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Marine seismics with a pulsed combustion source and Pseudo Noise codes

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Key words: correlation, direct sequence, impulse seismics, pseudo noise, seismic source, time coding

Abstract

There has been a long-standing debate concerning how dangerous seismic surveys are with respect to marine life. Marine seismic work today is dominated by airgun technology, where high energy is generated by a release of compressed air into the water. The objective of the "Time coded impulse seismic technique" project is to examine whether a new low energy acoustic source can be used for seismic purposes. If the method turns out to be successful, the low output energy and continuous operation will make the source suitable in environmental sensitive areas. The Low level Acoustic Combustion Source (LACS) is a petrol driven pulsed underwater acoustic source. It operates at a few meters depth, and each shot can be digitally controlled from the surface by a computer located in the mother vessel. A presentation of the recorded LACS signal characteristics, the modulation, the Pseudo Noise coding/decoding principles and field test results, is given. The importance of using an optimized code with fine resolution and of using the near field recording as correlator sequence is demonstrated. Clear correlation peaks could then be seen from the bottom and sub bottom reflectors.

Introduction

The Low level Acoustic Combustion Source (LACS) is an acoustic source, which originally was designed as a ship sound simulator for the Norwegian Navy. When fired in rapid succession, the source has a sound similar to a ship. Since its frequency contents is comparable to an airgun, a suggestion to examine its seismic potential was made. Since the output energy is lower than an airgun's, a shorter penetration depth can be expected. The source was therefore considered to have a certain potential for shallow seismics with a streamer or for deeper applications where the source could be at rest, e.g. zero offset Vertical Seismic Profiling. The low peak pressure level would be an advantage in environmental sensitive areas.

A streamer field test in 2004 with single LACS shots on shallow sediments in

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Byfjorden outside Bergen in western Norway showed a certain seismic potential. Since then the technique has changed to time coding of a sequence of pulses. A sequence of pulses has higher total energy and therefore larger penetration depth. One of the practical obstacles of time coded sequences is that transmission and reception occur simultaneously. This puts certain requirements on the dynamic range of the recording equipment. Digitizing with 24 bit resolution has proven sufficient so far. Furthermore, the reflected sequences must be extracted from the compound signal. Correlation is the typical approach to handle this problem. In order to get the desired correlation peaks from the reflections, the sequence of pulses must have an autocorrelation function which looks like a delta function. A delta function cannot be achieved in practice, but a quality factor of the coding is the spike to sidelobe ratio. Optimization of the code has gone through two phases so far. During the first field test, the autocorrelation function had a peak to sidelobe level of 5:1. During the second field test the autocorrelation peak to sidelobe ratio had improved to 10:1. The optimization of the autocorrelation function is an important part of the project and of this article. Spiky autocorrelation functions can typically be achieved with Pseudo Noise coding which was used with the LACS for both of the two field tests. In order to apply the Pseudo Noise codes to the signal, the code must be attached to a modulation. Pulse position modulation with fine resolution has so far been the best way to achieve the highest peak to sidelobe ratio.

The first field test also demonstrated the importance of using the near field hydrophone as correlator signal instead of a synthesized sequence based on the planned fire times and the source signature. A breakthrough with the time coding method came with the second field test when the optimized codes were used, and the near field hydrophone recording was used as correlator signal. Clear correlation peaks could then be found from the shallow sediments.

In addition to the environmental aspect, the LACS also has other advantages. It is easy to use since it is a single source, is fired from the surface, and is driven by a tank of petrol and air from a small compressor. Because of the limited amount of equipment necessary to operate the source, it is also expected to be fairly inexpensive in use.

Compared to sources which use expansion or contraction of air, such as explosives, airguns or imploding sources, the LACS does not have any bubble complications since no gas is released into the water. Bubble noise is not of any concern in the LACS case since the exhaust is conducted in tubes up to the surface. A typical counter measure against bubble noise is to use a tuned array of sources. The bubble noise from an array of sources is reduced since the bubble noise from each individual source is added incoherently.

Regarding energy, compressed air sources are superior compared to the LACS. On the contrary the LACS has a superior fire rate compared to the air sources. The LACS has a fire rate of up to 11 shots per second. Integrating the energy from a series of pulses is the way of accounting for the shortage of energy.

The expected penetration depth and the resolution of the measurement depend on the centre frequency, the bandwidth and the integration time. To determine these parameters is the scope of the “Time coded impulse seismic project.” The manufacturer Naxys has designed the source and is responsible for the field tests while the University of Bergen does the coding and decoding of the source.

