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ANALYSIS OF A SHALLOW-WATER ACOUSTIC COMMUNICATION CHANNEL

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This paper analyses the physical characteristics of the acoustic channel during the ROBLINKS underwater communication experiments. It is demonstrated that marginal changes of the sound speed profile have a profound effect on the propagation in the shallow-water environment, and hence on the quality of acoustic communication links. Further, the Doppler spread experienced by the sound appears to be partly due to movements of the vertical receiver hydrophone array. Typical values for the time spread and Doppler spread are 10 ms and $\Delta f / f_0 = 2 \times 10^{-4}$, *in a channel with a 20-m depth and a length of several km.*

1. INTRODUCTION

ROBLINKS aims at the development of "long-range, shallow-water **rob**ust acoustic communication **links**" [1]. The project partners are TNO Physics and Electronics Laboratory, Thomson Marconi Sonar and the Ruhr Universität Bochum. In the first year of the project, communication signals were defined for transmission during sea experiments in May 1999. The trial location was the North Sea near the coast of The Netherlands. With a depth of 20 m and signalling ranges between 1 and 10 km, the acoustic channel is very shallow. As a consequence the communication signals experience pronounced multipath propagation, which may severely complicate information retrieval. To investigate the channel impulse response, FM sweeps were transmitted on a frequent basis during the trial. Moreover, monochromatic signals were transmitted to measure the frequency spread suffered by the sound. In this paper the received FM and CW signals are analysed, and the results are interpreted in relation to the communication signals.

2. EXPERIMENTAL SET-UP

The experiments took place on the North Sea, about 10 km off the Dutch coast, at depths between 18 and 22 m, and at signalling distances between 1 and 10 km. For a detailed overview of the location and experiments, the reader is referred to [2]. Here, it suffices to say that the acoustic source was deployed at a 9-m depth from an anchored vessel (HNLMS Tydeman), and that the receiver, a 20-hydrophone vertical array, was deployed from a fixed platform (MeetPost Noordwijk, MPN). The acoustic source is omnidirectional in the horizontal plane, with a source level of 190 ± 5 dB in the band 1-15 kHz.

3. WORKING METHOD

To examine the multipath propagation, and the stability of the channel over time, two kinds of linear FM sweeps were transmitted. Once a day a 10-min period was devoted to a series of 40 Hanning-weighted, 2-s FM sweeps in the band 1-14 kHz. Here, matched-filter techniques permit to monitor multipath variations during the 10-min time span.

A long-term channel examination is enabled by FM sweeps that were transmitted prior to each communication signal. These pulses range from 1 to 14 kHz, have a duration of 10 s and are unweighted. On average three of them were scheduled per hour, for a total duration of 14 hours. The replica signal fed to the matched filter is split into three subbands ranging from 2-6 kHz, 6-10 kHz, and 10-14 kHz. In this manner the multipath character and long-term stability of the channel are monitored for three frequency bands.

In addition to the 10-s FM pulse, a CW signal was transmitted to examine Doppler spreading introduced by moving reflective surfaces and motion of the source relative to the receiver. The CW signals also have a duration of 10 s and a frequency that equals the carrier wave frequency of the subsequent communication sequence.

4. RESULTS

4.1. Short-term stability

During the trial, which covered 8 measurement days, a series of 40 LFM sweeps of 2-s duration was launched once a day. The repetition time of the sweeps amounted to 15 s. In Fig. 1 a typical example is shown of the multipath arrivals for transmission over a 5-km range. It is observed that the dominant arrivals are stable over the 10-min interval, and further that there is a plurality of fainter arrivals up to, say, 8 ms. This stable short-term channel behaviour is also observed on other days, whereas the time spread is observed to decrease somewhat with an increasing transmission range. For instance, structural arrivals up to 15 ms are observed for a signalling distance of 1 km.

4.2. Long-term stability

To monitor the channel response over longer time spans, we made use of the 10-s LFM pulses transmitted ahead of each communication sequence. As it is impossible to present all results in this paper, we will restrict ourselves to the most interesting cases that best demonstrate the channel characteristics. We consider the matched-filter outputs for the frequency band from 6 to 10 kHz and plot them against time for a hydrophone in the centre of the water column (Fig. 2.). As it appears, the sound intensity swells from the morning towards the afternoon, and subsides again towards the evening. Since the source-receiver distance did not change during the day, with the transmitter platform anchored at 2 km from the immobile receiver platform, and since the source intensity was kept constant, the phenomenon has to be accounted for by environmental changes.

