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MODERN METHODS OF UNDERWATER POSITIONING APPLIED IN SUBSEA MINING

1. Introduction

Underwater positioning is inextricably linked with Marine Mining and so called Offshore Mining and has equal importance with surface positioning with GNSS as main system. It is essential in almost all the phases of offshore hydrocarbon industry, from exploration, drilling, engineering and construction to the monitoring and maintenance of production systems. Underwater absolute or relative position is being utilized in different kinds of survey, navigation systems, in real time [3]. Applications are common and relatively widespread in what is essentially a specialized area like:

- the tracking vehicles, structures and towed sensors,
- locating and marking out underwater structures, pipelines and cables,
- the monitoring of drilling and dredging operations
- survey and monitoring of numerous objects.

Of the various forms of radiation, sound travels best through water. As a result of this characteristic, underwater sound has been used in underwater positioning systems [3]. Hence in the offshore industry and available bibliography, underwater acoustic, acoustic positioning, has been accepted as the official name for underwater positioning.

Acoustic positioning systems were developed in the 1950s and 60s to provide support to various US research projects and activities [3]. Over the years, prompted by demand from the offshore energy industry exploring deeper and deeper water areas, acoustic positioning and tracking systems have undergone a lot of technological changes. The worth mentioning

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is fact that the definition of deep water varies depending of what kind of activity is taken into consideration. Offshore drilling often considers deep water greater than 2500 m. Generally if offshore survey project is concerned the depths greater than 600 m is assumed as deep water.

Satellite based positioning systems have introduced global coverage, whereas acoustic positioning systems remain localized and typically cover only a few square kilometers 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 [3]. Unlike surface positioning systems (GNSS etc.) underwater acoustic positioning systems are dedicated for highly specialized users. The thing which is significant, is the fact that, to the best of the author's knowledge, there is no single system used by Polish surveyors on the Polish territory.

Over the last few years inertial navigation systems are observed offshore being introduced as additional source of position, especially as far as pipe line inspection are concerned. They are very useful in some cases and may decrease the cost of operation significantly but still require acoustics as aided system. In this paper INS will be not discussed.

2. 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 [3]. For the purposes of this document, the primary methods under consideration are the most commonly used techniques, long baseline (LBL), ultra short baseline (USBL), which exhibit the key principles and considerations associated with acoustic positioning. Application of both methods require deep user involvement as it comprises time consuming methods of calibration, array transponders coordinates determination, producing sound velocity profiles etc.. All of this make the underwater positioning complex and extensive solution hence for purposes of this paper the subject was limited to the basic issues.

Other methods such as short baseline (SBL), long ultra short baseline (LUSBL) as a combination of basic method are not covered in this paper.

2.1. Long Baseline (LBL)

LBL systems take their name from the distance between seabed transponders or beacons which can be as much as several kilometers, usually not more than 50~2000 m. LBL system is a high accuracy solution. Depending on the frequency applied the accuracy varies from 0.02 m for extra high frequency, 0.15 for medium and 0.5 low frequency. The higher frequency the lower accuracy. The conventional long-baseline acoustic position systems normally use Kalman Filter correction to handle the problem of positional errors [7]. A typical LBL positioning system consists of one transceiver and at least three transponders. The transceiver is mounted on a submersible or a surface vessel, which is the target to be positioned. The transponders are installed on the seafloor to form an array (Fig. 1). Before positioning the target, transponders will be deployed on the seafloor. Their positions (or at least the distances between each other) need to be known precisely. The deployment and retrieval of transponders on the seafloor are performed by a surface ship, or by divers or an underwater automatic vehicle. The transceiver on the target pings each transponder on the seafloor. The travelling time of the transmitted signal from the target to the transponders and backwards is measured. Knowing the sound velocity at the site allows this measurement to be converted directly to the travelling distances. Once the distances from all transponders to the transceiver are obtained, a unique point where all these distances intersect is obtained via calculations and this point is the position of the transceiver. This method is called “trilateration”. The calculated transceiver’s position is within and referenced to the transponders array [4].

