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Acoustic Positioning

Improved Acoustic Positioning for DP Operations

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The demands of the offshore, research and defence industries for reliable and accurate subsea positioning in ever more difficult waters have increased significantly over the last few years. In a DP context these demands have been accompanied by a need to maintain and indeed increase update rates and positioning accuracies and repeatability while operating from ever more powerful and noisy vessels. This has created significant challenges for the manufacturers of acoustic positioning equipment.

Several methods have been used to increase the range and reliability of existing systems to try and meet these increased challenges. All have an element of compromise in achieving their solutions, as existing signalling technology has reached the practical limits of its capability. New signalling technology is necessary to overcome these problems and address the growing needs of the industry. Nautronix have developed Acoustic Digital Spread Spectrum waveform designs to overcome many of the limitations of existing technology, and provide reliable and accurate positioning to meet the increasing demands of the industry

Introduction

Deep-water acoustic positioning systems have traditionally relied on either Long Base Line (LBL) or Short Base Line (SBL) methodologies for position calculations. In some systems a combination of these techniques is 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 can be characterised by the following equation:

$$\sigma^{2}_{TOA} \propto \frac{1}{\overline{F}^{2}\left(2\frac{E_{s}}{N_{0}}\right)}$$

Equation 1 : Variance of the TOA estimate

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 for positioning 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:

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 reliability of acoustic positioning systems. For example, the Nautronix RS5D, an SBL based system, uses a pulse duration of only 800 µs.

> Any tonal pulse must contain several cycles (oscillation periods), typically more than 10. This allows time for system transients (in both transmitter and receiver hardware) to die down so that a significant portion of the transmission (or reception) is in the "steady state". A 20 kHz pulse (the lower end of the RS5D transmit spectrum) with 10 cycles would have duration 500 us. This suggests that, for low frequencies at least, RS5D is close to the minimum practical pulse duration. In principle it would be possible to reduce the pulse duration of higher frequency pings. However, given that transmissions are *peak power limited*, a reduction in pulse length will result in a reduction in *transmitted energy*, which will in turn impact on the probability of detection as detection probability is a function of received signal *energy*, not power. Furthermore, absorption of acoustic energy in seawater is more severe at higher frequencies. This makes it even less desirable to reduce pulse duration at higher frequencies.

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 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 tracking area. 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 and therefore the Signal to Noise Ratio. The energy of a sinusoidal pulse is the product of the RMS Receive Source Level (RSL) and the duration of the pulse. The equation as:

$$SNR = (SL - TL) - (NL - AG_h)$$

Equation 4: The SONAR Equation

Where:

SNR	is signal to noise ratio at the hydrophone in dB
SL	source level at beacon **in dB**
TL	the transmission loss in dB
NL	the noise level at the receiver in dB
AG_H	the array gain of the hydrophone in dB

Note: SL-TL is the received source level
NL-AG is the effective noise level
All dB values are 'ref 1 µPa at 1 m'

The array gains of the hydrophone is a factor of the beamforming in the transducer. There is a limit to the 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. For USBL systems the beam width should ideally be more. 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:

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

Equation 5: Transmission Loss of the Acoustic Link

Where:

R the range of the acoustic link in meters

α 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 area as the acoustic signal travels through the medium. The acoustic designer can not 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 (the higher the frequency the higher the absorption loss). It also depends on salinity, temperature and pressure. A portion of the energy of the acoustic signal being absorbed by the medium and 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 generally between about 10 to 50 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.

[A graph of the propagation loss vs. range would be a good illustration and summary of the previous paragraph…] [Also you could add a point on lowering your frequency which doesn't necessarily help… Explain why]

The only factor completely under the control of the acoustic designer is the source level of the beacons ,and modulation technique. 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 the industry comes the requirement for longer battery life, yet at the same time increased power output to counter the losses detailed above. At such powers it is difficult, if not impossible, to provide the required battery life in a manageable unit.

