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Simulated performance of an acoustic modem in a multipath channel

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ABSTRACT

This paper presents a numerical approach to simulate the performance of an acoustic modem operating in shallow water. The acoustic transmission in the shallow water channel is modelled as an impulse response function using a multilayered, range-independent ray tracing model. It is assumed that the performance is not only limited by signal-to-noise ratio (SNR), but also by the signal-to-corruptive multipath ratio (SMR). Numerical results are shown for both coherent (PSK) and incoherent (FKS) modulation schemes.

The evaluation parameters that provide the estimated performance of the communication system are maximum range, datarate and available acoustic power. Optimum receiver depth is derived for shallow water channels such as the North Sea. The shallow water communication channel exhibits randomlike behaviour. This fact makes interpretations of numerical results very difficult. By introducing temporal variability in the model this problem is overcome to some extend.

INTRODUCTION

This paper presents the initial stages of the design of an acoustic communication system for use in shallow water. A communication system as such may be entitled an underwater acoustic modem. Acoustic modems can be used for transmission of control and data sequences to autonomous underwater vehicles (AUVs) or bottom moored sensors. Limited power availability and transducer size impose severe restrictions on the design of acoustic modems for such equipment. However, also the physical channel has crucial influence on the performance of the modem, as we will be discussed in the following.

We focus on a shallow water environment such as the North Sea with water depth no more than a few hundred metres and acoustic frequencies in the tens of kilohertz, i.e. with possible transmission ranges of up to tens of kilometres, Ref. [1]. Hence, the depth-to-range ratio may be 1:100 or even more. An acoustic channel of such extreme geometry may be denoted "ultra-shallow".

Underwater acoustic communication in such an environment is known to be a difficult task due to the complex behaviour and random nature of sound propagation, see f. ex. Ref. [2]. This is reflected in the fact that only few communication systems are commercially available, Ref. [3].

The shallow water channel often consists of horizontal layers of different sound speed. This fact requires that careful attention be given to the depth position of hydrophones to obtain a reasonable signal-to-noise ratio (SNR). However, the shallow water channel exhibits a waveguide effect and, therefore, the geometrical spreading will tend from spherical towards cylindrical. Hereby, the problem is changing from being one of maximising the SNR to one of appropriately exploiting the multipath structure. The transmission loss of the channel will never be truly cylindrical due to the energy loss caused by boundary interaction and also due to the fact that the multipath arrivals will never coherently interact in perfect constructive interference.

Simulation of the shallow water transmission channel is similarly complicated by the complex multipath structure. Various modelling approaches have been taken, Refs. [4]-[10], but all suffer crucial limitations. Either by being based on unrealistically simple channel models, for instance by assuming constant sound speed. Conversely, a physically realistic channel model will produce randomlike output due to extreme sensitivity of input parameters. We claim that for a propagation model to be useful for underwater communication it has to be both based on coherent addition of multipath arrivals and include temporal variability of the channel.

In this paper a novel simulation technique is presented which on one hand is physically realistic yet reduces the communication system performance to an evaluation parameter which is clearly interpretative. We apply a convenient measure for examining the multipath channel: The signal-to-corruptive multipath ratio (SMR), originally proposed in by Zielinski et al. in Ref. [11]. Given this definition, we have previously studied the influence of a layered sound speed profile on performance of underwater communication systems using a numerical ray tracing model, Ref. [5]. The present paper reports the results from extended numerical studies, as well as an attempt to model temporal variability of the channel impulse response and study its influence on communication system performance. The temporal variability is introduced by allowing the acoustic signals to be modulated as they scatter from the time-varying sea surface waves.

The paper is organised as follows. The sound propagation model will be outlined. The definition of SMR and how it may be derived from the ray tracing model will be introduced. Several results from the numerical analysis will then be shown using environmental parameters given for typical shallow water scenarios. A reasonable value of SNR will restrict the maximum range and carrier frequency. To obtain an error-free communication link the computed SMR will allow an estimate of the baudrate of the communication system.