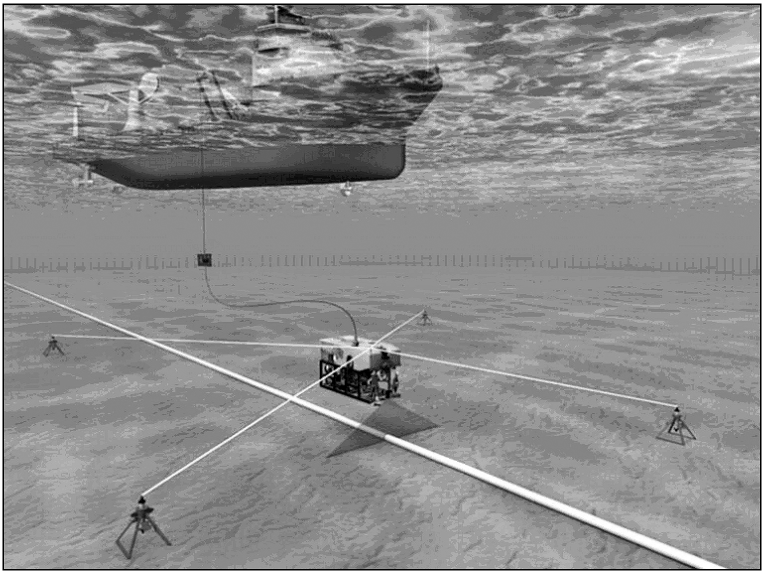


Fig. 1. Illustration showing a LBL system configuration [3]

General LBL position estimation problem was visualized at Figure 2. There is an object denoted O at some unknown location (x, y, z). There are some number N of reference sensors located at known positions (x_i, y_i, z_i). The goal is to estimate the unknown location of the object utilizing timing measurements of pulses which propagate between the objects and the reference sensors.

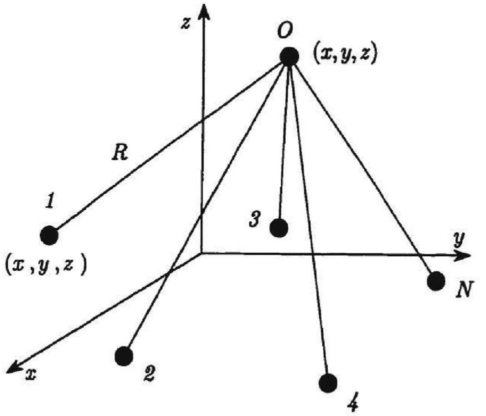


Fig. 2. General position estimation problem [2]

In a spherical case a signal is emitted from the object at some emission time t^e propagates with a velocity c and arrives at some numbers of receivers at time t_i^a. In this situation the mathematical positioning model is given by [2]:

$$R_i = c\left(t_i^a - t^e\right); \qquad i = 1 \ldots N \tag{1}$$

Where:

$$R_i = \sqrt{\left(x - x_i\right)^2 + \left(y - y_i\right)^2 + \left(z - z_i\right)^2} \tag{2}$$

is the geometrical slant range between the source and receiver. Conversely, if all reference sensors transmit vice receive, the positioning model becomes:

$$R_i = c\left(t_i^a - t_i^e\right); \qquad i = 1 \ldots N \tag{3}$$

Where t_i^e is the emission time from the i^{th} sensor. In either situation, the emission time(s) are known and the so-called transit time: $t_i^t = t_i^a - t_i^e$ is known. Thus both situation can be represented by [2]:

$$R_i = ct_i^t; \qquad i = 1 \ldots N \tag{4}$$

This mathematical model is termed spherical and represents a sphere in analytical geometry. LBL acoustic systems provide accurate fixing over a relatively small area and 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 [3]. Modern heading reference units and attitude sensors with fibre optic units and ring laser gyros providing accurate observations with high update rates are now commonplace in many acoustic positioning solutions. These units do require careful alignment on their host vehicle or structure. Their introduction has enabled underwater vehicles to achieve enhanced positioning solutions. There are various types of signaling available for use in acoustics. These include tone based, such as pulsed, chirp modulation signaling and digital spread spectrum signaling (Wideband Technology).

2.2. Ultra Short Baseline

The development of the first USBL was stimulated by a requirement to support diving vessel operations. These needed an additional independent localised method for dynamic positioning (DP) to ensure safe operations. At that time (1977), before the advent of Differential GPS, radio positioning systems were not capable of providing the necessary positional accuracy and precision needed for 24 hour diving operations in the North Sea's new fields [3]. The name comes from the short baseline which is established between elements of transducer. The USBL methodology is applicable only for shallow water positioning or deep water low accuracy positioning, because USBL position accuracy deteriorates with depth quite fast. The accuracy of the system is estimated as 0.2–1% of slant range. USBL generally provided a reliable local relative system that complemented other short range high precision systems such as taut wire and Artemis. Its use rapidly spread to a number of survey activities and applications most notably in the positioning of a variety of underwater sensors units relative to a survey vessel [1].