So given these various factors, what can the acoustic designer do improve the system repeatability and battery life? 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 accuracy). 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 interference. 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

There are additional limitations to the existing Frequency Shift Keyed (FSK) [Tone Burst] signalling technology. These include:

- Limited number of channels
- Lack of ability to work with other systems in close proximity
- Poor immunity to propagation multi-path
- Lack of ability to operate in high noise environments

- High Transmission power requirement
- Inadequate signalling reliability and security.
- Lack of ability to operate over long ranges

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These factors can have a very significant impact on the success or otherwise of any operation, and for this reason, the use of underwater acoustic systems has been very conservative, particularly in deep and ultra-deep water operations, where the use of acoustics could provide very significant benefits. However, by overcoming these factors, the full benefits of acoustics can be realised, and can allow new methods to be employed for subsea operations that can lead to substantial cost savings and potential risk reduction.

Nautronix have, through a highly successful 6-year development programme for defence applications, developed exactly such a signalling technology that effectively minimises all of the above problems, and allows significantly improved positioning performance. It is called Acoustic Digital Spread Spectrum, or ADS^2. This technology is now available in a number of Nautronix acoustic positioning products.

HOW ADS^2 WORKS

As mentioned earlier, the accuracy of any acoustic positioning system is heavily dependent on the accuracy of TOA estimates. As stated in equation 1, the variance of the TOA estimate is inversely proportional to the bandwidth of the acoustic signal. Conventional signals are sinusoidal (ie tonal) pulses. These signals, which are sometimes referred to as *narrowband signals*, have bandwidth equal to the inverse of the pulse duration. ADS^2 signals, which are members of a general class of signals known as s*pread spectrum* signals, have bandwidth much larger than the inverse of the pulse duration. The amount by which the bandwidth is larger is called the *bandwidth expansion* factor. The following discussion illustrates how the use of ADS^2 signals leads to a significant improvement in performance.

Pulse Detection and Matched Filtering

The signal processing techniques used to determine TOA are derived from *pulse detection* theory and often include the use of a *matched filter*. The precise nature of a matched filter will not be discussed in this paper. Qualitatively speaking, a matched filter responds “best” to the acoustic pulse to be detected and tends to attenuate other signals, including noise. An extremely important feature of ADS^2 pulses is the characteristic of the matched filter output. When a conventional pulse is passed through a matched filter, the output has (more or less) the same duration as the pulse itself. An ADS^2 pulse, on the other hand, produces an output whose energy is concentrated in an interval much smaller than the duration of the pulse. This process is called *pulse compression* and it is a direct consequence of the spectrum spreading – the amount of compression is the inverse of the bandwidth expansion.

To illustrate the role of the matched filter in TOA measurement consider Figure 1, which depicts a conventional tonal pulse waveform, and Figure 2, which is the response of the matched filter to the waveform in Figure 1. The important characteristics of the signal in Figure 1 are its TOA, which is 2 ms, and its duration, which is 5 ms.

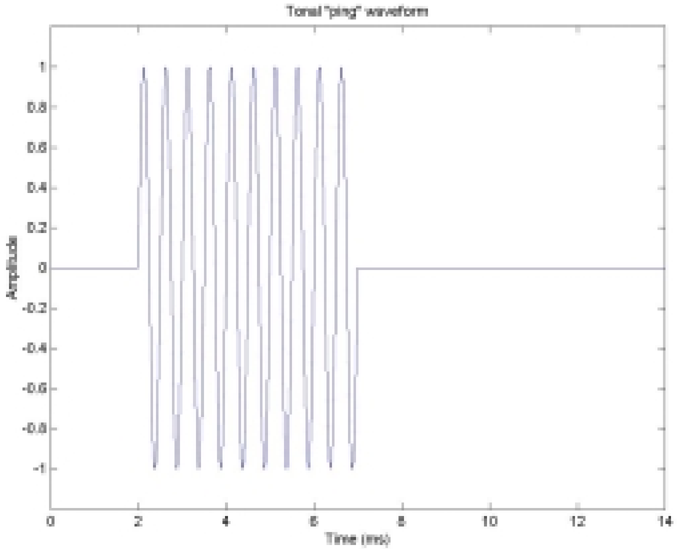

Figure 1: Conventional tonal pulse

The matched filter response is observed to begin at 2 ms – the TOA. It exhibits increasing oscillations until exactly 7 ms. This is an important feature of the matched filter response – for a pulse of duration *T* seconds, the matched filter response reaches a maximum precisely *T* seconds *after* the TOA.

