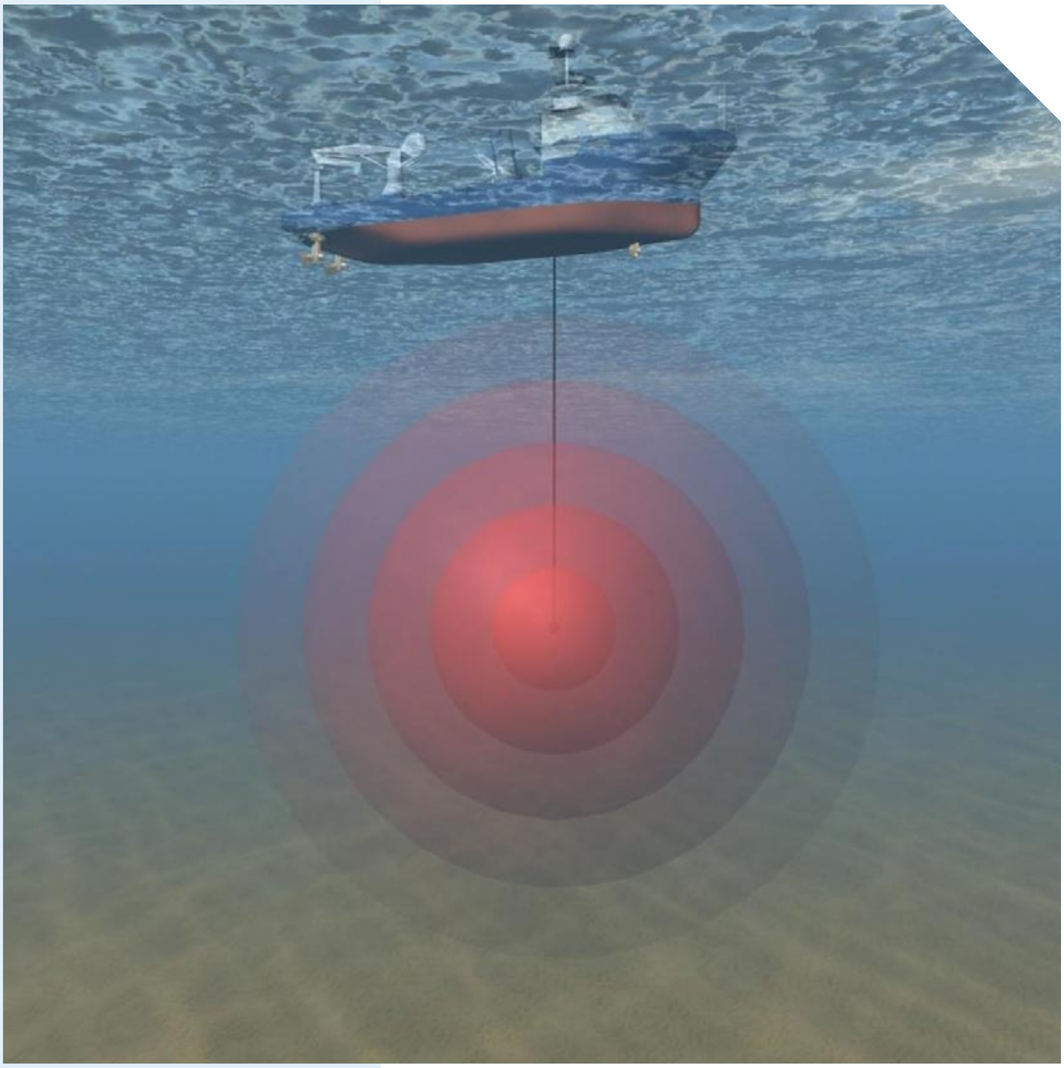
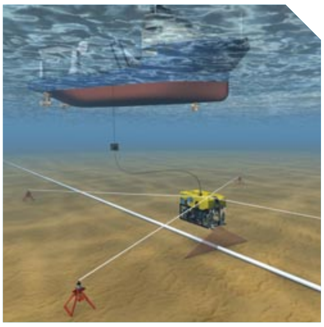
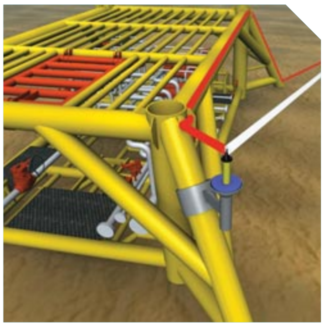
Deep Water Acoustic Positioning







International Marine
Contractors Association

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IMCA M 200, IMCA S 013
October 2009

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There are also five regional sections which facilitate work on issues affecting members in their local geographic area – Asia-Pacific, Central & South America, Europe & Africa, Middle East & India and North America.

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Deep Water Acoustic Positioning

IMCA M 200, IMCA S 013 – October 2009

This document is dedicated to the memory of Brian Beard, who was a long-standing member of IMCA's Offshore Survey Division Management Committee, whose ideas and early support for this document were key to its development.

Appendices

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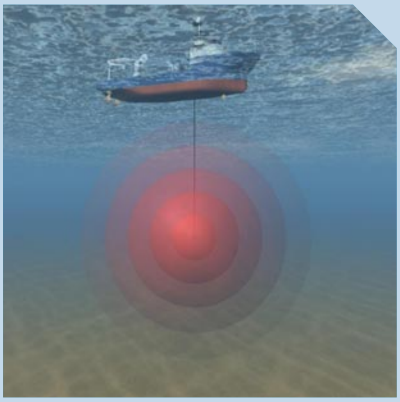

Executive Summary

This guidance document was commissioned by the IMCA Offshore Survey Division to provide an authoritative guide for users and potential users of acoustics for underwater positioning (especially in relation to deep water activities). The document covers the basics of acoustics and signalling, the equipment required, methods of acoustic positioning and their limitations, and the operation and performance of acoustic positioning systems.

The focus is on the use of acoustic positioning systems and techniques for deep water operations. However, it should be recognised that many of the techniques and applications are also applicable to shallow water and in these circumstances the user should consider the pros and cons of the approaches available for use.

This document does not attempt to compare and evaluate different manufacturers, their products, services or the specific performance of systems – nor does it set out to provide a prescriptive set of procedures. Rather, this document is designed to provide consideration and guidance for the use and operation of any of the main types of systems.

In considering deep water acoustics, this document focuses on the use and application of acoustics for positioning tasks and how a user should consider the various factors influencing the selection of operational techniques for different applications. The main part of the document is intended to inform and bring a general understanding of deep water acoustics to the reader. More detailed technical appendices are provided for in depth study.

No endorsement or recommendation of a specific type, model or make of system is offered here, however, the use of diagrams, references to proprietary elements and systems is inevitable in a specialised niche technology such as acoustic positioning.

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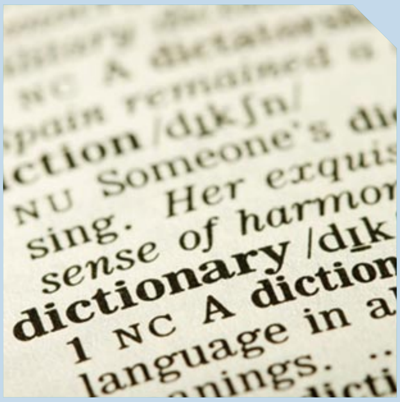

Glossary of Terms

Absolute accuracy	Often called the geodetic accuracy, or total accuracy, it is the measure of accuracy with which a positioning system can determine its positions with respect to a well-defined reference frame or reference system co-ordinates such as a geodetic datum. For USBL and LBL systems, the absolute accuracy will always be affected by and limited by the accuracy of the reference surface positioning system such as DGNSS
Acoustic/DVL	Doppler velocity logs are used to measure the speed of a vehicle over the seabed. Combined with precise heading, the system can generate a standalone relative 'dead reckoning' positioning solution based on speed and direction alone. The measurement data comprises speed in three perpendicular axes, calculated from the Doppler shift of the acoustic signal returned from the seabed as the vehicle passes over. Altitude above the seabed is also calculated. There is no external reference and the bottom tracking, depending on the frequency used by the system, requires the underwater vehicle to stay close to the seabed to maintain the lock of the acoustic signals. Typically the DVL data is used to aid an integrated position calculation incorporating USBL, LBL or inertial systems
Amplitude	The size or strength of the signal
Array	An alternative name for a network of seabed units
AUV	An autonomous underwater vehicle carrying its own positioning sensors and computation, as well as power. They are used with increasing frequency for survey and inspection tasks
Baseline	Either the distance between the receive elements of the USBL technique or the distance between the seabed transponders of an acoustic positioning system. Essentially in both cases, the reference points are considered fixed in their relationship at an ultra-short or short or relatively long distance
Beacon	A colloquial term for a transponder or other seabed unit that transmits acoustic ranges or data
BOP	Blow out preventer
Box-in	The method of determining the accurate position of a seabed unit is described as a box-in as the surface vessel traditionally circles around to create a form of 'box'. The observations are then considered to be balanced – in line with survey best practice of observing from the outside to the middle. The effects of any residual errors or biases should be minimised in this way

Calibration	Acoustic positioning units, their signals and their positions all need to be very accurately determined to avoid any error or bias. This is achieved by a series of calibrations. The first is a mechanical, electrical and acoustic calibration of each of the units as they are produced. Manufacturers have sophisticated tests and measurement processes to ensure their equipment is of a consistent standard. Acoustic centering and turn-around times are determined amongst others. Once deployed in-field, the units must have an accurate position determined for them so that their acoustic ranging offers accurate positioning. This determination of the co-ordinates is described as a calibration and may involve a 'box-in' (see above), or the use of inter-station acoustic signals to produce baseline measurements between the stations and thus enable a network solution to be calculated
Cavitation	The source of acoustic interference caused by the mechanical action of propellers that cause the water to bubble and aerate. The collapsing bubbles create the sound that disturbs the acoustic systems
CPU	Central processing unit
CTD	The conductivity, temperature and depth unit is for measuring the component elements that influence the speed of sound in water. It is usually deployed from a surface vessel or carried onboard an ROV
DAU	Data acquisition unit
dB/decibel	Unit measure of sound. The measurement of sound uses a logarithmic scale of which the decibel is the unit most frequently referred to. A decibel is quoted in terms of the energy that is received at a distance of one metre from an acoustic source. It effectively measures the relative intensity of the transmission signal and a receipt signal across an acoustic travel path of a certain distance
Depth sensor	A small sensor measuring pressure to allow calculation of depth. Output data may be transmitted to the topsides equipment via a cable or umbilical or even transmitted acoustically. It operates autonomously (or with power supplied) to deliver values at a relatively high data rate. Depth values may be applied in the onboard processing to aid the position calculation
DGNSS	Differential global navigation satellite system
DI	Directivity index
DP	Dynamic positioning
DT	Detection threshold
DVL	A Doppler velocity log utilises the Doppler effect in sound travelling through water to measure ocean currents, vehicle speed over ground, and height above seabed
EHF	Extra high frequency
Error types	There are three main types of error: ◆ Gross errors or blunders – These are very large mistakes usually due to an operator error or mistake. Due to their size and effect, these are generally quickly spotted and dealt with. For example, entering a value of 1,336.5m water depth when it should be 1,136.5m would be classed as a 'blunder' ◆ Systematic errors – These may be of a variable nature or introduce a constant bias. They usually originate from known sources in the system or process. The sign of the value for a systematic error usually remains the same over a long period but changes can occur. For example, the incorrect application of the equipment delay in a transponder would represent a 'systematic error' ◆ Random errors – These are the remaining variable errors of the measurements after all the blunders and biases have been removed. These are considered to be random in nature, having a normal distribution around a mean. It is these errors that are dealt with by the statistical processes and qualitative assessments on the data sets observed

FSK	Frequency shift keying is a form of digital signal modulation wherein the data transmitted is encoded in changes or shifts in frequency. Numerous designs and techniques of FSK exist. In its most simple form, 2-FSK (two frequencies) is used to transmit binary data bits. These noughts and ones (0s and 1s) are transmitted in such a way as to represent bits of data and the period or duration of the signal at any one frequency forms part of the design. More complex variants of 4, 6 and 8-FSK occur
GNSS	Global navigation satellite system
GPS	Global positioning system
GUI	Graphical user interface
HF	High frequency
Hydrophone	An underwater microphone device designed to receive sound waves under water. It is sometimes used to refer to the combined projector and hydrophone assembly but strictly speaking it is simply the listening device
IMU	The inertial measurement unit is the heart of the inertial navigation system. It consists of a set of three accelerometers or inertia sensors that enable the relative movement of the unit to be described. They are not inherently accurate on their own as the sensors are very small and prone to excessive drift rates. Inertial navigation therefore relies heavily on aided measurements such as Doppler, heading and perhaps altitude to reduce the measurement drift
INS	Inertial navigation system is a navigation aid that uses a computer and motion sensors to continuously track the position, orientation and velocity (direction and speed of movement) of a vehicle without the need for external references. They are used widely in civil aircraft and military applications and increasingly in ROVs and particularly AUVs
IRM	Inspection, repair and maintenance
LBL	Long baseline acoustic positioning system
LF	Low frequency
LUSBL	Long and ultra-short baseline
Main control processor unit	Vessel-based equipment used by the operators to manage and collect acoustic positioning data. It includes real-time data collection, processing, quality control and display functions (also known as 'topsides' equipment)
MF	Medium frequency
Mobile unit	A surface vessel such as a dive support vessel, floating production storage and offloading unit, drilling rig or other, or underwater objects that have been fitted with acoustic transponders to enable them to be positioned and tracked
MODU	Mobile offshore drilling unit
MSL	Mean sea level (sea surface reference level)
Network	A series of seabed units deployed onto the sea floor
NL	Noise level
Pinger	An acoustic beacon set to transmit at a fixed and regular interval
ppt	Parts per thousand
Precision and accuracy	The degree of closeness or conformity of an observation to its true value – inaccuracy in position appears as a bias or offset from its true value
Precision or repeatability	Precision or repeatability is the term applied to the relative grouping of the observation set or data population. It is the degree of distribution of a series of values and although high precision is desirable, it does not necessarily guarantee high accuracy. This is often a parameter that is wrongly assumed to indicate high accuracy but a small distribution of data will not always ensure that its average is close to the ideal or 'truth'

Projector	A unit designed to create the sound or acoustic signal transmission underwater
Ray bending	A characteristic of the variation of the speed of sound in the water column. This variation will tend to alter the direction of the acoustic energy wave. The effect is to bend the acoustic signal towards volumes of water where the speed of sound is lower. There are different layers of such water throughout the oceans
Ray trace	Ray trace analysis is used to determine to what extent the SVP has an effect on accoustic signals depending on where they are transmitted from and where the receiving hydrophone is situated. This is a critical analysis of deep water operations, as a deep water channel of relatively slow speed will tend to attract signals.This can cause acoustic 'blind spots' to occur. The degree of refraction of the acoustic signals may be gauged by carrying out some ray path or ray trace analysis
Real time kinematic	Surface positioning acts as the reference to the outside world for deep water acoustic positioning systems. Currently the most accurate method of positioning using GPS is to observe the phase signals and resolve the integers to derive an accuracy of a few centimetres. Techniques may vary but a common approach is to use a high grade receiver that can allow a fast processor to resolve the phase integers in real time whilst also continually moving. This is called the 'real time kinematic' approach. It relies on augmented data sets from a reference station. These may require a high data rate telemetry which often means that the range of the transmissions are limited to line-of-sight. Some services have produced satellite data link services to overcome these shortcomings
Relative accuracy	This is the accuracy quoted for an object positioned relative to other objects, such as seabed assets using the same system. However, for USBL operations, each vessel has a different solution and so the term may be less suited. It is usually the accuracy that is required of a LBL or USBL system where operations require positioning relative to other seabed assets rather than to a global co-ordinate, geodetic or other reference frame. Acoustic positioning systems provide good relative accuracies, especially LBL solutions that operate independently of water depth and are attractive for deep water positioning
Repeatable accuracy	Repeatability is the measure of the nearness that a position solution allows a mobile unit, to return to – a position whose co-ordinates have been derived previously from the system
Resolution	The ability of the positioning system to resolve very small values provides a level of the potential of the system to discriminate between observations and can be representative of the performance capability of the system. However, it is more realistic, due to the many small residual error sources, to consider resolution as a way to assess the capability of a measurement and its suitability for a given task or specification. This can be clock resolution or the acoustic filter width in an acoustic positioning system
Responder	A beacon which on receiving an electrical trigger supplied via a cable or umbilical which replies after a short fixed time delay after the interrogation signal (this delay is the responder turnaround delay). A responder has the same function as a transponder, but is connected via a cable to the signal that commands the unit to transmit. It does not need to 'hear' a remote surface or sub-surface acoustic signal
RL	Reverberation level
ROV	A remotely operated vehicle is a tethered subsea vehicle capable of engineering, inspection and remedial work
Salinity	One of the key parameters in determining the speed of sound in water. This is an equivalent measurement to the conductivity value
SBL	Short baseline
Seabed unit	Acoustic device placed on the seabed for positioning purposes

Ship's equipment	In-water ship's equipment such as the hydrophone. This is often permanently fitted or deployed through the hull of the vessel and is not to be confused with the topsides equipment
SL	Source level
Snell's law	The extent to which a signal is affected by the varying sound velocity profile. The signal path is traditionally broken into sections of discrete rays – each having a direction that is defined by Snell's law which states that $\cos\partial/C$ is constant, where ∂ is the angle of incidence and C is the speed of sound
SNR	Signal to noise ratio
Sonar	An acronym formed from the words SOund, NAvigation and Ranging
Sonar Equation	An equation that attempts to describe the balance between the performance of a transmitter, usually on the left-hand side and the operating conditions usually on the right-hand side that cause decay or loss of signal. The Sonar Equation is therefore very useful in planning how an acoustic signal may be used, given knowledge of its specification and of the environment in which it works
SPU	Signal processing unit
Spud-in	To start the well drilling process by removing rock, dirt and other sedimentary material with the drill bit
SSBL	Super short baseline acoustic positioning system
Station	A term used to describe a seabed transponder or unit that acts as a reference for the positioning of any mobile units (vessels) or other tracked assets
SVP	Sound velocity profile. As the speed of sound in water varies, it is necessary to build up a complete profile of the ocean from surface to seafloor in order to determine the most accurate speed of an acoustic signal. There are a wide variety of devices that can be deployed through the water column to collect temperature, salinity and other data which are then used to calculate an SVP
TAT	Turn-around time
TCP/IP	Transmission control protocol/Internet protocol – a suite of communications protocols used to connect computers together
Thermocline	In many seas and oceans the speed of sound in water does not change constantly from seabed to surface, owing to the presence of a cooler and denser layer of water known as the 'thermocline'. At the thermocline, sound velocity profiles often display a change in direction of the trend of measured values, meaning that decreasing speed of sound suddenly 'changes direction' and begins to increase. This causes acoustic signal paths to be bent with resultant loss of acoustic positioning if this is not adequately planned for
ToF	Time of flight
Towfish	Towed body
Transducer	A device that converts energy from one form to another, typically electrical energy into an acoustic energy or sound. In acoustics such devices are also able to do the reverse and are properly referred to as 'electro-acoustic transducers'
Transmission loss	Attenuation of transmitted signals along their path towards a receiver – the energy is attenuated by the presence of minute particles in the water causing dispersion and interference and absorption by the water itself
Transponder, beacons or station	A seabed unit that receives acoustic commands or signals and replies to them. The action of 'transmit as response to a signal' command gives the unit its name 'transponder'. The acoustic positioning system tracks and positions one or more beacons which receive an acoustic interrogation signal. In some LBL and hybrid systems, these units may also be deployed as a reference for the mobile

	positioning. In such cases these beacons operate as fixed transmitting units or stations, mostly on the seabed or on special frames mounted on structures
TS	Target strength
Turn-around time	Each of the seabed and subsea units has to receive a command or an acoustic signal and transmit a response. The time taken for this process to initiate and conclude is referred to as the turn-around time. If not properly taken into account, turn-around time can cause biases in position. The settings are normally set by the manufacturer at the time of construction and will have been tested and calibrated prior to issue
µPa	MicroPascal is a unit of pressure energy of sound in water
USBL	Ultra-short baseline acoustic positioning system
UTC	Universal time co-ordinated
Vp	Velocity of propagation in water
VRU/motion sensor	A vertical reference unit is a self contained unit (excluding power) that uses accelerometers to detect motion in any one of the three axes. This information is converted into an up, down, pitch, roll and yaw value. A VRU can be interfaced to the underwater vehicle for control or the data may be transferred to the surface for integration into the position calculation. It is suited to dynamic operations where there is the need for accurate offsets or attitude. The VRU automatically compensates for the ROV, AUV or the surface vessel's roll and pitch movements Note: onboard the vessel the USBL system relies on an VRU to determine the motion and corrections to ensure the accurate offsets from the surface positioning to the hydrophone unit

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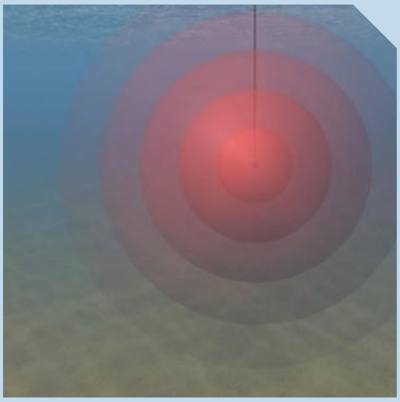

Introduction

Of the various forms of radiation, sound travels best through water. As a result of this characteristic, underwater sound has been used for many applications. The use of these techniques in a formal process is known as 'sonar' or 'acoustic systems'. The term 'sonar' is an acronym derived during World War II for application to military systems, and is formed from the words sound, navigation and ranging. In this document the terms 'acoustics', 'acoustic systems' and 'acoustic positioning systems' are used.

Acoustic positioning systems were developed in the 1950s and 60s to provide support to various US research projects and activities. Over the years, prompted by demand from the offshore energy industry, acoustic positioning and tracking systems have played an increasingly important role. Applications are common and relatively widespread in what is essentially a specialised area. The tracking of towed sensors and vehicles, locating underwater pipelines and cables, the monitoring of drilling and dredging operations as well as the survey and monitoring of numerous objects, are now common applications.

Acoustic positioning plays a role in almost all the phases of the offshore hydrocarbon industry, from exploration, drilling, engineering and construction to the monitoring and maintenance of production systems. In recent years the significance of acoustic positioning has increased as more activities have taken place in deep water areas.

Prior to the development and introduction of GPS satellite technology, radio positioning systems were used for accurate positioning of vessels on the sea surface. At best, these systems provided regional coverage. Satellite-based positioning systems have introduced global coverage, whereas acoustic positioning systems remain localised and typically cover only a few square kilometres at a time. This limitation creates difficulties for certain projects, particularly pipeline installation and cable-laying work, where accurate positioning is required for a long linear route. However, many users of the acoustic positioning systems accept limited cover and perhaps even limited accuracy in relation to the outside and 'real world' in order to ensure that reliable and repeatable positioning is available for their specific area.

The ability of a system to provide accuracy, coverage and reliability is discussed later, but it is important to realise that no single acoustic positioning system provides all the answers for the various applications. For many, there will be a trade-off between several systems – each of which offers some advantage relative to another.

It is intended that this document is an aid to the reader in understanding the way in which systems operate as well as their particular strengths, and the various deep water positioning applications for which any given system may be considered suitable.

The definition of 'deep water' varies hugely depending on what sector of the marine and offshore industry is being consulted. Hydrographers concerned with the safety of life and navigation may consider depths greater than 200 metres (m) as deep, whereas the offshore drilling companies often now consider deep water as greater than 2,500m. For the purposes of this document the definition of deep water is greater than 600m.

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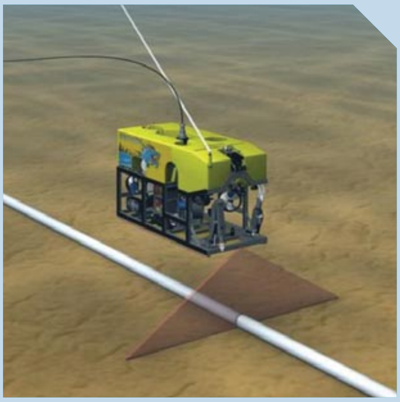


Basics of Deep Water Positioning Systems

Acoustic positioning systems measure ranges and directions to transponders fitted to underwater vehicles and objects, or derive acoustic ranges from stations deployed onto the seabed. These latter units are held stationary by a clump weight with buoyed mooring (or some other form of fixed seabed framework). Several types of system such as ultra-short baseline and short baseline systems provide positioning relative to a host vessel or vehicle, whereas long baseline systems allow either a relative or absolute positioning framework to be developed. Many other scenarios exist including beacons being installed on remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs) and other types of towed vehicles. The systems have been developed specifically to meet the challenges of operating in deep water with sufficient accuracy and system reliability. The main elements of deep water acoustic positioning systems will include:

- Transmission and reception of acoustic pulses to track or position a limited number of objects – both static and mobile;
- Processing and applying corrections to data to provide accurate and consistent performance parameters;
- Incorporation of peripheral data such as speed of sound in water, depth, heading and motion;
- Display of position relative to a certain reference system, e.g. vessel;
- Some form of noise and interference mitigation to enable continued working in harsh environments.

