Advanced Long Baseline Acoustics for Precise Deep Water Structure Mating

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1. ABSTRACT

In 2000, Halliburton Energy Services started developing a Subsea Well Intervention System, or SWIFT Riser System, for use in very deep water. This consisted of a Lower Riser Package (LRP) with a Pyramid Up Guidance System (PUGS) installed on top. The LRP with the PUGS is located on the seafloor. The lubricator and corresponding PUGS connection is run from the vessel and mated with the LRP. There would be no connection between the PUGS and the LRP during the lowering of the LRP. Therefore, a means to provide precise relative positioning between the two units was required to enable the mating of the two.

The deepwater aspect and the desire to provide a self contained solution made traditional methodologies, including Long Baseline (LBL) acoustic positioning, impractical. Halliburton SubSea devised a unique application of LBL acoustics and brought it to Thales GeoSolutions (Pacific) to see if it could be included in their real-time integrated navigation package, WinFrog, already used by Halliburton SubSea. The application was refined by Thales and implemented in WinFrog as the INVERTED LBL application. This is a completely new positioning methodology and has great potential for deep-water construction projects in the future.

This paper will describe how the INVERTED LBL approach provided the means to precisely determine the relative position, orientation and attitude of the PUGS with respect to the LRP during the critical final descent and mating in extremely deep water and includes a summary of two trials performed.

2. INTRODUCTION

Given the increasing number of subsea trees being deployed internationally, operators are growing increasingly concerned with reducing the cost while increasing the availability of subsea well intervention services. Halliburton Energy Services is a leader in the field of designing and developing advanced solutions to meet the oil and gas industry's evolving requirements. To this end, Energy Services developed the SWIFT Riser System. The SWIFT system was designed to combine all slickline, electric line and coiled tubing well intervention capabilities into a single, "SMART" composite, coiled tubing with embedded conductors and fibre optics.

The essence of the SWIFT system is a composite riser spooled with a close fitting composite work string. This eliminates the need for motion compensation due to the compliance of the riser and work string. Returns from the well are routed up a separate composite return line that also carries the conductors and fibre optic lines for the control system.

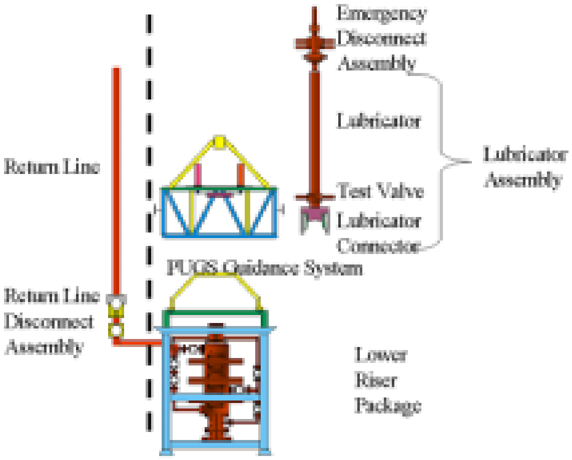


Diagram of subsea equipment (above)

The SWIFT system includes a LRP with a PUGS installed on top. The LRP with the PUGS is located on the Xmas tree and remains attached during the intervention with a control umbilical to surface. The lubricator and corresponding PUGS connection is run from the vessel on a compliant flexible riser system with the close tolerance coiled tubing intervention string inside. The lubricator is fully equipped with the tools required for the work to be done. The mating of the PUGS to the LRP is done without guidelines. Therefore, a means to provide precise relative positioning between the two units was required to enable the mating of the two.

The positioning requirement for the PUGS system is to provide precise relative positioning between the LRP and lower PUGS frame and the incoming lubricator with the corresponding connection. The system enables accurate guidance and docking before the actuation of the critical connector seal between the two. The requirement to build a system for deep water and the desire to provide a self contained solution made traditional methodologies impractical. Another Halliburton division, Halliburton SubSea, provides their various divisions with positioning and navigation systems and expertise. Energy Services asked SubSea for input in designing the means to provide the accurate relative positioning of the PUGS and the LRP. SubSea uses the Thales GeoSolutions' real-time integrated positioning and navigation software package, WinFrog.

