*Proceedings of the Sixth European Conference
on Underwater Acoustics, ECUA'2002
24-27 June 2002, Gdansk, POLAND*

Acoustic Communication Experiments in the Westerschelde Shipping Lane using Direct-Sequence Spread Spectrum Signals

P. A. van Walree[a], M. B. van Gijzen[b] and M. Pattipeilohy[c]

[a]*TNO Physics and Electronics Laboratory, Oude Waalsdorperweg 63, P.O. Box 96864, 2509 JG The Hague, The Netherlands, e-mail: vanWalree@fel.tno.nl*
[b]*CERFACS, 42 avenue Gaspard Coriolis, 31057 Toulouse CEDEX 1, France , e-mail: vangijzen@cerfacs.fr*
[c]*Twente University, Drienerlolaan 5, P.O. Box 217, 7500 AE Enschede, The Netherlands, e-mail: m.pattipeilohy@student.utwente.nl*

Summary

Spread-spectrum underwater acoustic communication signals were broadcast in the vicinity of a busy shipping lane. Four spreading code lengths were applied, leading to bit rates between 65 and 667 bit/s in the passband between 10 and 14 kHz. Excellent results are obtained for a track over a predominantly flat bathymetry, whereas communication from inside the shipping lane upward to the coast turned out to be more challenging – yet with good results. It is shown that multipath propagation adversely affects the quality of the received signals, and that this effect is overcome by using a longer spreading code.

1. Introduction

The research presented in the paper is performed within the EC Fifth Framework Program (FP5) project ACME on underwater acoustic communication networks [1]. Among the project partners are Thales Underwater Systems (TUS, FR), ORCA Instrumentation (FR), the University of Newcastle (UNC, UK), the Dutch Ministry of Transport, Public Works and Water Management (Rijkswaterstaat, NL), and The Netherlands Organization of Applied Scientific Research (TNO, NL). The project aims toward the continuous monitoring of the underwater environment in areas where communication with conventional means (radio buoys, cables) is impossible, such as shipping lanes and fishing grounds. A typical area of interest is the Westerschelde in the Southwest of the Netherlands, where real-time availability of current data from within the shipping lane is desired to increase the safety of cargo traffic to and from the port of Antwerp, Belgium.

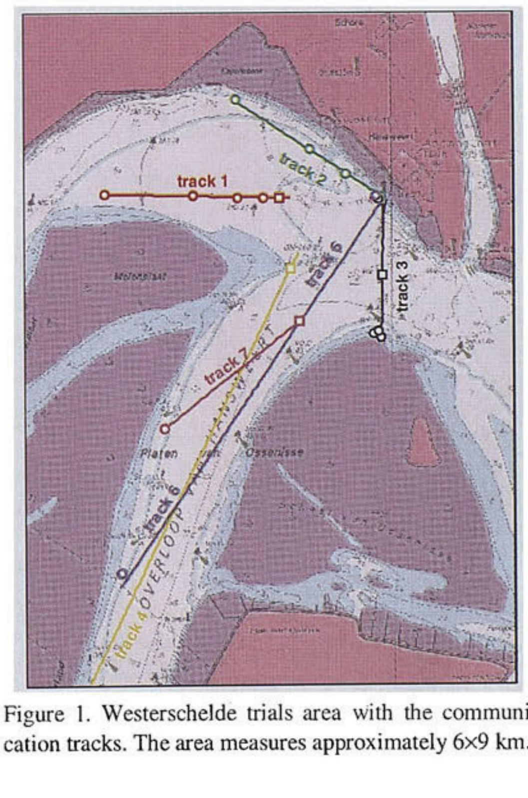

Figure 1. Westerschelde trials area with the communication tracks. The area measures approximately 6×9 km.

As a first step toward a network that conveys ADCP (current) measurements from the shipping lane ashore, point-to-point acoustic communication experiments were carried out in the Westerschelde in June 2001. The chosen area is the intended location for a prototype acoustic communication network, to be realized in 2003. This paper describes the set-up of the trial and focuses on the direct-sequence spread spectrum communication signals that were defined by TNO. These signals form only part of the experiments carried out during the trial. Other signalling schemes were defined by UNC, TUS, and ORCA [2].

