AN EVALUATION OF USBL AND SBL ACOUSTIC SYSTEMS AND THE OPTIMISATION OF METHODS OF CALIBRATION – PART 1

D R C Philip DipHS, FRICS *Philip & Associates Ltd, UK*

*Faith in man's capacity to learn from his mistakes (*experiences) gives hope of improvement.* * Author's comment.
Extract from Dorothy Rowe 'Depression the Way Out of Your Prison', Routledge & Kegan Paul, London and New York, 1983, pp 42.
The opinions expressed are solely those of the author

Abstract

The paper will first review the history and development of Ultra Short Baseline (USBL) and Short Baseline (SBL) systems and highlight the issues in current practice. A detailed evaluation of the various component parts of a complex 'hybrid' system will then be presented. This will highlight the significance and potential sources of error present in the various types of observations used to determine position and depth. A brief summary of the particular mathematics required to solve the 3-D solutions will be followed by a review of various geometrical options for data collection and their validity, strengths and weaknesses in determining the correct calibration corrections. Some problems, pitfalls and puzzling observed practices will be presented and discussed. This will be followed by an illustrative example of critical analysis of a USBL calibration data set. Final conclusions will be drawn and the potential developments for offshore positioning will be suggested.

1. Introduction

USBL Systems have been in use offshore for 25 years. See [1] for a historic summary of acoustic manufacturers' developments. The development of the first USBL was stimulated by a requirement to support diving vessel operations. These needed an additional independent localised method for dynamic positioning (DP) to ensure safe operations. At that time (1977), before the advent of DGPS, radio positioning systems were not capable of providing the necessary positional accuracy and precision needed for 24 hour diving operations in the North Sea's new fields. USBL generally provided a reliable local relative system that complemented other short-range high precision systems such as taut wire and Artemis.

The offshore surveying community seized upon the usefulness and effectiveness of relative acoustic positioning. Its use rapidly spread to a number of survey activities and applications most notably in the positioning of a variety of underwater sensors units relative to a survey vessel. These ranged from the towfish positioning of site and route survey vessels, through ROV positioning in assisting construction support activities and pipeline inspections, to contemporary deepwater tracking of AUVs or UUVs.

The advances in acoustic technology and the increasing exploration requirement for drilling in deeper water depths have stimulated further demand. The dynamic positioning of drilling rigs in deepwater has caused further advances in acoustic positioning especially in those tropical areas where DGPS performance is seriously degraded by the effects of ionospheric scintillation. It is worth noting that Long Basline USBL (LUSBL) and SBL acoustic performance is significantly better than DGPS as it is of higher precision and is a purer white noise system rather than the combination of coloured and white noise present in DGPS. Its main drawback is its slower update rate.

These diverse and different requirements and needs have created a variety of view points on what is being provided, how it should be used, who has responsibility for each of the parts of the system in use and when and how it should be calibrated. This paper will endeavour to show how this has sometimes led to a confused, and not entirely effective, approach to the understanding of the accuracy, reliability, repeatability and calibration of these acoustic systems and suggest how understanding could be improved and better more consistent performance provided.

2. USBL Principle Measurements and Sources of Error

It should be noted first that a basic USBL observation has no redundancy, is a dynamic process and has a complexity with its six linked observations (see Figure 1) that is not immediately obvious to the casual observer. Although USBL performance is still remarkably effective and extremely useful the user should never forget these caveats and look to other complementary and supplementary ways of enhancing and safeguarding performance and reliability. This is only possible with a proper and complete understanding of the principal measurements, the potential sources of error, and the best methods of controlling or reducing the significance of any likely error in the calibration and maintenance of a complex system.

The final processed acoustic positioning result involves making six separate real time measurements, which are linked in time, from three very different instrumentation packages whilst additionally having a good knowledge of the water column velocity profile, the medium in which the acoustic measurements have been made.

The three instrumentation packages are:

Acoustic Unit
- Through hull or over side pole mounted transducer(s)
- Topside unit for control and display
- Subsea unit(s) transponder or responder

Heading Reference Unit
- Gyrocompass(es) or LRG(s) or FOG(s) or RTK GPS

Vertical Reference Unit
- Pitch and Roll sensor unit(s)

The basic measurements themselves are one acoustic signal travel time (range), four angle measurements and one azimuth measurement. Poor performance or mishandling of any one of these contributing components will clearly degrade the final result. What has actually been measured and what has perhaps been over simplistically presented is partially responsible for some of the lack of awareness evident today. How many users are aware, study or even observe the raw acoustic angle measurement on any acoustic data string? How many acoustic systems even provide the actual raw observations in the data string?