TRANSDUCERS AND ACOUSTIC POWER

Power availability will be limited when the transducer is mounted on a self-contained unit as an AUV or a bottom sensor. Therefore, a directive transducer is chosen with a source level of 190 dB including directivity gain and a carrier frequency at 20 kHz. The communication channel is expected to be SMR limited and not SNR limited. A detailed calculation of the maximum allowed transmission loss will, therefore, not be given. Instead, using the sonar equation an estimated maximum permitted transmission loss, TL, is found assuming the noise level to be NL=50 dB and required signal-to-noise ratio to be SNR=20dB:

$$TL = SL - NL - SNR = 190 - 50 - 20 = 120 \text{ dB}$$

In the subsequent calculations this conservative value of TL will not be exceeded.

THE RAY MODEL AND BOUNDARY CONDITIONS

A numerical ray model has been implemented to model acoustic propagation in shallow water, for details see Ref. [5]. To improve efficiency of the model the propagation algorithm is semi-analytical. It applies solutions for sound speed profiles that are piecewise linear in depth and range-independent, i.e. the paths follow either straight lines or circular arcs.

Boundary interaction is very important in the shallow water channel. As will be shown in the subsequent section with numerical results, even the strongest paths are refracted and have been multiply reflected or scattered from either the lossy bottom or the rough sea surface. In fact, the presence of a direct path, i.e. one that has not interacted with any boundary, is unlikely in the shallow water channel.

Scattering from the sea surface is a complex, randomly varying process. Most of the energy is expected to be reflected in the specular direction in the extreme geometry. The fraction of coherently scattered energy may be derived from the Rayleigh scattering number, R:

$$p_{scattered} = e^{-\frac{1}{2}R^2} * p_{incident} = e^{-2k^2h^2\sin^2\Theta} * p_{incident}$$

where k is the acoustic wave number, h is RMS surface roughness and θ is the grazing angle of the incident acoustic field. For the present environment typical parameters for R will be less than unity and the surface may be considered “slightly rough”, Ref. [13], that is in the scattering region that follows the perturbation scattering theory. R increases for higher frequencies, larger surface waves and larger grazing angles, and then the incoherent part of the scattered field will dominate. The rough surface will tend from a reflector to many point scatterers and this will have dramatic influence on the multipath structure because geometrical spreading loss will change entirely.

In the scattering region of "slightly rough surfaces" the temporal variability of the surface waves will impose a modulation on the scattered signal proportional to the surface wave spectrum, as has been demonstrated for instance in Ref. [14] and Ref. [15]. A time-varying simulation following this phenomenon has been implemented. The realisation of the statistical process is similar to the one presented in Ref. [4].

Bottom interaction is modelled by assuming that the bottom will be a reflector with a complex impedance given by sound speed, density and absorption coefficient. Changes in the bathymetry and small scale roughness are ignored. The latter could be implemented similar to the time-invariant sea surface scattering loss.

There are other physical processes relevant to acoustic propagation that are not included in the model. These are, for instance, presence of bubbles near the surface, scintillation caused by microscale sound speed fluctuations, and biological activity. We consider such phenomena as anomalous conditions, and they will, hence, not be included in the present analysis.

The output of the ray model will be the impulse response function of the channel, h(t). It is assumed to be a sum of delta functions with amplitude, a_i, and delay, τ_i:

$$h(t) = \sum_{i=1}^{\infty} a_i \delta(t - \tau_i)$$

By identifying all eigenrays for a specific channel geometry, the ray model output is an estimate of all coefficients (a_i , τ_i).

SIGNAL-TO-NOISE RATIO (SNR) AND SIGNAL-TO-MULTIPATH RATIO (SMR)

This section will present the tools for analysing the output of the ray model in terms of parameters that may evaluate the performance of a communication system. The Signal-to-corruptive Multipath ratio (SMR) introduced by Zielinski et al., Ref. [11], is a convenient measure to evaluate transmission of phase modulated signals (PSK) and the definition of SMR will be given, although in a slightly modified version. For completeness, the equivalent definition of SMR for incoherent modulation such as frequency hopping, FSK, will be given as well.