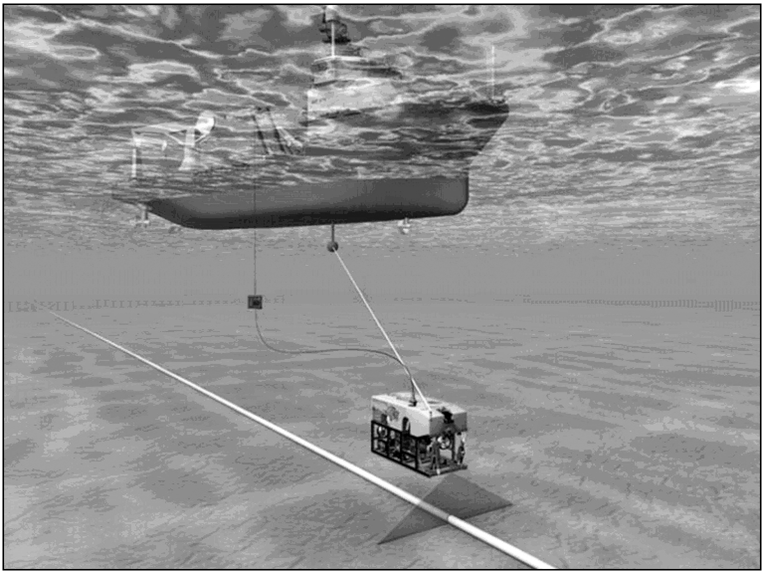


Fig. 3. Illustration showing a USBL system [3]

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 [3]. 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. The principles of measurements are visualized at Figure 4. Instead of using the trilateration to calculate a subsea position, the USBL measures both the range and the angle from the subsea target to the transceiver array (Fig. 4). An important assumption is that the wave front of the acoustic signal is planar at the transceiver array. To avoid ambiguity in phase angle measurement, transceivers in the array are separated by only half of the wavelength (usually 10 cm or less) of the acoustic signal. To determine the azimuth angle, the phase difference of the signal from the target between two receivers in the array is measured relative to the array's baseline [4].

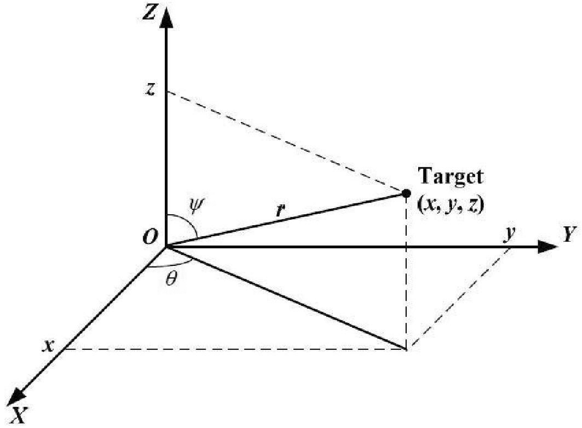


Fig. 4. USBL range and angle measurement [4]

Here the azimuth angle is defined as the angle between the positive *X*-axis and the target position vector (the line points out to the target from the coordinate origin) projected onto the horizontal *X–Y* plane. If a third receiver is used, orthogonal to the first two, the elevation angle, which is the angle between the positive *Z*-axis and the target position vector, can be determined. The distance from the transceiver to the target, *r*, is the amplitude of the target vector. It is obtained by measuring the time of arrival, as in LBL and SBL systems. A complete figure is shown at Figure 4 and the Cartesian coordinate (x, y, z) of this target is given by [4]:

$$y = r \sin \psi \cos \Theta \tag{5}$$

$$x = r \sin \psi \sin \Theta \tag{6}$$

$$z = r \cos \psi \tag{7}$$

This is critical for the USBL technique as, unlike the LBL 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. Absolut coordinates of transponder can be calculated when the system is combined with GNNS system.

3. Underwater metrology — case study

Metrology is an essential part of the subsea industry where acoustic positioning is employed - whether as part of pipeline tie-ins, subsea developments, and increasingly repair and maintenance operations. The most frequent task is spool piece metrology. A spoolpiece metrology consists of the determination of the relative position and attitude of the flanges of two structures for the design of the interconnecting spoolpiece (Fig. 5).