The dashed line which follows the positive oscillation peaks in Figure 2 is known as the *envelope* of the matched filter response. This waveform can be generated by processing the matched filter output using an *envelope detector*. The envelope is subsequently processed by a *peak detector* which timestamps the maximum value. The TOA is found by subtracting *T* seconds from this timestamp.

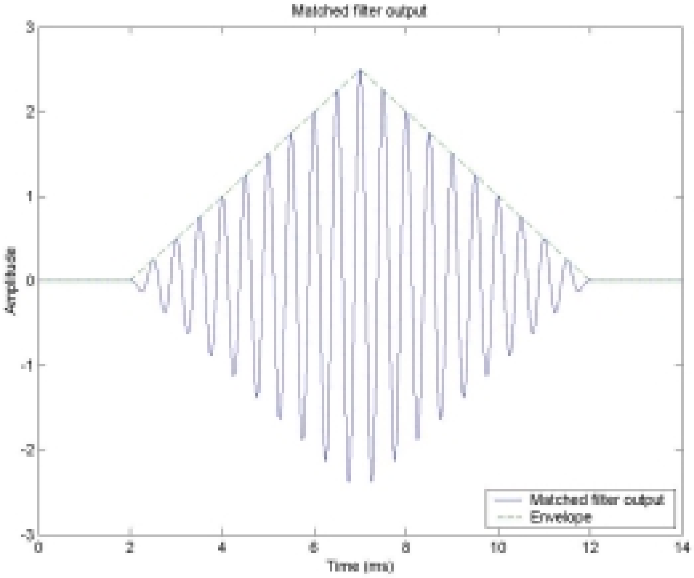

Figure 2: Matched filter output to conventional tonal pulse

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Figure 3 illustrates the effect of noise on TOA estimation. The input to the matched filter in this case has been contaminated by noise (the signal component is the same as Figure 1). In this case the actual peak in the matched filter output does not occur at 7 ms as expected. Instead, as a result of the random variations due to noise, the TOA estimate is incorrect by around 0.22 ms (which translates to around 34 cm).

