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DESIGN SESSION

The Use of Advanced Acoustic Waveforms to Improve Positioning Systems

William R. Garmer

Nautronix, Inc

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ABSTRACT

The working depth for the offshore drilling industry have increased significantly over the last several years and has created a series of problems for acoustic equipment designers. The traditional method of maintaining the necessary Signal-to-Noise Ratio (SNR) of the acoustic signals has been increasing the output source level of the acoustic beacons. Unfortunately this has technique has resulted in reduced beacon battery life. In addition, we have reached the practical limits for output source level in terms of projector and magnetic component designs. Nautronix has introduced a new acoustic positioning system that utilizes advanced acoustic waveform designs to help solve these problems. This article will cover these acoustic waveforms and demonstrate how they improve operational ranges and system performance.

THE PROBLEM

Deep-water acoustic positioning systems usually rely on one of two techniques; either Long Base Line (LBL) or Short Base Line (SBL). In some systems a combination of these two techniques are used. These techniques depend on an accurate estimate of the Time Of Arrival (TOA) of acoustic signals from bottom mounted beacons. The variance of the TOA is given by the following equation:

$$\sigma^2_{TOA} \geq \frac{1}{\overline{F}^2 \left(2\frac{E_s}{N_0} \right)}$$

Equation 1 : Variance of the TOA estimate [1]

Where:

$\overline{F}^2$ = the mean square bandwidth of the signal

$\left(2\frac{E_S}{N_0} \right)$ = the SNR of the received signal

From equation 1 we can see that to improve the repeatability of an acoustic positioning system (i.e. reduce the variance of the TOA estimate) the designer has to either increase the SNR or the bandwidth of the received acoustic signal.

The traditional acoustic waveform used in the offshore drilling industry is the sinusoidal pulse. This waveform consists of a pulse of a single frequency. The bandwidth of this signal is given by:

$$B = \frac{1}{T}$$

Equation 2: Bandwidth of a Simple Sinusoidal Pulse

Where:

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[1] Steven M. Kay, Fundamentals of Statistical Signal Processing – Volume 1 Estimation Theory (ISBN 0-13-345711-7), p. 55

B = the bandwidth of the signal in Hz
T = the duration of the signal in seconds

Equation 2 shows that decreasing the duration of a sinusoidal pulse increases the bandwidth of the signal. This has been one of the traditional methods of improving the repeatability of acoustic positioning systems. For example, the Nautronix RS5D, an SBL based system, uses a pulse duration of only 800 µs. The other method is increasing the SNR of the received acoustic signal. The options for the acoustic designer to increase the SNR are limited by the physics of the acoustic link.

THE ACOUSTIC LINK

As mentioned in the discussion of the TOA estimate, the SNR of the received acoustic signal is given by:

$$SNR_{REC} = 2\frac{E_S}{N_0}$$

Equation 3: SNR of the Received Acoustic Signal

Where:

E_S = the energy of the received signal in Joules
N_0 = the noise spectral density in Watts/Hz at the hydrophone

Equation 3 shows that there are basically two ways to increase the received SNR: increase the energy of the received pulse or reduce the noise into the hydrophone. The acoustic system designer has very limited choices when it comes to reducing the noise. The noise spectral density at the hydrophone is a factor of the ambient environmental noise, thruster noise, and beamwidth of the hydrophone. Of all these factors, the only one under direct control of the acoustic designer is the hydrophone beamwidth. By narrowing the beamwidth, using acoustic baffling or beam forming, the designer can attenuate thruster and ambient environmental noise into the hydrophone. Unfortunately the narrower the beamwidth the smaller the grid beacons on the sea floor. This is especially a problem for deep water LBL mode of operation that usually requires the beacons be spread out over a grid equal to the water depth. Beam forming can solve this problem but significantly adds cost and complexity to the design of the hydrophone.

