AN EVALUATION OF USBL AND SBL ACOUSTIC SYSTEMS AND THE OPTIMISATION OF METHODS OF CALIBRATION – PART 3

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Part 1 and 2 were published in *The Hydrographic Journal* No. 108, April 2003 and No. 109, July 2003 respectively

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.

7. Optimum Solutions – The Need for Detailed Analysis and Quality Assurance

Potentially any iterative least squares solution will provide the optimum result provided the correct algorithms are applied, the geometry is good, the observations are of good quality and perhaps most significantly the correct weights are assigned to the individual observations. The introduction of least squares as the most appropriate mathematical methodology for offshore positioning computations [32], when changing from the traditional two pattern or two range fix to multiple patterns and ranges met some initial conservative resistance. The benefits of increased redundancy in the observations and the increasing computational power at the surveyor's disposal has now resulted it being readily accepted but the concept of 'weighting' has to a very large degree either been studiously avoided or ignored by many offshore. The 'easy option' has been to weight all observations equally and use a unit weight matrix. Unfortunately this flies in the face of the practical realities of what has actually been measured. The computational power and completeness of least squares together with its ability to provide the most pleasing result is a potential danger. A tacit unthinking acceptance of the results provided by many sophisticated programs is very evident offshore. In the most extreme case the author has actually seen calibration results accepted and used where a detailed examination would have clearly indicated that the seabed calibration transponder was actually moving systematically across the seabed throughout the calibration. There have been other examples where the results were clearly of limited value, inconsistent and of generally poor quality once the data was examined more closely. The solution is to collect and analyse the data in a much more detailed and thorough manner such that there is assurance that the least squares results obtained are indeed correct and valid and that all instrumentation is working normally and correctly.

No dataset will ever be perfect but its detailed analysis can provide very real and important insight into the performance of all contributing instrumentation, the actual sea conditions experienced during the calibration and the soundness of the method adopted. The example of analysis provided is purely illustrative and highlights the principles and some of the possible variations in performance that could be experienced by any system and any user and should not be taken as reflecting the particular performance of a particular system or a particular user.

The data set will be used to show the effects of a variety of sources of error and how they can be validated in a way that both improves understanding and increases confidence in the validity and real quality of the final results. It should also highlight any weaknesses or poor performance in the 'hybrid' system with its many contributing systems and different types of measurement. This

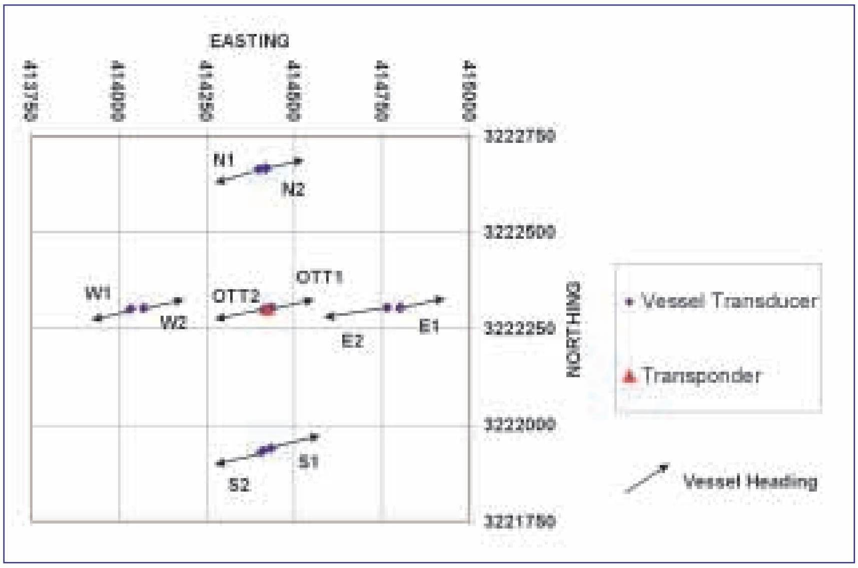

Figure 16: Observation Geometry

illustrative dataset was gathered in just over four hours in a deepwater offshore area without any tide. Ten sets of observations were gathered over the top of the transponder and at four cardinal points on two reciprocal vessel headings - see Figure 16.

Consider firstly the resultant raw transponder 2-D positions shown in Figure 17, after editing any of the raw data that contains gross errors, a rapid evaluation of the various symmetries of the positional groupings can be made. A significant horizontal alignment (yaw) error is self-evident causing the large circular distribution of the 8 cardinal point data sets. The distribution and symmetry of the uncorrected transponder position data provides a very clear indication of the errors present and the overall consistency of the data.

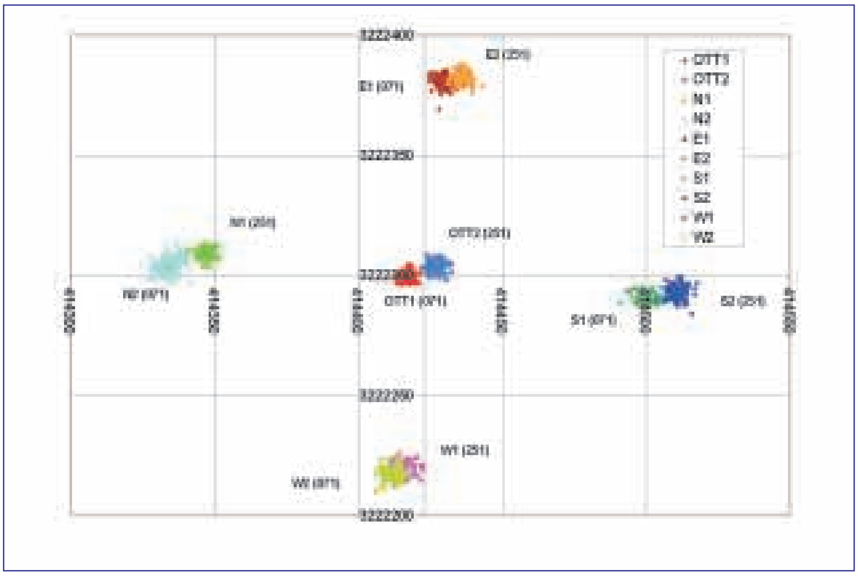

Figure 17: Raw Transponder positions (edited)

