present communication channel characterizations performed on in-situ measurements from the Baltic and North Sea. The communication channels were probed using Pseudo Random Binary Sequences (PRBS), obtaining time-variant channel impulse responses through matched filtering. Characteristics central to communications were obtained. Included are: Multipath and Doppler- spread, and stationary time. Measurements were acquired in the joint European project "UUV Covert Acoustic Communications". The project aims to design an acoustic communication system between an unmanned underwater vehicle (UUV) and a support mother ship. The first sea trials of the project focused on the acquisition of noise and long-range, low-frequency communication channel data for the explicit purpose of building an acoustic channel simulator.

1 Introduction

The joint European project "UUV Covert Acoustic Communications" aims at the design of an acoustic communication system between an unmanned underwater vehicle (UUV) and a support mother ship. To achieve the objective of covert communication over long ranges in littoral waters, knowledge is required on the influence of the environment on the communication system. The first sea trials of the project therefore focused on the acquisition of noise and data for the characterization of the acoustic communication channel.

Section 2 discusses briefly how the performance of a communication system is affected by the characteristics of the acoustic channel, and further how to do a statistical characterization of a doubly spread communication channel. Section 3 describes sea experiments conducted in the Baltic and the North Sea in August 2007 for the purpose of acoustic channel characterization. In section 4 results from the sea experiments are presented for a few selected cases.

2 Channel characteristics

The main factors influencing the performance of an underwater communication system are the transmission loss, noise, reverberation and temporal and spatial variability of the acoustic channel. The available bandwidth, range and signal-to-noise ratio (SNR) at the receiver are primarily determined by transmission loss and ambient noise. The available bandwidth is in general range dependent due to frequency-dependent transmission loss.

Time-varying multipath often imposes severe limitations on the system performance. A particular problem of underwater communications is the low sound speed, which causes very large time and Doppler-frequency spread. While vertical channels exhibit little multipath, the long range horizontal channels we are dealing with here may have very long time-spread due to multipath propagation. Time-varying multipath causes degradation through several mechanisms:

Multipath causes time-spread. If the time-spread is larger than the symbol duration intersymbol interference distortion (ISI) occurs. The channel is said to exhibit frequency-selective fading (the channel act as a filter). If the time-spread is much less than the symbol duration, the channel exhibits flat fading. In this case there is little ISI, but fading due to destructive interference of non-resolvable multipaths can cause low SNR.

Time-variability causes Doppler-frequency spread. A time-varying channel can be characterized by its coherence time. If the coherence time is shorter than the symbol duration, the channel is said to be fast fading. In this case severe, irreducible distortion occurs. A channel is said to be slow fading if the coherence time is much longer than the symbol duration. The degradation in this case is a loss of SNR. A slow fading channel can be regarded as quasi-static.

For mobile systems, the spatial variability of the channel also needs to be taken into account, and will represent an additional complication.

Statistical description of doubly spread channels

In general the underwater acoustic channel is spread in both time (delay) and Doppler due to time-varying multipath propagation. A useful model for such doubly spread channels is a random linear time-variant (LTV) system. There are several equivalent ways of characterizing such systems. One is through the time-varying impulse response $h(\tau,t)$ as a function of delay time τ and geotime *t*. The input $x(t)$ and output $y(t)$ of the system are related by the superposition integral

$$y(t) = \int_{-\infty}^{\infty} h(\tau,t)x(t-\tau)\,\mathrm{d}\tau \quad .$$

Another useful description is the Fourier transform of $h(\tau,t)$ with respect to geotime, called the spreading function

$$S(\tau,\upsilon) = \int_{-\infty}^{\infty} h(\tau,t)\exp\left(-2\pi \mathrm{i}\upsilon t\right)\mathrm{d}t \quad ,$$

which can be seen to represent the output as a weighted sum of delayed and Doppler shifted replicas of the transmitted signal.