A full treatment of the physics of underwater acoustics is beyond the scope of this document. However, some general description is required to enable the reader to appreciate some of the aspects covered later. The Sonar Equation is often required by underwater acoustics engineers to aid in the design and planning of operations, rather than during field work. Further discussion of the Sonar Equation can be found in Appendix 1.

In order to better understand the critical elements of acoustic positioning systems and the environment in which they operate and to aid in the evaluation and assessment of the possible use of acoustic systems, some important aspects are described in the following sub-sections.

4.1 Acoustic Positioning Methods

Methods of deep water acoustic positioning vary in terms of accuracy, precision, design and frequency dependent on their commercial requirements and the operational and environmental conditions in which they will be used. For the purposes of this document, the primary methods under consideration are the most commonly used techniques, long baseline (LBL) short baseline (SBL) and ultra-short baseline (USBL), which exhibit the key principles and considerations associated with acoustic positioning. For completeness, however, other methods are briefly covered in this section.

In all cases, it is only possible to monitor and assess the quality and reliability of the systems if there are sufficient observations and data redundancy supported by careful system calibration and monitoring during operation.

System	Advantages	Disadvantages
LBL	Highest potential accuracy Accuracy preserved over wider operating area One hydrophone needed Redundant data for statistical testing/quality control	Requires multiple subsea/seabed transponders Update intervals long compared to SBL/USBL systems Need to redeploy and recalibrate at each site
SBL	Good potential accuracy Requires only a single subsea pinger One time calibration	Accuracy dependent on shipboard VRU and heading sensor/gyro compass Multiple hydrophones required through the hull
USBL	Good potential accuracy Requires only a single subsea pinger or transponder One time calibration	Highest noise susceptibility Accuracy dependent on shipboard VRU

Table 1 – Advantages and disadvantages of acoustic positioning systems

4.1.1 LBL

LBL systems take their name from the distance between seabed transponders or beacons which can be as much as several kilometres. The beacons are deployed onto the seabed in an array and are then, as transponders, set to transmit when interrogated by a user hydrophone.

LBL acoustic systems provide accurate fixing over a relatively small area. Three or more transponders located at known positions on the seabed are interrogated by a transducer fitted to the surface vessel, towed body or autonomous object. If at least three ranges are measured from a mobile hydrophone to transponders at fixed co-ordinated seabed locations, then the hydrophone position co-ordinates can be computed. The LBL method provides accurate local control and high repeatability. If there is a redundancy (e.g. four or more position lines), the quality of each position fix can also be estimated and this is often a consideration when selecting a system for use.

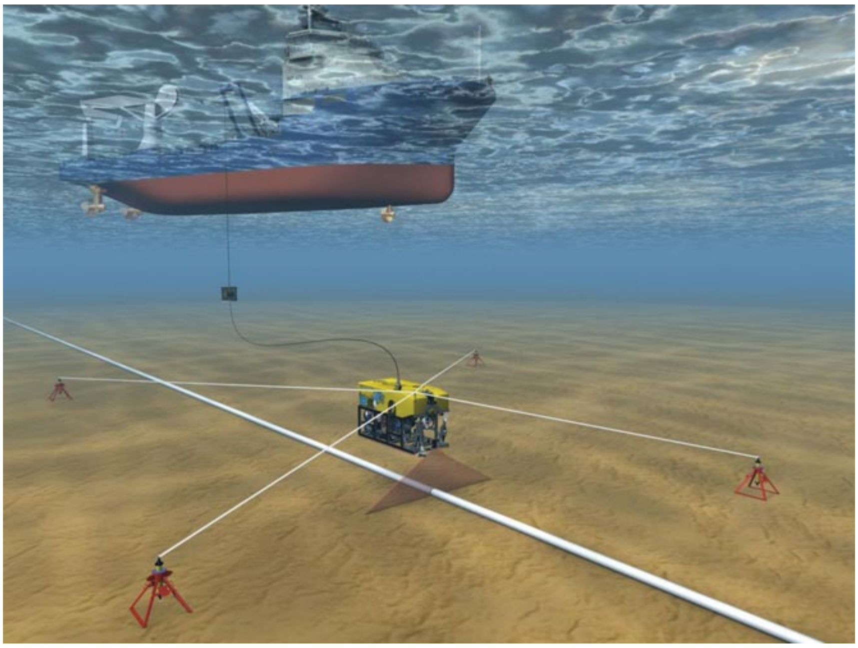


Figure 1 – Illustration showing an LBL system

4.1.2 SBL

In this type of system the baseline referred to is that between the receive transducer (hydrophone) units on or below the hull of the host vessel. It requires a pinger, responder or transponder to operate the system. No fixed beacons on the seabed are required and the system positions relative to the surface vessel. The transducers for such a system are usually deployed through dedicated tubes in the hull and are generally separated by between 10 and 50m, dependent on the form of vessel on which they are fitted. The SBL system uses relative range and direction observations to transponders to determine position relative to the surface vessel.

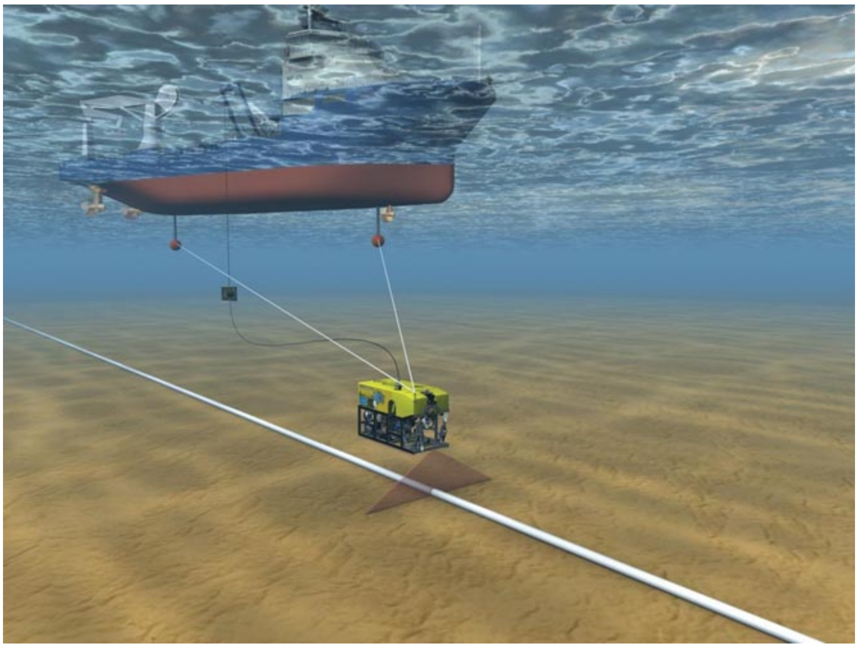


Figure 2 – Illustration showing an SBL system

4.1.3 USBL

This system is similar to that of the SBL system but adopts a very short and single combined transmitter and hydrophone unit, the transducer, for acoustic reception and any pulses or commands generated. Generally, the distance between elements in the transducer on USBL systems is of the order of 10cm.

The system computes the relative position of the transponder from the transducer in terms of a range and a bearing referenced to the system's heading unit. This is usually the ship's or the survey gyrocompass. System observations are corrected for transducer pitch and roll experienced during the measurement process using a dedicated motion or vertical reference unit (VRU) and the acoustic range is scaled correctly by application of the sound velocity profile (SVP) through the water column.

Although the physical size of the ship's equipment often makes it an attractive option for marine departments, the USBL transducer requires very careful installation, alignment, calibration and adjustment to ensure the measurements are accurate. This is critical for the USBL technique as, unlike the LBL and SBL techniques, the two observations of range and direction mean it is not possible to generate error statistics with redundant observations. As a consequence of these limitations, USBL is used in conjunction with attitude and heading sensors to maintain its positioning accuracy. At the start of a major project, the system needs to be thoroughly checked and tested to verify its settings and provide a means of quality control. This process varies but usually involves a period of time for the vessel to undertake a series of manoeuvres that describe an offshore calibration.

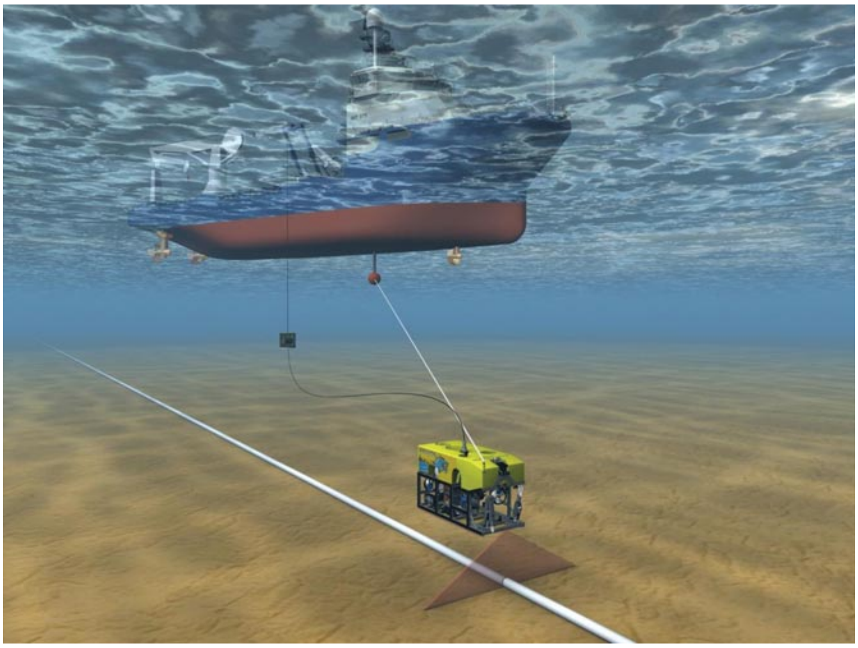


Figure 3 – Illustration showing a USBL system

4.1.4 Combined Acoustic Systems

These systems have been developed by the manufacturers to improve their ability to provide solutions for complex offshore positioning applications and are designed to combine the benefits from two or more of the methods described above to provide a reliable position solution with a good level of redundancy and quality control. The systems may offer a number of improvements such as: faster update rates of positioning, better defence against certain sources of errors or interference, combined assets employed and the possibility to support multiple operations more efficiently.

4.1.5 Hybrid Systems

The dual pursuits of higher accuracy and decreased project costs, typically measured in vessel time, have driven the development of hybrid positioning solutions for use in deeper water. Acoustic positioning with depth aiding and heading sensors attached to an underwater vehicle have been available for some time, but recently the falling cost of inertial measurement units (IMUs), Doppler velocity logs (DVL) and associated attitude sensors has enabled the development of solutions that integrate the sensor data to produce a single coherent position output. These 'hybrid' solutions still often rely on acoustic signalling but in some cases this is relegated to a secondary function, as the inertial navigation elements may be favoured and weighted in the position solution accordingly. The benefits of integrating multiple sensor data is in the creation of a reliable position solution when acoustics alone may experience difficulties or be unable to deliver the accuracy or vessel efficiency required. Additionally, there is the possibility of better quality position solutions enhanced with redundant sensor data, which allow additional statistical error estimates to be generated.

A number of such solutions have been developed for autonomous underwater vehicle (AUV) positioning, very high accuracy short range metrology type work and for ROV activities requiring additional positioning support for existing ship-based USBL equipment.

This subject is covered in more detail in Appendix 2, Section A2-6.

4.2 Equipment Components

The following diagram outlines the configuration of typical USBL equipment on an offshore vessel. It is preferred, but not always possible, for the acoustic data network to be integrated into the existing systems fitted onboard. This reduces the amount of time and effort required to install, test and verify that the individual acoustic data network and system components are all operating satisfactorily.

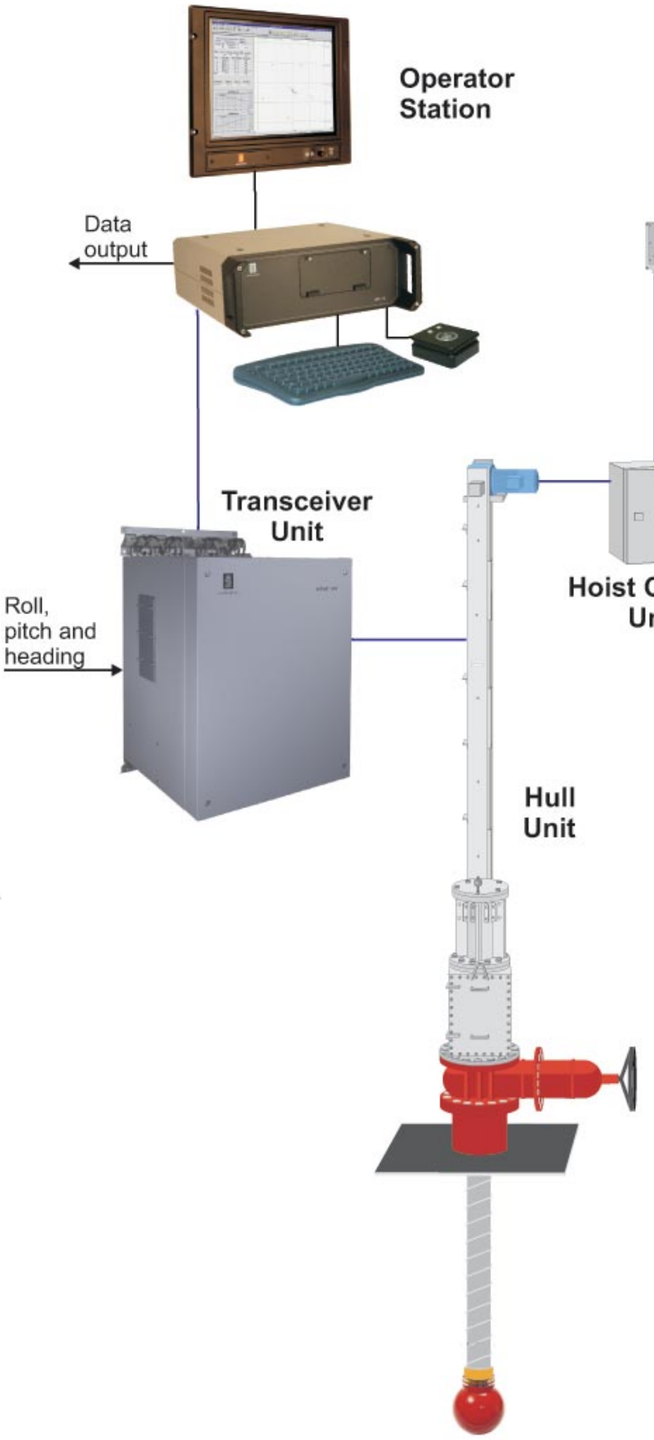


Figure 4 – Basic components of a USBL system

Acoustic manufacturers produce a variety of combinations of units and systems to meet the ever increasing demands of offshore survey, engineering and construction users. Systems developed for use with ROVs, AUVs and integrated systems are common. They have their own terminology for certain parts of the system. To maintain standard descriptions for the main units of an acoustic positioning system, the following terms and descriptions have been adopted. A full glossary table of terms and names with descriptions can be found in Section 2.

Below is a summary of the equipment and the main component parts which make up a typical acoustic system.

4.2.1 Transponder, Beacon or Station

Figure 5 – Typical transponders used for surface and underwater position reference

Each transponder, beacon or station comprises:

- Subsea housing rated to a specific water depth;
- Integral battery pack which provides power over a period pre-determined for the unit and its operation;
- Integrated electronics package to process any acoustic signal commands and maintain scheduled transmissions;
- Frame stab, frame collar or flotation collar to secure the beacon in place;
- Optional acoustic release system;
- Optional integral serial port to telemeter data from external sensors, such as depth, heading or pitch/roll.

4.2.2 Ship Receiver Equipment (Topsides)

- Central processing unit (CPU) or data acquisition unit (DAU) comprising:
  - Transmitter, receiver, central processing and I/O unit;
  - Hull mounted or through-hull deployed transceiver/hydrophone unit;
  - Hydrophone deck cable assembly.

4.2.3 User Interface

- Ruggedised desktop PC workstation with operating system, application software and monitor;
- Data port and local area networking units (serial or TCP/IP) for output of serial data for third party applications.

4.2.4 Heading and Attitude Sensors

Modern heading reference units with fibre-optic units and ring laser gyros providing accurate observations with high update rates are now commonplace in many acoustic positioning solutions. Their solid state and low power requirements allow their use underwater where space, power and weight are at a premium. These units do require careful alignment on their host vehicle or structure. Their introduction has enabled underwater vehicles to achieve enhanced positioning solutions.

Attitude sensors have also developed rapidly in recent years through the use of micro-electronics and now solid state and actively damped components provide accurate pitch and roll data to further reduce positioning errors. Their rapid data update rates, as fast as 100Hz, support applications such as multi-beam echo-sounders that are used to image and map the seabed.

4.3 Acoustic Frequency

The availability and selection of frequencies for use in deep water acoustic positioning is generally limited to the lower and medium frequencies (8 kHz to 16 kHz) when considering any systems that transmit through the complete water column. However, for systems operating exclusively at the seabed, the choice of frequencies is wider (15 kHz to 75 kHz), and for very accurate solutions, still higher frequencies are used (40-100+ kHz). Many systems already in use with a track record in relatively shallow water can operate and provide good positioning in deeper water.

The selection of low, medium or high frequency systems is part of the planning when the ranges, coverage and accuracy need to be considered for the application or applications anticipated. The implications of the choice of frequency affect the following aspects of an acoustic system:

- Accuracy of the measurements and positioning;
- Size of the equipment;
- Possible range and coverage achievable;
- The likelihood of frequency clashes and interference.

These are discussed further in Appendix 3.

4.4 Signalling Techniques

There are various types of signalling available for use in acoustics. These include:

- Tone based, such as pulsed;
- Chirp modulation signalling;
- Digital spread spectrum signalling.

Recently there have been significant developments in the design and application of new signalling methods that have had a great impact on deep water acoustic positioning systems. To overcome some of the limitations with conventional narrow band acoustic communications, acoustic transmissions have been developed that use the spread spectrum technique. This signalling technology spreads the digital code and messaging over a relatively large (or wide) segment of the frequency spectrum, typically more than 10 times greater than would be required for conventional narrow band communications. Adopting this technique has meant that signalling becomes more resilient to interference and has enabled improvements in the use of power. This allows more signalling, better measurement of the time of arrival of a signal and potentially greater data throughout, so that more users can operate at the same time. New signalling techniques offer some significant benefits including:

- Increased accuracy of measurement;
- Increased range and coverage;
- Increased resistance to multi-path (spurious signals reflected by the seabed or subsea structures);
- Improved signal to noise ratio.

A disadvantage may be that the increased frequency range could open up the possibility of signal interference in some part of the spectrum but although the wider spectrum is used, the interference itself should not be any worse than traditional systems.

There is further information in Appendix 4.

4.5 Velocity of Sound

The speed of sound in water, or the velocity of propagation of sound in water, is one of the most critical and ultimately limiting factors in enabling acoustic positioning systems to operate with optimal accuracy and reliability.

The velocity of sound in water is affected by the following factors:

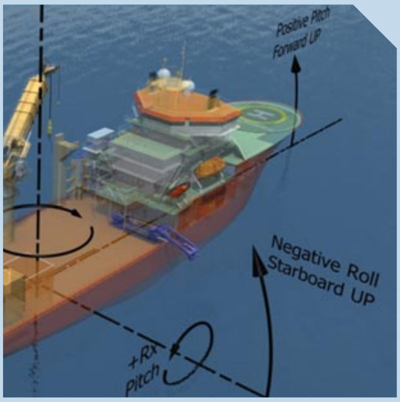
- Temperature – Seawater temperature varies throughout the water column and may be subject to diurnal change also;
- Thermoclines – Layers of water in which the temperature changes rapidly with increasing depth. The dynamic nature of these thermoclines may not always be apparent as the period of change could be weeks or months;
- Pressure and density – Changes in the density of water and the increasing pressure as depth increases will influence the transfer of acoustic energy;
- Salinity – For oceanographic projects, the water's salinity can affect the speed of sound and the travel path of the transmitted acoustic signal. Where fresh water remains unmixed, perhaps in sea lochs or near river mouths, the effect on the speed of sound can be very dramatic.

There are two main instruments used to measure the velocity of sound in water:

- The sound velocity profiler which directly measures the time taken to transmit an acoustic signal over a known baseline of the order of a few decimetres, and calculates therefore 'observes' the local velocity of sound directly;
- The conductivity, temperature and depth (CTD) probe which has sensors to measure conductivity, temperature and depth. From this data, the velocity of sound may be derived through empirical formula.

More information on the factors affecting the velocity of sound and the instruments and techniques used to measure it can be found in Appendix 5.

5



Operations

The following sections give some detail on considerations when planning an offshore project requiring acoustic positioning. It should be noted that there are significant differences between the installation, mobilisation and calibration of a ship based USBL system and the equivalent process for an LBL system.

5.1 USBL

For successful USBL operations, the system should be installed and accurately aligned on the vessel followed by rigorous calibration of the ship's equipment and seabed units to ensure that the expected or specified quality of the positioning is achieved. This process may take as long as a day and involve the vessel transiting to a suitable site for calibration checks. Once the system has been tested and the calibration process completed, the ship or vessel is ready to commence positioning as soon as a transponder or beacon has been deployed. Accuracies will vary depending on the water depth and the precision and thoroughness of calibration of associated sensors.

5.2 LBL

By contrast, it is only when the network of stations are deployed to the seabed that time can be spent ensuring acceptable performance and accuracy are achieved by careful calibration of the seabed transponders (stations). The system, once deployed and calibrated, is then available for the user. Dependent on the co-ordination of the stations, the performance of an LBL array of stations is not generally related to the water depth. This is only partly true as the station co-ordinates are essentially derived from the vessel surface positioning by global navigation satellite system (GNSS). However, the mobile unit being tracked is positioned in relation to the seabed stations and so its location is relative to these points and their associated co-ordinates.

5.3 Array Planning

Acoustic systems operate in a harsh environment which may have undesired effects on the signals in the water causing degradation in the accuracy of the positioning solution. Unfortunately, the performance of acoustic arrays cannot be guaranteed by careful planning, as it relies on predicted values for environmental parameters and cannot always foresee sources of acoustic interference. To ensure successful deep water positioning operations, it is essential to systematically identify the issues which may influence the system performance and address each in turn to build up knowledge and mitigate the associated risks. Environmental data will influence selection of equipment whilst equipment will, in turn, influence methods of deployment and recovery. These aspects of the operations will be largely dictated by the required operational characteristics of the positioning.

Array planning applies mainly to the operation of LBL systems in deep water. However, some of the elements discussed here should be considered for USBL operations as well.

The planning of the layout of an acoustic array should be a logical, objective and methodical process to derive a consistent and reliable result in the field. Unfortunately, the planning of acoustic arrays is not often totally methodical and logical as it relies on predicted values for the environmental conditions and the possibility of interference. Several points should be borne in mind:

- Appendix 1 relates to the Sonar Equation and outlines the way a consistent assessment may be derived from the accumulation of a series of parameters. The usefulness of the equation is limited by the lack of accuracy in the values representing these parameters, so the planning requires the surveyor to take a very conservative and safe approach. This can lead to an apparent over-abundance of seabed units but, when measured against the risk of signal loss or poor positioning performance and resulting delays to vessel operations, this is a small price to pay and can be regarded as a form of insurance.
- The planning should consider the SVP and establish if the required signal path will be achievable and not suffer blanking. Large horizontal offsets between the surface vessel and seabed objects could be restricted and the inter-station observations of a LBL beacon for calibration purposes may be limited in range. As a rule, the array design should always allow for reduced ranges either due to the limitation induced by the environment or due to man-made noise during operations.
- In deep water, the primary issue is attaining adequate seabed coverage, as illustrated in Figure 6 below. The seafloor coverage in this figure is limited by the fact that the transponder projector is located at the seabed and the acoustic signal path is being refracted upwards. For planning purposes based on such a model, the inter-station distances may have to be limited to around 1,000–1,200m.