A phase-modulated signal may be demodulated in the receiver using in-phase and in-quadrature demodulation followed by an integrator within the time frame of a symbol, T_s. The output of the demodulator will detect the averaged phase of the current symbol and, therefore, the corresponding binary word.

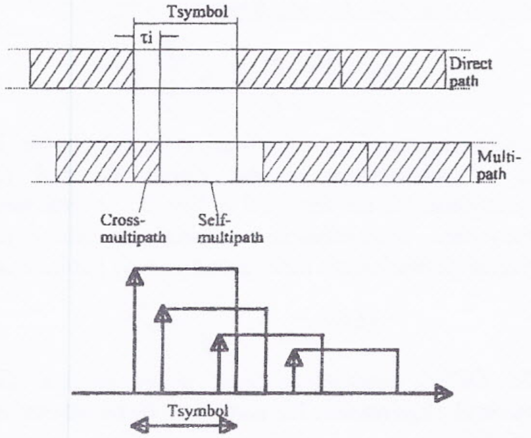

Figure 1: Intersymbol interference

Corresponding to the impulse response function of the channel every delayed version of the transmitted symbol will influence the received signal, R. This is known as intersymbol interference (ISI). The influence is proportional to the ratio of the delay to the symbol period, as depicted in Fig.1 for one of the three multipath arrivals.

When considering the received signal in a phase diagram as shown in Fig. 2, every multipath component may be represented as a phasor.

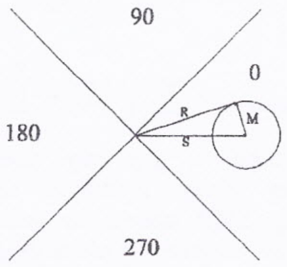

Figure 2: Phase diagram for QPSK modulation

The signal strength, S, is defined as the sum of the direct path and the self-multipath, where self-multipath is the part of the multipath structure that is present within the time frame of the currently received symbol, see Fig. 1.

$$S = \left|\sum_{i=1}^{r} (1 - \frac{\tau}{T_s}) S_i\right|$$

where r is the number of self-multipaths, each represented as a phasor in the phase diagram:

$$S_i = a_i e^{2\pi i f \tau_i}$$

The corruptive multipath strength, M, is defined as the coherent sum of delayed multipaths, i.e. the tail of the previously received signal present in the time frame of the current signal denoted crossmultipath. The definition of multipath strength is a sum of interference from the adjacent symbol and of previous signals with delays, $\tau_i > T_s$.

$$M = \left| \sum_{i=2}^{r} \frac{\tau_i}{T_s} S_i + \sum_{i=r+1}^{\infty} S_i \right|$$

The relations of how the total, received phasor, R, is a combination of the signal, S, and the multipath, M, are depicted in Fig. 2. As indicated, error-free transmission is obtained when the Signal-to-Multipath ratio is sufficiently limited as,

$$SMR_{QPSK} = \frac{S}{M} > \sqrt{2}$$

for QPSK modulation (four phase levels). The general requirement for error-free transmission for (n)PSK is

$$SMR_{nPSK} > \frac{1}{\cos(90 - \frac{180}{n})}.$$

We complete this section by introducing the equivalent definition for an incoherent modulation type such as frequency shift keying (FKS). In the case of incoherent modulation the phase of the signal is obviously unknown. This leads to a redefinition of S and M, by carrying out the summation of multipath arrivals incoherently:

$$S_{incoherent} = \sum_{i=1}^{r} (1 - \frac{\tau}{T_s}) |S_i|$$

and

$$M_{incoherent} = \sum_{i=2}^{r} \frac{\tau_i}{T_s} |S_i| + \sum_{i=r+1}^{\infty} |S_i|$$

i.e. the calculations are only concerning the amplitude of every multipath arrival. The corresponding SMR cannot be redefined in a similar fashion, because the phase diagram in Fig. 2 has no meaning for incoherent signals. However, the value of SMR may still provide useful information, when it is considered as a measure of the "self-noise" that is generated by the communication system. Hence, it can be used to determine the threshold level for the frequency decoder, as indicated in Fig. 3.