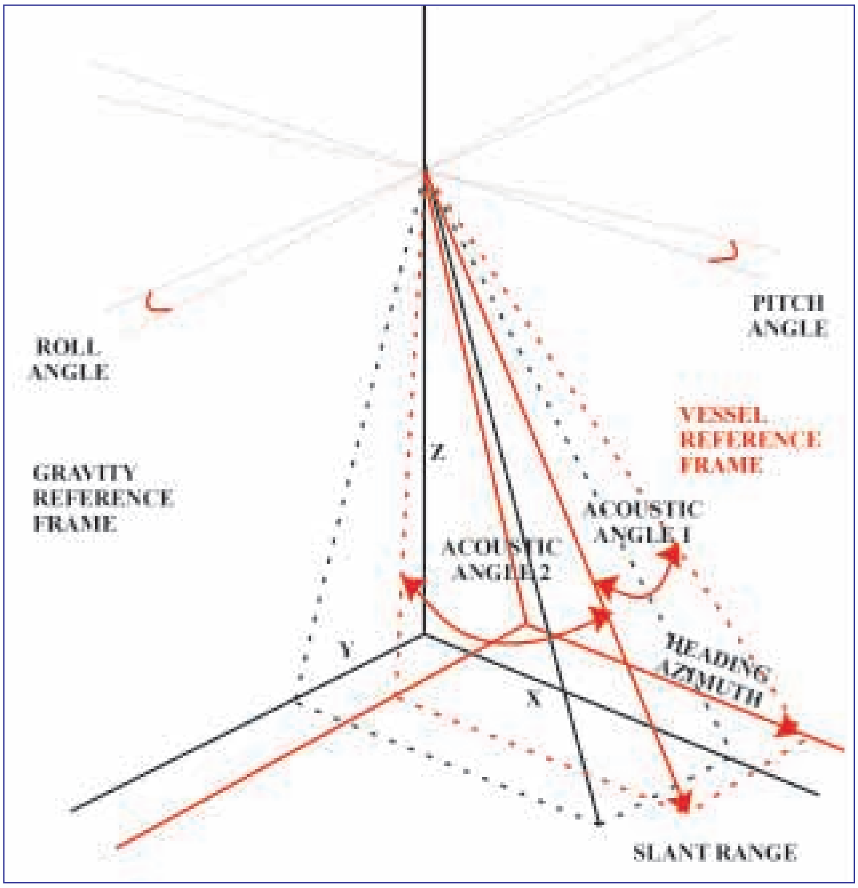

Figure 1: USBL measurements

USBL and SBL systems need to be considered as 'hybrid' systems that use a number of very different technologies. Although acoustics is a very vital component in the overall process, the associated supporting technologies are just as important and cannot be ignored.

The 'black box' engineering approach is potentially made worse today when the processed DGPS result is also linked together with the USBL data and what is finally presented may just be a processed 'acoustic position' in WGS84 or other selected datum.

	MEASURED	DISPLAYED	PRESENTED
DGPS Position	Lat/Long/Ht	$E1_{ship}$,$N1_{ship}$	
Travel Time (Range)	Time	$X_{relative}$	$E2_{transponder}$
Acoustic Inclination x Angle	Angle 1	$Y_{relative}$	$N2_{transponder}$
Acoustic Inclination y Angle	Angle 2	$Z_{relative}$	
Vessel Pitch Angle	Angle 3		
Vessel Roll Angle	Angle 4		
Vessel Heading Azimuth	Angle 5		
Acoustic Velocity Profile	m/s m		

Table 1

SBL systems can have up to 8 separate acoustic heads on larger DP deepwater drilling vessels. This increases both the lengths and numbers of baselines available and hence the redundancy of the acoustic observations. A trade-off of this benefit is the loss of accuracy in the longer baselines due to the possible effects of flexure in the poles and vessel itself. Seabed pinger units provide passive ranging by automatic transmissions on time but similar principles are involved in combining all the observations to provide the acoustic positioning solution.

2.1 Offsets and Alignment

Starting with the absolute basics of the overall system it should be appreciated that the various components of the overall system are often physically separated from each other and their relative relationships need to be accurately and precisely known.

The physical mounting, alignment and offsets of different elements of these units further complicate how the observations are combined. All offsets of all sensors must be accurately known in all three dimensions. Attempts to use USBL calibration routines themselves to determine offset measurements are a misguided sop to careless or incorrect installation. The use of general arrangement (GA) design drawings is also seen as an unreliable approach to a simple and straightforward need for accurate dimensional control. The differences between theoretical design and final as-built dimensions are often quite surprising. Once a good quality dimensional control survey has been completed it needs to be well documented and retained as a vital reference throughout the life of the vessel. Any and all subsequent changes need to be carefully managed and logged. One additional difficulty is actually defining the axes of a large vessel. Permanent reference marks should be installed to assist future installations and calibrations.

Given the choice of a cabin in the bow of a vessel or amidships near the centre of gravity everyone know which they would prefer to occupy and which would make life more comfortable. The same logic applies to the location of instrumentation packages. Ideally these should be mounted in a position on the vessel which keeps the motion dynamics the vessel may experience to a minimum. This is not always the case.

The physical mounting of the respective instrumentation packages also requires great care as each has a set of three axes which should be parallel to the each other and the axes of the vessel. Gross misalignments occasionally occur which can cause great confusion and waste much time. More often the misalignments are small but significant and just degrade the overall performance of the whole system. As will be seen later, the dynamic calibration routines determine a collective pitch, roll and horizontal alignment (yaw) correction rather than individual corrections for each instrumentation package. The greater the care taken in the installation and alignment of the various measuring systems the greater the likelihood of good overall system performance - see [2] and [3]. A static calibration is vital in validating the heading, pitch and roll alignments. Some units are additionally fitted with tilt sensors that are ideal in a static situation.