2. Sea trials

Communication tracks were defined over ranges from 200 m to 5 km, both in and outside the shipping lane(s). Fig. 1 shows the trials area with the communication tracks. Tracks 3, 4, 6 & 7 are in the main shipping lane, track 2 crosses a secondary shipping lane. Tide-lands are green on the map. Tracks 2, 3 and 6 have measurement pole Hansweert as a common extremity.

Experiments were carried out with a bottom-mounted (remote) modem and a second modem (local), deployed from MS Lodycke, a research vessel operated by Rijkswaterstaat. Moreover, a two-hydrophone array was lowered from the ship to capture signals for laboratory analysis. Fig. 2 schematically shows the deployment of the array. A frame was used to place the remote modem on the seafloor, together with a battery pack sufficient for a day of experiments.

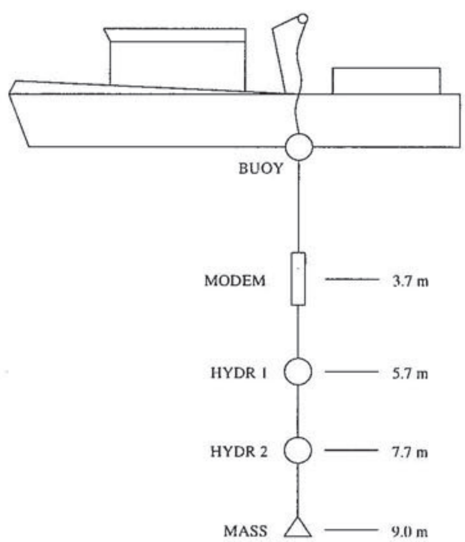

Figure 2. Deployment of the local modem and hydrophone array.

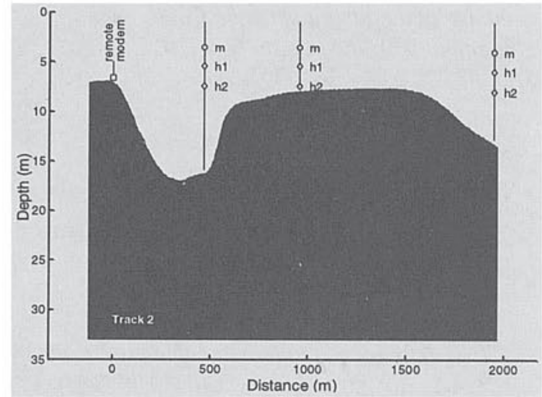

Figure 3. Experiments over track 2.

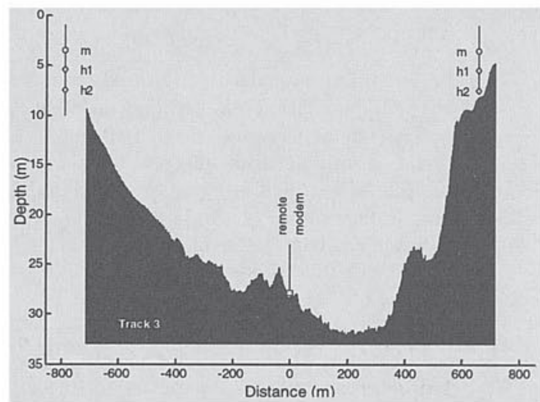

Figure 4. Experiments over track 3.

The acoustic modems (model ORCA MATS 200) transmit in the band from 10 to 14 kHz. The maximum source power is 185 dB, but often the modems were operated at a lower level. A multi-channel data-acquisition system was used to sample the hydrophone signals at 48 kHz and to store the data on hard disk for laboratory analysis. In addition to the acoustic experiments the environment was monitored with, among other things, CTD drops, current measurements, and bottom grabs. Linear frequency-modulated (LFM) and continuous-wave (CW) pulses were fitted into the signalling schemes to assess the channel impulse response and Doppler spread. Finally, ambient and shipping noises were recorded.