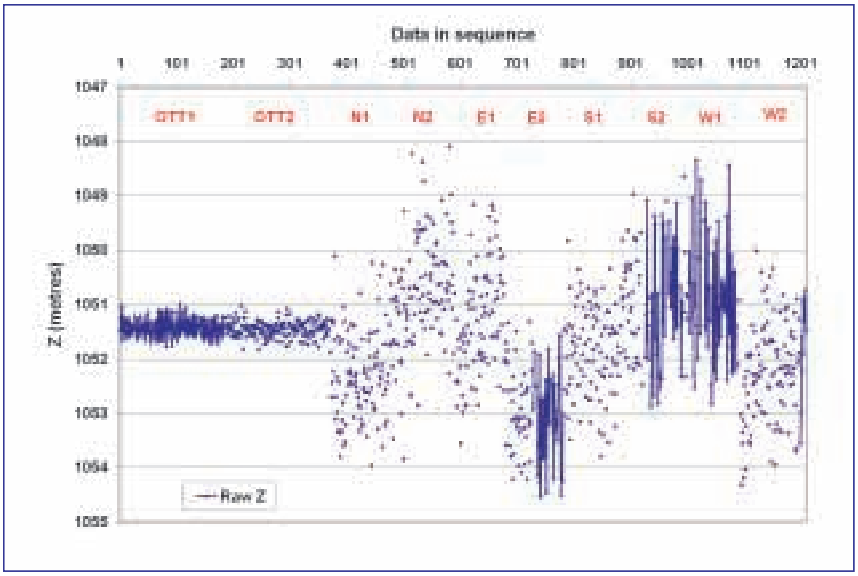

Figure 18: Raw Z (edited)

	Mean Z metres	SD (1 sigma)	Cardinal Point Pairs	Mean Z metres	Matched Headings	Mean Z metres
OTT1	1051.43	+/- 0.15				
OTT2	1051.45	+/- 0.14	OTT1 & 2	1051.44		
N1	1052.29	+/- 0.80				
N2	1050.80	+/- 1.02	N1 & N2	1051.55	N1 & S2 (251)	1051.62
E1	1051.33	+/- 0.99				
E2	1053.02	+/- 0.75	E1 & E2	1052.18	E2 & W1 (251)	1051.97
S1	1051.90	+/- 0.90				
S2	1050.95	+/- 1.00	S1 & S2	1051.43	N2 & S1 (071)	1051.35
W1	1050.92	+/- 1.02				
W2	1052.18	+/- 0.92	W1 & W2	1051.55	E1 & W2 (071)	1051.75

Table 5

The particular headings used for the vessel (071° and 251°) do not exactly match the cardinal points chosen. However the paired data sets N1, N2 and S1, S2 mainly indicate the pitch error whilst E1, E2 and W1, W2 mainly indicate the roll error. A similar pattern is clearly evident from the over the top sets OTT1 and OTT2. These also have negligible position errors due to horizontal alignment but support the presence of pitch and roll alignment errors. The separation of the matched pairs of data sets clearly indicates that the pitch error is larger and much more significant than the roll error.

Further confirmation of the presence of pitch and roll errors is evident in Figure 18 which illustrates the Z variation of the transponder. Again it should be noted that the Z values of the OTT sets are not affected by either pitch or roll or by heading misalignments. What these particular data sets confirm is the quality of the range data, as evidenced in Table 5, with a standard deviation of ±0.15m (1 sigma) compared to the cardinal point Z values which have been downgraded by the angle and motion measurement errors with standard deviations of about ±1.00m (1 sigma). Balancing and grouping particular data sets using the geometry of the observation scheme provides a simple test of the consistency of the Z data.

By reversing the vessel heading at the cardinal points the effects of the pitch and roll errors are also effectively reversed. The mean Z value of each pair should be close to the true value. Similarly if opposite cardinal points are considered with similar vessel headings the combined effects of the pitch and roll errors are also counterbalanced. Had the cardinal points matched the vessel headings then the pitch and roll errors would have been more clearly separated. It is evident that the Z values from E1 and E2 appear slightly out of sympathy with the other data sets. The paired mean Z values and the various matched pairings are shown in Table 5.

It is also worth reviewing the basic raw attitude data sets to see what motion characteristics are evident. The dynamics of the vessel motion - pitch, roll and heading (yaw) - are demonstrated in Figures 19, 20 and 21. The supporting statistics are shown in Table 6.