The acoustic designer has more options when it comes to increasing the energy of the received signal. The energy of a sinusoidal pulse is the product of the RMS Receive Source Level (RSL) and the duration of the pulse. The RSL is given by the well know SONAR equation as:

$$RSL = SL - AG_P - TL - AG_H$$

Equation 4: The SONAR Equation

Where:

SL = the transmitted source level in dB ref 1µPa @ 1m
AG_P = the array gain of the projector in dB

TL = the transmission loss in dB

AG_H = the array gain of the hydrophone in dB

The array gains of the projector and hydrophone are a factor of the beamforming in these transducers. There is a limit to amount of beamforming that the can be done. This is constrained by the operating geometry of the acoustic system. In SBL systems, where the acoustic beacon is expected to be almost directly under the ship, both the projector and hydrophone can have a significant amount of beamforming. As noted earlier, beamforming of the hydrophone on the ship helps reduce thruster noise into the positioning system. This is a major advantage for SBL based systems in deep-water operation. In LBL systems, the requirement to spread out the beacons limits the amount of beamforming to about ±45° about vertical. This limit controls the amount of array gain that can be used. The acoustic designer also has only limited control over the transmission loss of the acoustic link. The transmission loss is a factor of the range, which is fixed by the requirements of the industry, and the frequency of the acoustic link. The transmission loss is given by:

$$TL = 20\log(R) + a\left(\frac{R}{1000}\right)$$

Equation 5: Transmission Loss of the Acoustic Link

Where:

R = the range of the acoustic link in meters

a = the absorption loss coefficient in dB/km

The first part of equation 5, $20\log(R)$, is the spreading loss of the acoustic signal. This loss is a result of the power of the transmitted signal being spread over an increasing as the acoustic signal travels through the medium. The acoustic designer cannot control this factor. Over the range of 3500 meters the spreading loss is approximately 71 dB. The absorption loss coefficient is a factor of the frequency of the acoustic signal. A portion of the energy of the acoustic signal being converted into heat causes absorption loss. The farther the signal travels the more energy is lost. The operational frequency range of acoustic positioning systems is between about 10 to 30 kHz. The absorption loss over this frequency range is between 1 and 5 dB/km. At a 3500 meter, the difference in absorption loss between 10 and 30 kHz is about 14 dB. Despite the fact the absorption loss is much smaller than the spreading loss, it is still a significant factor. Unfortunately the lower the operating frequency, the more difficult the job of baffling the hydrophone. In addition, the acoustic designer has to contend with operating with a multitude of acoustic equipment operating in the same frequency range and the need to have several beacons operating at the same time.

The only factor completely under the control of the acoustic designer is the source level of the beacons. Over the last several years the industry has witnessed a marked increase in the output source level of the beacons used in acoustic positioning systems. Beacons with output source levels of 202 dB are common and source levels as high as 214 dB are available. These high output source levels have resulted in shorter battery lives. With the deeper working depths of drilling operations today, the average time on a well has increased to over 180 days.

So given these various factors, what can the acoustic designer do improve the system repeatability? If the designer selects increasing the received SNR by increasing the duration of the acoustic pulse then the bandwidth of the signal is reduced (which decreases the system repeatability). If the designer selects increasing the bandwidth of the signal by reducing the duration of the acoustic signal then the energy of the received signal is reduced. In addition, the wider the bandwidth of the acoustic signal the fewer the number of beacon channels that are available to the system user and the lower the resistance of the system to outside interferers. Any option that increases the energy of the received acoustic signal (i.e. increasing the output source level of the beacon or increasing the duration of the acoustic signal) ultimately reduces the battery life of the beacons. Modern waveform design techniques can help simplify these issues.

WAVEFORM DESIGN

Over the last decade, the wireless industry has been moving towards the use of spread spectrum waveforms. This drive has been forced by the explosion is users demands for higher data rates and the lack of RF bandwidth to support these rates. In addition, users are now more mobile than ever. The RF users expect to be able to surf the web, receive faxes, and use their cellular phones while travelling. These requirements mean that engineers in the mainstream communications industry now are facing the same complex channel characteristics as found in the underwater acoustic channel. These characteristics include frequency selective fading and signal multipathing. Many of these spread spectrum techniques can be used in the underwater industry.