In terms of optimising and reducing the significance of offsets and the effects of long lever arms with separated systems it may also be worth considering the co-location of all sensors in the body of the transducer head itself. The significant reduction in size of the various electronic packages and their solid-state nature makes such a solution practically feasible today. This will also eliminate the problems of pole and vessel flexure. The attitude of the transducer head can then be directly observed at the time of the measurements.

Turning now to each individual measurement and its determination in a little more detail should enable a better understanding and appreciation of the many parts that combine to make the whole.

2.2 Travel Times (Acoustic Slant Ranges)

Firstly, the measured acoustic travel time has to be converted to a slant range. It is the ability to measure time very accurately today that is at the core of the significant advances in all electronic positioning technologies. Turn-around times in the internal electronics of the transducer and transponder/responder should be considered as being accurately known and compensated for by the equipment manufacturer. Quality system checks in the manufacturing should have ensured and documented this. In reviewing and analysing the calibration data there is an opportunity to check that no gross electronic errors are present. However attempts to determine small electronic delay errors in the calibration solution are unlikely to be valid as they will tend to be masked and the correlation with other larger sources of error means a valid solution is unlikely. This will be examined in more detail when reviewing the calibration geometry and identification of errors later in the paper.

A typical speed of sound in seawater is 1500m/s; by comparison the speed of light is 299,792,458m/s - some 200,000 times faster. This has advantages and disadvantages in the acoustic measurement processes. A timing precision in terms of a hundredth of a millisecond is quite satisfactory for a ranging acoustic measurement but totally unsuitable for GPS. On the other hand, the fact that 2 seconds has elapsed in the time taken to transmit and receive from a transponder in 1500 metres water depth means that the dynamics of the vessel and the prevailing sea state now play a significant part in the noisiness of what is being measured. There is also the major issue of timing synchronisation for all individual observations, which will need to be accurately time tagged. Subsequently the correct de-skewing of all observations is critical.

The travel time can be obtained from active acoustic ranging systems in two ways. It is usually achieved via the two-way travel time from the transducer to a transponder and back to the transducer. Alternatively, if the acoustic unit is connected directly to a responder by an umbilical link (eg. towfish/ROV), it is achieved by the one-way travel time from responder to transducer through the water column. No matter which method is used both rely on knowledge of the water column velocity profile. It is surprising to see that this vital requirement is sometimes neglected and a often very crude and rudimentary estimate may be relied upon.

Other indirect passive acoustic methods that use pingers (automatic transmission on time) need additional information (correct depth) to provide an estimated range. Their real advantage is their ability to measure time differences at regular short intervals, irrespective of depth. Advances in acoustic technology now enable even active ranging systems to make more regular measurements at shorter intervals by stacking transmissions in the water column, but the latency of the data remains the same in both cases even though the update rate has improved.

At its simplest, converting the measured time to range is a simple and straightforward relationship and as far as velocity is concerned any error is purely scalar. This is complicated by three factors. The first is the variation in velocity through the water column. The second is any diurnal and temporal variation caused by changes in the water body between day and night and the movement and physical changes of the water body caused by tidal streams or currents. The third is the vessel movement between the initial transmission and final reception of the acoustic signal. In deepwater the time that has elapsed becomes increasingly significant if the range accuracy is to be maintained.

$$\text{Slant range} = \frac{(\text{Total 2-way travel time} - \text{turn around delays}) \times (\text{Mean Velocity})}{2}$$

As a scalar quantity the mathematical derivation of mean velocity should be the *geometric mean*. However the *arithmetic mean* will be in reasonable agreement, provided the velocity sampling interval is sufficiently frequent, although the result will always be equal to or slightly greater the geometric mean. In early USBL acoustic systems only the mean velocity was entered as a single parameter. Later an additional option to enter a second velocity at the transducer head was added. Today the complete velocity profile can be entered into most modern systems and the full ray path can be used convert the time measurement to distance.

The transmission path will not be a direct straight line but depending on the variation in the velocity gradients may be subject to ray bending. The sound path will describe a series of curves related to the variations in the velocity gradient. In near vertical transmissions this will not be very significant purely in terms of range, but as will be seen later it is potentially of far greater significance for phase or angular measurements.

The accuracy of a typical good quality CDT probe today is very well documented in [4] where the accuracy of the respective sensors are quoted for depth (0.7dbar), temperature (0.01°C), and salinity (0.01ppt). When these values are combined they collectively provide a theoretical velocity accuracy of <0.05m/s. This is conservatively downgraded to ±0.25m/s in absolute terms due the empirical nature of the velocity equations used to compute sound velocity. It should be noted that these formulae have particular bounding limits based on a particular range of values. See [5] for a variety of formulae and their limits. In a water depth of 1000 metres this conservative velocity estimate is equivalent to ±0.17m or 0.017%. The use of a direct reading velocimeter may be considered a simpler and more direct method of measuring velocity. Their potential accuracies are also quoted as ±0.05m/s.