In this paper we focus on results from tracks 2 & 3. The bathymetries are visualized in Figs. 3 & 4, together with the positions of the remote modem, the local modem (m), and the hydrophone array (h1, h2). Track 2 crosses the secondary shipping lane and a flat part, whereas the communication over track 3 is directed from the bottom of the main shipping lane ashore. This configuration is challenging because of the shipping noise and the upward bathymetry, which is often accompanied with a pronounced timespread.

Multipath propagation is often the main difficulty with underwater communication in shallow water as it gives rise to timespreading of the communication signal [3]. When the time-spreading exceeds the symbol duration, intersymbol interference occurs. Another complication is ambient noise, the more so in densely shipped coastal areas. One of the methods to tackle timespreading and noise is the use of spread-spectrum communication signals, where robustness is built in at the expense of the data rate.

3. The transmitter and receiver

TNO defined spread-spectrum signals using maximum-length sequences as the spreading code in combination with binary-phase shift keying. The combination of PSK and a spreading sequence is known as direct-sequence spread spectrum (DSSS). Table 1 gives an overview of the transmitted signals. All signals contain the same information: a plain ascii text totalling 2176 bits. The feedback taps and sequence lengths are determined by a shift register with N cascaded flip-flop circuits. The output sequence is periodic with a period $\leq 2^N$-1. When the period equals 2^N-1, which occurs for certain combinations of feedback taps, the output is called a maximum-length sequence [4]. Among the properties of ML sequences is a binary-valued autocorrelation function.

The individual zeroes and ones of an ML sequence are known as chips. The DSSS signals are sampled at 48 kHz with an integer number of samples per chip. The bit rates in Table 1 follow

Table 1. Description of the spread-spectrum signals.

Name	Feedback taps	Seq. length	Bit rate (bit/s)	Duration (sec)
DSSS1	[2 1]	3	667	3
DSSS2	[3 1]	7	286	7
DSSS3	[4 1]	15	133	15
DSSS4	[5 2]	31	65	31
DSSS5	[5 4 2 1]	31	65	31

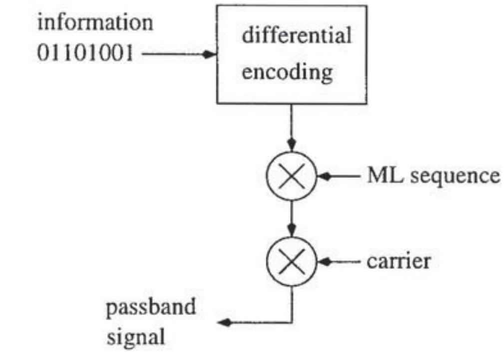

Figure 5. The DSSS transmitter.

from the fact that a single bit spans one period of the ML sequence. Fig. 5 illustrates the transmission chain, with the incoming bit stream followed by differential encoding, spread-spectrum modulation and multiplication with a carrier wave at 12 kHz to shift the signal to the passband between 10 and 14 kHz. Differential bit encoding is applied to avoid the risk of swapping all zeroes and ones after a case of temporary phase confusion.

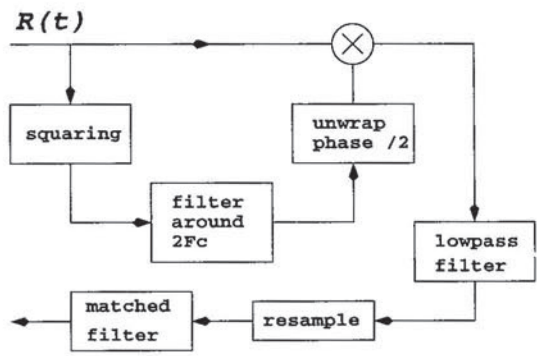

Figure 6. The DSSS receiver.