There are two basic techniques for generating spread spectrum signals. Direct Sequence (DS) places phase shifts into the basic acoustic pulse and frequency hopping transmits the signal over a group of frequencies. The following discussion will focus on the DS method since it is the method being developed by Nautronix for it new RS925 system.

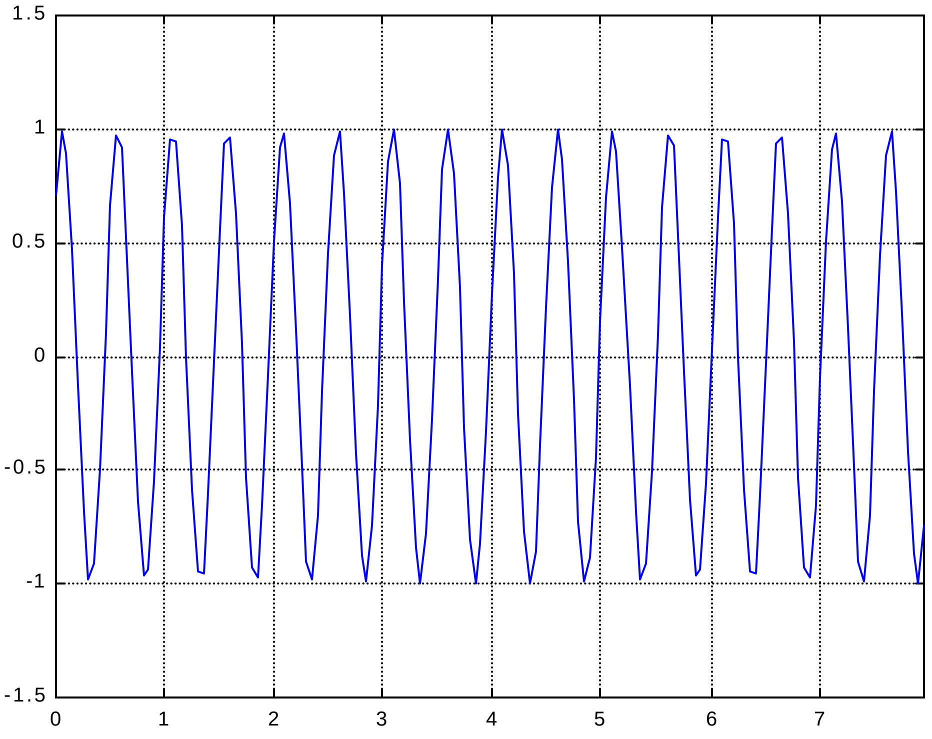

Figure 1 shows a sinusoidal pulse with a frequency of 19.8 kHz with a duration of 800 µs. This is a typical waveform for NAUTRONIX RS5D SBL systems.