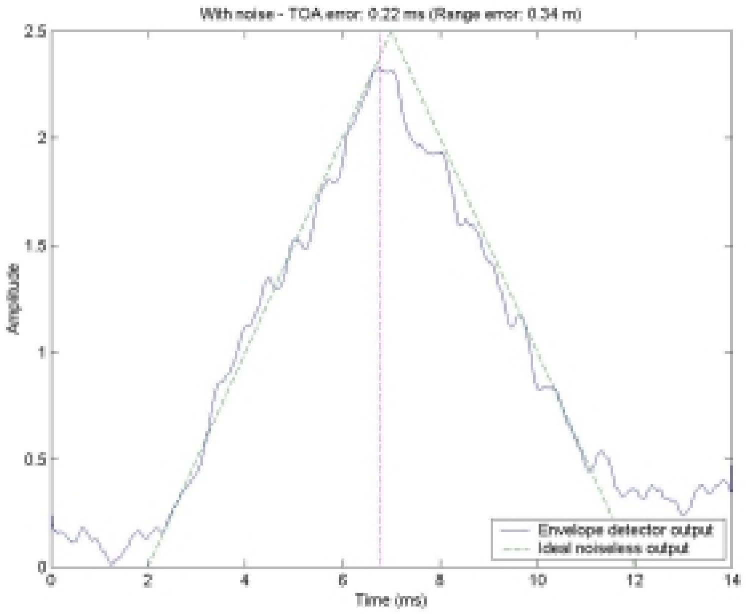


Figure 3: The effect of noise on TOA estimation using conventional signals

Noise Performance of ADS^2 Signals

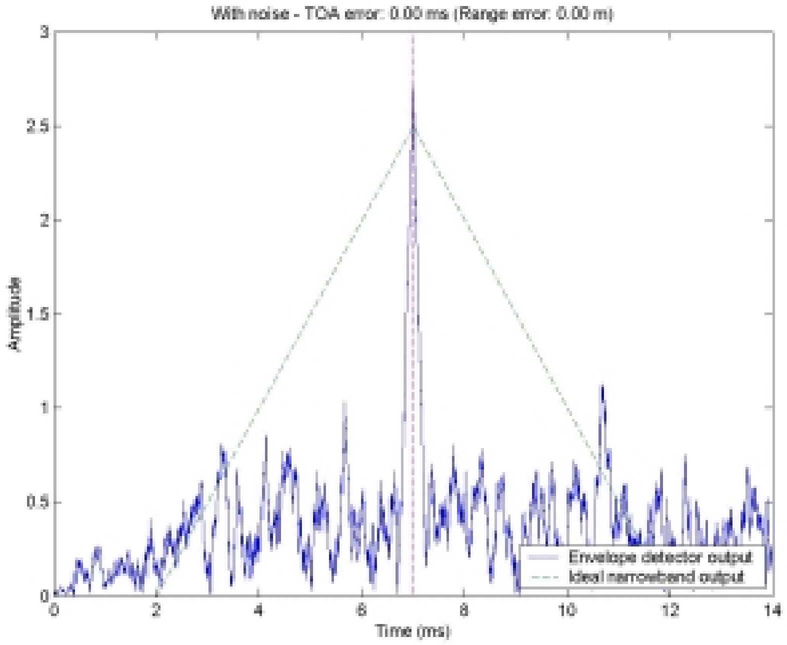


Figure 4: The TOA estimate using ADS^2 signal

Figure 4 illustrates the TOA estimate generated using an ADS^2 signal. This figure, like the previous ones was generated through computer simulation. To generate Figure 3 and Figure 4 the same noise sequence was added to the signal pulses. Both signal pulses have TOA 2 ms and duration 5 ms. The signal pulses have the same energy but, because of the increased signal bandwidth, the in-band signal to noise ratio is actually *significantly worse* in the ADS^2 case. Despite this, the improvement in TOA estimate is significant (the error is now negligible).

Notice also that the portion of the matched filter response which has amplitude greater than 1 is significantly less than in the narrowband case. This is the pulse compression effect described earlier. To appreciate how pulse compression leads to the observed performance improvement, consider the ideal narrowband envelope detector output, as shown in Figure 4 with the dashed line. In the presence of noise, a small random variation will be added to this ideal line. To produce an error of 0.5 ms in the TOA estimate such that, for example, the measured peak occurs at time 6 ms instead of 7 ms we would require that the noise signal at 6 ms is somewhat greater than the noise signal at 7 ms. To produce the same TOA error in the ADS^2 case the difference between the noise signal at 6 ms and 7 ms would need to be much larger (as is apparent by visual inspection). The likelihood of the noise sequence taking on such a characteristic will be dependent on the variance (ie *power*) of the noise signal. Clearly the ADS^2 signal can tolerate significantly higher noise levels than conventional narrowband signals.

Pulse Detection in Multipath Channels

Figure 5 shows the matched filter response to a conventional pulse in a multipath channel. In this channel there are two propagation paths, one with delay 2ms and one with delay 4 ms. This kind of scenario often arises in shallow water channels where the signal is reflected from the sea surface (or sea bed) and can also arise when hydrophones (or beacons) are deployed near large subsea structures which can act as reflectors.

The matched filter response (approximately) follows the ideal envelope until time 4 ms. This corresponds to the arrival time of the second propagation path and the resulting interference between the two arrivals causes distortion of the matched filter response. Clearly, the increase in TOA error due to multipath is significant (compare the error in Figure 5 with that of Figure 3 which used the same noise sequence).