At the receiver side of the communication link the incoming signals are filtered to remove noise outside the passband. The resulting signal $R(t)$ is subsequently fed to a straightforward reception chain, the key elements of which are depicted in Fig. 6. A squaring loop is applied to recover the phase of the carrier. The signal is squared, which gives a spectral peak at twice the carrier frequency f_c. A narrowband filter extracts the double carrier, after which the phase is unwrapped and halved. The ensuing carrier phase is then used to demodulate the incoming signal $R(t)$. A lowpass filter leaves the baseband signal, which is downsampled to 3 samples per chip to reduce further computation time. Subsequently the signal is matched-filtered with a replica of the ML sequence, which gives positive and negative peaks in the filter output, depending on the sign of the original bits. Finally, symbol timing is achieved by means of a blockwise bit search. A "comb" with a tooth spacing corresponding to the expected bit duration is moved through the matched-filter output. The locations where the comb clicks in best are taken to correspond to the bit positions. This method effectively corrects for small deviations of the bit rate from its average value.

4. Results

4.1 Track 2

The majority of signals transmitted along track 2 are successfully processed in the reception chain. Table 2 tabulates the bit error rates for all signals and distances, and both hydrophone channels. Although the results are very good indeed, it has to be mentioned that the conditions were ideal. In the absence of wind the water surface was flat as a mirror. The channel timespreading is small; Fig. 7 shows the channel impulse response obtained by matched-filtering a received LFM sweep with a replica. This is quite a favourable response with one dominant arrival and only a few other, less pronounced arrivals close together. To arrive at a value for the timespread, we calculated twice the second central moment of the multipath intensity profile [5]. The values thus obtained are collected

Table 2. Bit error rates for track 2. Note that a BER of 4.6E-4 corresponds to a single bit error.

Signal	Channel	500 m	1000 m	2000 m
DSSS1	1	0	1.7E-2	0
	2	0	0	0
DSSS2	1	0	4.6E-4	0
	2	0	0	0
DSSS3	1	0	3.7E-3	0
	2	0	0	0
DSSS4	1	9.2E-4	X	0
	2	0	0	0
DSSS5	1	4.6E-4	0	0
	2	0	0	4.6E-4

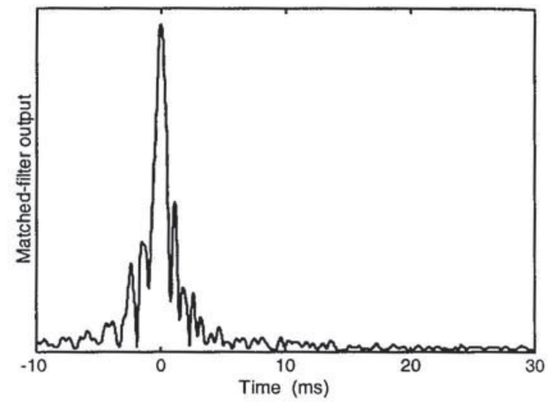

Figure 7. Channel impulse response for track 2, ch1, 2000 m.

Table 3. Channel parameters for track 2. TS=timespread, DS=Doppler spread, SL=signal level, NL=noise level.

CHANNEL	TS (ms)	DS (Hz)	SL (dB/√Hz)	NL (dB/√Hz)
ch1 500m	10.5	1.2	88	58
ch2 500 m	5.9	0.86	92	59
ch1 1 km	4.4	0.66	89	71
ch2 1 km	3.4	0.93	92	71
ch1 2 km	3.5	0.66	92	75
ch2 2km	4.1	0.96	89	75

in Table 3, together with values for the Doppler spread (calculated in a similar fashion using the power spectral density of received CW signals [6]), the signal level and the ambient noise level. These values are determined with the LFM and CW signals transmitted either a few minutes before a block of DSSS experiments or immediately following the block. It is remarked that the modem source level was not constant during the experiments: 179 dB at 500m, 182 dB at 1000 m and 185 dB at 2000 m.