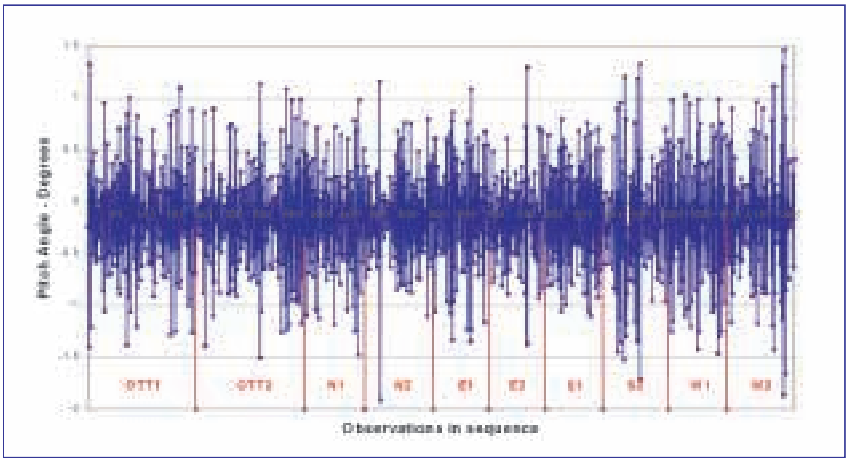

Figure 19: Vessel pitching motion

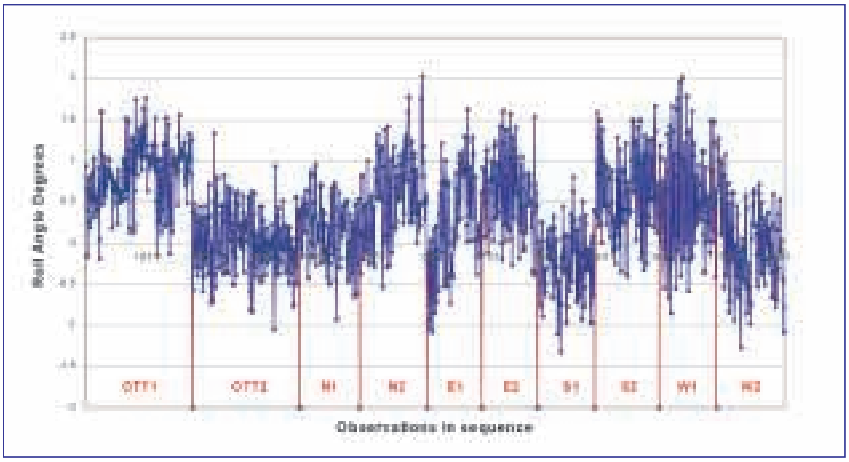

Figure 20: Vessel rolling motion

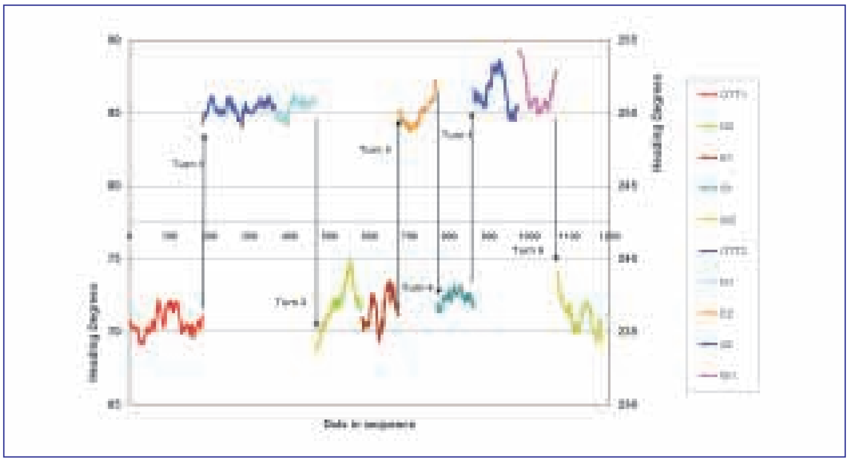

Figure 21: Vessel headings

A slightly puzzling characteristic is evident in the roll information. Whilst the mean pitching angle and the pitch standard deviation are consistent for all ten data sets, the mean roll angle exhibits some variability from one data set to another. This could be attributed to the effects of windage on the vessel causing a particular list for each data set however there is some evidence of a changing trend in some of the data sets. This raises a question mark over the reliability of the roll data. There is also evidence of good correlation between the heading variation and the roll variation. The accuracy of motion sensors can be directly affected by the quality of any heading information provided. To complicate matters further the accuracy of the conventional gyrocompass is also affected by pitch and roll. The variation in the vessel heading at the cardinal points is a combination of the sea state and the manoeuvrability of vessel and the performance of the DP system coupled with the heading sensor performance affected by the dynamics of the vessel.

The simplest and most effective way of determining the best estimate of the true position and depth of the transponder is as indicated earlier in Section 4 by computing a 3-D box-in position using only the high precision observations of the slant ranges together with the DGPS data and vessel heading to correct for the physical offset between GPS antenna and transducer. The potential sources of error are limited by using only acoustic ranges. This will test the quality of the slant range data very effectively. By using a fixed heading for a box-in there is the potential for systematic positional error caused by any offset errors. This is not detectable from a single box-in, but by carrying out a second box-in with a reciprocal heading the comparison of box-in results will highlight any significant offset error. Some caution must be exercised in making due allowance for the varying performance of DGPS. These are not white noise systems but coloured with some temporal positional variation. It would be incorrect to suggest an offset error of a few decimetres when the positioning standard (DGPS) will be varying by significantly more than this.

The two resulting data sets have been further sub-divided using alternate fixes to demonstrate the effect of using different data sets. The results are shown in Figures 22 and 23. The number of observations to be used in any computation needs to be considered carefully in relation to the standard error of the basic observations themselves. Too few and there potential for the least squares result to be not truly representative. Too many and there is wasted effort for no significant advantage.

The slant range residuals are very similar at ±0.16 metres and match the Z observations directly over the top of the transponder. The position and depth results show no significant differences between common data sets (for A and B, ΔE 0.03m, ΔN 0.03m and Δd 0.04m whilst for C and D, ΔE 0.12m, ΔN 0.03m and Δd 0.00m) but a small systematic difference between the mean of the two different sets with a different vessel heading (between 071° and 251°, ΔE 0.56m, ΔN 0.09m and Δd 0.11m). This is not seen as reflecting a significant or real offset error but more an indication of the coloured positional variation of the DGPS caused by different satellite geometries and different observation periods. Whilst the use of a standard DGPS system would be satisfactory for most calibrations there are new offshore requirements (monitoring high temperature pipelines to detect absolute seabed positional movement) where the use of a higher order control by long range 'Phase DGPS' (High Performance DGPS) could prove beneficial. The

	Pitch	Pitch SD	Roll	Roll SD	Heading	Heading SD
OTT1	-0.15	0.53	0.83	0.38	70.61	0.77
OTT2	-0.18	0.50	0.03	0.38	250.34	0.45
N1	-0.18	0.51	0.15	0.38	250.39	0.58
N2	-0.17	0.45	0.58	0.51	71.84	1.47
E1	-0.15	0.55	0.24	0.61	71.52	1.08
E2	-0.18	0.44	0.62	0.62	249.90	0.79
S1	-0.15	0.52	-0.24	0.40	72.32	0.47
S2	-0.21	0.59	0.62	0.50	251.45	1.22
W1	-0.20	0.64	0.54	0.64	251.51	1.34
W2	-0.15	0.60	-0.02	0.52	71.16	1.10
		SD of Mean	SD of Mean			
MEAN	-0.17	+/- 0.02	0.34	+/-0.35		