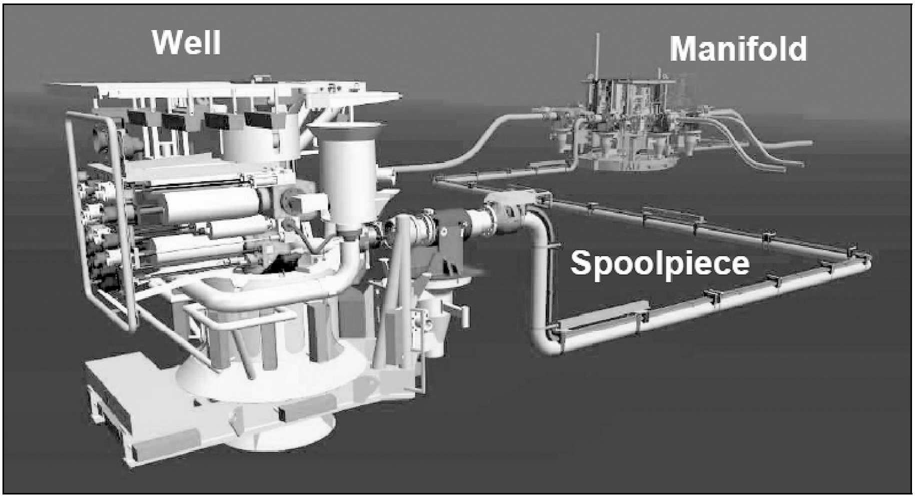


Fig. 5. Typical design of a spoolpiece interconnecting two structures (e.g. a well and a manifold) [5]

Typical flange separation distances to be bridged by the spoolpieces amount to several tens of meters. The relative flange geometry has to be determined subject to strict tolerances. Typical tolerance values are: relative flange position: ±50–100 mm and relative flange attitude: ± 0.5–1.0°. Only long baseline method meets the requirements concerning accuracy.

In general the following figures need to be reported for the spoolpiece design (Fig. 6):

- horizontal distance L between flange reference points,
- depth difference between flange reference points,
- horizontal angles α and β between flange axes and a direct line connecting flange references points,
- pitch and roll of the flanges (in the axes of the flanges),
- height above seabed of flange reference points,
- seabed bathymetric profile along spoolpiece design route.

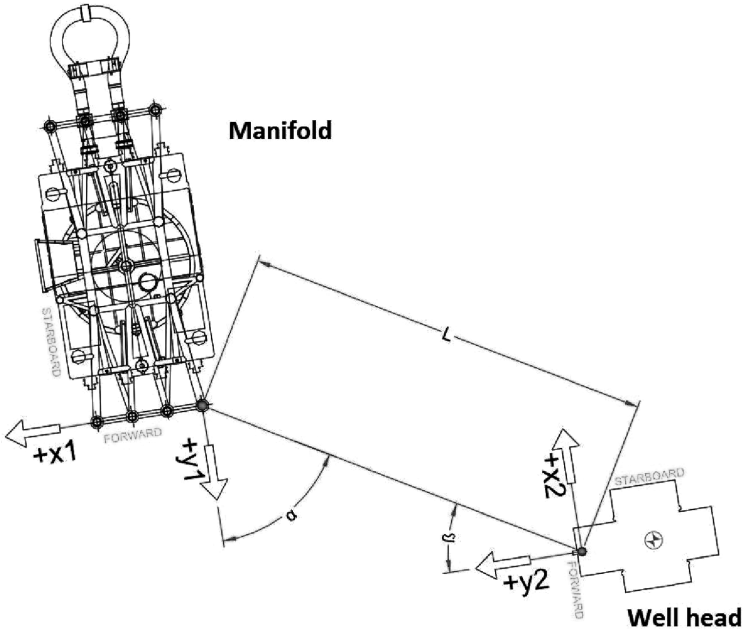


Fig. 6. Spoolpiece metrology figures to be reported for spoolpiece design [5]

Transponders are placed on the structures at know offsets (from a dimensional control survey) to the flanges using specific metrology interface tooling (Fig. 7).

The transponders are part of an array of LBL transponders further deployed spread around the structures. In acoustic metrology the functionality of the system is used to compute the slant range between seabed transponders. A minimum of four transponders are installed at each metrology location. The transponders are deployed to form a sound geometrical network or array with baselines between each pair that are of approximately equal length. The baseline lengths are computed from acoustic observations and the measured velocity of sound in seawater at the array location. The computed slant ranges between transponders are used, together with the observed transponder's depths and nominal deployment positions, as inputs for a least squares mathematical adjustment. The array adjustment will determine the relative plan positions of each transponder within the array. The spoolpiece metrology attitude tolerances are met by performing measurements with accurate subsea gyroscopes mounted on remote operated vehicle and inclinometers built in transponders.