LACS coding related to other technologies

The Vibroseis chirped signal

Sharply spiked autocorrelation functions for pulsed codes go back to the 1950s when compressed radar pulses were used in low-level transmitters. A chirped pulse of long duration provided enough energy and bandwidth to increase the range and sustain the resolution (Cook and Siebert, 1988). A matched decompression filter was used to receive the energy of the signal. The Vibroseis (e.g. Baeten and Ziolkowski 1990) land and marine seismic sources are based on the same principle as the chirped radar.

Telecommunication

With the advance of electronics, the coding techniques have become digital. Direct Sequence Spread Spectrum(DSSS) is a type of signal with sharp correlation properties. DSSS is used in military communication systems as Low Probability of Intercept transmitters and jamming resistive receivers. The DSSS technique is also used in civilian communications to give protection against multipath propagation or as a channel in a code division multiplex system (e.g. Proakis and Salehi 2002, pp. 731-752). Global Positioning System (GPS) (e.g. Freeman 1994, p. 2017) is one of the most common telecommunication systems which uses direct sequence. Although these codes have narrow and sharp autocorrelation functions, the technique cannot be used in seismics since radio signals most often are phase modulated. Seismic sources do not have this capability.

The SOSIE and mini-SOSIE method

In land seismics, pseudo random codes are used in the mini-SOSIE system which is a hand held vibrator for shallow seismic land surveys (Barbier, 1982,1983). Its coding principle is very similar to the PN coding of the LACS source. An advantage with the mini-SOSIE is that the source is at rest. If the LACS source is moving, the channel may become non-stationary and correlation will not work well. Based on these considerations, the LACS source is in its present form assumed to have its highest potential in shallow streamer surveys and for zero offset Vertical Seismic Profiling (VSP) of boreholes.

Pulsed coding has also been tried for marine seismics. Barbier and Viallix (1973) describe SOSIE as a "new tool for marine seismology" where any seismic source which can be fired randomly may be used. Their experiment was demonstrated with a sparker source. The LACS seismic principle seems to be very similar to the SOSIE method. The main difference may be the high fire rate of the LACS and its lower frequency contents.

Description of the LACS

The source is based on a single cylinder combustion engine. In its present state, the output pressure is around 0.5 barm peak to peak, and the fire rate is up to 11 times a second. The explosion of the gas in the chamber creates a downward moving wave and an upward moving wave which is reflected by the sea surface. The resulting pulse is a summation of the downward moving wave and the reflected wave from the sea surface. Bubble noise is prevented by tubes which conduct the exhaust up and above the surface. A picture of the LACS during deployment during the first field test can be seen in Fig. 1.

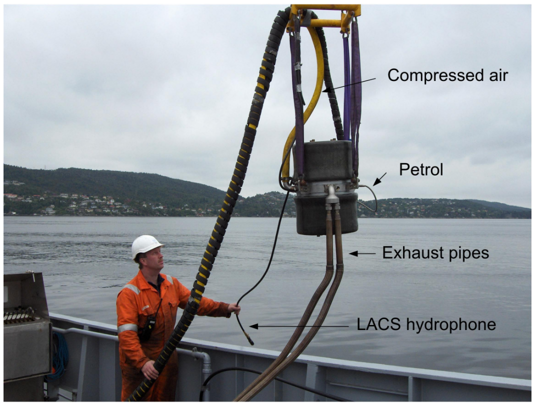

Fig. 1 Deployment of the Low-level Acoustic Combustion Source during the first field test with Pseudo Noise (PN) sequences. Up to 100 pulses were fired in each sequence.

The LACS Pseudo Noise (PN) sequence coding and modulation principle shown by simulation

In order to design a good correlation function, it is necessary to combine digital modulation with the randomness of the PN sequence. There are two practical modulation options, Amplitude Shift Keying (ASK) and Pulse Position Modulation (PPM).

In all simulations, the 50 recorded LACS pulses of Fig. 2 has been used as building blocks. In order to combine the modulation with the PN code's logical "zeros" and "ones", the modulation must be assigned to the logical levels which are called chips in telecommunication terminology.

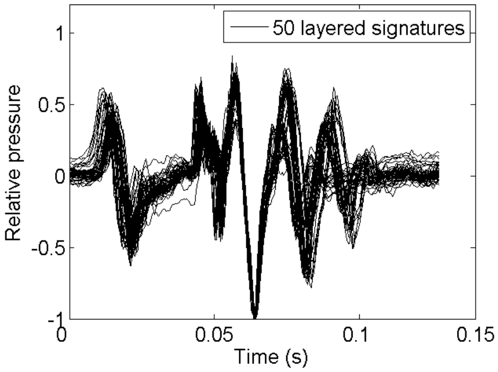

Fig. 2 Fifty different recorded LACS pulse signatures were used in the simulations.