Because of the good propagation conditions, the bit constellation is already excellent for the shortest spreading code (DSSS1). Fig. 8 shows a segment of the output of the filter matched to the ML replica, as well as the estimated bit positions.

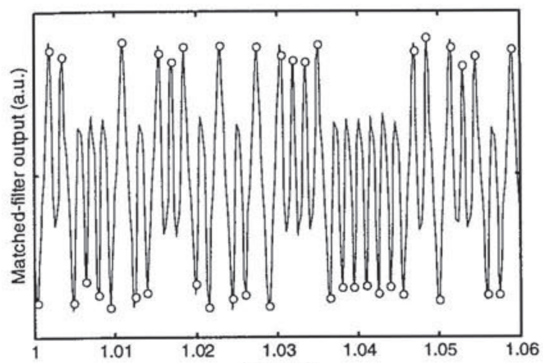

Figure 8. Matched-filter output and symbol timing for the DSSS1 signal. (Track 2, 2000 m, ch1.)

4.2 Track 3

Track 3 is more challenging. Large container ships passing through the main shipping lane produced noise levels up to 80 dB/√Hz at the local modem. For the remote modem the noise could be much louder, as the ships basically sailed straight over the frame with only ~ 10 m between the propellor and the modem. Whenever a ship sailed over the remote modem it was impossible to establish a communication link between the two modems. Another feature of track 3 is the bathymetry, which goes from the bottom of the shipping lane upward to the coast.

For the sound propagation conditions we need to distinguish between the two moorings on track 3. There are no communication results for the first mooring at 800 m (cf. Fig. 4). The bathymetry scan, which was taken after the acoustic experiments, shows that the deployment of the remote modem was rather unfortunate: it was placed just behind a seafloor hill (Fig. 4). Consequently, the absence of a direct path led to a timespread exceeding 20 ms. As a matter of fact, almost all attempts to establish a communication link between the two modems failed in this configuration. The situation changed when MS Lodycke was moored at the other side of the main shipping lane. Table 4 gives the results.

Table 4. Bit error rates for track 3

signal	channel	640 m
DSSS1	1	3.0E-2
	2	3.3E-2
DSSS2	1	1.4E-2
	2	0
DSSS3	1	9.2E-4
	2	0
DSSS4	1	0
	2	4.6E-4
DSSS5	1	6.4E-3
	2	0

The channel timespreads during the experiments over track 3 were larger than during the experiments over track 2. Fig. 9 illustrates the deteriorated channel impulse response, compared to Fig. 7. Table 5 tabulates the other relevant channel characteristics. The modem source level amounted to 185 dB for the experiments over track 3.

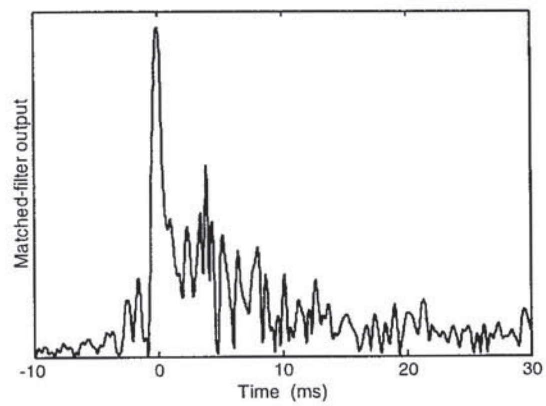

Figure 9. Impulse response for track 3, 640 m, ch1.

Table 5 Channel parameters for track 3. TS=timespread, DS=Doppler spread, SL=signal level, NL=noise level.

CHANNEL	TS (ms)	DS (Hz)	SL (dB/√Hz)	NL (dB/√Hz)
ch1 640 m	11.7	3.5	95	73
ch2 640 m	13.0	1.3	95	73

Despite the respectable timespread along track 3, and despite the increased Doppler spread, the reception chain did a proper job. The shipping noise was limited during the DSSS experiments, as there was no container ship in the immediate neighbourhood. In general one would expect better results the longer the spreading code, owing to the increased robustness with respect to timespreading and noise. This is not immediately obvious from

Table 2 and Table 4, since all BER's are reasonably low. However, there is a difference. This is revealed by plotting the bit constellations for DSSS1 (sequence length 3) and DSSS4 (sequence length 31) in Fig. 10 and Fig. 11, respectively. Note that the selected segment is the same segment displayed in Fig. 8 (i.e. it contains the same 40 bits).