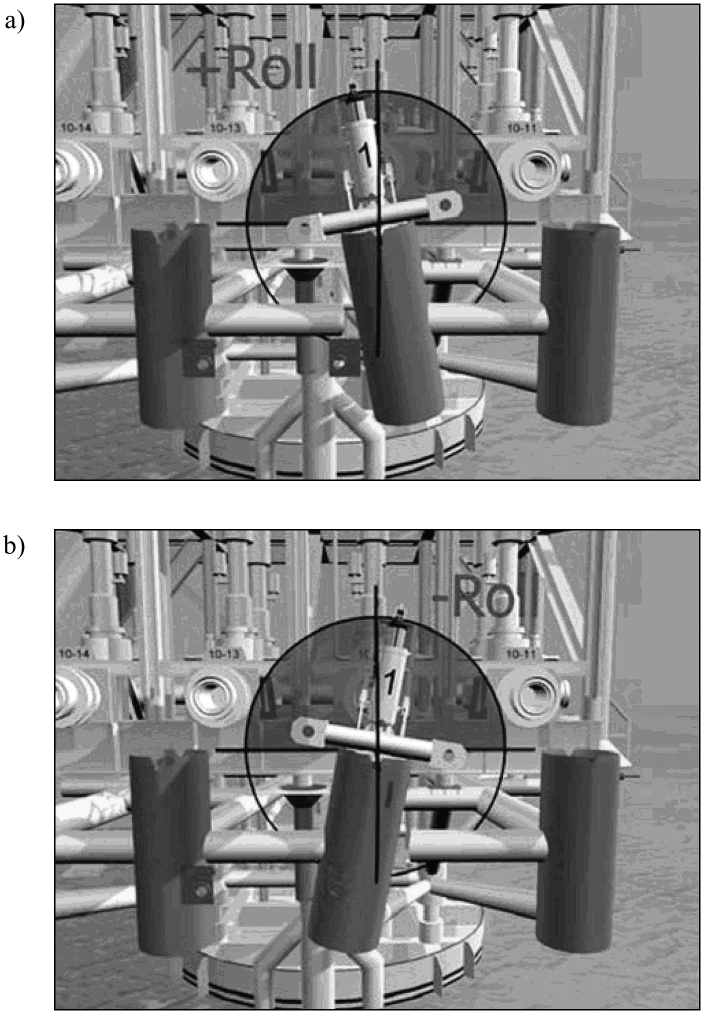


Fig. 7. Interface tool used to place the LBL transponder at the structure flange [5]

Installing an LBL system in a absolute grid reference requires the network to be calibrated and adjusted utilizing the surface positioning system [8]. As such it is important to measure all ship LBL system offsets with reference to the navigation systems.

Relative calibration is based on baselines measurement between all transponders deployed for a particular metrology measurement set and nominal deployment. Ranges together with the observed transponder's depths should be measured between all transponders in both directions. A minimum of ten (10) valid ranges in each direction are required for an acceptable dataset with an angle of cut of greater than 60° (if practically possible) (Fig 8). Data should be analysed online to ensure that valid data are achieved. Initial transponder positions shall be entered as "start positions" for the transponders. However, transponder positions shall be assigned full freedom of movement during the adjustment. Histograms displayed in the acoustic software shall be utilised to edit acoustic baselines so that normal distribution results are obtained. This process ensures that spurious data are removed, and that any significant change in Sound Velocity Profile over the observation period is detected [8]. Extended Kalman Filtering algorithm is applied to estimate the baseline distance between transponders.

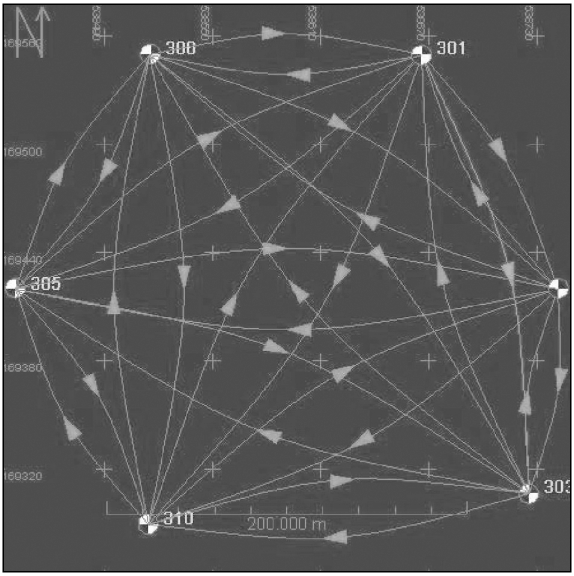


Fig. 8. Baseline calibration

An absolute calibration is required if the absolute position of the array coordinates, including the orientation is related to the working grid and true north. Calibration can be obtained by fixing two transponders on known coordinate positions on fixed seabed structures, or by calculation and transferring an absolute position from a surface positioning system such as a GNSS system to a baseline array. It is so called box in calibration. The location of the transponders are found by measuring a large number of ranges from the transducer on the vessel to the transponders. The true position of the transponders lies at the point (calculated) where all the ranges cross. Least Square adjustment is used to estimate position (Fig. 9).