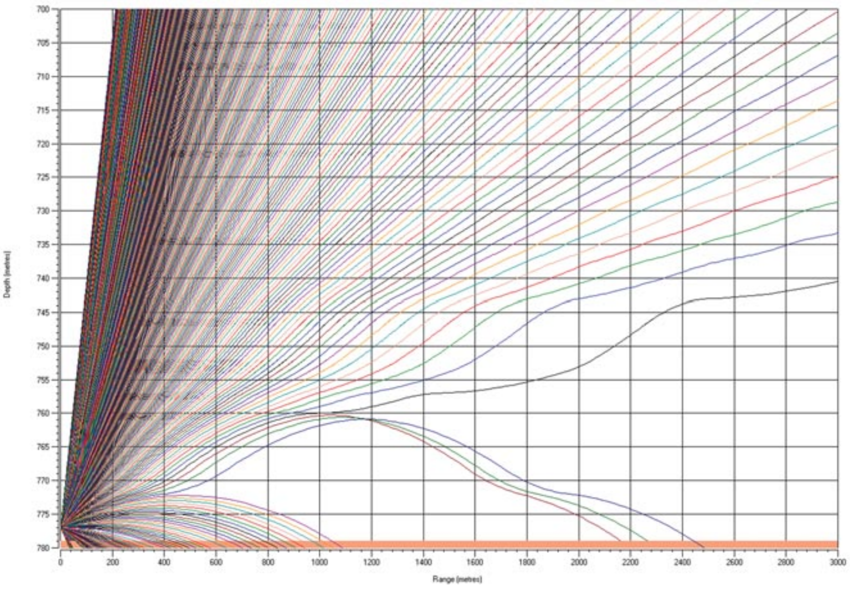


Figure 6 – An example of acoustic refraction limiting inter-station signals

5.3.1 Geometry Planning and Preparation

The coverage and accuracy of an LBL array are essentially independent of water depth. However, the control and co-ordination of the seabed beacons needs to use a link to surface satellite positioning systems which often limits the absolute accuracy. Many applications near to or on the seabed do not require absolute 'global' accuracy but rather concentrate on high relative accuracies between subsea structures and assets.

Alternatively, uses of USBL systems are always referenced back to the surface vessel. However, for certain applications, especially involving dynamic positioning (DP) operations, positioning is related to certain seabed assets. This may be achieved by onboard processing of positioning data from particular seabed transponders on the assets. In such cases, the geometry is often dictated by their layout and distribution.

5.3.2 Geometry

Geometry is a term used by surveyors to indicate the spatial arrangement of stations from which observations are being used to determine a position. Ideal geometry is where the stations are distributed evenly around the 'mobile' that is being positioned. Poor geometry is where all the stations are on one side of the mobile within a sector of less than 90°. In terms of the geometry and layout of a network of LBL transponders, like any survey control stations, the array should be designed to provide strong geometry in the required work area.

In addition, the planning should ensure that, if the vertical component of the objects' position is to be solved by using acoustic ranges, the array design of the beacon network should include vertical separation. The network of beacons should be deployed such that the relative merit of each unit is similar in terms of their predicted performance. In this way, the presence of an error or bias in the measurement can be detected and that observation rejected. Even if this should occur, the balanced geometry of the beacon array should allow the continuation of positioning without undue jumps or shifts. Furthermore, the balancing of the beacons around an area of work is important for acoustic positioning systems so that the relative distances of the acoustic signal paths are similar. This will minimise any relative effect of the environment, such as residual errors in the velocity of sound, on the acoustic signal paths.

For a discrete area of work, the number of beacons or the settings of the USBL system necessary to ensure all objects are tracked successfully is a function of the water depth, coverage required, specified accuracy requirements and the nature of activities.

The situation is made more complex if the activities involve through-water tracking of objects or if a long linear route or object is to be positioned, e.g. a pipeline or umbilical. In this case, the geometry and location of the beacons along the entire route should be carefully considered in order to ensure both good geometry of signals and the availability of at least one redundant (additional) beacon. This may require the use of a large number of beacons. However, the acoustics engineer and surveyor will have established both a minimum number and optimum number of beacons to enable positioning to continue in the event of a failure. A disadvantage of this is that too many beacons may use too many acoustic channels and therefore limit the performance of the acoustic systems and hence the operations in hand.

The geometry planning should also take account of the work area and assess the likelihood of damage to a beacon or the possibility of blanking or obstruction of acoustic signals by existing seabed structures.

5.3.3 Distance Restrictions on Range

Of the three main types of systems described in this document, the two that are referenced to the surface vessel, i.e. the USBL and SBL methods, are limited to providing range and coverage of an area centred on their host vessel. Based largely on frequency, the range achievable is represented by the practical depths at which the units can provide seabed positioning. USBL systems are generally limited to less than 4,000m, whereas SBL systems can extend this range to over 4,000m. Unfortunately, it is expensive and unwieldy to build and install units of the physical size required to achieve the desired accuracies, in particular, the direction component required by deep water acoustic operations. LBL systems are not constrained in the same way as the USBL and SBL systems, and so an LBL system can use different frequencies more effectively to develop longer range and cover greater areas of operation. A note of caution is necessary, as the marine environment has a strong influence on the way the acoustic signals travel. It is common that close to the seabed in deep water, acoustic signals will not travel between beacons separated by more than 2,500-3,000m and in some cases by more than 1,500m.

Appendix 3 also covers some of the effects frequency has on the range of acoustic positioning systems.

5.3.4 Terrain

The local seabed terrain has the potential to block acoustic signals, and an incline in the seabed can impact the effective range of acoustic signalling. This is especially the case when operations are near the seabed.

When planning an LBL array, it is necessary to consider the effects on acoustics of local ridges or troughs in the seabed and sandwaves, and any changes to the overall terrain across a project area. The nature of the seabed is also important, whether it is solid or consisting of soft mud into which equipment may sink. Clump weights and strops can be designed to avoid this.

Whilst in general the seabed may be featureless, small undulations can occur with ridges and troughs of several metres. This could be sufficient to obstruct the acoustic signalling between the seabed transponders or stations and the mobile unit being tracked. This can be overcome by designing the seabed frame to allow the transponder to 'see' over the undulations. Other designs may allow the transponder to float above the seabed but these may experience some movement due to currents.

5.4 Mobilisation

Although many deep water operations will be based from dedicated vessels with fully installed, calibrated and functioning systems, there are times when a vessel of opportunity is used. In such cases, extra care should be taken during the installation, calibration and operation of the system prior to positioning operations.

In addition to any specific system installations, mobilisations require good planning and properly organised logistics to ensure that delivery, installation, calibration and set up all conclude successfully to allow operations to commence. Vessel mobilisation should not be underestimated and sufficient time and resources must be allowed to complete the mobilisation work and to verify it has all been carried out properly.

5.4.1 Transducer (Hydrophone) Installation and Deployment

It is necessary to install the hydrophone in a position that is relatively noise free, safe from obstructions and signal blanking, and ideally offers access for maintenance. Generally, some form of compromise is necessary. In addition, the hydrophone will need to have its linear and rotational motion compensated for in order to remove biases due to these effects.

It should be recognised that for some specialised operations, the surface vessel will not have a suitable system already installed. In this case a temporary system may be mobilised and this installation may take place in less than optimum circumstances. This could result in the acoustic tracking being prone to performance problems. The consequences of poor installations are almost impossible to overcome in the field.

The selection of a hydrophone location is usually based on the following criteria:

- Ease of access for maintenance and possible raising and lowering;
- Ability to clear the hull by a suitable amount (greater than 2m);
- Level of noise and presence of any obstructions;
- Relative motion of the unit with respect to the ship's centre of gravity and reference points.

For multiple hydrophone installations each unit requires consideration of the above criteria, and, in addition, the relative distribution of the other hydrophones must be considered.

5.4.2 Transducer Pole Design

The basic criteria for a transducer pole is that it should withstand the rigours of the motion and forces acted on it by the water when the vessel is at sea and it should provide a stable point, with minimal vibration, to generate and receive acoustic signals. It is therefore important that any chosen location for a transducer pole is free from local acoustic interference.

Some operations have used ships of opportunity and successfully deployed an over-the-side pole for temporary use. Such a mounting is by its nature prone to vibration, which can seriously affect the acoustic signalling at the transducer head.

Having selected a suitable location point on the vessel, the physical size and length of the transducer pole should be considered. If it is too long, it could flex in the water when the vessel is underway. In general, a clearance from the hull of 1-2m is considered adequate, but it is recommended that the manufacturer is consulted to ensure that their recommendations and experience are taken into account. The diameter needs to be of sufficient size to provide a rigid mounting for the transducer, typically 10 inches.

Another aspect that should be addressed is the possibility of a round transducer pole rotating, either during installation or when operations are underway. The transducer heads of most USBL systems need to be aligned accurately and fixed so that a reliable direction can be derived for any received ranges.

Figure 7 – An example of a transducer pole for installation through the hull

5.4.3 USBL

One of the attractions of the USBL system is its relatively straightforward installation, requiring only a single through-hull pole with a single transducer head. However, the overall system requires quite a number of properly installed, checked and calibrated ancillary sensor units. In order to allow these sensors to operate at their optimum they are often distributed around the vessel.

The alignment of the USBL transducer and associated reference frame is critical and, therefore, it is essential that the heading reference and motion sensor itself should be accurately aligned, both in relation to the ship's reference frame and to the orientation of the USBL transducer.

Wherever possible, mobilisation should be carried out by the manufacturer and qualified engineers and for most installations of this sort of equipment, dry docking of the vessel is necessary. Alternatively, a system may be installed with the vessel alongside, but in such cases many of the accurate alignment parameters may not be measured accurately enough. Once installed and fully tested, the calibration can be completed by fully competent operators and engineers when the vessel goes to sea.

5.4.4 LBL

The installation of an LBL system involves a ship-mounted hydrophone and a network of seabed stations (or transponders). This represents a quite different process than that for a USBL installation. The LBL ship's equipment needs to be placed free from any source of noise interference but there is no alignment or motion sensor involved in the positioning. Accurate range measurement data is necessary for the location of the stations or transponders and their accurate co-ordination or calibration. This involves the time-consuming 'box-in' technique (see 5.6.2.1), so numerous alternative techniques have evolved to improve the process. The main alternative is to generate inter-station baselines and only conduct a limited number of box-ins to determine absolute geographic positions and sufficient data to enable a statistical assessment of network accuracy.

For deep water construction operations where ROVs are present, the requirement for a transducer deployed from the vessel can be replaced by a similar transducer mounted on the ROV. This allows the array to be interrogated locally at the seabed rather than through the entire water column, with the ROV umbilical being used for communications from the surface. For the box-in technique referred to above, the USBL system's transducer can be used, subject to system specification, to interrogate the seabed transponders for ranging requirements.

5.5 Methods of Deployment and Recovery

The use of seabed units and various transponders in deep water requires that they are properly secured with appropriate fixings and that safe methods for deployment and recovery are adopted. Frequently the housings and pressure vessels required for use in deep water are large and heavy, requiring lifting equipment and special storage facilities to keep them secure whilst onboard. The deployment of systems commences with the testing and checking of units on deck prior to placing them on the seabed.

For the units being taken to the seabed, there are several approaches used. The simplest is achieved by attaching a clump weight and a flotation collar to the transponder and releasing the unit over the side. The unit will then drop to the seabed where it will be monitored for correct operation and its co-ordinates determined by means of a box-in method.

More sophisticated methods include using an ROV to place the unit directly into a frame or tripod at a pre-determined location on the seabed. This is, of course, a slower process and requires the ROV either to transport the units or for a work basket to be used to lower the units to the seabed for collection by the ROV. This method is used when the acoustic beacons need to be placed in specific holders on seabed assets.

The above options apply to both USBL transponders/stations as well as LBL stations.

A number of factors influence station deployment, including:

- Design of deep water transponder frames;
- Suitability and use of acoustics as DP references;
- Depth rating of acoustic equipment;
- Power levels and battery technology.

These and other issues regarding actual deployment of acoustic systems in deep water are covered in Appendix 7.

5.6 Methods of Calibration

Having established that the conditions and design of the acoustic system support the planned operation, the operations should also plan to include the calibration of the acoustic system and the frequent monitoring of the subsea environment. These associated activities are vital for successful acoustic positioning.

To provide accurate positioning, it is necessary for the geodetic control to be valid, accurate and consistent across the whole area being surveyed. Consequently it is necessary to derive co-ordinates of an appropriate accuracy and reliability for each beacon or station placed on the seabed. This is achieved by a technique involving calibration of the network or array of units. The box-in and network adjustment of the seabed units are the most common methods adopted. These techniques are discussed in the following sections.

5.6.1 USBL

To calibrate a USBL system it is necessary to identify and quantify several basic types of errors:

- Rotational errors – These are errors about the three axes (heading, pitch and roll) and are independent of each other. An error in either pitch or roll causes the range to appear either too long or too short. The size of the error depends on the heading of the vessel and its position relative to the seabed transponder.

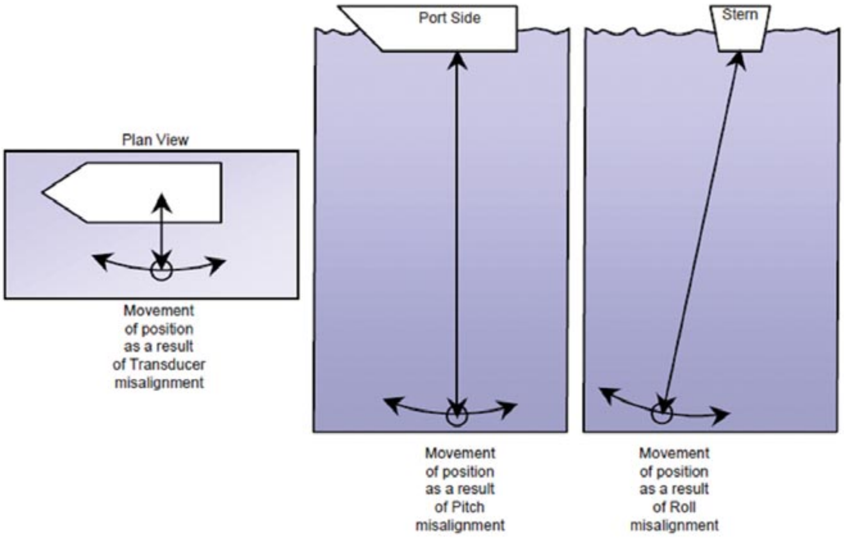


Figure 8 – Basic types of error in USBL calibration

- Range errors – There are two types of range errors: linear errors and scalar errors. To establish the presence of these errors, it is necessary to observe range data at different distances to expose either error. Linear errors or fixed errors occur when the range is consistently too long or too short. This may be due to an error with the equipment turn-around times. These settings should be checked and validated prior to mobilisation. Scalar errors may also be detected by taking observations at different distances. The size of the error depends on the range to the transponder. Scalar errors are typically caused by using an incorrect value for the speed of sound in water.
- External errors – These can affect the performance of a USBL system and limit its usefulness. Before calibrating and using the USBL system, these possible error sources should also be eliminated or at least reduced to a minimum. Examples of external errors are:
  - the accuracy of the surface navigation system
  - the synchronisation of sensors with the GNSS system
  - incorrectly measured antenna offsets
  - misapplication of sign conventions and other reference information
  - movement of beacons or transponders
  - severe variation in water depth or noise and acoustic reflections.

Contractors unfamiliar with any particular USBL systems should consult manufacturers for recommendations on calibration methods.

Of particular importance in external errors is the application of sign conventions which requires further explanation. There is no universal convention for measurement of vessel movement and rotation. For example, a vessel pitch with a resulting upward movement of the bow can be measured as either a positive or negative value depending on the system in use. Special care should be taken with inclinometers, VRUs and motion sensors to ensure that the signs of rotation are as expected by the USBL system. A typical arrangement of sign conventions is illustrated in Figure 9 below:

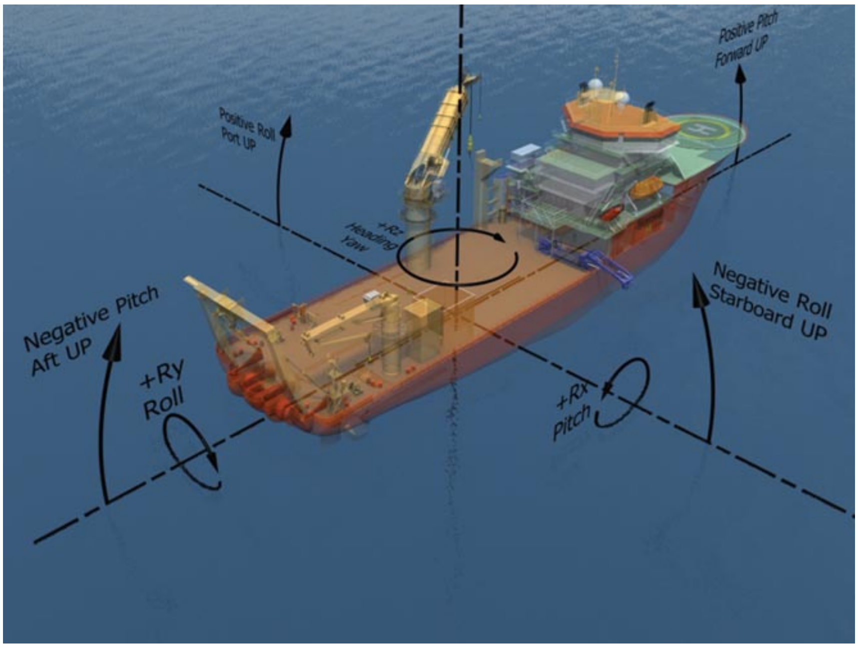


Figure 9 – Typical arrangement of sign conventions

There are many other hard to identify potential errors which could also affect data, most of which are small. To reduce the effects of these potential errors, it is important to gather sufficient data evenly distributed about the transponder beacon during the offshore calibration procedure. In addition, the process of computation by least squares aims to minimise these errors.

A number of checks and procedures should be in place for a USBL calibration. Corrections derived from these calibration tests are normally stored in the USBL unit and a log should be kept of the initial setting parameters, the dates of every check made and any changes observed. The tests include:

- Dry dock tests:
  - transducer alignment relative to vessel's head
  - three dimensional offsets from transducer(s) to vessel's reference point(s)
  - three dimensional offsets from satellite positioning systems to vessel's reference point and hence to the USBL transducer and VRU
  - VRU for draft and port/starboard tilt settings;
- Offshore checks:
  - spin test, with the vessel spinning above a seabed deployed transponder and the resultant transponder position being monitored for any spurious movement
  - determination of Z or depth component error
  - pitch and roll test
  - alignment and range test.

5.6.2 LBL

The two main methods to achieve a properly calibrated LBL acoustic array are as follows:

5.6.2.1 Box-in Method

The vessel manoeuvres around a single seabed transponder and collects acoustic slant range measurements to it, whilst recording the accurate position of the vessel's transducer using GNSS and motion sensor units. Subsequent processing of the vessel position and range data allows the position of the seabed transponder to be determined. The route the surface vessel takes around the transponder can be a circle, triangle or a square. There are advantages and disadvantages to each type of manoeuvre. The procedures adopted should take account of any potential shortcomings and ensure the data collected is suitable for the requirements of the operation. A variation on the box-in technique is called the 'top-down' calibration where the transponder position is determined in USBL mode by taking an average position. This method provides a quicker result but is less robust in terms of accuracy.

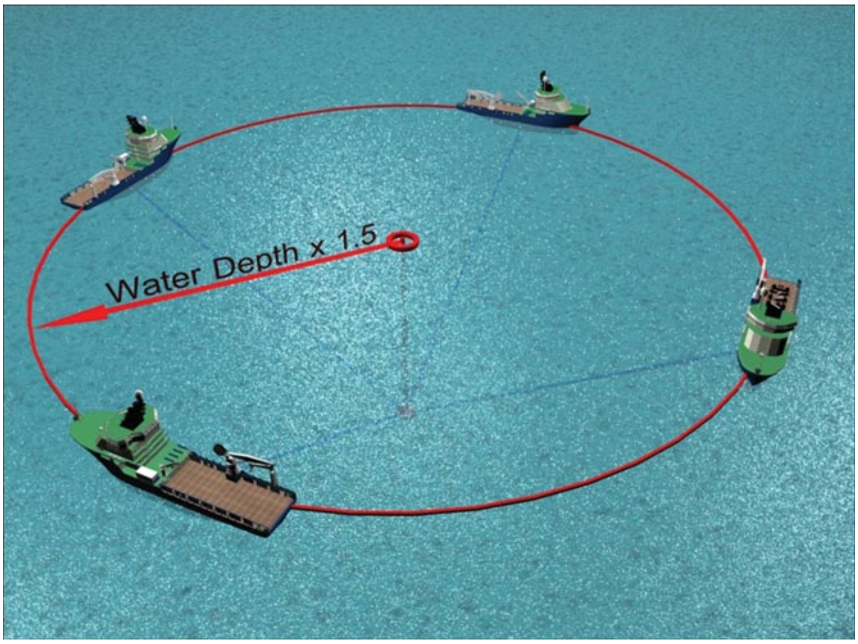


Figure 10 – The box-in method

5.6.2.2 Direct Measurements of Baselines

Intelligent transponders can generate inter-station measurements or baselines. The sequence is normally initiated from the vessel and enables the beacons that are relatively close to one another to generate a series of measurements between the transducers. These slant ranges are then used to form a network of observations which when repeated provide an accurate and robust solution. By introducing the 'known' positions of the transponders that were 'boxed in' into the network, statistical computation methods can be used to determine the co-ordinates of all transponders in the network. Care should be taken to measure and control the depths of the beacons on the seabed to avoid errors propagating throughout the array.

Although potentially very accurate, as each end of the baseline is fixed, the outer beacons of an array may suffer from relatively poor geometry and care should be taken to ensure the velocity of sound is accurately measured to avoid unwanted scale errors. This is true of the whole network of beacons but less well controlled and identified at the edges of the array. This approach is valid for any network of transponders that have acoustic signal paths 'visible' to one another. Some low frequency LBL systems may have their beacons distributed a little too far apart to receive the acoustic signal from an adjacent or relatively nearby beacon. In such cases the box-in method should be adopted for all transponders.

5.7 Quality Control

To ensure that the performance of deep water positioning is appropriately accurate and reliable, quality tests and checks should be carried out on various parameters and variables:

- Calibration – Accurate set up of positioning equipment prior to operations is vital. The process is described more fully in Section 5.6 above.
- Fundamental positioning variables (position, heading and speed) – Operators need to monitor the positioning solutions in order to detect gross errors such as sudden shifts or jumps in the data streams for these variables. Duplicate or multiple sensors, though costly, can be of value in checking the accuracy and reliability of data for critical operations.
- Update rate and signal/noise ratio of acoustic systems.
- Redundancy – The use of more observations than are required to compute a position to allow statistical checks and estimates to confirm good, accurate and reliable data.

5.8 System Performance

The performance of an acoustic system is ultimately limited by the acoustic conditions in the water. The combination of the various signal losses, noise sources and detection capabilities should not exceed the signal level available from the desired signal source. Noise from vessel thrusters and other man-made sources, as well as aeration and turbulence, will all be detrimental to efficient acoustic positioning. At long ranges, the energy of the acoustic pulse will decrease and decay. If the detector is limited or insensitive then there will be no measurable acoustic signal. As each project will have its own unique combination of parameters, the actual limits of a system in a specific set of conditions may be ill-defined in advance of the operation. In addition, temperature layering in the water column and other environmental effects can cause errors, especially when the horizontal displacement or range from the vessel is large.

The following sections outline the performance of deep water acoustic systems with respect to various technical acceptance criteria.

5.8.1 Users and Frequency Allocation

The move into deeper water means that more and more simultaneous acoustic positioning operations are being carried out in a relatively small area. This puts pressure on the limited acoustic bandwidths available for the various systems and may lead to acoustic pollution which can completely blank out the users and objects being tracked.

Interrogation and reply frequencies are assigned to transponders so that the ranging pulses or data telemetry functions can be achieved without interference. Typical channel separation for a 24-36 kHz system could be 500Hz. Leakage of one signal or acoustic pulse from one channel to another adjacent channel will result if the chosen frequencies are not separated sufficiently.

For operations where there will be multiple users of acoustic systems from a number of different vessels or installations in close proximity, an acoustic frequency management plan is required that pre-assigns channels to each transponder in the water, thus avoiding interference and associated delays to vessel operations. Ideally, one user or vessel is made responsible for the implementation of the management plan at site and for the control of corrective actions in the event that there is interference.

5.8.2 USBL Position Updates in Deep Water

A further characteristic of deep water USBL operations is the time required for the acoustic signal to travel from the surface unit to the seabed for the seabed unit to reply and for the signal to travel back to the surface. In 750m of water this is around 1.5s per transponder. If interference or corruption of the acoustic signals from one beacon by those of another is to be avoided, then each beacon may need to transmit at a slightly different time, such that each beacon transmits its response at a different time offset following reception of an interrogation message. This may add several seconds to the reply being obtained and leads to an update rate for sub-surface positions as slow as one position update every 2 or 3 seconds (or even slower for deeper waters). In water depths measured in kilometres, these time delays may become critical to the continued success of operations. For ROV positioning in deep water, the introduction of local motion measuring systems such as DVL or inertial navigation system (INS) systems can provide additional data that maintains a position solution in between acoustic updates. The situation for LBL operations is usually not as severe as the baseline distances from the seabed transponders to the mobile hydrophones are less than the depth.