As shown in Fig. 3 ASK modulation uses two chips to represent logical 1 and logical 0 respectively.

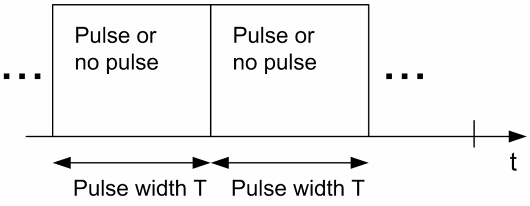

Fig. 3 Pseudo Noise coding with ASK modulation. During the fixed intervals, a pulse is transmitted or skipped randomly.

Logical 1 is presented by one of the pulses of Fig. 2 while logical 0 is presented by skipping a transmission. The duration of a logical 0 is equal to the duration of a logical 1. An example of a 10 second long ASK modulated PN sequence is shown in Fig. 4.

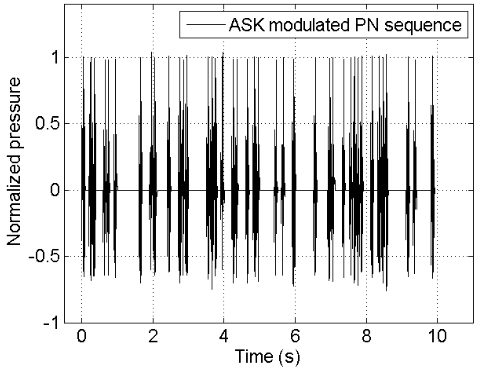

Fig. 4 An ASK modulated PN sequence.

Since logical 0 and logical 1 occur statistically with equal probability, only 50% of the sequence consists of transmitted pulses. The darker bars of Fig. 4 are consecutive 1s while the open spaces are consecutive 0s.

In PPM, the coding is determined by the position of the next pulse which is randomised. N start positions can be defined by dividing the signature interval following a transmitted pulse into N equally spaced pieces. As shown in Fig. 5, the next pulse will start in one of the N available positions.

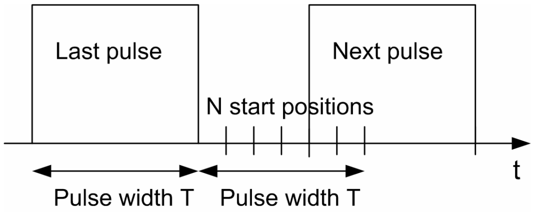

Fig. 5 PPM start position definition. The next pulse can start in one of N available start positions.

The distance between each consecutive starting point is therefore T/N. The chip in PPM is represented by the random time since the end of the previous pulse plus the pulse signature itself. Thus PPM uses N different chips. An example of a PPM modulated PN sequence is shown in Fig. 6

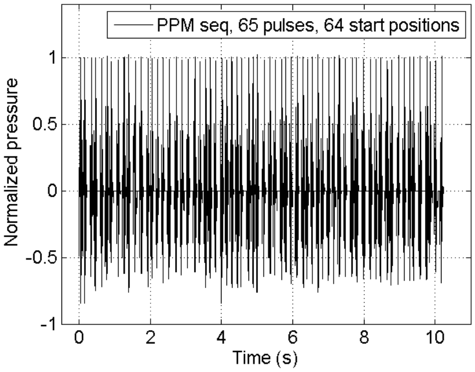

Fig. 6 An example of a PPM modulated sequence.

Properties of the autocorrelation function

The autocorrelation function shows how well each reflection can be separated from neighbouring reflections. Ideally, the function should look like a delta-function.

As shown in Fig. 7a and b, the PPM modulated PN sequence has higher correlation peak and lower sidelobes than the ASK version. The correlation peak is higher since the PPM modulation contains more pulses than the ASK version. In PPM, the average distance between the pulses for a long code is 0.5 pulse width while it for ASK is 1 pulse. The PPM has therefore an average duty-cycle of 67% while the ASK modulation has an average duty-cycle of 50%. The PPM correlation top should therefore be 33% higher with PPM than with ASK. For the specific example of Fig. 4 and 6 with a sequence duration of 10 seconds, the number of pulses in the ASK case is 44 while the number of pulses in the PPM case is 66. The relationship between the correlation peaks is therefore 65/44=1.48 which is slightly higher than the theoretical value 1.33 for an infinitely long sequence.