The other matter of real significance is the accuracy of the acoustic measurements of the received signal itself. It is refreshing and pleasing to see that in 1998 Kongsberg-Simrad had quantified the expected range accuracy for HIPAP with respect to received signal strength at the transducer [6]. The latest theoretical specification [7] details are:

HiPAP 500	**S/N (dB rel.1 micro Pa)**		
Single System	20dB	10dB	0dB
Range Accuracy (m)	0.10m	0.15m	0.20m
Receiver Beam	10 Degrees		
Coverage	±100 Degrees		

Table 2

It should be noted that this assessment is based on the following:

(i) Free line of sight between transducer and transponder
(ii) No influence from ray bending
(iii) Signal to noise ratio in water is in the 250Hz receiver band
(iv) No error from heading and pitch/roll sensors

The significance of signal to noise and measurement accuracy and precision needs to be understood and appreciated by all users. It should be provided for all acoustic instrumentation and acoustic measurements. The subject of signal to noise is not straightforward and is potentially confusing as there are a number of different ways it can be defined particularly with regard to the bandwidths used in the signal to noise ratio. There are three different bandwidths that are typically used. These are:

(i) With a noise bandwidth in a 1 hertz band – generally referred to as square root of hertz
(ii) With a noise bandwidth equal to the bandwidth of the received signal
(iii) With a noise bandwidth equal to some other wider bandwidth – usually the total receiver bandwidth of the system.

It is always important to compare like with like for an objective evaluation. The significance of signal to noise was identified as an important factor in satisfactory DP performance [8]. It was also clearly stated in [9] that '*the ratio of noise with respect to signal (the signal to noise ratio) is the single most important factor in determining the performance capability of an underwater acoustic system*'. A number of contributing factors need to be carefully considered in assessing both the signal and the noise.

Increasing the power used to create the acoustic transmission can increase the source level (SL) of the transponder. This will either require a very large battery pack or reduce the endurance. The other alternative is to focus the acoustic beam and limit the effective beamwidth to a narrow sector. The required operational envelope between transponder and vessel then needs to be carefully managed. The source level of any transponder and its beamwidth needs to be known and evaluated in any practical application.

For an array of transducer elements, with space diversity, performance can also be significantly improved by signal processing and effectively narrowing and steering the reception beam. This improves the signal strength by the directivity index (DI). It is also possible, by design, to desensitise a transducer in a particular sector by shielding such that performance is enhanced in the received signal direction but significantly reduced in the direction of dominant background noise sources such as that generated by vessel thrusters and propellers. The noise reduction index (NRI), as demonstrated by [10], for a signal directly below the transducer head indicates a significant improvement in the S/N ratio, potentially providing a significant increase in the ranging capability, when comparing Sonardyne's different transceiver heads. It is important to realise that noise is pervasive particularly in shallow water (<600 metres) and reverberation from the seafloor can spread the noise from other directions not just from the original source of the noise. The particular practical application of any system needs to carefully analysed taking due account of all factors. Particular systems may be better suited to particular situations.

The location of transducer heads can be critical in terms of performance as can the noisiness of vessels' propulsion systems. Azimuth thrusters are a very significant source of noise compared to tunnel thrusters. Any thrusters with variable pitch are also likely create a more serious amount of noise, as the reduced attack angle of the blades will effectively beat the water and create much aeration. Background noise levels on any vessel need to be monitored. In fact improved thrusters design, which reduced noise levels, would make a significant improvement to acoustic performance. Most acoustic instrumentation today provides the capability to continuously measure and monitor noise levels but it appears to be a facility rarely studied by many users despite its direct impact on the quality of the acoustic positioning.

It is not proposed to make any direct comparisons between systems merely to highlight some of the different factors that should be taken account in assessing likely performance of any system. This can be reasonably predicted if due account of all contributing factors is taken. See [9]. The sonar equation (below) can be used in determining whether there is sufficient signal present to provide measurements. Knowing the signal excess remaining, the resulting quality and precision of these measurements can be predictably well estimated.

$$SE = SL - TL - DT - N + PL + (DI + NRI)$$

where:

SE is the signal excess
SL is the actively emitted source level
TL is the transmission loss (combination of spreading loss and absorption loss) - this is the term with the greatest uncertainty, as it can't actually be measured
N is the ambient noise level, given, for example, by the Wenz curves, and practical experience with thrusters – of significance is the effect of reverberation – noise is pervasive and can be trapped in the water column depending on sea state and type of seabed - water depth is also of significance
DT is the detection threshold – detectable level above noise background, usually a fixed number around 12-DB
DI is the directivity index of the array
NRI is the noise reduction index
PL is the pulse length gain given by 10log10(pl), where pl is the length of the pulse in seconds

An interesting parallel to the problems of noise is given in [11]. This indicates the relative merits of two different approaches to dealing with noise. It is concluded that the combination approach of directional and processed omni-directional microphones provides the optimum solution for hearing. Whether such an approach would be possible in the design of an acoustic transceiver array for acoustics is well beyond the author's technical knowledge, but no doubt the potential for further advances in acoustics, in overcoming the problems and challenges of noise, still exists.

For that matter any electronic signal processing measurement would benefit from monitoring signal strength – this includes DGPS. Poor or fluctuating signals give unreliable and inaccurate measurements and should therefore be treated with great caution; see [12] for the effects of multipath. One of the simplest and most effective real-time quality indicators of any electronic measurement is signal strength. It therefore needs to be continuously monitored and potentially should be used as a weighting factor to continuously update estimates of observation standard errors in more effective least squares adjustment and Kalman filtering routines. A time-series of signal strength would indicate any abnormal observation very simply. It is a vital parameter that is largely ignored by the offshore surveying community.