Thales GeoSolutions (Pacific), Inc. has been providing real-time navigation and positioning systems and services to a variety of offshore industries, including oil and gas exploration, survey, marine construction, submarine cable installation and fleet management for twenty-five years. Their current integrated navigation software, WinFrog, is in use around the world in all of these markets. One component of this package is the acoustic module, which provides a comprehensive suite of Ultra Short Baseline (USBL) and LBL capabilities for the calibration and application of acoustic systems for the positioning and tracking of underwater vehicles and structures.

In this case, like many other instances in the past, SubSea devised a unique application of LBL acoustics and brought it to Thales to see if it could be implemented within WinFrog. Thales refined the application and the models and algorithms were designed and implemented within WinFrog as the INVERTED LBL application. This is a completely new positioning methodology that addressed the requirements for the SWIFT Riser System.

3. THE LBL SOLUTION

The SWIFT Riser System will be deployed in water depths of up to 3000 metres. It is necessary to be able to accurately monitor the PUGS with respect to the LRP during its descent to the seafloor, with the final 20-30 metres requiring very high accuracy relative positioning. The requirements for this final stage include the determination of the PUGS position, orientation and attitude (pitch and roll) relative to the LRP.

It is important to note that the LRP is to sit on wellheads that are generally expected to be level to within 1°. As the PUGS is extremely heavy, it is designed to hang suspended in a level attitude. Thus, the critical components are the relative orientation and position of the PUGS. The PUGS is designed to be able to mate with the LRP when the two are out of alignment by up to 40°.

The PUGS will be tracked from the surface vessel during the descent using an USBL acoustic system. Positioning during the final 20 to 30 metres of descent and the docking itself will be done using Long Baseline Extra High Frequency (LBL EHF) acoustics.

The conventional approach to LBL acoustic positioning has been to deploy transponders on the seabed to form a fixed network array and determine their positions through calibration. The interrogating unit (transceiver or smart transponder) is then mounted on the dynamic vehicle and its position is determined by measuring ranges to the fixed transponders. The concept proposed by Halliburton is the inverse of this.

Given an array of static transceivers whose spatial relationship is a relative network of known points, range measurements from each of these to a single dynamic transponder can provide the data required to solve for the transponder position using a least squares adjustment. As with any adjustment, there are several important points to consider. First, the number of observations (measurements), and therefore, the number of static transceivers in the network, must be equal to or greater than the number of unknowns that are being solved for. In this case there are three unknowns, position (X and Y) and depth (Z). The use of more than three measurements improves the results of the adjustment. Second, there must be strong geometry in the relationship of the static transceivers network and the dynamic transponder. Third, the position computed for the dynamic transponder is relative to the static transceiver array. It is only accurate in the absolute sense if the static transceiver network is accurately positioned in “real world” coordinates.

At this point, it is important to consider the relative spatial relationship of the static transceivers. Given a vessel, all positional information must be referenced to a specific arbitrarily assigned point called the Common Reference Point (CRP). It must also be referenced to a specific arbitrarily assigned orientation, generally a line parallel to the respective vessel centre line from stern to bow. This orientation and CRP define a local vessel based coordinate system. Applying this to the static transceiver array, a CRP is assigned to a central point within the network and a reference for the orientation is selected. The static transceivers are then accurately measured within this coordinate system. The adjusted position of the dynamic transponder is also relative to this coordinate reference frame.

The positioning of the single dynamic transponder can be expanded to include an array of transponders that are attached to a dynamic but rigid structure. This structure is assigned a CRP and reference orientation to create a local coordinate system. The transponders are fixed and their spatial relationship within this local reference frame can be accurately measured with respect to the CRP and with each other. Range measurements from each of the static transceivers to each of the transponders produce an independent solution for the position of each transponder. Adding the known baseline lengths between each dynamic transponder pair as constraints to the adjustment results in improved solutions for the transponder positions that are no longer independent of each other.

The last stage in the process is the solution of six more unknowns, specifically the attitude (pitch and roll), orientation and CRP position (X, Y and Z) of this dynamic structure. A least squares adjustment is used. There must be at least six observations. The observations in this adjustment are the spatial relationships between the dynamic transponders, three for each transponder pairing (▲X, ▲Y and ▲Z). This adjustment requires a minimum of three transponders in the dynamic array. This provides two transponder pairings (not three as one might expect). The third pairing is the equivalent of combining the other two, not an independent observation. Including a fourth transponder results in redundancy in the adjustment, improving the results, the expected accuracy and the quality control and monitoring options. Using sufficient transponders to ensure redundancy in the least squares solution is standard practice.