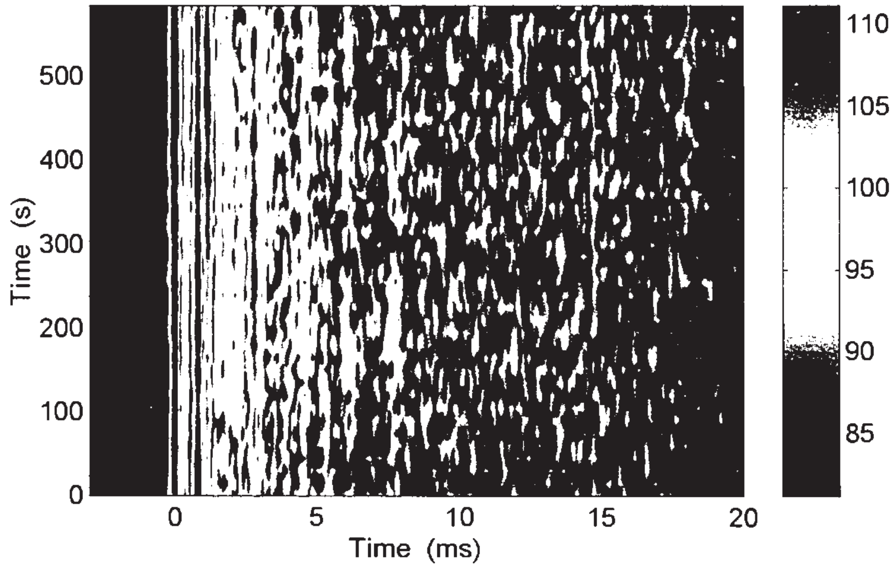

Fig. 1. Matched-filter outputs for 40 FM sweeps spread over 10 minutes (vertical axis). The colours denote sound intensities in dB re 1 μPa. (May 2; Tydeman anchored at 5 km from MPN; lowermost hydrophone.)

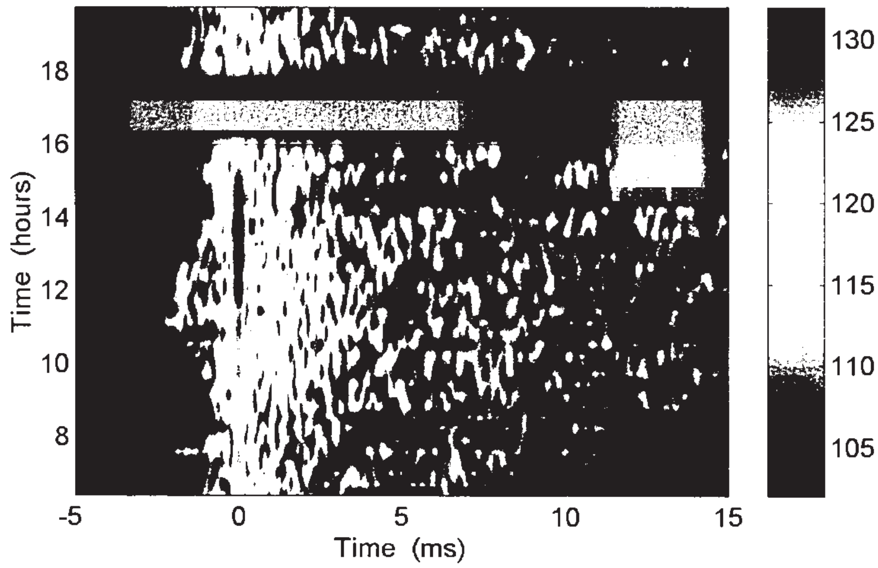

Fig. 2. Sound intensity of FM sweeps received on hydrophone 10, halfway the water column, during a day of communication experiments. The replica signal is band limited to 6-10 kHz. The vertical axis denotes the Universal Time Co-ordinated. Further note that there were no FM sweeps transmitted between 16 and 18 hr. (May 5; Tydeman anchored at 2 km from MPN.)

It will prove interesting to consider also the spatial distribution of sound across the water column. To this purpose we processed the received signals of all hydrophones at three points in time. Fig. 3 displays random indications for times at which hydrophone 10 in Fig. 2 experiences a weak, strong, and weak sound intensity, respectively. A feature that leaps to the eye is the curvature of the patterns. Indeed, this simply reflects array deformation due to the current. More interestingly, there are significant intensity variations over the array. Within the scale of the plot (15 dB) complete fading occurs at certain hydrophones. Further, the situation at noon is totally different from the situations in the morning and evening. Hydrophones that are favoured at one point in time can be poor off at other times.