Table 6

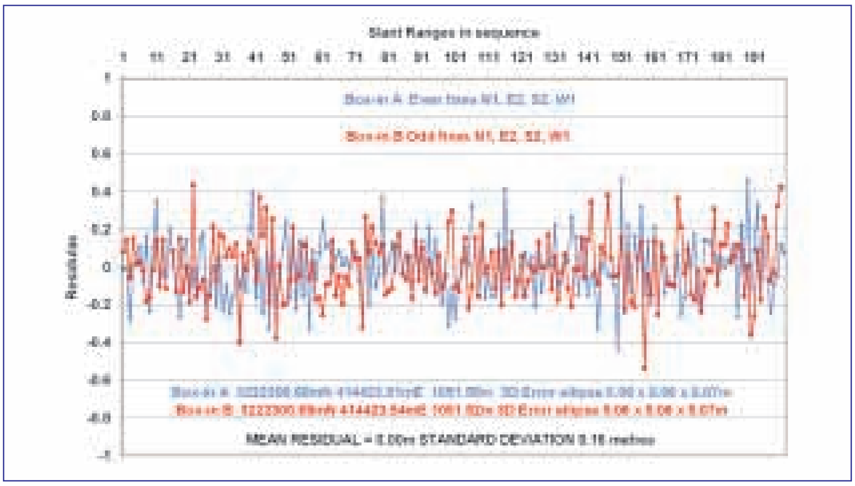

Figure 22: Box-in range residuals – vessel heading 251

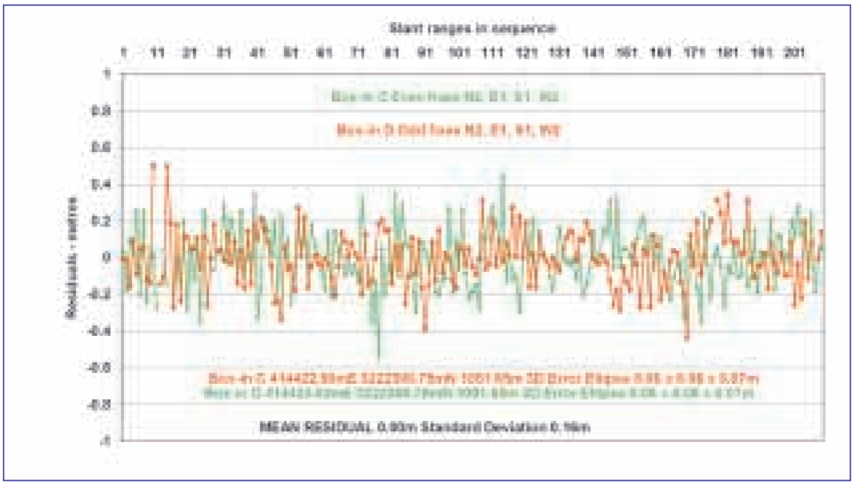

Figure 23: Box-in range residuals – vessel heading 071 True

upgrading of USBL performance also requires a more accurate and precise calibration.

By comparing the box-in derived depth (Z value) and the directly observed Z value from OTT an additional check is also provided on the used mean water column sound velocity. In this instance the mean box-in depth of 1051.62 metres compares reasonably with the mean OTT value of 1051.44 metres suggesting a small error in the velocity of 0.02% equivalent to 0.25 metres per second. It should be noted that in this instance the observations were made in an area with no tide so no tidal corrections were applied. In an area with tide corrections would need to be applied to allow meaningful comparisons and ensure the correct conclusions were drawn.

Having established the best estimate of the transponder position and depth using only the slant ranges one can start to review the alignment errors present. Taking the mean of the box-in results the correct bearing to the transponder can be computed and then compared this with the observed azimuth. This is illustrated in Figure 24 and Table 7. It should be appreciated that the apparent significant variation in the yaw alignment C-Os for each individual cardinal point is caused by the additional affects of pitch and roll alignment errors. When the observation sets are balanced by suitable pairings such that the pitch and roll alignment errors are cancelled out then the mean yaw misalignment for each pair, heading group and overall mean can all be seen to be in very good agreement. Also evident are the similar precisions of each set of yaw observations with an average standard deviation of ±0.43°.

By applying the mean horizontal alignment (yaw) correction to all the data it is possible to examine the other angular measurements. These are shown in Figure 25 and Table 8. Again there is evidence of the roll sensor anomalies having a detrimental effect on the measured acoustic angles with some systematic differences in the means but a similar standard deviation for each cardinal point data set. The latter confirms the combined precision of both the acoustic angles and motion sensors.

Again having derived the angular alignment corrections these can be applied to the data sets and the residuals of Theta X and Theta Y can be calculated and are shown in Figure 26 and Table 9.

The most striking trends in the residuals of ϕ_X and ϕ_Y data is the apparent systematic pattern where there is a marked difference in the precision of one angle with respect to the other angle. This trend is related to the heading reference performance and the location of the cardinal point observations in relation to the actual transponder where the roll anomalies have again degraded the results.

The final acid test of the calibration results is to use the derived alignment corrections on the original data set and see how consistent the resulting corrected positional information appears. This is first shown in Figure 27 as an Easting and Northing time series.

This shows a noisier but similar general trend to that of stand-alone DGPS with a short-term precision of less than ±2m but a longer term drift caused by the changing satellite geometry. This is likely to have been exacerbated by the combined performance of the USBL system. The step change seen at data point 580 corresponds to the roll abnormality previously seen. Looking next at a scatter plot of the transponder

	Azimuth C-O	SD (1 Sigma)	Cardinal Pairs	Vessel Heading Groups	Overall Mean
N1	-12.16	+/- 0.40			
N2	-14.03	+/- 0.46	-13.095		
E1	-12.74	+/- 0.43		-12.935 (251)	
E2	-13.33	+/- 0.38	-13.035		-12.987
S1	-12.27	+/- 0.44			
S2	-13.73	+/- 0.43		-13.000 -13.040 (071)	
W1	-12.52	+/- 0.44			
W2	-13.12	+/- 0.44	-12.820		