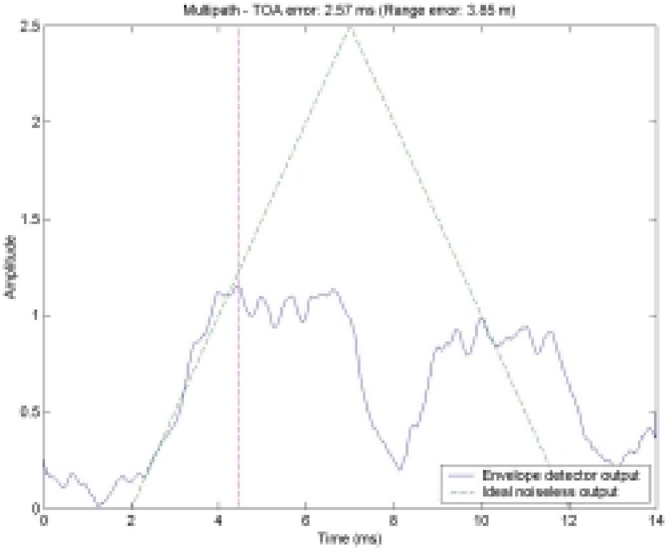


Figure 5: The effect of multipath on TOA estimation with conventional signals

Multipath Performance of ADS^2 Signals

Figure 6 shows the matched filter response to an ADS^2 pulse through the same channel used to generate Figure 5. Clearly the TOA estimate is unaffected by the presence of multiple propagation paths.

The two multipath arrivals are visible as two large peaks in the signal envelope. As far as the receiver is concerned, it would appear that two (nearly) identical pulses have been sent in rapid succession (overlapping in fact). The matched filter has produced a large peak for each of these “pulses”. As a result of pulse compression, the significant portion of the two responses does not overlap (ie there is no interference). This is in contrast to the narrowband case in which the two responses do overlap and suffer from interference.

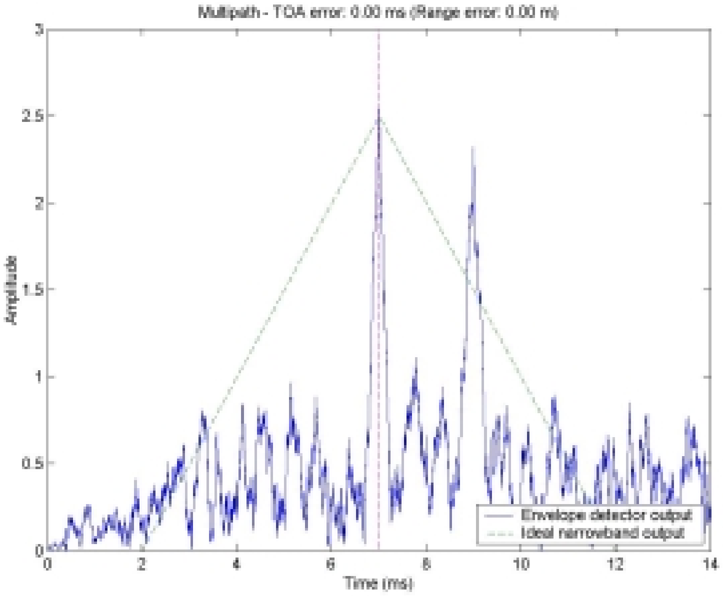


Figure 6: TOA estimation in a multipath channel using ADS^2 signals

BENEFITS of ADS^2

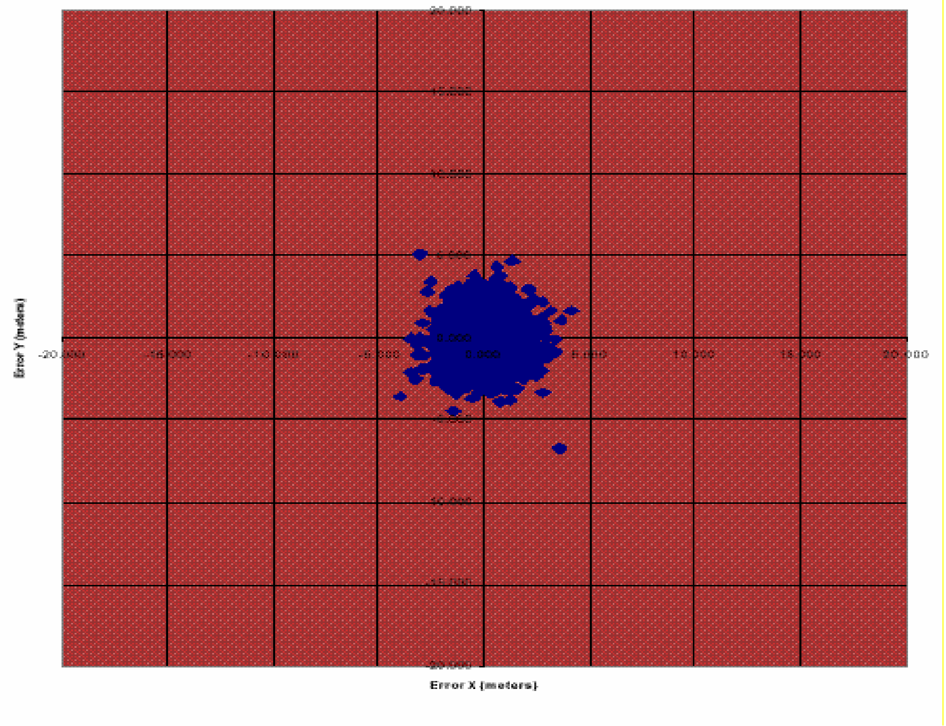
The introduction of Nautronix’ ADS^2 signalling technology has led to a number of key benefits for acoustic system users, including the following:

- ADS^2 allows a number of concurrent channels to co-exist in the same frequency band. This in turn allows Spectrum management to be significantly improved and simplified, with real and significant additions to operational capability and an ability to work with other systems in close proximity.
- High immunity to propagation multi-path, allowing improved reliability.
- Ability to operate reliably in high noise environments including high vessel noise and thrusters wash areas.
- Ability to operate reliably over long ranges using significantly lower transmission power, whilst maintaining high accuracy.
- Very secure and reliable signal channel, allowing critical control to be implemented.

The Benefits for DP

ADS^2 signalling provides significant benefit to DP operations, as detailed above, with the result that positioning accuracy, and most importantly integrity are improved enormously. Additionally ADS^2 signals can be 'stacked' in the water column, an important characteristic when operating in deep water. With existing signalling adjacent interrogations or signal returns will interfere with each other, and update rates in deep waters are therefore limited by the speed of sound. The stacking of ADS^2 signals means update rates to the DP system can be maintained almost irrespective of water depth or range. Since the same Signal to Noise Ratio at the hydrophone can be achieved with a significantly lower output power from the beacon, there is little if any penalty in beacon battery life. Faster updates allow the DP system to better estimate the vessel position, and to both settle, and react faster.

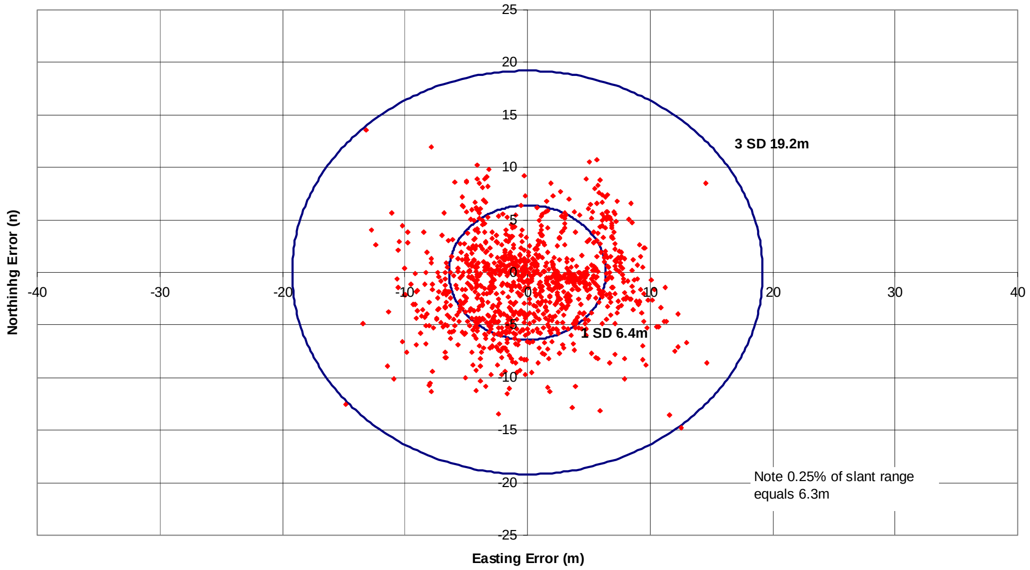
The data below shows a plot from the Nautronix RS925 (SBL/LBL) system using ADS^2 signalling from 2700m water depth on a deep water DP drillship, one of the noisiest environments for acoustics. The drillship was operating in full DP mode during data acquisition using 8 thrusters in a moderate sea state. Note the tight scatter plot and the 2.5m RMS accuracy.



