AN EVALUATION OF USBL AND SBL ACOUSTIC SYSTEMS AND THE OPTIMISATION OF METHODS OF CALIBRATION – PART 2

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

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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.

3. 3-D Computations – Local and Global Reference Frames

USBL or SBL observations are a three dimensional vector in the vessel co-ordinate system. This can create some initial difficulties as traditional perceptions usually result in a simplification of what is seen - considering positioning data in two (horizontal) dimensions and height or depth, quite separately, in a third dimension. The latter is often given much less importance and is mistakenly seen as less critical. However with the possible exception of levelling, all survey observations are three-dimensional (including GPS) and need to be treated carefully as such at all times. As will be seen later, in the analysis of the calibration geometry, it is the derived Z value that is critical in correctly determining pitch and roll corrections.

Most acoustic manufacturers initially process the raw observed acoustic data converting the observed slant range (R) and acoustic inclination angles (θ_X, ϕ_Y) and producing preliminary X_1, Y_1 and Z_1 co-ordinates of the transponder in the vessel reference frame co-ordinate system relative to the transducer head. See Figure 4.

$$X_1 = R*\sin\theta_x$$
$$Y_1 = R*\sin\phi_y$$
$$Z_1 = R*(1 - \sin^2\theta_x - \sin^2\theta_y)^{1/2}$$

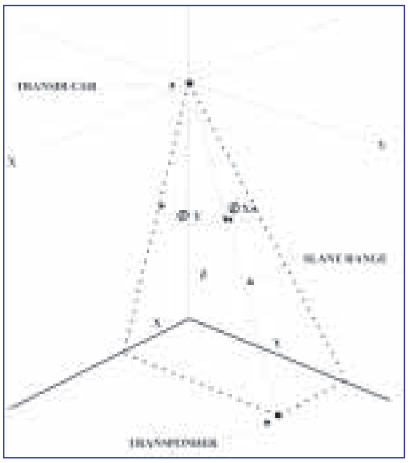

Figure 4: Acoustic Measurement

These preliminary local co-ordinates are then corrected for any known misalignments in the manufacture and installation of transducer head itself in its three principal axes with respect to the vessel reference frame. This may be carried out effectively as a sequential 3-step process. It should be noted that the order of applying the rotation angles of roll misalignment(ϕ_{ax}), pitch misalignment (θ_{ay}) and heading misalignment (ψ_{a2}) is vitally important. In any rotational computation using Euler angles a strict convention must be followed. According to Euler's rotation theorem, any rotation may be described using three angles. If the rotations are written in terms of rotation matrices B, C and D, then a general rotation A can be written as [A]=[B].[C].[D]. The three particular angles giving the three rotation matrices are called Euler angles. There are a great many conventions for Euler angles, depending on the configuration of the axes about which the rotations are carried out and the order the individual rotations are applied. Any convention used is arbitrary but once decided must be consistently followed at all times. The mathematical reason for this is that rotations about different axes do not commute.

$$[B].[C] \neq [C].[B]$$

The situation is further complicated if a tracking transducer has been used (i.e. a transducer head that has been physically turned relative to vessel heading), in effect providing an additional angle measurement. In this case this potentially large rotation correction is generally applied first. The end result of either the 3 ('zyx' convention fixed transducer) or 4 ('zyxz' convention tracking transducer) step process is a provisional corrected set of co-ordinates of the transponder in the local vessel reference frame with respect to the transducer head X_2, Y_2, Z_2.

It should be noted that the 'convention' descriptions used above have specified the axis about which each rotation is applied and the order. For example, when applying a roll rotation it could, by definition, be about the x-axis and will change the Y and Z co-ordinates but leave the X co-ordinate unchanged. In a sense any convention is arbitrary and one person's X is not necessarily the same as another person's. A common theme to many offshore applications is the alternative use of the terms forward, starboard and down. These are unambiguous and not clearly understood. However once computations begin people will revert to their own X, Y, and Z conventions. It is important that these are stated.

Due to the dynamic movements of the vessel such as pitch, roll and yaw, local co-ordinates will fluctuate wildly depending on the sea conditions and the induced vessel movement. It is therefore necessary to correct for the actual attitude of the vessel by applying the observed pitch and roll (ϕ_X, ϕ_Y) at the time of the received signal and further corrections are applied computationally, theoretically returning the vessel to a level plane and producing revised local co-ordinates of the transponder X_3, Y_3, Z_3. Again if Euler angle rotations are applied the same convention must be followed once more. In many instances it may also be necessary to change the local co-ordinate origin from the transducer head to the defined vessel reference point such as the centre of gravity. The 3-D offsets of the transducer from the vessel reference point will also need to have the attitude of the vessel applied to them - again following the same Euler angle convention. The derived ΔX, ΔY and ΔZ values are then added to the revised local co-ordinates. What is finally produced and displayed is now a local set of coordinates X_4, Y_4 and Z_4 of the transponder with respect to a specified vessel reference origin of a vessel that is level.

Although Euler convention still applies in traditional geodetic computations in some cases, owing to the very small rotation angles, combining of three rotation matrices can be simplified because the cosines of small angles tend to unity and the sine of very small angles tends to the angle itself. In these circumstances the application of three rotation matrices does commute - see Bomford [24]. USBL angles are not small and therefore require full rigour and care in their application.

The key significance of the Euler convention that must be employed in particular systems is the fact that the acoustic data string information has often been processed already. Effectively the particular manufacturer has previously defined and used a convention in translating the angles and distance observations into X, Y and Z coordinates. Any attempts at re-computation for calibration must follow precisely the same convention in reverse if the original raw observations are to be regenerated. This is not a detail about which there is much general awareness within the surveying community and yet it is vital if computations using Euler angles are to be carried out rigorously and correctly. The key is the sequence in which the rotation matrices are applied. The sequence described above requires great care in its application as some of the angles are comparatively small and any mistake in the sign or sequence will affect the validity of the result but may not be immediately apparent. It is worth noting that when researching the use of Euler angles a rather appropriate webpage was found entitled '*Euler angles are evil*'. It is probably a very fair description. Certainly it is difficult to keep track of multiple rotations.

An alternative computational method that could be considered more appropriate is the use of Euler parameters. These are quaternions. What you may ask is a quaternion? They are a further development of complex numbers which enable attitude computations to be carried out in a mathematically more elegant and straightforward manner. By concatenating a sequence of rotations the transformation from one reference frame to another is achieved in one operation. This has the advantage over sequential matrix rotation operations of requiring fewer operations and therefore saving computing time and perhaps more significantly facilitating computational accuracy. Quaternions are widely used in inertial navigation computations because of their integration properties. The derivative of a quaternion is a linear differential equation. A quaternion representing the combined rotation from a real-world reference frame to a local vessel reference frame is a differential equation that is linear in the Euler parameters. By comparison the corresponding equation using Euler angles is highly non-linear - see [16]. It is perhaps time that the offshore surveying community appreciated the significance of quaternions, particularly where complex rotations are involved. Their major limitation is that they have no physical interpretation but they do have redundancy thus providing a check on any computations performed.

Having looked at the specific conventions followed by some prominent acoustic system manufacturers it is evident that there are some differences that may cause some confusion. It should also be appreciated that motion sensor outputs may also have their own conventions. It is vitally important that these are all clearly understood and consistent. An example of axis definition and rotation convention is shown in Figure 5.