This omission and weakness in approach may possibly be related to conservative surveying traditions, which originally used largely mechanical and optical measurements. The strength of a tape was not a consideration as such although care was taken in the tensions applied and its support. The advent of electronic and acoustic distance measuring has required a much more detailed evaluation and appreciation of the technologies involved and the actual electronic measurement techniques used in the timing and phase measurements.

2.3 Angle Measurements

The five angles are measured in three radically different ways, to varying accuracies, with different potential sources of error. The instrument packages are the acoustic unit, a pitch and roll sensor and a gyrocompass or heading reference. The vessel itself is the dynamically moving platform on which all the instrument packages are installed and from which the measurements are made.

2.3.1 Acoustic Unit

As the name implies USBL originally used a baseline of about 0.06m (HPR model) between pairs of transducer elements to measure phase differences in the incoming acoustic signal, such that the relative phase angle of the incoming signal was measured relative to the baseline between the two elements. If, as a minimum, a third transducer element is located orthogonal to the first baseline then the acoustic phase angle in a second plane can be determined. The relative directions between the transducer and the transponder are established. Both angles are measured with respect to the transducers reference frame which should be directly related to the axes of the vessel. Acoustic baselines in more modern transducer heads have increased a little but are still very short.

It should be self-evident that baseline length has a direct effect on the achievable angular accuracy. SBL systems have a significant advantage in this regard, particularly on larger vessels where the baseline length can be increased significantly in the fore and aft direction for ship shaped vessels and in both axes for semi-submersible vessels. As the use of acoustics has moved into deeper water the greater distance between transducer and transponder has increased the significance of angular error. As a result a greater accuracy has been required. What was a perfectly satisfactory angular accuracy in 100 metres water depth is much less satisfactory in 1000 or even 2000 metres water depth.

However it should also be appreciated that even the poles on which the transducer heads are deployed, well below the hull, have a flexibility that may cause movement. This may vary with the forces experienced on the pole caused either by the vessel speed through the water or the effects of thrusters wash. The length, strength and rigidity of the pole and the tolerance of its guidance system have a direct influence on the relative baseline constancy between separate heads. In the case of a single head, any flexion of the pole will effectively change the alignment of the head itself. Although these movements are small they are potentially of significance and degrade the angular accuracy. In addition it should be appreciated that large vessels themselves also flex significantly in the dynamic environment of the sea. Over time permanent distortion of the structure may occur.

Sonardyne's 'big head' transducer has effectively increased the reliability of the angular measurement by increasing the baseline lengths to approximately 0.15m. Additionally, five transducer receiving elements are used to measure four acoustic angles (phase differences) rather than using two pairs of orthogonal elements. The 'Qbsum' figure, generated by least squares from these redundant phase difference measurements, provides a measure of the deviation of the received signals from that which would be expected from a plane wave arriving at the face of the transceiver. The resulting output is provided as direction cosines of the incoming acoustic 'wave vector' in the reference frame of the acoustic array. This information is used to estimate the position quality and is available in the output data string.

Kongsberg-Simrad's latest acoustic system, HiPAP, has also radically changed the way the angles are now measured as the transducer head has about 240 separate elements spread over a larger spherical area, effectively increasing both the baseline length as well as the redundancy. It is able to sense the greatest signal amplitude from many transducer elements to determine direction more accurately. Potentially this is of great significance as acoustic angle measurements now have much greater redundancy and much improved precision and reliability. Details of these collective observations and their consistency are available, but not generally used by most users. The angular accuracy on axis is detailed in Table 3. Also provided, is the improved angular accuracy if dual heads are used. Although there is an improvement, it is not as significant as might be anticipated because of the limitations of pole and vessel flexion. Again the same caveats and bandwidth definitions as stated earlier for the ranging accuracy apply to these specifications.

HiPAP 500	**S/N (dB rel.1 micro Pa)**		
Single System	20dB	10dB	0dB
Angular Accuracy (°)	0.12°	0.18°	0.30°
Receiver Beam	10 Degrees		
Coverage	± 100 Degrees		

HiPAP 500	**S/N (dB rel.1 micro Pa)**		
Dual System	20dB	10dB	0dB
Angular Accuracy (°)	0.085°	0.13°	0.21°
Receiver Beam	10 Degrees		
Coverage	± 100 Degrees		

Table 3

An alternative description used by some acoustic systems for solely defining the random effects of angular inaccuracy in the acoustic phase measurements is to quote its effect in terms of 2-D positional accuracy as a percentage of slant range i.e. SD error (% Slant range). It is important to appreciate that this not in anyway related to the ranging accuracy itself. The advantage of this type of description is that it automatically takes care of the geometrical changes between transducer and transponder as the slant range slope angle changes. For near vertical acoustic angles this positional accuracy figure can be translated directly into angular accuracy on axis.

$$\text{Angular Accuracy } (°) = \sin^{-1} [(\text{SD Error as \% of Slant Range})/100]$$

e.g. SD Error = ±1.0 (% Slant Range) is equivalent to ±0.57° - conversely an angular accuracy of ±0.12° is equivalent to 0.21% of slant range.

It is indicated in [8] that testing of transceivers in a quiet test tank provides '*D_{rms} values of better than 0.1% of slant range, often as low as 0.03%*'. The detrimental effects of noise and backscatter are also graphically illustrated in a logarithmic plot of % slant range against signal/noise (dB) in band. The linear plot clearly confirms the direct relationship between D_{rms} values and signal to noise (dB) in band at the receiver. The angular accuracy will be equivalent for near vertical angles. The signal to noise ratio is more critical in its consequences for phase measurements.