5.8.3 Geodetic Control

All survey/positioning operations are referenced to a geodetic datum that provides a fixed reference for the co-ordinate system and that defines the shape of the earth in mathematical terms through the use of a spheroid model. Several hundred different geodetic datums are in use around the world based on historical work conducted by national geodetic organisations. With the introduction of GPS, a global datum (World Geographical Reference System (geodetic datum) WGS84) was developed. It is important that the relationship between WGS84 and the local geodetic datum is known and applied correctly in positioning computations. Failure to do this can result in positioning errors of up to 200m. A database of the spatial relationships between WGS84 and geodetic datums in use in various locations is held by the International Association of Oil & Gas Producers (OGP) Survey and Positioning

Committee (previously the European Petroleum Survey Group) and should be consulted prior to operations.

The global accuracy of WGS84 is sufficient for most applications, however, the high accuracy demanded by surveying and geodetic users has resulted in the frequent use of the international terrestrial reference framework. This has a temporal element as well as a spatial element that reflects movements of the earth's crust. Augmentation of the basic signals by DGNSS or real time kinematic solutions further improve accuracy for the surface reference positioning.

5.8.4 Acoustic Noise and Possible Causes of Interference

The most significant problem for acoustic positioning is noise – i.e. unwanted energy in the frequency band used by the positioning system leading to degradation of signal. Such noise can be divided into two categories, firstly, environmental or external noise and secondly, noise generated onboard the host vessel of the acoustic positioning system, such as self noise (noise generated by the ship or ROV).

The main environmental noises are:

- External shipping noise;
- External noise from machinery such as drilling operations;
- Other acoustic systems – simultaneous operations;
- Biological (marine life) noise;
- Wind and rain.

Distinguishing between environmental noise and mechanical or artificial interference is not always straightforward when operating acoustic systems. It is possible to categorise the possible man-made or self noise sources as acoustic interference.

Interference from other acoustic equipment may be a significant problem, particularly in deep water developments, and some form of plan to manage frequencies may be appropriate.

Various other noise sources exist, such as seismic activity noise and molecular agitation noise, but these are normally less significant and, in the case of seismic activity, less frequent.

There are a number of further possible causes of acoustic interference. These are:

- Changes to the velocity of sound in water – The velocity of propagation of sound in water is one of the most critical and ultimately limiting factors in enabling systems to provide their potential accuracy.
- Internal waves in deep water – These occur below the surface of the sea. They are normally associated with bodies of water where the density is very well defined and can be considered stratified or layered but where there are localised rapid changes in water temperature caused by the internal wave. The change in temperature can be severe, resulting in significant errors in acoustic positioning and, in some cases, loss of positioning all together.
- Ray bending – A phenomenon produced by the variation in the layering and condition of the water.
- Acoustic blanking – A phenomenon produced by ray bending in which there is inadequate acoustic signal from an area.

Further information on acoustic noise and interference can be found in Appendix 6.

5.8.5 Achievable Accuracies

The accuracy of acoustic positioning is dependent on a number of variables and a wide variety of potential errors which need to be minimised or eliminated. The most significant of these potential errors are discussed elsewhere in this document.

The overall accuracy of an acoustic fix will depend on:

- Water depth;
- The accuracy with which a transponder array is established relative to a geodetic datum;

- Determination and suppression of multi-path effects (reflections). This is particularly noticeable in the vicinity of fixed structures such as production platforms and is often worse for USBL and SBL systems than for LBL systems;
- The accurate determination of sound velocity, velocity gradients and the amount of refraction;
- Frequency used – accuracy and resolution increases with increasing frequency, but at the expense of the range and the power required;
- The geometry of the ranges that create the position solution and, to a degree, seabed topography, i.e. whether or not there is a 'line of sight' between transponders;
- The sophistication of the processing system and software being used;
- Errors in time measurement owing to the presence of noise in the received signals.

This list is not exhaustive but covers the majority of significant influences on acoustic positioning accuracy.

6

Associated Topics

This section provides observations and comments relating to the technical, software and engineering elements which should also be considered for deep water acoustic positioning.

6.1 Integration of Systems

The derivation of position relies on adequate data. An acoustic positioning system on its own in deep water may have considerable limitations and deficiencies and so peripheral sensors are used to augment the solution. This process requires the integration of this data in a computation. This is a complex process and to achieve an optimum solution the timing, relative weights (i.e. how much merit each observation is given in a position computation) and some form of qualitative estimate of the errors for quality control is required. This all requires expert design and testing.

6.2 Communications

The fundamental of acoustic positioning is the transfer of an acoustic signal from point to point. However, associated with this process is the need to command and control the system and to transfer any peripheral data or information. Such communications can be compromised by excessive range, by noise in the water column or by other sources of interference described earlier, thus stopping the overall operation. It is often overlooked in the planning of operations but is a key element in ensuring the success of the operation of the system.

6.3 Software, Interfacing and Display

Related to the integration of data for the computation of position is the configuration of the hardware units, their interfacing to allow data flow and the software to manage this. These components of the acoustic positioning system are internal and usually at least partly hidden from the operator. However, when testing and planning a project it is good practice to ensure that all the system components are compatible with the version of software and interfacing available.

6.4 Additional Peripheral Sensors and System Interfacing

Peripheral devices can vary enormously in their capability, quality and purpose. For deep water operations they are also engineered for the extreme conditions and may be housed in a solid unit for operation at the seabed. These are key units and require to be fully tested as a functioning unit as part of a complete system in order to ensure that the required data flow can be achieved.

6.5 Permitting and Legislation

Many deep water projects occur in relatively remote places where the logistics of transportation of system units must be carefully planned. In addition, project planners should take into account the fact that the components of some deep water positioning systems are considered to be of dual use (military) and additional time should be allowed for the preparation and processing of additional forms and certificates.

6.6 Training and Competence

To ensure the success of projects it is necessary to have suitably experienced and qualified personnel to calibrate, control and operate the systems, so it is important to select the team carefully. This may not always be possible so it's important to review the team and their knowledge and experience with deep water acoustic positioning. Manufacturers and other specialist providers offer a number of training opportunities.

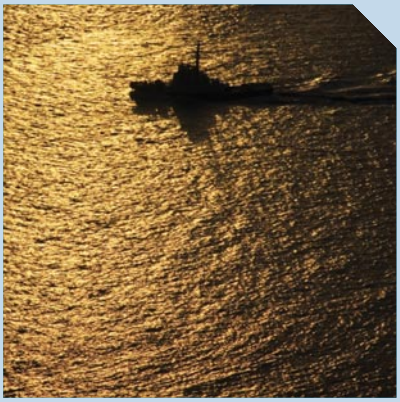
6.6.1 Positioning Courses

General courses that cover the basics of geodesy, positioning theory and design as well as some basic acoustic positioning elements are required. Ideally they need to be of short duration and provide the attendees with suitable course notes and practical exercises to demonstrate the key elements covered.

6.6.2 Acoustics Courses

Specialist courses covering the basics of acoustics and also relating to practical operations. As well as covering the theory of acoustics and the operation of specific hardware and software packages, it is important to provide a practical element to training personnel that includes rigging of transponders, deployment, calibrations and actual operations.

7



Applications of Acoustic Positioning in Deep Water

7.1 Dynamic Positioning

Assets	Permanently installed SBL or USBL systems onboard the vessel. All positioning can be maintained from the vessel and is either relative to the vessel, a seabed transponder or another reference positioning system such as GNSS. At least one (but usually four to five) seabed transponders (beacons), are deployed.
Objects tracked	The surface vessel that is required to maintain its position.
Accuracies	Many DP applications deliver positioning relative to some seabed asset such as a wellhead or a pipeline. This results in an accuracy that is often not related to depth. Alternatively the positioning is established relative to the surface GNSS system onboard the vessel. This may result in accuracies of several metres to over 10m depending on the water depth and the dynamic nature of the velocity of sound profile.
Methodologies	The permanently fitted SBL or USBL acts as a reference for the vessel. The chosen location, such as a well, is entered into the DP console, and the positioning systems checked to make sure they are operating correctly and no alarm conditions are present. The vessel manoeuvres onto the location and the reference seabed transponder is deployed. If a single transponder for a USBL system is deployed, this is normally located close to the well location or even onto a special frame on the well itself. A second back-up unit may also be deployed to provide some redundancy should a failure occur. If a combined LUSBL system is being used then four seabed transponders should be deployed within their range and within the beam 'footprint' of the vessel transducer units. These units usually have a limited beam width of around 25-30°.
Limitations	The inherent accuracy of the system may be low, relative to the survey requirements of the project. In 1,000m of water, for example, existing DP systems may achieve a positioning accuracy of ±4-10m.
Points to note	The surface positioning is usually referenced to GNSS which has an accuracy of ±1-2m for standard systems. Comparisons should therefore take account of this when analysing and planning operations. Full survey applications in deep water will often require the deployment of additional assets. These may communicate and work with the DP system. It is therefore important that the flexibility of the DP systems and the availability of data sources and interfacing are thoroughly checked.

7.2 Towed Body ('Towfish') Positioning

Assets	USBL systems fitted onboard a survey vessel or vessel of opportunity. All positioning can be maintained from the vessel and the reference for the survey data collected is maintained relative to the towfish. The vessel position can be referenced to the real world through a positioning system such as GNSS. At least one USBL is installed but frequently requirements state that it is necessary to have some form of back-up. It is also recommended that, where possible, two transponders are installed on the towfish.
Objects tracked	The towed body or towfish is required to maintain its position either along a route or corridor or perhaps along a regular line pattern.
Accuracies	Many towed body applications deliver positioning relative to the GNSS used by the towing vessel. Otherwise the positioning can be established relative to a sub-surface target. However, this is usually a quality control and verification process. A permanently fitted USBL system should be able to position a towed body to better than 0.5% of the slant distance between the towed body and the surface vessel.
Methodologies	The permanently fitted SBL or USBL usually acts as a reference from the vessel to the tracked objects. The transponder is deployed on to the towed fish. If a single transponder for a USBL system is deployed, this is normally a transponder or responder type of unit that transmits using either localised battery power or the integral power from the tow cable, and receives its trigger pulse through the tow cable rather than through the water column, thus increasing reliability. Care should be exercised in adopting a pre-installed USBL system if it has not specifically been designed for tracking towed units. This is due to the required aft-looking directional sensitivity required of the hydrophone and receiver array. Typically, these systems have a beam width of around ± 10-35° from the vertical and so if it is downward facing, it may not properly detect the towfish that is laid back from the vessel whilst under tow. Modern beam steering systems may overcome this limitation. It is becoming common practice to support the acoustic positioning with accurate depth data and, where relevant, in deeper towing situations, altitude data.
Limitations	The inherent accuracy of the system may be low, relative to the survey requirements of the project. In 1,000m of water, existing systems may offer positioning accuracy of ±10-15m for towed fish astern, dependent on the aspect ratio of the depth and layback of the towed fish. The larger the fish or the lower the tow speed the deeper the unit is likely to be and, depending on the sensors carried the unit may be required to be close to the seabed. Sensors frequently used include heading reference gyros and motion sensors, as they provide corrections for the positioning as well as the survey sensors carried. The use of these sensors increases operational costs as well as the time taken to check and calibrate the overall sensor and positioning systems. Accuracy is related to the layback distances, which may be in excess of several thousand metres. This means that the acoustic path will travel through significant layers of the water column and thus the sound velocity profile (SVP) must be established and frequently updated to remain as accurate as possible. Position updates may be regular and frequent, however, the travel path, being astern of the surface vessel, may be prone to signal interference and loss of signal caused by noise from the vessels propeller wash.
Points to note	The surface positioning is usually referenced to GNSS which has an accuracy of ±1-2m for standard systems. Comparisons should therefore take account of this when analysing and planning operations.

7.3 Riser Monitoring

Assets	Topsides equipment to operate a USBL system fitted onboard the surface vessel, its associated transceiver or hydrophone unit and the sub-surface transponders deployed onto the riser and associated well assets (e.g. blow out preventers

	(BOP)). The required signalling and measurements may all be maintained from the vessel and as this system monitors angles, rather than actual position, the reference is either an absolute inclination from the vertical or some relative measurement when the values are compared to a reference unit. At least one (but typically two) transponders are deployed, one to the riser and one to the BOP.
Objects tracked	Monitoring and assessment of any deviation of the riser from the vertical. The basis of this system is acoustic data telemetry.
Accuracies	Many different sensors are available for use in such an application and so it is not practical to offer specific accuracies or limits of performance. However, there are a number of acoustic monitoring systems that have integrated inclinometers installed, providing readings to a fraction of a degree. They have been found to offer a useful riser inclination dataset, via acoustic telemetry capable of supporting dynamic drilling operations in deep water.
Methodologies	The aim is to maintain a vertical drilling arrangement between the drilling vessel, the drilled well and the seabed riser. The surface vessel DP maintains station in all weathers and environmental conditions, which may result in some deviation of the riser. The sub-surface units are installed onto the riser and BOP in order to monitor verticality and report back to the surface via acoustic telemetry the inclination values. Either absolute values or relative values between the units are provided to the surface where the computing system derives any adjustments in position to be made by the surface vessel in order to maintain a vertical riser. A second back-up unit may also be deployed to provide redundancy should a failure occur.
Limitations	The system relies on the accurate alignment and stability of the sub-surface units deployed onto the riser. These units will have either battery power or perhaps power derived from the BOP or riser. Data telemetry via an acoustic link may be prone to interference from drilling and vessel noise. However, as this is the main risk, manufacturers have developed robust systems using frequencies, power and data codes to mitigate this interference.
Points to note	Acoustic positioning is also available during riser monitoring for the surface vessel or other objects such as ROVs. The use of battery powered units means that there is no requirement for power to be delivered from the surface.

7.4 Pipelay Positioning

Assets	USBL systems or combined LUSBL systems fitted onboard the pipelay vessel. A further vessel may also be associated with this vessel to provide survey and monitoring capability. Positioning in deep water environments may not always be maintained from the pipelay vessel and for critical areas, use is made of seabed deployed LBL arrays. The seabed transponders are used at critical points along a pipe route, such as crossover points with an existing pipeline or where there may be requirements for high accuracy, as at lay-down of the end of the pipe. The LBL array will vary in its size and number of units from as little as five or six to many tens of units for a complex area of work. Objects to be positioned include the pipelay vessel, the pipe itself and ROVs present to provide visual monitoring and perform other tasks. As well as ROV and subsea assets being positioned, the pipeline will have transponders fitted during deployment at crossovers of existing pipelines and near to the pipeline termination where an exact length of pipeline must be added to allow the pipeline end to be laid within a target box. The transponders fitted to the pipe may have inclinometers and depth sensors fitted to provide further information via acoustic telemetry, such as any residual twisting of the pipeline once it has settled on the seabed.
Objects tracked	The pipelay vessel, the pipeline itself and any ROVs present.
Accuracies	Many elements influence the accuracy of pipelay positioning. Surface USBL systems will usually provide an accuracy of 0.1% to 0.3% of range to the pipeline touch-down point, whilst an LBL array will provide a relative accuracy of ±0.2m

	to ±1.0m in relation to a manifold or termination structure. Accuracies are dependent on the survey control and frequencies of the acoustics.
Methodologies	USBL systems will most commonly be used to provide positioning for the pipeline by the installation of transponders along the pipe at frequent intervals in order to monitor the catenary and touch-down on the seabed. An ROV may also be positioned, preferably with the same system, in order to monitor and alert the operators if the pipe is seen to be misplaced, or difficulties are encountered on the seabed. Where the new pipeline is being laid across an existing pipeline, a pair of transponders are installed on the existing pipeline either side of the route to provide a 'gate', through which a pipeline mounted transponder is guided. When approaching a critical area, e.g. across an existing pipeline, use is made of several LBL transponders to ensure the pipe is placed within its intended corridor.
Limitations	The accuracies of the USBL system are relatively poor compared to the more expensive seabed deployed LBL array but, with modern systems and VRUs, they are applicable for pipelay in open waters. Operators are now using combined and integrated solutions to maintain both accuracy and a high update rate for pipe-tracking and positioning.
Points to note	The surface positioning is usually referenced to GNSS which has an accuracy of ±1-2m for standard systems. For deep water, USBL accuracies may be relatively poor, however, the introduction of inertial navigation systems (INS) to augment acoustic positioning has meant that USBL systems are more commonly used for positioning pipelay operations. This should be taken into account when analysing and planning operations.

7.5 AUV and ROV Positioning

Assets	USBL systems fitted onboard a surface vessel, sometimes augmented with a sparse array of seabed LBL units. In addition, the AUV or ROV may have INS and other associated sensors fitted. The concept of inverted USBL has been developed to maximise the benefits of the quiet subsea vehicle. More details of this are included in Appendix B. Various combinations of systems offer options for use with underwater vehicles, particularly AUVs, due to their ability to operate autonomously at significant distances from the surface ship. ROVs are more restricted in their scope of operation around the surface ship from which they are deployed. All positioning methods may be applied depending on the nature of the operation and may require additional sensor data from heading reference units, altitude, depth and DVL systems.
Objects tracked	The ROV or AUV during IRM or construction operations, or when travelling over a regular search or survey grid using survey sensors. The units may also be configured to track a specific underwater cable or pipeline route using specialist additional sensor units.
Accuracies	Many integrated solutions support a variety of applications and deliver positioning both in absolute terms to the surface and the real world, as well as relative to some seabed assets such as a wellhead or pipeline, or to an acoustic transponder. Overall accuracies are typically 0.05%-0.3% water depth with relative values at better than 1m. Note that the use of tightly integrated solutions means that the acoustic positioning element may no longer be the main component or the limit for accuracy.
Methodologies	ROVs used for survey usually have a USBL responder or a subsea transducer as well as depth, altitude, gyro and DVL sensors. More recently, inertial navigation systems have been introduced. These sensors all aid in positioning as their update rate and resolution combine with the more slowly updating absolute accuracy of the surface USBL data. An AUV can also carry depth, altitude, heading and velocity sensors to develop its onboard integrated position solution.

	Note that the acoustic positioning component forms the link to the real world and is an essential aid to the positioning process, reducing the inherent errors of an INS solution which may grow larger over a short period of time due to drifts in the accelerometers.
Limitations	The inherent accuracy of the USBL system may be low relative to the positioning requirements for the ROV or AUV. Whilst ROVs carry power, umbilicals and tethers limit their range from the surface vessel, suiting the use of USBL positioning which can be augmented by other sensors. Alternatively, the AUV has to carry its own limited power supply and must employ an efficient positioning solution that will cover the range and duration of the AUV sortie. An AUV may travel relatively long distances and, therefore, its positioning regime needs to be well planned to allow frequent updates to the onboard INS from acoustic and associated sensor data.
Points to note	There are relatively few types of AUV systems and their positioning must be well planned to ensure adequate coverage and accuracy is achieved. Tightly integrated position solutions collect a variety of data inputs and combine them in a way to derive consistent positions. A variety of additional sensors such as heading reference units, motion sensor, INS system, DVL, depth and altitude unit, are used to provide sufficient data types to enable the positioning to continue for long periods of time over relatively large areas. Many ROV operations and applications exist. However, power, data collection, telemetry and monitoring are via the ROV tether and the role of acoustics may be limited.

7.6 Construction Positioning and Installation of Structures

Assets	Ship based systems and seabed units where LBL accuracies are required. Additional units are attached to the structures to be installed and are used to monitor and control the lowering and installation of structures onto location. Additional data, such as heading and attitude sensor data, is frequently used in order to monitor orientation and settlement on the seabed. Within localised LBL arrays, the use of multiple acoustic transponders mounted on the structure can be used as an additional source of information to derive the orientation of the structures.
Objects tracked	The structure being deployed and installed. Acoustic transponders are attached to the structure to position it. The system may often be configured to also track a specific underwater object such as an ROV used to confirm the placement of a structure or to recover some of the acoustic transponders used.
Accuracies	For construction operations, the specified tolerances for placing assets on the seabed are often based on relative distances, engineering designs and technologies. For acoustic positioning, the requirement therefore is to maintain high accuracy (metre or sub-metre) positioning of the structure being deployed relative to other seabed assets. Over short distances and in a specific area, the use of LBL is often applied. USBL from the surface vessel can often be too limited in accuracy for this application, although it is commonplace to use additional sensors to remove potential error. Accuracy requirements may vary from sub-metre to several tens of metres depending on the exact operation, thus allowing USBL to be used for some structure installations.
Methodologies	The permanently fitted SBL or USBL offers a link to the outside world and data telemetry to recover sensor data from the transponders deployed on a structure. SBL or USBL accuracy may be insufficient, and so the use of LBL and associated sensors can provide a workable solution for many installations. ROVs may also be used to monitor the installation. Due to engineering tolerances, LBL systems can be used to provide a relatively accurate and fast update rate.
Limitations	The inherent accuracy of ship-based USBL systems may be too low, relative to the survey requirements of the project. In 1,000m of water, for example, existing USBL systems, may offer a positioning accuracy of ±3-6m whereas there may be

	a requirement for accuracies of ±1m relative to existing structures dependent on design and engineering. In such cases, installation of additional acoustic positioning equipment of the desired accuracy such as an LBL array may be required. Additionally, positioning latency can affect how easily the installation can be completed. Careful planning and sufficient redundancy are vital to avoid expensive mistakes or failures.
Points to note	The surface positioning is usually referenced to GNSS which has an accuracy of ±1-2m. For deep water structure installation, LBL and integrated sensor solutions dominate as well as intelligent transponders allowing the telemetry of heading and attitude data to support the installation. Comparisons should therefore take account of this when analysing and planning operations and their costs.

7.7 Relative Measurement

Assets	Transponders being located at the points of measurement and interest as well as LBL arrays or USBL systems on the surface vessel.
Objects tracked	The main objective is not to derive position but is the measurement of distance or even inclination relative to some reference plane. The system may, however, need to be configured to track a specific underwater object such as an ROV. Alternatively, referencing one transponder to another using USBL measurements can provide a position solution independent of surface satellite positioning systems. This method can be used for structure installations where a higher relative accuracy than USBL is required, but the expense of an LBL array is considered unnecessary.
Accuracies	The operation to measure relative distances, positions and associated parameters often takes acoustic positioning away from its original purpose. Accuracies therefore are not in terms of traditional positioning accuracy values, but in terms of relative measurements. A common task is assessment of the condition or status of a seabed asset and, as such, precision and repeatability are of importance rather than absolute value.
Methodologies	The permanently fitted SBL or USBL usually acts as a reference for the vessel. The chosen application will usually be relative to a specific location of known co-ordinates.
Limitations	The installation of the units on existing seabed assets requires ROV deployment and recovery as well as careful power management.
Points to note	Although a relative exercise, the surface positioning is usually referenced to GNSS which has an accuracy of ±1-2m for standard systems and which can provide some quality control on the relative measurements. Comparisons should therefore take account of this when analysing and planning operations.

7.8 Metrology

Assets	Two pipeline flanges are to be connected together by a prefabricated spool. Subsea metrology is the process of determining the spatial relationship between them. The process involves the determination of the distance between the flange ends, relative depths, relative angles, relative pitch/roll of each flange and the profile of the seabed along the intended spool route. Spools can be as short as 5m and as long as 50m.
	There are several metrology techniques using non-acoustic methods, but for the purpose of this document the assets are an LBL system with transponders installed in special brackets on seabed assets and special frames/tripods on the seabed. All positioning can be maintained from and referenced to the vessel, the seabed transponders, or another positioning system such as GNSS. At least one (but usually four or five) seabed transponders are deployed depending on the number and relative arrangement of the points to be measured.

Objects tracked	The main objective is not the positioning of a unit but the relative vector between certain specific points as described above. However, the close attendance of an ROV means that the system may also be configured to track an underwater object such as an ROV during associated seabed measurements.
Accuracies	The operation to measure relative distances, positions and associated parameters often takes acoustic positioning away from its original purpose. Accuracies therefore are not in terms of traditional positioning accuracy values but in terms of relative measurements. With modern acoustic techniques, relative accuracies of 5cm or better can be achieved with detailed engineering planning and carefully controlled observations and measurement.
Methodologies	The very high precision and accuracy required for metrology requires the use of modern acoustic techniques such as spread spectrum signalling and relatively high frequencies. Relative distances, vectors and the attitude of some seabed assets are all important parameters to be derived from metrology techniques. Positioning itself in terms of co-ordinates and locations is not usually required.
Limitations	The inherent accuracy of the system may be low in absolute terms, however, the aim is to derive relative vectors and separations between assets, such as a spool piece and riser. Different update rates and the measurement of correct offsets between key points may mean this kind of positioning system is of little practical use for any other tasks or positioning operations during the project.
Points to note	Absolute positioning as such is not actually required – it is very accurate measurements that are needed. A specific capability to achieve the required data may often mean this configuration is not used for any other aspects of the overall deep water project. Preparation for metrology measurements is critical with extensive research of the assets that are to be tied together and review of design/engineering drawings being required. For new structures it is essential that a dimensional control survey is conducted in the fabrication yard prior to deployment and is used to determine the three dimensional relationship between the transponders and the points of interest on the flanges.