The detailed time-behaviour of the system functions is generally not known. To obtain a statistical characterization of the channel, the impulse response is considered as a random process. To obtain a practical channel characterization the Wide Sense Stationary Uncorrelated Scattering (WSSUS) assumption is also invoked. The channel can then be described by one of four equivalent 2nd order correlation functions [1], where the Scattering function $P_s(\tau,\upsilon)$ is the most useful for our purpose. The channel scattering function is defined by

$$P_S(\tau,\upsilon)=E[|S(\tau,\upsilon)|^2]$$

The scattering function is a two-dimensional power spectrum density in delay and Doppler. Under WSSUS conditions the scattering function completely describes the 2nd order statistics of the channel.

Two connected functions are the power delay profile $P_{\mathrm{d}}(\tau)$ and the Doppler power spectrum $P_{\mathrm{D}}(\upsilon)$. The power delay profile, also known as the multipath intensity profile, represents the average received power versus delay and is obtained by integrating the scattering function over the frequency shift

$$P_{\mathrm{d}}(\tau)=\int_{-\infty}^{\infty}P(\tau,\upsilon)\,\mathrm{d}\upsilon\quad.$$

Integration over time delay yields the Doppler power spectrum

$$P_{\mathrm{D}}(\upsilon)=\int_{-\infty}^{\infty}P(\tau,\upsilon)\,\mathrm{d}\tau\qquad.$$

The Fourier transforms of $P_{\mathrm{d}}(\tau)$ and $P_{\mathrm{D}}(\upsilon)$ characterize the coherence bandwidth and coherence time of the channel, respectively.

Stationarity

When characterizing or modeling random linear time-variant (LTV) channels, the WSSUS assumption is usually invoked. An interpretation of the WSSUS assumption is that scattering from different delays and different Doppler frequencies are uncorrelated. The WSSUS assumption is violated for many real channels. A more practical approach is to assume the channel is Quasi-WSSUS [1], i.e., the channel behaves as a WSSUS channel for a restricted interval of time *(T_S)* and band of frequencies *(F_S)*. T_S and F_S are known as the stationary time- and bandwidth respectively of the channel.

The stationary time- and bandwidth can be estimated from the correlation function

$$R_H(t,f,\Delta t,\Delta f,)=\mathrm{E}\left\{H(t,f+\Delta f)H^{*}(t-\Delta t,f)\right\},$$

where Δt and Δf describes time and frequency lag, and $H(t,f)$ is the time-varying transfer function given by

$$H(t,f)=\int_{-\infty}^{\infty}h(t,\tau)e^{-j2\pi\cdot f\tau}\mathrm{d}\tau=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}S(\tau,\upsilon)e^{j2\pi(\upsilon t-\tau f)}\mathrm{d}\tau\mathrm{d}\upsilon$$

Denote the maximum rate at which R_H varies in the time (t) and frequency (f) direction by $\gamma_{\max}$ and $\theta_{\max}$ respectively. The stationary time- and bandwidth are then given by $F_S=1/\gamma_{\max}$ and $T_S=1/\theta_{\max}$.

.A channel is said to be Quasi-WSSUS if

$$B<<\frac{1}{\gamma_{\max}}=F_S$$

and

$$T+T_m<<\frac{1}{\theta_{\max}}=T_S\,,$$

where *B* is signal bandwidth, *T* is signal duration and T_m is the multipath spread of the channel [1,2].

3 Sea Trial

The first UCAC sea trial took place in September 2006 at two locations with significantly different propagation conditions. One site was located in the Baltic Sea near the Danish island of Bornholm; a second site was in the North Sea west of the Norwegian city of Bergen. The main goal of the sea trials was the characterization of the acoustic communication channel. For this purpose a set of probe signals was transmitted with a submerged projector towed by a surface ship. A 128-element, 40-m aperture vertical line array, deployed from another surface ship, was used to acquire raw acoustic data.

The probe signal used for the impulse response measurements is a pseudorandom binary sequence. This signal is a binary phase-shift keyed waveform using a repeated sequence of pseudorandom bits. The probe signal uses an m-sequence of length 255, at a rate of 1750bit/s, which is repeated 205 times to achieve total signal duration of 30 s.

The carrier frequency of the probe signal is 3850 Hz and the frequency band is between 2100 and 5600 Hz. With these parameters, the output of a filter matched to the m-sequence is a continually updated measurement of the channel impulse response approximately seven times per second.

The sea trial and the environments are described in more detail in [3], while a detailed description of the probe signal is found in reference [4].