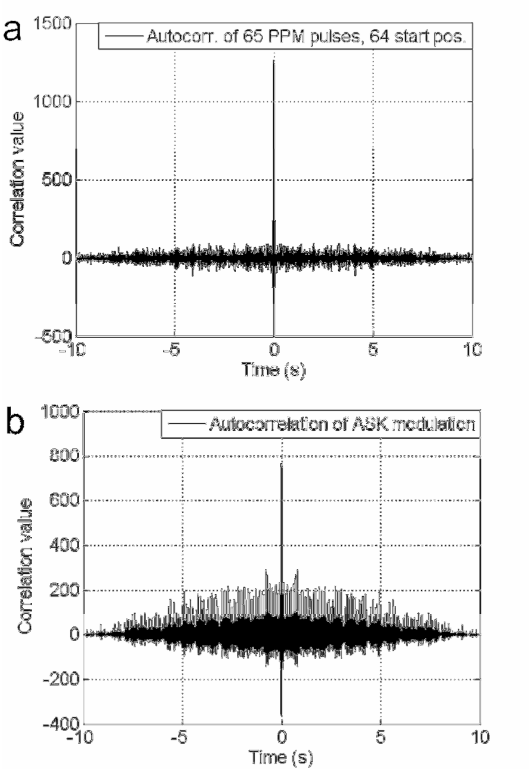

Fig. 7 The autocorrelation functions of the the PPM sequence of **Fig. 6** and of the ASK sequence of **Fig. 4**. The PPM sequence has better peak level, and also better peak to sidelobe ratio.

When Fig. 7a and b are zoomed to the time interval from 0 to 1 second, harmonic lines occur with ASK but is absent with PPM. This result is not unexpected since a fixed chip duration with ASK results in several repeated pulses which give lines in the autocorrelation function. If the number of start positions is high compared to the number of pulses in the PPM case, periodicity is avoided and the lines do not occur. With PPM it is interesting to notice that the sidelobes outside 93 ms are less than 0.1 times the main peak. See Fig. 8. Reflections down to 1/10 of the outgoing sequence can then be detected which is the dynamic range of the method.

Within one pulse width, the autocorrelation function is limited by the autocorrelation of the pulse signature. This means that the sequence has a poorer ability to detect weak signals that are closer than 93 ms from a stronger signal.

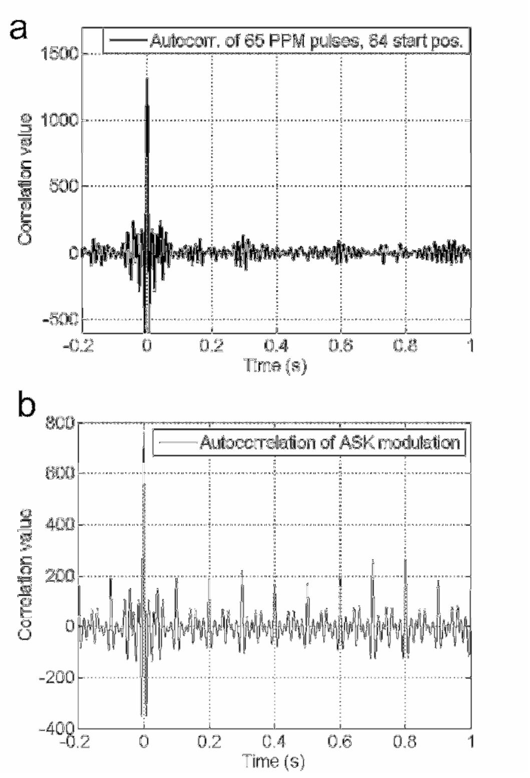

Fig. 8 Zoomed autocorrelation functions of PPM and ASK. PPM has lower sidelobes than the ASK which is dominated by periodic spikes.

A weak reflection which is smaller than 25% within the 93 ms from a larger neighbouring reflection, will disappear in the sidelobes. Improvement of the sidelobe level within the pulse width can only be achieved by changing the signature which is determined by the mechanics of the LACS. Alternative mechanical solutions which can improve the autocorrelation function of the signature are outside the scope of this article.