The other significant factor, outside the user's control, that directly affects acoustic angular measurements is the velocity profile of the water column. The effect of ray bending was briefly mentioned earlier but no evaluation was shown. Its significance can be easily determined using Snell's Law, assuming a horizontally stratified water column. In essence as the sound wave passes from one layer with velocity v_1 to another layer with velocity v_2 it is refracted. The amount of refraction is related to the angle of incidence and velocity change:

$$(\sin \theta_1)/(\sin \theta_2) = (v_1)/(v_2)$$

A useful property of this relationship for multiple layers is that the ray coefficient 'a' is constant such that:

$$(\sin \theta_1)/(v_1) = (\sin \theta_2)/(v_2) = (\sin \theta_3)/(v_3) = (\sin \theta_4)/(v_4) = \dots\dots\dots = a$$

Normally the initial starting angle and initial velocity are used to trace the ray path for a variety of situations. It is then possible to plan and predict what will happen and identify any shadow zones and potential limitations of the acoustics. With USBL and SBL observations the ray tracing can be computed in reverse as the receive angles have been measured and the velocity profile from transducer to transponder is known. The true relative co-ordinates can then be computed with respect to the vessel reference frame.

The key question is that of the significance of ray bending. This is most easily demonstrated by taking some examples of typical velocity profiles and some theoretical angles. In the case of an area like the North Sea two simplified extremes of water column profile can be considered - one from late winter/early spring and a second from late summer/early autumn. In the former case the water column is well mixed by the winter storms with no thermocline and fairly constant temperatures and salinities. There will be a slight increase in velocity with depth. In the latter case a strong near surface thermocline has developed with the calmer weather and heating effect of the sun.

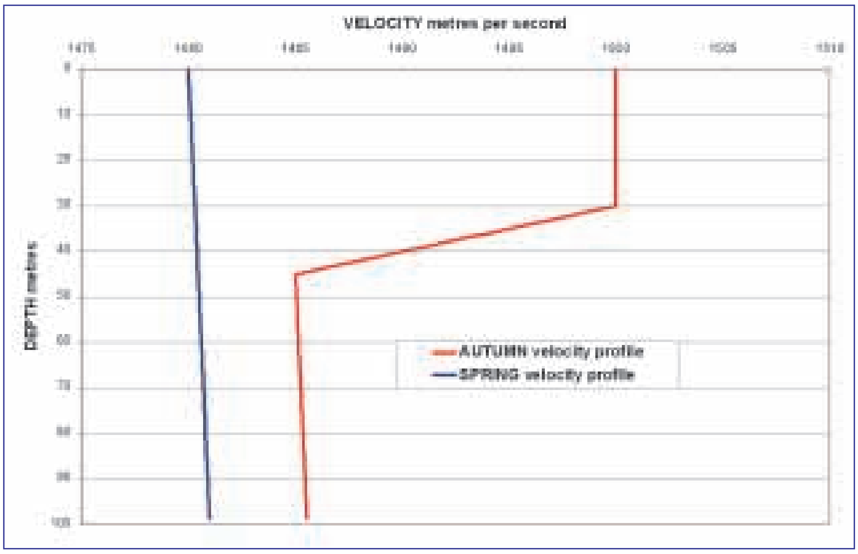

Figure 2: Seasonal changes in water column velocity profiles

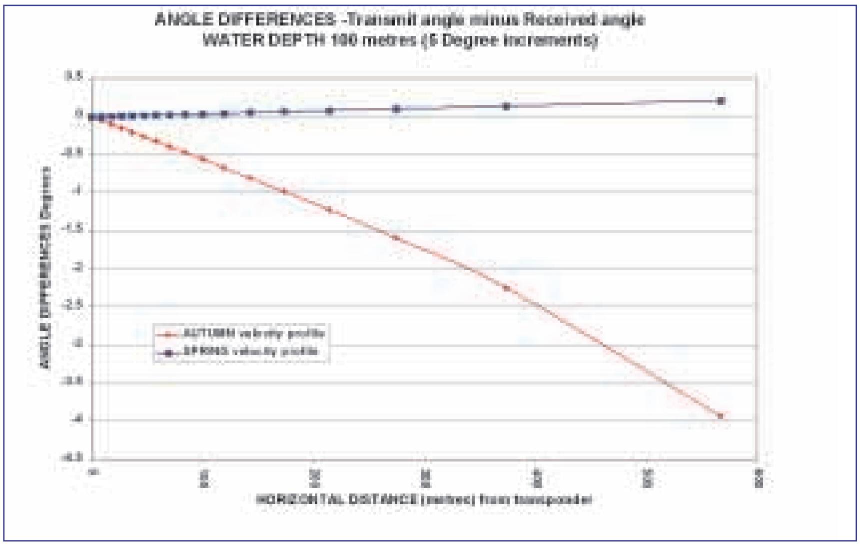

Figure 3: Ray bending effects

It is clear that ray bending is of increasing significance in order to maintain the accuracy of acoustic measurements particularly as the horizontal separation between transducer and transponder is increased. The presence of any thermocline will also have a significant effect.