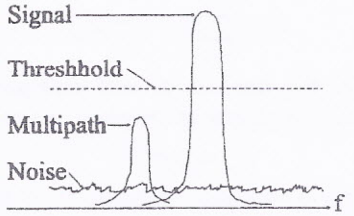

Figure 3: Threshold level for FSK modulation

CHANNEL GEOMETRY AND ENVIRONMENTAL PARAMETERS

A set of parameters was chosen to define the channel geometry and the environmental conditions. These values were used in all of the numerical calculations.

Two typical shallow water scenarios are studied: a) The North Sea with a winter sound speed profile and b) the North Sea with a summer sound speed profile. The specific channel geometry is given in Table 1. The sound speed profiles are shown in Fig. 4.

Channel depth	40 m
Source depth	38 m
Range	20 km
RMS wave height	0.15 m
Bottom sound speed	1670 m/s
Bottom attenuation	3.4 dB/m
Bottom density	1.77 g/cm^3
Signal carrier frequency	20 kHz

Table 1. Channel geometry.

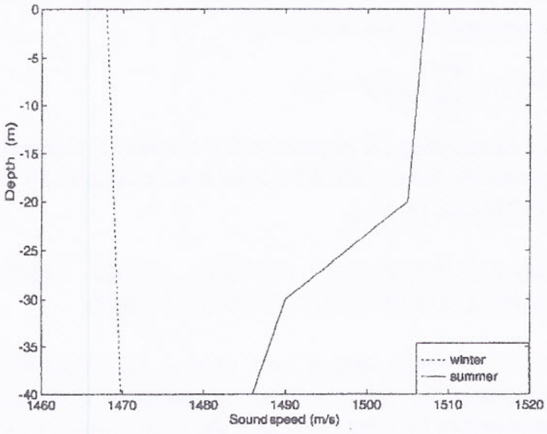

Figure 4: Sound speed profiles

As shown, one is slightly upward refracting. The other is more complex, however with a tendency to downward refraction.

RAY TRACE AND IMPULSE RESPONSE CALCULATIONS

This section will present examples of ray traces and their corresponding impulse response functions for the two scenarios. The complexity of the channels is shown by the sample ray traces in Fig. 5. The corresponding impulse response functions are presented in Figs. 6 and 7.

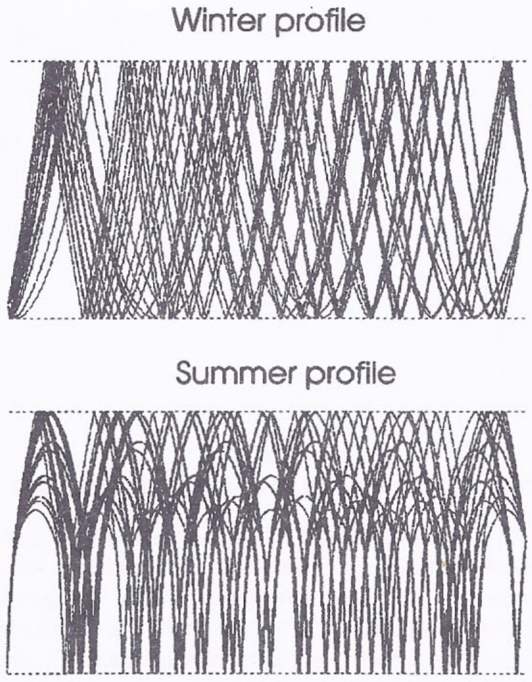

Figure 5: Ray traces (Receiver depth: 20 m)