4 Results

A useful characterization of the underwater channel for communication purposes is how the channel is spread in time and Doppler. One case from each of the trial areas are analyzed below.

4.1 Propagation conditions

Baltic Sea

The site in the Baltic Sea featured a water depth between 60 and 90 m, and a strong sound channel with the axis at a depth of about 30 m below a surface mixed layer of thickness 15 m as shown in Fig.1. Both source and receiver are located in the sound channel at 35 and 30 m respectively. Wind speed varied between 1.5-4.5 m/s during the run.

Transmission loss modelling using the Bellhop ray tracing model, Fig.2, shows that rays within the cone ±15 deg are trapped in the sound channel while only rays steeper than ±15 deg contribute to the field in the surface layer. Hence the signal received in the sound channel consists of guided rays, while the signal received in the surface layer consists of surface and bottom interacting rays.

North Sea

The water depth in the Norwegian trials area varied between 200 and 300 m with an overall downward refracting sound speed profile, see Fig.1. The source was located at 60 m and the receiver at 40 m depth. The wind speed was 4 m/s during the run.

Fig.3 shows modelled transmission loss with bottom reflected rays eliminated. The figure shows that several families of refracted waves contribute to the field, resulting in a complex arrival structure. There will also be a contribution from bottom-surface reflected rays which is not shown in the figure.

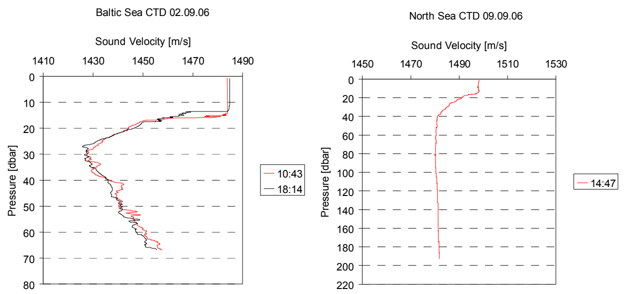

Fig.1 Sound speed profiles for Baltic Sea (left panel) and the North Sea (right panel).

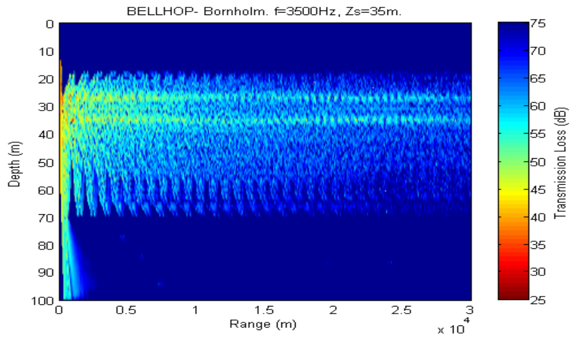

Fig.2 Coherent transmission loss in the Baltic Sea. Bottom reflections eliminated.

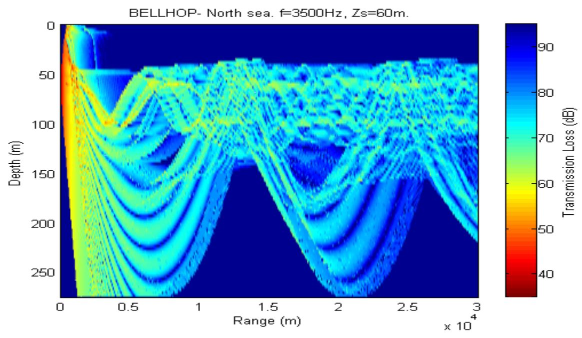

Fig.3 Coherent transmission loss in the North Sea. Bottom reflections eliminated. A weak sound channel is evident.

4.2 Delay spread

The Power delay profile for a source and receiver located in the sound channel at a range of 32 km in the Baltic Sea is shown in Fig.4. Fig.5 shows how the power delay profile evolves with range. The total time-spread increases monotonically with range from about 20 to 100 ms. An interesting point is that the late arrivals carry more energy than early arrivals, similar to the deep-sea sound channel. This effect is more pronounced at longer ranges. Transmission loss is low due to the combined effect of sound channel propagation and weak absorption caused by low salinity.