Kongsberg-Simrad has changed its convention during the 25 years in which it has manufactured acoustic systems. In the original HPR systems (1977 onwards) the first convention was a left-handed co-ordinate system (X starboard, Y forward and Z down). This changed in May 1998, with the introduction of APOS software, to a right-handed system (FORWARD x, STARBOARD y, DOWN z). Definitions of pitch and roll have remained unchanged and positive roll was and is starboard side down and positive pitch was and is bow up. Newer systems using the APOS convention can still generate the older type of telegram (data string).

Sonardyne use a right-handed system but with FORWARD y, STARBOARD x, UP z. The processing sequence of the vessel attitude of pitch and roll rotations uses a proprietary method. Positive pitch is bows up and positive roll is starboard down.

Nautronix use a variety of definitions that are particular to specific systems. It is therefore important that the particular convention in use is clearly understood by any third party software. In their latest RS925 SBL/LBL the user interface defines co-ordinates in the vessel system as positive forward and positive starboard while the absolute system position is provided in Easting and Northing.

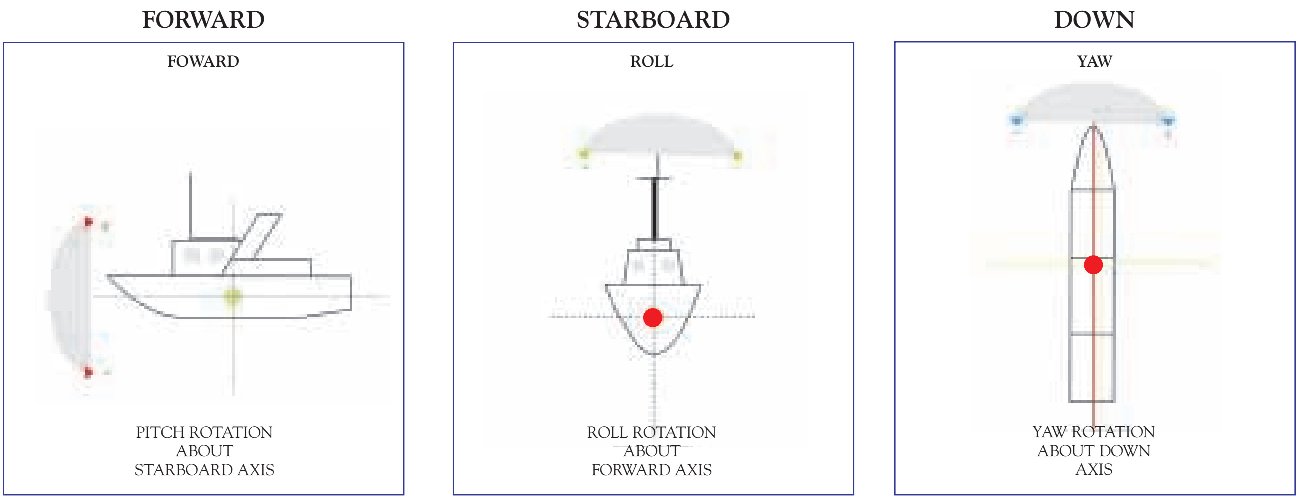

Figure 5: Pitch, roll and yaw rotation conventions

It is therefore absolutely essential that the equipment manufacturers are fully consulted on all individual units. Surveyors should not be too surprised at how often mistakes or misunderstandings can occur. Any exchange of such critical information requires absolute clarity. At the present time there is no standard convention used offshore, although there appears to be some progress towards a 'consensus approach'. An early type of motion sensor provided a logical and sensible concept that reflected its own measurement principles - see [25] - with its 'gravity vector' convention. Other motion sensor providers have adopted this convention to produce similar outputs. This provides a simple relationship between the gravity vector and Euler angles and there is no possible confusion in the rotation sequence. This is similar to the convention used for 3-D visualisation with the concept of the 'view vector'. In the case of the 'view vector' convention [26] *'all calculations are passed through quaternion intermediates to avoid numerical instabilities in using Euler angles directly'*. In the case of USBL calculations the angles used should never approach these numerical instabilities so that the use of quaternions could be avoided. It is suggested that an 'International Offshore Convention' which uses the 'gravity vector' and the 'acoustic wave vector' should be actively promoted and adopted by all providers and users of angular rotation data.

Even something as simple and straightforward as the Z rotation in geodetic datum transformation computations has created problems. There are two different but well-established survey conventions in common usage - namely Bomford and Bursa-Wolf. Applying a wrong sign in any calculation effectively doubles the error. Similarly 'convergence' in co-ordinate projection systems and the differences between grid and true bearings have probably caused more surveying mistakes than almost any other issue. This leads on to the need to relate the local co-ordinate reference frame to a global reference frame. The local reference frame is continuously moving as the vessel moves therefore there is a need to be able to relate one to the other. The changes in the relative relationship between transponder and transducer needs to be correctly related in an absolute sense for meaningful navigation and positioning. The common links are position, orientation and gravity.

A global reference frame is, by definition, fixed with respect to the axis of rotation of the earth and the approximate gravitational centre of the earth, its origin. The other two axes are by definition orthogonal with an arbitrary selection of a zero meridian plane enabling a set of unique space co-ordinates to be defined. This approach is not in common usage instead a mathematical shape, a spheroid, is defined to best fit the surface of the earth or a particular part of it and convert space co-ordinates to latitude, longitude and ellipsoid height. Even this mathematical description of angular co-ordinates and height can be difficult to use and visualise. As a result spheroids are mathematically projected onto to a flat plane and presented as Easting and Northing in metres. See Figure 6.

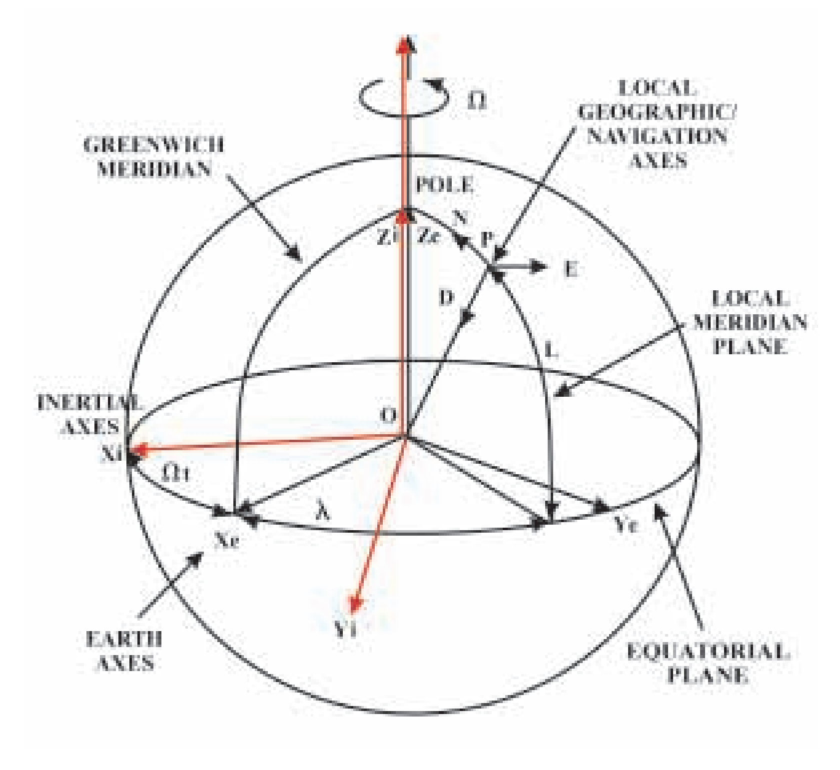

Figure 6: Global Reference Frame

In the process they become systematically distorted and the differences between grid azimuth and true azimuth are created, as are the differences between true and grid distances. It is not proposed to go into a detailed explanation but merely highlight the mathematical complexity and the need for clarity in defining the reference frame and datum and its associated spheroid and the type of projection and its typical defining parameters of central meridian, scale factor, false Easting, false Northing and latitude of origin.