7.9 Well Positioning

Assets	Permanently installed SBL or USBL systems onboard the vessel. All positioning can be maintained from the vessel, and positioning is either relative to the vessel, the seabed transponder or another positioning system such as GNSS. Usually four or five seabed transponders are deployed. For well positioning requiring high accuracy positioning, LBL arrays are used. This is normally required in situations where the new well has to be positioned relative to an existing structure such as a manifold or a series of previous installed well heads.
Objects tracked	The surface vessel and/or the associated drill string suspended down to the seafloor. The system may also be configured to track a specific underwater object such as the ROV monitoring the drilling and initial spud-in of the well. In deep water a number of associated units are used to maintain a safe well: the BOP, a temporary guide base or simply the drill string may require positioning or monitoring. The transponders deployed will be fitted to specific points to ensure the well unit and the drill string are correctly placed and accurately positioned.
Accuracies	The overall field development plan will normally state the required accuracies for the positioning of each well. This dictates how the acoustics may have to be planned and designed to achieve this. From the surface, the positioning of wells will be to an accuracy of approximately 0.2-0.7% of water depth. For LBL operations, the accuracy of positioning will be 10-20cm relative to existing structures.
Methodologies	The permanently fitted SBL or USBL usually acts as a reference for the vessel. The chosen location of the well is entered into the DP console and the positioning systems checked to ensure they are operating correctly and no alarm

conditions are present. The vessel manoeuvres onto the location and the reference seabed transponder is deployed. If a single transponder for a USBL system is deployed, this is normally located close to the well location or onto a special frame on the well guide base or the well itself. Back-up units may also be deployed to provide some redundancy should a failure occur. For LBL operations, the array is either installed by ROV from the drilling rig and calibrated relative to existing structures or it is deployed in advance by one of the anchor handling vessels or by a survey vessel.

Limitations

The inherent accuracy of the system may be low relative to the survey requirements of the project. In 1,000m of water, for example, existing systems may offer positioning accuracy of ±3-6m whereas there may be a requirement for accuracies of ±1-4m for the installation of a subsea structure such as a well guide template. In such a situation, installation of additional acoustic positioning equipment of the desired accuracy, such as an LBL array, would be required. Additionally, positioning latency can affect how easily the installation can be completed.

Points to note

The surface positioning is usually referenced to GNSS which has an accuracy of ±1-2m for standard systems. Comparisons should therefore take account of this when analysing and planning operations.

It is important to include time in the overall drilling schedule for deployment of LBL arrays – for their calibration and for confirming the quality of the positioning data prior to commencing drilling operations.

7.10 Long Term Structure Monitoring and Positioning

Assets

Permanently installed LBL or similar systems. A network or array of units is deployed and calibrated on the seabed. Associated peripheral devices such as an attitude, pitch and roll sensor or a heading reference unit may be used.

Objects tracked

The main objective is to monitor and report any relative movement or settlement of an asset over the long term. Although data is relayed to the surface, usually by acoustic telemetry, the operation is often over relatively long term periods and requires dedicated installed systems. The system may also be configured to be compatible with an ROV so that any further inspection or possible remedial work can be carried out, relative to the same positioning reference.

Accuracies

Long term positioning and monitoring of relative movement requires relatively high precision but not usually high absolute accuracy, so the LBL array can be set up relative to the seabed assets to provide sub-metre relative measurements and positioning.

Methodologies

The permanently fitted LBL array acts as a reference and the peripheral devices provide the required associated sensor data for telemetry to the monitoring operators. The units are monitored by placing a transponder. Accurate determination of their positions relative to the permanent LBL reference will be required.

For long term operation, the battery powered units will require careful set-up to ensure a balance is obtained between the frequency of data packets transmitted and the sensitivity to any movement that may take place.

Limitations

As battery power is limited, data is transmitted only as appropriate to monitor the expected movement. Systems such as these are often dedicated to their task and cannot offer much flexibility for associated operations.

Points to note

The monitoring relies often on associated sensor data that is acoustically transmitted to a surface operator for review. Battery powered systems transmit at a relatively low interval to preserve the limited power available.

7.11 Acoustic Data Telemetry

Assets	The main function associated with acoustic positioning systems is their capability to telemeter packets of data. Data is sourced from the internal mechanics of the sub-surface units such as the transponders, or from external devices such as heading reference units or attitude, temperature or other sensor data. Acoustic telemetry is not a high volume system but can offer sufficient capacity to enable operators to assess critical functions. For key applications, the use of dedicated acoustic telemetry systems may be preferred to an acoustic positioning system that also offers a data channel.
Objects tracked	Non-acoustic data – as from external devices such as heading reference units or attitude, temperature or other sensors – transmitted acoustically.
Accuracies	Data telemetry requires the use of a data packet design to handle the content. This may be designed for speed of through-put, or for data fidelity and robustness. These may not be compatible and so a compromise is required. Data corruption is a critical element to be managed by these systems.
Methodologies	There is a range of methods adopted to ensure the accurate and swift transmission of data across an acoustic link. Many methods use proprietary techniques and error correction algorithms. Commands are issued for the regularity of the transmissions, the data content and any error recovery or correction techniques to be applied. Systems often communicate 'one to one' although there are some that broadcast data 'one to many'. For some systems, there is a form of message validation to aid in the identification and acknowledgement of any transmissions.
Limitations	The inherent relationship between frequency, data capacity and telemetry range. Long range low data rates versus short range high data rates – the operations planner has to choose or reach some compromise.
Points to note	Surface vessels are often the receiving points for telemetry data. Battery power and data content dictate the update rate. The frequency of the system will often limit the range and data content capability. Dedicated systems are designed for data telemetry whereas acoustic positioning systems usually have an integrated data channel with limited capacity.

7.12 Out-of-Straightness Positioning

Assets	Permanently installed SBL or USBL systems fitted onboard the vessel to maintain a reference to the outside world. However, the main positioning and measurement activity is achieved using seabed units either as part of an LBL array or specific transponders that can communicate between themselves and provide positioning of suitable precision. At least one (but usually four or five) seabed beacons are deployed, and if an ROV is to move along a pipeline and measure relative distortions and bending, very high resolution sensors will be used.
Objects tracked	An ROV required to move along a pipe and maintain its position on top of the pipe at a stable speed. The system may also be configured to track other ROVs.
Accuracies	Out-of-straightness is notoriously difficult to capture by way of acoustic measurements and so reliance is placed on other sensors – INS, DVL and odometer units – available to ROVs. The resulting accuracy will be required to identify distortions of several parts per thousand of the distance travelled along the pipe.
Methodologies	The permanently fitted SBL or USBL usually acts as a reference for the vessel. An ROV will then locate itself to the top surface of the chosen section of pipe to be surveyed. The ROV will travel along the pipe and measure its position with the aid of wheels or rollers, DVL, INS, acoustic positioning and the camera systems, identifying any distortions or bends. The surface vessel may manoeuvre to maintain its position relative to the ROV if it is travelling over a long distance. In very deep water, for example, greater than 1,500m, the use of an LBL system may

be desired as this can provide a relatively frequent update of position for the ROV when used in conjunction with DVL and INS.

Limitations	The inherent accuracy of the system may be low in absolute terms but over its short range of operation the accuracy and resolution will be of the highest quality. In such a situation, additional acoustic positioning equipment, sensors and cameras may all be required.
Points to note	The surface positioning is usually referenced to GNSS which has an accuracy of ±1-2m for standard systems, however, the accuracies required for an out-of-straightness survey are relative rather than absolute. There are two aspects to out-of-straightness surveys, vertical and horizontal, with vertical surveys looking for potential upheaval buckling of the pipeline whilst horizontal surveys look for lateral movements over time.

Appendix 1

The Sonar Equation

The Sonar Equation is often only required by underwater acoustics engineers to aid in the design and planning of operations, rather than during field work. However, it is useful to understand the basics of the Sonar Equation, as it is an aid to describing the main sources of limitations that constrain acoustic positioning systems.

Sonar systems may be either active, or passive, in their operation. Active sonars provide their own sound source and listen for echoes as they are reflected from a target. Passive sonar equipment has no such source. These are simply listening devices dependent on a target to act as a source and emit its own noise (e.g. the engine noise from a ship or communication sounds from a cetacean). Acoustic positioning systems generally use the active Sonar Equation, although there are positioning systems available that may use each of the approaches.

For an acoustic system to operate, the hydrophone (or receiver) has to detect an acoustic signal. To achieve this, it is necessary that the signal level is greater than the noise level (NL). This is shown in Equation 1.

$$SL > NL$$

Equation 1 – The Sonar Equation

This basic form of the Sonar Equation can then be expanded in terms of the various sources of noise and associated sonar parameters. These parameters can be separated into three groups relating to:

- The equipment – source level (SL), directivity index (DI), detection threshold (DT);
- The medium – transmission loss (TL), reverberation level (RL) and NL;
- The target – target strength (TS).

Note. TS is no longer a specific key measure of how good an acoustic reflector or transmitter is the target or beacon for positioning, as these units transmit their own signal. For acoustic positioning systems this knowledge is used to aid in determining what the operational limits of the system are.

The Sonar Equation, by incorporating the above elements, provides a consistent approach that forms a basis for the calculations that determine the range of an acoustic system. In this way, it can be used to aid in the prediction of a system's performance.

A1.1 Source Level

Sound is generated by the creation of a mechanical wave. The mechanical element is the displacement of the medium (in this case water) about the source unit. The wave created is longitudinal, in that the motion of the particles conveying the energy or wave is parallel to the direction of travel. This motion creates a pressure wave and its magnitude is measured in microPascals (μPa). A Pascal is a unit of pressure equal to one Newton per m^2. However, acoustic sound levels are normally specified in decibels (dB). Decibels are units used for measuring the relative strength of a signal. The expression is the logarithmic ratio of the strength of a signal relative to some reference signal level.

Underwater acoustic signal levels are specified in dB referenced to 1μPa at 1m; thus the relationship may be stated as:

$$A = 20 \log 10 \, (a)$$

where:

a – is the amplitude of the source level in μPa

A – is the amplitude in dB

Unfortunately there are limits to the increase of the source level. These limits depend on the transducer design, the environment and the frequency of the generated acoustic signals. If too much power is introduced, then cavitation will occur. When cavitation occurs, the water around the transducer is in effect boiled by the energy produced and causes the acoustic signal to fail.

Consequently the acoustic system needs to be designed to operate within a number of limits and still perform whilst taking account of various influences. The Sonar Equation is extremely important for designers and users of acoustics to aid in the planning and operation of systems. The Sonar Equation is founded on the concept that the transmitted signal must be equal to, or exceed the effects of, any signal loss, interference or noise, so that the signal may be detected by the receiver. A fuller version of the Sonar Equation therefore includes the following key parameters:

SL	Source level
TL	Transmission loss
NL	Noise level
DI	Directional index
DT	Detection threshold

A1.2 Transmission Loss

This parameter is made up of two main components: spreading, and absorption. Spreading of the signal assumes that the acoustic energy spreads spherically outwards away from the source. This is not always the case and in shallow water the restricted environment can help to retain some of the energy. However, in deeper water, such as this document is concerned with, the situation is described in Figure 11 below. In this case, acoustic energy dissipates evenly in a spherical manner.

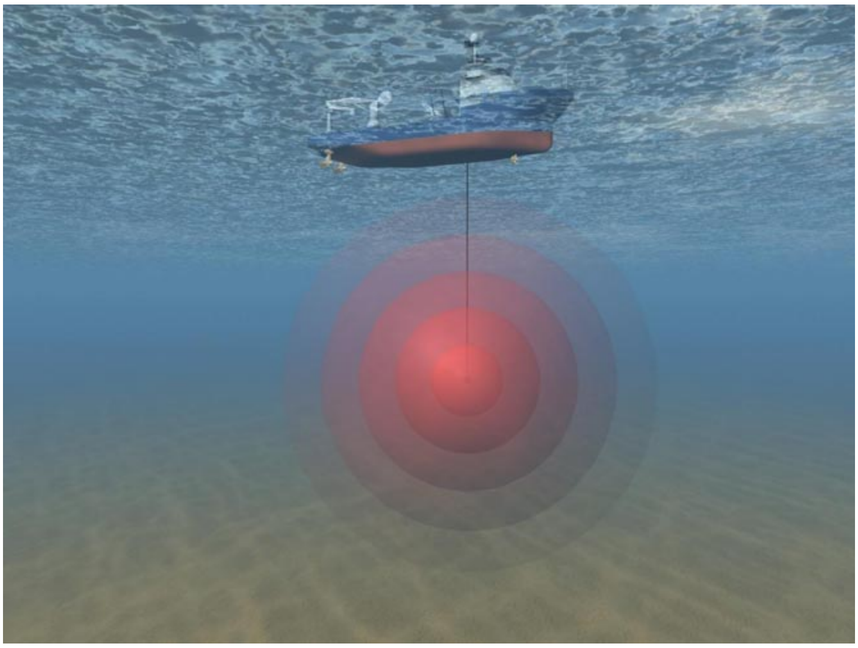


Figure 11 – Example of spherical spreading of an acoustic pulse

The second component of TL is that of absorption where the energy of the acoustic pulse is converted into heat. The absorption is related to the frequency of the acoustic pulse being generated as illustrated in Figure 12 below.

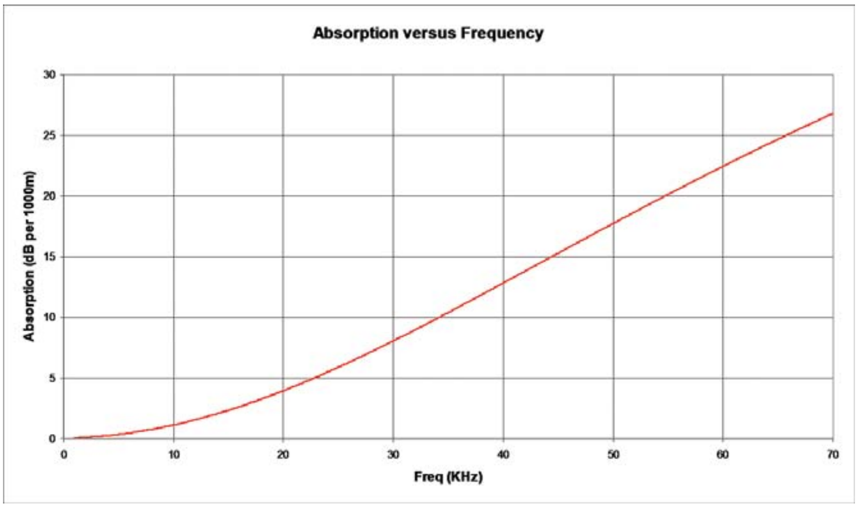


Figure 12 – Absorption is related to the acoustic frequency adopted

Thus TL is a key element in determining whether a system will be successful for an operation. With knowledge of this attribute, most acoustic sources are designed to focus the acoustic energy into a narrower beam in order to improve the signal efficiency. This effect is accounted for in the Sonar Equations by the DI.

A1.3 Directivity Index

This parameter is introduced to represent the capability of the acoustics system for spatial filtering and focusing of the energy and signals to enhance performance. The technique is used in both transmit and receive elements of many systems. In an isotropic noise field, the noise energy is considered to arrive from all directions and be of equal amount. The focusing is achieved using directional transducer hydrophones that are designed to listen in a focused and specific direction rather than omni-directional hydrophones which will listen in every direction equally.

By reducing the effective TL, the system becomes more effective. On receive units, this technique is used to focus the listening elements. The concept is shown in the figure below for the transmission of signals.

The directivity can be an important element in the design and, therefore, the operation of many acoustic positioning systems. However, the installation on a ship does not experience noise that is isotropic. The noise level coming from above the transducer hydrophone is often much greater than the noise level from below. In this case of an uneven noise distribution, the definition of the DI is given by:

$$DI = 10\ \text{Log}\left[\frac{\text{Intensity of the noise signal measured by the directional receiver}}{\text{Intensity of the noise signal measured by an omni receiver}}\right]$$

This term is often referred to as the ‘array gain’.

A1.4 Detection Threshold

The detection threshold (DT) is a parameter defined by the overall acoustics system. If the observed signal to noise ratio (SNR) exceeds the ratio set by the DT, then an object or target will be considered present due to the detection of its signal.

A1.5 Noise Level

Another term that has numerous variations is the acoustic noise. This consists of two sources or types of background noise masking the signal we wish to detect:

- Noise background or NL – This is a steady state, isotropic (equal in all directions) sound which is generated by, amongst other things, wind, waves, biological activity and shipping. For deep water operations this should be the dominant source of noise.
- Reverberation background or RL – This is the slowly decaying portion of the sound that is back-scattered from the acoustic SL input. In the sea, two excellent reflectors are the sea surface and sea floor. Additionally, sound may be scattered by particulate matter (e.g. plankton) within the water column. Acoustic reverberation noises decay relatively rapidly with time. Due to the nature of this effect and the anticipated separation of the water surface and the relatively deep seabed from the sound source, it is considered less likely to dominate.

Although both types of background are generally present simultaneously, it is common for one to be dominant.

Sonar performance can be improved by having both directional source and directional hydrophones, provided that they are directed towards the target and using appropriate frequencies to avoid signal loss.

In this document the passive Sonar Equation is considered and the specific case where the source and receiving transducer elements (the hydrophone) are coincident. For a system such as a USBL or SBL where the transducer emits a pulse to trigger, the acoustic return signal from the beacon, the two way travel path may be significant. The vessel's transmission may be of a higher power than the battery powered sub-surface unit and the relative power levels of the signals should be considered for the operations.

$$SL - 2TL - NL + DI > DT$$

Equation 2

The Sonar Equation may have a number of different forms, but each one with or without additional terms, aims to represent the factors involved in acoustics. For example, a variation on Equation 2 above has the parameter 2TL showing TL to indicate the acoustic signal having to travel in one direction, e.g. for an LBL system. In this case the equation takes the form:

$$SL - TL - NL + DI > DT$$

Equation 3

As most systems transmit their signal and then 'listen' for the return transmitted signal, this form of the passive Sonar Equation is likely to represent the way in which these systems can be represented by the Sonar Equation.

The Sonar Equation is an aid in understanding the influences on acoustic signal performance. The accuracy achieved will largely depend on the methodology adopted, the frequencies and signalling used by the acoustic system, the layout of the units and the underwater environment.

Appendix 2

Methods of Acoustic Positioning

There are three primary techniques used in acoustic positioning systems categorised by their baseline lengths between certain elements of the system. In all cases, it is only possible to monitor and assess the quality and reliability of the systems if there are sufficient observations and data redundancy.

The three systems are:

- Long baseline (LBL);
- Short baseline (SBL);
- Ultra-short baseline (USBL) or super short baseline (SSBL).

There is also a fourth possibility:

- Hybrid technology systems using a combination of these techniques.

The combined systems come in several varieties:

- Long and ultra-short baseline (LUSBL);
- Long and short baseline (LSBL);
- Short and ultra-short baseline;
- Long, short and ultra-short baseline;

Typical baselines are as follows:

System	Baseline length
Ultra-short baseline (USBL)	<10cm
Short baseline (SBL)	10-50m
Long basline (LBL)	100-6000+m

Table 2 – The typical baselines of the main types of acoustic positioning systems

A2.1 LBL Systems

LBL acoustic systems provide accurate fixing over a relatively wide area. Three or more transponders located at known positions on the seabed are interrogated by a transducer fitted to the surface vessel, ROV, towed body or autonomous object which will be operating in the vicinity. The transducer mounted on the object to be positioned interrogates the transponder array and only ranges are measured as the baseline distances between the seabed transponders have already been determined.

Calibration is achieved in one of several ways. The most common is to allow each transponder to interrogate all the others in the array, in turn. If the vessel has a GNSS or other geographically-referenced system, the transponder array may also be geographically calibrated. Accuracy is related to the separation of the transponders (based on frequency) and may be sub-metre to a few metres. Owing to the relatively slow speed of sound in water, the update rate can be slow in deep water for objects near the surface. For seabed objects the update can be only a few seconds and the data may then be relayed to the surface without interrupting the positioning.

The inter-station baselines joining pairs of seabed transponders can vary in length from less than 100m to over 6km depending on the water depth, seabed topography, acoustic frequency used and the environmental conditions. The LBL method provides accurate local control and high repeatability. If there is redundancy, i.e. four or more position lines, the quality of each position fix can also be estimated and this is often a consideration when selecting a system for use.

The LBL technique also provides a position solution that is not referenced to any one vessel but is either locally referenced, e.g. to seabed manifolds and wellheads, or referenced to an absolute position using GNSS or a similar system. In this respect it differs from other acoustic positioning methods in that it is essentially static equipment placed on the seabed acting as a reference, giving the system the ability to provide a relatively large area with high accuracy positioning independent of water depth. Whilst the positioning of objects is carried out relative to the seabed transponders and benefits from a stable and relatively large coverage, the positions of the transponders themselves must be accurately determined. This process of calibration or, more correctly, co-ordination, relies on the links to the surface survey vessel and its positioning system.

For many reasons, the accuracy achieved with such arrays may vary considerably, not least due to the frequency used, the separation and accuracy of the calibrated position of the beacons and the geometry of the acoustic ranges they deliver to the hydrophone or receiver. This is discussed in Sections 5.3.1 and 5.3.2.

Seabed transponders cannot be fixed or deployed as accurately as land based systems. Once laid, however, a pattern of transponders needs to be fixed relative to each other and then tied into the geodetic datum in use. The latter is usually achieved using GNSS. Recalibration of an LBL array of beacons is required each time it is deployed (the exception is if pre-installed frames are present), the positions of which are already accurately surveyed.

Commonly, the methods adopted are based on either a direct ranging to each beacon from a surface vessel using the box-in method, or the beacons each transmit to each other over the baseline separation. These distances are used in a network adjustment to determine a consistent array of beacon co-ordinates. Calibration is covered in more detail in Section 5.6.

In deep water areas and, in particular, water depths of over 1,000m, where the accuracy of the surface referenced types of positioning deteriorates, LBL systems often become more appropriate. LBL systems are common for use in drilling and construction operations in deep water areas, and in particular, very deep water.

A2.2 SBL Systems

In this type of system, the baseline referred to is that between the receive transducer (hydrophone) units on the hull or below the hull of the host vessel. Such systems require a pinger, responder or transponder. No fixed beacons on the seabed are required and the system positions relative to the surface vessel. These transducers are deployed through dedicated tubes in the hull and could be as little as a few metres to tens of metres apart on large vessels such as deep water drilling vessels and mobile drilling units (MODUs). The SBL system uses relative range and direction observations to transponders to determine positions relative to the surface vessel. The SBL interrogates the transponder and the return signal is received by several transducers which then discriminate the direction of the return signal. The arrival of the signal allows for the derivation of the range or distance between the transponder and the reference point onboard the vessel. The transducers form a plane below the hull of the vessel that acts as the reference of the system and must be accurately determined with respect to any reference datum onboard the vessel. Due to vessel movement (pitch and roll), real-time information on the attitude of the transducer array is required and the corrections for pitch and roll applied to ensure stable and accurate positioning is achieved.

The system operates by requiring the seabed pinger to transmit a signal and the transducer units to receive the signal. The transducer units all receive the signal at a slightly different time. This enables the system to determine the direction of the return signal, and the time of arrival at the master unit allows the system to derive the range. Depth is normally entered either manually or via a sensor to aid in maintaining the accuracy of the system.

Due to the longer baselines of the receive and transmit units below the surface vessel's hull, the accuracy is usually better than for USBL systems. Some vessels have as many as eight hull penetrations for tubes or poles on which the transducers are deployed. All of these should be positioned accurately and their relative offsets known for the operations to benefit fully from the SBL system.

SBL systems typically operate with a minimum of four transducers to allow some redundancy in the observations. The introduction of four more units below the hull allows for deep water operations as the larger the array, the better the directional discrimination of the SBL system.

A2.3 USBL Systems

This type of system is similar to that of the SBL system, but adopts a very short and single combined transmitter and hydrophone unit which contains multiple receiver elements. The USBL system again measures the direction and range of a signal from a transponder or pinger. Although its physical size often makes it an attractive option for marine departments, the USBL transducer requires very careful installation, alignment, calibration and adjustment to ensure the measurements are accurate. This is more critical for the USBL technique as, unlike the LBL and SBL techniques, there is no redundancy.

The vessel must deploy at least one transponder (usually battery-powered) for USBL systems to function. These units may be deployed by wire-line from the vessel, by an ROV or simply dropped overboard with an acoustic release for recovery.

An interrogating pulse is transmitted from the transducer. This pulse is received by the transponder on the seabed (or ROV structure) which is triggered to reply. The transmitted reply is received by the hydrophone elements on the transducer. The transmit/receive time delay is proportional to the slant range. The transducer hydrophone elements derive the vertical and horizontal angle of the returned acoustic signal by measuring the received signal phase at each element. In this way, the range and direction to the transponder from the transducer are computed.

To compute a position relative to the vessel and, ultimately, a global position for the transponder, the vessel heading and VRU are used to correct the measured angles. As the system relies on the use of these external sensors, it is imperative that the alignment of the transducer (and the measurement elements) with respect to the axes of these sensors is accurately calibrated.