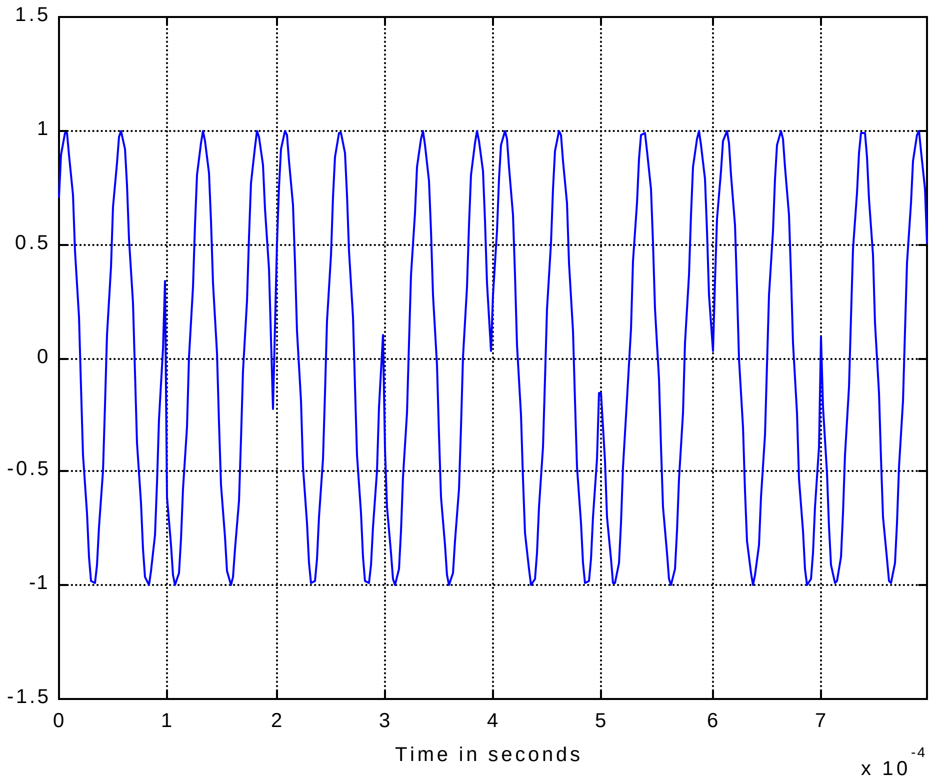

Figure 2 shows the same waveform in which seven phase reversals have been added. These phase reversals have spread the energy of the signal over a much wider spectrum than the normal sinusoidal pulse. Normally we would not add phase reversal sequences to a pulse as short as 800 µs since it already has a relatively wide bandwidth. Where this technique has application is taking long pulse duration, which have relatively narrow bandwidths, and spreading the energy across a much wider bandwidth to reduce the variance of the TOA estimate.

Figure 3 shows the spectrums of a 800 μs 19.8 kHz sinusoidal pulse and a 10 ms 19.8 kHz spread spectrum pulse. The spectrum of the 10 ms pulse was spread using a series of phase reversals also known as Phase Shift Keying (PSK). From equation 2, the bandwidth of 800 μs sinusoidal pulse is 1250 Hz while the bandwidth of 10 ms pulse is 100 Hz. Figure 3 shows that these two signals have approximately the same bandwidth. This means, with the same SNR, these two signals would have the same TOA variance but the output source level of the 10 ms beacon could be significantly smaller.

Another advantage of using spread spectrum signal is an increase in the SNR of the received signal. During reception, the spread spectrum signal is "de-spread." In this process the signal energy across the bandwidth is re-combined coherently while the noise energy in the band sums non-conherently. The result is an improvement in the SNR by a factor of equal to the square root of the ratio of the spread spectrum bandwidth to the base band (non-spread spectrum signal). For the signal shown in figure 3, this improvement would equal the square root of 1300 Hz divided by 100 Hz or a factor of 3.6 (about 5.5 dB). This is factor is call the "process gain" and would add directly to the SONAR equation (equation 4).