To reiterate, the results of these adjustments are relative to the local coordinate reference frame of the static transceivers. From them, the distance from the static transceiver CRP to the dynamic structure CRP in terms of XYZ relative to the static transceiver local coordinate system can be calculated. This approach is particularly well suited for application to the SWIFT Riser System since it is required that the PUGS be positioned relative to the LRP. The results can be transformed to an absolute sense by referencing the static transceiver network to what is referred to as real world coordinates, WGS84 for example.

The nature of this LBL application is the inverse of the standard application. This led to the term, which has been adopted for it, INVERTED LBL.

4. APPLICATION OF THE LBL THEORY

The application of this approach involved a software component and a hardware component.

4.1 INVERTED LBL IN WINFROG

The implementation of the new INVERTED LBL application within WinFrog was designed and incorporated into the LBL capabilities. This allowed taking advantage of the fundamental functionality already in place as part of the existing comprehensive WinFrog LBL module. The implementation included operator interfacing, automation of processes when feasible and reasonable, graphical and alphanumerical display of the data input, adjustments and resulting vehicle positioning for complete monitoring of operation and quality control. Flexibility was built in to the design so that the application would not be restricted to only the SWIFT Riser project.

In addition, the results of the INVERTED LBL application had to be available for access by another software package, Halliburton's Visualization software.

4.2 THE PUGS AND LRP IN WINFROG

The PUGS attached to the LRP was approximately 2.6 metres square and 1.9 metres from the bottom to the mating surface. A pyramid shaped frame, approximately 2.0 metres square at its base, was located in the centre of the mating surface and extended to a height of approximately 1.0 metre above this surface.

The PUGS being lowered to mate with the LRP assembly was approximately 2.5 metres square with an approximate height of 1.7 metres. It was designed to mate to the LRP using the pyramid shape on the LRP to assist guiding it into the correct orientation.

The LRP and PUGS units were considered vessels in WinFrog. Each was designated a CRP and a line of orientation reference.

The horizontal centre of the bottom of the PUGS being lowered was assigned as its CRP. The horizontal centre of the mating surface of the LRP's PUGS was assigned as its CRP.

4.3 ACOUSTIC HARDWARE

The acoustic system selected for positioning the PUGS relative to the LRP during the final stages of the mating was the Sonardyne EHF ROVNAV Mk4 system with Sonardyne EHF transponders. The ROVNAV unit is an acoustic control unit housed in an underwater casing with connections for two transceivers and a communications cable to a peripheral computer. Among other features, the two ROVNAV transceivers can be sequentially instructed to interrogate transponders. The Sonardyne transponders proposed are known as Mark 4 Computing and Telemetering Transponders (COMPATT) with the "Simultaneous" feature. These COMPATTs can be instructed by the ROVNAV to interrogate other transponders and then send the observed range data back to the ROVNAV. Communications between the ROVNAV and this Simultaneous COMPATT is done via acoustic telemetry. EHF is required to provide the measurement resolution necessary to enable the determination of the transponder positions to the accuracy required, especially for the determination of the orientation and the attitude of the PUGS.

The original design called for one ROVNAV system with two transceivers and one Simultaneous COMPATT to be mounted on the LRP. The ROVNAV transceivers were located at two diagonally opposite corners with the COMPATT mounted on one of the remaining corners. The ROVNAV transceivers would interrogate the transponders on the PUGS and then instruct the Simultaneous COMPATT to do the same. For reasons discussed later in this paper, this was changed to a final configuration of two ROVNAV systems each with two transceivers mounted on the LRP, one on each corner of the structure. This provided the greatest separation possible between each transceiver, thus providing the best possible geometry for the solution of the transponders on the PUGS. The transceivers were mounted on the top of the LRP, pointing up. The communications cable from the ROVNAV was connected to the surface and the WinFrog computer. In the final installation, this would be via the cable connection from the LRP to the surface support vessel.