Of the modulation options ASK and PPM, the PPM version is clearly the best choice. When the PPM modulation has an N of 2, the autocorrelation function is similar to the ASK version. Lines occur when the number of start positions are low. As the number of start positions increase, the lines disappear. The autocorrelation function does not improve significantly after 16 available start positions. Fig. 9 shows how the autocorrelation function improves with increased number of available start positions. During the first field test, the autocorrelation function had a non optimized autocorrelation function very similar to Fig. 9a. A comparison with e.g. the autocorrelation function used by the mini-SOSIE coded with the Swept Impact Seismic Technique, the peak to sidelobe level ratio is also approximately 5:1 (Cosma and Enescu, 2001, figure 1). Fig. 9b shows the autocorrelation function similar to the codes used in the second field test.

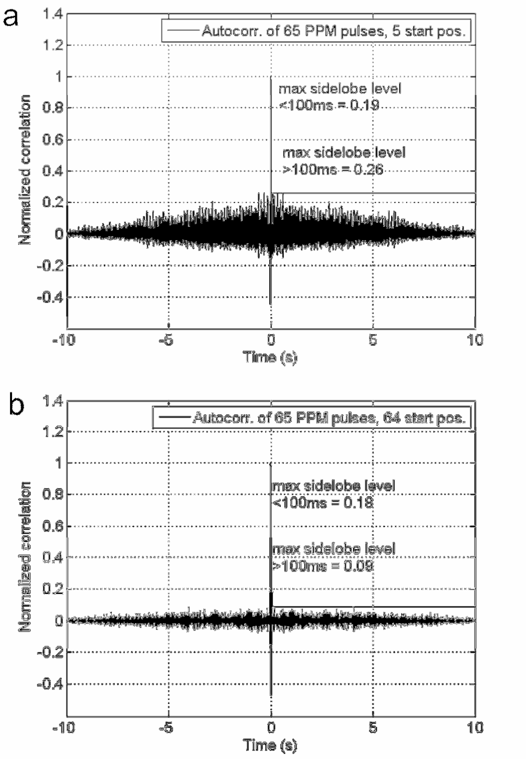

Fig. 9 The PPM autocorrelation as a function of available start positions. The sidelobes fall with an increasing number of N.

PN sequences and Gaussian noise

Since the output level of the LACS is low, the reflections will also be low. Therefore a synthesized PN sequence based on PPM modulation has been simulated against Gaussian noise to check that the sequence can be detected when the signal level is lower than the noise level. In Fig. 10a, a white pulsed PN sequence can be seen hidden in Gaussian noise with a standard deviation of one. Fig. 10b illustrates that the sequence can be detected even if the signal to noise level is negative. The correlation peak occurs at the centre of the hidden PN sequence.

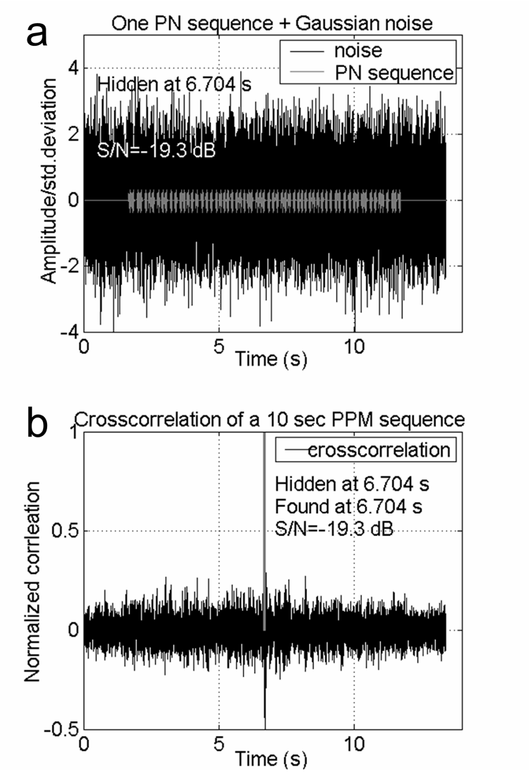

Fig. 10 PN sequence hidden in Gaussian noise (10a). A correlation integrates the pulses to a spike (10b).

In order to produce a detection probability curve against Gaussian noise, the experiment of Fig. 10 was repeated 1000 times for each signal level. The number of detected sequences divided by the 1000 attempts determines the detection probability.

In Fig. 11 the detection probability is plotted versus the signal to noise ratio. S is the signal energy of the sequence while N is the energy of the Gaussian noise. At approximately -23 dB the detection probability is 0.9. This means the highest correlation peak has been the correlation peak of the sequence in 900 of the 1000 attempts.