The situation is further complicated by the fact that different people in different parts of the world use a number of different geodetic reference frames. Although DGPS and its associated datum, WGS84, are currently the standard satellite positioning system in use offshore it is often necessary to transform from this global reference frame to another geodetic reference frame. This should not affect calibration provided the correct parameters are entered but great care is required if global co-ordinates are needed on a particular datum. There is a common misconception that geographical co-ordinates alone are somehow unique in defining position. The fact that the same point can have a variety of geographical co-ordinates on different datums can and does cause much confusion. The apparent positional differences can be large.

USBL observation and calibration is a dynamic 3-D process which takes place on the sea surface; this is a changing surface, not just in terms of sea conditions, but also in response to the effects of tide. A fundamental flaw of the majority of USBL calibration software is that the effect of tide is totally ignored. In some areas where tide is negligible its omission is clearly not significant but if in an area like the North Sea, with a typical tidal range of between 1 and 4 metres, ignoring the rise and fall of the tide during the minimum 2-4 hours that the collection of calibration data takes, renders the derived pitch and roll corrections almost meaningless. For a valid calibration the tidal corrections must be applied to bring all observed data to a common level datum. The 3-D solution then becomes meaningful and of real value. It is slightly bizarre to see calibration software being used to compute pitch and roll corrections to five decimal places of a degree and yet making no attempt to apply tidal corrections. Whilst observed tidal information is not often readily available offshore, the ability to predict the rise and fall of the tide at different locations provides a much better estimate than doing nothing. If this is combined with some specific measures during the calibration procedure the tide can effectively be observed thus ensuring that the derived Z values are correctly reduced to a common level datum.

Realising the importance of the third dimension Z is one of the keys to obtaining a valid result. Understanding just how critical this parameter is to the solutions obtained is fundamental to the correct calibration methodology. Determining the best estimate of the true depth of the calibration transponder is as important as determining the best estimate of the correct position (grid or geographical co-ordinates). The primary requirement of a valid calibration is to determine the most accurate location of the calibration transponder in all three dimensions.

Calibration, by definition, requires a standard against which any errors or irregularities in the roll, pitch and yaw alignments in the vessel reference frame can be determined. A transponder is used as the fixed reference position on the seabed. In the dynamic offshore situation the surface positioning 'standard' for the vessel is usually DGPS. It is not proposed to go into any great detail about DGPS performance but it should be appreciated that this is not a perfect system and its performance can vary systematically with time and satellite geometry as coloured noise rather than white noise (random). However if used correctly and monitored carefully an absolute 2-D positional accuracy of ±0.75 metres can be achieved from averaged observations made over periods of time when combining DGPS and acoustics - see [27]. Instantaneous DGPS accuracy could typically range from ±1.5 metres to ±3.0 metres with a few occasional periods as poor as ±5.0 metres. One of the simplest ways of monitoring DGPS performance is to study the derived spheroidal height; poor height performance is usually a reliable indicator of degraded positional performance. With the quality of geoidal models currently available to define the separation of the geoid (MSL) from a particular spheroid it is good practice to ensure that the measured antenna height above sea level, after allowing for tidal variation from MSL, corresponds to the observed spheroidal height.

With the increasing availability of long range phase GPS there is a strong case for using a higher order and better quality GPS system to perform acoustic calibrations. The improved 3-D quality of the positioning will not only improve the 2-D calibration standard but also provide supporting height information that is sufficiently accurate to confirm the actual rise and fall of the tide. A number of GPS providers can now provide not only the standard DGPS service at the 1 metre level but also have enhanced systems which can provide positioning at the 1 decimetre level in all three dimensions - see [28] and [29]. The overall quality of a rigorous and complete calibration should remain valid for some time unless there are material changes to any components of the hybrid USBL or SBL system. The reliability of modern electronic equipment is such that frequent calibration should be unnecessary provided the overall quality and consistency of calibration results can be clearly demonstrated.

In theory if a dataset has provided local and global co-ordinates it is possible by use of an iterative process of non-linear least squares fitting to derive a solution which will converge to provide the overall misalignment of the local reference frame in terms of roll, pitch and yaw. However the validity of the solution depends on first observing sufficient good data, with sound geometry to allow a valid solution to be determined allowing for the noisiness of the data in a dynamic situation. Although we have only three unknowns in the rotation matrix there are nine correlated matrix elements. This is complicated further by the fact that the local reference frame co-ordinates are based on six separate observations of varying quality and potential sources of error. Other potential sources of error such as the sound velocity and any fixed (constant) error such as a turn around delay (index error) will further complicate the final solution. It is evident that a number of calibration software packages make no attempt to weight the individual observations and, as has been shown, there is considerable variation in the quality of the individual observations which combine to provide the acoustic position. If observations are not weighted correctly least squares does not provide the most probable answer, just an apparently pleasing mathematical result with minimised numbers, but the numbers have no real meaning in terms of accuracy, precision or reliability.

4. Calibration Geometry

In reviewing the overall performance of a hybrid system the strengths and weaknesses of all the different types of observation need to be evaluated and the actual method of calibration needs to ensure that all practical sources of error are clearly identified and determined. Due to the complexity and correlation of the observations it is necessary to simplify the process and procedure in such a way that some errors are either eliminated or reduced to a negligible effect while others are maximised. This should increase confidence in the correctness and validity of the solution. *The study of errors is as important as studying the observations themselves* [30].

Using the fixed seabed transponder as the reference point it may be worth first assigning some systematic errors to the vessel observations and noting the effects these will have on the FORWARD (x), STARBOARD (y) and DOWN (z) co-ordinates of the transponder with respect to the vessel reference frame. Suppose that initially a 1° pitch error is assigned in a 100 metre water depth and a transponder is approached with the unit directly ahead of the vessel before passing over it and then leaving it astern. Clearly this will have no effect on the STARBOARD (y) value assuming this is the beam axis across the vessel. Not unexpectedly the most significant variation is experienced in the DOWN (z) value which progressively increases as the separation distance increases, but with opposite sign depending on whether ahead or astern. Directly over the top of the transponder there is no significant error in the DOWN (z) value. What is perhaps not intuitively as obvious is the effect on the FORWARD (x) value. The error is significant and systematic but changes by a few centimetres with a typical error of 1.7m whether directly