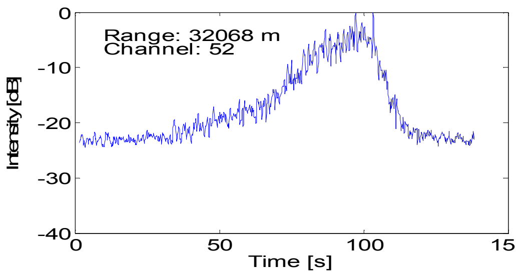

Fig.4 Power delay profile for a receiver at depth 35m and range 32 km range in the Baltic Sea.

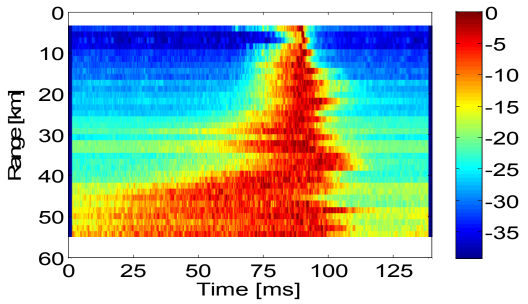

Fig.5 Evolution of the power delay profile versus range for a receiver at depth 35m in the Baltic Sea.

The delay profile for the North Sea, Fig.8 and Fig.9, shows a typical minimum phase impulse response, where the largest arrivals come first. However, the evolution of the delay-profile with range is much more complicated than in the Baltic Sea, indicating a more challenging modelling task. The total time-spread is in the order of 30-100 ms.

A non-minimum phase impulse response, i.e. when the largest arrival is not the first arrival, is more challenging for the communication receiver than the minimum phase case.

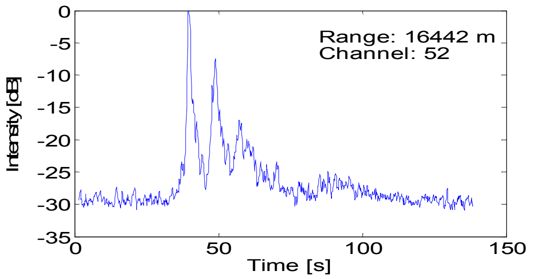

Fig.8 Power delay profile for a receiver at depth 40m and 16.4 km range in the North Sea.

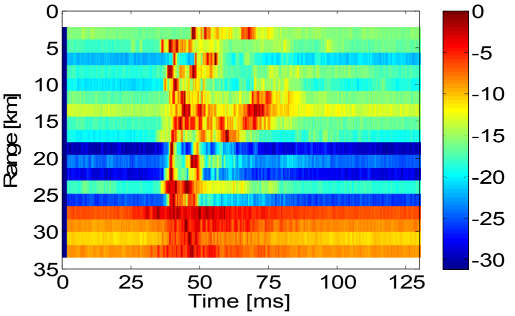

Fig.9 Evolution of the power delay profile versus range for a receiver at depth 40m in the North Sea.

4.3 Doppler spread

Fig.10 shows Doppler spectra measured by a receiver in the sound channel in the Baltic Sea. Three different cases are shown; the upper panel shows Doppler spectra versus range for a ship moving at a constant speed of 3m/s away from the source. The middle panel shows Doppler spectra versus time when the ship is anchored at 50 km range, while the lower panel again shows Doppler spectra from the moving ship but this time corrected for the time-varying Doppler shift induced by platform motions due to waves. The procedure for removing Doppler induced by platform motion is described in [6]. The figure clearly shows that time-varying Doppler shift induced by platform motions causes a broadening of the Doppler spectra, and obscures the true channel Doppler spectra.