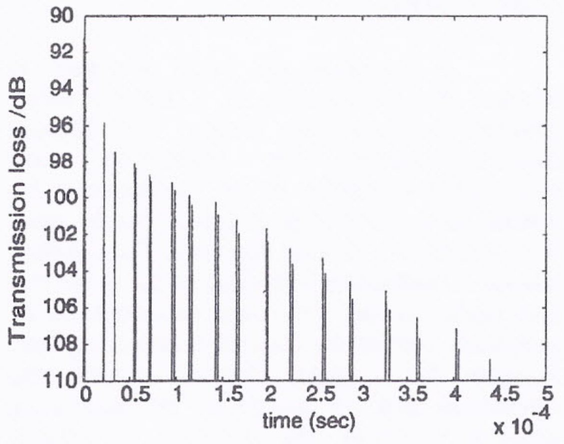

Figure 6: Impulse response for winter profile

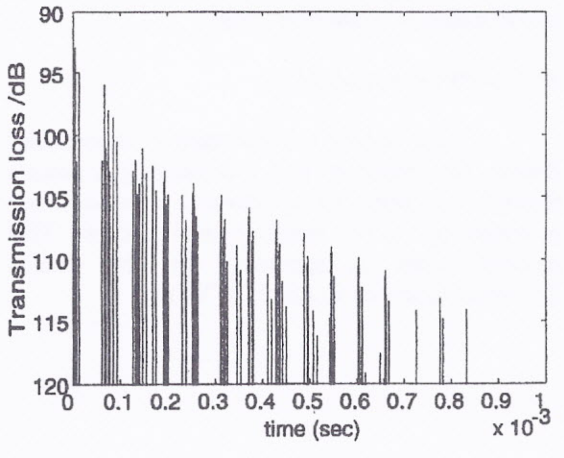

Figure 7: Impulse response for summer profile

The impulse response functions clearly show the complex behaviour of the shallow water channel. The time period of one cycle of the carrier is 1/20kHz = 50 μs implicating that many multipath arrivals will interact.

COMPUTATION OF TIME-INVARIANT SIGNAL AND MULTIPATH

The performance of a prospective communication system is now evaluated by computing time-invariant values for S and M. The symbol rate is 2000 symbol/s, i.e. the datarate is 4000 bit/s.

One parameter of the system that may be modified immediately in the field is the receiver depth. Consider, for example, a situation where the receiver is not firmly mounted on the hull of a ship but rather hanging below the ship in a cable of variable length. Hence, we model a situation where the receiver depth is varied. Numerical results for S and M as function of receiver depth are shown in Fig. 8 and 9.

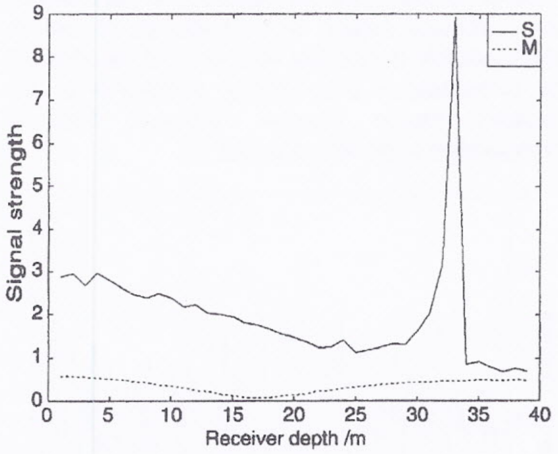

Figure 8: S and M for winter profile

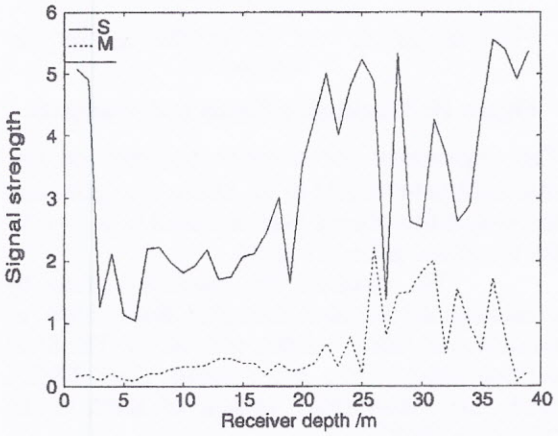

Figure 9: S and M for summer profile

The computation for the winter profile show that favourable communication conditions are found for receiver positioned near the surface. The narrow peak of S at 38 m is believed to be a numerical artifact of the model. The computation for the summer profile only provides limited results that are suitable for interpretations. A tendency of increasing M with depth is noted. From this result we conclude that the downward refracting channel will degrade the performance of the communication link for the receiver positioned near the bottom. This might be surprising since it is also here that the highest total sound level is found.