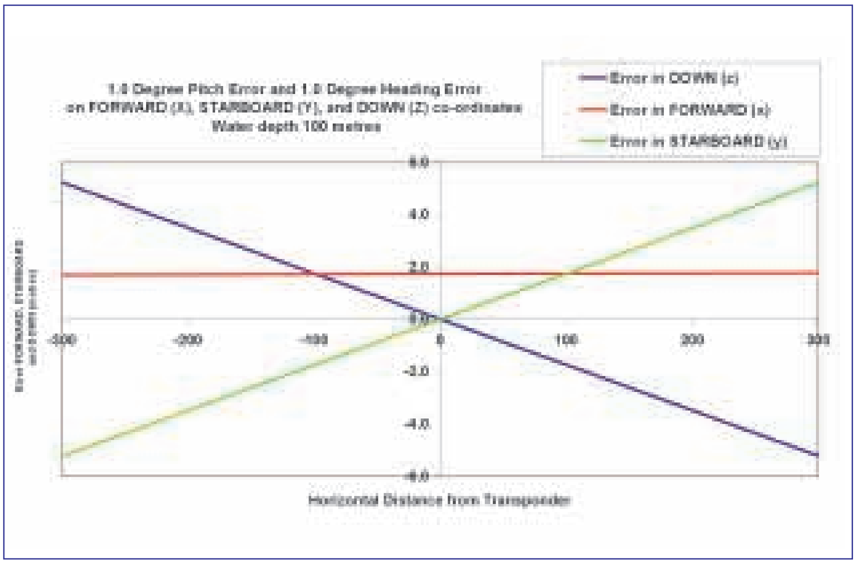

Figure 7

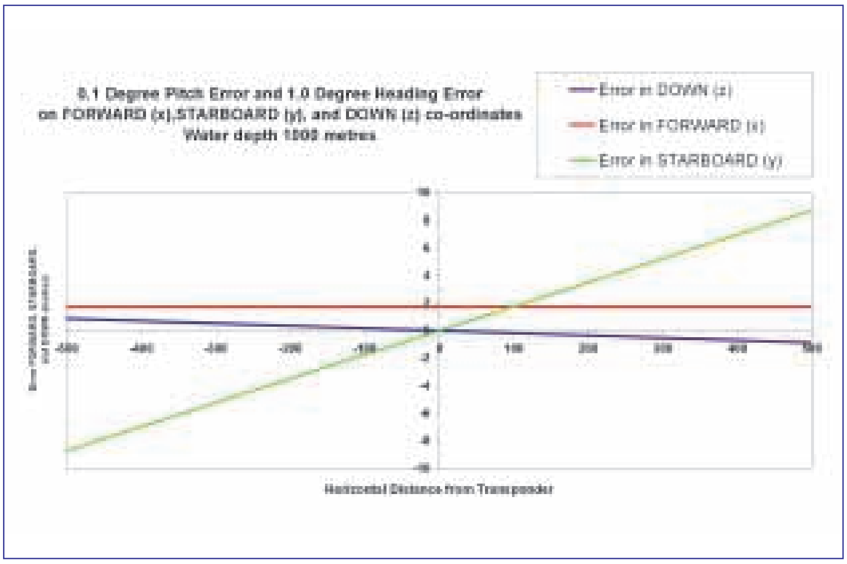

Figure 8

over the transponder or 300m ahead or astern. When considering the effect of a 1.0° heading error, a similar progressive change will be seen in the size of STARBOARD (y) error from ahead or astern but with a reversal of sign and no error when over the top of the transponder. See Figure 7.

If the same exercise is repeated in a 1000 metre water depth and the theoretical pitch error is reduced to 0.1° there is still a FORWARD (x) error of 1.7m - see Figure 8. Clearly if the same test was applied for a roll error with the vessel moving athwart ships of the transponder a similar effect will be seen on the STARBOARD (y) co-ordinate. This highlights the absolute criticality of both pitch and roll sensor in deeper water.

By the same token systematic errors in the acoustic inclination measurements will have a comparable, almost constant error in the FORWARD (x) and STARBOARD (y) co-ordinates. If the vessel heading is maintained there will be no apparent change in the transponder x and y position errors. The only indication of pitch, roll and acoustic inclination angle errors is in the DOWN (z) variation. If however the heading is reversed and the exercises are repeated equal but opposite errors in FORWARD (x) and STARBOARD (y) and DOWN (z) are created. This therefore provides a more powerful and complete solution and is the key to obtaining an effective calibration result.

It would appear to be attractive to spin the vessel directly above the transponder thus describing a circle representing the combination of the pitch and roll angle errors with the radius of the circle being the combined effect of the X and Y errors. Unfortunately spinning a vessel over a fixed point is not easy unless wind and sea conditions are very benign. In any sort of sea with a fresh wind blowing parts of the turn would be very fast and other parts very slow. The vessel thrusters would need to work quite hard on some headings and very little on others resulting in significant variation in the acoustic noise generated. The vessel motion will also vary significantly on different headings. Most critically varying angular acceleration in the spin will have a direct effect on the performance of a gyro and the pitch and roll sensors - see [21]. Thus additional errors will be introduced that are not really indicative of normal performance and therefore continuous spins are not suitable for calibration purposes. An alternative could be a series of step turns with waiting periods to allow all the motion sensors to settle. However this would make the operation much more protracted and the noise problem would still persist. Unfortunately an X and Y offset error between the global reference DGPS antenna and the vessel acoustic transducer reference will also create a similar effect. Identifying and separating the true causes of the error then becomes more problematic.

The significant factor in heading error is that even with a constant vessel heading the error changes with respect to absolute positional relationship of transducer to transponder. In both cases, above, it has no effect on the DOWN (z) value. Reversing the vessel heading does not change the effect of a horizontal alignment error. In the operational scenario of a water depth of 1000 metres for a towfish with a typical layback of three times water depth the resultant STARBOARD (y) error will be of the order of 52m. For an ROV with a horizontal offset from the transducer of 30 metres the STARBOARD (y) error is only 0.5m. The calibration method may need to take due account of how the particular system is to be used and focus more critically on particular parameters.

As a final review of the effects of particular individual errors, an error in the sound velocity and an index error are considered in the same two depth scenarios. As can be seen in Figures 9 and 10 the FORWARD (x) errors are zero when over the top of the transponder but progressively increase as the separation distance increases for velocity error. In the case of a fixed error (index error) the FORWARD (x) error rises quickly and then changes very little by the time the time the vessel is 1 times the water depth away. The DOWN (z) errors created by a fixed error are at a maximum directly over the top of a transponder and progressively reduce as the horizontal separation increases. A velocity error introduces a constant error to the DOWN (z) value regardless of the horizontal separation.

Just two simple scenarios have been considered. If the geometry is changed the effects of a combination of all the errors will become increasingly complex and correlated. For a valid solution is essential that the individual errors are correctly identified. Looking at all the components of a basic USBL observation the strengths and weaknesses of individual measurements are immediately obvious. As the distance between transponder and transducer increases the effect of the individual angular errors is magnified. The same cannot be said for the acoustic range measurement provided the velocity profile of the water column has been accurately determined - see Table 4.

		Standard Error	100m	1500m
Travel time (Slant range)		0.15m	0.15m	0.29m **
Acoustic velocity profile **		0.017%	0.02m	0.26m
Acoustic Angle θ_x	Depth	0.3°	0.52m	7.85m
Acoustic Angle θ_y	Depth	0.3°	0.52m	7.85m
Pitch angle	Depth	0.1°	0.17m	2.62m
Roll angle	Depth	0.1°	0.17m	2.62m
Heading azimuth (Horizontal Distance)		0.5°	0.87m	13.09m