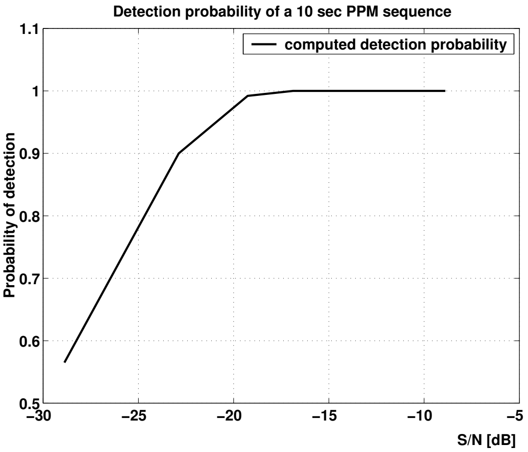

Fig. 11 The PN sequence with a negative S/N ratio can be detected with the probability given on the vertical scale.

Field tests

Data have been recorded from two field tests with different geometry. A second field test was necessary in order to obtain clear correlation results.

Field test 1

Field test 1 geometry

The LACS was tested in Byfjorden outside Bergen on the 28th of June 2005. As shown in Fig. 12, the LACS was positioned 5 m below the vessel while a hydrophone was positioned 90 m below the vessel and 250 m above the sea bed. There are glacial layers of different thickness between the sea bed and the crystalline basement (Mangerud,1995).

In order to be sure to exclude the problem with a non-stationary channel, the only movement of the vessel was current drift. A consequence was a movement of approximately 0.2-0.3 knots.

Since the previous recording of the signature, the LACS had been rebuilt in order to give a higher fire rate. The objectives of the test were therefore to record the new signature in addition to getting correlation peaks from the sediments.

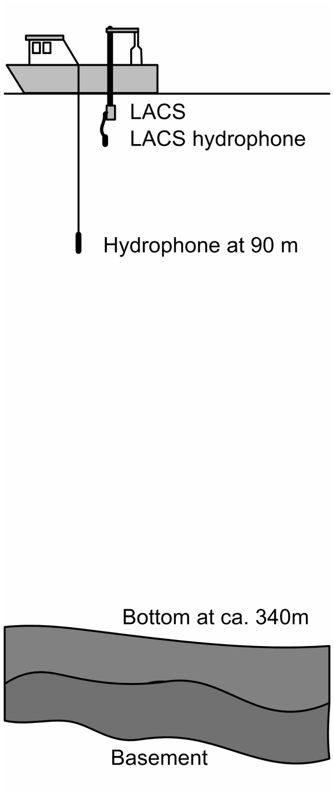

Fig. 12 The geometry of the first field test. A synthesized sequence based on the pulse signature and planned fire times, was correlated with the recording of the hydrophone at 90 m depth.

In order to be able to measure the pulse, reflections from the bottom could not be received within the pulse width of around 100 ms. This was easy to achieve since the distance to the bottom was around 250 m which gave a bottom reflection delay time of more than 300 ms at 1500 m/s.

Field test 1 signal characteristics

The first transmitted pulse of a sequence is free from bottom reflections. 50 of these far field pulses were shown in Fig. 2. The pulses repeat well. A FFT was calculated for each of the 50 pulses. The result can be seen in Fig. 13. The centre frequency is around 70 Hz and most of the energy is between 15 and 130 Hz. Some of the pulses have frequency components as low as 5 Hz. The bandwidth is comparable to an airgun array but more narrow than the watergun and sparker sources (**Vanneste** et al. 2000, p.5).

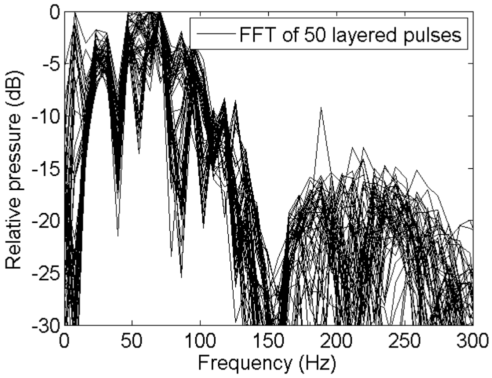

Fig. 13 The normalized absolute value of the FFT of the 50 LACS signatures of **Fig. 2.**

Field test 1 correlation results

A crosscorrelation of a synthesized signal with the hydrophone recording was expected to give correlation peaks for the reflectors. The PN sequence used in the correlation is synthesized by the first pulse of the recording and the planned fire times of the sequence. The synthesized PN sequence is shown in Fig. 14.