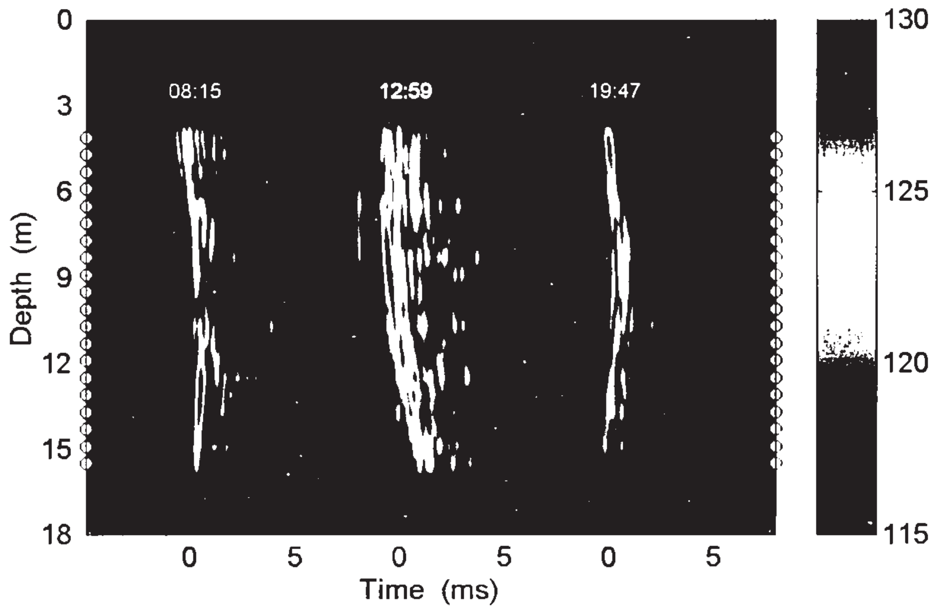

Fig. 3. Sound intensities probed by the vertical line array at three points in time. Note that the colour scale is limited to 15 dB to suppress the fainter arrivals and to emphasize intensity differences. The hydrophone positions are indicated on the y-axis by white disks. (May 5; Tydeman anchored at 2 km from MPN.)

To account for the observed phenomena, we consider the sound speed profile in the water column. The SSP is determined from CTD measurements performed every two hours on HNLMS Tydeman. Eight profiles for May 5 are plotted in Fig. 4. At first sight, the SSP changes imperceptibly over the day. There is little to no profile structure, only the gradient is somewhat stronger in the morning and evening than at noon. Adoption of the profiles into the PROSIM broadband normal-mode simulator [3], together with values for other environmental quantities suggested by, e.g., sediment core measurements, nonetheless reveal a strong influence on the propagation. The results are plotted in Fig. 5, in a manner equivalent to the measured data in Fig. 3. Apart from an agreement between the maximum sound intensities, there are striking similarities between the structures. Both Fig. 3 and Fig. 5 display an intensity minimum in the water column centre in the morning and evening, and a maximum at noon. Of course, there are differences between measurement and model too, but given the simplifications in the model calculation, like the range-independent scenario, the agreement is already remarkable. The mere substitution of three, slightly different SSP's roughly reproduces the distribution of sound over the water column.

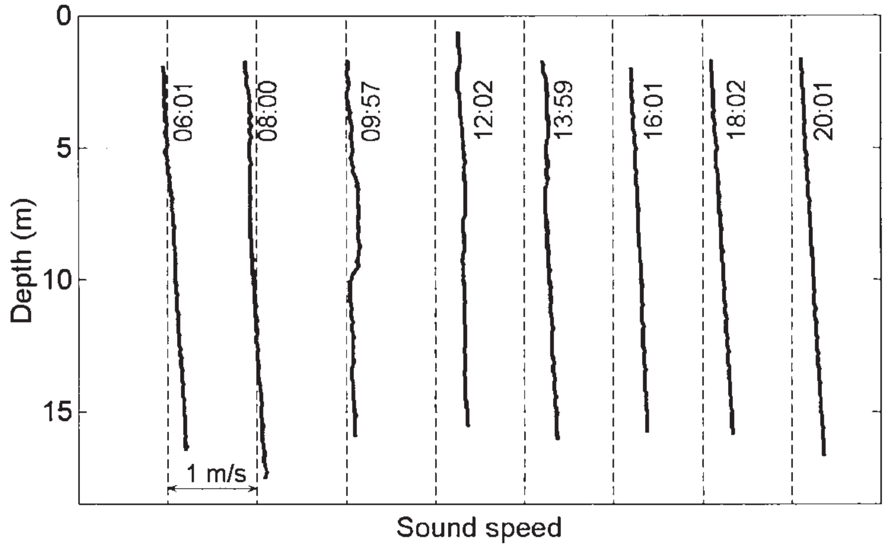

Fig. 4. Sound speed profiles for May 5, determined from CTD measurements that were carried out every two hours at the transmitter platform. The vertical dashed lines to the left of each SSP correspond to a speed of 1489 m/s.