Table 7

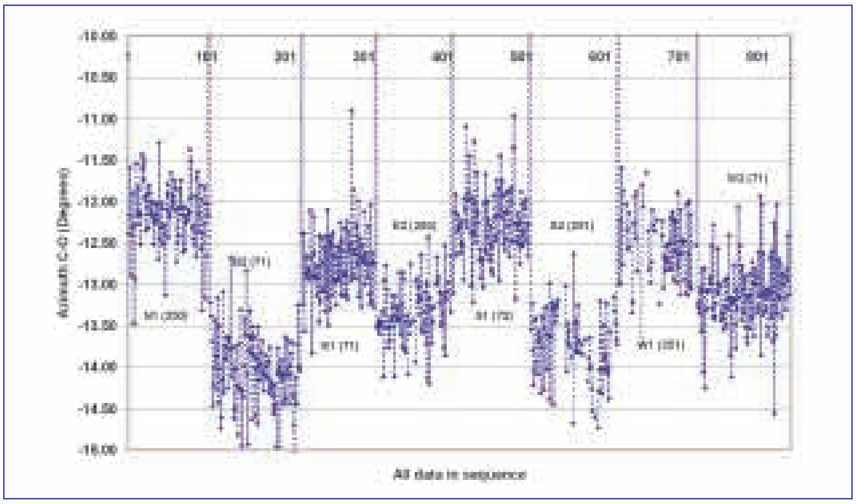

Figure 24: Cardinal point azimuth C-O

Data Set	φx Degrees	φx SD (1 sigma)	φy Degrees	φy SD (1 sigma)
OTT1	-0.091	+/- 0.14	-0.295	+/- 0.12
OTT2	-0.042	+/- 0.13	-0.203	+/- 0.12
N1	-0.044	+/- 0.11	-0.286	+/- 0.13
N2	-0.046	+/- 0.13	-0.328	+/- 0.15
E1	+0.042	+/- 0.14	-0.101	+/- 0.15
E2	-0.029	+/- 0.12	-0,265	+/- 0.13
S1	-0.080	+/- 0.11	-0.216	+/- 0.13
S2	-0.027	+/- 0.15	-0.210	+/- 0.16
W1	+0.059	+/- 0.15	-0.098	+/- 0.16
W2	+0.005	+/- 0.13	-0.087	+/- 0.13
MEAN	-0.025	-0.209		

Table 8

positions, the distribution looks generally random in Figure 28, with no particular grouping standing out with individual cardinal points assigned individual colours.

As a further test in Figure 29 the data has been segregated by colour for the two vessel headings. Once more the distribution is essentially random.

Turning now to the third dimension of depth, the corrected Z values still exhibit systematic differences as indicated in Figure 30. The most likely explanation for this is the performance of the roll sensor as identified earlier.

An alternative method of correcting the Z value is to use the computed horizontal distance between the transducer and the derived transponder position and the slant acoustic ranges. This is shown in Figure 31. This process eliminates the angular measurement and again highlights the accuracy and precision of the acoustic range measurements. The slight discontinuity evident between E1 and E2 is most probably a small shift in the DGPS positioning. A horizontal change of 0.5m is all that is required to bring the E1 Z-data into agreement.

The most likely cause of the roll sensor not providing consistent information is the manoeuvring of the vessel. Referring back to Figure 21 it is evident that the vessel has turned through 180 degrees on six occasions during the collection of data. There was no evidence that a significant waiting period was allowed after each turn to allow the motion sensors and gyrocompass to settle. As previously explained, it is recommended that vessel turns are minimised during calibrations.

It is suggested that the required primary vessel heading for holding station most effectively with minimum ship's power and minimum noise is first established. The cardinal points should then be chosen to be ahead and astern and port and starboard of the transponder. This will make the subsequent evaluation of the pitch and roll errors easier to review and provide a clear indication of the respective magnitude of the vertical alignment errors present. The sequence of data collection should then start 'over-the-top' of the transponder on the primary heading. The vessel should then move to each of the four cardinal points in turn. A short settling period should be allowed once in position at each cardinal point and on the primary heading calibration data should be collected. On completion the vessel heading should be reversed and after allowing a longer settling period the cardinal points should be re-visited and a second set of data collected on the secondary heading. Finally the vessel should return to the over-the-top position for the final data collection. It is also suggested that additional data should be gathered as the vessel slowly moves from one cardinal point to the other. This data should not be used as the principal data set for determining the alignment corrections but as a secondary check once the calibration has been completed. This will provide more changes in the relative geometry between transducer and transponder.

In the data example used there was no tide so no tidal corrections were applied. In an area with tide a prediction should be generated for the period in question and the start and finish over-the-top Z values used to confirm or adjust the predicted rise or fall of the tide. Application of the change in tidal height needs to be first applied in the box-in computation such that vessel transducer positions are all on the same level datum. The derived depth of the transponder will then be on the same vertical datum and the horizontal position will be correctly derived. In determining the pitch and roll alignment corrections the tide will need to be re-applied to the derived transponder depth for each cardinal point observation set.

Finally an alongside calibration should be carried out to ensure that no large errors are present prior to sailing. This should also reinforce confidence in the dynamic calibration with comparable results. The illustrative data set has confirmed the overall quality of the various measurements. The accuracy, precision, and reliability of the range data stands out and was as predicted. The malfunctioning of the roll sensor was identified from the detailed analysis. There is sometimes a tendency to concentrate too much on the final result without properly looking in sufficient detail at the various component measurements that are all needed to provide the final result. It should be appreciated that in this analysis the mean is the simplest implementation of least squares when used with simple datasets and appropriate geometry.

Summarising the statistical results (1 sigma values) provides a good overview of the USBL calibration operation and quality of all the contributing factors and the overall 3-D positioning quality that can be achieved in a water depth of over 1000 metres with a horizontal offset between transducer and transponder of over 300 metres.

Sea Conditions and Vessel Dynamics

Average Heading Motion	±0.93°
Average Rolling Motion	±0.48°
Average Pitching Motion	±0.53°

Additional useful statistics to describe the vessel dynamics would include heave, surge and sway as well as wind speed and direction, sea state and vessel noise.