Table 4

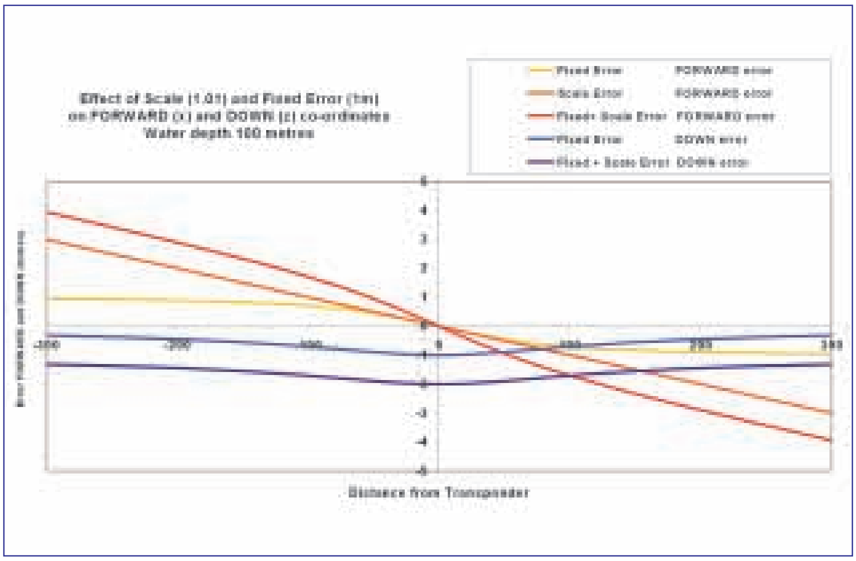

Figure 9

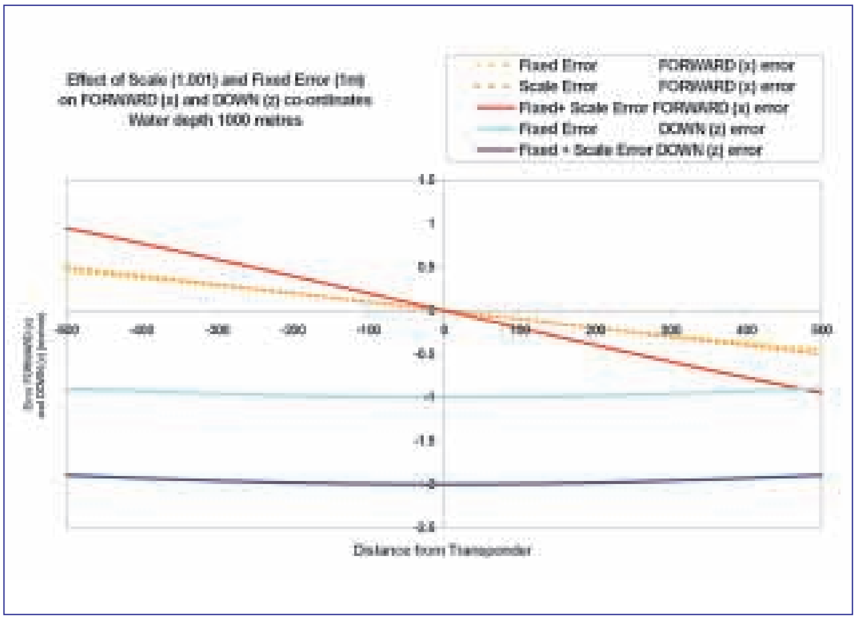

Figure 10

It is clearly not very meaningful to assume that all observation standard errors will collectively have an effect in all three dimensions. It is the relative relationship between the transponder and transducer that is critical to the propagation of errors. For an ROV operating close to a vessel the critical factor will be the depth; as depth increases the pitch and roll and vertical alignment become more crucial. For a towfish towed behind a vessel the increased layback will increase the significance of the vessel heading and horizontal alignment.

The acoustic slant range is clearly the most accurate and precise observation. It is surprising that, as indicated earlier, many users appear unaware of this and mistakenly assume that the local X, Y, and Z values that have been collectively provided by the USBL or SBL System are a real indicator of range accuracy. This misapprehension is sometimes unnecessarily reinforced by the overly simplistic description of USBL and SBL system accuracy as a percentage of slant range. This mistaken generalisation of a complicated set of observations is self-defeating and downgrades real understanding and appreciation of the inherent strengths and weaknesses of the USBL system. The percentage figure was explained earlier in Section 2.3.1. It is a very simple process to reconstitute the slant range from the output X, Y, Z values. This is uncontaminated by any angular errors.

$$R = (X^2 + Y^2 + Z^2)^{1/2}$$

As will be shown in the data analysis, these estimates of standard error can be proven to be realistic. The calibration method therefore needs to use this ranging strength as effectively as possible. The easiest approach is to box-in the transponder.

A basic concept in all survey observation schemes is to achieve geometrical balance in such a way that all gross and systematic errors will be identified either by the abnormal size of the residuals or the errors will cancel. These residuals should not exceed the anticipated standard error (3 sigma) of each observation. The worst thing that can be done is to use weak geometry and assume that the adjustment process and software will somehow redress the balance. It may appear at first sight slightly paradoxical but good geometry with less precise observations may actually provide a far better and more truthful result than precise observations with poor geometry. Multiple observations improve confidence in the observations and provide a good indication of the overall consistency of a particular set of observations. They should also enable outlier observations to be identified and rejected. However that precision needs to be geometrically tested further by other independent redundant observations.

The classic offshore method of determining an absolute seabed transponder position is by the box-in. By observing slant range measurements symmetrically around the transponder optimum geometry with very well balanced observations can be achieved. Potentially the most significant error in any ranging measurement is a velocity error. An index error due to an internal equipment delay could also manifest itself as a constant error. By balancing the observations the effect of both the velocity error and any fixed or constant error is nullified in the 2-D horizontal position determination. It is possible to use completely the wrong velocity and have a gross fixed error and still obtain the best estimate 2-D position provided the observations are geometrically balanced. The velocity error and fixed error would show themselves either as an error in the third dimension of depth, if this was allowed to float, or if a fixed depth was used, then the residuals would all exhibit a systematic trend and rather than being randomly distributed about zero all would have a similar non-zero value and magnitude.

Traditionally offshore practice has used a fixed transponder depth; if the residuals indicated a significant systematic error then a more pleasing result was obtained by arbitrarily changing either the velocity or the depth. This was a cosmetic practice that reduced the size of the residuals but made little or no difference to the transponder 2-D position. Fixed depth was used because it simplified the reduction of the slant range to horizontal range and a least squares solution in 2-D is slightly easier to program than a 3-D solution. By computing the box-in as a 3-D solution the position and depth is effectively determined directly by the box-in computation with minimised residuals which will indicate the true precision and consistency of the slant range observations. However the depth determination is not geometrically balanced. A significant difference between the computed depth and say the bathymetric depth after making due allowances for the length of the transponder strop, transponder itself and tide would indicate some doubt in either the bathymetric depth or the acoustic velocity, but make no difference to the horizontal position.

Since the true depth is required the observations must be geometrically tested by other means. This can be achieved by observing the slant range directly above the transponder. This will add nothing to the horizontal positioning accuracy but will clearly highlight any error in the acoustic velocity. The scalar effect of velocity error will affect the shortest ranges (from vertically above) by the least amount. Systematic differences in the residuals from above compared to the slant ranges from around the box-in circle would therefore be expected. The greater the horizontal separation between transponder and transducer the greater the residual differences will appear. Unfortunately the effect of an index error, a fixed error, is not resolved; an alternative method of determining the correct depth is therefore essential. To this end digi-quartz depth sensors fitted to transponders would be ideal. The use of strain gauge depth sensors, which are much less accurate, should be approached with great care and requires specific calibration for the actual depth of operation. In many cases bathymetric data is already available from an echo sounder or swathe system and it should be possible to have reasonable confidence in the determined independently true seabed depth.

In the traditional box-in the vessel circled the transponder continuously acoustically ranging to the transponder. As a result the heading of the vessel was also continuously changing. This had the added advantage that if an offset error existed between positioning antenna and positioning transducer it would be nullified by equal and opposite effects on opposite sides of the circle, although it would still be evident in the residuals. However, as indicated earlier, any form of turn is going to degrade some heading and attitude sensors. This has sometimes been countered by carrying out a second box-in in the reverse direction. Due to the presence of other errors a constant vessel heading is generally used in USBL calibrations. It is therefore important to provide the same geometrical balance by observing a second set of additional observations on a constant reciprocal heading. This may appear superfluous and wasteful but it does ensure that the solution is rigorous. There are also other advantages in using two constant reciprocal headings.