Some advanced USBL systems use a form of beam-steering of the elements to focus the energy and enable a higher resolution of the direction of the pulse. Manufacturers have developed advanced techniques to enable multiple tracking and positioning of deep water objects using a series of elements that focus the energy and acoustic signals to ensure good performance in any direction. Other techniques adopted include moving or tracking heads for USBL systems. In these, the directivity of the signals is focused by moving the sensor orientation. This is particularly useful if the object to be tracked is moving in a particular sector, such as a towed survey side scan sonar system astern of the vessel, rather than an ROV that is below the vessel.

Semi-mobile systems are available for use but these are usually restricted in their size (and weight), such that their use is preferred for shallow water operations. It is not advised that temporary or 'semi-mobile' installations are used for deep water operations unless great care is taken and a substantial frame created for the hydrophone unit.

Unlike conventional LBL and SBL methods, there is no redundant information on standard USBL systems from which position accuracy can be estimated. Accuracy is normally stated as between 0.5 to 1% of the maximum slant range measurement.

A2.4 Combined Acoustic Systems

These systems offer either multiple options for users by combining different methods or focus on removing the limitations of a particular system so that both positioning and data telemetry may be provided.

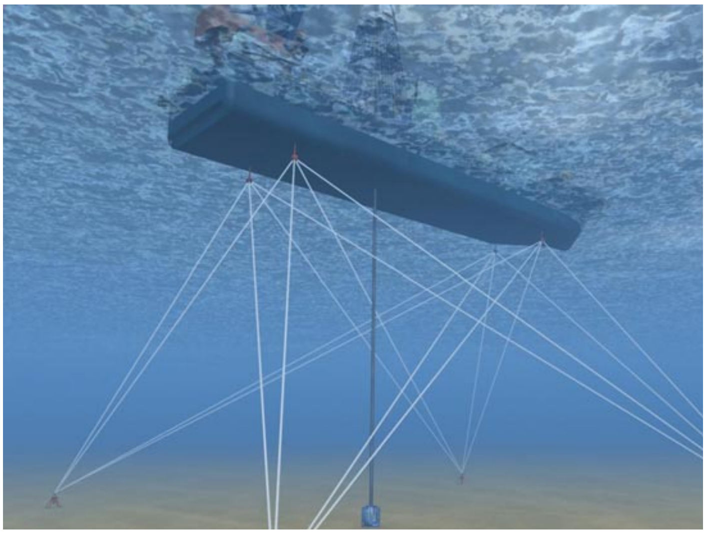


Figure 13 – Combined LSBL system

Multi-user systems are required when more than one vessel is working in close proximity and wishes to use the same acoustic system, e.g. a drilling vessel in an oilfield might have a construction barge with an ROV support vessel at the same location, all wishing to hold station in deep water using DP and also using acoustic positioning to monitor subsea operations such as an ROV intervention or pipeline touchdown. This simultaneous use of acoustic positioning systems means that there is significant potential for 'acoustic pollution'. To solve this problem there are a number of combined approaches possible:

- Synchronised broadcast of the beacons;
- Master surface vessel with radio telemetry synchronisation to other vessels;
- More channels within the same band through signal processing techniques;
- The use of different frequency bands for different operations.

The above techniques often involve proprietary methods and designs to enable system providers to differentiate their product from others. In Figure 14 below, an LBL system is operating in conjunction with two vessels operating their own USBL systems. The LBL system is able to operate and provide positioning for all the vehicles and vessels whilst at the same time the USBL of a surface vessel is able to communicate with its seabed transponders. Approaches such as this offer increased data rates, better reliability of data and acoustic positioning from the seabed to the surface, and the ability to ensure all vessels and objects tracked remain on the same reference positioning system.

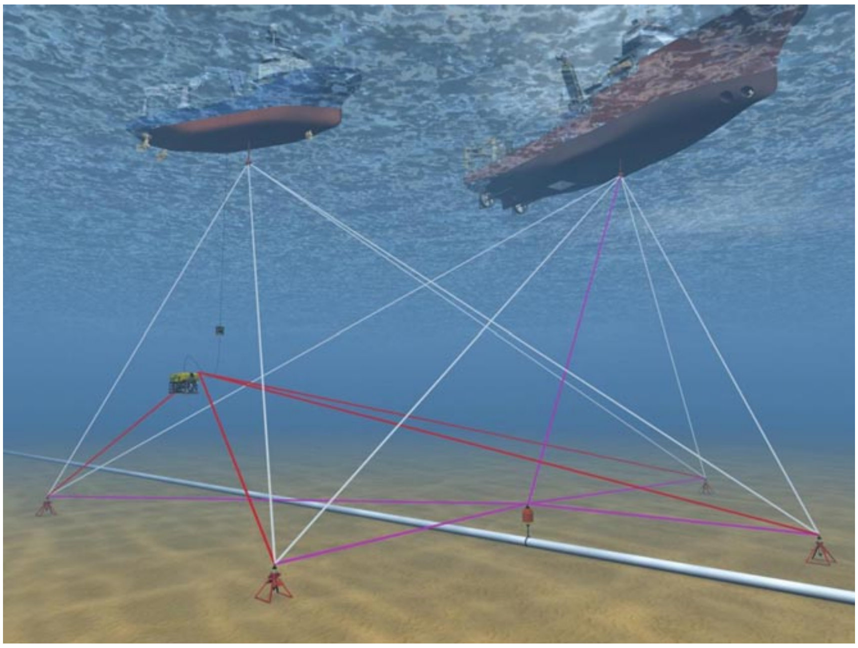


Figure 14 – Combined LUSBL

A2.5 Inverted Arrays

The move into deeper water has required the acoustic positioning manufacturers to develop even more solutions and innovative implementations of their various systems. One such approach is the inverted USBL system.

By placing the transceiver unit of the USBL system in the towed body or subsea vehicle the observations are collected at that subsea vehicle and therefore available for use immediately in support of its positioning and route following activities. By mounting the transceiver in this way some operational benefits are gained such as the low noise environment of the towed unit, close physical coupling with any attitude or motion sensor. By providing this approach an added capability is introduced for acoustic positioning systems and that is the rendezvous and docking below the surface of an AUV.

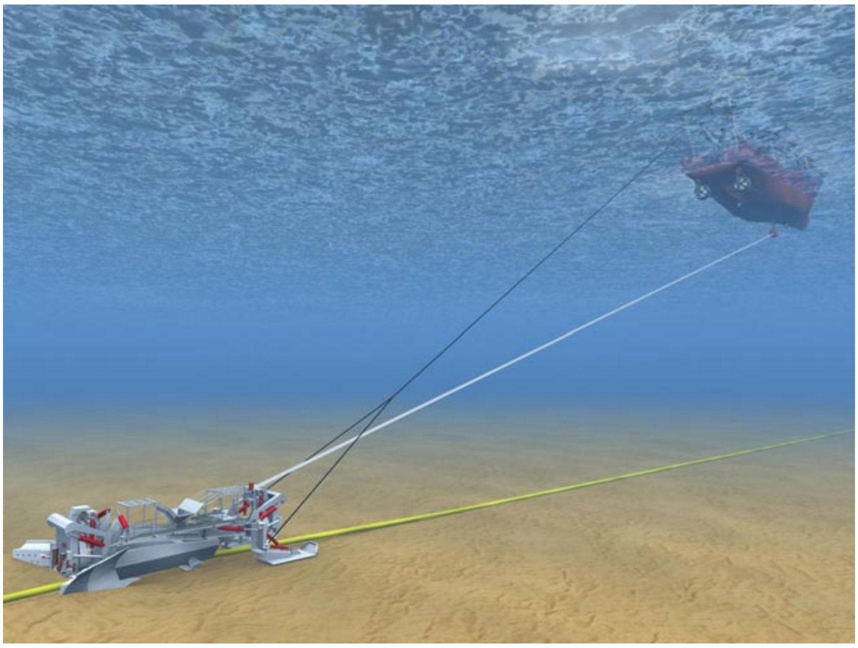


Figure 15 – A schematic of an inverted USBL system for a cable burial plough

A2.6 Hybrid Technology Systems

These have developed for a number of reasons and have enabled various survey and construction activities by removing some of the weaknesses of acoustics systems by combining them with another form of technology. Commonly, peripheral sensors are used to improve and augment the performance of acoustic positioning. In this category, however, the sensors have been integrated at a deep level and are essentially part of the product delivered by the manufacturer rather than an option for the user to select and add sensor data.

Most common among the main systems is the integration of some form of an IMU that offers specific characteristics complementing acoustic positioning systems. Taken alone, the advantages of observed data from an IMU may be limited due to short term drifts in the accelerometers, however, when combined with data from a USBL or LBL system, there can be significant advantages for certain operations.

It is beyond the scope of this document to describe the nature of the integration between acoustics and IMUs. However, a top level description is provided to provide a basic understanding of the methods.

A2.6.1 Integrated Acoustic and IMU Solutions

A small number of tightly integrated solutions have been developed as 'off-the-shelf' systems for operators. They usually rely quite heavily on the use of satellite positioning systems as a source of augmentation along with various peripheral units, and in particular, the use of INS.

There may be two primary units: the ship's surface unit comprising GNSS, inertial motion unit and subsea transducer, and the sub-surface unit that comprises an acoustic transponder and associated peripheral devices such as a depth sensor and DVL unit. In deeper water the solutions may include a sub-surface INS.

The system obtains the exact position of the surface vessel using the GNSS and surface heading, INS and other peripheral units. This position is then used as a reference for the acoustic USBL observations to establish an exact position for the tracked underwater object. This accurate position of the underwater unit is then relayed down to the underwater unit. The data is then integrated into the INS onboard the underwater vehicle, or asset being tracked, to establish its own high accuracy position. Each time there is a position update at the surface, it is relayed acoustically and received by the underwater system which then incorporates it into the solution by merging it with the associated peripheral depth, altitude and DVL data.

Accuracies will vary depending on the configuration of units and modules selected but potential accuracies of better than 0.2% of water depth may be achievable.

An alternative approach to obtain both stable and accurate positioning with a high update rate in deep water is to integrate acoustics with an inertial motion unit (IMU). The system derives an accurate solution by linking data from the IMU with accurate surface data and the USBL observations. A typical configuration would include three main units: the subsea systems, ship's transducer and an onboard processing computer.

The underwater unit's senor data is transmitted to the surface vessel acoustically and integrated with the surface data to derive an accurate sub-surface position for the underwater object. The underwater sub-surface unit may comprise an inertial motion unit, DVL, pressure (or depth), altitude and a heading reference unit. All this sensor data needs to be transferred to the surface. This is achieved through the use of an acoustic data link. Certain solutions have an integral acoustic modem in the USBL system. The data once received, is transferred to the processing computer where the surface reference positioning GNSS, as well as the USBL positioning and any sensor data, are combined in a tightly coupled filter solution.

It is possible to use SBL or LBL for acoustic aiding to improve real-time positioning. There is also potential to further improve the results by post-processing and it is claimed that accuracies of better than 0.1% of water depth are achievable.

Appendix 3

Frequency

Frequencies for use in deep water positioning are generally limited to the lower and medium frequencies for through-water systems. For systems operating exclusively at the seabed, however, the choice of frequencies is wider and for very accurate solutions a relatively high frequency is used. Thus, many systems already in use and with a track record of successful operations in relatively shallow water can operate and provide good positioning for deeper water projects.

The selection of low, medium or high frequency systems is part of the planning when the ranges, coverage and accuracy must be considered. In the following list of frequencies, possible resolution, not accuracy, of the measurements, is indicated. From this level of resolution the accuracy is often considered in direct relation to these values but in reality the accuracy of a system is the measurement accuracy (resolution and repeatability) coupled with external calibration and environmental factors.

Band frequency		Typical resolution
Low frequency (LF)	8-15 kHz	0.5m
Low frequency (LF)*	8-12 kHz	0.05m*
Medium frequency (MF)	18-36 kHz	0.25m
Medium frequency (MF)*	18-36 kHz	0.03m
High frequency (HF)	30-64 kHz	0.05m
Extended high frequency (EHF)	50-110 kHz	0.03m

* The spread spectrum or wideband signalling techniques, rather than toned pulses, offers an improved measurement resolution

Table 3 – Example frequency and measurement resolution

Whilst the above list is useful and planning takes account of these values, the environment has an impact on the ability of the system to achieve these measurement accuracies and then to convert them into accurate positioning. The parameter which has the greatest influence is the speed of sound in water. The influence of this parameter increases with the distance over which these systems operate.

The implications of the choice of frequency affect the following aspects of an acoustic system:

- Accuracy of the measurements and positioning;
- Size of the equipment;
- Possible range and coverage achievable;
- The likelihood of frequency clashes and interference.

A3.1 Accuracy of Measurement

The frequency adopted by the positioning system has a direct bearing on the accuracy of the measurements and consequently the accuracy of the positioning. Accuracy usually decreases with frequency whereas the range will increase. There will always be a compromise between range and accuracy.

The accuracy of the measurement is dependent on the internal system timing, the velocity of sound in water, and the resolution and repeatability of the signalling – and for positioning, the geometry of the system.

A3.1.1 Acoustic Timing

Acoustic signals have an electronic signal path as well as a seawater path, both of which must be taken into account in the determination of a range. Hardware and firmware should take into account internal delays and signal path for the pulses, both in the transmit and receive units and also in units that both receive and transmit in response. This latter reception, process and transmission take a short period of time known as the turn-around time or delay. In the following table, some example figures are shown to illustrate the effect a certain frequency may have on this internal system process.

Frequency band	Channel frequency	Channel bandwidth	No. of channels	Pulse length	Detection time	Validation time
LF	12 kHz	120 Hz	10	8 ms	2.0 ms	6.0 ms
MF	22 kHz	200 Hz	12	4 ms	0.8 ms	3.2 ms
EHF	96 kHz	800 Hz	14	1 ms	0.2 ms	0.8 ms

Table 4 – Internal frequency related signal timings

Fortunately the manufacturers have developed tests so that appropriate software and firmware are applied to establish the exact internal system delays and to use corrections to compensate for the delayed signals. Figure 16 below is a generic illustration of how the component parts of the acoustic pulse affect the resolution and repeatability of the measurements.

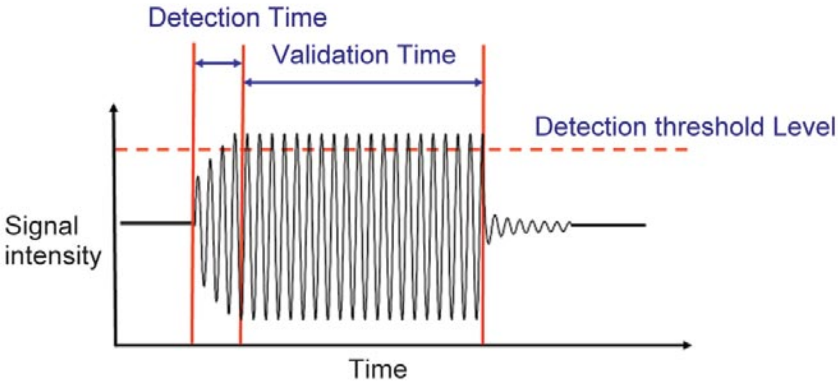


Figure 16 – The acoustic pulse over increasing time from left to right

Doppler affect should also be taken into account. This is a shift in the frequency of a signal as detected by a receiver when the transmitter object is perceived to be moving with respect to the receiver unit. Of course the receiver could be moving and the transmitter stationary but the relative movement would still create a Doppler shift effect. Fortunately, most objects move at relatively slow speeds and so for acoustic positioning the effect is quite small. However, movement does introduce some complications for the signal processing within the acoustic positioning system as the period of time between a pulse and a reply from a transponder could be such that the transducer will have moved far enough to warrant some form of correction to the measured paths. In addition, the movement of the transducer head on a surface vessel should be compensated for at a high update rate in order to ensure that any angles of incidence of the return signals are accurately referenced.

The compensation for this movement is inevitably only a close approximation to the truth. There may be some residual effects reducing the accuracy of the acoustic positioning.

A3.1.2 Accuracy

The measurement accuracy of the various units available is discussed above. However, for positioning, the environment is the dominant and often limiting factor. By taking account of the measurement resolution, the turn-around time, the relative movement of the units and the appropriate compensation for the velocity of sound in seawater and calibration of the equipment, then the typical performance of the acoustic systems may be summarised as follows:

Frequency	Accuracy (ppt = part per thousand of the baseline)
LF – 12 kHz	0.05% Slant Range (SBL)
MF – 22 kHz	0.03% Slant Range(SBL, USBL)
HF	0.02% Slant Range (USBL)
LF	± 0.5m + 1 ppt (LBL)
MF	± 0.25m + 0.5 ppt
HF	± 0.05m + 0.25 ppt
EHF – 96 kHz	± 0.03m + 0.05 ppt

Table 5 – Typical accuracy for different frequencies

A3.2 Physical Size and Frequency

There is a direct relationship between the size of a transducer and the frequency at which it operates, and between the size of the transducer and its directivity. Directivity is improved if the diameter or size of the transducer is increased and thus transmission loss reduced.

The formula for the DI is:

$$DI = 20\ Log_{10}(\pi d\lambda)$$

Where 'd' is the diameter of the transducer and λ is the acoustic wavelength. This is therefore a critical parameter for any USBL, SSBL or SBL system as the acoustic ranges may be well determined but their direction relies on very (ultra) short physical baselines.

Consequently it is good to make the transducer as large as is practically possible for any given frequency. Unfortunately, this is both expensive and imposes limits on where it can be installed onboard a vessel. As this is frequently impractical, it is vital to properly calibrate, identify and quantify the sources of error in USBL and SBL systems and compensate for them.

A3.3 Range and Coverage Achievable

Acoustic positioning systems measure ranges and, in some cases, directions to beacons that are deployed on the seabed or fitted to ROVs, or other towed objects. The accuracy achieved will depend on the technique used, range and environmental conditions. It can vary from quite a few metres to a few centimetres. Acoustic positioning systems are generally available in the following 'standard' frequency bands:

Classification	Frequency	Max range
Low frequency (LF)	8-16 kHz	>10 km
Medium frequency (MF)	18-36 kHz	2-3½ km
High frequency (HF)	30-64 kHz	1200 m
Extra high frequency (EHF)	50-110 kHz	<700 m

Table 6 – Typical maximum ranges for different frequencies

Whether or not use of different frequencies will deliver acoustic positioning of the desired accuracy will be limited by the environment and other factors rather than the direct range measurement itself. An additional phenomenon of acoustics is that acoustic signals can be affected by the path along which they are travelling – so much so that this 'ray bending' effect can actually prevent signals being received well within the theoretical performance of a system.

Appreciation of the possible limits to range and extent to which an acoustic system can operate is important.

A3.4 Coverage – the Layout and Geometry of the System

The selection of frequency has an impact on the potential range of an acoustic signal. When coupled with a specific methodology, frequency can influence the useful coverage available in deep water. Careful consideration at the planning stage is required, so that the desired accuracy and reliability may be obtained without undue use of assets and unnecessary deployment and recovery of units to and from the seabed. The coverage is often a key element in the design of an acoustic positioning operation. Various systems and methods can offer different coverage depending on their frequency.

A3.4.1 USBL

Referenced to the surface vessel, the system can only provide coverage directly surrounding the vessel. This is adequate for many operations such as DP and ROV related work, but can be limited for extended construction or installation works.

The frequencies used by the typical USBL tend to be towards the high end of any frequency band. This keeps the physical size of the units to a minimum, as size can influence the accuracy of the signalling and the installation costs. Ultimately this restriction in size limits the accuracy of the system, as the signals return from the seabed area their range may be well measured but the resolution of their direction can become increasingly inaccurate.

A3.4.2 SBL

Whilst providing positioning with reference to the surface vessel, the added transducers and increased baseline enable an SBL system to better determine the direction of an acoustic signal return and provide the potential for higher accuracy than USBL. The added complexity and expense of the transducer arrays on the hull of a vessel mean that it is often built for long term operations, and reliability becomes a key parameter, more so than accuracy. SBL systems are often used for operations such as DP for drilling and floating production storage and offloading unit vessels.

A3.4.3 LBL

The LBL acoustic positioning system is independent of the surface vessel and can therefore extend its coverage over relatively large areas and offer multiple users high accuracy positioning close to the seabed. In terms of range, the LBL system is more dependent on the frequency selected as the methodology enables the system to expand and scale up in the number of units and cover an increasingly large area.

A3.5 Frequency Clashes and Interference

Frequency clashes occur when there are a greater number of users and transmissions in the water than acoustic positioning systems can sustain at once.

Recent advances in signal technology have, for all practical purposes, removed these limitations. Older, traditional systems have yet to overcome this problem and may suffer long periods of down time and lost signalling due to the problem.

Frequency clashes occur when there are too many acoustic signals generated and in the water at any one time. This should be taken into account at the planning stage of a project, and many USBL and LBL operations are planned with great care to ensure that there is no frequency clash or interference. Unfortunately, the demands for faster positioning update rates, the increased use of telemetry in association with positioning and the extended ranges at which the systems are being operated mean that frequency clashes can still occur.

A further influence is the nature of the seawater environment. Well layered water bodies exist that can cause acoustic signalling to carry across extended ranges well beyond the normal planned and required distances to such an extent that nearby systems in busy oilfields may suffer acoustic pollution.

Appendix 4

Spread Spectrum Techniques

The recent development of digital spread spectrum signalling in acoustics offers several potential advantages over existing tone based pulse signalling or ‘chirp modulation’ signalling. Some of these potential advantages are outlined here.

A4.1 Measurement Accuracy

The introduction of low cost and low power digital signal processors has enabled manufacturers to take advantage of spread spectrum technology and to develop acoustic applications. Figure 17 below illustrates the relative signal power available.

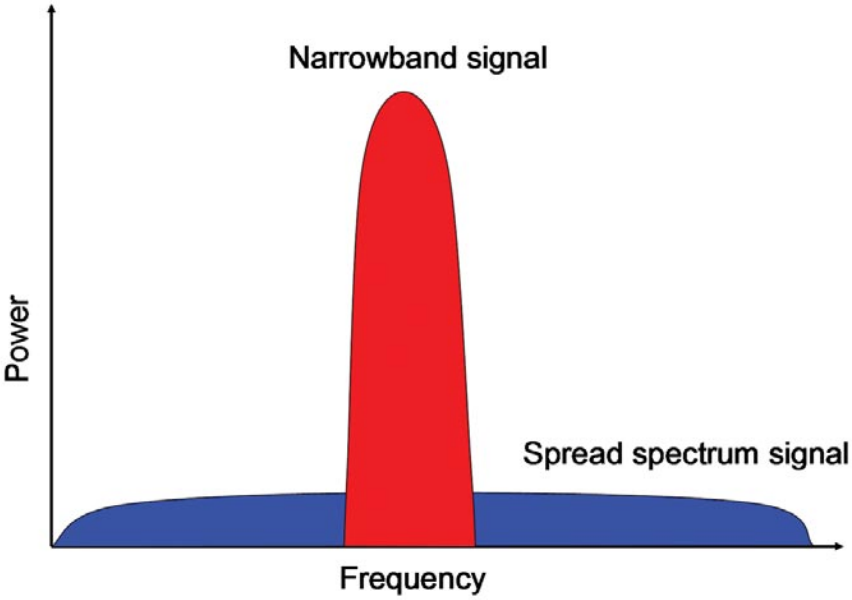


Figure 17 – A pulsed narrow band signal

The signal path resolution and the precision of the timing, by the system, are directly proportional to the bandwidth used. As can be seen in Figure 17 above, the bandwidth is significantly greater for a spread spectrum technique than for traditional methods and the narrow band signal uses more power. In terms of the signal power, the spread spectrum signal requires relatively low power across a relatively bandwidth.

A4.2 Range and Coverage

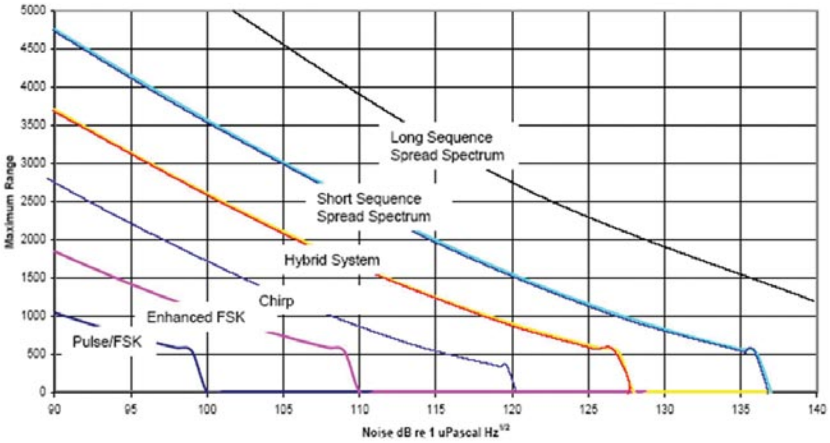


Figure 18 – Comparison of range capability with signalling methodology

A4.3 Resistance to Multi-Pathing

As mentioned above, the use of the digital spread spectrum approach enables a number of signalling and measurement advantages to be gained over the traditional pulsed tonal signalling. Mitigation of multi-path is one such advantage where the correlation techniques of matching the incoming signal, or code, to the self-generated reference code allow for the direct match to be acquired and then this high degree of correlation is used to accept or reject a signal. A well defined correlation peak is usually generated, as seen in Figure 19 below, when the signalling matches, and this aids in the process of rejecting unwanted multiple signals that have some signal strength and some degree of correlation creating a secondary but lesser peak.