Four COMPATTs were mounted on the bottom of the PUGS pointing down, one on each corner of the structure. As in the case of the LRP, these transponders were located such that the baselines between them were as long as possible. This again strengthens the geometry for the transponder position solution and the subsequent solution for orientation and attitude.
The mounting of the acoustic hardware on both structures must take the following into consideration:

- Protection from damage due to the collision of any hardware in the water with the units' cabling, casing and the sensitive transducer unit. (Both the transponders and the transceivers have a transducer.)
- Extension from the structures themselves to provide the clearest possible line of communication between any transceiver on the LRP to the transponders on the PUGS.

4.4 TIMING ISSUES

The issue of timing of this process requires addressing. Ideally, all range data would be acquired and therefore valid for the same epoch. However, with the acoustic system proposed (and any other available system), any one transceiver pair (i.e. any transceiver control unit) can only interrogate the transponders and listen for the replies with a single transceiver at a time. Even when using multiple transceiver pairs, when it actually would be possible to trigger the interrogation of the transponders by one transceiver in each pair simultaneously, the interrogations must be synchronized such that at any time, only one transceiver is interrogating and listening for replies. WinFrog synchronizes the operation of each transceiver on multiple Sonardyne systems including the application of a configurable delay between the receipt of replies by one transceiver and the interrogation by another to allow for reverberation to die down. In this application, the result is that the range data is actually valid for different epochs.

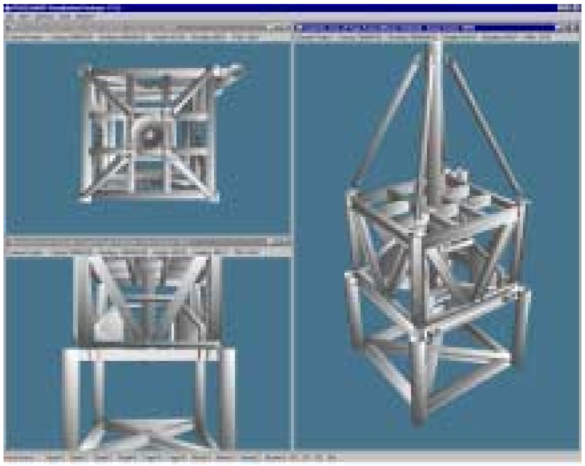
This was addressed within WinFrog as follows. Upon the completion of an interrogation/reply cycle for any transceiver, this data is combined with the latest data available for all the other transceivers and input to the adjustments. While this results in a portion of the data used for each computation cycle being old, it was felt that for the purpose of the initial implementation and trials that this was acceptable and would not grossly impact the calculations, given the dynamics of the structures being positioned. The optimum cycle time for collecting range data for one transceiver is one second. It is expected that in practice this will be two seconds. Therefore for three transceivers on the LRP, the total cycle time to collect a complete observation set will vary from three to six seconds, assuming all interrogations are successful.

An algorithm to automatically scale the weight associated with the data based on the age of that data relative to the newest data in a computation cycle was considered and will be implemented in future software revisions.

5. THE VISUALIZATION UTILITY

The WinFrog package incorporates multiple plan and profile graphic windows for the presentation of vessels to facilitate their navigation. While these provide the basics required for the positioning of the PUGS and LRP, it was felt that a more graphical display would be of benefit in assisting the bridge crew during the docking operation. Rather than incorporate this display into WinFrog it was decided to implement it as a separate Visualization Utility.

The utility was developed by Halliburton SubSea using the Microsoft DirectX toolkit. DirectX is a set of low-level application programming interfaces (APIs) that include support for high-performance 2-D and 3-D graphics, sound and music, input, force feedback, multimedia streaming and network communication. The display simply shows the relative locations of the LRP and PUGS. The LRP/PUGS components are represented as a rendered 3D model, displayed in three views or windows – plan, elevation and perspective. In each case, the window scale and orientation can be adjusted either manually by the user or automatically.



Example of the docking display (above)

WinFrog constantly updates the Visualization Utility via a serial connection, passing the current set of position data for the PUGS and the LRP, including orientation and attitude. This allows the visualization software constantly to update the views.

6. TRIALS

Two trials were undertaken in the testing and validation of the INVERTED LBL approach. The first was a tank trial performed at Halliburton's facilities in Aberdeen, Scotland. Its objective was to validate the LBL concept. The second was at Loch Linnhe in Scotland. The objective of this second trial was to evaluate the LBL positioning and the actual mating of the PUGS to the LRP in open water.