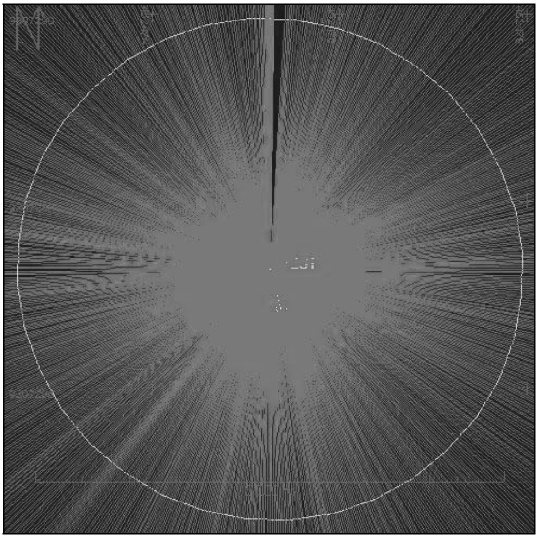
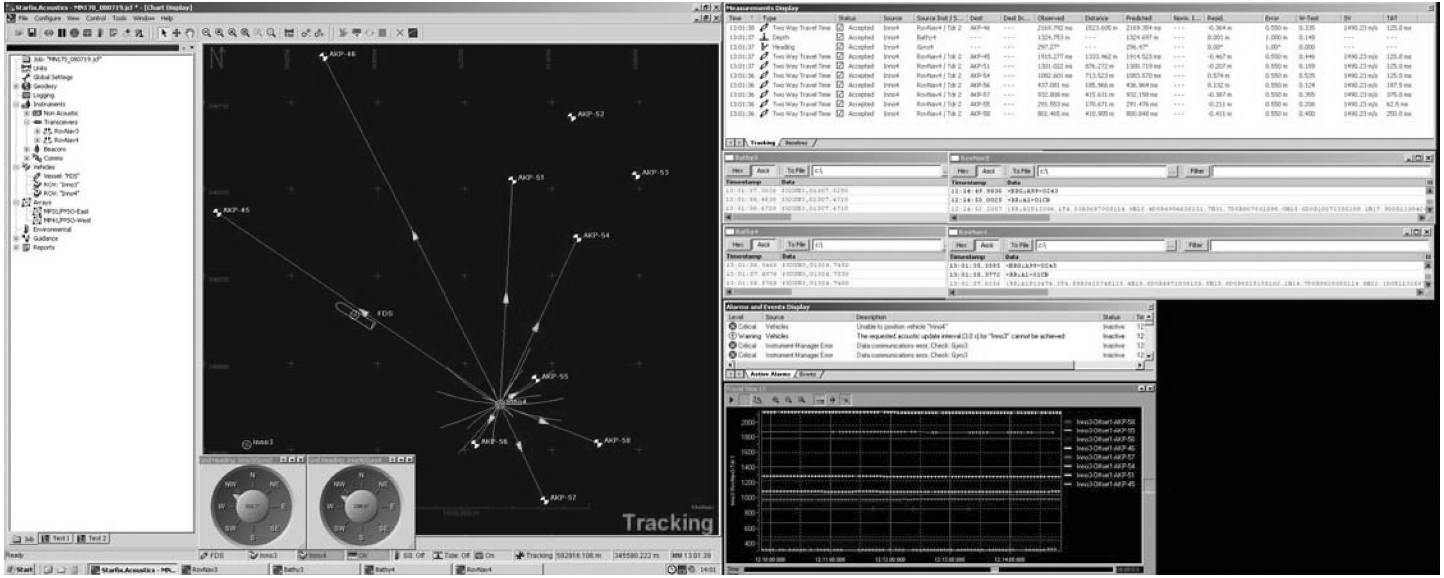


Fig. 9. Box in calibration

After baseline and box in calibration the spoolpiece metrology can be performed. Measurements logging sessions are taken depending on requirements and position of all surface vessels, mobile vehicles, reference transponders and waypoint in Cartesian format are monitored. Absolute positions and attitude of structures reference points can be determined with high accuracy.