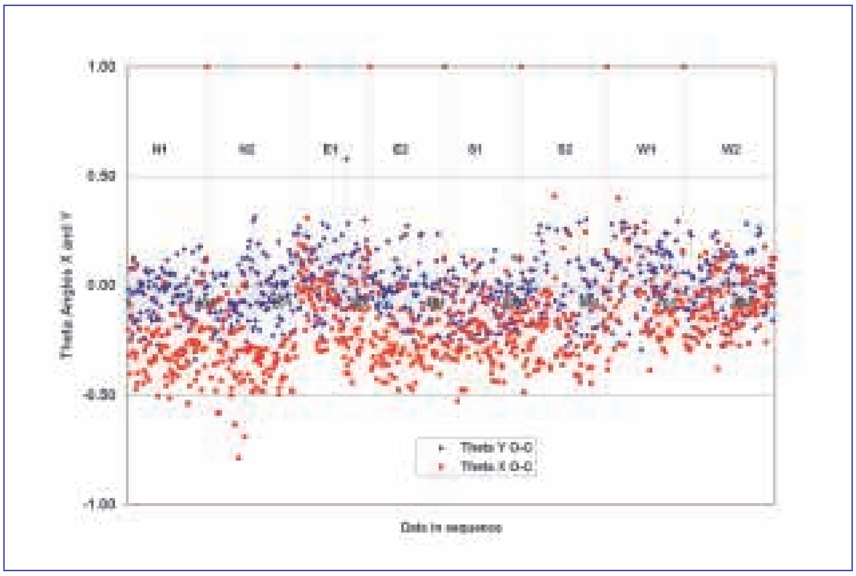

Figure 25: Theta X and Y O-cs

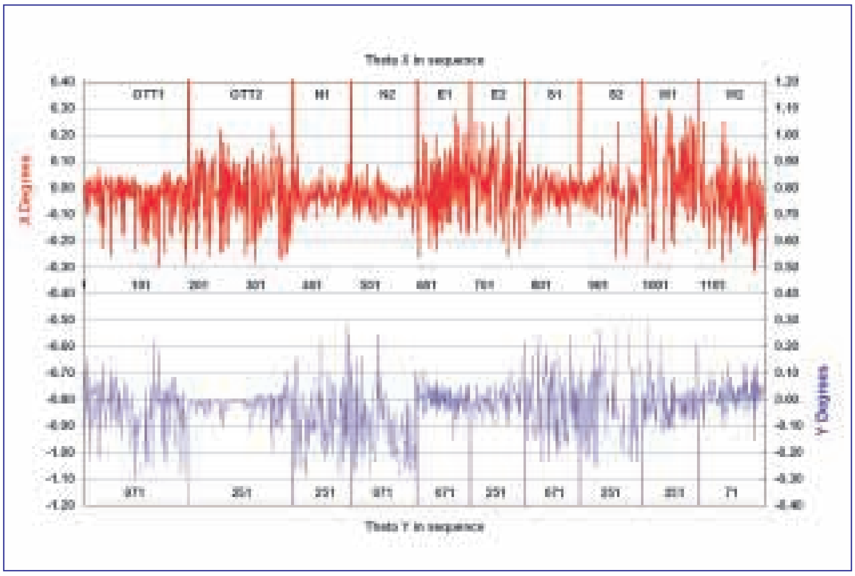

Figure 26: Acoustic angle Theta X and Y residuals

Combined Measurement Performance Statistics

Horizontal alignment (Z) YAW	±0.43°
ϕ_y alignment (Y) ROLL	±0.13°
ϕ_x alignment (X) PITCH	±0.13°
Acoustic Ranging	±0.16 metres
3-DBox-in Precision	±0.06 x 0.06 x 0.07 metres
2-D DGPS/LBL Accuracy	±0.5 metres
1D Acoustic Depth Accuracy	±0.2 metres
Average DGPS/USBL 2-D Positional Accuracy	±3.95 metres (0.36% of slant range)
Average USBL 1D Depth Accuracy	±0.95 metres

Potentially with a higher quality surface positioning system, a more consistent set of roll motion measurements and a higher quality heading reference unit the overall performance of USBL and its calibration could be significantly improved in a water depth of over 1000 metres. Overall performance can be seen to be directly affected by all contributing systems. The particular strengths and weaknesses of all observations need to be carefully evaluated in the calibration method used such that the required accuracies are provided.

8. Conclusion and Recommendations

Superb technology, correctly used, provides very good results. Old practices need to be continuously reviewed and updated as knowledge, awareness and understanding improve. This is the dawn of a new acoustic era. The change from tone transmissions to spread spectrum provides many new opportunities and challenges. It is hoped that more open discussion and greater awareness of all the issues will collectively improve performance.

It is vitally important that sufficient explicit good training is provided for all users, whether mariner or surveyor, such that the correct operation of a system as sophisticated as USBL or SBL is improved. Insufficient training and knowledge is potentially a dangerous state of affairs. It is not in the best interest of either the users themselves or the acoustic system manufacturers to have good acoustic systems poorly or incorrectly operated.

It should be noted that USBL calibration is not a unique problem. There is a great wealth of information in associated areas in which the same Euler angles problem is available for research and improvement of overall understanding. It is apparent that the offshore survey world is perhaps too isolated and conservative in its approaches to the best resolution of some of these issues. 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.

Offshore surveying mathematics may need to advance into the 21st Century by using 18th Century complex numbers. With the computational power now available it is possible to carry out what is necessary more quickly and more rigorously. The elegance and efficiency of quaternions could assist greatly in rotational matrix computations. In fact the profession's approach to all 3-D computation should be radically reviewed.

There is a dangerous complacency in unthinking use of least squares as the panacea of all adjustment problems without due attention to the weight matrix and the real quality and correlation of observations. Effective Kalman filtering routines also need careful application. Without a proper understanding and knowledge of the real quality of observations both computational routines are of limited value. Surveying expertise signifies a proper and complete understanding of all the measurement observations and their real quality.

This author has found his thirty years working offshore fascinating and he is still learning. It has quite mistakenly been suggested that the advent of GPS has somehow made traditional surveying an outdated technical profession. This could not be further from reality. Remarkable measurement technologies continue to advance and their true potential and complexity is expanding. The future of 3-D navigation, positioning and surveying will be an advanced hybrid combination of the many diverse technologies which encompass all aspects of the world we live in. The true value that could be added to offshore surveying by providing a better service and better information, more clearly, without significant cost should be clear to anyone with real vision and a genuine interest in improving performance.