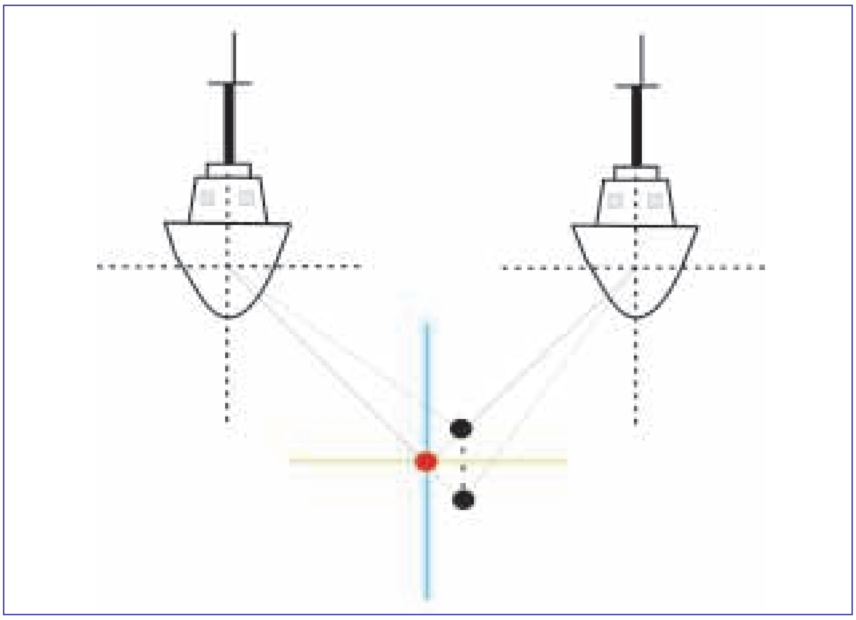

Figure 11: Roll error - similar error in the starboard direction, equal and opposite errors in down direction

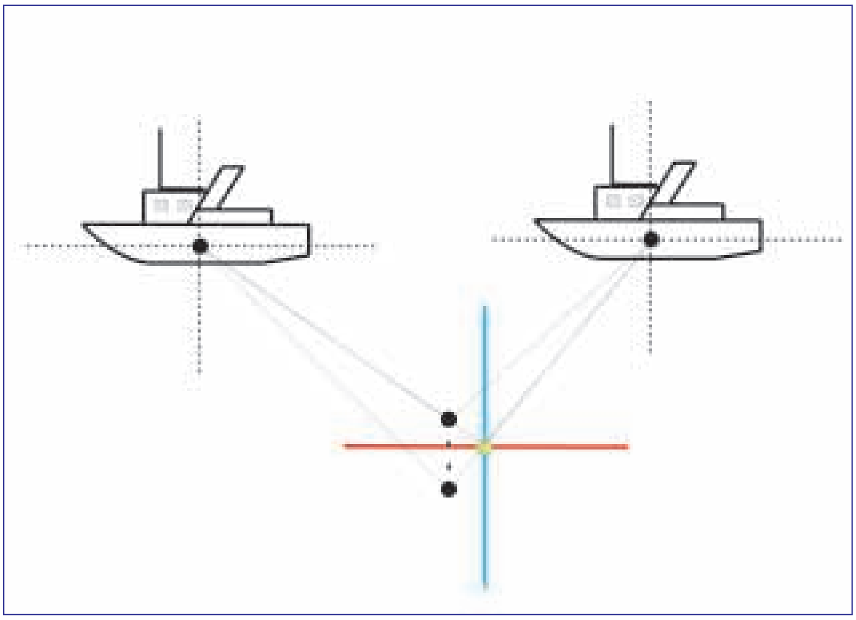

Figure 12: Pitch error - similar error in forward direction, equal and opposite errors in down direction

The basic concept of changing face on theodolite horizontal angle observations is a very well known land surveying practice which eliminates any alignment errors in both the transit axis of the telescope and the sighting axis if it is not truly orthogonal to the transit axis. Effectively equal and opposite errors are included in each angle measurement on each face. The mean of two observed angles on opposite faces thus effectively eliminates systematic alignment error. The difference between the two faces is twice the horizontal error. Acoustic calibration methods should try to mimic this. However rather than remain in one location the same effect is generated by moving the vessel systematically either side of the transponder and by reversing the ship's heading at the static cardinal collection points.

There is also a need to do the same in the vertical. In the case of the theodolite it is not possible to remove the effects of any misalignment in level merely by changing face if there is a significant height difference between sightings. However in the offshore calibration

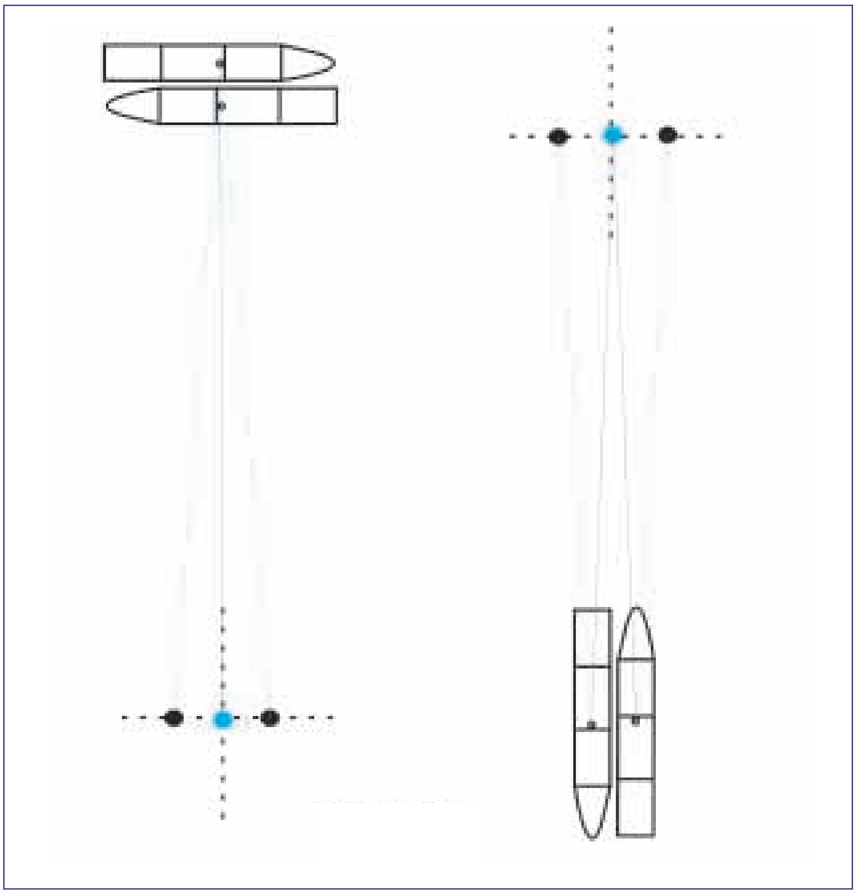

Figure 13: Equal and opposite forward and starboard errors with reversal of vessel heading at cardinal points