The measurement list shows row and estimated values and the quality of each measurement being used for tracking vehicle or body as they are received. Co-ordinates are calculated using a mathematical optimal estimator which allows for the weight of predicted and measured positions to be set depending on vehicle dynamics (Fig. 10) [6].

The direct impact on the accuracy of the attitude measurements has the centralising and the orientation of the transponder in the crucifix tooling (Fig. 7). Hence every effort should be made to position and align the transponders exactly at the center of the tool. In order to eliminate any bias of the metrology tooling, it is recommended to have few sets of inclination measurements undertaken, with the tool being rotated by 180° after each set. The depths of the structures is recorded during successive measurements on both manifold and well with the paro scientific digiquartz depth sensor built in the transponders. In most cases there is a need to reduce obtained values to the desired level (MSL) using the vertical offset for the digiquartz tool and others. The heading of the structures determination is performed in two ways, calculated between two transponders mounted along the structures and with use of Remote Operated Vehicle (ROV) equipped with fibre optic gyrocompass. ROV docks to purposely designed docking bar perpendicularly fixed to the structures. After data collection and processing the final results (Fig. 11) are generated. On the bases of it the spoolpiece element joining manifold and well will be manufactured.



Time	Type	Status	Source	Source Inst / S...	Dest	Dest In...	Observed	Distance	Predicted	Norm. I...	Resid.	Error	W-Test	SV	TAT
13:01:38	Two Way Travel Time	☑ Accepted	Inno4	RovNav4 / Tdr 2	AKP-46	---	2169.792 ms	1523.605 m	2169.394 ms	---	-0.364 m	0.550 m	0.335	1490.23 m/s	125.0 ms
13:01:37	Depth	☑ Accepted	Inno4	Bathy4	---	---	1324.753 m	---	1324.697 m	---	0.001 m	1.000 m	0.149	---	---
13:01:37	Heading	☑ Accepted	Inno4	Gyro4	---	---	297.27°	---	296.47°	---	0.00°	1.00°	0.000	---	---
13:01:37	Two Way Travel Time	☑ Accepted	Inno4	RovNav4 / Tdr 2	AKP-45	---	1915.277 ms	1333.962 m	1914.523 ms	---	-0.467 m	0.550 m	0.446	1490.23 m/s	125.0 ms
13:01:37	Two Way Travel Time	☑ Accepted	Inno4	RovNav4 / Tdr 2	AKP-51	---	1301.022 ms	876.272 m	1300.719 ms	---	-0.207 m	0.550 m	0.189	1490.23 m/s	125.0 ms
13:01:36	Two Way Travel Time	☑ Accepted	Inno4	RovNav4 / Tdr 2	AKP-54	---	1082.601 ms	713.523 m	1083.570 ms	---	0.574 m	0.550 m	0.535	1490.23 m/s	125.0 ms
13:01:36	Two Way Travel Time	☑ Accepted	Inno4	RovNav4 / Tdr 2	AKP-56	---	437.081 ms	185.966 m	436.964 ms	---	0.132 m	0.550 m	0.124	1490.23 m/s	187.5 ms
13:01:36	Two Way Travel Time	☑ Accepted	Inno4	RovNav4 / Tdr 2	AKP-57	---	932.808 ms	415.631 m	932.158 ms	---	-0.387 m	0.550 m	0.355	1490.23 m/s	375.0 ms
13:01:36	Two Way Travel Time	☑ Accepted	Inno4	RovNav4 / Tdr 2	AKP-55	---	291.553 ms	170.671 m	291.476 ms	---	-0.211 m	0.550 m	0.206	1490.23 m/s	62.5 ms
13:01:36	Two Way Travel Time	☑ Accepted	Inno4	RovNav4 / Tdr 2	AKP-58	---	801.465 ms	410.905 m	800.848 ms	---	-0.411 m	0.550 m	0.400	1490.23 m/s	250.0 ms