ADS^2 signalling can perhaps provide most benefit for DP operations when available in a USBL format. This allows the system to be installed on most DP vessels as both a useful positioning system and a DP sensor. With many new builds being designed to support deep water operations and others being upgraded, the advantages of including a USBL system capable of working reliably and accurately in these depths is obvious.

Nautronix have designed 2 systems to meet this requirement, NASDrill USBL to suit the drilling market and NASPos USBL for the survey, ROV and construction markets. Both utilise a Hydrophone capable of installation through a 10" gate valve, allowing easy and cheap installation, and retrofit to most existing vessels.

The plot below was taken from a box in calibration of a NASPos USBL system installed on a DP cable lay vessel operating in 2500m water depth, The hydrophone was installed through a gate valve to a depth of 2m below the keel, and weather conditions were calm. As can be seen from the results, the data is stable and significantly more accurate than traditional systems can achieve.



Note 0.25% of slant range equals 6.3m

DP performance is significantly constrained by the quality of the reference sensor information available to it. As the demands on DP operations increase, so have the demands on sensor reliability and stability. Nautronix as a manufacturer of both DP and Acoustic systems recognised this limitation and developed ADS^{2}Acoustic systems to meet the growing needs of the industry.

The effect of the accuracy and integrity (stability) of the acoustic position demonstrated in the examples above for DP operations cannot be overemphasised. Effectively the 'noise' of the acoustic sensor has been reduced significantly. This allows the gain for that sensor within the DP system to be increased, effectively increasing its bandwidth and therefore the holding capability of the DP system. As well as reliability, the DP system efficiency is improved. Since the DP is 'quieter' it is more fuel efficient, and machinery wear is reduced. The Nautronix RS925 system is used as the primary sensor of preference on most of the vessels it is installed on for these reasons.

The accuracy and integrity of ADS^2 based acoustic systems are such that many customers now feel confident to undertake a number of operations using only RS925 and NASPos USBL, which would previously be done with LBL techniques. The result is obviously significantly reduced operational time and thus cost savings.

Two recent examples demonstrate the point. On a recent North Sea operation the customer elected to use a NASPos USBL system to position a towed unit during its transit from yard to installation location. The job was completed successfully, but most importantly with the NASPos USBL system installed on the towing tug, and operating through the tug wash. The customer commented that no other system they had tried could achieve this, and as a result they saved the use of an accompanying vessel just to operate the acoustic system from.

On another job off China, the NASPos USBL system was used to successfully track a towed fish at ranges out to 3500m, as a result of which the customer did not need to use a chase vessel stationed above the tow fish to carry out the acoustic positioning.

SUMMARY

Acoustic signalling technology has not changed much since it was first used for positioning. In that same period, significant advances have been made in underwater operations, in particular developments in ever deeper water. These developments require the use of high specification DP vessels which rely on high quality sensors to be able to perform. The vessels are also generally larger and more powerful, and thus a difficult environment for acoustic systems. Nautronix as a manufacturer of both DP and Acoustic systems have recognised these increasing demands, and the fact that they cannot be met by traditional acoustic signalling methods. Through an extensive development project they have successfully overcome the not insignificant hurdles associated with developing Acoustic Digital Spread Spectrum (ADS^2) signalling for positioning. The result is a suite of acoustic positioning products which are capable of providing significantly increased range, accuracy and noise immunity over existing systems.

The performance of DP systems is significantly constrained by the quality of the reference sensor information on which they rely. As DP operations move into deeper water, and the demands put on them increase, the requirement for reliable sensors also increases. DGPS has to some extent solved the problem for a surface position reference, but Subsea references are being stretched to their limits and often beyond them.

This paper has shown how ADS^2 technology, as implemented by Nautronix, addresses the problem of unreliable acoustic sensors. By explaining the limitations of existing acoustic signalling techniques, and the advantages gained by applying Nautronix unique ADS^{2}signalling, it has been shown how DP system performance has been enhanced by the use of ADS^{2}Acoustic sensors.

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