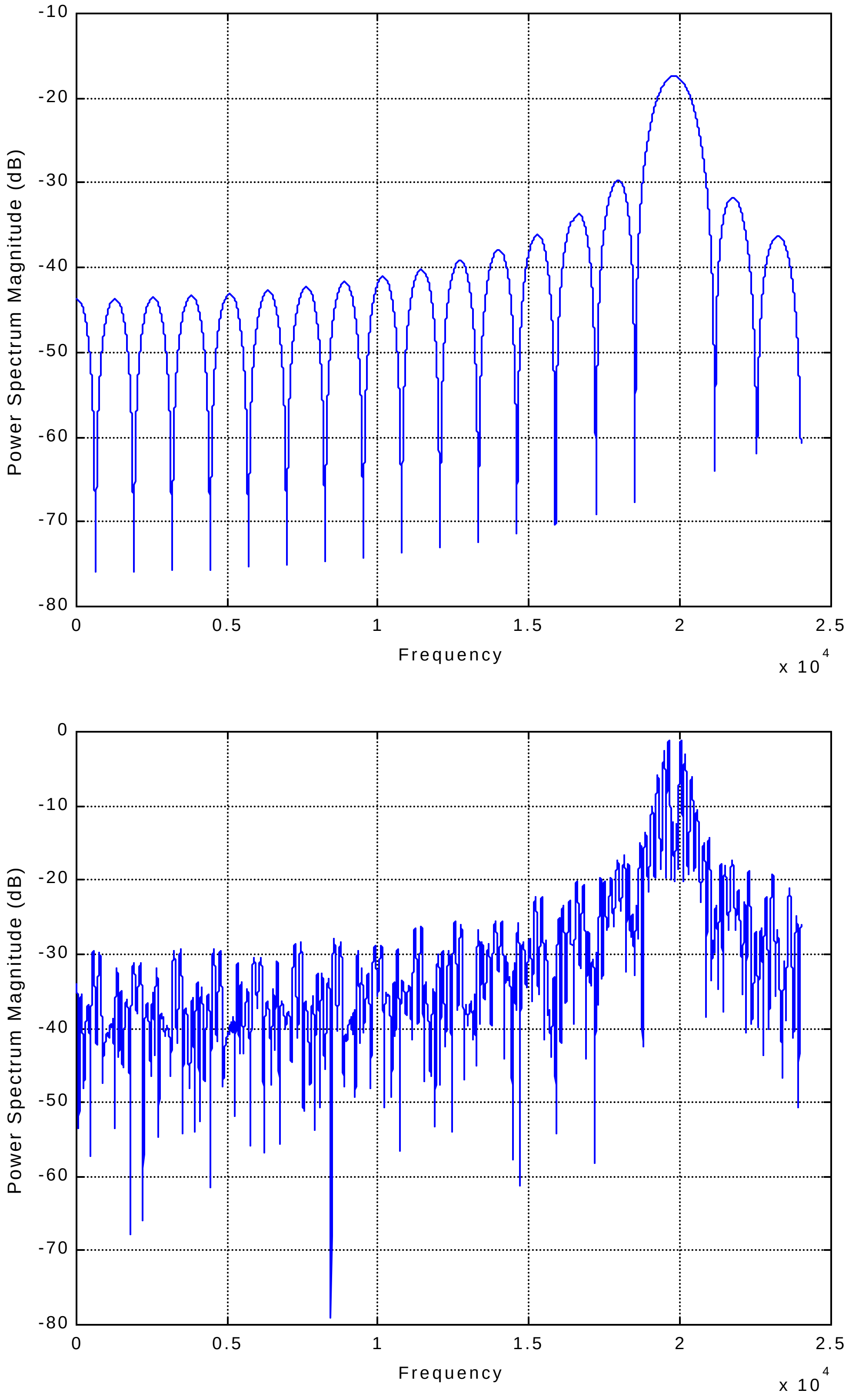

Figure 3: Power Spectrum Density of a 800 us Pulse and 10 ms PSK Pulse

CONCLUSIONS

This paper has demonstrated that spread spectrum techniques used in wireless community can be adopted for improving the performance of acoustic positioning system. The advantages shown are:

- Improved SNR of the received signal without increasing the transmitted source level
- Increased battery life in subsea beacons by decreasing the transmitted energy levels
- Improve TOA estimation accuracy by creating wider signal bandwidth

While these advantages are important there is another factor that makes the use of these waveforms critical for the future of the commercial acoustic equipment design. With the increase in the operational depths of drilling industry has come an increase in the interference generated between neighboring vessels. This has been caused by the increase in the output power of the subsea beacons along with drilling vessels operating much closer. Waveforms using long PSK sequences can be differentiated from other similar waveforms on the same frequency. This means that each vessel could have its own set "code" sequences for its beacons that would be different from those of any other vessel. This would ensure that vessels operating in the same area would not interfere with each others acoustic.

Presently the Nautronix RS925 uses a PSK sequence of up to 15 phase reversals with a 10 ms pulse duration. This combination allows the RS925 to achieve an accuracy of 0.15% of water depth in 3500-meter water when operating in SBL only mode with beacons having an output source level of 196 dB. The improvement in the TOA estimate has allowed the beacon grid for the LBL mode of operation to have only a 1000-meter spacing in 3500-meter water depth. Even though a sequence length for the RS925 is not yet sufficient to allow all the beacons to operate on the same frequency, beacons set with different sequences can operate as closely at 100 Hz. This allows the RS925 to use many more beacons than the RS5D system.