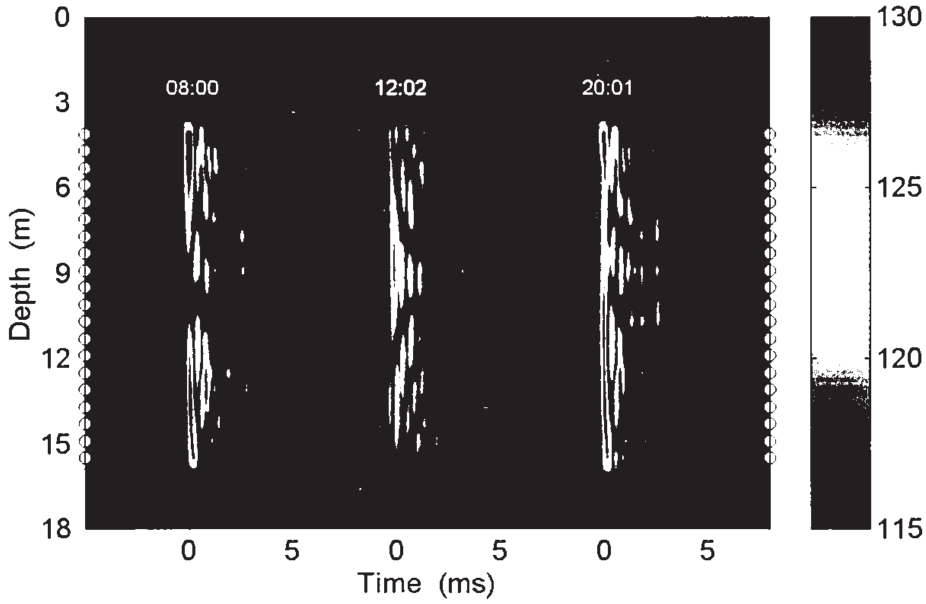

Fig. 5. Results for broadband normal mode calculations based on three sound speed profiles. Model input parameters are: water depth 18 m, source depth 9 m. Sediment: sound speed 1700 m/s, relative density 1.9, attenuation 0.8 dB/L, thickness 15 m. (The precise subbottom parameters are of little consequence for the results.) Finally, the simulation was carried out for a 2-s square LFM pulse from 6-10 kHz at a 190-dB source level. The scenario is range independent.

So far, we restricted ourselves to the frequency band from 6 to 10 kHz. A similar analysis for the 2-6 kHz band shows that this band is hardly affected by the SSP variations. The sound intensities are much more stable in time and uniform over the water column. By contrast, the 10-14 kHz band behaves even more erratic than the 6-10 kHz band. For communications in passbands above 6 kHz the sound fading can be of great consequence. A hydrophone without a dominant arrival is not a good communication channel. Not only because the SNR is lower, but also because it needs more extensive equalization to unravel the subsequent arrivals.

4.3. Doppler spreading

Frequency spreading is a detrimental effect that also complicates the realization of robust acoustic communication links. It is possible to determine the Doppler spread by inspection of the received CW signals. Defining the Doppler spread Δf as $\Delta f^2 = \int P f^2 \mathrm{d}f \Big/ \int P \mathrm{d}f$, where f denotes the sound frequency and $P = P(f)$ the power spectrum [4], we find $\Delta f / f_0$ between 1×10^{-4} and 3×10^{-4} for all examined signals (with f_0 the centre frequency).

It seems that the Doppler spread receives a contribution from current-induced array vibrations. This is revealed by a comparison with other hydrophones that were rigidly mounted to MPN. The Doppler spread on these hydrophones can fall well below those on the array hydrophones. However, the distinction between the fixed and 'mobile' hydrophones is not always clear. This relates to the fact that the current varies with the tide, but supposedly also to the fact that the array motion can be very complex [5].

As to the consequences for the communication link, it suffices to say that the ROBLINKS communication algorithms were designed to withstand Doppler spreads of several hertz, and hence that the found values should not pose insurmountable problems in this regard.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] **D. Cano, M.B. van Gijzen, A. Waldhorst,** Long Range Shallow Water Robust Acoustic Communication Links ROBLINKS, In *Third European Marine Science and Technology Conference, Lisbon,* Volume III, pp. 1133-1136, 1998.

[2] **M.B. van Gijzen, P.A. van Walree, D. Cano, J.M. Passerieux, A. Waldhorst, R.B. Weber, C. Maillard,** The ROBLINKS underwater acoustic communication experiments, To appear in *Proceedings of the fifth European Conference on Underwater Acoustics*, ECUA 2000.

[3] **F. Bini-Verona, P.L. Nielsen, F. B. Jensen,** PROSIM Broadband Normal Mode Model: A user's guide, SACLANTCEN SM-358 Technical Report, 1998.

[4] **S. Haykin**, *Communication systems*, third edition, John Wiley & Sons, page 747, 1994.

[5] **R. King,** *A review of vortex shedding research and its applications*, Ocean Engineering, Vol. 4, pp. 141-172, 1977.