Looking to the not too distant future it is likely that the ultimate hybrid system will be developed for a variety of offshore vessels. This will have a combination GPS/Glonass/Galileo satellite system providing positioning and attitude in 3-D as a global reference, an inertial

	Theta X mean	Theta X SD	Theta Y Mean	Theta Y SD
OTT1	-0.03	+/- 0.07	-0.04	+/- 0.10
OTT2	-0.02	+/- 0.11	-0.01	+/- 0.04
N1	-0.02	+/- 0.04	-0.07	+/- 0.11
N2	-0.04	+/- 0.04	-0.11	+/- 0.11
E1	-0.01	+/- 0.12	0.00	+/- 0.04
E2	+0.02	+/- 0.11	0.00	+/- 0.05
S1	-0.01	+/- 0.05	-0.02	+/- 0.11
S2	-0.02	+/- 0.08	-0.02	+/- 0.12
W1	+0.05	+/- 0.14	-0.01	+/- 0.08
W2	-0.04	+/- 0.11	+0.02	+/- 0.05
MEAN	-0.01	+/- 0.13	-0.03	+/- 0.13

Table 9

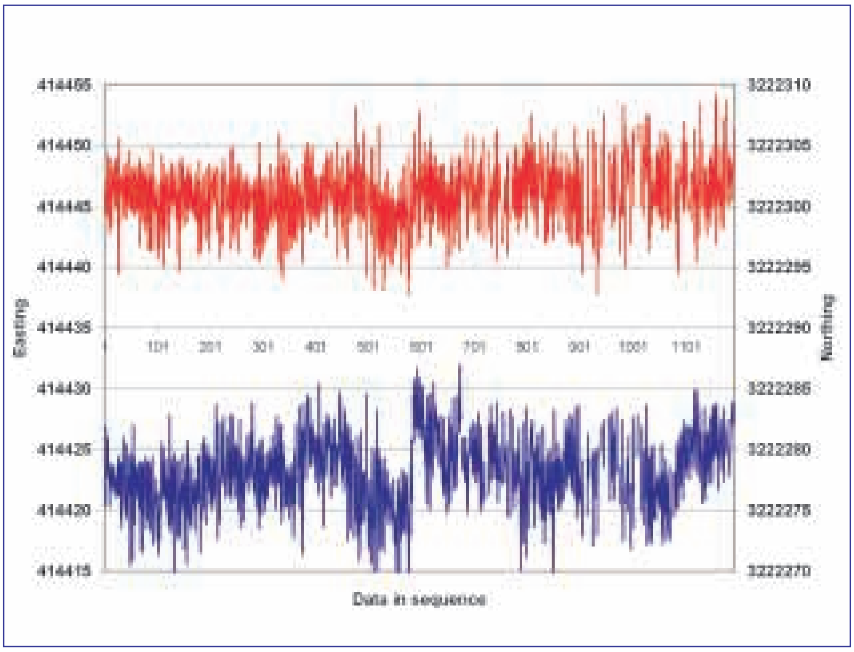

Figure 27: Corrected USBL transponder position

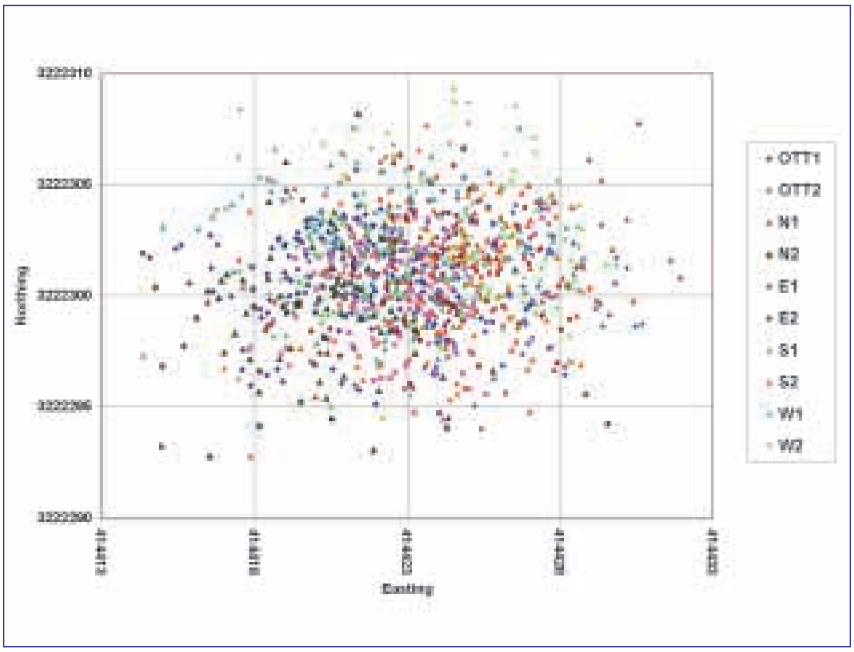

Figure 28: Scatter plot corrected data

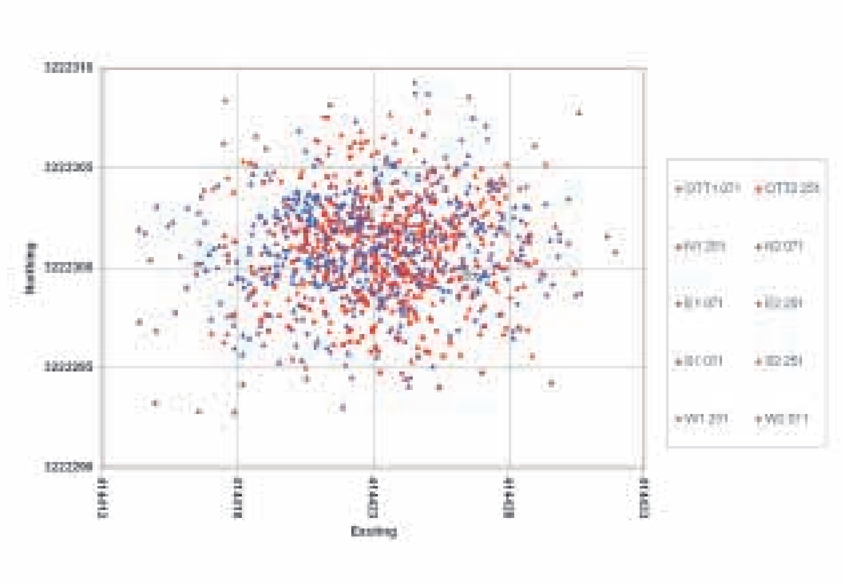

Figure 29: Scatter plot reciprocal vessel headings (blue 071, red 251)