2.3.2 Pitch and Roll Unit – Motion Sensor

Acoustic angle measurements alone would be of little value unless the attitude of the vessel was also known. It is by combining the two acoustic angles with the two vessel angles of pitch and roll, together with the vessel heading, that the true relative relationship between the vessel transducer and transponder is established. The principal method of measuring pitch and roll angles is by the use of accelerometers. There have been a number of very significant advances in the motion sensor technologies used to provide pitch and roll information. These have already been introduced to a number of other offshore surveying activities such as swathe bathymetry and, perhaps even more significantly, in inertial navigation, particularly in the development of the AUV positioning. It is surprising to see that there has been very little cross-fertilisation of ideas or experience or more open discussion on performance and effective calibration. The most significant contribution to the overall success of AUVs has been the positioning quality and control provided by inertial navigation combined with the Doppler velocity log - see [13] and [14]. This has created an ideal stable platform for gathering the best quality hydrographic and geophysical data.

At their simplest accelerometers measure acceleration by sensing the inertia force generated by a change in velocity with respect to their particular mounted reference frame. The measured acceleration will have three components: rotational acceleration, gravitational acceleration and linear acceleration. Thus as a minimum two accelerometers mounted orthogonally, together with knowledge of the local gravity, provide the vertical reference to which all such measurements are made. Today most motion sensor units actually have three orthogonal linear accelerometers together with three orthogonal angular rate sensors and collectively provide the additional outputs of heave, surge and sway. Currently these are not used in USBL systems but heave is used in swathe bathymetry systems. There appears to be no technical reason why this could not provide an additional input to the hybrid acoustic system and reduce the horizontal and vertical movement variation in the acoustic slant range measurements.

There are a great variety of ways acceleration can be measured to provide pitch and roll outputs. These range from something a simple as a tilt sensor, which can only be used when stationary, to open- or closed-loop systems using in principle a suspended mass. The open-loop systems measure the actual induced movement caused by the change in velocity. Closed-loop systems measure the changing force needed to maintain the mass stationary and provide better linearity. This paper will not endeavour to go into any specific detail but would suggest the following references as providing very worth-while additional reading [14], [15], [16], and [17].

Whatever type of pitch and roll sensor is used, its performance in the dynamic environment of the vessel needs to be known and understood. As technology has advanced and costs have reduced it is likely that a variety of different instrumentation packages will be encountered offshore. For effective use their acceptability for a particular task and situation may need to be re-evaluated. The resolution of each unit in terms of the minimum anticipated acceleration that can be measured needs to be known, together with the linearity of its performance and its susceptibility to bias from temperature changes.

Errors are present in all systems and inertial systems certainly involve a very different concept that is probably not yet fully understood or appreciated by many in the offshore surveying industry. The effectiveness of any accelerometer and the outputs produced by complex software integration are dependent on knowing both the true heading of the sensor and local gravity. The latter varies and cannot be neglected - see [18] - if the best accuracy is to be achieved. The performance of pitch and roll sensors can be significantly improved if additional aiding is provided in terms of good quality of speed and heading information. Failure to provide such information will degrade the output attitude information during and immediately after a turn. [19]

Accelerometers also suffer from the effects of noise and drift that introduce 'random walk' and bias in their outputs. It should be appreciated that their quoted accuracies are generally RMS values of total error. The note of caution stated in [15] -'*many of these instrument errors vary each time you switch the system on – INS have good days and bad days*' - needs to be heeded. Effective calibration requires quite specific manoeuvres and states of the vessel. This requirement is clearly backed up in [13] when reporting on Doppler inertial navigation in an AUV and indicating that '*a special mission has been designed to provide optimal observability of the error states and thus calibrate the navigation system*'. The ability to observe and determine errors is the key to the effectiveness of any calibration. A static vessel has no significant motion noise and any biases are almost constant.

Ideally then, the very first part of any USBL calibration should start before the vessel even sails with the vessel tied up alongside and stationary - see [2]. Whilst alongside calibrations of vessel heading reference systems, such as gyrocompasses, are sometimes carried out, the calibration of pitch and roll sensors are much more rarely carried out. The latter calibration has been recognised, by those using swathe bathymetry systems, as vitally important in terms of the final quality of their seafloor mapping. They even take the time to reverse the ship's head to balance their calibration observations. On occasions the vessel can also be deliberately listed, using the ballasting systems, to induce some variation in both pitch and roll but with a stationary vessel. The same need and importance should also be realised for USBL and SBL systems and their pitch and roll sensors.

It should also be noted that roll accelerations are generally more violent than pitch accelerations particularly on larger vessels. In practical terms there is a need to reduce the vessel motion to a minimum in any calibration method. This generally also has the additional advantage of minimising the power required to hold station and should reduce the acoustic noise around the transducer head.

The frequency and need to carry out any calibration routine relates to the overall status of the instrumentation. The first calibration requirement will be when it is initially installed. Subsequent re-calibrations will be needed on a regular basis dependent on performance, location, circumstance and opportunity. The replacement of a particular unit clearly requires re-calibration. The documentation of all calibrations needs to be retained in a vessel database. The trends in calibration results may help to detect either a slow degradation in performance or a malfunction in a particular unit or even an incorrect calibration result.