SIMULATIONS OF SIGNAL AND MULTIPATH IN A RANDOMLY FLUCTUATING CHANNEL

The fluctuations shown in Fig. 9 represent an inherent feature of the shallow water channel. They are caused by coherent interference of the many multipaths. Hence, the results of Fig. 9 can be interpreted as a snapshot of the channel without providing the full statistics of the channel. As mentioned earlier, we will attempt to remove the randomly fluctuating behaviour of the channel by computing a time-varying realisation of the summer profile impulse response. Such a computation is presented in Fig. 10.

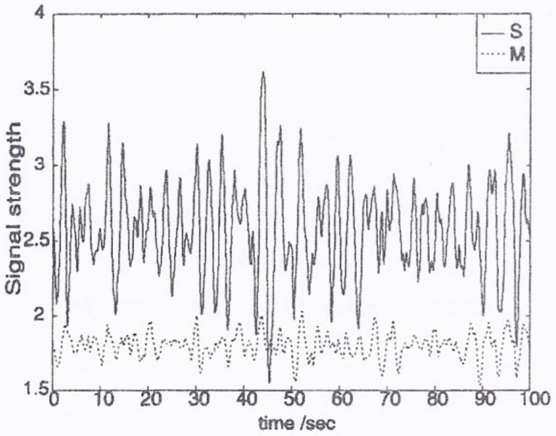

Figure 10: Fluctuating Signal and Multipath

The requirement for errorfree transmission was that SMR to be limited to $\sqrt{2}$. Using this definition, the probability of error was estimated as $p_e = 0.47$ for the computation in Fig. 10.

We complete the numerical study by presenting the Signal-to-Multipath Ratio, SMR, as a function of receiver depth, see Fig. 11. The SMR corresponding to Fig. 9 is denoted "Static SMR", while the time-varying version of SMR is the "Dynamic SMR".

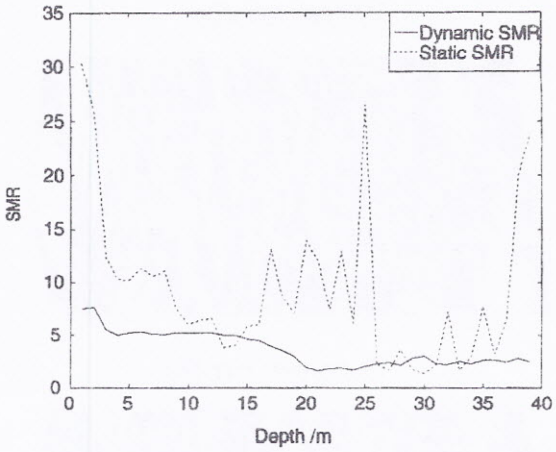

Figure 11: Static and dynamic SMR (summer)

In Fig. 11 it is observed that the dynamic SMR is a smoother curve, i.e. it is easier interpretable. The conclusion of the calculation with temporal variability is similar to the one made for the static channel, i.e. better performance is obtained for receiver positioned near the surface.

CONCLUSIONS

A numerical ray model was used to simulate the performance of a shallow water, acoustic communication system. For different channel scenarios the simulations show considerable variability of the performance. No general conclusions of performance can be made from just the two channel scenarios. The channels showed a randomlike behaviour in the sense that even slight changes of the input parameters would completely change the channel impulse response. However, for a given channel scenario, the simulations and, in particular, by introducing temporal variability, the algorithm to compute Signal and Multipath, proved to be an efficient tool for the analysis of the performance acoustic communication in shallow water.

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