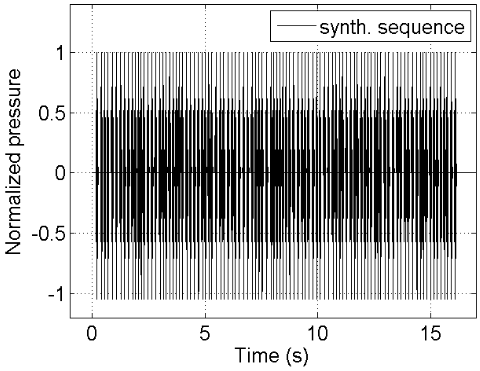

Fig. 14 A synthesized deterministic Pseudo Noise sequence based on the source signature and the planned fire times of the PN sequence

The recorded data of the actual transmitted sequence which is logged by the hydrophone at 90 m is shown in Fig. 15.

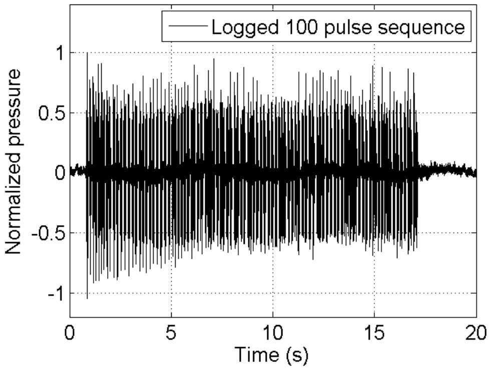

Fig. 15 One of the hydrophone recordings which contains the outgoing wave plus reflections from the bottom, sediments and basement.

The crosscorrelation between the synthesized sequence and the logged sequence is shown in Fig. 16.

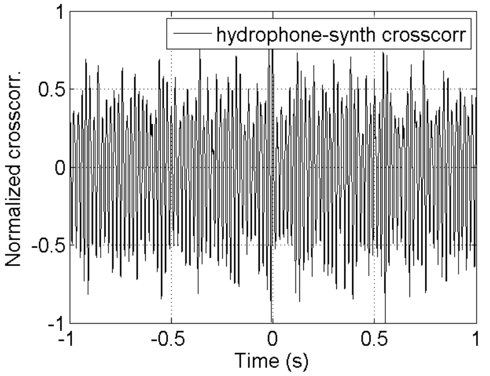

Fig. 16 The synthesized sequence based on planned fire times and the hydrophone recording are uncorrelated. No large correlation peaks occur.

No correlation peaks appear which means that the synthesized PN sequence and the recorded sequence are very uncorrelated. The analysis shows that this disappointing result is mainly caused by a non-optimal code and inaccurate fire times of the LACS. This problem was corrected to the following field test by using optimized codes and the LACS hydrophone recording as correlator signal.

Field test 2

Field test 2 geometry

Fig. 17 shows the geometry of field test 2 which was done in the same fjord one year after the first test.

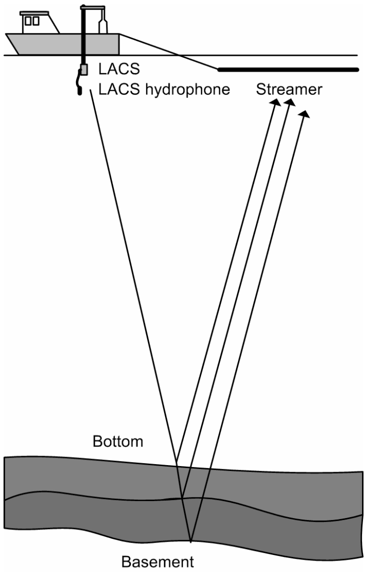

Fig. 17 Field test two was done with a streamer. Recorded data from the LACS hydrophone was correlated with recorded streamer data to obtain correlator peaks from bottom and sub bottom reflectors.

Based on the poor field test 1 results several changes were made. A streamer was used to provide more gain from the bottom, the autocorrelation function was optimized with a fine resolution PPM coding and the LACS hydrophone was recorded and used as correlator sequence. This would guarantee that the correct fire times were used. Using the LACS hydrophone, is analog and compliant with Barbier's recommendation for the mini-SOSIE system; "It is necessary to record the transmission instants. This is done using a sensor which is fixed to the rammer's base plate."(1983, p. 9).

Field test 2 correlation results

A recording of one of the logged sequences by the LACS hydrophone is shown in Fig. 18. A 10 s sequence containing 42 pulses was used.