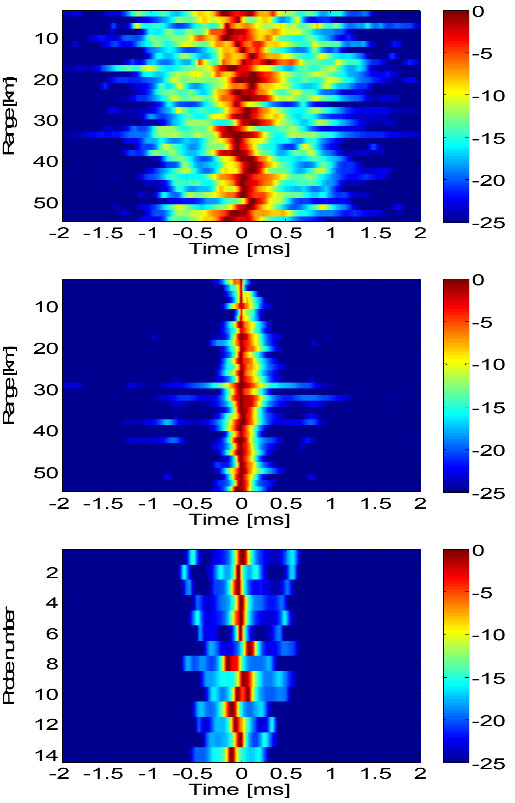

Fig.10 Doppler spectra measured in the sound channel in the Baltic Sea. Upper panel: ship moving at constant speed. Middle panel: Ship anchored. Lower panel: moving ship, spectra corrected for time-varying Doppler shift.

The (uncorrected) Doppler spread measured in the North Sea is significantly larger than in the Baltic, as is easily seen by comparing Fig.10 and Fig.11. This is consistent with the modelling results in Sec. 4.1.

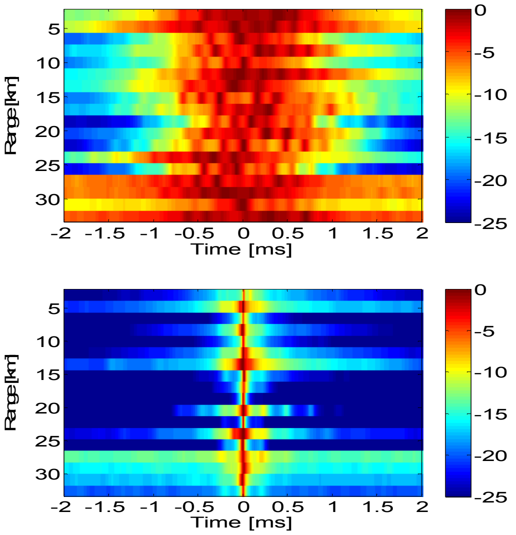

Fig.11 Doppler spectra measured at 40 m depth in the North Sea. Upper panel: ship moving at constant speed. Lower panel: moving ship, spectra corrected for time-varying Doppler shift.

4.4 Stationarity

In the estimation of the correlation function R_H, the ensemble averaging should be replaced by time-averaging, assuming ergodicity. The short extension of the measured time-varying impulse responses allows very little time-averaging to be performed, resulting in relatively high variance. Table 1 and 2 contain stationary times for selected frequency lines in the North Sea and Baltic Sea. Since we are seeking the maximum rate of variation along all frequency lines in R_H, the lines with the smallest stationary time indicates the stationary time at the given location. The stationary times have been estimated to 16 seconds for the Baltic Sea and 10 seconds for the North Sea

Frequency	3100 Hz	3850 Hz	4600 Hz
Stationary time	17 s	17 s	16 s

Table 1 Stationary times for selected frequency lines. Results are obtained in the Baltic Sea at range 11 km.

Frequency	3100 Hz	3850 Hz	4600 Hz
Stationary time	Not measurable	10 s	23 s

Table 2 Stationary times for selected frequency lines. Results are obtained in the North Sea at range 10 km

5 Conclusion

We have shown results relevant to acoustic underwater communication, obtained from time-varying impulse responses measured in the North Sea and the Baltic Sea.

The influence of ship induced movement was removed to obtain true channel Doppler spectra.

The Doppler spread in the North Sea was significantly larger than in the Baltic Sea. This result is consistent with propagation modelling, showing significantly more surface interaction at the North Sea site.

Multipath spread was measured to vary between 20 and 100 ms in the North Sea, for ranges between 2 and 32 km. In the Baltic Sea, the multipath spread increased monotonically from 30 to 100 ms for ranges 3 to 52 km. The general shapes of the multipath profiles were different at the two locations; with the Baltic Sea having a minimum phase profile while at the North Sea site the strongest arrivals came first.

Stationarity times were estimated to 10 seconds in the North Sea and 16 seconds in the Baltic Sea.

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