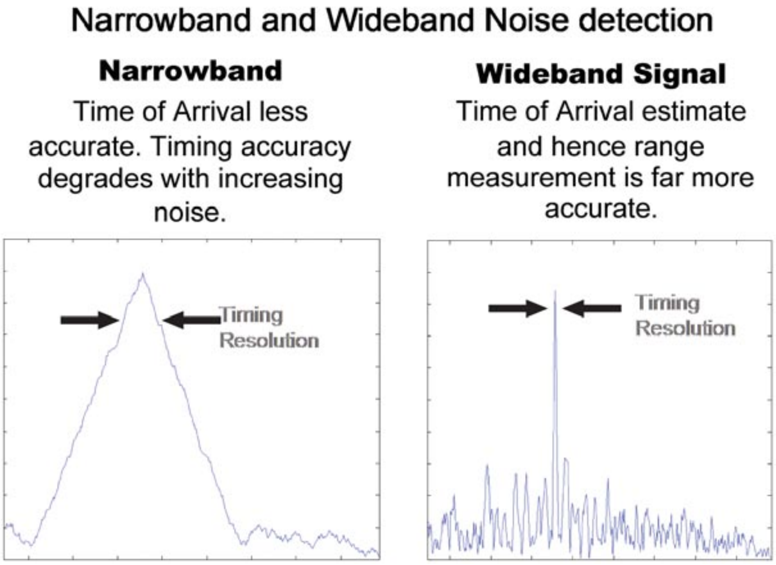


Figure 19 – Relative accuracy of narrowband and wideband methods

The ability of spread spectrum techniques to swiftly resolve the correct signal aids in the rejection of other signals and allows for more channels, or codes, to be adopted within a specific central frequency band.

A4.4 Improved Signal to Noise Ratio

The methods of correlating the transmitted signal and code are generally very sensitive and proprietary areas for manufacturers. However, there are significant gains in performance, as can be seen in Figure 20 below. From the Sonar Equation developed the concept of being able to predict a system's performance, in terms of signal level versus the transmission loss and then developing this as a measure of range capability.

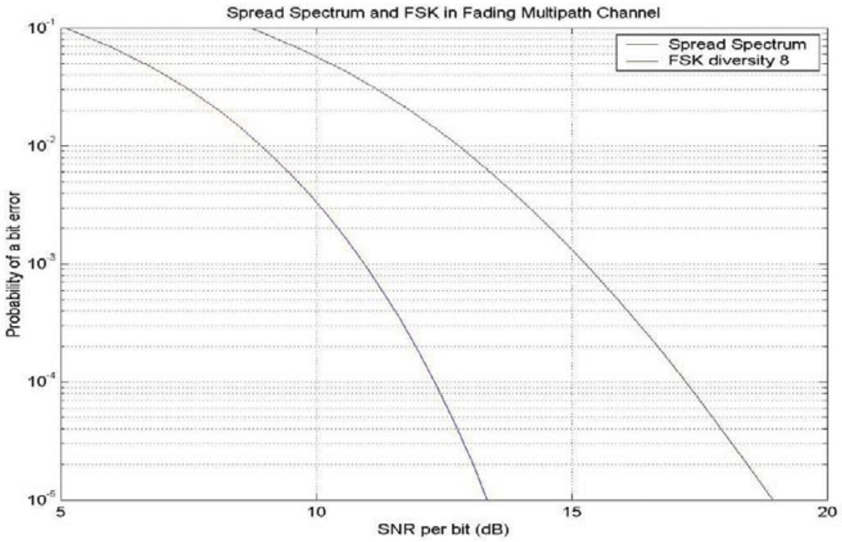


Figure 20 – Comparison of modulo 8 FSK and spread spectrum SNR

Typical values for the increase in signal to noise ratio are between three and five dB, depending on the traditional method and the frequency adopted.

A4.5 Signal Measurement Accuracy

A further step forward is made when considering the accuracy of the actual timing and range measurements themselves. This is best illustrated in Figure 21 below. The timing process is based on the correlation of the coded signals and enables the precise resolution of the point of interest. As the reference code and received code are compared, their matching results very precisely pinpoint instants in time that can then be used for the resultant ranges and other measurements.

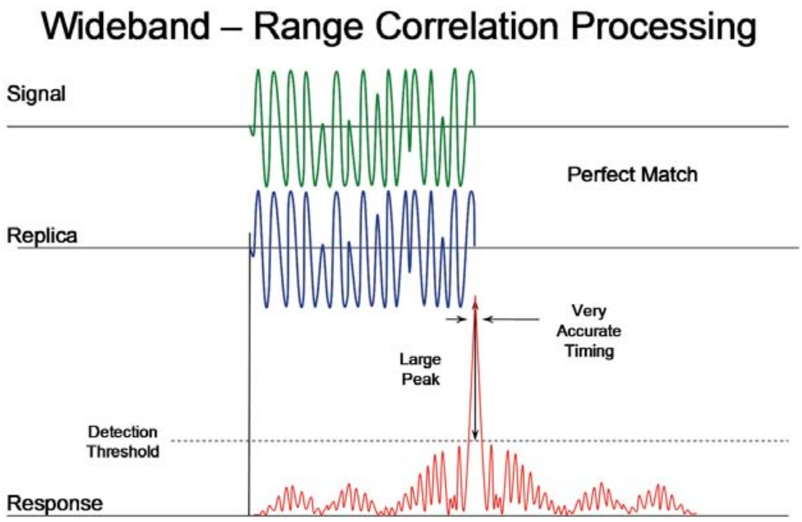


Figure 21 – Spread spectrum (wide band) signal timing

Appendix 5

Velocity of Sound

The speed of sound in water or the velocity of propagation of sound in water is one of the most critical and ultimately limiting factors in the potential accuracy of acoustic positioning systems.

Seawater is not a uniform, isotropic medium. The velocity of sound in water is affected by changes in temperature at 1m/sec per 0.24°C (the dominant factor), salinity at approximately 1m/sec per 1/875 part and depth or pressure at a rate of approximately 1m/sec per 60m increase in depth. Acoustic positioning systems rely on an exact knowledge of the velocity of sound in seawater and in particular a mean value for the route the acoustic signal takes between transmitter and receiver. Often this is not exactly known and so model and approximation techniques are used to derive values that are considered accurate for deep water acoustic positioning operations.

Owing to the dynamic nature of the subsea environment, it is costly and time consuming to take many observations to establish the exact values for the velocity of sound in water. Whilst the ideal would be to obtain continuous measurements, this is not generally practical. Instead, a SVP is built up from the measurements taken, which will represent the full water column from sea surface to seabed, and this is used in the survey area.

This SVP is usually obtained by using an independent temperature/salinity/depth probe or velocity profiler, which is 'cast' into the sea, lowered down through the water column and carefully recovered. A representative set of SVPs would be collected for a project. Initially several SVP sets would be gathered each day to establish the nature of the work area. After this, it is often possible to reduce the frequency of 'casts' to perhaps daily. The casts should also be collected across the area of operation dependent on its size and the variation in water depths across it.

A5.1 Temperature

The temperature at the sea surface varies with the geographic position on the earth, the season and the time of the day. The temperature parameter can be a complex one with variations spatially, temporally and especially through the water column between the surface and seabed. It cannot easily be predicted and so surveyors must collect numerous SVP casts. These are then used to build up a picture of the rate of change of the velocity of sound and to establish the frequency at which further measurements must be taken to ensure that the acoustic positioning systems remain accurate.

Temperature variation is the dominant factor controlling the variation in sound velocity between the surface and the lower limit of the thermocline. Once below the thermocline, pressure becomes the principal influence.

A5.2 Pressure

Seawater pressure has a significant impact on the variation of sound velocity. The speed of sound in water increases at 1m per second for every 60m of depth.

A5.3 Density

Water density is dependent on temperature, salinity and pressure. The largest influence is the compressibility of water with depth.

A5.4 Salinity

Salinity of water is the measure of the quantity of dissolved salts. It is usually defined as the total amount of dissolved particles in parts per thousand (ppt or ‰) by weight. In practice, salinity is not determined directly but is computed from the refractive index or electrical conductivity. These parameters have direct relationships to the amount of suspended particles of salt in water and have been well established. The average salinity of seawater is around 35‰. Typically the salinity is measured with a CTD cast using the observable parameter, electrical conductivity.

A5.5 Instrumentation

This subsection describes the units used for determining the velocity of sound.

Figure 22 – A series of mini velocity probes and sensors (Valeport Limited)

The sound velocity profiler is the most common instrument used to measure the SVP through the water column. This instrument has one pressure sensor to measure depth and a transducer and reflector arrangement to calculate directly the velocity of sound. This is done by timing the two-way travel time of the acoustic signal between the transducer and reflector.

The CTD probe is an electronic instrument with sensors for conductivity, temperature and depth. The electrical conductivity of the seawater is measured directly and together with the pressure (depth) and temperature the velocity of sound may be derived.

When taking casts to determine the velocity of sound, care should be taken to ensure the instrument is calibrated. The unit should be in inserted into the water for approximately 10 minutes prior to commencing a profile in order to allow the metal and composite surfaces to adjust to the water temperature.

The SVPs recovered should always be checked for erroneous data and periods when the equipment may have been lying on the seabed or has come out of the water when near the surface, as may happen in a heavy swell. It is wise to record all data at frequent and regular intervals and during both downwards and upwards stages. The resulting two profiles can then be inspected and compared to confirm they are similar, after which the profiles are often averaged to create the final profile.

A5.6 The Sound Velocity Computation

The reference most used by offshore surveyors is the UNESCO (United Nations Educational, Scientific and Cultural Organization) document which describes the various formulae that can be used to derive the velocity of sound, and recommends the use of specific formula for certain conditions such as deep water, continental shelf, arctic conditions and fresh water environments. This was later updated by the Hydrographic Society whose Special Publication SP 34 details a range of formulae and advice on their appropriate use. The preferred formulae are often applied by software within the equipment used or in the recording unit.

Appendix 6

Acoustic Noise and Interference

A6.1 Acoustic Noise

A6.1.1 Biological Noise

Marine life can provide some interference with whales generally creating low frequency noises and dolphins producing wide band signals. The extent to which whales or dolphins interfere is not fully understood, but current environmental monitoring aims to protect these animals and ensure that the acoustic positioning and tracking systems do not harm or endanger them.

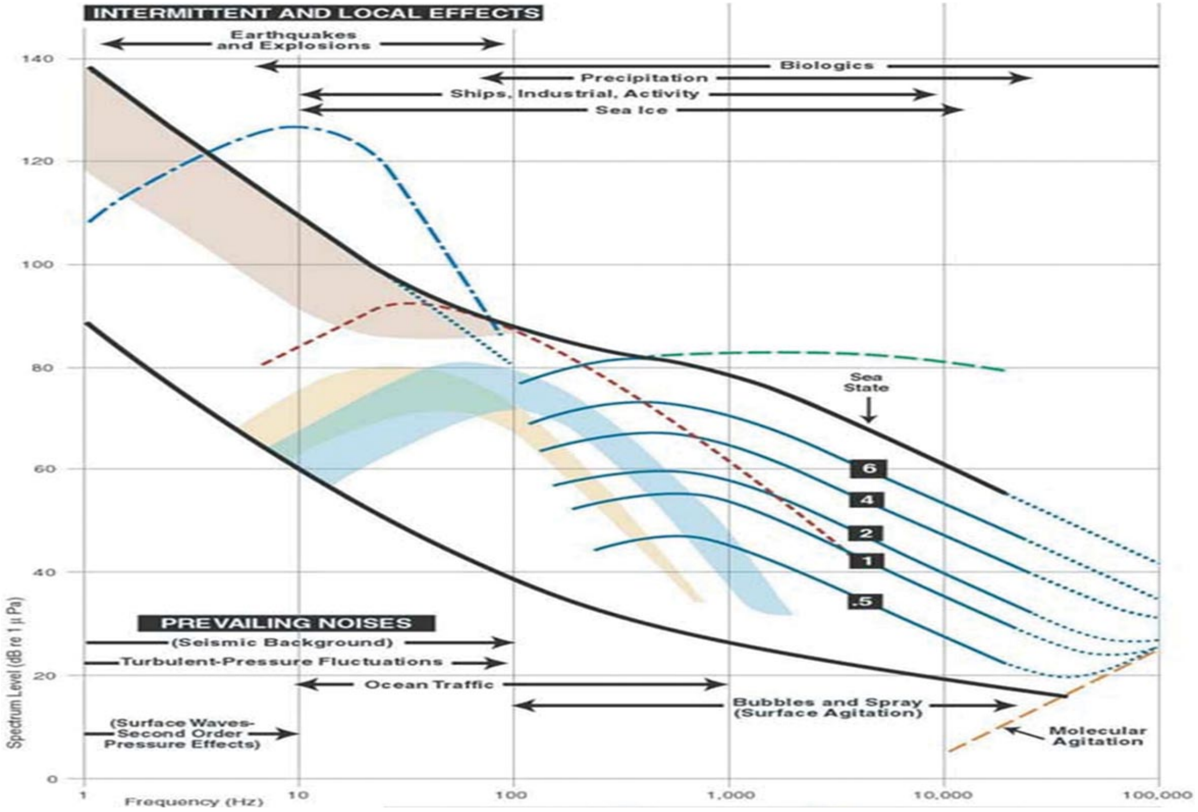


Figure 23 – Sources of environment and man-made noise

A6.1.2 Wind and Rain

For acoustic tracking systems that use frequencies in the 15 to 35 kHz band, the dominant environmental noise source is usually weather generated surface noise, i.e. wind and rain. This is significant enough that the performance of acoustic tracking will change with the weather conditions. However, for the deep water applications and use being considered in this document, this influence should not be significant and even for near surface hydrophones/transducers may be mitigated by adjusting power and pulse settings.

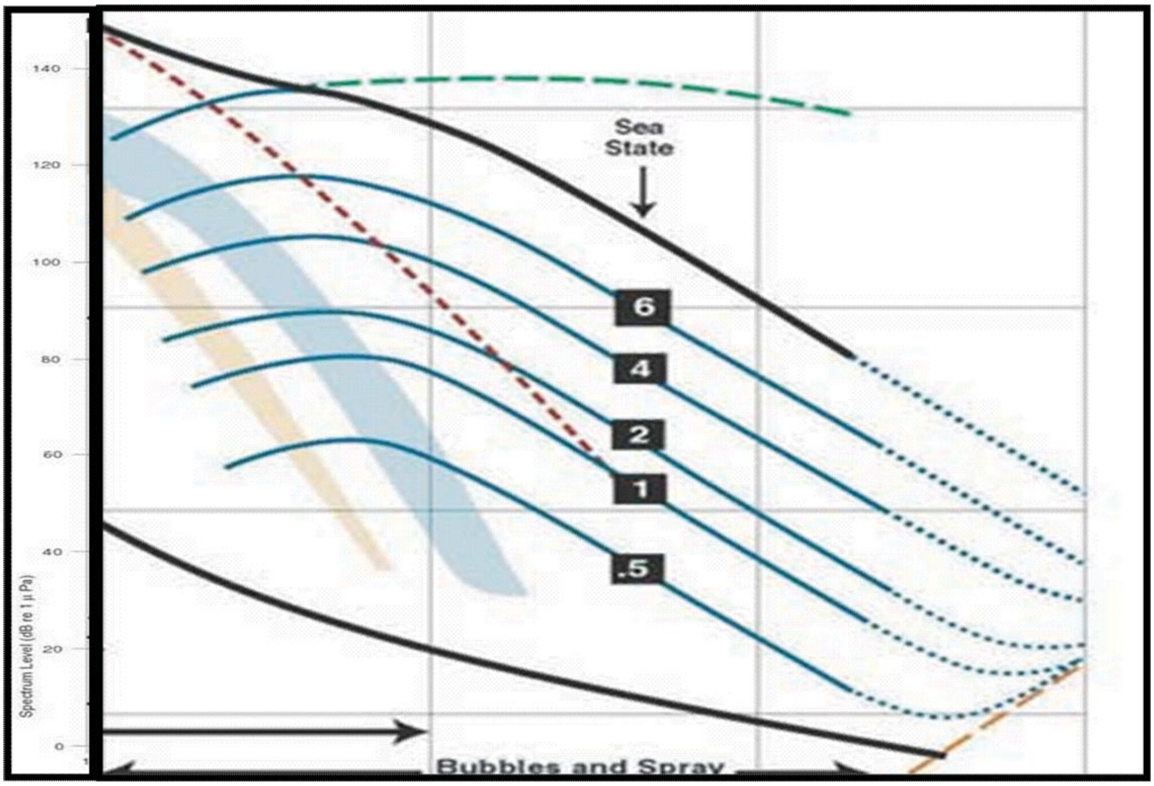


Figure 24 – Noise caused by sea surface conditions

Distinguishing environmental noise and mechanical or man-made interference is not always straightforward when operating acoustic systems. It is possible to categorise the possible man-made or self noise sources of interference.

A6.1.3 Self Noise

Self noise is the noise generated by the ship or ROV carrying the tracking system or beacon. The main sources of self noise are:

- ship noise;
- flow noise;
- reverberation;
- multi-pathing noise.

Self noise varies greatly from one vessel to another and from one day to the next. It is very difficult to measure reliably an accurate self noise level of a ship. However, surveys are a common occurrence so as to aid in the placement of the transducer and to ensure that the specific operating frequencies can still be transmitted and received.

Self noise is usually the unknown factor which makes it difficult to predict the performance of an acoustic tracking system.

A6.1.4 Cavitation (Ship Noise)

One of the main causes of acoustic interference is the noise produced by the ship's propeller. As the propeller speed of rotation increases, it causes pressure imbalances and for some of these, the very low relative pressure causes steam and bubbles which are the source of cavitation. This is illustrated in Figure 25 below.

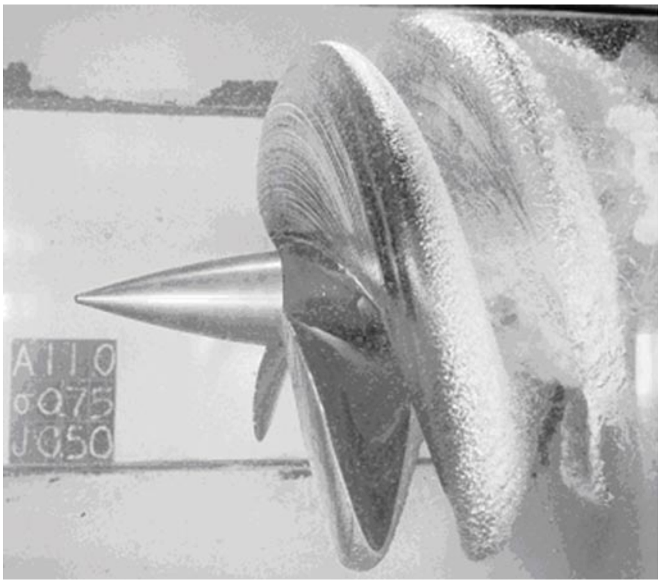


Figure 25 – A common cause of interfering acoustic noise is propeller cavitation (Photo: University of Newcastle)

As the ship's propeller moves away from the bubbles, the pressure increases causing the bubbles to collapse and produce a continuous, sharp, hissing noise. This cavitation noise is loud and has a wide bandwidth and so can interfere to a significant degree in the frequencies used for acoustic positioning.

A6.1.5 Flow Noise

For certain operations, such as DP, the self noise from thrusters, cavitation and drilling machinery may be dominant whereas for other applications, such as surveying using towed bodies, the flow noise may be a limiting factor. As flow speed increases, friction between an object and the water increases, resulting in turbulence and progressively increasing noise due to fluctuating static pressure in the water. This is shown in Figure 26 below. Example (A) shows a relatively clean and laminar flow state while example (B) shows the presence of turbulent water around the object.

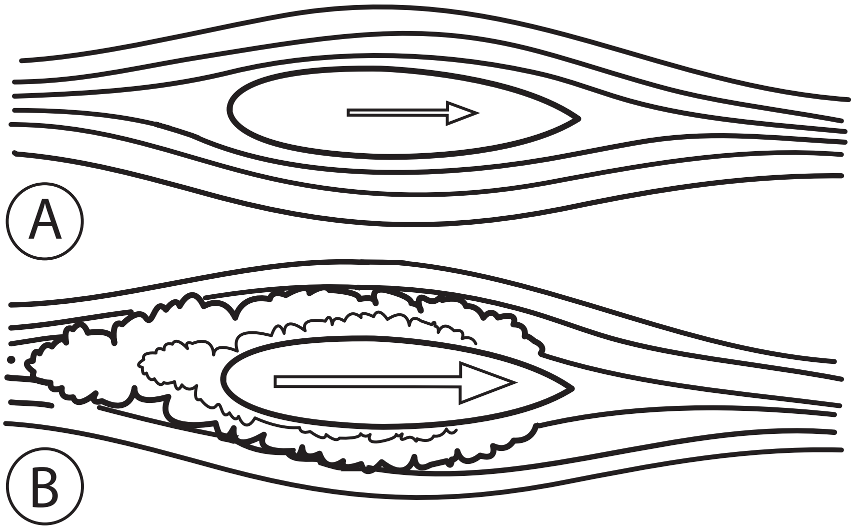


Figure 26 – Flow noise in (B) acts as a cause of interference

At very low speeds there is no observable flow noise. A slight increase in speed changes the flow pattern from laminar to a turbulent condition and, as a result, strong flow noise will be observed. Further increases in speed increase the intensity of this noise. If a hydrophone is placed in a region of turbulence, fluctuations of pressure will occur on its face and it will measure the result, a low frequency flow noise. Flow noise is a function of speed, with a sharp threshold. Flow noise may increase to such a degree that a vessel speed limit may be required with consequent impact on operations.

A6.1.6 Significance of Vessel Noise Surveys

The importance of establishing levels of self noise and other possible noise sources can be critical for deep water operations where the surface vessel installation has to be able to receive relatively weak signals from the sea floor. When a project-specific deep water acoustic positioning system is being used on a vessel for the first time and there is some doubt as to its operability, in order to better understand what the limits may be, a full acoustic noise profile survey may be carried out.

This requires valuable vessel time, however, it does establish if the systems proposed for installation will actually achieve their required purpose and succeed in providing good acoustic signalling and reception.

The procedure is to stream a calibrated listening hydrophone and to record the acoustic data acquired by the hydrophone as the vessel carries out various operations such as being under way, on DP with thrusters, remaining close to station but without thrusters, and then a general series of measurements with the propeller pitch and thrusters at various settings. A further recording of the ambient noise, by letting the vessel drift in the vicinity of the test, is also recommended as this gives a baseline for the noise survey. In this way, a comprehensive profile of the noise coming from the vessel can be built up and may be used to establish if the acoustic positioning system, when fitted, can operate without too much acoustic pollution.

A6.2 Signal Reverberation

Signal reverberation (or echo) is caused when an acoustic signal is transmitted and bounces or reflects off objects in the water causing unwanted in-band noise. In this case the effect is only really a problem for active sonar systems. The possible likely sources of reverberation objects are:

- sea surface;
- seabed;
- ship's hull;
- subsea equipment such as drilling templates, BOP and riser;
- flotation module and sensor array on an ROV.

An example of an acoustic reverberation is shown in Figure 27 below. It can be seen in the vertical axis (Y axis). The amplitude rapidly decays over the time which is represented by the horizontal axis (X axis).

Figure 27 – Reverberation noise against time

All acoustic positioning systems are subject to possible interference and disruption due to noise. A potentially significant problem is caused by solid metal objects close to the source, receiver or the travel path of the acoustic signal. Such objects can generate spurious reflections which are referred to as multi-path.

A6-2.1 Multi-Path

Multi-path is caused by acoustic signals travelling through nearby objects, thereby creating a refractive and multiple series of signals which take a slightly different path to the receiver than that of the direct signal. The reason it can be significant is because whilst acoustic processors often take account of the many delays that can affect an acoustic signal, they may not make sufficient allowance for signals arriving early. This can happen because the speed of sound is much faster in a solid object such as steel than it is in water.

For example, a baseline between two LBL beacons along a pipeline may suffer from multi-path effects with the system taking account of the first (and spurious) return caused by the signal using part of the steel pipe to travel the distance between the two beacons. In extreme cases, multi-path can cause beacons and transponders to operate and appear to provide normal ranges and signals when they are in fact being reflected. The good surveyor and project planner will ensure there is redundancy of beacons or stations to allow the positioning system or post-processing to isolate and remove these erroneous signals.