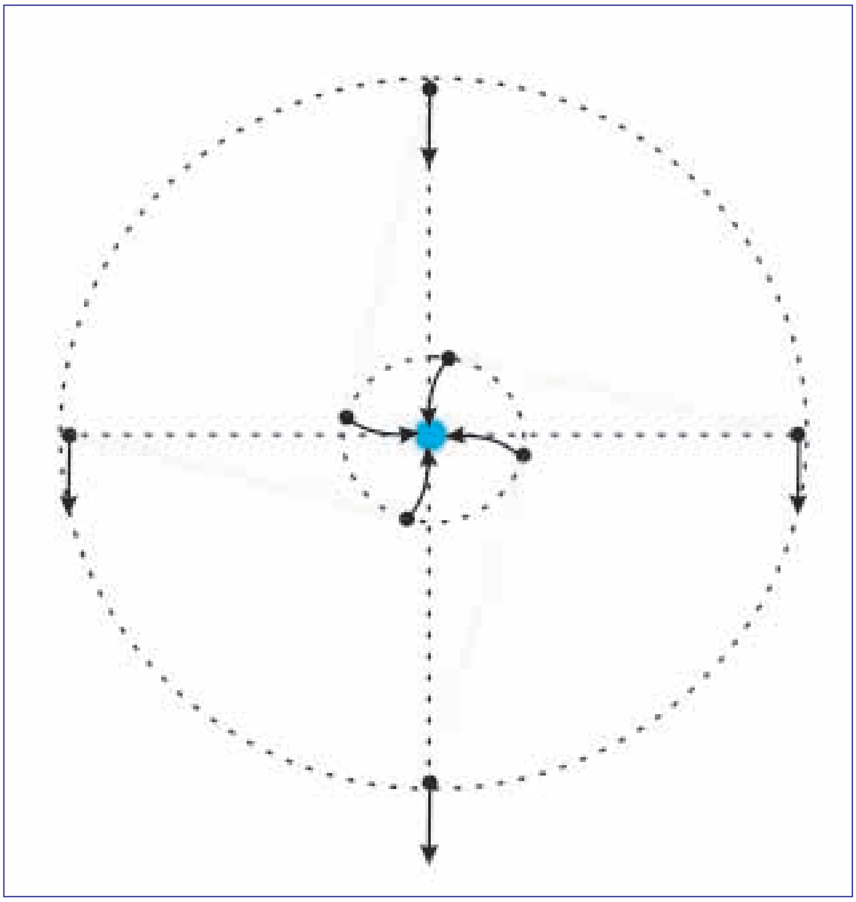

Figure 14: Yaw error

situation measurements are made to a fixed transponder and if the slope distance is maintained the vertical angles will be similar.

The combined effect of the misalignments and geometrical changes created by positioning the vessel at the cardinal point locations is demonstrated for roll in Figure 11 and for pitch in Figure 12 - the vessel headings are similar and the vessel is first port or starboard and secondly ahead and astern of the transponder. The roll error creates a similar error in the starboard direction but equal and opposite errors in down direction. The pitch error creates a similar error in forward direction and equal and opposite errors in down direction. When the vessel heading is reversed then an equal and opposite error will be seen in both the vessel axes - Figure 13.

In the case of horizontal misalignment the balance is achieved by the cardinal point locations where the vessel is located. Reversal of the ship's heading merely duplicates these observations and should confirm that there is no bias in the gyrocompass on different headings. The geometrical effect and the balance are illustrated in Figure 14.

Qualitative and quantative evaluation of the prevailing sea conditions and associated vessel movement also needs to be determined to provide a real measure of the likely quality of the calibration. Essentially the pitch, roll and heave of the vessel introduce significant noise to the observations. While these could be considered as random in nature over a short period of time, there is likely to be some variation over an extended period and on particular headings vessel motion characteristics may also vary. Clearly the greater the variation in motion and the greater the extent of the vessel motion the less the overall reliability of the calibration.

5. Review of Current and Alternative Calibration Solutions

The actual principles of USBL calibration have been somewhat confused by the various alternatives provided over the years. As a result a great variety of procedures have been developed and there is no common offshore standard or method. It is apparent that some are not particularly well thought out. In some the logic is weak because the geometry is poor and thus unlikely to provide consistent and reliable results. In others there are serious drawbacks which either degrade the performance of the instrumentation or create a very noisy environment and seriously degrade the quality of the data. It is recommended that some current practices and software are re-examined in light of all the issues raised earlier in the paper.

It is the accurate and precise determination of the calibration transponder position and depth together with a good quality data set that is critical to the validity and effectiveness of the calibration procedure.

The earliest attempts to define a calibration procedure suggested a two-part process. The first part involved locating the vessel directly above the transponder and conducting a 360° spin. This was intended primarily to highlight any gross error in the offsets of the antenna and transducer. There was sometimes some confusion about internal acoustic offsets related to different vessel reference points as opposed to the positioning antennae. Whilst this procedure was theoretically valid for shallow water where small pitch and roll errors would not introduce significant error this is not the case in deepwater where both offsets and pitch and roll errors have similar effects – separating the various error components from this data set alone is not possible. Assuming the data is reasonably quiet a plot of the transponder position will describe a circle. The radius of the circle represents the combined error. As noted earlier, the two major drawbacks are firstly the rotational acceleration which will degrade the gyrocompass and the pitch and roll instrumentation and secondly the noise generated in rotating a vessel which will probably significantly degrade the acoustic performance.

The second part involved maintaining a constant vessel heading and moving to four cardinal points where once stopped data was logged. Traditionally the ideal distance from each cardinal point to the transponder was typically somewhere between one and three times the water depth. Essentially this distance from the transponder was a variation on a traditional transponder box-in procedure. Historically acoustics were used in shallow water and many of the practices adopted are a relic of those early box-in procedures which relied on the accuracy and precision of acoustic ranging. Today the move to much deeper water has resulted in revised practices. By comparison the optimum distance is now quoted as half the water depth or 500 metres, whichever is the smaller. This reduces the amount of ray bending that might occur as the more vertical the path through the water column the less the bending. It also utilises the best part of the transducer beam with the greatest signal to noise ratio.

There have also been some advocates of the circular box-in as a method for calibrating a USBL system but this approach suffers from poor instrumentation dynamics and geo-metrical weakness in solving the pitch error. There are few survey activities which actually require a vessel to go round in circles. Its main potential advantage is the speed of the operation but if it does not provide a good result it is a wasted effort.

Further variations and refinements have been suggested. The one that attracted much attention was the use of a 'triangle' method rather than cardinal points. The transponder is located at the centre of the triangle. The vessel was again required to maintain a constant heading but this time whilst continuously moving along the sides of the triangle around the transponder. The claimed advantage of this method was that the distribution of the data was better and that this would provide a more robust mathematical solution when solving for all possible errors. However this has never been mathematically proven; in fact a theoretical simulation carried out by Kongsberg–Simrad [31] demonstrates that this claim is unfounded. In addition it also requires a vessel with a particular DP capability. Again the most significant disadvantage is the acoustic noise generated by moving a vessel in such a manner while collecting data continuously. If the vessel could be stopped and station maintained using minimum power this would reduce the noise and the dynamics of the situation to a minimum.

An additional variation suggested for non-DP vessels is the 'figure of eight' in which the transponder is situated at the crossover of the eight. The northern circle is carried out clockwise and the southern circle anti-clockwise. The main disadvantage is the turning of the vessel, which introduces rotational accelerations and degrades the motion and heading sensors. A more useful refinement is to simplify the figure of eight into two triangles comprising 4 straight-line runs during which data is gathered - Figure 15.

The basic method that is advocated by most acoustic manufacturers, but with some variations, is the cardinal point scheme. Kongsberg-Simrad recommend that the vessel occupies the four primary cardinal points around the transponder on a fixed heading. A fifth observation location is situated directly over the transponder and at this location up to 4 fixed headings are observed. In total eight data sets are collected at these five points. Sonardyne also recommend the four cardinal points are occupied together with a fifth location over the top of the transponder using two fixed headings (reciprocal); this provides a total of 10 data sets.