6.1 TANK TRIALS

The test tank used for these trials was a large round steel walled tank located on Halliburton's premises in Aberdeen, Scotland. The tank was approximately 6 metres in diameter and 8 metres deep. It sat entirely above the ground and had several viewing portholes at varying depths and locations around the perimeter. An onsite crane mounted on the tank deck was used for deploying the LRP and PUGS.

Prior to the test, the tank environment was of concern for the operation of the acoustics. The confined water body and close proximity of the steel walls would exaggerate known problem sources for acoustics, specifically reverberation and reflection.

The objectives of the tank trials were as follows:

- Confirm the concept for this unique application of the LBL acoustics for determining the position, orientation and attitude of the PUGS with respect to the LRP
- Confirm the operation of the software developed to implement this concept
- Evaluate location of the acoustic hardware on the PUGS and LRP units for optimum performance and protection.

It was determined early in the trials that the acoustic environment of the tank made the required telemetry communications with the Simultaneous COMPATT unusable. It was also decided that the cycle time required for a complete set of measurements was too long when it included the telemetering of the data from this COMPATT. Therefore, the COMPATT was replaced by another transceiver.

The trials also indicated areas where the software required modifications to improve both ease of use and the display of data and results for the purpose of monitoring and quality control. Most of these were made on site and were tested during the trials.

The location of the acoustic hardware was adjusted occasionally through the trials to determine a balance between performance and protection.

These trials proved that the INVERTED LBL solution provided steady and reliable results when the acoustic data was reliable, thus validating the concept. It was also shown that the measurement cycle time, even though it was slowed more than recommended, and the approach taken for the processing of the data resulted in reasonable response times to changes in the position and orientation of the PUGS.

6.2 LOCH LINNHE TRIALS

The second set of trials was performed from a barge with a crane on Loch Linnhe. They provided the opportunity to test the application of the INVERTED LBL concept in open water. The first phase was performed with the barge dockside, the second when it was in open water. These trials were supported with an underwater Remotely Operated Vehicle (ROV).

The first phase was similar to the tests performed at the tank trials. First, the LRP and PUGS, connected by strops so that the LRP hung below the PUGS, were suspended in the water. Next, the LRP was placed on the bottom and the PUGS lowered to it. For both of these tests, position, attitude and orientation of the PUGS relative to the LRP were monitored with WinFrog and the ROV.

The second part of the test required that the barge move away from the pier to deeper water. The LRP was deployed to the bottom and again the PUGS was lowered to it. This trial included the use of USBL to monitor the initial descent to the bottom. The operation was again monitored with WinFrog and the ROV.

The trials were a considered a success. The following issues were isolated and addressed during the trials:

- Though the performance of the acoustic hardware was greatly improved over that observed in the tank trials, a significant problem was noticed with the acoustic signal travelling through the steel of the PUGS structure when the PUGS was close to the LRP. Since sound travels through the steel faster than through water, the observed ranges were considerably shorter than they in fact were. This affected the observations between transceivers and transponders located diagonally opposite each other on the PUGS and LRP. The software was modified to allow the operator to easily deweight the diagonal ranges from the adjustments and alternatively reweight them back in.
- The re-setting of initial unknowns at various stages of the operation for use in the least squares adjustments was determined to be incomplete and was corrected.
- The alphanumerical data displays were still considered confusing and were improved.

The results of the trials validated both the application of the INVERTED LBL concept and the design of the PUGS for the mating itself. In addition, they confirmed that the acoustics would perform reliably in open water. The graphic images generated by the software enabled the winch controller to choose the moment in the wave cycle to dock the lubricator.

7. CONCLUSIONS

The WinFrog INVERTED LBL concept and its application to the SWIFT Riser project were proven by the trials. The concept of the PUGS mating mechanism itself was also validated by the trials. This software is now a part of the WinFrog LBL module.

It is recommended that a multiple transceiver acoustic system that is capable of interrogating a transponder array with any one of its transceivers and observing the replies on all transceivers be investigated. This would provide the information required to derive the range data to all the transponders from all the transceivers in a single epoch.

It is now possible to start considering this approach for similar precise deep-water requirements such as mating Deepwater Pipeline Intervention Systems. In this scenario, the transceivers would be located on the structure being lowered because the structure built into the pipeline would not have the return lines to the surface required for the communications with the ROVNAV systems, but the structure being lowered would. The concept is the same, but inverted yet again.