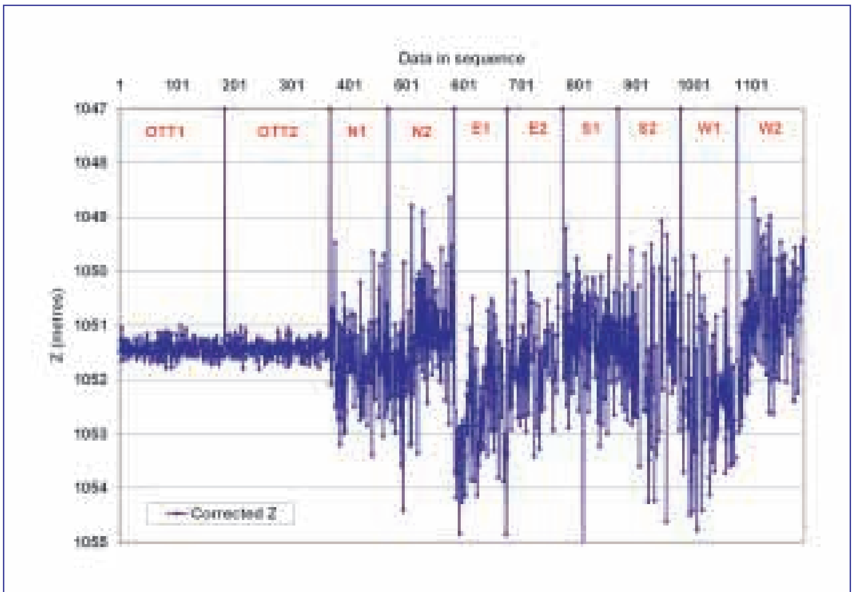

Figure 30: Corrected Z values (edited)

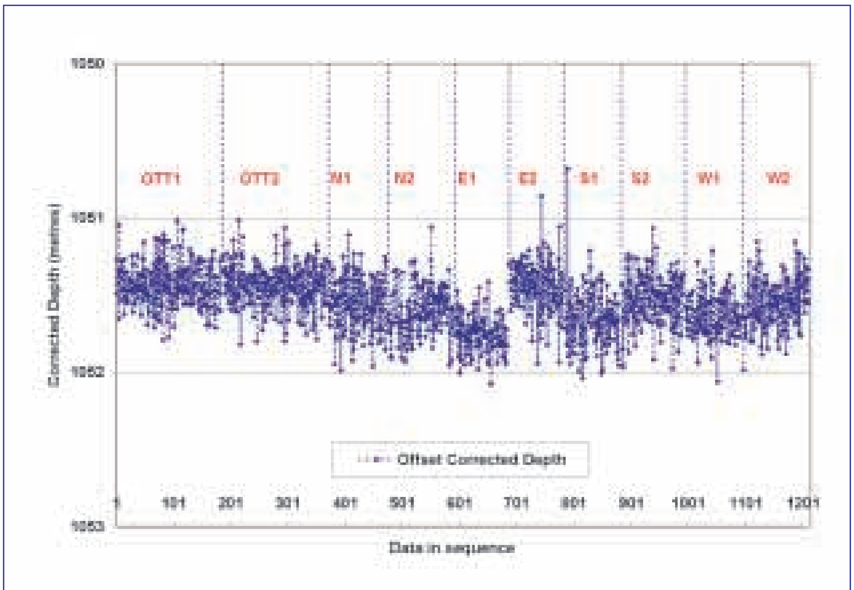

Figure 31: Vessel offset corrected depth

navigation unit also duplicating all these positioning and attitude functions but as a local reference system and an acoustic system which is capable of simultaneously performing acoustic positioning of itself and other remote subsea vehicles with an acoustic command, control and data telemetry functions.

Postscript

Those whose lives are fruitful to themselves, to their friends, or to the world are inspired by hope and sustained by joy; they see in imagination the things that might be and the way in which they are to be brought into existence. In their private relations they are not preoccupied with anxiety lest they should lose such affection and respect as they receive: they are engaged in giving affection and respect freely, and the reward comes of itself without their seeking. In their work they are not haunted by jealousy of competitors, but are concerned with the actual matter that has to be done. In politics, they do not spend time and passion defending unjust privileges of their class or nation but they aim at making the world as a whole happier, less cruel, less full of conflict between rival greeds, and more full of human beings whose growth has not been dwarfed and stunted by oppression

Extract from Bertrand Russell's *Proposed Roads to Freedom – Anarchy, Socialism and Syndicalism*, Henry Holt, New York, 1919, pp186-187.

Acknowledgements

My thanks to Mr David Whitcombe of Shell UK Ltd for permission to consult a private report on GPS Attitude Determination.

The author would also like to thank Mr Morten Berntsen, Mr Hans Petter Jacobsen, Mr Finn Otto Sanne and Mr Ian Florence of Kongsberg-Simrad A/S, as well as Dr Dick Hazelwood, Mr Nigel Kelland and Mr Nick Smedley of Sonardyne International Ltd, Mr Guy Bromby of Aquadyne A/S and Mr Phil Doolan of Nautronix. All have responded positively to questions and requests for information. Their feedback to the initial draft of the paper was also very much appreciated and all their comments and suggestions have hopefully made a significant contribution to the final version.

Discussions on USBL calibration with Mr Ed Garrett-Jones of Svitzer Survey Ltd and Mr Tony Drake of BP Exploration Ltd also assisted in the preparation of this paper.

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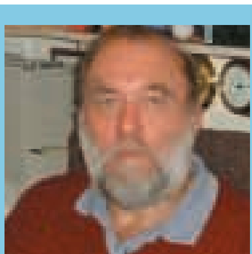

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