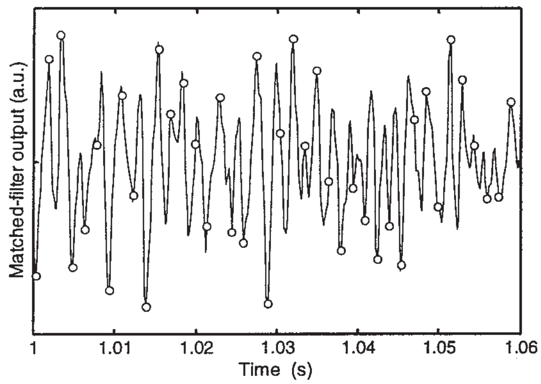

Figure 10. Matched-filter output and symbol timing for the DSSS1 signal. (Track3, 640 m, ch1.)

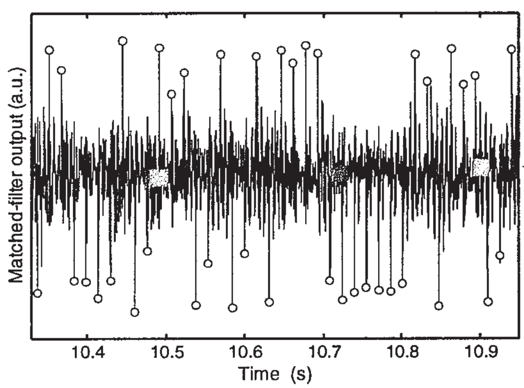

Figure 11. Matched-filter output and symbol timing for the DSSS4 signal. (Track3, 640 m, ch1.)

As it appears, the zeroes and ones are just barely separated for DSSS1. Here, multipath propagation is not convincingly tackled with a spreading code of only 3 chips. Fig. 11 shows a drastic improvement in the constellation when a 31-chip spreading code is used. However, the bit separation still falls short of the result in Fig. 8, which emphasizes the fortunate circumstances encountered on track 2. Not surprisingly, the constellations for the intermediate ML-sequences (not shown) fall in between those of Figs. 10 and 11.

5. Conclusions

In this paper we have presented shallow-water acoustic communication experiments carried out in the vicinity of a crowded shipping lane. It is shown that spread-spectrum signals can be made resistant to a fair degree of timespreading, and that longer spreading codes offer an increased robustness. Future work will concentrate on a more refined symbol timing method and on the addition of an equalizer to further mitigate the effects of timespreading.

Acknowledgements

The authors owe much gratitude to Rijkswaterstaat and the crew of MS Lodycke in particular for their enthusiastic assistance during the experiments. The project partners are acknowledged for their contributions and support.

References

[1] Acme home page: http://flipper.ncl.ac.uk/acme/

[2] ACME – 1st Periodic Report, Ref. TUS SAS 01/S/EGS/NC/450/JMP, 2002.

[3] D. B. Kilfoyle and A. B. Baggeroer: The state of the art in underwater acoustic telemetry, IEEE Journal of Oceanic Engineering, Vol. 25 (2000) pp. 4-27.

[4] R. L. Peterson, R. E. Ziemer, and D.E. Borth: Introduction to Spread-Spectrum Communications, Prentice Hall 1995, pp. 113-115.

[5] S. Haykin: Communication systems, John Wiley & Sons 2001, 4th ed., pp. 539-540.

[6] P. A. van Walree, M. B. van Gijzen and D. G. Simons: Analysis of a shallow-water acoustic communication channel, Proceedings of the 5th European Conference on Underwater Acoustics, Lyon, 2000, pp. 561-566.