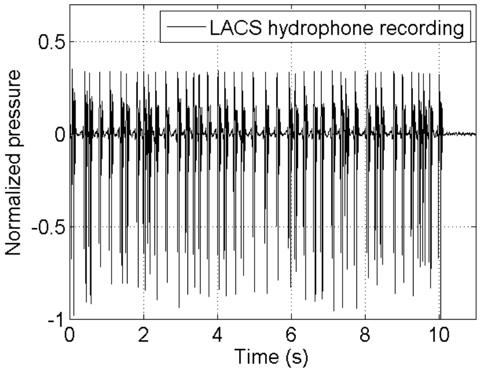

Fig. 18 In a new field test, a recording was taken from the LACS near field hydrophone and used as a correlator sequence.

The autocorrelation of the sequence is shown in Fig. 19.

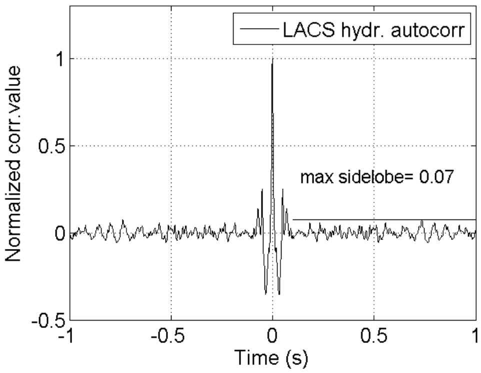

Fig. 19 The autocorrelation function calculated from the recorded LACS hydrophone is very similar to the simulated version of **Fig. 8**a and 9b.

The spike to sidelobe level of around 1:0.07 is even for practical purposes the same 1:0.08 ratio which was achieved with simulations. The sequence length was chosen to be 10 s partly to be comparable with the airgun fire rate and partly to be more certain that the stationary requirement of the channel would be met. If the reflectors change within the sequence length, the channel is non-stationary. It is less likely that the channel change within 10 s than 17 s.

Fig. 20 shows the correlation of the logged LACS hydrophone and the streamer recording. The bottom /sediment/basement reflections are located around the two clear correlation peaks.

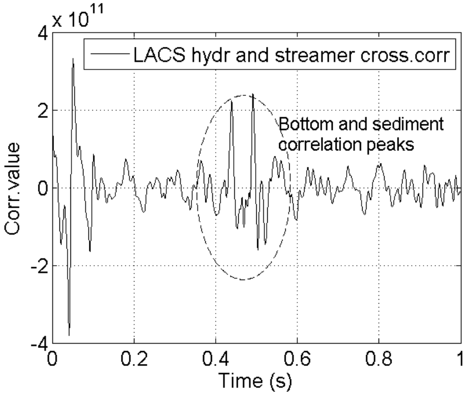

Fig. 20 When the LACS near field hydrophone recording was correlated with the streamer recording, correlation peaks of the bottom and sediments could be recognized.

Discussion

Doppler

A problem with chirped signals in marine seismics is that a source and receiver motion affects the seismic data (Hampson and Jakubowicz, 1995). Based on the following consideration, the Doppler shift is most likely not a problem for a pulsed source with narrow bandwidth. A simple way to think of a seismic pulse is a sinusoid of a specific centre frequency multiplied by a rectangular function. An approximation of the LACS pulse would then be to describe it as a 100 ms wide pulse with a centre frequency of 50 Hz. A vessel speed of 10 knots is about 1% of the sound speed in water. A change of the frequency by 1% gives a numerically calculated change of the correlation peak by only 0.5 ms. Seen in relation to the resolution a 100 Hz bandwidth gives, 0.5 ms is a small value.

Stationarity of the channel

A requirement for a correlation to work well is that the channel is stationary. As the vessel moves in a streamer survey, the reflectors which represent the channel will change with the change of the profile. Assume that the reflector is described as R(t). An intuitive thought is that the correlation must take place twice during the fastest frequency component of R(t) in order to be able restore the R(t) profile completely. This is analog to Nyquists's sampling rate (e.g Proakis and Salehi, 2002, p.48). There are no indications that a too long integration time was used on field test 2.

Conclusion

The first field test with the LACS coded with PN sequences demonstrated the importance of using a recorded sequence as correlator signal. A synthesized correlator sequence did not work at all.

It was also discovered that it was possible to improve the autocorrelation properties of the PN codes used in the first field test. This could be done by increasing the resolution of the pulse position modulation. With a fine resolution of pulse positioning, the sidelobes of the auto correlation function fell with a factor of three.

The next field test confirmed the auto-correlation properties of the simulated sequences. Correlation peaks representing the bottom and sub bottom reflectors could clearly be found with this new approach.

Acknowledgements

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