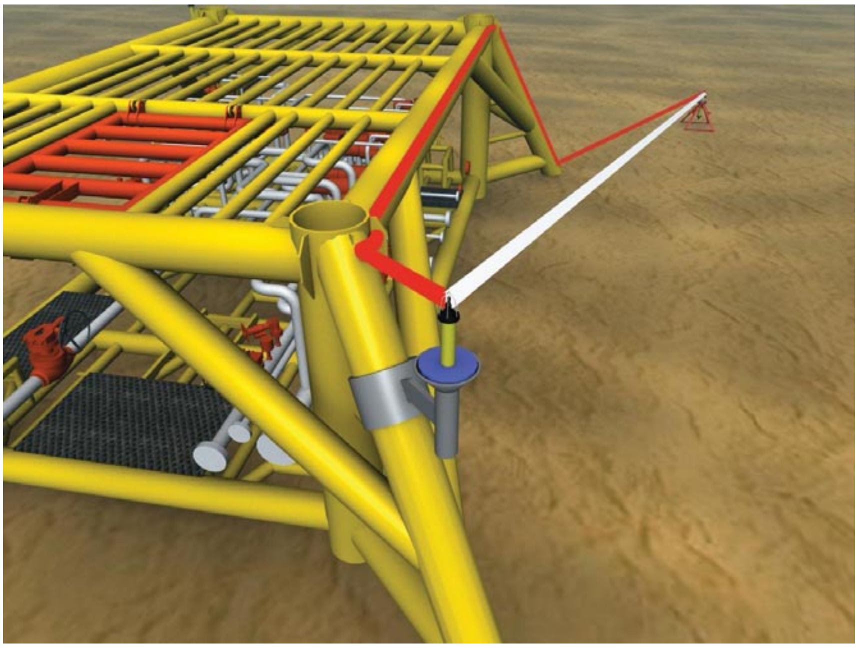


Figure 28 – Extreme multi-path can cause erroneous signalling and positioning

Consideration has been given so far to reflective multi-path from a surface or object, however, even if there are no solid objects in the water, multi-path of the signal still can occur. This scattering multi-path, sometimes termed micro particle multi-path, is not well understood, but has the effect of distorting and stretching the signal. Possible causes are thought to include:

- particles in water;
- micro temperature variations;
- dissolved salts in the water.

Micro particle multi-path is at a minimum when a signal passes vertically through the water column. Generally it is overshadowed by the more significant ray bending due to the variation in the water environment. Ray bending is covered in more detail below.

A6.3 Acoustic Interference

A6.3.1 Effects of Internal Waves in Deep Water

Internal waves are phenomena that occur below the surface e are normally velocity profiles. Velocity profiles are the measurement of the variation in the speed of sound in water against depth. Conditions for internal waves may include a sharp fall in the density and temperature in the water column. The thermocline will indicate a relatively rapid change creating a form of layering.

The physical effects of internal waves may vary but in general they can be considered to have wavelengths of several hundred metres creating currents of between 1-2m with amplitude of tens of metres, perhaps as large as 100m.

The impact on an acoustic positioning operation is to introduce rapid changes in the temperature which may cause signal loss between the surface and seabed.

If the presence of internal waves are considered a possibility, then the first course of action is to set up a monitoring system to observe and quantify the problem (bearing in mind their presence may be seasonal).

A6.3.2 Ray Bending

Ray bending is a phenomenon produced by the variation in the layering and condition of the water. For sound propagating in seawater, an elastic medium, various mathematical solutions are used to model this phenomenon. One approach is ray theory. This provides a useful insight to the likely presence of acoustic signals and may be used as part of a planning process to determine the suitability of a system. The figures in this section are examples of the ray theory process used to create ray trace diagrams.

Using Snell's law, ray trace diagrams may be constructed to represent the refraction of the sound in layers of water.

In the example shown in Figure 29 below, data for the water column temperature and velocity of sound was collected off the coast of Western Australia in water of 200m depth. The signalling remains well defined along the sea floor to a distance in excess of 2,500m, whereas the signals to the surface are less well defined beyond 1,300m. In deeper areas the effects can be more complex, especially when relatively well stratified bodies of water converge and overlap one another.

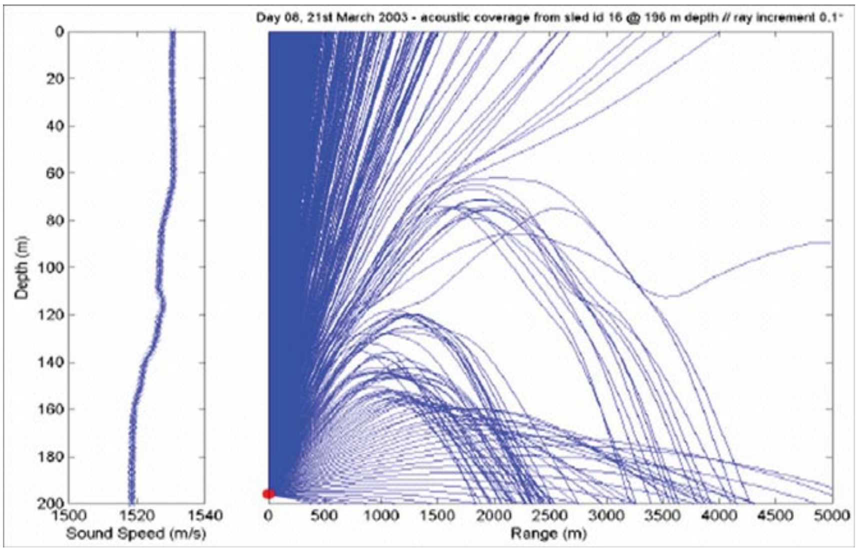


Figure 29 – Layering in the water can produce significant ray bending effects

In the example shown in Figure 30 below, the deep water velocity profile off the coast of West Africa appears to be good to the surface but does not offer signalling across the seafloor beyond 1,000m and for a cautious approach only as much as 700m. In such a deep water area, the use of LBL would require special attention to avoid the loss of ranges and acoustic signalling.

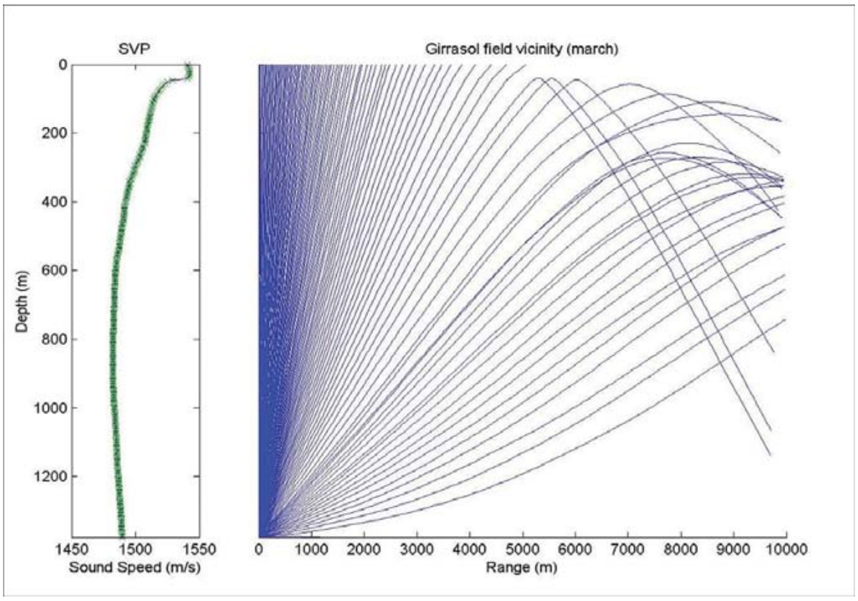


Figure 30 – Deep water conditions resulting in poor signalling at the seabed

A6.3.3 Acoustic Blanking

Sound travels in straight lines, but only when the velocity is constant everywhere throughout the area. This is not the case for seawater and so some acoustic signal, or ray bending occurs. For sound propagating in seawater, the velocity gradients dictate this process and will constrain the acoustic signalling to travel in certain directions and in certain layers. In other areas and layers, the presence of any desired acoustic signal, from the transducer, transponder or beacon, will be negligible. The gradient depends on the velocity profile and it is this gradient that produces certain channelling effects that may limit the presence of the signal in the upper shallow layers or in the lower, deeper areas.

It is this possibility of signal loss and the impact that the loss of acoustic signalling would have on an operation that makes it critical to establish as early as possible, and preferably well before any field operations commence, exactly what sort of water environment is present and how that affects the acoustic positioning.

One scenario is when the gradient creates a form of sound channel. A sound channel occurs when a negative-velocity gradient overlies an iso-velocity or positive-velocity gradient. See Figure 31 below.

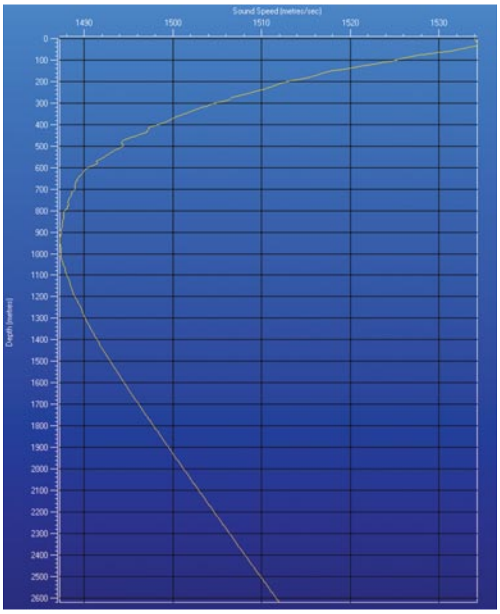


Figure 31 – Deep water profile of seawater velocity of sound

In Figure 31 above, at around 1,000m water depth, we see the velocity gradient change from negative to positive. This is known as the axis of the sound channel.

The axis is the level of minimum sound speed. An extreme change in the velocity and gradient values will produce a channelling effect due to the way acoustic signals are refracted towards the slower sound. Consequently, the sound both below and above the axis are refracted towards this level creating a channel.

Appendix 7

Deep Water Acoustic Operations

A7.1 Station Deployment

The sequence for the deployment of the seabed beacons and transponders is considered important as it often dictates the overall level of system performance that can be achieved. The first beacon to be deployed in the area is a critical one as it must be placed correctly for the required coverage and performance. To avoid problems, project planning should ensure that a clear signal path is likely without multi-path being present. Prior to deploying over the side, the unit should be checked for charged batteries, properly functioning sensors and, if appropriate, the direction of the reference heading sensor.

The location on the seabed should be clear of localised noise. Once the beacon has made touchdown or is placed on the seabed, the depth setting and power levels should be checked and the unit set to transmit to check the transponder functions.

A number of factors influence station deployment, including:

- design of deep water transponder frames;
- suitability and use of acoustics as DP references;
- depth rating of acoustic equipment;
- power levels and battery technology.

A7.2 Deep Water Frame Designs

Various designs of seabed frame for transponders exist, generally made of steel and designed to withstand conditions on the seabed. The likely risks to the frame include: accidental damage by the other vessels and assets including ROVs; slumping or settling that may occur due to the weight of the frame on the seabed; and corrosion that may result in a failure of some part of the frame or failure to recover the transponder.

For large deep water projects, hundreds of frames may be required but not all will be populated by transponders. The approach now is to deploy the required number for operations and to move and re-pot the transponders in the frames for each activity. In this way, only a fraction of the total numbers of frames require a transponder at any one time.

The transponder frames are typically made of steel and are between 1.5m and 3m high. They generally have a tripod design with a small plate for the slot into which the transponder is fixed. The weight of the transponder sitting in a well machined slot with tight tolerance is sufficient to keep it in place. A frame may have between two and four slots. An alternative design is the sled design with a simple base and column for the transponders. These appear less rigid but may allow for better recovery due to their slimmer overall shape and, with less material, could be more cost effective. Various designs are available and some are recommended by the manufacturers for the installation of seabed transponders.

Examples of recently used designs are shown in Figure 32 below.

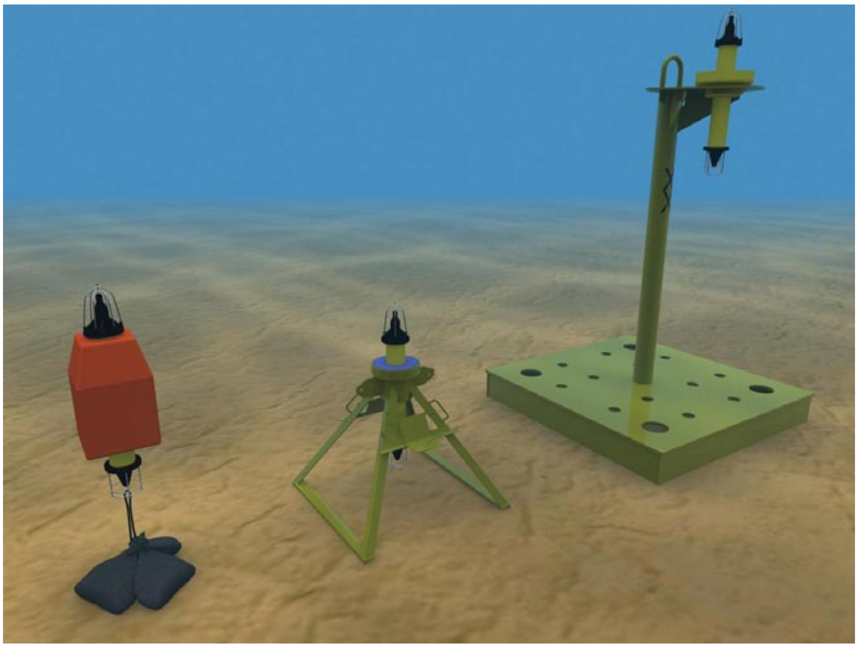


Figure 32 – Examples of transponder frames

A7.3 Characteristics and Suitability of Acoustics as DP References

DP requires that the acoustic positioning system provides independent quality controlled position solutions at each measurement, and is of a design that includes redundancy of equipment and sufficient observations to prevent any positioning failures.

As an aid to navigation, the inputs to a DP system must be reliable. Manufacturers have adopted the approach of building two sets of hardware and integrating the operator systems to reduce the burden of dual operations. Whilst this represents a convenient approach, it does suffer from potential exposure to a single point of failure in the acoustic positioning system. In order to reduce this risk, DP systems require high reliability, particularly in deep water, whereas acoustic positioning systems for survey and construction purposes require high levels of accuracy and the flexibility to position multiple objects, some of which are at or near the seabed.

Acoustic positioning systems sacrifice some redundancy and reliability for high performance. Such systems sometimes require configuration, resetting, adjustment or calibration for each individual operation. This is rarely acceptable for marine DP operations requiring suitable measures for safety at sea. Consequently, DP systems may operate at lower frequencies to ensure that acoustic signal energy has the power to reach the beacons rather than at higher frequencies promising greater accuracy in exchange for lower range.

This means that it is often quite difficult to appreciate the need for a specialised and specific USBL system or LBL system when there is an existing DP system onboard capable of operation in deep water. The dilemma is that the DP unit should remain separate from any ad hoc changes and needs to remain operational and can provide the necessary positioning and guidance and alarms for the vessel.

Sharing DP acoustic positioning with survey applications is feasible but may not be practical because of the fundamentally different requirements of DP acoustic positioning systems and survey acoustic positioning systems. This issue is covered in more detail in IMCA S 010 – The shared use of sensors for DP and survey operations.

A7.4 Depth Ratings

The application of acoustic positioning in deep water beyond 600m can impose challenges on the design, build and operation of the systems and the various sensor components of the units involved. For international operations associated with deep water acoustic positioning, some consideration should be given to the transport of the systems and also to the various legislative customs and importation laws for equipment.

For deep water operations the acoustic positioning system equipment should be tested to at least operational depth plus 10% even though there is a margin of safety in the design. Water pressure at 600m will rapidly expose any weakness in design or build quality, causing water ingress.

In terms of USBL and SBL systems that are required to provide positioning in deep water, they should prove reliable at transmitting and receiving ranges and deriving the direction of the sources. Claimed ranges from the manufacturers are typically for ideal conditions and should, therefore, be checked carefully as environmental conditions may increase signal losses.

Certain countries apply strict rules to the export and import of certain types of technology. Acoustic positioning systems together with the numerous associated peripheral devices often come within this restricted class of products.

A7.5 Data Telemetry

Data telemetry is an ever expanding activity that acoustic positioning systems and a number of elements are worthy of note in this context.

- Data from sensors – For a number of applications, depth, temperature, altitude, pitch and roll, heading, pressure or other specific sensor – data may be collected and transmitted via a dedicated channel.
- Packet messaging – Many of the data sets are too large to send the whole message complete in one transmission, therefore some form of compression or segmentation of the data is required. Data rates may vary from sensors and the nature of the project will influence the method adopted.
- Buffering – In some cases individual data packets are too large for a single transmission and so the acoustic unit must handle this by buffering internally. As acoustic signals travel at relatively slow speeds through the water when compared to electronic data, the issue of data latency and the arrival time of a data packet should be considered together with the possible segmentation and packet messaging strategy. Buffering is to be avoided but where it is necessary, the ship based system should be able to receive each data set and then compile the full message.
- Use of channels – As acoustic positioning systems use various channels to supply commands or to transmit data, it may be possible for the operator to configure the system to enable multiple channels to carry data so as to increase the data capacity of the link and perhaps to mitigate any data latency. Where the channels are not dedicated to data telemetry, then the data must be interleaved with the acoustic positioning signalling. This may further reduce the volume of data possible to be transmitted.
- Telemetry and data transmissions – The use of subsea modems offers the operator to transmit as much data as possible through an acoustic link. A number of options exist in terms of their power, frequency and the messaging strategy. Military applications often concentrate on the covert nature of the signalling, but for commercial data transmission the unit will often be able to optimise the data volume at the limited range over which the system may operate.
- Protocols – There is no internationally accepted specific standard for acoustic data transmission and so each manufacturer has been able to develop and use its preferred method. This will be influenced by the choice of application, frequency and power used as well as the signal encoding techniques.
- Frequency and data capacity – In broad terms, just like radio waves, the higher the frequency the greater the data capacity. For acoustic modems the same principle applies, however, there is also a trade off in as much that the frequency shall limit the distance over which the data can successfully be transmitted and received. Higher frequencies may not be appropriate for deeper water operations due to this limitation.

A7.6 Power Levels

The battery capacity of various elements of an acoustic positioning system may be quoted in terms of its ability to perform a number of transmissions. This is an important parameter to be considered when designing and operating the units. Each unit may be set to transmit at a specific power level. However, should the ranges between units be excessive or should there be significant noise, then power settings may need increasing, which may lead to lower battery life. The increase of power levels may be in decibels. The operator should be aware that an increase of 3dB represents a doubling of power which has a consequent impact on battery life. There are other environmental parameters, of which temperature is perhaps the most important, which can influence 'real world' battery life. Many modern acoustic systems have data telemetry capability such that the operator may interrogate the unit and remotely determine battery status and power levels.

A7-7 System Maintenance

A network of beacons or transponders requires monitoring and some maintenance to ensure good levels of performance are achieved. This includes:

- setting the transducer and beacon transmit power levels;
- measuring battery voltage of each transponder;
- regular measurement of the SVP in the network to take into account any variations over time;
- measuring the depth of each unit.

A7.8 Multiple Vessel Users

A recent problem for operators of acoustic positioning systems has been the influence of the environment on the ability of the acoustic positioning system to provide reliable signalling to a number of users. This has occurred due to several reasons. In deep water the natural ambient noise is quite low and so once a series of transponders or beacons is deployed, their signals will often transmit across much greater distances than is necessary. This effectively produces interference for other systems in the local area.

Recent case studies have shown that there is a need to carefully assess the environment to avoid signal and acoustic pollution. Multiple vessels and users extend the range and coverage required but, by doing so, also increase the number of acoustic transmissions and opportunities for interference. Planning of the logistics and scheduling may highlight if there will be clashes or saturation.

A further problem is that there have traditionally been a limited number of signal channels to operate on and once a full system is deployed and several surface and sub-surface units are set up for tracking, there is a lack of available channels or frequencies to accommodate additional units, or objects, to track.

Recent developments by several of the manufacturers have sought to overcome the worst of this by developing broadcast systems and adopting digital coding to increase the potential number of channels and users in a system to several hundred, thereby effectively making it unlimited for most projects.

A7.8.1 Simultaneous Position Fixing and Information Supply

Whilst the aim of the acoustic positioning system is to create a series of signals that will enable a processing unit to derive a position, the system very often needs to also report the condition, status and measurements from the system or peripheral devices. Acoustic messages with associated data for the sensors or the condition of the system are vital if the operator is to manage and avoid problems.

These secondary transmissions may actually be more critical as they often carry the sensor data messages and alert the operator to any problems.

A7.9 Interface with Different Sensors

It is not the intention of this document to provide a thorough review of the sensors listed but to illustrate their application and some elements of their use that the reader should be made aware of.

A7.9.1 Motion Reference Units

The use of a motion reference unit may be for the attitude and orientation of the surface ship that requires this knowledge for compensating the observations from a USBL system. Other uses include the ROV and AUV sub-surface bodies that may wish to compensate their motion to ensure accurate positioning and measurements are obtained. For the former, a variety of units may be considered but in general they will offer a high data rate, at around 50 Hz.

The sub-surface application of these units is more considered. For an AUV the power requirements should be kept to a minimum along with little weight or volume. On an ROV, however, power is not the limit, but often space to install the pressure housing to contain the unit is a limiting factor.

Data formats are usually relatively simple with the high data rates requiring a simple and uncomplicated message format that may be issued at 50 Hz, or even at a rate of 100 Hz. The critical factors for these units are their alignment and calibration along with the accurate time stamping of any data. The timing is critical to avoid introducing errors due to latency and buffering or signal delays that would put the motion sensor data out of synchronisation with the other sensors and data sets.

A7.9.2 Heading Sensors

Traditional north seeking gyrocompasses are slowly being replaced by a series of new technologies to derive a heading reference, including underwater GNSS-aided solutions and fibre-optic gyros.

In all cases the accurate alignment is critical and again the timing of the data outputs. Data rates are not too high at perhaps a few Hz but the lack of an independent check means that these units may experience some bias or errors that are very difficult to identify. Frequent operational checks and calibrations are required to ensure they maintain their accuracy and secondary systems are carried to avoid any critical system failures.

A7.9.3 GNSS

Surface positioning is referenced by use of GNSS. There are several variants of the satellite systems available. The oldest and most established is the US built satellite positioning system, GPS, originally built for military use and now dominated by commercial and civilian users. In deep water, the surface reference will simply be the starting point for the accumulation of observations to create a position at or near the seabed. This accumulation process also adds to the errors and so it is good practice to keep the errors on the surface to an absolute minimum so as to reduce the propagation of the errors.

High accuracy systems are now being advertised at better than 20cm, with 10cm being typical.

A7.9.4 IMU

These are highly sensitive units that detect the inertial movement of a body and translate that sensor data into relative movements in the local X, Y and Z axes of the unit. The axes of the IMU must be related to either the ROV, ship or AUV frame and then to the 'real world' (or simply direct to the real world if possible).

These sensor units produce very high data rates of 100 to 500 Hz. Timing is critical and because they have a high drift rate in absolute terms, they require external or additional measurements to bind their errors and keep the derived positioning accurate. They are essentially 'black boxes' with modelling and filtering requirements that mean a powerful processor is required and considerable effort is spent on developing accurate elements and parameters for these models to ensure reliable accuracies can be achieved.

A7.10 Checks and Quality Control

Additional parameters must also be collected and monitored – the key one being the speed of sound in water (or velocity of propagation) which can often limit the ability of the acoustic system to perform accurate positioning. For each well location and installation, an accurate value would be required and checks made to ensure no degradation of quality.

Appendix 8

Battery Technology

Whilst there is an interesting range of battery chemistries in use in subsea applications, much depending on the size of the equipment being deployed and on the financial resources available, the primary types of battery used in the commercial oil and gas sector are alkaline batteries and lithium batteries. More expensive silver-zinc batteries or heavy duty molten salt batteries are generally only found in military underwater applications.

A8.1 Lithium Batteries

Lithium batteries are very attractive to the oil industry due to a combination of high energy density, high voltage, high current capability, wide temperature range, a long shelf life of up to 10 years with little loss of capacity and stable operating voltage. The transport of batteries using lithium ion and lithium metal technology (together with many other battery technologies) is regulated by a series of mode specific mandatory regulations applicable to international transport. These regulations are reflected in national transport regulations in many parts of the world. Lithium thionyl chloride (Li/SOCl2) batteries are probably the most commonly used type. All batteries are potentially hazardous, but this type of lithium battery particularly so. These batteries can be damaged by short-circuits, overheating, mechanical damage and exposure to water. Such treatment can start chemical reactions and high currents inside the battery which can generate very harmful noxious gases and/or danger of explosions.

A8.2 Alkaline Batteries

Alkaline batteries based on zinc-manganese oxide chemistry are a more established and older technology developed in the 1960s and used widely across the world (every-day domestic batteries are of this sort). Though these batteries have a lower energy density than lithium batteries, they are both cheaper and easier to dispose of. The shelf life of alkaline batteries is less than that of lithium batteries. An alkaline battery will retain 85% of its capacity after four years storage at room temperature.