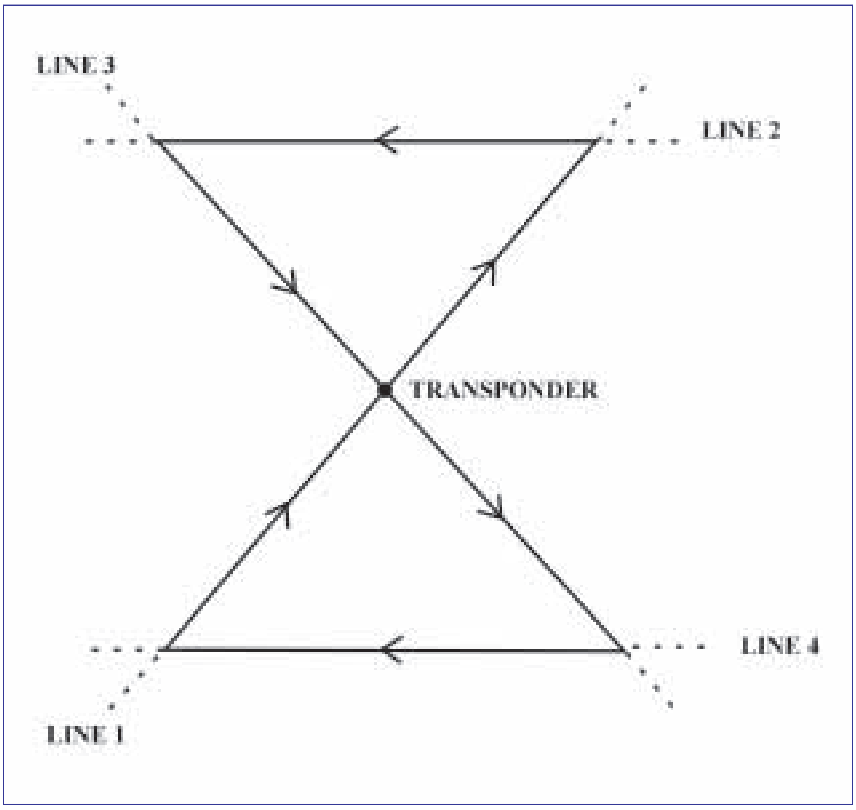

Figure 15: Four line figure of eight

An additional situation that should also be considered is that of the DP Drilling vessels which deploy an array of transponders or pingers. Once again the recommended best practice is to observe at four cardinal points and the central location. Again reciprocal headings should be observed at all five locations. An array that has intelligent transponders has the additional advantage that acoustic baselines can be measured directly on the seafloor. A grid-on-grid computation then allows the absolute position and orientation of the seabed transponders to be determined as well as determining the attitude alignment corrections.

6. Additional Aspects of Calibration

6.1 Relative or Absolute?

In the early days of USBL usage there was an attempt to suggest that they were essentially only relative positioning systems. As such it was suggested that they did not require absolute calibration. Indeed this set the precedent and resistance to taking the time to carry out effective and rigorous absolute calibrations. The 'relative argument' is only valid if the position and heading remain the same. On DP this may be the case for long periods but every now and then, and usually at a critical moment, it may be necessary to suddenly and quickly change heading or position. Any significant error in the absolute calibration will then start to degrade the positional change in a manner that will not be apparent to the casual observer and may well unexpectedly worsen an already critical situation.

A number of years ago this author witnessed a DP rig change its heading by 90 degrees simulating the effect of a sudden significant change in current direction and strength (eddy current). According to the acoustics the rig rotated about the well. However according to the GPS it had moved 30 metres out of position. When the calibration was re-observed a significant error was found in both the pitch and roll sensors. The GPS was right and the pitch and roll sensor were wrong and so therefore was the acoustic position.

Potentially a change in position of that magnitude could have resulted in the rig either changing its operational status (Amber Alert) and preparing to disconnect or even carrying out an emergency disconnect (Red Alert). There is clearly a significant safety advantage in having a correctly calibrated system. It could be argued by some that the time needed to carry out a proper calibration is an unnecessary expense and a waste of valuable rig time. However the consequences might be a lot more expensive. An effective risk assessment might help improve the understanding of those unfamiliar with positioning systems. Most people understand the need to service their cars at regular intervals. Hybrid complex USBL and SBL systems also need to be maintained. It is perhaps time that system calibrations became a documented part of the long-term planned maintenance routine of USBL and SBL systems on any DP vessel.

6.2 Computational Rigour

Much current software is not as rigorous and correct as it could be for any possible situation. Surveyors have long had a tradition of evaluating the significance of any particular factor or error source in a particular situation; if it is deemed to be insignificant then they congratulate themselves on saving time and effort by not taking it into account. In times when calculation required considerable effort and energy this was common sense and good discipline. Today when computers handle data tirelessly without making mistakes if programmed correctly, surveyors should be setting their sights even higher at being completely rigorous in all their basic computations. The danger is that circumstances change, the situation is not re-evaluated and the surveyor is caught out by inappropriate approximations and shortcuts. Everything should be computed rigorously and correctly and very precisely the first time round and the solution only rounded when presenting the final result for which the true precision and accuracy should also be stated.

6.3 Vessel Manoeuvrability and Characteristics

The type of vessel used will significantly affect the optimal calibration routine which should be applied. A vessel with a full DP capability will clearly be able to perform any set of specific movements reasonably easily if sea conditions, wind, tidal streams and current allow. However for a single screw survey vessel with limited thrusters the ability to perform such a set of manoeuvres is clearly going to be reduced, although still possible, and will rely on some skilled ship handling.

Poor or unsuitable locations for any of the measuring elements will also degrade performance. For example if the transducer head has a lot of aeration around its location or propeller wash passing directly over the face this is likely to significantly degrade performance. Sometimes it will be difficult to avoid such problems but a variation in the vessel head with respect to where observations are being made may improve matters. Again a heading change with respect to the prevailing wind and sea may significantly change the way the ship's power is applied to hold station. Generally a slow turning large main engine propeller will create more power and less noise than a smaller high revving thruster. Any user needs to be aware of the location of the transducer(s) with respect to all propulsion units and optimise the vessel heading to minimise acoustic noise. Additionally the actual noisiness of the vessel must be clearly known and the necessary signal strengths and transducer sensitivities be sufficient for effective measurements to be made in a range of operating conditions. The noise signature of the vessel should be known and documented. It may be that particular pitch settings have a significant effect. In summary the particular idiosyncrasies of any vessel should be tested and documented.

Once the vessel has been positioned reasonably close to the intended cardinal point locations in order to collect the calibration data, the time required to collect the one or two hundred sets of measurements is comparatively short. Vessel noise should be reduced such that good data is obtained. A slight slow drift off position with good data is more useful than perfect station keeping but poor data.

6.4 The Use of Kalman Filtering

The ability to sample data at very rapid intervals allows filters to be used to reduce the effects of noise and improve performance. However there is a caveat - only if the system is linear and the noise random will a Kalman filter work correctly. A compromise for non-linear systems requires the interval over which the filter is applied to be short such that the linearity is realistically modelled. Some caution should be exercised against over-filtering data. It is sometimes tempting to provide too pleasing a result rather than show deteriorating performance.

The concluding instalment, Part 3, will be published in *The Hydrographic Journal* No. 110, October 2003

Correction to Part 1

The highlighted equations in Section 2.3.3 should all read …*Secant(Lat) not …*Second (Lat)

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