DP vessels, depending on their class, may have additional redundant systems to prevent single point failures. Thus more than one vertical reference unit (VRU) will be present. It is therefore important to know which VRU is being used by the USBL or SBL system and if a full system calibration is being performed then all outputs should be monitored and analysed so that any offset between the different VRUs can be determined.

2.3.3 Heading Reference Unit

The traditional source of vessel heading information has been the gyrocompass. Its performance and limitations are generally well understood by the offshore survey community, but may be worth restating. These are for a typical marine gyrocompass:

Settling Accuracy = ±(0.5 °)*Second (Lat)
Dynamic Accuracy = ±(0.7°)*Second (Lat)
Repeatability = ±(0.3°)*Second (Lat)

It should be noted that as one moves away from the equator the performance of any mechanical gyrocompass degrades and by latitude 60° North or South is twice as poor as at the equator.

Gyrocompasses are mechanical devices which rotate at high speed and a gimballed gyro that can take at least 2-3 hours to settle on powering up. They also take time to re-stabilise particularly after completing a turn. Typically seismic specifications have stated that a steady run-in course should be maintained for about 20-30 minutes to allow a gyrocompass to settle correctly and remove any bias introduced by a large turn. The same requirement applies to swathe bathymetry systems which rely on a gyrocompass. Whilst perfectly adequate for general vessel navigation gyrocompasses do not really provide the most accurate and precise heading information and are liable to significant short-term variation particularly after turning. These effects are well demonstrated in [20] which indicates good dynamic performance in a steady straight trajectory ±0.16° but significant variation caused by the damping effect that is directly related to the rate of change of the heading with extremes of ±1.0°. A linear change in speed would also have a damping effect but not as significant as angular acceleration. By comparison, the standard against which the gyrocompass was being tested was a short baseline GPS system using double difference carrier phase processing. The estimated accuracy of the later was ±0.04°. Broadly similar results are also shown in [21] but with similar dynamic effects also seen on pitch and roll sensors.

An additional heading error is present in the traditional gyrocompass. This is caused by the gimbals of the unit. The error is small in calm conditions but with substantial pitch and roll the error becomes more significant. The errors are introduced as the heading measurement is made in the body axes (deck-plane) rather than in the horizontal plane. They are however theoretically predictable and, as shown in [22], when measured they agree with the theory. With pitch and roll information available they can therefore be corrected to maintain the accuracy of the gyrocompass.

A typical marine gyrocompass also relies on a speed and latitude switch setting which may need to be changed and updated depending on the vessel activity and location. On some modern units there is the option to provide real-time updates of position and speed directly from a GPS receiver to the gyrocompass. Any failure to update the switch settings will introduce errors in their heading outputs. The other consideration that should be borne in mind is the manoeuvres the vessel may make when carrying out a calibration. A vessel spinning directly above a transponder will have degraded the heading information significantly when using a traditional mechanical gyrocompass. Ideally calibration manoeuvres need to take account of the movements of the vessel and cannot be ignored if a valid and true result is to be obtained.

As indicated earlier, other alternative heading references are now also available and their superior performance would indicate that the heading reference unit (HRU) might need to be updated if sources of error are to be significantly reduced. The capabilities of very short baseline GPS, and a number of commercial units now available which can provide heading information that is an order of magnitude better than a traditional gyrocompass, have been touched upon. Significant advances in heading technology have also been provided by the Fibre Optic Gyro (FOG) and the Ring Laser Gyro (RLG). Both rely on the Sagnac effect. The speed of light travelling in opposite directions around a loop will be differently affected by any rotational change in the loop. The RLG works by comparing the frequency of the two signals and the rotation can be determined. In order to overcome the physical imperfections (back-scatter) of the mirrors reflecting the light, a small oscillating dither is applied to the unit that enables even very small rotations to be detected. The FOG is a later development that uses interferometric measurement of coherent light injected in opposite directions around a fibre optic coil. Both these systems are a cheaper and an order of magnitude more accurate than the traditional gyrocompass but suffer from a larger scale factor error in their angular measurements. There is presently some conservative resistance to the adoption of these units as the navigational equivalent to a gyrocompass on marine vessels but this will eventually pass. In fact it has been demonstrated [23] that a combination of three FOGs and three quartz accelerometers was adequately able to satisfy the ISO 8728 tests applied to the OCTANS gyrocompass.

Sadly some other marine traditions have lapsed. The over-reliance on GPS and diminishing need to use the gyrocompass and speed log for dead reckoning have reduced the importance of the gyrocompass for basic navigation. The regular habit of gyro checks using sun azimuths by sextant angle or pelorus has become a distant memory on a significant number of vessels. Whilst the errors are not large they are often significant - typically of the order of 1-3°. The provision of multiple gyrocompasses on some vessels has also created an over confidence in their reliability. Whilst their collective agreement could be an indicator on their correctness, it could just as significantly be that they are all in error by a similar amount. The absolute validity of the heading outputs needs to be independently checked on a regular basis, particularly where they provide the supporting absolute azimuth measurements for USBL or SBL systems.

Again it should be appreciated that DP vessels, depending on their class, have additional redundant systems to prevent single point failures. Thus more than one HRU may be present. It is therefore important to know which HRU is being used and if a full system calibration is being performed then all outputs should be monitored. In some instances a blended result from all HRUs can also be used – again reinforcing the requirement to calibrate all units. Any change necessitated by failure or poor performance of a particular unit should be seamless.

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