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12:14:49.9836  <BRG;A99=0243
12:14:50.0025  <BB;A1=01CB
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13:01:35.3881  <BRG;A99=0243
13:01:35.3772  <BB;A1=01CB
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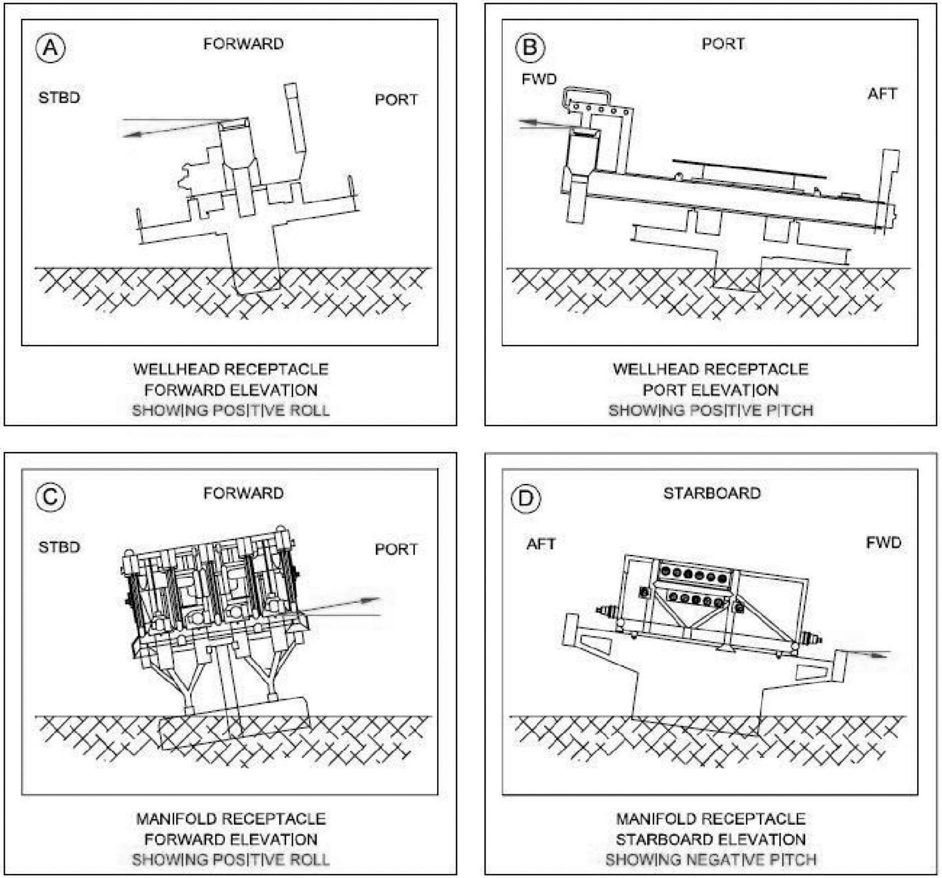
Level	Source	Description	Status	Tir
Critical	Vehicles	Unable to position vehicle "Inno4"	Inactive	12:
Warning	Vehicles	The requested acoustic update interval [3.0 s] for "Inno3" cannot be achieved	Inactive	12:
Critical	Instrument Manager Error	Data communications error. Check: Gyro3	Inactive	12:
Critical	Instrument Manager Error	Data communications error. Check: Gyro3	Inactive	12:

Fig. 10. LBL Fusion software screenshot [6]



Manifold Pitch, RX1	-0.70	°
Manifold Roll, RY1	0.43	°
Manifold height above seabed	4.21	m
Well Pitch, RX2	0.30	°
Well Roll, RY2	0.02	°
Well height above seabed	1.60	m
Horizontal distance L between CHCR Datum Points	18.46	m
Horizontal angle alpha between Y1 axis and direct line between reference points	58.07	°
Horizontal angle beta between Y2 axis and direct line between reference points	27.09	°
Difference in elevation DZ between reference points	1.21	m

Fig. 11. Field data processed to a final results

4. Conclusions

This paper is yet by no means complete as the subject of underwater positioning is broad and multilevel. Based on available bibliography and personal experience with acoustic systems, the author made an effort to choose the most important information regarding principles of working and demonstration of potential application. The author aimed at indicating the complexity of underwater positioning subject and its complicated operating procedures. Currently, the navigation position for the underwater submerged bodies is measured by the conventional Long Baseline acoustic position system, and the errors are mostly modified by the Kalman Filter theory [7]. Unlike surface positioning satellite systems, underwater acoustic ones are definitely not plug and play devices for the users. The scientific research in field of underwater positioning concerns mainly the enhancing of functionality and operational range in terms of depth and horizontal distance between transponders. The present research comprises also the integration of underwater acoustics with Inertial Measurement Units and the use of acoustic range aided Inertial Navigation Systems (INS) for deep water high accuracy subsea positioning. This hybrid is gaining rapid advance in the offshore survey industry and makes an interesting alternative for LBL only positioning since there is no need for the time consuming deployment of full number of transponders and their calibration.

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